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MATERIA: Smart Electricity Systems - Prof. Chicco, Bojoi, Bompard

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POLITECNICO DI TORINO

local energy system

DISTRIBUTED ENERGY RESOURCES

Prof. Gianfranco Chicco

Dipartmento Energia "Galileo Ferraris"

01RUK - Smart Electricity Systems

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INTRODUCTORY

ASPECTS

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Outline

(1) ▪ Introductory aspects and terminology

(2) ▪ island operation and micro-grids ~~Notes on the local generation resources~~

(4) ▪ Capability curves of the generation systems

(3) ▪ Evolution of rulemaking and standards

(5) ▪ General aspects on grid connection

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Current terminology

- **DER** Distributed Energy Resources — 3 different aspect
- **DER = DG + DR + DS, with:**
  - **DG** Distributed Generation
  - **DR** Demand Response — active participation of the users
  - **DS** Distributed Storage — ACCUMULO
- **RES** Renewable Energy Sources

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the generation system has to be prepared for the load

Faster to cover the peak

Decoupling generator and load:

storage (expensive)

stored energy

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with the local generation is more difficult predict the load
Excess of generation: current in the other direction

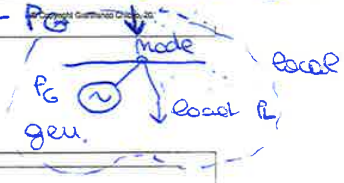
Development of local sytems

- The development of distributed generation and storage has been initially *limited* by the lack of suitable technologies available at accessible costs to the generality of the users
- Then, the technology development in the generation systems, grid interface, communication, control and protection, together with the evolution of the markets and rulemaking, have *increased* the level of local generation connected to the electrical distribution networks
- Past and current developments may be seen with successive *periods*:
  - *Preliminary* period (indicatively, from the Eighties to the end of the Nineties), with evolution of the technologies but limited applications
  - *Initial growth* period (from the end of the Nineties to about 2010), with increase of the installations but limited impact on the grid
  - *Intermediate growth* period (in progress in the last years), with significant impact on the grid operation
  - *Advanced growth and consolidation period* (already happening in some jurisdictions), reaching the limits for DER diffusion

no storage: full → cut generation

$P_L - P_G$

NET POWER
see only the difference



DG penetration

- DG *penetration* in the distribution systems is typically quantified by using *ratios* between the amount of DG and of the load served (or the amount of generation from the conventional supply system
- These *ratios* may be defined:
  - in terms of *installed power*, e.g., $\chi = \frac{A_{DG}}{\hat{A}_{load}}$ or $\chi' = \frac{\hat{A}_{DG}}{A_{supply}}$
    with *rated power A* in [kVA] and upper symbols for *peak* values
  - in terms of *energy* [MWh], e.g., $k = \frac{W_{DG}}{W_{load}}$ or $k' = \frac{W_{DG}}{W_{supply}}$
- *Scalar* DG penetration indicators are often used for *synthetic* information
- However, scalar values *cannot* represent the diffusion of DG sources at *different locations* and their availability at *different periods* of the day

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installing power but zero energy
using the right indicator

TOP generation
solar irradiance

P → 20%
E → 4%

Technical aspects

standard, limit in the connection

- Various technical issues are related to the *DER operation* in distribution systems:
  - ✓ *short-circuit currents* could increase at the distribution system nodes with respect to the normal levels (without DG) due to the contribution of the DG not controllable by the distributor
  - ✓ short-circuit currents could exceed the short-circuit capability declared at the system nodes, affecting the *protection device sizing* inside the MV/LV substations
  - ✓ a rapidly evolving regulation refers to the *quality* of the electricity supply
  - ✓ from the *network structure* viewpoint, the presence of multiple generation sources is raising the question on whether it would be convenient to adopt more or less *weakly meshed* networks for the distribution systems
  - ✓ in weakly meshed networks, several problems encountered could be solved with *techniques* already used for the *transmission system* analysis
  - ✓ present distribution system *sizing* and *protection schemes* prevent from immediately adopting meshed structures

change circuit breaker → kA ↑↑

PQ power quality

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Stiffness ratio

- The network strength is generally quantified by evaluating the *short circuit power* S_{ccR} of the network and the contribution S_{ccDER} of the DER to the short-circuit currents
- The *stiffness ratio* is defined as $R = (S_{ccR} + S_{ccDER}) / S_{ccDER}$
- The ratio R is evaluated at the point of common coupling (PCC), except when there is a transformer dedicated to a single user (in this case, the ratio R is computed at the High Voltage side of the dedicated transformer)
- Example: for un 20 kV feeder with S_{ccR} = 50 MVA at the PCC and installation of a synchronous machine with contribution to the short circuit currents S_{ccDER} = 3 MVA, the stiffness ratio is R = 53/3 = 17.67
- With high R (> 200) the problems (voltage variation, harmonics, flicker) are limited
- With low R (< 50), the problems may require to fix *rules* to *limit* the possibility of connecting new DER to the grid

$\frac{S_{ccR} + S_{ccDER}}{S_{cc\,DER}}$

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short circuit power: conventional definition

$S_{cc} = \sqrt{3}\, V_n I_{cc}$ [MVA]

↑ short circuit current

upper side of the system

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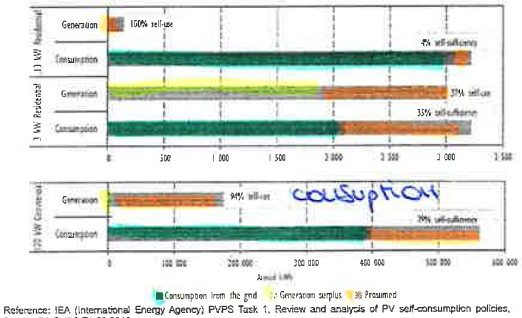
100% self consumption
9% self sufficiency

SELF-CONSUMPTION AND SELF SUFFICIENTY

consumo



Reference: IEA (International Energy Agency) PVPS Task 1, Review and analysis of PV self-consumption policies, Report IEA-PVPS T1-28:2016

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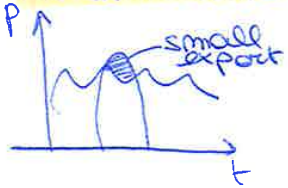
consumption

PROSUMER produced and consumed in the same time



CHOICE OF THE DG SOLUTION

The choice of the DG technology to be installed depends on

- ***location***: many DG sources require availability of primary source (e.g., wind, sun, tides,…)
- ***modularity***: some technologies can be installed in modules of different or multiple size, with possible future expansion
- ***combined generation***: some applications may need combining different types of energy
  - ✓ *cogeneration* (heat and electricity)
  - ✓ *trigeneration* (electricity, heat and cooling)
  - ✓ *multigeneration* (e.g., with heat demand at multiple enthalpy levels, electricity and cooling)
- ***cost effectiveness***: the cost involved include installation, operation and maintenance
- ***environmental impact***: potential effects concerning emission, noise and visual impact

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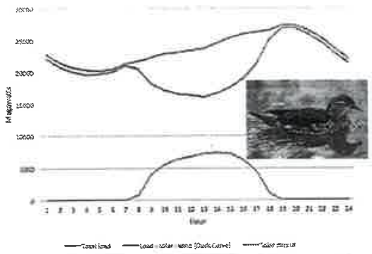
THE DUCK CURVE

- Differences arising from the presence or absence of *RES generation* due to ambient conditions
- High *evening ramps*
- Would the presence of EVs *improve* the situation?

electric vehicles

California hourly electric load vs. load less solar and wind (Duck Curve) for October 22, 2016



http://www.caiso.com/market/Pages/ReportsBulletins/DailyRenewablesWatch.aspx

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TOTAL LOAD AND LOCAL GENERATION

local generation

SUN

incerta

covering the slope is difficult, supply extra energy if there are clouds, storms...

STORAGE: POWER AND ENERGY?

- *Different* applications
- *Indicative* features
- *Energy*-based:
  - long times
  - slow provision of the service (fornitura)
  - low power needed from the infrastructure
- *Power*-based:
  - short times
  - fast provision of the service
  - high power needed from the infrastructure

Energy Storage Association, http://energystorage.org/

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Islanding

- ***Non-intentional*** islanding is generally ***prohibited***:
  - ✓ ***voltage*** and ***frequency*** cannot be guaranteed within the ***quality levels*** prescribed by the regulations
  - ✓ non-intentional islands must be ***detected*** and ***eliminated*** as fast as possible
- For ***intentional*** islands:
  - ✓ one/more generators should be able to ***support voltage supply*** to the island
  - ✓ local units must be able to satisfy loads and load ***variations*** without experiencing dynamic problems in their voltage and frequency control systems
  - ✓ ***power quality*** aspects in the island should not exceed specific limits
  - ✓ ***reliable*** units and careful coordination of protections are needed
  - ✓ since DR is owned and managed by operators independent of the distribution system operator, ***coordinating*** the activities for ensuring islanding operation and providing satisfactory ***communication*** is a challenging task

demande response

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Microgrids

- The demand for and supply of energy within the *microgrid* is monitored from a ***control center*** to optimizes the use of DER (***DG***, ***DR*** and ***DS***)
- Main ***advantages*** of the ***microgrids***:
  - high *availability*
  - possible combined management of the *energy mix* (electricity, heat, cooling, gas, water, hot water, etc.)
  - *modular* operation planning
  - possible *resource optimization* inside the microgrid
  - *synergies* for personnel resources, primary energy purchase, maintenance, billing and supply services
  - increase in *economic efficiency*
  - possible *integrated energy bill* with fixed cost reductions for the consumers
  - *reduced vulnerability* of the local energy supply system due to the multiplicity of local resources

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Microgrids

normally operating alone

- ***Microgrids*** are *small* distribution systems containing generation and load, whose operation could be totally separated (***autonomous***) from the main distribution system or connected to it (***non-autonomous***)
- Conceptual *difference* with respect to intentional islands:
  - *intentional islands* are *normally connected* to the network and may operate separately only when required (e.g., to assist the system restoration after a fault)
  - *microgrids* operate *normally* as *independent* systems and *may be* connected to the network (in the non-autonomous cases) in emergency cases (to improve the continuity of supply after a fault in the network or in the microgrid) or according to *economic conveniences* due to the electricity prices for energy or reserve service
- The ***autonomous*** micro-grids operation is critical, due to the possible problems in *voltage* and *frequency* control

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Microgrids

- ***Benefits*** from a ***microgrid*** system occur for different types of companies and organizations
  - rural communities far from the existing power grids
  - large industries with many local and scattered sites
  - industrial parks
  - island communities
  - power providers in developing countries lacking of infrastructure

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The ENTSO-E Document (1/4)

document sent to european commission

entsoe

Commissioner Oettinger
European Commission
B-1049 Brussels

Daniel Dobbeni
President

Tel +32 2 741 09 50
Fax +32 2 741 09 51

Subject: Automatic frequency disconnection settings of installed photovoltaic (PV) panels in some European countries

18 July 2011

Dear Mr Oettinger,

This letter is to brief you on a security of supply issue arising from the automatic frequency disconnection settings of installed photovoltaic (PV) panels in some European countries and to request your support in encouraging the national Regulatory authorities in impacted countries to facilitate the timely implementation of remedial actions.

Due to the interconnected nature of the transmission system until such remedial actions are implemented the synchronous Central European power system is at increased risk to significant frequency deviations of a magnitude that would generate a widespread loss of supply.

https://www.entsoe.eu/about-entsoe-e/Pages/default.aspx

The ENTSO-E Document (2/4)

In several European countries, connection standards applicable to photovoltaic panels and other distributed generation have been or are still specifying that the panels automatically disconnect from the grid whenever the system frequency reaches 0.2 or 0.3 Hz deviations from the required normal value of 50.0 Hz.

Current information from our Member TSOs, including for example Germany and Italy, indicate that the significant growth in photovoltaics in recent years has resulted in a PV installed capacity (with such settings) approaching 25 000 MW. At these levels there is clearly a risk of an instantaneous generation loss far in excess of the 3000MW generation loss 'ride-through' design limit for the Continental European system.

Some countries have already changed their distribution connection standards appropriately, but others have not yet been able to do this due to complex standard setting procedures involving manufacturers and other parties. The "Requirements for Grid Connection Applicable to all Generators" Network Code should address this when it becomes binding across Europe (expected for early 2013, perhaps with transition periods) but the severity of the issue requires action to be taken ahead of this.

https://www.entsoe.eu/about-entsoe-e/Pages/default.aspx

The ENTSO-E Document (3/4)

In addressing the current frequency disconnection settings on installed PV panels a two phased approach has been proposed (although every TSO should define the best approach for its responsible area):

1. PV units which have the capability for (low cost) on-site re-programming or standard inverter swaps should be modified to achieve graduated disconnection frequencies at small increments, e.g. 100 mHz, between 50.3 and 51.5 Hz.
2. Design and implementation of a PV retrofitting program in each affected country so that the existing units also align with the new connection standards harmonised with those for conventional units (to stay connected in the frequency ranges of 47,5 – 51,5 Hz and, in case of overfrequency, active power reduction in proportion to the overfrequency, (as stipulated in the draft Requirements for Grid Connections Applicable to all Generators Network Code).

avoid disconnection when possible

Phase one will reduce the risk and should be readily achievable giving some comfort whilst phase two is implemented. Given the risks to system security of the Continental European power system we recommend these actions are progressed without delay.

However, before these actions can be implemented there are a number of issues relating to ownership, accountability and cost recovery that would need to be resolved by the national regulatory authorities of the affected countries.

https://www.entsoe.eu/about-entsoe-e/Pages/default.aspx

The ENTSO-E Document (4/4)

We are therefore requesting your support in highlighting the importance of this issue to the relevant regulatory authorities and consequently the need for any regulatory issues precluding the implementation of the remedial actions to be addressed as a priority.

Given that this issue impacts a significant number of member states and will take some time to resolve it may be opportune to include it as a briefing item on the agenda for the July member state meeting on grid stability/security of supply with an update at the September Energy Council meeting. Should you consider this to be appropriate I will action the production of suitable presentation material.

Sincerely,

Dobbeni

Daniel Dobbeni
President
ENTSO-E

https://www.entsoe.eu/about-entsoe-e/Pages/default.aspx

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Active and Passive Users

- *User:* subject that uses the network to *inject* and/or *take* electricity
- The Users are partitioned into:
  - *Active Users* for production: Users that use any equipment (rotating or static) that converts any form of useful energy into electricity, connected to the network (also not continuously). The Users installing Uninterruptible Power Supply (UPS) systems are excluded
  - *Passive Users:* all the Users not belonging to the previous definition, including installations to supply *electric vehicles* (battery charging stations), installations to supply *public lighting systems*, and *temporary/provisional* installations (to supply civil works, circuses, etc.)

Standard CEI 0-21 (2016)

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Objectives of the Standard CEI 0-16

- Define the technical *criteria to connect the* Users to the electrical distribution network with rated voltage in AC up to 1 kV included
- For the *Active Users*, the Standard is aimed at:
  - defining the startup, operation and disconnection of the local production plant
  - *avoiding* the islanding operation of the local production plants on portions of the Low Voltage network of the DSO
  - *defining* some prescriptions concerning the production plants operating in *isolated service* on the *internal network* of the Producer; these prescriptions are *not* applicable to the connection of the production plant to the DSO network

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CAPABILITY LIMITS OF THE GENERATORS

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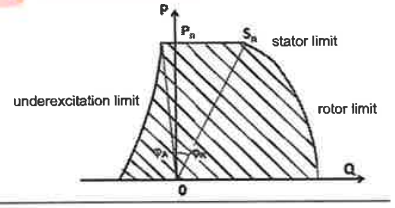
Capability curve of synchronous generator

- The *capability* curves of *synchronous* generators are defined by taking into account the limits referring to stator, rotor, mechanical and operation in underexcitation mode
- *For synchronous generators with active power P_n < 400 kW, for $P = P_n$:* the power factor has to be regulated between 0.98 in reactive power absorption and 0.9 in reactive power injection

P_n < 400 kW



Italian Standard CEI 0-16

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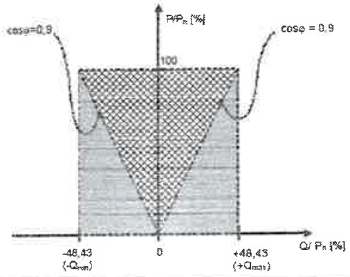
Inverter connection to the Low Voltage grid

- For inverter-based grid connection in systems with total power higher than 6 kW, the Standards define *rectangular* and *triangular* capability limits



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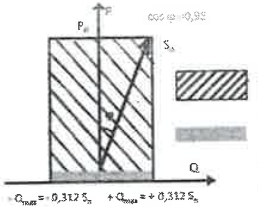
Capability curve for wind systems

- For wind generators of full-converter type or with Doubly Fed Induction Generator, the characteristic is *rectangular*



power electronic design difficult operating

Italian Standard CEI 0-16

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GENERAL ASPECTS

OF GRID CONNECTION

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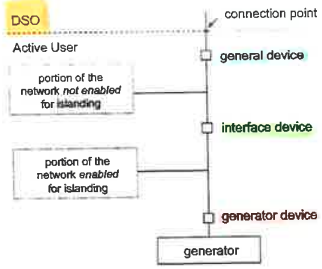
General scheme

- *Location* of the protection devices



loss of supply from the top
→ interface device open

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DSO: distribution system operator
local generator does not supply all the local load
open interface device → island

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Voltage variation range

- The current rules require that the local plants *remain connected* to the grid for a wider set of operating conditions with respect to the past
- The local production plants, under any load condition, must remain *permanently connected* to the Low Voltage or Medium Voltage network for voltage values in the grid connection point included in the range (Vn is the rated voltage)

$$85\%\ Vn \le V \le 110\%\ Vn$$

- The Active User must guarantee that these operation intervals are respected by both the *interface protection* and the *generator protection*
- The DSO *monitors* the respect of these requisites

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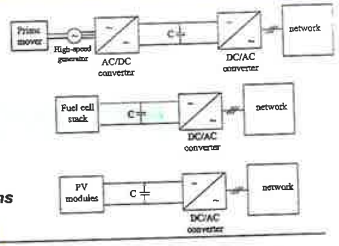
Inverter-based network interfaces

- Most *local sources* generate power in *DC* (Direct Current) or AC (Alternating Current) at frequency *different* from 50 Hz (network frequency)
- These sources are *interfaced* to the external network through *inverters*
  - ***microturbines***
  - ***fuel cells***
  - ***photovoltaic systems***



we are already DC

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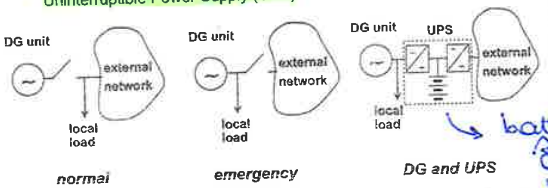
only side of connection with the network

higher frequency

Modes of operation of the local DG units

- ***Backup supply***
  - the DG unit *off-line* in normal operation and is switched *on* in case of emergency (service interruption from the external network)
  - the DG unit can be combined with *storage* systems to provide Uninterruptible Power Supply (UPS)



batteries supply batteries from batteries in case of problems

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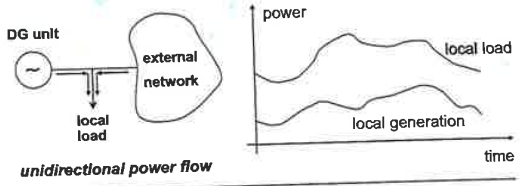
Modes of operation of the local DG units

reduced off peak

- ***Peak shaving***
  - the DG unit is *always connected* to the external network
  - the local generation *never exceeds* the local load
  - the power flow from the external network to the local load is always *unidirectional*



PEAK SHAVING

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it is not possible this direction

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Smart Electricity Systems

COMBINED PRODUCTION SYSTEMS

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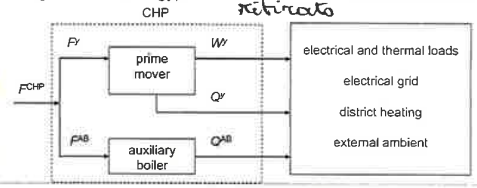
Combined production

- The *black box* contains some key elements:
  - the cogeneration *prime mover* motore primo
  - the *auxiliary boiler* (with possible supply through a different fuel)
- The outputs from the CHP system interact with the *loads*, with the rete di teleriscaldamento *electrical grid* (in a bidirectional way), and in case with the *district heating network*, and in certain circumstances part of the heat (not forming the useful energy) can be *withdrawn* to the external ambient ritirato



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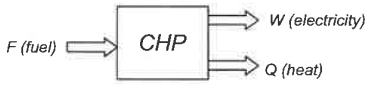
Combined production

- ***Cogeneration*** (or ***CHP***, Combined Heat and Power) refers to *simultaneous* production of electricity and heat, obtained by using the same fuel source sorgente
- The *effectiveness* of cogeneration depends on the possibility of reaching *energy savings and environmental benefits* with respect to the *separate production of* electricity (from the electrical grid) and heat (through local boilers) in an economically competitive way
- *Black box model*:



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MOTORI PRIMI

Prime movers (commercial applications)

- *Internal Combustion Engines* (ICE) motori, supplied with gas or diesel
  - sizes up to some dozens of MW_e
  - excellent performance at partial loads
  - emissions from diesel units higher than those from gas units
- *Gas turbines*
  - sizes from about 5 MW_e
  - relatively low emissions
  - efficiency decreasing at partial loads
- *Microturbines*
  - indicative sizes in the range 25-300 kW_e
  - lower emissions with respect to ICE
  - efficiency decreasing at partial loads (but less than gas turbines)

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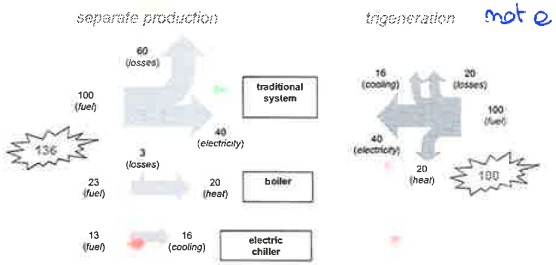
cop: coefficiente di prestazione

Trigeneration

different possibility

- *Combined generation of electricity, heat* and *cooling*
- Convenient with respect to separate production with *equal demands*
- *Sankey diagrams*

not a single machines, a set of machines



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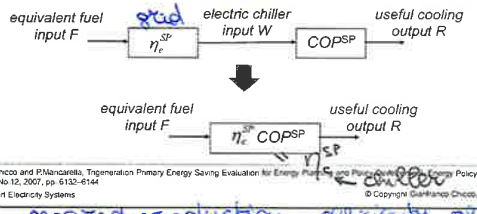
Trigeneration Primary Energy Saving

- Acronym *TPES*
- *Extension* of the *PES* used for cogeneration
- A *reference value* for *cooling* in *separate production* is needed:
  - defined by taking into account the COP^{SP} of a reference *electric chiller*
- Since the *electric chiller* is fed by electricity, the reference value is obtained by considering the *chain* $\eta_e^{SP} = \eta_e^{SP} COP^{SP}$

COP > 1

refrigeratore elettrico

catena



G.Chicco and P.Mancarella, Trigeneration Primary Energy Saving Evaluation for Energy Planning and Policy Development, Energy Policy, Vol. 35, No.12, 2007, pp. 6132–6144
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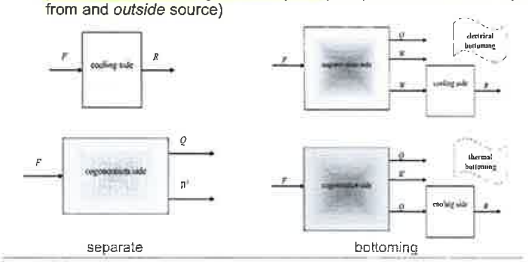
separed production efficiency of electricity

Trigeneration

- One of the main aspects is the *cooling generation mode*:
  - *Separate* (or parallel): cooling unit *not* supplied by electricity or heat
  - *Bottoming* (or cascaded): cooling unit supplied by electricity or heat produced *inside* the trigeneration plant (with possible *additional* input from and *outside* source)

output of the cogenerator

load chiller (input)



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Trigeneration Primary Energy Saving

- Definition:

$$TPES = \frac{F^{SP} - F}{F^{SP}} = 1 - \frac{F}{\frac{W}{\eta_e^{SP}} + \frac{Q}{\eta_t^{SP}} + \frac{R}{\eta_c^{SP}}}$$

electricity chiller

- *F* overall *fuel thermal energy input* (including the fuel feeding an auxiliary boiler or a *separate* cooling machine)
- F^{SP} total fuel thermal energy input needed for the separate production of the same energy vectors *W*, *Q* and *R* in the trigeneration system
- *W* net *electricity output* (including the electricity sold to the grid, excluding the electricity used to supply units inside the trigeneration system)
- *Q* net *heat output* (*excluding the thermal energy* used to supply units inside the trigeneration system)
- *R* net *cooling energy output* (excluding the energy used for cooling purposes inside the system)

G.Chicco and P.Mancarella, Trigeneration Primary Energy Saving Evaluation for Energy Planning and Policy Development, Energy Policy, Vol. 35, No.12, 2007, pp. 6132–6144
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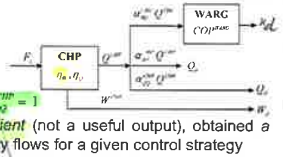
$$R_o = R^{CERG} + R^{WARG} = COP^{CERG}\left(\alpha^{CHP}_{RW}\,\eta_W\,\alpha^{GDS}_{YF}\,F_i + \alpha^{EDS}_{RW}\,W_i\right) + COP^{WARG}\left(\alpha^{CHP}_{RQ}\,\eta_Q\,\alpha^{GDS}_{YF}\,F_i + \alpha^{AB}_{RQ}\,\eta_T\,\alpha^{GDS}_{QF}\,F_i\right)$$

centro energetico

The *Energy Hub* model

- Overall system: *matrix* representation $\mathbf{v}_o = \mathbf{H}\cdot\mathbf{v}_i$
- The matrix entries can be determined by *visual inspection*
- Example for a *subsystem* with CHP and WARG (with no auxiliary boiler nor grid connection)
- Input array $\mathbf{v}_i = [F_i, 0, 0, 0]^T$
- Output array $\mathbf{v}_o = [0, W_d, Q_d, R_d]^T$
- The *topology* is represented by the *dispatch factors* $\alpha^{CHP}_{QQ} + \alpha^{CHP}_{RQ} + \alpha^{CHP}_{RQ} = 1$
- Q_d is the heat wasted to the *ambient* (not a useful output), obtained *a posteriori* after calculating all energy flows for a given control strategy
- *Energy balance*: $W_d = \eta_W F_i$, $Q_d = \eta_Q \alpha^{CHP}_{QQ} F_i$, $R_d = \eta_Q \alpha^{CHP}_{RQ} COP^{WARG} F_i$



$$\Longleftrightarrow \mathbf{H} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \eta_W & 0 & 0 & 0 \\ \eta_Q\,\alpha^{CHP}_{QQ} & 0 & 0 & 0 \\ \eta_Q\,\alpha^{CHP}_{RQ}\,COP^{WARG} & 0 & 0 & 0 \end{bmatrix}$$

ambient

G.Chicco and P.Mancarella, Matrix modeling of small-scale trigeneration systems and application to operational optimization, Energy, Vol. 34, No. 3, March 2009, pp. 261–273
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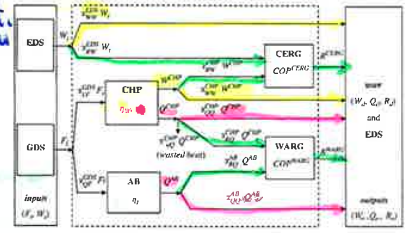
The *Energy Hub* model

- Larger example with Electricity Distribution System (EDS) and Gas Distribution System (GDS)

distribut. system



Inputs: W_i, F_i

Outputs: W_o, Q_o, R_o

G.Chicco and P.Mancarella, Matrix modeling of small-scale trigeneration systems and application to operational optimization, Energy, Vol. 34, No. 3, March 2009, pp. 261–273
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$$W_o = \alpha^{EDS}_{WW}\,W_i + \alpha^{CHP}_{WW}\,\eta_W\,\alpha^{GDS}_{YF}\,F_i$$

$$Q_o = \alpha^{CHP}_{QQ}\,\eta^{CHP}_Q\,\alpha^{GDS}_{YF}\,F_i + \alpha^{AB}_{QQ}\,\eta_T\,\alpha^{GDS}_{QF}\,F_i$$

$$\begin{vmatrix} 0 \\ W_o \\ Q_o \\ R_o \end{vmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \alpha^{CHP}_{WW}\,\eta_W\,\alpha^{GDS}_{YF} & \alpha^{EDS}_{WW} & 0 & 0 \\ \left(\alpha^{CHP}_{QQ}\,\eta_Q\,\alpha^{GDS}_{YF} + \alpha^{AB}_{QQ}\,\eta_T\,\alpha^{GDS}_{QF}\right) & 0 & 0 & 0 \\ COP^{CERG}\,\alpha^{EDS}_{RW} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} F_i \\ W_i \\ 0 \\ 0 \end{bmatrix}$$

The *Energy Hub* model

- *Plant coupling matrix* $\mathbf{H}$ for the larger example (from visual inspection):

$$\boxed{\mathbf{v}_o = \mathbf{H}\cdot\mathbf{v}_i}$$

output

$$\begin{bmatrix} 0 \\ W_o \\ Q_o \\ R_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \alpha^{\gamma}_{WW}\,\alpha^{GDS}_{Fy}\,\eta_W & \alpha^{EDS}_{WW} & 0 & 0 \\ \alpha^{CHP}_{QQ}\left(1-\alpha^{GDS}_{Fy}\right)\eta_I + \alpha^{\gamma}_{QQ}\,\alpha^{GDS}_{Fy}\,\eta_Q & 0 & 0 & 0 \\ \eta_{RF} & COP_c^{CERG}\left(1-\alpha^{EDS}_{WW}\right) & 0 & 0 \end{bmatrix} \begin{bmatrix} F_i \\ W_i \\ 0 \\ 0 \end{bmatrix}$$

with $\eta_{RF} = COP_c^{CERG}(1-\alpha^{\gamma}_{WW})\alpha^{GDS}_{Fy}\eta_W + COP_c^{WARG}\left[(1-\alpha^{CHP}_{QQ})(1-\alpha^{GDS}_{Fy})\eta_I + \alpha^{\gamma}_{QQ}\alpha^{GDS}_{Fy}\eta_Q\right]$

G.Chicco and P.Mancarella, Matrix modeling of small-scale trigeneration systems and application to operational optimization, Energy, Vol. 34, No. 3, March 2009, pp. 261–273
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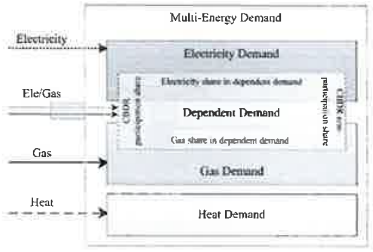
Dependency between energy vectors

- Consider the *dependency* of the different energy vectors to provide the same service, e.g., electricity and gas as substitutable resources



CBDR: Carrier-based Demand Response

Nafiar Neyestani, Mahar Yazdani-Damavandi, Madjeda Shafie-khah, Gianfranco Chicco, João P.S. Catalão, Stochastic Modeling of Multienergy Carriers Dependencies in Smart Local Networks with Distributed Energy Resources, IEEE Trans. on Smart Grid, vol. 6, no. 4, July 2015, pp. 1748-1762
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gas price different

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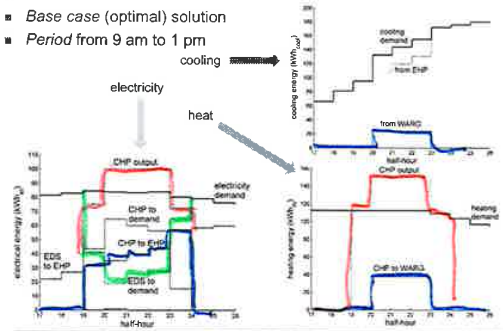
Multi-energy system optimisation

- *Base case* (optimal) solution
- *Period* from 9 am to 1 pm



P. Mancarella and G.Chicco, Integrated energy and ancillary services provision in multi-energy systems, Proceedings of the IREP 2013, Rethymnon, Crete, Greece, 25-30 August 2013
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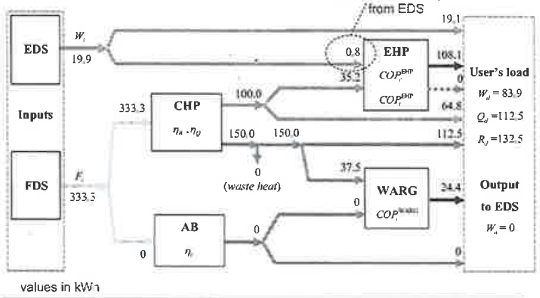
price high in a period → absisted by EHP

electric heat.. EHP

Initial solution at hour 10 am

- The EHP operates in *cooling mode*

first candidate to the reduction: EHP input from EDS



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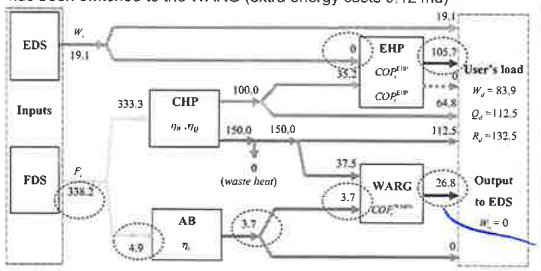
energy flow

reduce electricity input to EHP → money

electric heat pump

EHP input reduction (from EDS)

- The cooling output corresponding to the EHP input reduction of 0.8 kWh_{el} has been *switched* to the WARG (extra energy costs 0.12 mu)



P. Mancarella and G.Chicco, Integrated energy and ancillary services provision in multi-energy systems, Proceedings of the IREP 2013, Rethymnon, Crete, Greece, 25-30 August 2013
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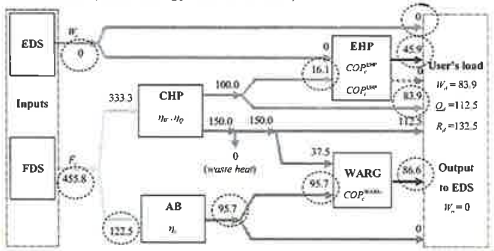
covered here

another possibility

EHP input reduction (from CHP)

- Part of the CHP electrical output supplying the EHP (19.92 kWh_{el}) is *shifted* to serve the electrical load and *reduce* the electrical input from EDS to *zero* (extra energy costs 2.92 mu)



Another portion of the cooling supply is *shifted* from the EHP to the WARG

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POLITECNICO DI TORINO

THE ROLE OF THE ENVIRONMENT

Prof. Gianfranco Chicco

Dipartmento Energia "Galileo Ferraris"

01RUK - Smart Electricity Systems

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Kyoto protocol

- United Nations Framework Convention on *climate change*
- Text *established* on December 11, 1997
- Deals with *quantified* emission limitation and reduction commitments
- Art.20: each Party shall implement and elaborate *policies* for:
  - enhancing the *energy efficiency* in relevant sectors of the economy
  - protecting and enhancing skills and reservoirs of *greenhouse gases*, promoting sustainable forest management and agriculture
  - research, promotion, development and increased use of *renewable forms* of energy, CO_2 sequestration technologies and advanced and innovative environmentally sound technologies
  - progressively reducing or eliminating *market imperfections*, fiscal incentives, tax and duty exemptions and subsidies in all greenhouse gas emitting sectors
  - encouraging measures to *limit emissions* of greenhouse gases

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Outline

- *Greenhouse* gases
- Local and global *emissions*
- The *emission factor* model
- *Indices* of emission reduction

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Greenhouse gases

CO_2	-	carbon dioxide
CH_4	-	methane
N_2O	-	Nitrousoxide
HFC	-	Hydrofluorocarbon
PFC	-	Perfluorocarbon
SF_6	-	Sulphur hexafluoride

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Emission balances

- Global emission balance
  - It does not take into account the location of the emission source with respect to the receptors
- Local emission balance
  - Takes into account the impact of large electricity production plants that may be located far from the area of interest
  - When the electricity production plants are far from the area of interest, their contribution can be reduced or even *ignored*
  - Deals with pollutants with relatively reduced propagation (e.g., NOx and CO in urban areas)
  - The separate production of heat is considered to be inside the area of interest

consider/ not consider it depends

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Reference values

- There are different approaches to establish the *conventional* values of the emission factors in *separate productions*, based on:
  - *average values* of the emission factors for the production mix over the territory
  - *emission factors* for technologies adopting the *same fuel* (e.g., natural gas), considering
    - *average technologies* for *sizes similar* to those of the system analyzed
    - the *best technologies* available for *similar sizes*
    - the *best technologies* available *without* size limits

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Index of emission reduction in the global emission balance

- Index of CO_2 *emission reduction*

$$CO_2ER = \frac{\left(m_{CO_2}\right)^{SP} - m_{CO_2}}{\left(m_{CO_2}\right)^{SP}} = 1 - \frac{\mu^{P}_{CO_2} F}{\left(\mu^{W}_{CO_2}\right)^{SP} W + \left(\mu^{Q}_{CO_2}\right)^{SP} Q}$$

combined generation

convenience if $CO_2ER > 0$

energy → fuel
heat → mass

← useful energy / heat

- The index can be extended to other greenhouse gases by introducing the Global Warming Potential (*GWP*), related to the CO_2 emissions
- For the generic greenhouse gas *p*, the *equivalent* emission factor used in the definition of the *indices* is

$$\mu^{X}_{CO_2eq,p} = GWP_p \cdot \mu^{X}_{p}$$

equivalent gases

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the highest value is 1
the lowest value is no limit: it can be worst and worst

Local emissions

- The *local emissions* represent a problem when the local generation technology introduces a quantity of pollutant higher than the one existing in the reference situation
- In *urban areas*, the effect of some pollutants (e.g., NOx) can be *added* to the pollution present in the ambient (for instance, due to road traffic), worsening the situation regarding people's health
- For cogeneration technologies, the emissions at *partial loads* are drastically worse than the ones at rated load
- *Regulatory limits* are often stringent, limiting the diffusion of sources producing local pollutants

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Other greenhouse gases

- The Global Warming Potential (*GWP*) is used to represent *other greenhouse gases* (GHG) seen as global pollutants
- For a generic GHG *g* the *equivalent* emission factor is

$$\mu^X_{CO_2eq,g} = GWP_g \cdot \mu^X_g$$

- The *overall contribution* of the various GHGs belonging to the set ***G*** emitted from the same source is

$$\mu^X_{CO_2eq} = \sum_{g \in G} \mu^X_{CO_2eq,g}$$

- By using the *equivalent emission factors* related to CO_2:

$$PCO_2ER = 1 - \frac{\mu^F_{CO_2eq} F}{\sum_{(X,x)\in D} \mu^{X,RP}_{CO_2eq} X}$$

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Other pollutants … SO_2

- The *Acidification Potential* (*AP*) is the potential of a substance to build (produce) and release H^+ protons, expressed in relative terms with respect to SO_2 as the *reference* substance
- Consider the set ***G*** of *relevant* substances $g \in G$
- Introduce the emission factor v^X_g (g/kWh) with respect (riguardo) to acidification, with $AP_{SO_2} = 1$
- Define the *equivalent emission factor* with respect (riguardo) to SO_2

$$v^X_{SO_2eq,g} = AP_g \cdot v^X_g$$

- Define the SO_2 *equivalent* emissions $\quad v^X_{SO_2eq} = \sum_{g \in G} v^X_{SO_2eq,g}$

P. Mancarella and G. Chicco, Operational optimization of multigeneration systems, chapter 10 in J.P.S. Catalão (ed.) Electric Power Systems: Advanced Forecasting Techniques and Optimal Generation Scheduling, CRC press, Taylor & Francis Group, Boca Raton, FL, 2012, ISBN: 978-1-4398-9394-4, pp. 10.1-10.55

lateral

Other pollutants … R11

- The *Ozone Depletion Potential* (*ODP*) is the potential of a substance to (causare) deplete the stratospheric ozone, expressed in *relative* terms with respect to reference substance trichlorofluoromethane (CCl_3F, also identified as R11)
- Consider the set ***G*** of *relevant* substances $g \in G$
- Introduce the *emission factor* o^X_g (g/kWh) with respect to ozone depletion, with $ODP_{R11} = 1$
- Define the *equivalent emission factor* with respect to R11

$$o^X_{R11eq,g} = ODP_g \cdot o^X_g$$

- Define the R11 *equivalent* emissions $\quad o^X_{R11eq} = \sum_{g \in G} o^X_{R11eq,g}$

P. Mancarella and G. Chicco, Operational optimization of multigeneration systems, chapter 10 in J.P.S. Catalão (ed.) Electric Power Systems: Advanced Forecasting Techniques and Optimal Generation Scheduling, CRC press, Taylor & Francis Group, Boca Raton, FL, 2012, ISBN: 978-1-4398-9394-4, pp. 10.1-10.55

Related indicators

- Polygeneration Sulphur Dioxide Emission Reductions (*PSDER*), for *acidification*

$$PSDER = 1 - \frac{v^F_{SO_2eq} F}{\sum_{(X,x)\in D} v^{X,RP}_{SO_2eq} X}$$

- Polygeneration R11 Emission Reductions (*PR11ER*), for *stratospheric ozone depletion*

$$PR11ER = 1 - \frac{o^F_{R11eq} F}{\sum_{(X,x)\in D} o^{X,RP}_{R11eq} X}$$

P. Mancarella and G. Chicco, Operational optimization of multigeneration systems, chapter 10 in J.P.S. Catalão (ed.) Electric Power Systems: Advanced Forecasting Techniques and Optimal Generation Scheduling, CRC press, Taylor & Francis Group, Boca Raton, FL, 2012, ISBN: 978-1-4398-9394-4, pp. 10.1-10.55

sometimes difficult to measure the factors (emission) and we have different numbers
→ variations
difficult putting a number

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Smart Electricity Systems

STORAGE SYSTEMS

General aspects

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Politecnico di Torino

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Storage systems

The storage systems considered in the *standard* CEI 0-16 are defined as:

- A set of *devices* and control systems
- Used to *absorb* or *deliver* electricity
- Operating in *continuous mode in parallel with the* distribution network, or suitable to *alter the energy exchanges with the* network (input from or injection into), even though determined by voluntary disconnections/reconnections of part of the system or the whole system

Any storage system, even though connected at the DC side of a production plant, has to be always considered as a *generator*

Some systems *not considered as storage* operate only to:

1) provide *continuity of supply*
2) improve the voltage quality (voltage dips, light flicker, harmonics, unbalance, fast variations)

such as the UPS (Standard EN 62040), considered as *autonomous* with respect to the network, and the *static compensators* without internal storage

Definitions from the Standard CEI 0-16 and its Variant V2

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Decarbonisation scenarios

- The European *Roadmap* to 2050 indicates some *targets*
  - ✓ *High energy efficiency*
    - Based on the *primary energy saving*
    - New and more stringent standards for *buildings* and *devices*
    - Implementation of strategies for *renovation of* the existing buildings
  - ✓ *Diversification of the production resources*
    - Includes *nuclear* and technologies for CO_2 *capture and storage*
    - All technologies are competing with each other, *without incentives*
  - ✓ *Increase in the percentage of RES*
    - Support actions to reach 75% of the *final energy consumption* served by RES, with scenarios up to 97% for the electrical sector
  - ✓ *Common point*:
    - "The *share of renewables* rises substantially in all scenarios, achieving *at least 55%* in gross final energy consumption in 2050", which requires "*smart infrastructure including* ***electrical storage***"

European Commission, Energy Roadmap 2050 - impact assessment and scenario analysis, 2011

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Objectives for storage systems

- ✓ The main objective is the increment of the *flexibility* of the system, from various points of view:
  - *Quality of the electrical service*
    - Voltage control and reduction of the network *disturbances*
  - *Network management*
    - *Frequency control*, reduction of the *oscillations*
    - Planning and reinforcement of the system, *reserves*
    - Increase of the *stability* and reduction of *vulnerability*
  - *Energy management* (storage of the energy produced to be used later)
    - *Energy market*, also with active participation of the *users*
    - *Energy efficiency improvement* also in multi-energy systems
    - *Energy system planning*
    - Better use of the *existing* resources
- ✓ The choice of the best *mix of technologies* has to take into account all these characteristics

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$i(t)$ L energy stored from an inductor $W = \frac{1}{2} L\, i(t)^2$

$v(t)$ $\frac{1}{T}$ C $W_C = \frac{1}{2} C\, v^2(t)$

Radar-based comparison

- Comparison among *high-power applications* from *normalised* average data

M. Farhadi, O. Mohammed, Energy Storage Technologies for High-Power Applications, IEEE Transactions on Industry Applications, Vol. 52, No. 3, May/June 2016, 1953-1963

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The evolving nature of the electrical service

- The traditional view of the electrical service (without storage) is the one of a *just-in-time commodity*, where the generation follows the load (plus losses)
- The introduction of storage at different levels is changing the paradigm from just in time to *time-adjustable* commodity, virtually up to the condition in which the load follows the generation (with its uncertainty)

Just-in-time → Storage → Time-adjustable

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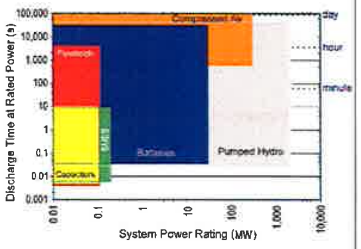
Electrical energy storage

HW

- Pumping storage hydro plants
- CAES: Compressed Air Energy Storage
- Electrochemical storage: batteries
- Mechanical storage: flywheels (volano)
- SMES: Superconductor Magnetic Energy Storage
- Thermal energy storage
- Supercapacitors
- Hydrogen
- Plug-in electric vehicles



http://www.conatureofenergy.org/technology/power-en

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5

modular
many flywheels

flywheels
if we have a each → more time

J $\Omega(t)$ $W = \frac{1}{2} J\, \Omega^2(t)$

Limits of the storage technologies

- Autonomy
- Power supply mode (rates of supply)
- Specific cost
- Space occupation
- Emissions

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6

only works in ideal conditions

$\frac{1}{T}$ open circuit → close → limited period

m cortocircuito SMES → open → P↑ but short time

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Come si leggono?
Cosa sono?
(trovatemi sopra)

insieme di valori con min e max
- capacità
- rete
- storage ⇄ mutualmente esclusivi, vincoli complementari

Deterministic model

- Coupled-in-time operation (accoppiata nel tempo)
- Storage unit *j*, time step *h*
- Energy *x* in the storage unit, average power *s*
- Superscripts: *s* for *injection* into the network, *p* for *input* from the network

$$\underline{s}_j^s \le s_{jh}^s \le \overline{s}_j^s, \quad \forall j, h \qquad \text{limits to injection in the network}$$

$$\underline{s}_j^p \le s_{jh}^p \le \overline{s}_j^p, \quad \forall j, h \qquad \text{storage limits (from the network)}$$

$$\underline{x}_j \le x_{jh} \le \overline{x}_j, \quad \forall j, h \qquad \text{limits to the energy stored in intermediate states}$$

$$x_{jh} = x_{j,h-1} + \eta_j^s s_{jh}^s - \frac{1}{\eta_j^p} s_{jh}^p, \quad \forall j, h \qquad \text{storage transition function}$$

$$\underline{x}_j^{end} \le x_{jH} \le \overline{x}_j^{end}, \quad \forall j. \qquad \text{limits to the final energy stored}$$

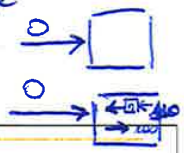
model charge and discharge

efficiencies

- Addition of complementary constraints (vincoli ziqui) in the main problem formulation, to *avoid simultaneous* charge and discharge

D. Pozo, J. Contreras, E.E. Sauma, Unit Commitment With Ideal and Generic Energy Storage Units, IEEE Transactions on Power Systems, Vol. 29, No. 6, November 2014, 2974-2984.

time step : it may change
is not the same
or, something change



STANDARDS ON STORAGE

Storage system configurations

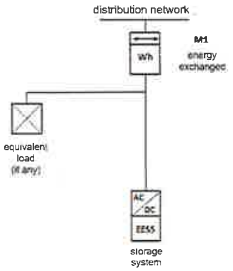
- The Standards CEI 0-16 and 0-21, and the Technical Rules issued (emesse) by the Energy System Operator "Gestore Servizi Energetici" (GSE) in Italy consider *different configurations of installation* of storage system in the production plants, depending on the storage *connection position* and *charging mode*:
  - *Passive User* with storage
  - Storage connected in *direct current downwards* (verso il basso) the production meter
  - Storage connected in *alternating current downwards* the production meter
  - Storage connected in *alternating current upwards* the production meter

Gestore Servizi Energetici (GSE), Regole tecniche per l'attuazione delle disposizioni relative all'integrazione di sistemi di accumulo di energia elettrica nel sistema elettrico nazionale, 15 giugno 2017 (in Italian)

Storage system configurations

Schemes indicated in the Standard CEI 0-21

- Points of connection of Passive Users with storage systems
- *Passive Users* installing a storage system in their plant become *Active Users*



http://www.gse.it/it/salastampa/news/Documents/Regole%20Tecniche%20Sistemi%20Accumulo.pdf

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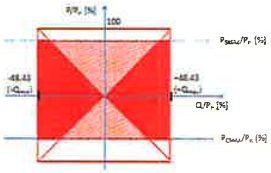
Capability curves with storage

- The presence of storage systems may affect the *capability curves*, that have to be drawn for the *overall* system (local generator plus storage)
- With electrochemical storage at Low Voltage, the capability is the combination of the inverter curve (circular) and of the battery (rectangle with height (P_{SMAX}-P_{CMAX}) and width equal to (|-Qi| + |Qi|) of the inverter)
- Storage system with bi-directional *converter in which the* battery *limits* the power during charge and discharge

Charge limit P_{CMAX}

Discharge limit P_{SMAX}



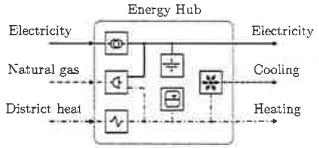
Standard CEI 0-21 (July 2016)

more conservative restriction

Storage in the Energy Hub model

- The *Energy Hub* model has been set up in the project Framework developed within the project "*Vision of Future Energy Networks*" (ETH Zürich and partners)
- Multiple energy carriers are converted, conditioned and *stored* in centralized energy hubs

vettori



Hybrid energy hub with electrical transformer, gas turbine, heat exchanger, battery storage, hot water storage, and absorption chiller

Geidl M., *Integrated Modeling and Optimization of Multi-Carrier Energy Systems*, PhD thesis, ETH Zürich, 2007

Geidl M., Koeppel G., Favre-Perrod P., Klöckl B., Andersson G., Fröhlich K., Energy Hubs for the Future, *IEEE Power and Energy Magazine*, January/February 2007, 25-30

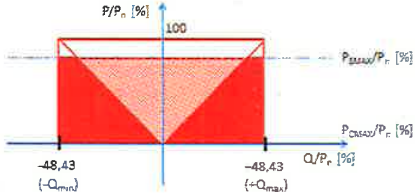
change schemes

symbols

black box → efficiency

Capability curves with storage

- Example with storage system connected to the DC bus of a photovoltaic generator with *inverter*



Standard CEI 0-21 (July 2016)

limiting the upper side

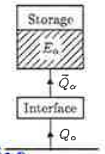
13

Storage in the Energy Hub model

- The model of an *energy storage unit* is set up by considering the energy stored E_α, the power Q_α exchanged with the external system, and the internal power $\tilde{Q}_\alpha$
- The internal storage is considered *ideal*, and the *storage efficiency* in the charging and discharging modes is associated to the interface
- In general, these efficiencies may *depend* on power and energy

$$\tilde{Q}_\alpha = e_\alpha Q_\alpha$$

$$e_\alpha = \begin{cases} e_\alpha^+ & \text{if } Q_\alpha \geq 0 \quad \text{(charging/standby)} \\ 1/e_\alpha^- & \text{else} \quad \text{(discharging)} \end{cases}$$



different efficiencies for charging / discharging

Geidl M., *Integrated Modeling and Optimization of Multi-Carrier Energy Systems*, PhD thesis, ETH Zürich, 2007

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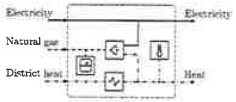
Example of Storage in the Energy Hub

- System with gas turbine GT, heat exchanger HE and *two storages* (gas tank at the natural gas input, and hot water at the heat output)
- Alternatively, using the model

$$\mathbf{L} = \mathbf{C}\mathbf{P} - \mathbf{S}\dot{\mathbf{E}} = \begin{bmatrix} \mathbf{C} & -\mathbf{S} \end{bmatrix} \begin{bmatrix} \mathbf{P} \\ \dot{\mathbf{E}} \end{bmatrix}$$



- With *storage*:

$$M_e^{eq} = \frac{\eta_{ge}^{GT}}{e_g}\dot{E}_g$$

$$M_h^{eq} = \frac{\eta_{gh}^{GT}}{e_g}\dot{E}_g + \frac{1}{e_h}\dot{E}_h$$

$$\longrightarrow \mathbf{S} = \begin{bmatrix} \frac{\eta_{ge}^{GT}}{e_g} & 0 \\ \frac{\eta_{gh}^{GT}}{e_g} & \frac{1}{e_h} \end{bmatrix}$$

- The *complete model* becomes

$$\begin{bmatrix} L_e \\ L_h \end{bmatrix} = \begin{bmatrix} 1 & \eta_{ge}^{GT} & 0 & -\frac{\eta_{ge}^{GT}}{e_g} & 0 \\ 0 & \eta_{gh}^{GT} & \eta_{hh}^{HE} & -\frac{\eta_{gh}^{GT}}{e_g} & -\frac{1}{e_h} \end{bmatrix} \begin{bmatrix} P_e \\ P_g \\ P_h \\ \dot{E}_g \\ \dot{E}_h \end{bmatrix}$$

energy storid matrix

Gerdi M., Integrated Modeling and Optimization of Multi-Carrier Energy Systems, PhD thesis, ETH Zurich, 2007

other way general model

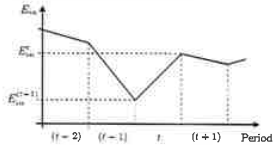
minus storage

increase input

how to incorporate storage

Time-dependent Storage in the Energy Hub

- The storage is considered in period t for the energy hub i:
- $\mathbf{E}_i^t$ is the energy stored at the end of period t
- $\mathbf{E}_i^{stb}$ are the standby losses in period t



- The *equivalent* storage power flow vector is

$$\mathbf{M}_i^{eq\,t} = \mathbf{S}_i^t \dot{\mathbf{E}}_i^t = \mathbf{S}^t \left[\mathbf{E}_i^t - \mathbf{E}_i^{(t-1)} + \mathbf{E}_i^{stb} \right]$$

energy standby

$-(E_i^{(t-1)} - E_i^{st})$

complex what happen in steps

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Evolution of the tariff structures

different prices during the day
multi-hour tariffs

- In parallel with the DSM studies, the tariff structures evolved with the creation of *time-dependent tariffs*:
- Time-Of-Use (TOU) rates:
  - Based on the partitioning of the year into *periods* with different tariff rates (e.g., multi-hour tariffs with *peak* hours, *intermediate* hours, and *low-load* hours)
  - The main aim of these tariffs is to convince the users to *move* their consumption to the *low-load* hours
  - The tariff rates are *predefined* and are kept *constant* for a relatively *long* period of time (e.g., one year)
- Real-Time Pricing (RTP):
  - Evolution of the TOU concept with *variation* of the tariff rates during time (e.g., at each hour) in a way defined closer to the real time (e.g., one day before)
- Spot Pricing (SP): (5 minute before, extreme)
  - Situation in which the tariff rates are defined *immediately before* the instant of consumption (conceptually with no lower limit, e.g., minute-by-minute)

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Load management today

- Real-Time Pricing (RTP)
  - variation of the *electricity rates* during time (e.g., at each hour, or less), communicated in advance by the provider (e.g., the day before, or less) to the consumers
- Demand Response (DR)
  - *voluntary* reduction of the electricity use in response to price incentives, aimed at improving the effectiveness of the electricity supply and reducing demand peaks
- Direct Load Control (DLC)
  - activities aimed at changing the shape of the load pattern according to the willingness to accept modifications of the supply characteristics with respect to standard or pre-defined conditions; can be subject to *automatic control*

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Load management today

- Nowadays, the basic aspects of load management correspond to different degrees of *customer participation* to the evolution of the electrical load, and can be seen from different perspectives
  sgravamento del carico
- Load Shedding (LS)
  - activity aimed at cutting out loads, driven by the System Operator to deal with emergency conditions of the system; priorities can be given to different customers, with *no customer participation*
- Interruptible Load Management (ILM)
  - activity aimed at cutting out loads following specific programmes *agreed* between System Operator and customers, to be applied at specific conditions and subject to remuneration as a specific service

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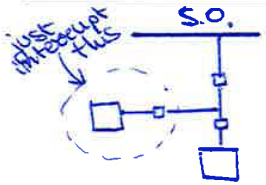
market, the management of the load has a different view

NO USER

air conditioner → load increase
if there is an emergency someone cut the load

THE USER CAN PARTECIPATE



at any time it could be cut (ex. 10kW), when is cut the load is not necessary to be zero

Controllable loads

- Temperature-based loads (electrical heating and cooling devices, air conditioners, refrigerators):
  - concur in forming the *peak load*
  - are typically driven by *thermostats*
  - the *cycling operation* of the thermostats is easily controllable
  - no need for interrupting the supply, only *adjustments*
  - the *limits* of application of load control has to be specified (e.g., minimum or maximum temperature allowed in the space)
  - the customers' *acceptance* of this type of control is generally good
- Lighting:
  - supply of lighting devices can be arranged into *groups*
  - some groups may be seen with *lower priority*
  - a *minimum* lighting effect has to be satisfied
- Low-priority appliances:
  - can be subject to intermittent interruption without significantly affecting their performance, or can be supplied from *dedicated paths* and subject to possible curtailment in case of need

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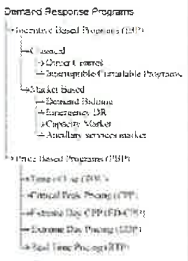
I cut the load if you pay...

Incentive-based programmes

- Some *classical* programmes with *incentives*:
  - *Load control* (e.g., by switching off for a short time devices such as air conditioners or water heaters)
  - *Interruptible/Curtailable* load programmes (the user reduces the load by a pre-determined amount)
- Some *market-based* programmes:
  - Offers sent by the users (*demand bidding*) to reduce the load in various types of markets
  - *Emergency programmes*, with load reductions in case of need (e.g., during a *heat wave*)
  - *Capacity markets*, with load reduction to provide *reserves*
  - Other *ancillary services*, with load reduction (or increase) offered or delivered in response to real-time price signals

offerta



M.H. Albadi, E.F. El-Saadany, A summary of demand response in electricity markets, Electric Power Systems Research 78 (2008) 1989–1996

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someone asks to partecipate, someone accepts

Price-based programmes

- Some programmes based on *prices*:
  - *Time of Use* (TOU): prices defined on the basis of the *time periods* (evolution of the multi-hour tariffs)
  - *Critical Peak Pricing* (CPP): specific prices defined for a *limited number of days* in the year (e.g., when a heat wave or cool wave is expected), known in advance (more than one day), with TOU tariffs in normal days
  - *Extreme Day CPP* (ED): similar to the CPP, with further specific prices defined for "extreme" days
  - *Extreme Day Pricing* (EDP): prices for extreme days not programmed and defined in the *short term* (e.g., the day before)
  - *Real Time Pricing* (RTP): price variable during time, defined on the basis of the cost of electricity, known on a day-ahead or hour-ahead basis

M.H. Albadi, E.F. El-Saadany, A summary of demand response in electricity markets, Electric Power Systems Research 78 (2008) 1989–1996

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Demand response programs
incentive based programs
- classical
  - direct control
  - interruptible/curtailable programs
- market based
  - demand bidding
  - emergency DR
  - capacity market
  - ancillary services market

price based programs (PBP)
- time of use
- critical peak pricing
- extreme day CPP
- extreme day pricing
- real time pricing

Costs and benefits for Demand Response

Example of partitioning of *costs* and *benefits*

a lot of costs

costumer education

M.H. Albadi, E.F. El-Saadany, A summary of demand response in electricity markets, Electric Power Systems Research 78 (2008) 1989–1996

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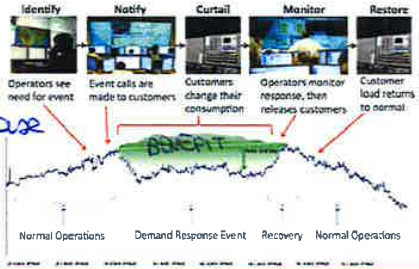
the partecipant must have extra technologies (costs)

Benefits for the system

- The users' participation may be useful to *prevent* potential problems for the system, for example if an excessive consumption is *expected*



J. Stromback, Status of Demand Response in Europe, Smart Energy Demand Coalition, EPFL Lausanne, Switzerland, 2015

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DR Access to Markets in Europe

- Year 2017

http://www.smarten.eu/wp-content/uploads/2017/04/SEDC-Explicit-Demand-Response-in-Europe-Mapping-the-Markets-2017.pdf

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Demand Response in Europe

- *Conclusions* from the Smart Energy Demand Coalition Report (2017):
  - The regulatory framework in Europe for Demand Response is *progressing*, but further regulatory improvements are needed
  - *Restricted consumer access* to Demand Response service providers remains a *barrier* to the effective functioning of the market
  - Significant progress has been made in opening *balancing markets* to demand-side resources
  - The wholesale market must be *further opened* to demand-side resources
  - Local System Services are *not yet commercially tradable* in European countries

http://www.smarten.eu/wp-content/uploads/2017/04/SEDC-Explicit-Demand-Response-in-Europe-Mapping-the-Markets-2017.pdf

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Demand Response Programmes in Europe

- In Europe the development of DR programmes is still *relatively limited* (the active ones are prevailingly load control and interruptability programmes for industrial users), also because of:
  - High implementation costs
  - Reduced *information* on the possible benefits from their use
  - Trend of the users to avoid changes in their lifestyle (with "storage" of resources of various types to reduce the possible discomfort)
  - *Limited amount* of the possible benefits in some cases (e.g., reductions in the electricity prices for households)
  - Limited dedicated *regulatory rules*

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DR BASELINE AND DR PERFORMANCE

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Determination of the performance variables

- Considering each interval *i* over a DR event period beginning at time 0 and ending at time *e*:
  - The *total performance* *p* is the integrated difference between the sum of the baseline b_i and the adjustment factor *a* (*constant* during the event period) less the consumption c_i

$$p = \sum_{i=0}^{e} (b_i + a) - c_i$$

  - The *capacity-setting performance* p_{avg} is the *average* performance during all intervals of the DR event where the program rules stipulate that performance is mandatory

$$p_{avg} = p / e$$

Baseline Variables
b = baseline average
d = non-event day
dn = nth highest energy usage day among previous 10 non-event days
i = time interval
c = highest kW energy consumption for a given time interval (i)

Adjustment Factor Variables
a = day-of adjustment
i-n = time interval starting n hours prior to event notification

Performance Calculation Variables
p = total performance
e = total time intervals during event

ENERNOC White Paper, The Demand Response Baseline, 2009

15

EXAMPLE OF DEMAND RESPONSE APPLICATION

Strategic behaviour

TO EVITATE!

- *Strategic behaviour* to artificially create favourable conditions in the determination of the baseline, leading to economic advantages in the determination of the reward after a DR event, has to be *avoided*
- The possibility of conducting strategic activities impacting on the baseline depends on the baseline *adjustment* approach and increases when the DR event is announced well *in advance* to the participants
- For example, considering ad *additive* adjustment the user could increase the load a few hours before the DR event, in order to have a *higher* baseline on the basis of which the demand reduction will be calculated
- *Pre-cooling* of the load is one possibility of increasing the load before the DR event, then cutting the supply to the cooling load during the DR event
- *Appropriate rules* have to be established to identify and mitigate the strategic behaviour

KEMA, Inc., PJM Empirical Analysis of Demand Response Baseline Methods, White Paper, 2011

try to get more benefits (quite reality). Aumentando l'area nel periodo di monitoraggio aumentare l'area su cui si calcolano i benefici

The demand side in the European project SiNGULAR

- *Implementation of a Demand Management System (DMS)*, coordinated by Intelen (Cyprus)
- *Demand Response* (DR) programmes:
  - Real Time Pricing (RTP)
  - Time Of Use (ToU)
  - Critical Peak Pricing (CPP)
  - Demand Bidding Program (DBP)

  About 100 selected electricity consumers in Crete
- Energy efficiency *tips and behavioural commitments* designed to impact on the user's everyday life concerning:
  - Lighting
  - Heating
  - Cooling
  - Electric Devices

  Energy measurements uploaded to the SiNGULAR platform every 15 minutes

SiNGULAR

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The virtual money (points) system

- The user gains *points* from DR programmes in the following way:
  - Real Time Pricing → 7 points for each kWh saved
  - Time of Use → 3 points for each kWh saved
  - Critical Peak Pricing → 10 points for each kWh saved
  - Demand Bidding Programme → 5 points for each kWh saved
- For each *tip or behavioural commitment* followed → 6 points
- After each *participation* in a DR programme → 10 points

SHS

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End-User Platform 1

Near-Real Time Consumption chart (updated every 15 minutes)

fasce

SINGULAR

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End-User Platform 1

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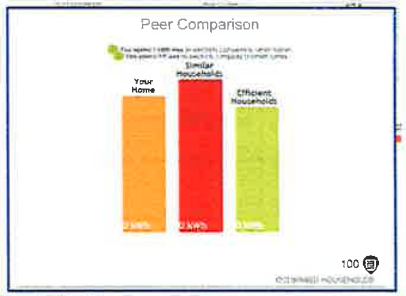
End-User Platform 1

Peer Comparison chart: compare users with similar households



visual idea

SINGULAR

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Smart Electricity Systems

STORAGE SYSTEMS
Power and energy applications

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Prof. Gianfranco Chicco

Dipartimento Energia "Galileo Ferraris"

Politecnico di Torino

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Drivers to storage development

(1) Riserva
- Need of (backup) power available in *short periods*

(2) Gestione
- Smoothing power *variations* (better integration of intermittent RES)

(3)
- *Power quality* improvement

(4)
- Enabling better *energy efficiency* (also in *multi-energy* applications)

(5) efficacia
- (Cost and price-dependent) *cost effectiveness*

(6)
- Improvement of the *air quality*

(7)
- Enhancing network *stability*
- Availability of "*moving*" energy resources
- Reduced system *vulnerability*
- System *reliability* improvement

(8)
- Users' participation in *demand response* (time-shifting of energy usage)
- Improve system *services* (up and down regulation capacity, ramp support)

V.A. Boicea, Energy Storage Technologies: The Past and the Present, *Proc. of the IEEE*, Vol. 102, No. 11, Nov. 2014, pp. 1778-1794

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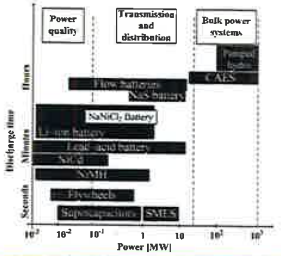
1

Timings of storage availability

(1) Riserva
- *Backup power* provision is a traditional application at short time scales (seconds/minutes), e.g. to avoid interruptions before starting a local generation system



compressed storage

V.A. Boicea, Energy Storage Technologies: The Past and the Present, *Proc. of the IEEE*, Vol. 102, No. 11, Nov. 2014, pp. 1778-1794

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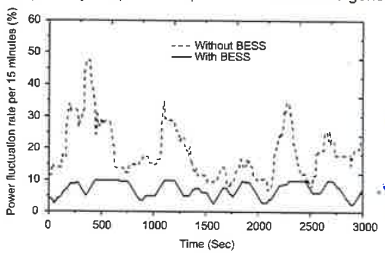
Smoothing the power variations

(2) Livellare
- Smoothing the power *fluctuations* with Battery Energy Storage System (BESS) in a hybrid plant with photovoltaic and wind generation



variation of power

with batteries very low variation

X. Li, D. Hui and X. Lai, Battery Energy Storage Station (BESS)-Based Smoothing Control of Photovoltaic (PV) and Wind Power Generation Fluctuations, IEEE Transactions on Sustainable Energy, vol. 4, No. 2, April 2013, 464-470.

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(8)

Enabling effective participation in demand response

- Storage availability heavily *conditions* demand response
- Upon a *request* (from the electricity "provider") to reduce "*now*" the electricity taken from the grid, with an associated economic *incentive*, in a moment in which we really need or will to complete our task:
  - If local storage is *available*, the response may be "YES" (not mandatory, but an *opportunity* to take)
  - If local storage is *not* available, the response has to be "NO" (thus, no incentive may be received)

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if we have storage I can continue cooking and switch off grid

MAIN TECHNOLOGIES FOR DIFFERENT OBJECTIVES

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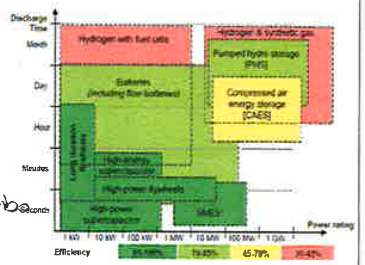
Improvement of the quality of service

- *Super-capacitors*
- *Flywheels*
- Systems based on *magnetic storage*
- Some types of *batteries*
  - *Nickel metal hydrides* NiMH
  - *lead acid*



http://www.4e-cms.org/implementations/SBC-Energy-Institute_Hydrogen-based-energy-conversion_FactSheet-v1.pdf
I. Wasiak, R. Pawelek, R. Mienski, Energy storage application in low-voltage microgrids for energy management and power quality improvement, IET Generation, Transmission & Distribution, 2014, Volume: 8, Issue: 3, pp. 463 - 472

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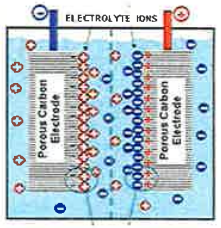
Super-capacitors

chimica stata

- Electrochemical capacitors (ECs) – also called "electric double-layer capacitors, "*Supercapacitors*" or "*Ultracapacitors*"
- When the two electrodes of an EC are connected to an external system, current flows until reaching complete charge *balance*
- The charge is stored *physically*, with no chemical reactions or phase changes
- The process is *fast* and highly *reversible*
- The discharge-charge cycles can be *repeated* without theoretical limit
- ECs are *better* than batteries for applications with high cycle life and charge/discharge times of 1 s or less

immagazzinata



Double Layer Capacitors
(Adsorbed layers of ions and solvated ions)

Energy Storage Association, http://energystorage.org/

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Flywheels

- FESS *applications* address power quality, reliability, ride-through capability and frequency response
- FESS may also be used in *satellites* and in *hybrid vehicles* that stop and start frequently, to provide track-side or on-board regenerative braking
- The FESS efficiency is relatively *high* (up to 95%, depending on the electrical machine and converter used)

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Flywheels

- *Advantages*:
  - High efficiency
  - High power density
  - Low degradation in time (no limit to charge/discharge cycles)
  - Low maintenance needed
  - No variation of the internal parameters
  - Fast charging
  - Easy determination of the state of charge
  - No environmental impact
  - Enabling service continuity
  - Operation at wide ambient temperature range (e.g., -20°C to 40°C)

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Flywheels

- *Drawbacks*:
  - High initial cost
  - Fast discharging
  - Mechanical stress when used in mobile applications
  - High precision needed in the design and manufacturing
  - Need for a mechanical infrastructure

X. Luo et al., Overview of current development in electrical energy storage technologies and the application potential in power system operation, Applied Energy 137 (2015) 511–536

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Flywheels

- Example of a 20 MW system for frequency control with 200 flywheels of 100 kW, 25 kWh each

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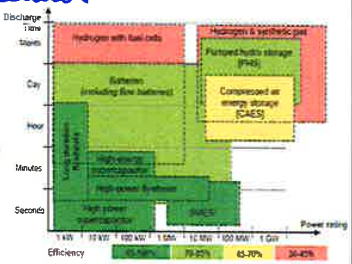
Frequency control

- *Primary regulation* frequency
  - Li-ion batteries
  - Sodium-sulfur batteries (NaS)
- *Secondary regulation*
  - *Flow batteries* Vanadium Redox (VRB)
  - ZnBr batteries
  - Compressed Air Energy Storage (CAES)



Scalability of the "flow batteries" (decoupling power vs. energy) -> **reserves**

http://www.4ts-cms.com/presentations/SBC-Energy-Institute_Hydrogen-based-energy-conversion_FactBook-vf.pdf

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"Cold" batteries for network applications

Technology	Specific energy [Wh/kg]	Efficiency	Cycles	Installation costs [€/kWh]	Annual O&M costs [€/kWh]
Pb	<50	80 ÷ 90%	<2500	300	15 (kWh capacity) 0.087 (kWh discharged)
NiCd	<80	60 ÷ 70%	<3500	800	15 (kWh capacity) 0.304 (kWh discharged)
Lithium-based	140	>90%	5000	500	10 (kWh capacity) 0.023 (kWh discharged)

large family

http://large.stanford.edu/courses/2012/ph240/ciosnay1/docs/EPRI.pdf; http://assets.fleicemarkets.net/public/sites/energy/reports/batterystoragereport.pdf
http://www.jrc.ec.europa.eu/sites/default/files/progetti/sistemi_di_accumulo_elettrochimico.pdf
http://eurostat.org/sites/default/files/eurostat_smartgrid_publication_may_2013.pdf

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Focus on electrochemical storage

- *Types of batteries*:
  - "cold": operate at *ambient temperature*, with the following main technologies:
    - Advanced Lead-acid (Pb) acido al piombo
    - Nickel-Cadmium (NiCd)
    - Lithium-based
  - "warm": based on the use of *salts* that have to be maintained at high temperature by using *warmers*, with reduction of the overall efficiency; main technologies:
    - Sodium Sulfur (NaS)
    - ZEBRA (NaNiCl)

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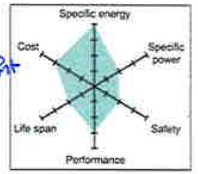
Lithium-based batteries

- Li-Ion Batteries
  - *Layers* of lithium contained in a structure composed of atoms of Cobalt and Oxygen ($LiCoO_2$) quite high
  - *Specific Energy*: 150 ÷ 200 Wh/kg
  - Number of charge-discharge *cycles*: 500 ÷ 1000
  - *Usage of lithium* lower than 60%: the *low* level of usage of the lithium in the cathode *penalises* the application of the technology when high storage capacity is required
  - The research is focused on *better utilisation of the active material*



http://batteryuniversity.com/learn/article/types_of_lithium_ion

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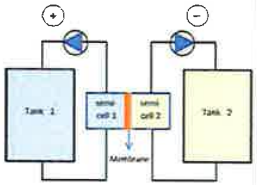
Flow Batteries

- The *flow batteries* are characterised by the *decoupling* between energy and power
- The chemical solution is contained into *tanks* and flows in two half-cells divided with a membrane due to the action of *pumps*
- The *power rating* depends on the *number* and *size* of the *cell stacks*



- The *power ratings* range from hundreds of kW to some MW
- The *energy rating* depends on the *volume* of the electrolyte *tanks*

P↑ remove E → size of the cell stacks
E↑ invest on the tank electrolite
volume of tanks

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Flow Batteries

- Zinc Bromine Flow Batteries (ZBFB)
  - The electrolytes are two isotopes of *Br*, which interact with the *Zn* of the electrode
  - Br is *highly corrosive* and this impacts on the useful lifetime
  - The irregular storage of Zn during the charge needs a *maintenance* process
  - The technology is *experimental* with *pilot projects*
  - The size reached by the batteries used reaches powers of 500 kW and 3 MWh of energy (discharge time 6 hours)

http://assets.ferdamarkets.net/public/sites/energy/reports/batterystoragereport.pdf
https://www.energystorageexchange.org/

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Flow Batteries

- Vanadium Redox Flow Batteries (VRFB)
  - The electrolytes are two isotopes of Vanadium -> reduced problems of polluting the cell membrane
  - Number of cycles: 1000 per year for 20 years
  - The technology is *experimental* with *pilot projects*
  - The size of the batteries used reaches values of *dozens of MW* with energy of about *10 MWh* (discharge time 2 ÷ 4 hours)
  - Batteries with higher size (200 MW and 800 MWh) are under construction (in China)

http://assets.ferdamarkets.net/public/sites/energy/reports/batterystoragereport.pdf
https://www.energystorageexchange.org/
http://www.utilityinnovations.com/news/72-uni-energy-technologies-strategic-partner-to-deliver-world-s-largest-battery
https://www.greentechmedia.com/articles/read/a-look-at-the-biggest-energy-storage-projects-built-around-the-world-in-the#gs.TL0UrCY
Z. Gary Yang, New Generation VRFB for Electrical Grid and Utility Applications, IEA Workshop on "The Role of Storage in Energy System Flexibility", Berlin, 29th October 2014 https://www.iea.org/media/wwwshops/2014/egrdenergystorage/Yang.pdf (available on line 29th October 2016)

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Applications of flow batteries

- The main applications are in *wind systems*
- In Japan: 4 MW, 90-minute (6 MWh) vanadium-based *flow batteries* added to a 30 MW wind farm
- Possible 6 MW power burst (*short term*)
- The wind farm *charges* the storage system
- The storage system *levels* the output to the distribution network, smoothing the frequency variations

https://www.asme.org/engineering-topics/articles/renewable-energy/flow-batteries-augment-wind-power

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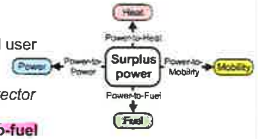
Introduction to "Power-to-X"

- **"Power-to-X"** is a way to store energy based on the transformation of the electricity produced for example from renewable sources in another energy vector
- This conversion aims at long-term energy conservation (days, months, or years)
- The conversion is able to:
  - Cover the consumption of a final user
    - **Power-to-Heat**
  - Create an *intermediate energy vector*
    - Power-to-Liquid
    - Power-to-Gas

    Power-to-fuel



- The literature often refers to the overall *process*, indicating **Power-to-Mobility** or **Power-to-Power**

mutuo uso

A. Sternberg, A. Bardow, Power-to-What? – Environmental assessment of energy storage systems, Energy & Environmental Science. DOI: 10.1039/c4ee03051f

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Power-to-Liquid

- Three fundamental *steps*
  - **Production of Syngas**
    - Electrolysis
    - Reverse Water Shift Process $CO_2 + H_2 \rightarrow CO + H_2O$
  - **Fischer-Tropsch Synthesis**
    - Converts the syngas into different hydrocarbon chains catene
  - **Refinement of the products**
    - Liquefied Petroleum Gas (LPG)
    - Kerosene
    - Lubricant oils
    - Naphta
    - Methanol
- The *efficiency* of the production chain changes with the technologies used (**55% ÷ 70%**)

http://www.uni-leoben.de/sites/default/files/media/277/documents/19_session_1_8_becker.pdf

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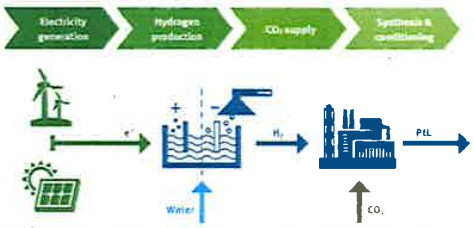
Power-to-Liquid

- This expression indicates the production of *liquid fuel* gas di sintesi
- The *intermediate* product could be *hydrogen* or *syngas*
- *Example* of process:



Source: Power-to-Liquids: Potentials and Perspectives for the future supply of Renewable aviation fuel, German Environment Agency, Sept. 2016, http://www.uba.de/news/2016_docs/161005_uba_hintergrund_ptl_bannemann.pdf

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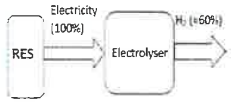
Power-to-Gas

- **Power-to-Hydrogen**



Advantages
- Process chain composed of a *single conversion* -> higher efficiency

Drawbacks
- *Hydrogen storage* needed
- The hydrogen may be injected in the *network in reduced* quantities

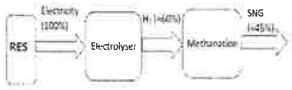
electroliser → H
single stage

- **Power-to-Methane**

Advantages
- The gas may be *injected* in the network
- H_2 storage sized to *decouple* electrolyser and methanation

not unique macchines

Drawbacks
- Lower efficiency



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Smart Electricity Systems

GRID INTEGRATION OF ELECTRIC VEHICLES

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Dr. Ing. Andrea Mazza

Dipartimento Energia "Galileo Ferraris"

Politecnico di Torino

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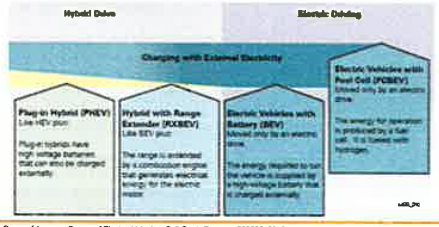
Categorisation of the vehicles

- PHEV - Plug-in Hybrid Electric Vehicle; vehicle with full hybrid drive and external charging facility
- RXBEV - Range Extender Battery Electric Vehicle; battery-powered vehicle with additional generator drive to increase range (range extender)
- BEV - Battery Electric Vehicle
- FCBEV - Fuel Cell Battery Electric Vehicle; battery-powered vehicle with fuel cell



Volkswagen Group of America, Basics of Electric Vehicles, Self Study Program 820233, 2013

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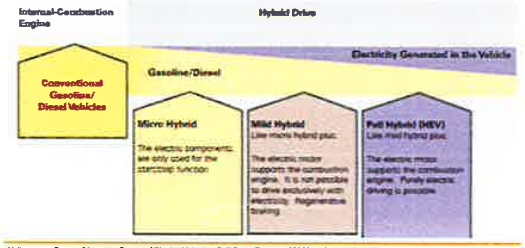
Categorisation of the vehicles

- Categories represented on the basis of the type of "fuel"
- Focus on the *electricity* generated in the vehicle
  - HEV - Hybrid Electric Vehicle; full hybrid vehicle



Volkswagen Group of America, Basics of Electric Vehicles, Self Study Program 820233, 2013

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Definitions

- The Standard IEC 61851 (*Electric vehicle conductive charging system*) Part 1 (*General requirements*) contains the following definitions:
  - A) Electric Vehicle (EV): any vehicle propelled by an electric motor drawing current from a rechargeable storage battery of from other portable storage devices (rechargeable, using energy from a source off the vehicle such as a residential or public electric service), which is manufactured primarily for use on public streets, roads or highways
  - B) EV supply equipment (EVSE): conductors, including the phase, neutral and protective earth conductors, the EV couplers, attachment plugs, and all other accessories, devices, power outlets or apparatuses installed specifically for the purpose of delivering energy from the premises wiring to the EV and allowing communication between them if required

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(1)

Diffusion of electric and hybrid vehicles

- Main *problems*:
  - the *power* needed for EV charging is *significant* for the interaction with the electrical network
  - *independent and non-coordinated control* of the EVs may cause serious problems to the electrical *network*
  - EVs are *loads* (and *storage* units, in case of possible V2G) *moving* in territorial areas with different characteristics
  - the number of EVs makes the individual control of each EV by the system operator intractable
  - if the information from each individual EV has to be sent to a central controller, the burden on the communication network could be enormous

intractable

more decomposed way

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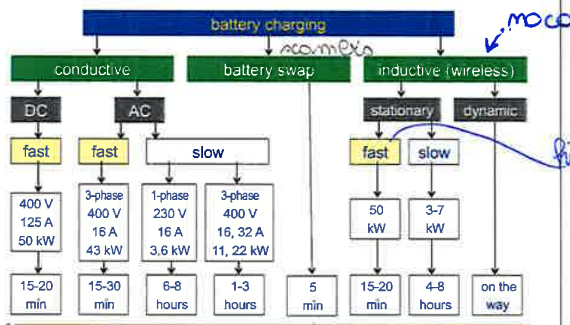
(2)

Charging modes



no conductor

complex

light power

washing car

everyone need 15-20 minuts

fueling

slow → charging at work or at home

Charging modes – Mode 1 charging

- Only for *conductive* charging
- **Mode 1 charging**: connect the EV to the a.c. supply network (mains) using standard socket-outlets

  rete di corrente
  - **not exceeding 16 A**
  - not exceeding 250 V a.c. single-phase or 480 V a.c. three-phase at the supply side (a little higher to supply the converter)
  - using the power and protective earth conductors
- Forbidden in the U.S.

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Charging modes – Mode 2 charging

- Only for *conductive* charging
- **Mode 2 charging**: connect the EV to the a.c. supply network (mains) using standard single-phase or three-phase socket-outlets
  - **not exceeding 32 A**
  - not exceeding 250 V a.c. single-phase or 480 V a.c. three-phase
  - using the power and protective earth conductors together with a ***control pilot function*** (dashed line) **and system of personnel protection against electric shock between the EV and the plug or as a part of the in-cable control box**

    linea tratteggiata

    spina

    cavo di controllo in linea
  - The in-line control box shall be located within 0.3 m of the plug or the EVSE or in the plug

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Types of sockets and plugs

- From the Standard IEC 62196-2 (2011): Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 2: Dimensional compatibility and interchangeability requirements for a.c. pin and contact-tube accessories

Configuration type	Standard Sheet	Applicable accessories	Rated voltage V	Rated current A	Phase
1	2-I	Vehicle couplers	250	32	Single-phase
2	2-II	Accessories	250	70	Single-phase
			480	53	Three-phase
3	2-III	Accessories	250	16	Single-phase
			250	32	Single-phase
			480	63	Three-phase

Type 1 Type 2 Type 3 (a and b) Type 3c

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Smart charging

- Why is *smart charging* important?
- Some *indications* from the Smart Energy Demand Coalition (SEDC):
  - Cars are *parked* for over 90% of their lives
    http://www.reinventingparking.org/2013/02/cars-are-parked-95-of-time-lets-check.html
  - The average EU household *consumes* around 10 kWh a day
    https://www.ovoenergy.com/guides/energy-guides/how-much-electricity-does-a-home-use.html
  - Charging an electric vehicle to drive a *daily distance* of 40 km takes around 5 kWh or more, examples:

vehicle to grid

Model	Battery capacity [kWh]	Max. Autonomy [km]	Max. km/kWh	Min. Consumption @40km [kWh]
Tesla Model S	100	600	6	6.7
Tesla Model X	100	565	5.65	7.1
Renault Zoe	41	380	9.3	4.3
	22	200	9.1	4.4
Nissan Leaf	30	250	8.3	4.8
	24	160	6.7	6

  - The daily household consumption then *increases* of ≈**50%** or more

global number

Smart Energy Demand Coalition, The Importance of Smart Charging, April 2017, www.smartenergydemand.eu
https://www.repubblica.it/motori/sezioni/attualita/2017/04/20/news/auto_elettriche_la_classifica_per_autonome-163442884/

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variable prices

Smart charging

- What is *smart charging*?
- *Definition* from CEN-CENELEC (the European standardisation body):
  "... when the charging cycle can be altered by external events, allowing for adaptive charging habits, providing the EV with the ability to integrate into the whole power system in a grid and user-friendly way"
- *Key elements* of smart charging
  - Dynamic pricing
  - Charging infrastructure
  - Interoperability & standardisation of the charging infrastructure
  - Standardised data for vehicle drivers, consumers, service providers or aggregators
  - Business models for *innovative services*
  - Vehicle to grid services, demand response and ancillary services

ftp://ftp.cen.eu/CEN/European/Standardization/hot/topics/ElectricVehicles/SmartChargingReport.pdf
Smart Energy Demand Coalition, The Importance of Smart Charging, April 2017, www.smartenergydemand.eu

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one of the tools to response

Charging methods

- Charging methods used in the U.S. (charging *duration* depending on the EV's battery pack):
  - **Level I**: 120 V AC, 16 A (= 1.92 kW). Typical U.S. residential grounded outlet, charging duration about 10 hours
  - **Level II**: 208÷240 V_{AC}, 12÷80 A (= 2.5÷19.2 kW), requires a special charging ~~dock~~ zone to be installed at households, charging durations about 4÷7 hours
  - **Level III**: 300÷600 V_{DC}, very high currents (hundreds of amperes), e.g., 480 V and 125 A, charging duration about 15÷30 min

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(3)

G2V Impact on the distribution networks

- Main aspects:
  - additional power demand, impacting on the power generation needs
  - possible *emissions* associated with the EV life cycle
  - the role of *demand side management* (DSM) strategies in supporting EV penetration
  - *economic* impacts of EVs on electric utilities
- Applications:
  - *large* electric system (with electricity *market*)
  - *island* (small) system (*without* electricity market)

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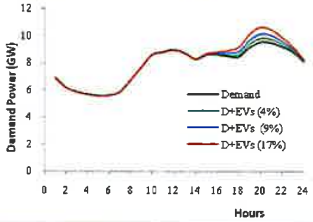
G2V Impact on the distribution networks

- Contribution of different *penetrations* of EV (charged during the *evening*) to the demand:
- *Independent* decisions by the user (without incentives): risk of increasing the *peak* of the residential load



C. Camus, J. Esteves, T. Farias, Integration of Electric Vehicles in the Electric Utility Systems, www.intechopen.com

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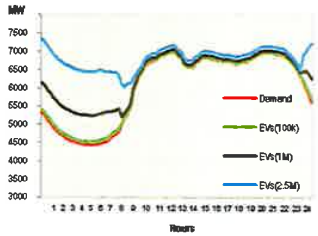
G2V Impact on the distribution networks

- Contribution of different *penetrations* of EV (charged during the *night*) to *load leveling*

23



beneficial for the system

good, has to be managed

C. Camus, J. Esteves, T. Farias, Integration of Electric Vehicles in the Electric Utility Systems, www.intechopen.com

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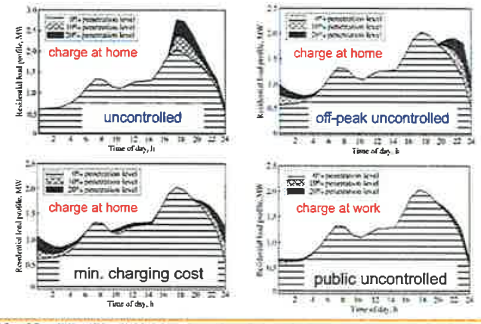
Residential EV charging



K Qian, C Zhou, M Allan, Y Yuan, Modeling of Load Demand Due to EV Battery Charging in Distribution Systems, IEEE Trans. on Power Systems, vol. 26, no. 2, pp. 802 – 810, 2011

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Example: Formulation C

- A unique *public company* manages the PLs and all the urban CS, allowing V2G and G2V
- There are CSs in the houses allowing G2V and V2G, managed by the user

charging type	mode	aggregate management			individual management	
		unique (for PLs+CSs)	PLs only	CSs only	PEV user	operator
PL	G2V	public				
	V2G	public				
Home CS	G2V				user	
	V2G				user	
Urban CS	G2V	public				
	V2G	public				

PL: Parking Lot
CS: Charging Station

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The Aggregator

- The aggregator manages a *portfolio* of Evs
- At time interval t, the aggregated power profile $P_A(t)$, seen as a load, depends on the demand $P_D(t)$, the local generation $P_G(t)$, and the sum of the contributions of the EVs $v = 1,\ldots, N$ (each of which may be positive or negative)

$$P_A(t) = P_D(t) - P_G(t) + \sum_{v=1}^{N} P_{EV}^{(v)}(t)$$

- The objective of the Aggregator is to control the EV charge/discharge in order to make the aggregated load profile meeting the target load profile $P_T(t)$ as close as possible

$$\min\{|P_A(t) - P_T(t)|\}$$

- Another objective may be the minimisation of the EV *charging costs*

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challenges
- VTG?
- time?
- % of charge

Control strategies

- The typical *control strategies* applied to the EVs are of two types:
  - *Direct control*: the controller decides and actuates the actions on the controlled EVs
  - *Incentive-based*: the controller sends *signals* and information on the rewards, to get actions from the controlled EVs
- Different EV *control strategies* are considered for the Aggregator:
  - *Centralized strategies*:
    - usually apply *direct control* of the EVs
    - their main *issues* are *scalability* of the solutions and need for wide *communication* infrastructures
    - the central controller knows *all* problem variables and constraints
  - *Distributed approaches*:
    - Each local entity knows the local parameters
    - The global parameters depend on the overall system and have to be communicated to each control entity

offer

V. del Razo, C. Goebel, and H.A. Jacobsen, Electric Vehicle Real-Time Charging Control with Vehicle-Originating-Signals, IEEE Trans. on Transportation Electrification, vol. 1, no. 2, pp. 150-167, 2015.

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Traffic models

statistical bases

- Strategic choices for the user to reach a destination:
  - *Departure* time
  - *Route* to follow
- Operational choices:
  - *Speed*
  - Vehicle *control*
- Suggested models:
  - *Activity-based* travel demand models (prediction of the activity needed)
  - Discrete and detailed *representation* of the *traffic*
  - *Agent-based* dynamic traffic simulation (to analyse the interaction among the users)

F. Purzo, Transport and traffic models for studying electric mobility, JRC Science and Policy Report, 2014

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Vehicle-Originating Signals

- The Vehicle-Originating Signals (VOS) approach maintains the simplicity of a centralised approach and distributes part of the computation to the EVs
- The VOS does *not* require iterative optimisation, therefore can meet real-time requirements in the applications
- The analysis is carried out by considering successive *time steps* k=1,2,...
- *Objective*: reducing the *difference* between a *target* load profile $P_T(k)$ and the aggregate power $P_A(k)$ consumed by a group of consumers
  - At each time step, every connected EV computes a need-for-charge (NfC) signal and a willingness-to-supply (WtS) signal, and sends them to the Aggregator
  - The Aggregator collects the signals and returns the charging instructions to the EVs

V del Razo, C Goebel, and HA Jacobsen, Electric Vehicle Real-Time Charging Control with Vehicle-Originating-Signals, IEEE Trans. on Transportation Electrification, vol. 1, no. 2, pp. 150-167, 2015.

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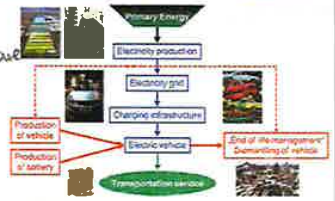
Notes on EV emissions

- EVs do not *directly* produce CO_2 emissions
- However, the assessment of the environmental impact has to be performed by using *Life Cycle Assessment* (LCA), including production, operation, and end of life
- The emissions occurring during the *production* of electricity (e.g. in coal power stations) have to be considered
- For an EV using renewable electricity from hydropower, only 10% of the GHG emissions could occur during operation, and 90% refer to its end-of-life



- Blue boxes: operation
- Red boxes production (left) and dismantling (right)
- Dotted arrow: possible recycling

www.iaphc.org

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all the process production... not totally free

(6)

Optimisation of the smart grid operation with storage systems and EVs

- Territorial distinction into *zones*
- *Hierarchical decomposition* approach in each zone
- *Local units* (generators and EVs) managed by an Aggregator
- *Two-level* model of the optimisation problem:
  - At the *high level*, the generator units and the EV Aggregators are dispatched together by the System Operator
  - At the *low level*, each Aggregator solves an optimisation problem by applying the indications received from the upper level

market

massimo profitto

W. Yao, J. Zhao, F.Wen, Y. Xue, and G. Ledwich, A hierarchical decomposition approach for coordinated dispatch of plug-in electric vehicles, IEEE Trans. Power Syst., vol. 28, no. 3, pp. 2755-2765, Aug. 2013

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(5)

Planning problem

scenario Based

- Optimal *location* and *sizing* of the PLs
- Information taken from *surveys* and data from the diary of *selected users* to determine *where* vehicles are parked in the region and for how long
- Survey of trips with the corresponding contracts (location and duration)
- *No home parking* considered (not of interest to find out PL locations)
- Parking duration *lower* than a given minimum (depending on the type of charging) is *removed*
- Objective function: total *profit* (revenues minus costs)
- *Revenues*:
  - from market transactions (day-ahead and reserve markets)
  - from the payment of the (hourly) parking tax
  - from the payment of the G2V service
- *Costs*:
  - actualised investment costs
  - actualised operation and maintenance costs
  - due to network losses
  - due to the V2G incentives given to the users

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cost for the distributor

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affidabilità
RELIABILITY → CONTINUITY OF SUPPLY (DISTRIBUTION) alimentazione

adeguatezza
ADEQUACY (TRASMISSION) SYSTEMS

Smart Electricity Systems

adeguatezza
ADEQUACY OF THE GENERATION AND TRANSMISSION TO THE ELECTRICAL DEMAND
richiesta

Prof. Gianfranco Chicco
Politecnico di Torino
Dipartimento Energia

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Reliability of generation and transmission systems – *Adequacy*

- For the generation and transmission system, reliability concepts refer to the *adequacy* of the production and transmission system to serve the load
- Adequacy is assessed (valutato) by considering pre/post-contingency conditions of the systems
- The main problems (immediati) addressed include
  - *Lack of generation*
  - Violation of the operation *limits* of the transmission lines (with overcurrents and possible trip of the protections)
  - Violation of the (qualitative) limits on the node voltages
- Steady-state (stat. stazionari) *models* are used

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Outline

affidabilità

- Reliability of *production* and *transmission* systems – *Adequacy*
- Probabilistic *load* model
- Probabilistic *generation* model
- Calculation of the *adequacy of the production system to the load*
  - *state enumeration* method
  - *convolution* method
- *Application* examples
- Calculation of the *adequacy* of the *production* and *transmission* system
  - *Contingency evaluation* method
  - *Monte Carlo* method
- Final *remarks*

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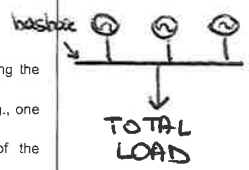
LDC "Load duration curve"
CDF "Cumulative distribution function"
PDF "Probability density function"
LOLP "Loss of load probability" (LOLE = expectation)
EDNS "Expected demand not served"
EENS "Expected energy not served"

Adequacy assessment

- Adequacy of the *production* system:
  - Only the *generation units* and the *total load* are considered, ignoring the transmission network (*single busbar model*)
  - The starting point are the *load patterns* (modello) for a pre-defined period (e.g., one year) and the characteristics of the generation units
  - The *adequacy indicators* calculated represent the adequacy of the production with respect to the load (probability to serve the load)
- Adequacy of the *production and transmission* systems:
  - The *generation units*, the *load* and the *impact of the transmission network* (rete di tr.) (with its possible outages) are considered
  - The starting point are the *load patterns* for a pre-defined period (e.g., one year) and the characteristics of the generation units and of the transmission system
  - The *adequacy indicators* calculated represent the probability to serve the load *through* the production and transmission systems



cut part of the load

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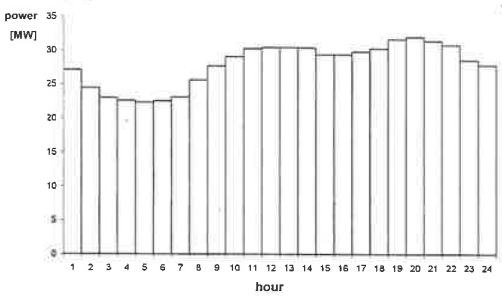
Hourly load pattern

modello



same of the maximum load top of the value we can find

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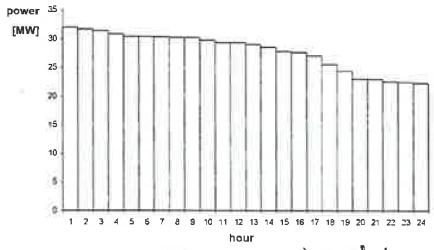
Hourly Load Duration Curve



modello ordinato

Starting from a load pattern represented by a set of power values, the *LDC* is simply built by in reordering the power values in descending order

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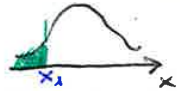
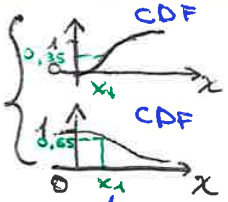
probability load function



we can construct

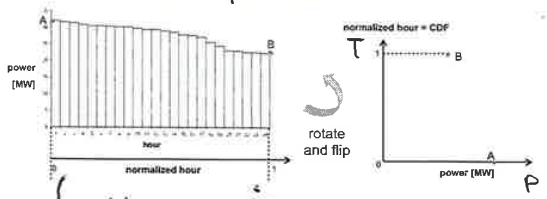


Areas is 1 → probability distribution

↓ cut the area

Probabilistic load model

- Cumulative Distribution Function (*CDF*) of the load:
  - Obtained from the *duration curve* of the hourly load power (in discrete form) by *exchanging* the horizontal and vertical axes and substituting the values on the time axis with the relative duration referred to the total time interval of analysis per unit



another axes all the steps divided by 24

→ from 0 to 1

↑ from 0 to 1

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we can use both

0,35 value of not exceeding

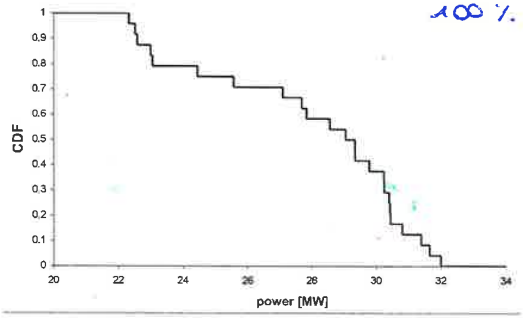
65 probability of not exceeding

1 - probability is more B

0 probability

CDF of the load power

100 % less



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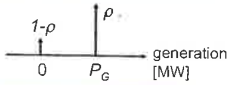
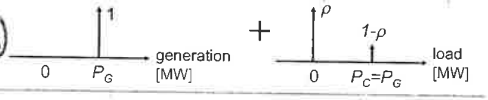
probability density function

PDF of the generation

- Considering the *generated power* P_G, the *availability coefficient* ρ and the *unavailability coefficient* $(1-\rho)$, it is possible to adopt two *alternative* representations for the generator model:
  - representation referring to the *generated power*



  - representation with *ideal generator* and *fictitious load* equivalent to the generator unavailability



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disponibilità

$\rho = \frac{\mu}{\lambda+\mu}$ (repair / failure)

P_C (generation) prob = 1

P_C

two scale

$P_C = P_G \Rightarrow$ prob = $1-\rho$ ideal generator but load is $1-\rho$

probability = availability of generator

Calculation of the adequacy indices

- *State enumeration* method:
  - The *tree* containing all the possible states is constructed by examining all the possible *combinations* of the states of the load and of the generation
- *Convolution* method:
  - Starting from the *cumulative curve* of the load $F_0(C)$, and from the model of a generator (with generated power P_G and availability ρ) as ideal generator and fictitious load, the contribution of fictitious load is *added* to the initial load, and the new cumulative curve of the load is determined through the relation

$$F_1(C) = \rho F_0(C) + (1-\rho) F_0(C - P_G)$$

  - The previous procedure is *repeated* for *each contribution of the* generators
  - The *total ideal generation* is calculated by summing up the generator powers
  - The adequacy indicators are determined by looking at the *intersection* between the CDF of the total load (including the fictitious loads) and the CDF of the ideal generation

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cumulative curve

total

Generation system availability

- Considering the generation G and the load C, the *adequacy* is calculated on the basis of the available *reserve* $(R = G - C)$ or of the production *deficit* $(D = C - G)$, by determining the indicators:
  - *LOLP* (Loss of Load Probability), expressed in per units, or in hour/year (*LOLE*, Loss of Load Expectation)

$$LOLP = \text{Prob}\{R \le 0\} = \text{Prob}\{D \ge 0\}$$

  - *EDNS* (Expected Demand Not Served), expressed in [MW], calculated on the basis of the cumulative curve of the load for the values corresponding to the production deficit

$$EDNS = \frac{1}{LOLP} \int_{D \ge 0} F(C)\, dC$$

  - *EENS* (Expected Energy Not Served), expressed in [MWh/period], related to the duration T [hour/period] of the observation period

$$EENS = EDNS \cdot T$$

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probability of negative or positive reserve deficit

taking all portion lowering ∞ deficit

Calculation example

- Simple example, with *two generators* and a total load *discretized* into three levels
  - *generator* 1: P_{G1} = 80 MW, availability = 0.95
  - *generator* 2: P_{G2} = 70 MW, availability = 0.94
  - *load* with PDF discretized at the levels 25 MW (prob. 0.3), 75 MW (prob. 0.45) e 140 MW (prob. 0.25)
- The *probabilistic model* of the *generators* is constructed in the form with ideal generator and additional fictitious load
- The *probabilistic model* of the *load* is constructed both as *probability density* (for the state enumeration method) and in *cumulative form* (for the convolution method)

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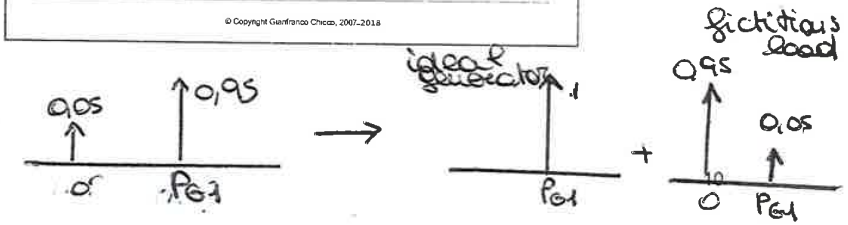

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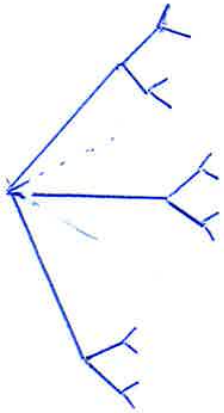
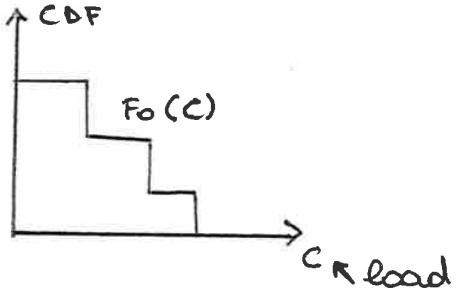


second method
we start from CDF



$$F_1(C) = \rho_1 F_0(C) + (1-\rho_1) F_0(C - P_{G1})$$

translated by 80 MW

$$F_2(C) = \overset{40\%}{\rho_2} F_1(C) + \overset{60\%}{(1-\rho_2)} F_1(C - P_{G2})$$

70 MW

IMPORTANT!

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Convolution method – Further steps

- Next, the contribution to the CDF of the *fictitious* load corresponding to the unavailability *of* generator 2 is added
- The result is the *new cumulative curve* determined on the basis of the relation $F_2(C) = \rho_2 F_1(C) + (1-\rho_2) F_1(C - P_{G2})$
- *Interpretation*: the load has probability ρ_2 of remain as it is, and probability (1- ρ_2) to increase the quantity P_{G2}
- In the application of the *convolution method*:
  - The *number of steps* of the CDF increases gradually during the construction of the curve
  - The *position of the steps* can be pre-defined on the basis of the values of generated power and of the initial discretized load
  - For systems with many generators and/or load steps, it is possible to set an equal *power step*, pre-defined to obtain all the generated powers and the load steps as values *multiple* of the power step

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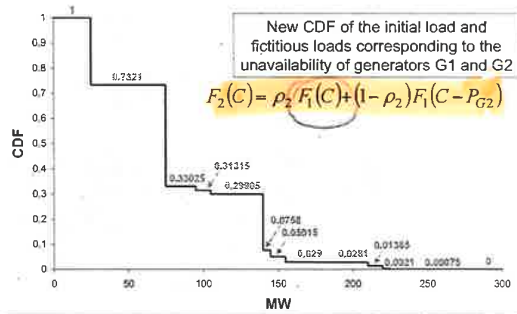
cumulative distribution function

CDF of the load



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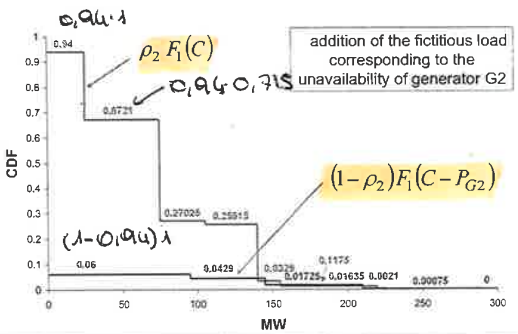
compare total load and total generation (ideal)

CDF of the load



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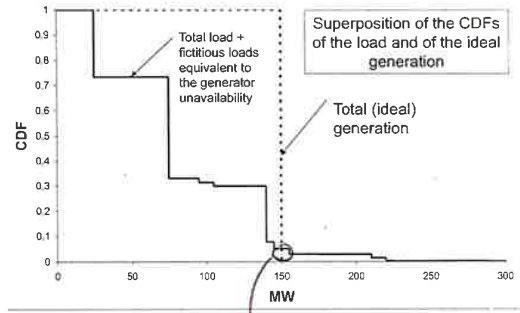
pag 14

0,94 · 0,715 = 0,6721
0,94 · 0,2875 = 0,27025
0,94 · 0,2725 = 0,25615
0,94 · 0,035 = 0,0329
0,94 · 0,125 = 0,0117

0,06 · 0,715 = 0,0429
0,06 · 0,2875 = 0,01725
0,06 · 0,2725 = 0,01635

Comparison between load and generation



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probability of having load > generation

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Removal of a generator

- Comments on the procedure used to *remove* the generator G2:
  - The first step that *disappears* corresponds to the load 95 MW
  - That step was due to the convolution between the initial load 25 MW and the *fictitious load* equivalent to the generator G2 having 70 MW, whose contribution is now subtracted
  - By consinuing the de-convolution process, also *the other steps* introduced by generator G2 are removed, and the CDF seen previously is exaclty reconstructed
  - This happens because the other generator has no value at the *same* power steps as generator G2
  - In general, possible steps corresponding to load values formed by the convolution between the initial load and *other generators* are not removed

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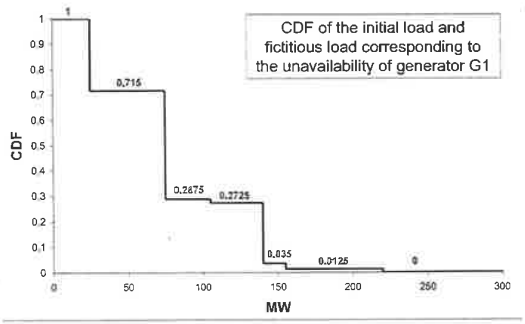
After the removal of generator G2

we obtained the same thing



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Replacement of a generator

deconvolution + convolution

- In the adequacy analysis it may be useful to evaluate the effects of he possible *replacement of a generator* with *another generator* with *different* power and/or availability characteristics
- The case of *replacement of a generator* can be handled by executing *successively* the procedure to remove a generator (*de-convolution*) and the addition of the new generator (*convolution*)
- The values of the adequacy indicators may provide useful inputs to identify the possible *advantages* of the replacement of the generator on the system adequacy

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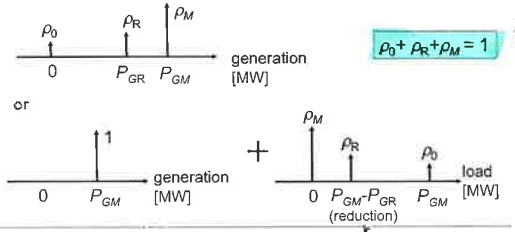
Model of a generator with more than 2 states

- It is possible to represent the model of a generator with *more than 2 states*, to represent its operation also with *reduced power* with respect to the generator capacity
- Example with model of the generator with *three states*:



$\rho_0 + \rho_R + \rho_M = 1$ probability

max - P_{GR}

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N NORMAL STATE : all the quantity in the limits

N-1 : remove one component and the system works

with any contingency we have no violation

control center → calculate

N-2 is more difficult, combination more

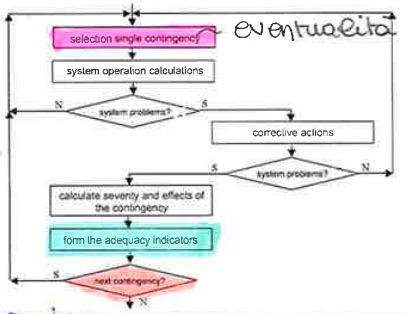
lost probably cause

common cause credible contingency

NORMAL
N-1 security
N-2 (cases)

we defined and select the contingencies

Contingency enumeration



eventualità

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We can find a possible solution if we find a problem

Put control action to restore the limits

The problem is critical if we have no solution

Contingency enumeration

- Selection of the *contingencies*:
  - Some credible contingencies are selected, on the basis of which the *contingency ranking* is constructed
  - typically all the contingencies due to the missing operation of a *single component* are selected (*N*-1 security, that is, operation with *N*-1 components in normal conditions), and a certain number of contingencies due to the missing operation of more than one component
  - The cases with missing operation of more components may include *multiple faults* independent of components that affect the *same area* of the system, multiple faults with *common cause*, multiple faults *induced* by missing or wrong operation of components or protection devices, faults that occur during the absence of some components under *scheduled maintenance*
  - The contingency ranking is prepared on the basis of suitable *performance indicators*

eventualità credibili

adatto

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square → if we take only the absolutes values as the importance goes down 0,25

0,5 → 0,25

1,2 → 1,44 > 1

lower than 1 increase the importance

IP small → we can solve the problem empirically

Performance indicators

- Definition of the *performance indicators*:
  - A simple indicator can be constructed by considering the *variable to be analyzed*, whose limit value is A_L, and that assumes the value A in the conditions under study, in the form:

$$IP_A = \sum_{\text{componente } i} \left(\frac{A_i}{A_{Li}}\right)^2$$

  - the *contribution* of the single variable evaluated for a single component is higher than 1 in case of violation
  - For the contingency ranking, it is needed to *weight* carefully the importance of the different quantities considered, by constructing composed indicators using *weighting coefficients* w_A, w_B, ... applied to each variable A, B, ...

$$IP = w_A\, IP_A + w_B\, IP_B + \ldots$$

  - The *weighting coefficients* are established and updated *empirically*

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Contingency enumeration

- For each contingency: eventualità
  - There is an evaluation of whether the effects of the contingency cause an *immediate problem* to the system (line currents exceeding the limits, node voltages too low, etc.), if not the next contingency is analyzed
  - If there are problems, initially there is a search for *corrective actions*, to be applied during the system operation by modifying the control variables (generated power, variable on-load tap changing ratios, possible load shedding, etc.) to return inside the admissible limits
  - If the corrective actions are *successful*, the contingency is *excluded* from the list of the hazardous events, and the next contingency is analyzed
  - If the corrective actions are *not successful*, the event is added among the possible causes of *missing adequacy* of the system, calculating the corresponding contribution to the adequacy indicators

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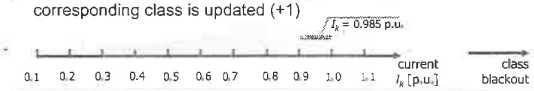
It can not converge
Approximate solution, no fast
Difficult applicate the right solution (we can use our sensitivity)

N

→ { divide by N
the sum is equal to 1
but if step = 0,1
the area ≠ 1
we need to divied
by step of
classes
→ PDF

Application of the Monte Carlo method

- The Monte Carlo method is applied by carrying out a *large number* of extractions (e.g., 10000 or more), in each of which all the values of the input random variables are extracted
- For each cycle, the system equations are solved, obtaining a value for *each variable* to be observed (e.g., branch currents, node voltages,...) typically expressed in per units or in per cent
- The results obtained are inserted into the *predefined classes* for each observed variable (a specific class is prepared to host the occurrences of lack of system operation), and the *counter* of the occurrences is progressively updated
- Example: for a current I_k = 0.985 p.u. at line *k*, the *counter* of the corresponding class is updated (+1)



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Power station not available → we not considere it

Application of the Monte Carlo method

- The *Monte Carlo* method:
  - Allows us considering *multiple contingencies* in the same event analysed
  - May fail to estimate the probability of occurrence of an *uncommon* event
  - The accuracy of the results depends on the *number of extractions (repetitions)* and on the possible presence during the analysis of contingencies with *very low probability* of occurrence but with *very dangerous effects*
  - As a general rule, the accuracy of the indicator calculated from the Monte Carlo method is proportional to the *square root* of the number of repetitions
  - Has to be executed many times to repeat the *set of observations under different* conditions (given by the different values of the input variables)
  - In the *sequential* Monte Carlo, there is the possibility of taking into account the *dependence on time* of some variables (e.g., the scheduling of the hydro resources)

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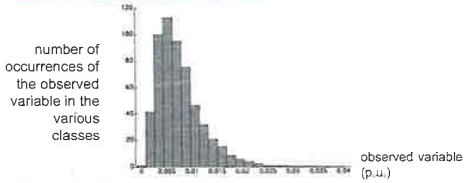
Results of the Monte Carlo method

- At the end of the extractions, the *statistics* of each observed variable are obtained in a discretized form



- The *probability density* of each variable is obtained by:
  - dividing the amplitudes of the classes by the *number of* Monte Carlo cycles
  - dividing the resulting values in each class by the *class width*
- The hazardous contingencies are represented (e.g., for a current) by the "blackout" class and by the classes with currents higher than 1 p.u.

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Considerations on the methods

- *Differences* between the contingency enumeration and the Monte Carlo method:
  - Different *mechanism* of selection of the contingencies
  - Higher *simplicity* of the Monte Carlo method in calculating the *statistics* of the operation states of the system
  - Higher *simplicity* of the contingency enumeration method to provide useful information for the comparison of *alternative solutions* to improve the operation of an area of the system
- *Similarities* between the two methods:
  - algorithms to calculate the *operaing conditions* of the system
  - test of possible *corrective actions*

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Lesson 1

DISTRIBUTED GENERATORS AND THEIR CONNECTION TO THE GRID

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Outline

- Course module objectives
- Distributed generation
- Distributed energy sources
- Front-end power electronic interface

Module objectives

- ***To provide the fundamental concepts in power electronics and conversion structures employed by distributed generation systems***

impiegate

- The practical aspects of power electronics will be shown with a 15 kVA laboratory prototype

- The waveforms related to the power converter operation have been obtained through simulations and experiments

battery -> capacity 100 A/h charge increase it same energy
in power electronic power is important

Posso avere la stessa energia
in + tempo o - tempo ma è
la stessa; differenza ... P

Teaching materials

- Useful references
  - Muhammad H. Rashid, "Elettronica di potenza", Prentice Hall Milano, 2008
  - R. Teodorescu, M. Liserre, P. Rodriguez "Grid converters for Photovoltaic and Wind Power Systems", Wiley &Sons
  - J. G. Kassakian, M. F. Schlecht, G.C. Verghese, "Principles of Power Electronics", Pearson, 2010.
  - Course notes R. Bojoi "Fondamenti di elettronica di potenza"
- Internet materials
  - Interactive Power Electronics Seminar (iPES), ETH Zurich http://www.ipes.ethz.ch

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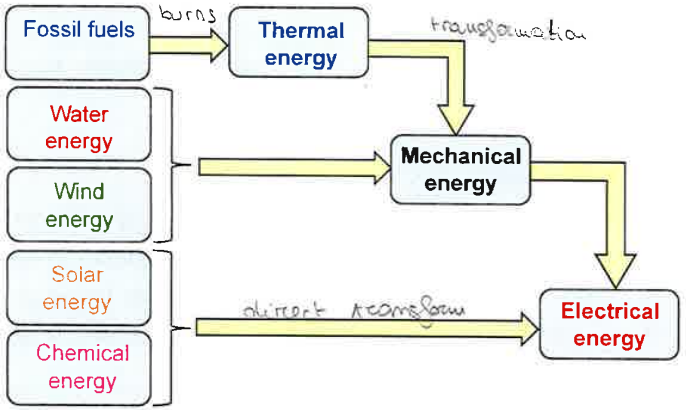
Distributed energy sources

- Examples of primary energy sources and their transformation into electrical energy



Distributed energy sources

- Most employed distributed energy sources: a list

(1) Microturbines (25 kW ÷ 500 kW)

(2) Internal combustion engines (5 kW – 7 MW) motori

(3) Wind turbines (1 kW – 5 MW)

(4) Micro-hydro turbines (1 kW – 5 MW)

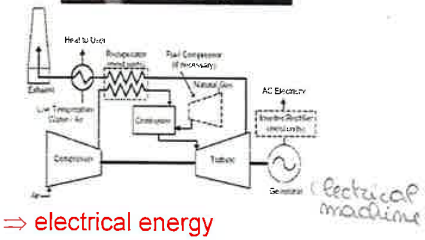
(5) Photovoltaic panels (1 kW – MW)

(6) Fuel cells (1 kW – 500 kW)

Distributed energy sources

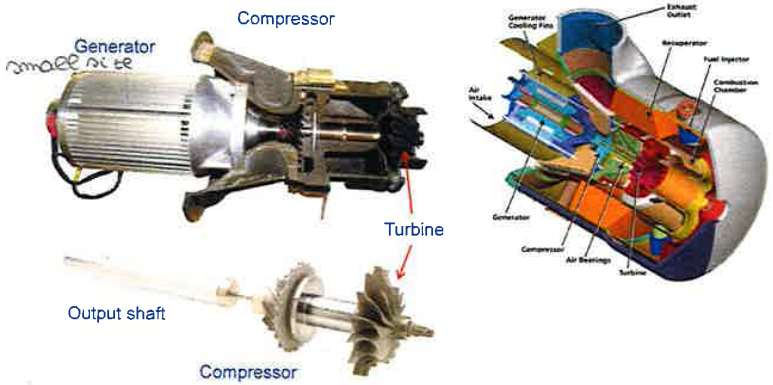
(1) Microturbines

- ✓ Fuel = natural gas
- ✓ Main elements: combustion chamber (camera), compressor, heat recuperator
- ✓ The turbine rotates an electrical machine operating as a generator



- ✓ **Indirect conversion**
  thermal energy ⇒ mecanical energy ⇒ electrical energy

Distributed energy sources



speed↑ Torque↓ generator small

- ✓ High rotational speed ⇒ 50000 ÷100000 rpm

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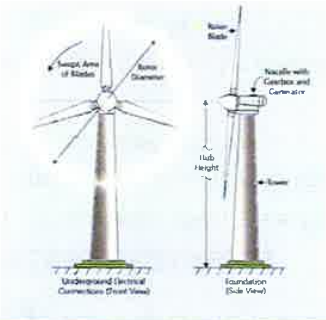
Distributed energy sources

- ✓ Very low rotational speed ≅ 10-20 rpm



- ✓ The gearbox output shaft rotates with a speed that is compatible with the electrical machines ≅ 1500 rpm

albero

Distributed energy sources

(4) Micro-hydro turbines

- ✓ The kinetic energy of water flow is transformed into mechanical energy by means of a turbine
- ✓ Low rotational speed (hundreds of rpm)
- ✓ Electrical energy production with an electrical machine operating as generator
- ✓ **Indirect conversion**
  water flow energy ⇒ mechanical energy ⇒ electrical energy

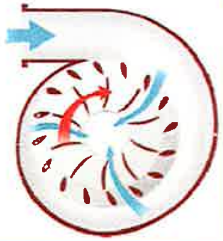
Distributed energy sources

- ❑ Hydro turbines used in distributed generation

❖ **Francis** P↑

- ✓ Most common (also for big power hydroelectric plants)
- ✓ Spiral casing, with wicket gates (yellow) for flow setting

Full flow setting



Minimum flow setting

Distributed energy sources

❖ **Pelton** P↓

- ✓ High efficiency
- ✓ Convenient for low flow and high fall levels (mountain plants)

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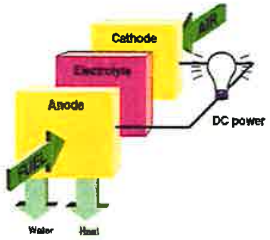
Distributed energy sources

(6) Fuel cells

- ✓ Use hydrogen (fuel) and oxygen from the air
- ✓ The fuel cell is similar to a battery only if the hydrogen and oxygen are continuously supplied



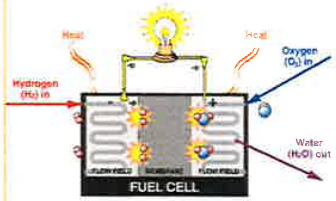
- ✓ The hydrogen and oxygen produce a reaction at electrodes level, producing electrons, water and heat

⇩

- ✓ **Direct conversion chemical energy ⇒ electrical energy !**

Distributed energy sources

Anode: the hydrogen divides into ions and electrons. The ions cross the electrolyte to the cathode, the electrons form an electrical current in an external circuit from anode to the cathode



Cathode: the oxygen, together with the ions of hydrogen and electrons from the external circuit produce water and heat

$$H_2 \rightarrow 2H^+ + 2e^- \qquad 1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

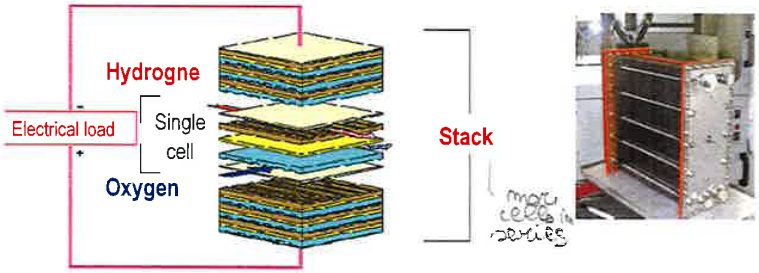
$$H_2 + 1/2\,O_2 \rightarrow H_2O$$

Distributed energy sources

- ❑ One cell generates 0.7V for a current density that depends on the surface of the electrodes (300 ÷ 1000 mA/cm^2)

⇩

- ❑ To get a sufficiently high voltage, more cells must be series-connected to get **one stack**



Distributed energy sources

- ❑ Electrolyte
  - ✓ Facilitates the movement of the hydrogen ions from the anode to the cathode
  - ✓ Its nature defines the type (technology) of the fuel cell
- ❑ The fuell cell technologies that are more employed today
  - ❖ **Proton Exchange Membrane Fuel Cells** - (PEMFC)
  - ❖ **Solid Oxide Fuel Cells** - (SOFC)

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Power interface to the grid

- The distributed energy sources have different oprating principles and use different energy transformations to get the electrical energy

(A) Microturbines, wind and water turbines

- ✓ They need electromechanical energy conversion
  ⇒ electrical machine operated as a generator

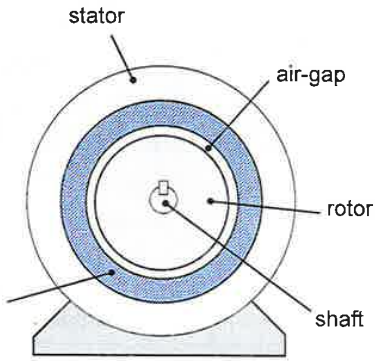
(B) Photovoltaic panels and fuel cells

- ✓ They are DC voltage sources

Power interface to the grid

(A) Microturbines, wind and water turbines

- Typically, the generator is an electrical machines are rotating three-phase machines:
  - ✓ Outer ferromagnetic cylinder (stator)
  - ✓ Inner ferromagnetic rotating cylinder (rotor)
  - ✓ Air-gap – air zone between stator and rotor



The stator contains the stator windings
cave
in slots (not shown here) at the air-gap

Power interface to the grid

- More employed (impiegate) electrical machine solutions

(A1) Syncronous (avvolto) machine (alternator)

- ✓ Wound excitation
- ✓ With permanent magnets

wound → avvolto
winding → avvolgimento

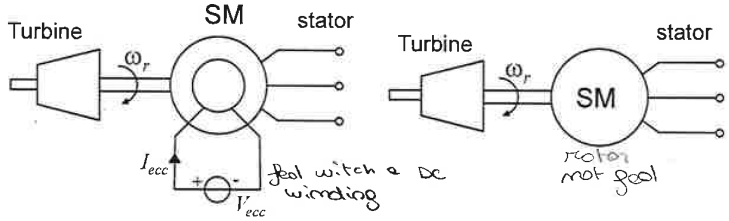
(A2) Asynchronous machine

- ✓ Wound rotor
- ✓ Squirrel-cage rotor

- The rotor is rotated by the turbine directly or by means of a transmission system (gearbox)

Power interface to the grid

(A1) Synchronous Machine (SM) (alternator)



- ✓ Wound excitation winding fed with a continuous excitation current I_{ecc} produced with a DC voltage source
- ✓ Excitation produced by permanent magnets mounted on the rotor

- The two solutions use the same stator

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Power interface to the grid

- Numerical examples for getting 50 Hz

$p = 1 \rightarrow n_s = 3000\ rpm$
2 poles

$p = 2 \rightarrow n_s = 1500\ rpm$
4 poles

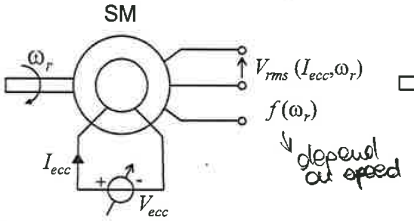
$p = 10 \rightarrow n_s = 300\ rpm$
20 poles

- Low synchronous speed needs a machine having a high pole-pairs number

gearbox disappear → generator speed ↓ poles ↑

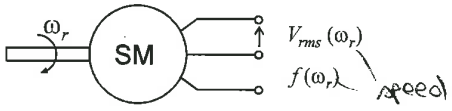
Power interface to the grid

SM with wound excitation



- The output voltage can be regulated by means the excitation current I_{ecc}

PMSM



- The output voltage cannot be regulated at constant operating speed

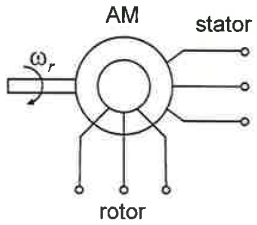
Power interface to the grid

(A2) Asynchronous machine (AM)

- The stator is very similar with the one of a synchronous machine and contains a three-phase winding
- Rotor
  - ✓ Wound = three-phase winding (star-connected) with 3 slip rings and 3 brushes for external supply
  - ✓ Squirrel-cage = shorted bars (equivalent to a shorted three-phase windings)

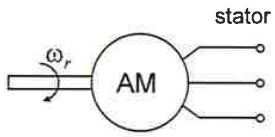
Power interface to the grid

AM with wound rotor



- Doubly-fed machine (stator and rotor supply)

AM with squirrel-cage rotor



- Single supply (stator)

can only work with slip < 0

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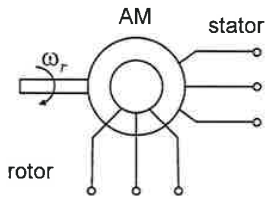
slot cogging
spread dispersione

Power interface to the grid

- AM with wound rotor
  - ✓ Doubly-fed machine I can work with $\omega_r \gtrless \omega_s$



- ❖ Stator ⇒ frequency f ω_s
- ❖ Rotor ⇒ frequency sf, s is the slip

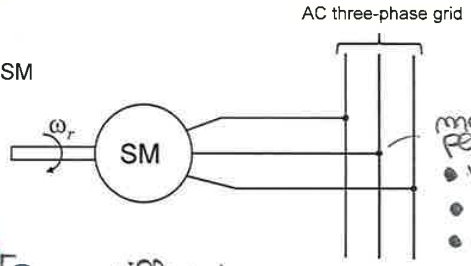
rotor in DC condition if $s = 0$, $\omega_r = \omega_s$

normal operation, Stator

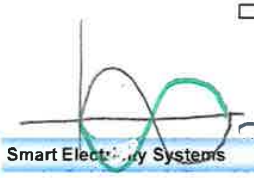
$\omega_r > \omega_s$ negative slip generate Power

Power interface to the grid

- With a synchronous or with an asynchronous machine it is possible to generate power using the mechanical power provided by a turbine (wind, hydro, micro-turbine)
- We need to connect the electrical machine to the LV or MV distribution grid
  - ✓ Example for PMSM

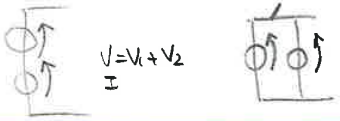


match perfectly
- V_{RMS}
- f
- same instantaneous values



different phases, not well

Power interface to the grid



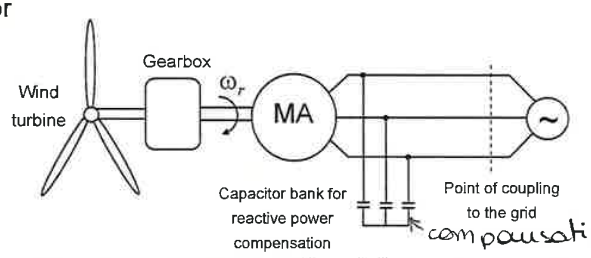
- The synchronous machine can be connected to the grid only if the machine generates the same frequency and the same instantaneous voltage (perfect synchronism with the grid) !

⇩

- ❖ Constant and controlled operating speed
- ❖ Voltage regulation through the excitation (impossible for permanent magnet SM)

Power interface to the grid

- The asynchronous machine can be connected to the grid; example for a wind turbine using an AM with squirrel-cage rotor



compensation of Q

matching speed direction to work

- ✓ The rotating field produced by the stator and the rotor speed must have the same sign

$\omega_r > \omega_s$ to generate P

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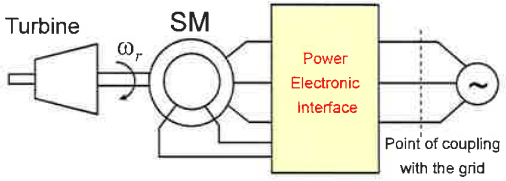
Power interface to the grid

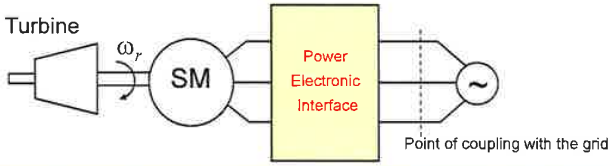
(A) Microturbines, wind and hydro turbines

- Syncronous machine with wound rotor



& degree of freedom

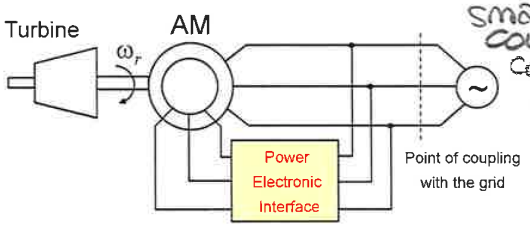
- Synchronous machine with permanent magnets



something connected to the stator: the converter must be design for the total power

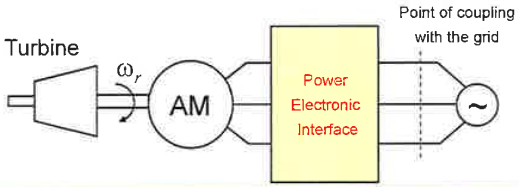
Power interface to the grid

- Asynchronous machine with wound rotor



only on the rotor
smaller power converter
cost reduced
(the power is about 30%)
maximum slip of an induction machines

- Asynchronous machine with squirrel-cage rotor

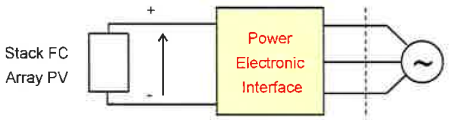


full sized

P
← ω → needed by generator

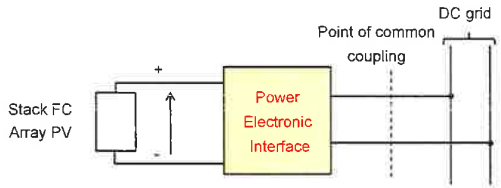
Power interface to the grid

(B) Photovoltaic panels and fuel cells



✓ At low power levels (<7 kW), the grid can be single-phase

- It is possible also an interface with a DC distribution grid



Power interface to the grid

- **The power electronic interface allows connecting to the grid the distributed energy sources for distributed power generation**

- **The power interface topology, its design and operating conditions strongly depend on the type of the distributed energy source**

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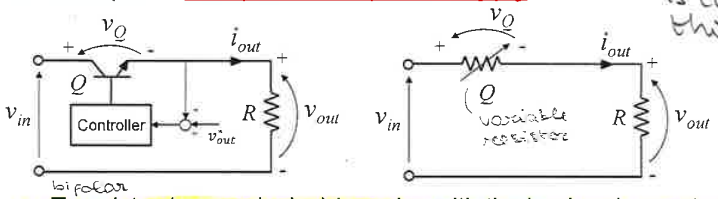
Electronic power converters

- Example 2: Low power DC power supply

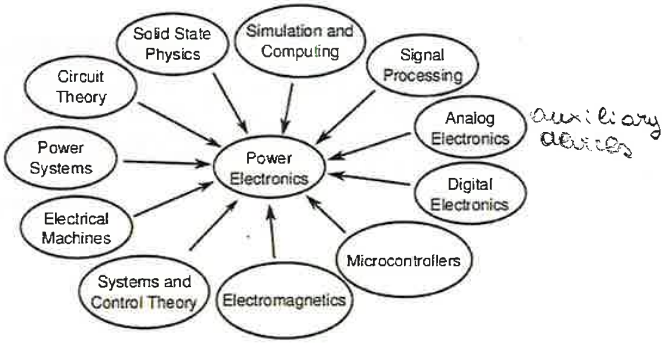
voltage regulation is continous using this method



- Transistor (power device) in series with the load and operated as a variable resistance (not as a switch!)
- Continous voltage regulation with low efficiency (that decreases at high load currents and low output voltages) due to the high voltage drop introduced by the transistor
- Practical solution in low power electronic circuits, best results when the output voltage is constant and close to input voltage

Electronic power converters

- Power Electronics = multidisciplinary enabling technology that deals with the study, the design and the control of power electronic converters

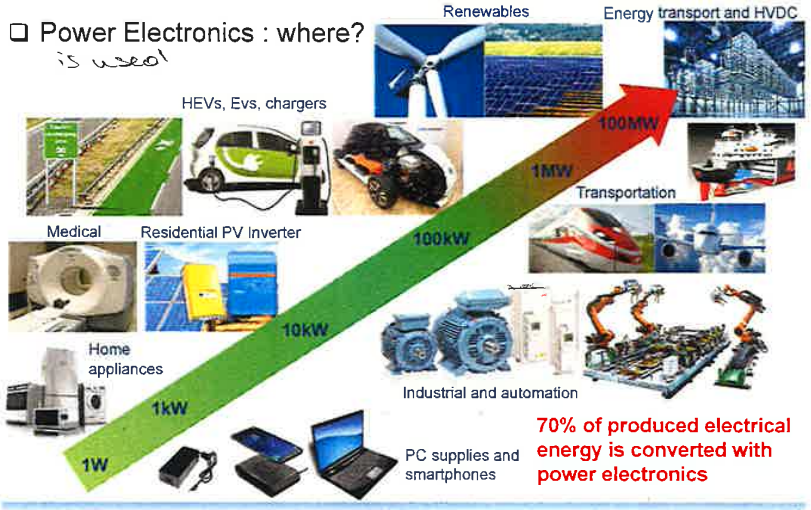


auxiliary devices

Electronic power converters

- Power Electronics : where?

is used



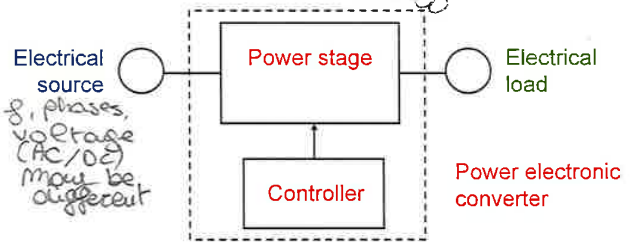
70% of produced electrical energy is converted with power electronics

Electronic power converters

- **Power electronic converters** = static converters employing semiconductor power electronic devices

implegare

electrical to electrical energy



f, phases, voltage (AC/DC) may be different

- The source and the load may have different voltages, currents and phase numbers; the power tranfer can be reversible but it depends of the converter structure

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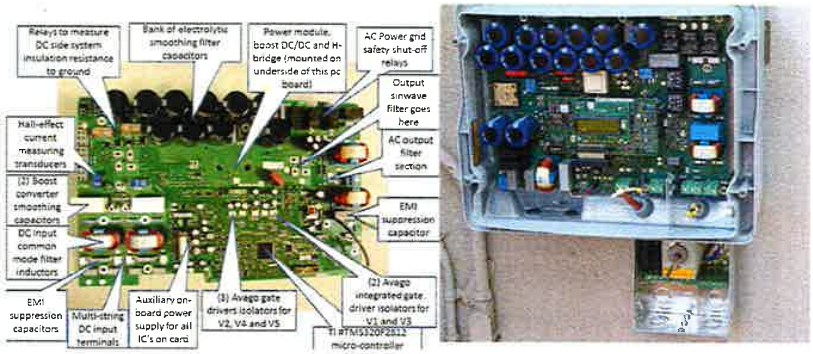
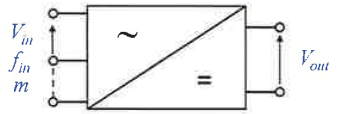
Electronic power converters

- Example of small converters for photovoltaic panels



Electronic power converters

- The classification of power electronic converters is mainly decided by the source and load characteristics (types)
  - **AC/DC converters (rectifiers)** from AC sources to DC loads

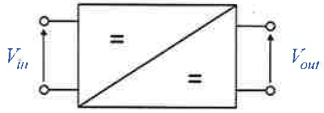


concatenato

- ✓ Input: rms line-to-line voltages $V_{in,rms}$ (usually constant), frequency f_{in} (usually constant), number of phases m
- ✓ Output: DC voltage $V_{out,dc}$ (constant or variable according to the rectifier topology) adjust the voltage

Electronic power converters

- **DC/DC converters** from DC sources to DC loads having different voltage levels chopper → in US only for elicoptero

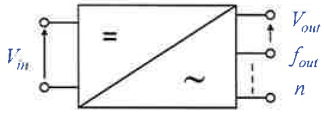


- ✓ Input: DC voltage $V_{in,dc}$ (usually constant)
- ✓ Output: variable DC voltage $V_{out,dc}$

MPPT: extract the maximum from the input (AC.. DC..)

Electronic power converters

- **DC/AC converters (inverters)** from DC sources to AC loads



- ✓ Input: DC voltage $V_{in,dc}$ (costant or variable depending on the electrical source) usually changing
- ✓ Output: rms line-to-line voltage $V_{out,rms}$ (costant or variable), frequency f_{out} (costant or variable), number of phase n

$n \uparrow \sim$ $i \downarrow$ (dato P, V)

one phase open 6 to 5, the others work

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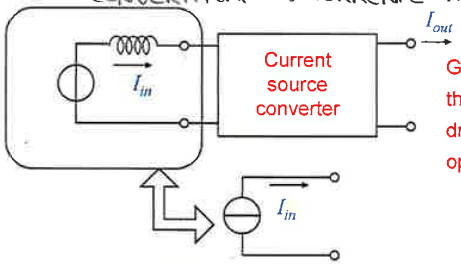
Electronic power converters

2) **Current source converters (imposed current)** = the source is a current source having a high internal impedance (inductive converter input)

CONVERTITORI A CORRENTE IMPRESSA



Given I_{in}, the converter imposes I_{out}; the load will respond with a voltage drop that depends on the load operating point

✓ **The load of a current source converter must be capacitive**

duality between the nature of input and output

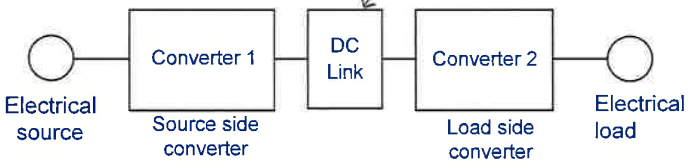
Electronic power converters

➢ Conversion type

✓ Direct = there is only one power stage between the source and the load

✓ Indirect = between the source and the load there are at least two power units that share a common link with energy storage; usually the connection is a DC link

energy tank

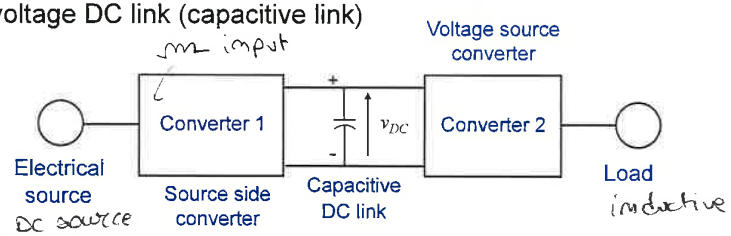


2 intermedie conversion

Electronic power converters

❑ The most employed indirect power conversion structure uses a voltage DC link (capacitive link)

m input



DC source

inductive

➢ The polarity of the DC link does not change

➢ The load side converter is a voltage source converter (generates a defined voltage to the load, while the load current depends on the load operating point)

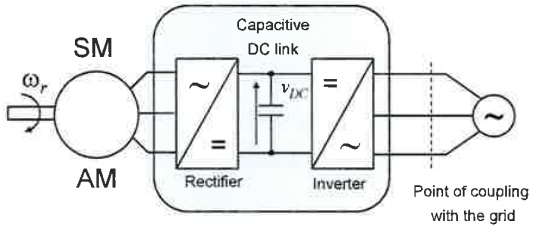
➢ Power range (tenths of W ÷ MW)

Electronic power converters

❑ What kind of power electronic converters are used for distributed generation?

permanent magnet

➢ Turbine with PM synchronous machine or with squirrel-cage induction machine



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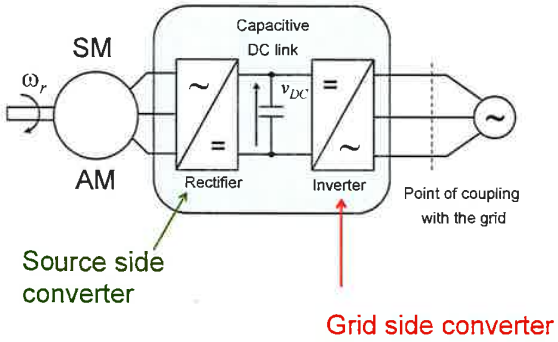
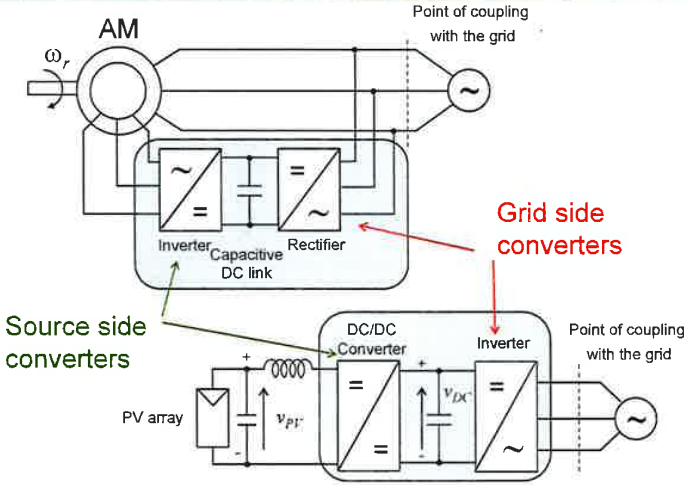
Electronic power converters

- Examples



Electronic power converters



Electronic power converters

- The power converters employed by the distributed generation consists of switching power poles built with power electronic devices that are operated as switches (open – OFF, closed – ON)

⇩

Switch-mode converter

power devices works like switches

Electronic power converters

- Commutation = dynamic process during which an electrical current is transferred from one power switch to another power switch

Before the commutation
S_1 –ON, S_2-OFF

After the commutation
S_1 –OFF, S_2-ON

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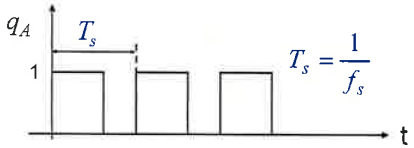
Switching power pole

- The output voltage depends from the input voltage V_{in} and the instantaneous value of the swicthing function $q_A(t)$

$$v_A(t) = V_{in} \cdot q_A(t)$$

- A switching operation is obtained when the $q_A(t)$ is periodic function of frequency f_s called switching frequency



$$T_s = \frac{1}{f_s}$$

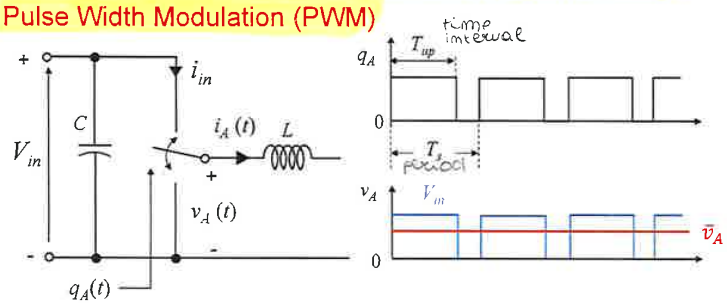
100 μs
10 kHz

200μs
5kHz

- The output voltage $v_A(t)$ is a pulse sequence of amplitude that is equal with V_{in}

Switching power pole

- The mean value of output voltage can be adjusted using Pulse Width Modulation (PWM)



mean voltage $V_A = \frac{1}{T_s}\int_0^{T_s} v_A(t)dt = \frac{1}{T_s}\cdot\left[T_{up}\cdot V_{in} + (T_s - T_{up})\cdot 0\right] = \frac{T_{up}}{T_s}\cdot V_{in} = d_A \cdot V_{in}$

$X = \frac{1}{T}\int_0^T x(t)\,dt$

- $d_A \in [0,1]$ is the pole duty-cycle

mean value
armonics

how much the diverter is in the up position

Switching power pole

- To adjust (regulate) the output mean voltage, the duty-cycle becomes a time-varying function whose dynamics is inferior to the switching frequency $\Rightarrow d_A(t)$

⇩

- The output mean voltage becomes a time-varying function (mobile mean value) whose dynamics is inferior to the switching frequency $\Rightarrow$ media mobile

MOVING AVERAGE

$$\bar{v}_A(t) = d_A(t)\cdot V_{in}$$

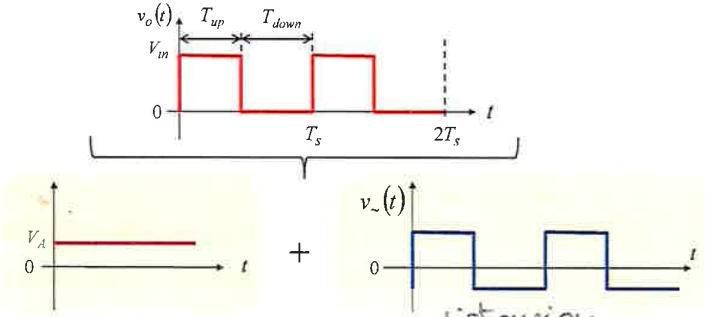
- $d_A \in [0,1] \Rightarrow$ the mean output voltage changes between 0 and $V_{in} \Rightarrow$ the pole is a DC/DC converter

f↑ almost continous function

10ms → 100 Ts
100 steps almost continous

Switching power pole

- The pole output voltage is a pulsed periodical waveform of amplitude V_{in} and contains:
  - DC component V_A
  - non-desired AC component (ripple) $v_\sim$ having zero mean value



distorsion
ripple

distorsion - different from ideal

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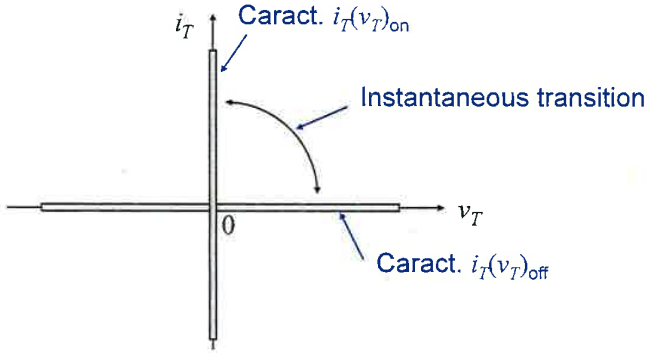
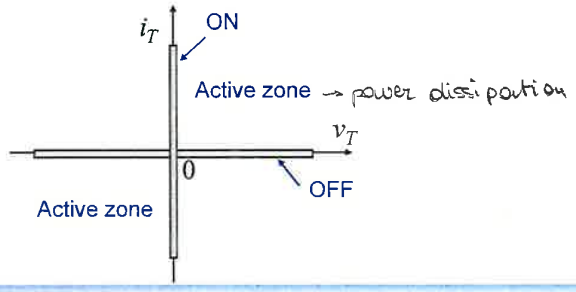
Power electronic devices

- For and ideal device, the transition from ON state to OFF state and viceversa is instantaneous (ideal commutation) ⇒ the dissipated power during the commutation is zero



Power electronic devices

- In the voltage-current plane, the device operating point lies always in zero power dissipation zones
- For the remaining zones (first and third quadrants) $p_T = v_T \cdot i_T > 0$; these quadrants are called active zones



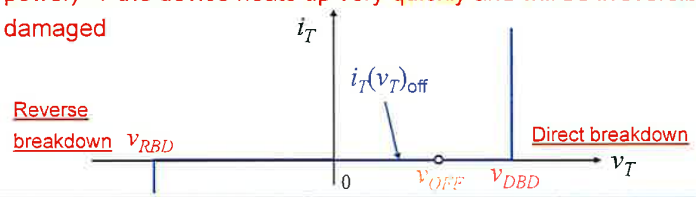
Power electronic devices

- Although the converter principle of operation is analyzed with ideal power devices, the converter design must consider real switches with their characteristics
- It is possible to consider a generic simplified device model that is valid for all devices used in practice

Power electronic devices

- The real device in the OFF state
  - Can withstand a limited voltage called breakdown voltage v_{BD}; some devices can block either positive/negative voltages, others only positive voltages
  - The device current is practically zero (ideal switch) if the applied voltage is less than the v_{BD} ⇒ the dissipated power in the OFF state is zero $p_{T(off)} = v_{T(off)} \cdot i_{T(off)} \cong 0$ can be neglected
  - Breakdown means entering in the active zone (excessive dissipated power) ⇒ the device heats up very quickly and will be irreversibly
  - damaged

operating point in the active zone



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Power electronic devices

- Given an operating condition with switching frequency $f_s = 1/T_s$, an ON state time T_{on}, and two commutations (OFF→ON e ON→OFF)
  - **Mean ON power loss** Remember!

$$P_{on} = v_{th} I_{o,mean} + r_d I_{o,rms}^2 \ (W)$$

$$I_{o,mean} = \frac{T_{on}}{T_s} \cdot I_o = d \cdot I_o, \ I_{o,rms} = \sqrt{\frac{T_{on}}{T_s}} \cdot I_o = \sqrt{d} \cdot I_o$$

  - **Mean switching loss** datasheet

$$P_c = \frac{E_{on} + E_{off}}{T_s} = (E_{on} + E_{off}) \cdot f_s$$

$$E_{on} = \frac{1}{2} V_{in} I_o t_{c(on)}$$

$$E_{off} = \frac{1}{2} V_{in} I_o t_{c(off)}$$

switching frequency

Power electronic devices Important! Exam!

perdite conduzione

- The conduction loss depends on the device current, device duty-cycle and ON-state characteristics of the device

perdite commutazione

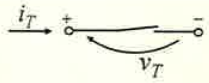
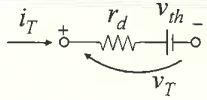
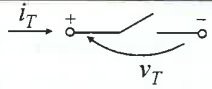
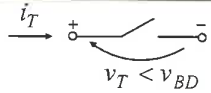
- The switching loss depends on the commutated voltage, the commutated current, switching times and switching frequency

$1/2 \ V_{IN} \ I_o \ t_{CON}$

t_{COFF}

- The total device loss P_d is the sum between the conduction loss and the switching loss

Power electronic devices

	IDEAL DEVICE	REAL DEVICE
ON	 Zero voltage drop and losses	 Non-zero voltage drop Limited current, conduction losses
OFF	 Zero current zero losses	 Practical zero current Limited voltage, practical zero losses
COMM.	Instantaneous commutation zero swicthing losses	Non-instantaneous commutation switching losses

Power electronic devices

- The electronic power devices can be considered as:
  - **ideal** when the objective is the source or the load operation (compute the output voltage, input current .....)
  - **real** when the analysis is aimed at computing the converter total losses for a thermal analysis ⇒ the data sheets must be used to get the devices parameters

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Power diode

c) **Schottky diodes**

- Very low ON state voltage drop (0.3-0.5V)
- Ultrafast diodes with very low switching losses
- Low breakdown voltage

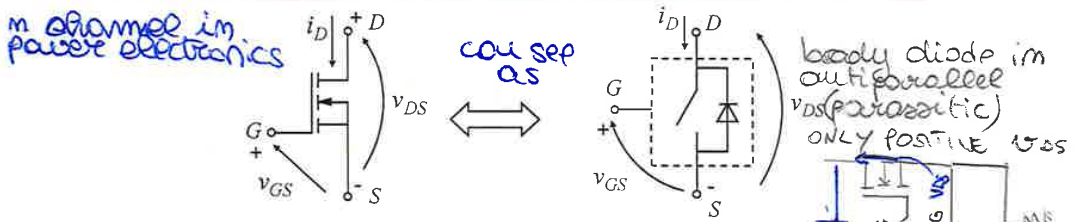
d) **SiC Shottky diodes** silicon carbon

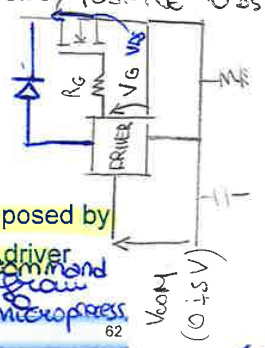
- Ultrafast diodes with extremely low switching losses
- High ON state voltage drop
- Available on the market at higher cost respect to other ultrafast diodes

MOSFET

2) **MOSFET** (Metal Oxide Semiconductor Field Effect Transistor)

n channel in power electronics





- Device with 3 terminals:
  - ✓ 2 power terminals: Drain (D) and Source (S)
  - ✓ 1 command terminal: Gate (G)
- **Voltage-controlled device** = the MOSFET state is imposed by the voltage v_{GS} applied between gate and source by a driver circuit

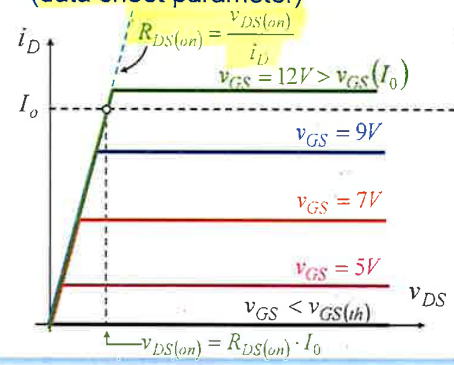
command from microprocess

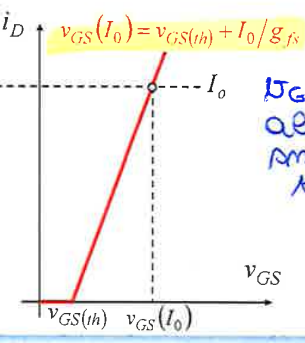
switch command 1 ⟶ ex. 19 V (v_{GS})

no v_{TH} → different tecnology start from origin
If the current becomes higher than a level we arrived in the active zone. we arrive before in the active zone if V_{GS} imposed is lower

MOSFET

- **OFF** if $v_{GS} < v_{GS(th)}$ and $v_{DS} < v_{DSS}$ (breakdown voltage)
  $v_{GS(th)}$ =(2÷4) V = threshold voltage
- **ON** if $v_{GS} > v_{GS(th)} + i_D/g_{fs}$, where g_{fs} [S] is the **trasconductance** (data sheet parameter)





V_{GS} is always smaller than 20 V

If we want to see a MOSFET as a small resistence, we must NOT exceed I_0. If we exceed I_0 the voltage becomes bigger and the driver shuts off the MOSFET (he measures the drop across the diode)

MOSFET

- Has an internal parasitic antiparallel diode mounted ⇒ the MOSFET can block only positive voltages
- In the ON state, the MOSFET is just an ON resistance (no threshold voltage) $R_{DS(on)}$ if the command voltage is sufficiently high
- The ON state resistance depends on the breakdown voltage V_{DSS} and also on the internal temperature

$$R_{DS(on)} \propto V_{DSS}^{2.5 \div 2.7}$$

⇓

very low conduction voltage

- Low voltage MOSFETs (<250V) have very low ON state resistances and thus low conduction losses

(ONLY) ON STATE: the driver analise the voltage across the diode and it can shuts off the MOSFET or sends a signal to change V_{com}

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IGBT

- The IGBt can be designed to block negative voltages
- To lower the ON state resistance, many IGBTs are designed to block very low negative voltages
- Given the same rated voltage, the ON state of an IGBT is lower respect to the ON state resistance of an MOSFET

⇩

- **Lower conduction losses respect to the MOSFET**

IGBT

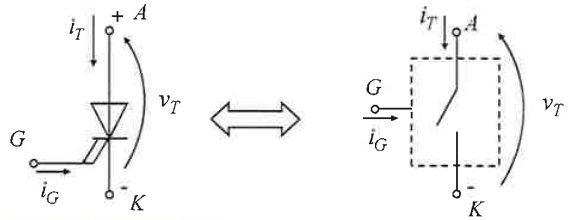
- The IGBTs are available today for voltages up to 3.3 kV and currents up to 1200 A
- The switching times are of order of 1÷5 μs

⇩

- The IGBT is the best choice for applications with voltages higher than 300V and switching frequencies up to 30÷70 kHz
- Typical command voltage levels:
  - ON : $v_{GE} = 12 \div 15$ V
  - OFF: $v_{GE} = (-5V \div 0$ V)

GTO

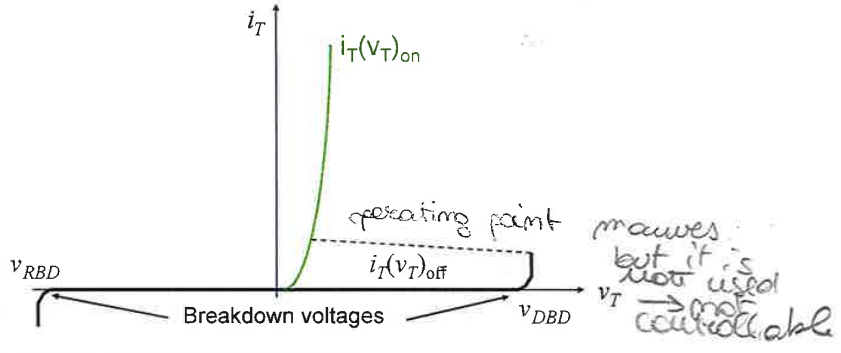
4) GTO (Gate Turn-off Thyristor)



- Device with 3 terminals:
  - ✓ 2 power terminals: Anode (A) and Cathode (K)
  - ✓ 1 command terminal: Gate (G)
- **Current-controlled device** = the GTO state is imposed by the gate current i_G provide by a driver circuit

GTO

- OFF → ON $i_G > 0$
- ON → OFF $i_G < 0$, $|i_G| = (1/5 \div 1/3) \cdot I_T$



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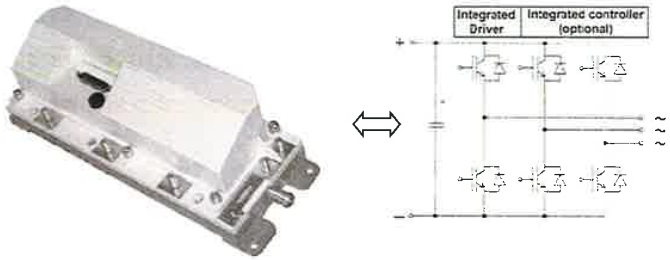
Technology advancements

- Highly integrated power converters = entire converter with sensors, drivers, heatsink and control

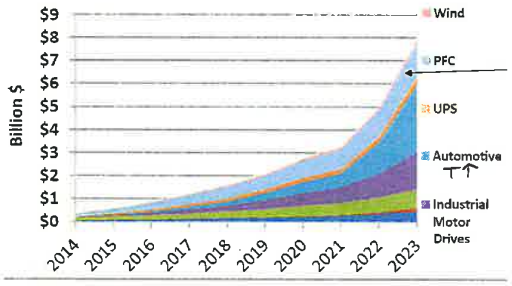


Technology advancements

- Wide Bandgap (WBG) devices
  - New materials
    - ✓ Silicon carbide (SiC)
    - ✓ Gallium nitride (GaN)
  - Advantages respect to Si
    - ✓ Higher operating temperatures
    - ✓ Very low switching losses
  - Disadvantages
    - ✓ The cost is higher (between 3 to 5) than Si

Technology advancements

- Although the cost of WBG converters is still high, it is expected a big development in the future



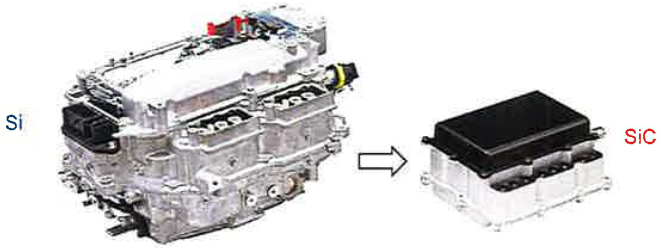
Source: Wide band power electronics – Department of Energy USA

PFC = grid connected converters

- Transportation and energy will require more WBG devices and the cost will drop

Technology advancements

- Comparison between traditional IGBT inverter (Si) and new SiC inverter (Toyota)



(source: http://www.ingenieur.de/mediaviewer/show/336692/336690#entry)

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Power losses

- Heatsink = element that transfers to the external environment the heat that is produced inside the power devices through
  - Convection (main part)
  - Irradiation (negligible part)

- The heatsinks use different cooling systems
  - Air-cooling (more economical)
    - ✓ natural convection
    - ✓ forced convection (fans)
  - Water-cooling (more efficient) for high power levels

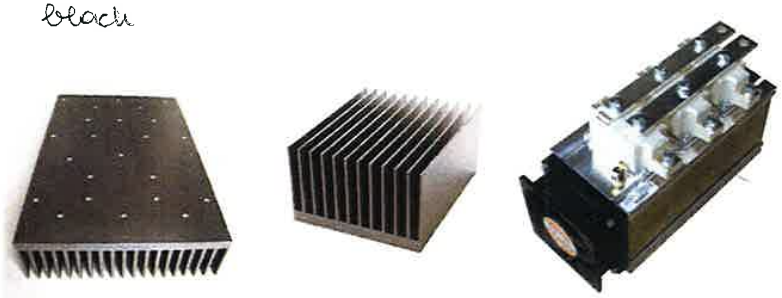
air volume ↑
liquid ↓

Power losses

- **Air-cooled heatsinks** = extruded/molded Aluminum
  - Dark color to colore scuro to increase irradiation effects
  - Vertical mounting

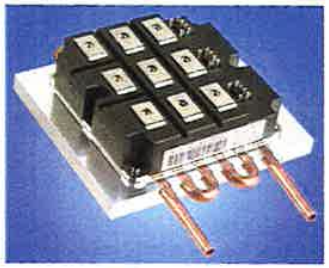
modellato

black



Power losses

- **Water-cooled heatsinks**
  - Aluminum plate with internal copper tubes for water flow



Power losses

- The real power devices can be considered initially as ideal to understand the power converter operating principles
  - Negligible ON state voltage drops respect to the converter operating voltages
  - The switching times are neglected

- On the contrary, the converter design needs the real devices with their parameters and parasitic effects

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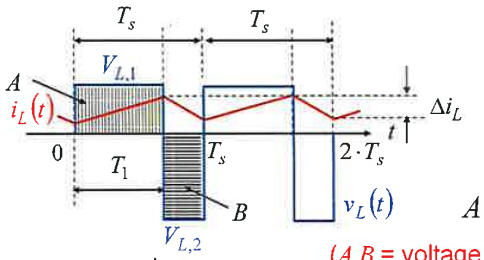
Inductor

- Inductor behavior at steady-state in switch-mode power converters
  - DC operation with variable values : the **mean value** of the voltage across the inductor is zero, while the instantaneous value is not zero
  - Non-sinusoidal AC operation: reactance whose value is proportional with the frequency, the voltage drop across the inductor is not zero
    ⇒ the inductor is an open circuit for infinite frequency

Inductor → minimisize L always

- Typical waveforms of DC operation: variable voltage v_L with zero mean value ⇒ i_L will have an oscillation (ripple)



low ripple value → f ↑

step cutting

$$V_L = \frac{1}{T_s} \cdot \int_0^{T_s} v_L(t)dt = 0$$

$$A = B \Rightarrow i_L(0) = i_L(T_s)$$

(A, B = voltage integrals)

$$\Delta i_L = \frac{1}{L} \cdot A = \frac{1}{L} \cdot B \Leftrightarrow \Delta i_L = \frac{1}{L} \cdot \underbrace{T_1 \cdot V_{L,1}}_{A} = \frac{1}{L} \cdot \underbrace{(T_s - T_1) \cdot |V_{L,2}|}_{B}$$

mean voltage = 0

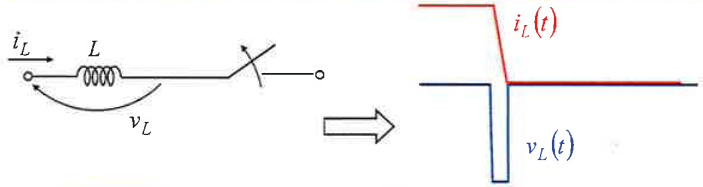
DC-DC converter DC-AC

Inductor

- An inductor accumulates energy in the magnetic field

$$W_L = \frac{1}{2} \cdot L \cdot i_L^2$$

- This energy cannot be maintained if the inductor is disconnected from the electrical circuit with non-zero current

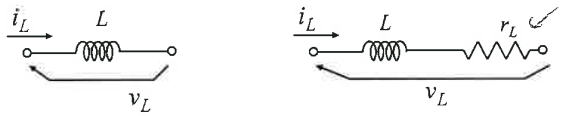


- Switch open = quasi-step current variation

$$v_L = L \cdot \frac{di_L}{dt} \to \infty \quad \text{Overvoltage!}$$

Inductor

- The commutation of the inductor current must be done from one power switch to another one
- The energy in an inductor can be ideally maintained if the inductor is shorted
- Real inductor = ideal inductance in series with the winding resistance (as small as possible to reduce the losses)



copper losses avvolgimenti

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Capacitor

- Capacitor behavior at steady-state according to the Circuit Theory
  - DC operation with constant values : the capacitor is an open circuit ⇒ the capacitor current is zero
  - Sinusoidal AC operation : the capacitor is a reactance whose value is inversely proportional with the frequency, the voltage drop across the capacitor is not zero
    ⇒ the capacitor is a short-circuit for infinite frequency

$X_C = \frac{1}{\omega C}$

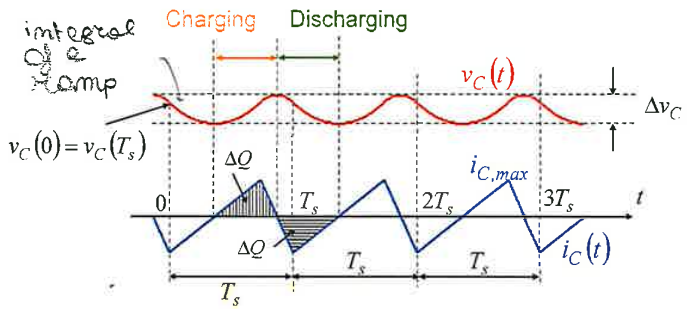
$f\uparrow$ capacitor is the preferred for current circulation

Capacitor

- Capacitor behavior at steady-state in switch-mode power converters
  - DC operation with variable values : the mean value of the capacitor current is zero, while the instantaneous value is not zero
  - Non-sinusoidal AC operation : the capacitor is a reactance whose value is inversely proportional with the frequency, the voltage drop across the capacitor is not zero
    ⇒ the capacitor is a short-circuit for infinite frequency

Capacitor

- Typical waveforms of DC operation: variable current i_C with zero mean value ⇒ v_C will have an oscillation (ripple)

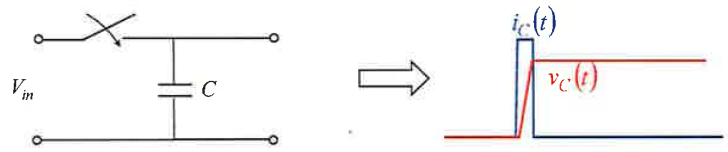


$$\Delta v_C = \frac{\Delta Q}{C} = \frac{1}{2}\cdot\left(\frac{T_s}{2}\cdot i_{C,\max}\right)\cdot\frac{1}{C} = \frac{1}{4}\frac{i_{C,\max}}{C\cdot f_s}$$ = peak-to-peak ripple

important! increase f_s

Capacitor

- The main problem is the connection of a discharged capacitor with a voltage source



- Switch ON = step variation of the capacitor voltage

$$i_C = C\cdot\frac{dv_C}{dt} \to \infty$$ Overcurrent! (inrush current)

connect converter to the source

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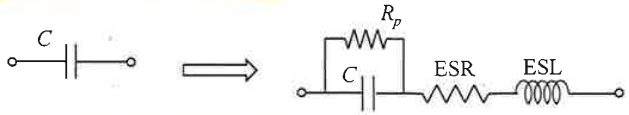
Capacitor

- **Real capacitor** = ideal capacitor in series with a small resistance and an inductance



- ESR (Equivalent Series Resistance)
- ESL (Equivalent Series Inductance)
- R_p – leakage resistance (very high value - MΩ)

- ESR limits the rms capacitor current due to the internal losses
- ESL limits the capacitor maximum frequency (the frequency must be lower than the resonance frequency between C and the ESL)

Capacitor

- Capacitor critical parameters:

  - **Voltage** – if the voltage across the capacitor exceeds the allowed value, the capacitor explodes
  - **RMS current**– produces a temperature raise due to the ESR; in some cases, the capacitors must be mounted on heatsink
  - **Temperature**– if the temperature exceeds the maximum value the capacitors are damaged irreversibly

Capacitor

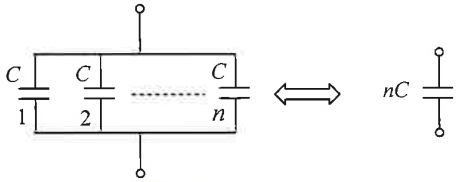
- Capacitor main parameters

  a) **Type (polarized, non polarized)**
  b) **Capacitance** (μF)
  c) **Rated Current** is the maximum rms current that can flow in a capacitor without producing an overheating
  d) **Rated voltage** is the maximum voltage that can be applied across the capacitor
  e) **Series resistance**
  f) **Maximum operating frequency** (limited by the ESL)

Capacitor

- Very often the capacitors are connected in series/parallel

(a) **Parallel connection**



- Total capacitance is $n \cdot C$
- The total rms current is n times higher than the rms rated current of a single capacitor
- The capacitors must be able to withstand the voltage (typically we connect in parallel identical capacitors)

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Lesson 3
DC-DC CONVERTERS

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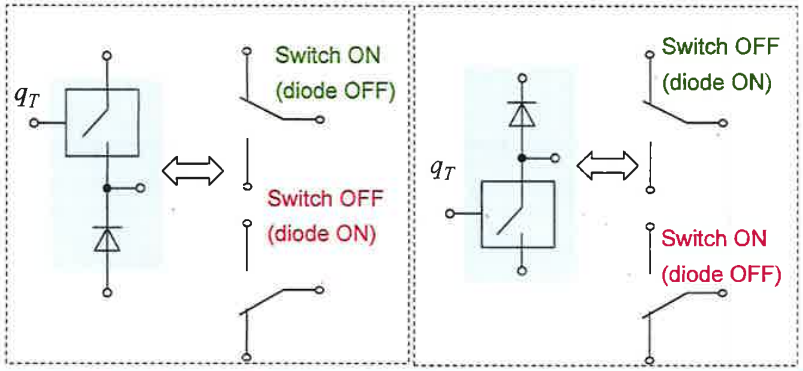
Outline

- Elementary DC-DC converters
  - Buck
  - Boost
- Pulse Width Modulators
- Single-phase inverter
- Three-phase inverter

Elementary DC-DC converters

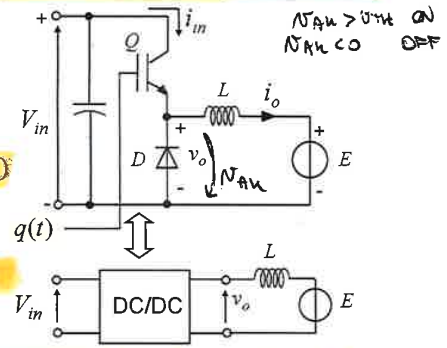
- The elementary DC/DC converters use a single canonical cell obtained with a controllable switch and a diode and using 2 different configurations



2 implementations are possible

Buck converter

- Switching power pole with capacitive input port and inductive output port
  - Transistor (UP)
  - Diode (DOWN)
  - **Active load LE**
  - E can be variable, $E \in \{0, V_{in}\}$
  - V_{in} is constant
  - Unipolar output with unidirectional current having constant mean value I_o



- **Pulse Width Modulation** = the transistor is operated with a switching frequency $f_s = 1/T_s$ and with a duty-cycle d imposed by the switching function $q(t)$

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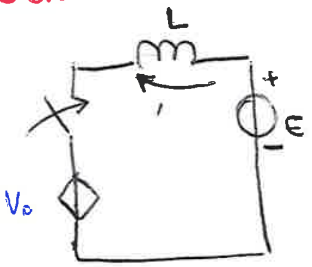
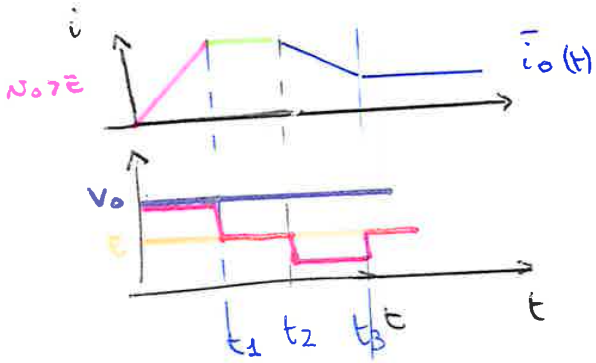
BUCK



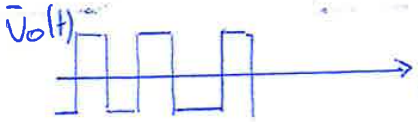


regulate mean current value (the real has a ripple, caused by the switching operation)

$v_L = V_o - E$

$\int v_L \rightarrow i \uparrow$

$v_o = E$

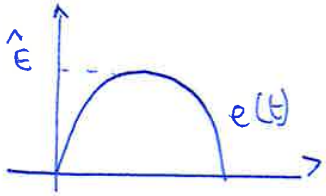


converter: regulate average value

$d \uparrow \quad V \uparrow \quad i \uparrow$

E must be between ø and V_{in} → buck

if E has this variation



$\hat{E} < V_{in}$

if we want $i = cost$ the duty cycle has the same shape of $\hat{E}$ (has to copy exactly)

if there is an error between i_o measured and the wanted:

voltage command is translated into D and then in the switching function

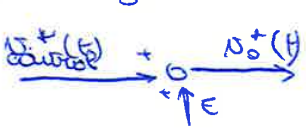
$V_o^*(t) \rightarrow V_o(t) \rightarrow d \rightarrow q(t)$

desired MOVING AVERAGE VALUE — voltage command

Another dinamic process where we have the switching operation

→ we act to regulate the output current

feedforward



at steady state $V_o^*(t) = E$

→ we need to put the difference for different

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Buck converter

- The inductor current has two components:
  - DC component due to the load current
  - AC component (ripple) due to the switching

$$i_L(t) = \underbrace{I_L}_{I_o} + i_{L,ripple}$$

triangular ripple with depend on D

  - Peak-to-peak current ripple

$$\Delta i_L = \frac{1}{L} \cdot \underbrace{(V_{in} - E) \cdot (d \cdot T_s)}_{A} = \frac{1}{L} \cdot \underbrace{E \cdot [(1-d) \cdot T_s]}_{B}$$

  - The maximum peak-to-peak current ripple is obtained when d=0.5

Buck converter

- If we consider an ideal (lossless) converter

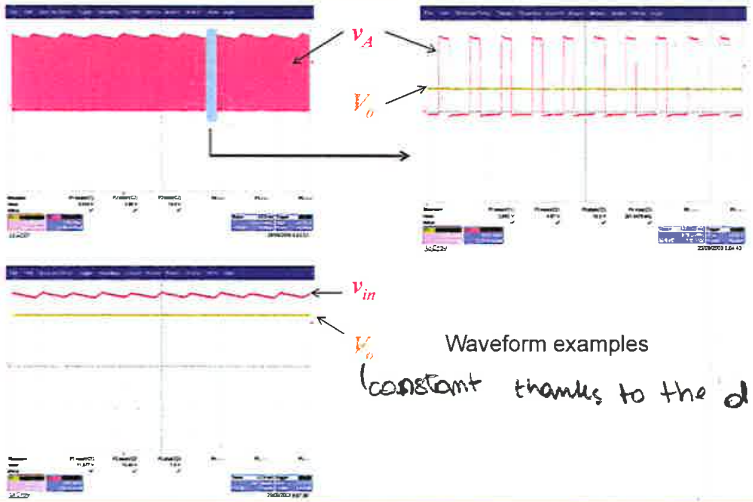
$$V_{in} \cdot I_{in} = V_o \cdot I_o \Rightarrow \begin{cases} I_{in} = \dfrac{V_o}{V_{in}} \cdot I_o = d \cdot I_o \\ V_o = d \cdot V_{in} \end{cases}$$

Equations of the ideal Buck converter

the current must be positive! Must not be reverse

Buck converter

real waveform



small time

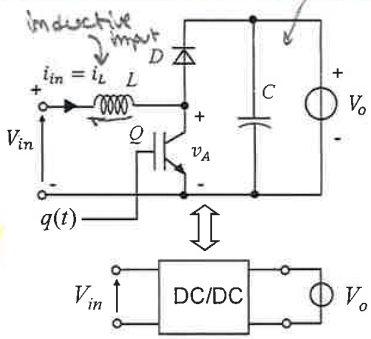
Waveform examples

constant thanks to the d

Boost converter

dual of buck

- Switching power pole with inductive input port and capacitive output port
  - Diode (UP)
  - Transistor (DOWN)
  - Voltage source at output V_o
  - V_{in} is unipolar and can be variable
  - Input current is unidirectional and having constant mean value I_{in}



- **Pulse Width Modulation** = the transistor is operated with a switching frequency f_s=1/T_s and with a duty-cycle d imposed by the switching function $q(t)$

DC steady state operation → $v_L = 0$

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Boost converter

- If we consider an ideal (lossless) converter

$$V_{in} \cdot I_{in} = V_o \cdot I_o \Rightarrow \begin{cases} I_{in} = \dfrac{V_o}{V_{in}} \cdot I_o = \dfrac{1}{1-d} \cdot I_o \\ V_o = \dfrac{V_{in}}{1-d} \end{cases}$$

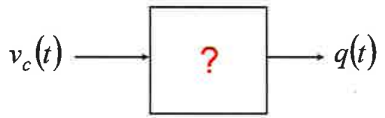
Equations of the ideal Boost converter

Boost converter

- At constant V_{in} value, the mean input current can be changed as follows:
  - Reduction of mean input current $\Leftrightarrow (1-d)V_o > V_{in}$ (VA)
  - Increase of the mean input current $\Leftrightarrow (1-d)V_o < V_{in}$ (VA)
- The duty-cycle variation is performed by the converter current control scheme to control the input current

PWM Modulators

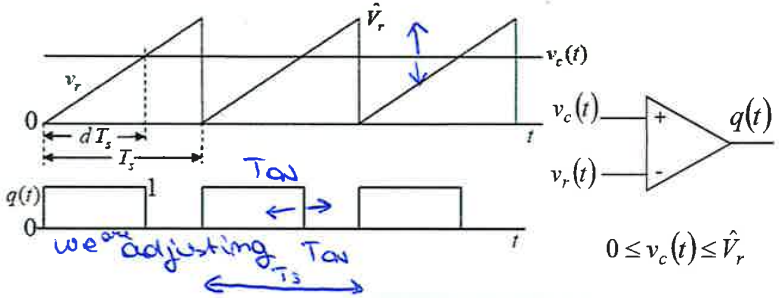
- A PWM modulator must generate the switching function $q(t)$ starting from a command signal $v_c(t)$ that is generated by the control block



- A modulator uses the comparison between the command $v_c(t)$ (called modulating signal) and signal whose period is equal with the switching period (called carrier signal) PORTANTE

PWM Modulators

- Example 1: the carrier uses a sawtooth (ramp) waveform whose peak value is $\hat{V}_r$ unipolar



$0 \le v_c(t) \le \hat{V}_r$

$$q(t) = 1 \text{ if } v_c(t) > v_r(t)$$
$$q(t) = 0 \text{ if } v_c(t) < v_r(t)$$
$$\Rightarrow d(t) = \frac{1}{\hat{V}_r} \cdot v_c(t)$$

peak value of the ramp

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PWM Modulators

- The number N is imposed by the desired switching frequency and the counter clock frequency

$$N = \frac{T_s \cdot f_{CLK}}{2} = \frac{f_{CLK}}{2 \cdot f_s}$$

- The number n_c depends by the desired duty-cycle that must be previously computed from the desired voltage command

$$n_c(t) = d(t) \cdot N$$

PWM Modulators

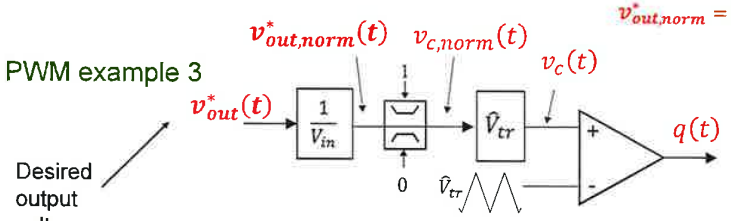
chiede non come fare per capire meglio

buck, boost cose complicate allora, teniamo steady state v_L ...

- Example for a Buck converter NON CHIEDE

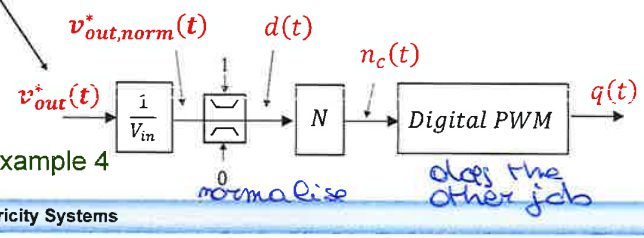
$$v^*_{out,norm} = \frac{v^*_{out}}{V_{in}}$$

PWM example 3



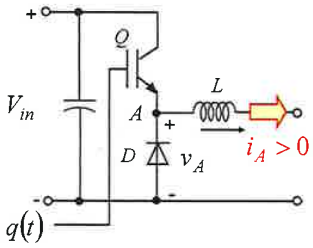
Desired output voltage

PWM example 4

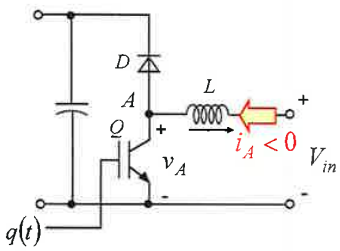


Bidirectional switching power pole

- The Buck and Boost switching power poles are unidirectional



BUCK
(positive current)

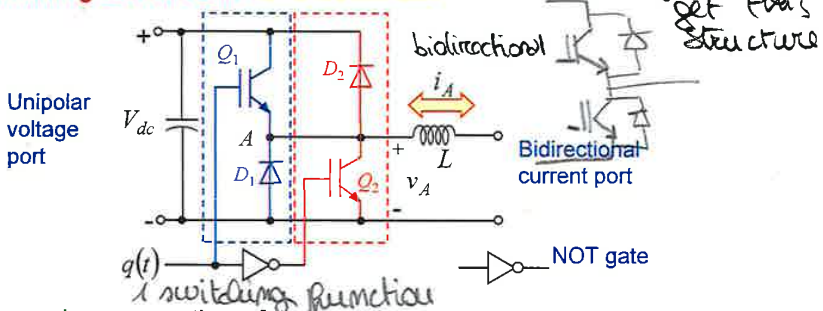


BOOST
(negative current)

Bidirectional switching power pole

- A bidirectional switching power pole can be obtained by connect together combining a Buck cell with a Boost cell

finally! get this structure



1 switching function

- The series connection of the transistors Q_1 and Q_2 is in parallel with a voltage source ⇒ they shall never be in ON state (both ON = short-circuit of v_{DC})

if up is on, down is off

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Lesson 4
GRID FRONT-END CONVERTERS (I)

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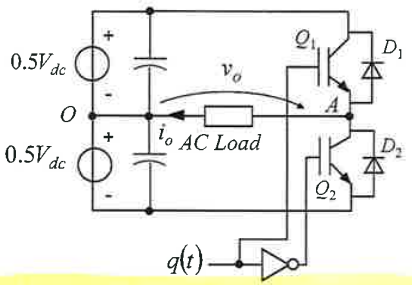
Outline

- DC-AC converters (inverters)
  - Single-phase inverters
  - Three-phase inverters

Single-phase half-bridge inverter

- One bidirectional switching power pole with symmetrical DC voltage supply $\pm 0.5V_{dc}$ with respect to central point O

DC link mid point o
bipolare, bidirectional



- The AC load is connected between the pole output A and the central supply point O

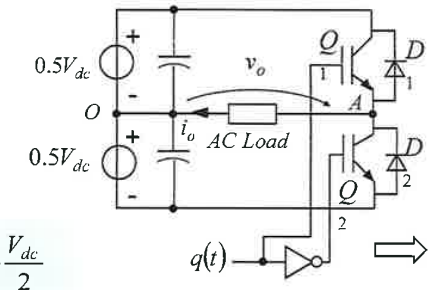
Single-phase half-bridge inverter

- Independently of the load current sign, the output voltage depends on the voltage supply and the switching function

✓ $q=1 \Rightarrow v_o=+0.5V_{dc}$

✓ $q=0 \Rightarrow v_o=-0.5V_{dc}$

$$v_o(t)=[2\cdot q(t)-1]\cdot\frac{V_{dc}}{2}$$



v_A depends only by $q(t)$

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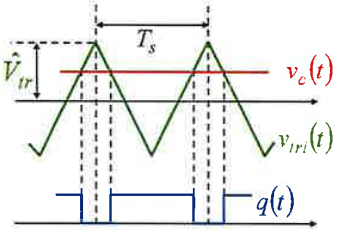
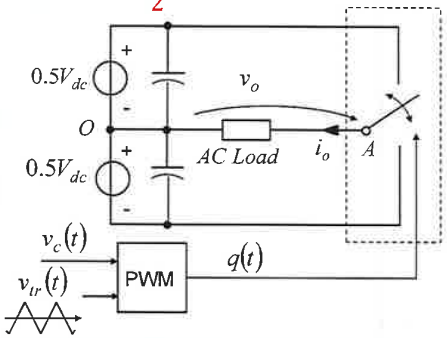
Single-phase half-bridge inverter

- 2-Level inverter

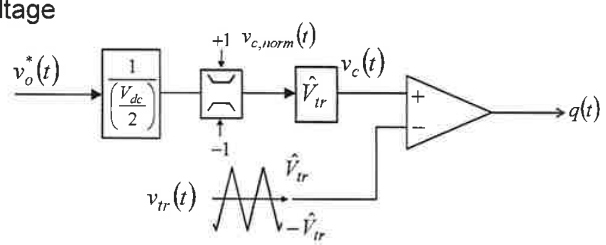
$$\begin{cases} If\ v_c(t) > v_{tr}(t) \Rightarrow q = 1 \Rightarrow v_o(t) = +\dfrac{V_{dc}}{2} \\ If\ v_c(t) < v_{tr}(t) \Rightarrow q = 0 \Rightarrow v_o(t) = -\dfrac{V_{dc}}{2} \end{cases}$$





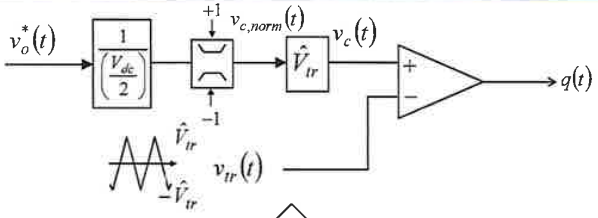
Single-phase half-bridge inverter

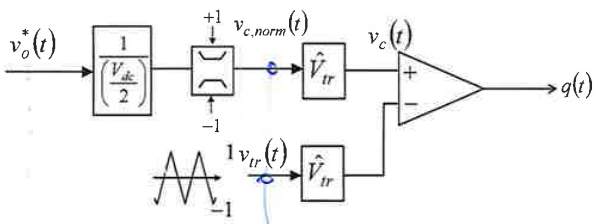
- The computation of the command starting from the desired voltage



- The ratio $\frac{v_o^*(t)}{(V_{dc}/2)}$ must be saturated at ±1 since the command must not exceed $\pm\hat{V}_{tr}$
- $v_{c,norm}(t)$ is normalized voltage command respect to $\hat{V}_{tr}$

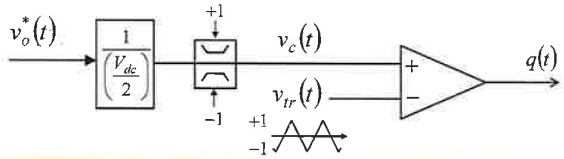
Single-phase half-bridge inverter



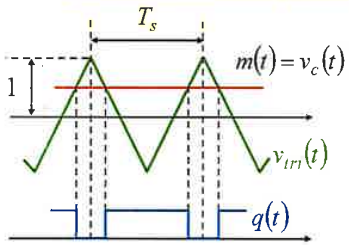


i need to compare this 2 comparaisl of normalised command and triangle

Single-phase half-bridge inverter



- The analysis of the inverter can be performed with a PWM block that uses a carrier $v_{tr}(t)$ with unity peak value



- Pole duty-cycle

$$d(t) = \frac{1}{2} + \frac{1}{2} \cdot v_c(t)$$

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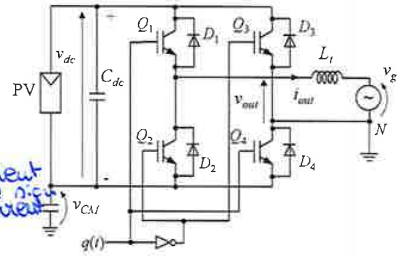
Single-phase full-bridge inverter

- 1-phase Full-Bridge (FB) inverter with bipolar modulation
  - ✓ Two pairs of switches (Q_1,Q_4) and (Q_2,Q_3) that have complementary operation

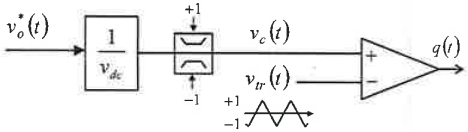
$$q(t)=1 \Rightarrow \begin{cases} Q_1, Q_4 - \text{ON} \\ Q_2, Q_3 - \text{OFF} \end{cases} \Rightarrow v_{out} = +v_{dc}$$

independent from the sign of the current

$$q(t)=0 \Rightarrow \begin{cases} Q_1, Q_4 - \text{OFF} \\ Q_2, Q_3 - \text{ON} \end{cases} \Rightarrow v_{out} = -v_{dc}$$

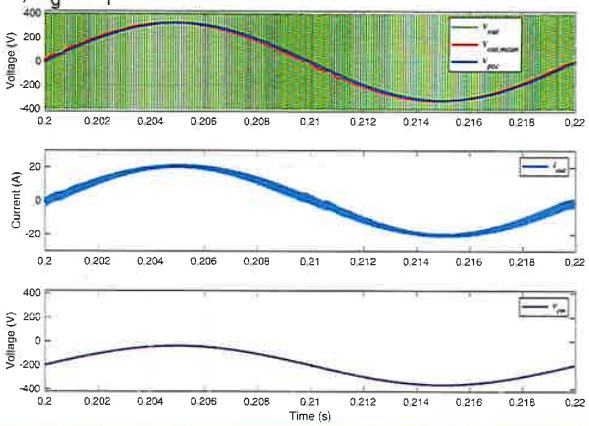


  - ✓ PWM generation



Single-phase full-bridge inverter

- Simulation result: v_{dc}=400V, 10 kHz, grid 230Vrms@50Hz, L_f=4 mH, L_g=80μH



PCC → blu m.a. v. of grid
Red → moving average value of inverter
ripple

Single-phase full-bridge inverter

- 1-phase Full-Bridge (FB) inverter with bipolar modulation
  - ✓ The instantaneous output voltage has two values $\pm v_{dc}$ at switching frequency ⇒ high filter inductor is needed NO
  - ✓ Difficult to get very high efficiency (<96%) NO
  - ✓ The common-mode leakage currents have no high-frequency component YES

⇩

- Although it has some advantages, 1-phase Full-Bridge (FB) inverter with bipolar modulation is not recommended for energy generation

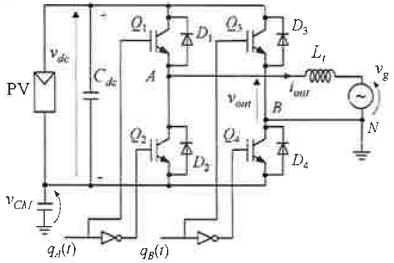
Single-phase full-bridge inverter

UNIPOLARE CONTROFASE

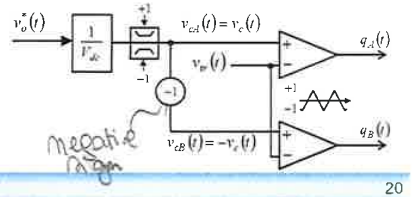
- 1-phase Full-Bridge (FB) inverter with unipolar modulation

same f but 2 commands

  - ✓ Two independent switching power poles A and B with two different switching functions
  - ✓ The normalized voltage commands for the two power poles are phase shifted by 180 electrical degrees



  - ✓ PWM generation



negative sign

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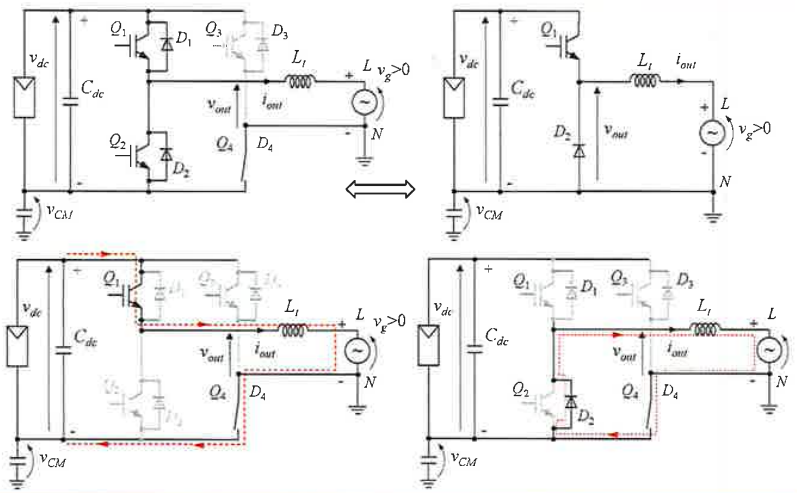
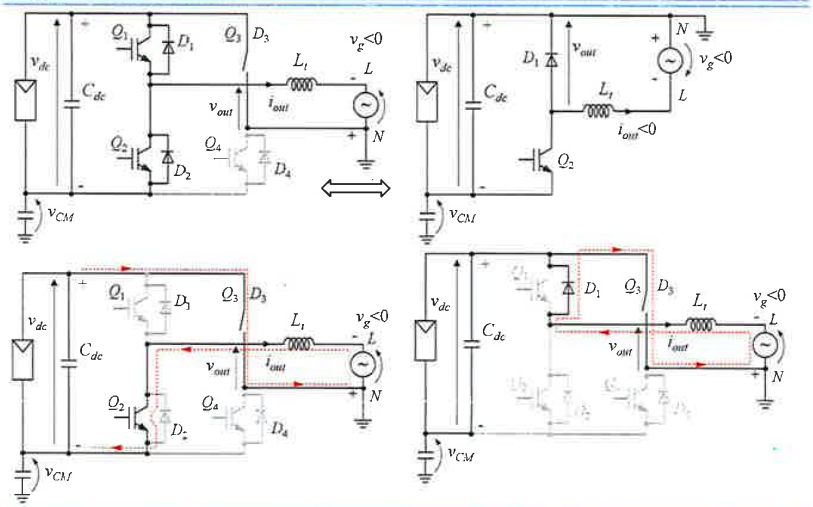
FB inverter with hybrid modulation



FB inverter with hybrid modulation



FB inverter with hybrid modulation

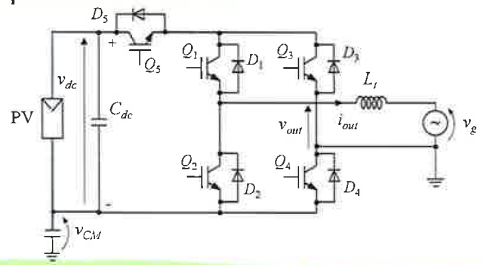
- Features:
  - ✓ The instantaneous output voltage changes between 0 and $+v_{dc}$ or between 0 and $-v_{dc}$ YES
  - ✓ High efficiency (<98%) YES
  - ✓ The common-mode leakage currents have square wave variation (not desired) NO

⇩

- FB inverter with hybrid modulation is not recommended for energy generation

H5 inverter

- Conventional FB topology with an additional switch in series with the positive DC link rail



- ➢ Q5 and bottom side switches work at high frequency
- ➢ Bridge upper side switches work at grid frequency, acoording to the sign of grid voltage
  - ✓ $v_g > 0 \Rightarrow Q_1 = \text{ON}, Q_3 = \text{OFF}$
  - ✓ $v_g < 0 \Rightarrow Q_1 = \text{OFF}, Q_3 = \text{ON}$

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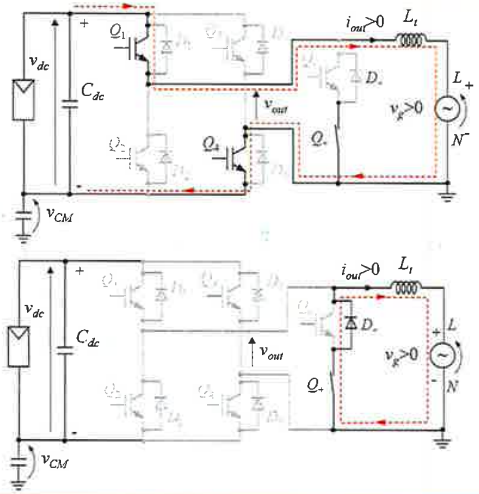
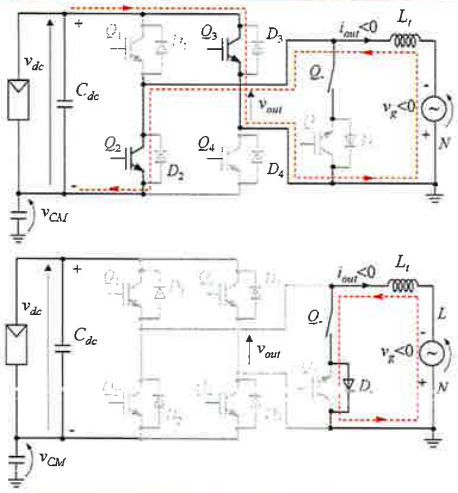
HERIC inverter

✓ Positive grid voltage



HERIC inverter

✓ Negative grid voltage



HERIC inverter

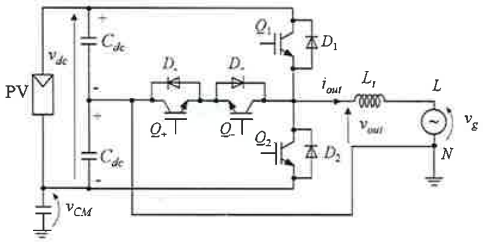
❑ Features:

- ✓ The instantaneous output voltage changes between 0 and $+v_{dc}$ or between 0 and $-v_{dc}$ YES
- ✓ High efficiency (96%) YES
- ✓ The common-mode leakage currents have no high frequency components YES

❑ Commercialized by Sunways AT series (2.7 – 5 kW)

Conergy inverter

❑ Half-bridge topology with an two switches in anti-series that are connected between pole output and DC link midpoint obtained with capacitors



➢ Additional switches are operated at the grid frequency

- ✓ $v_g > 0 \Rightarrow Q_+ = ON,\ Q_- = OFF$
- ✓ $v_g < 0 \Rightarrow Q_+ = OFF,\ Q_- = ON$

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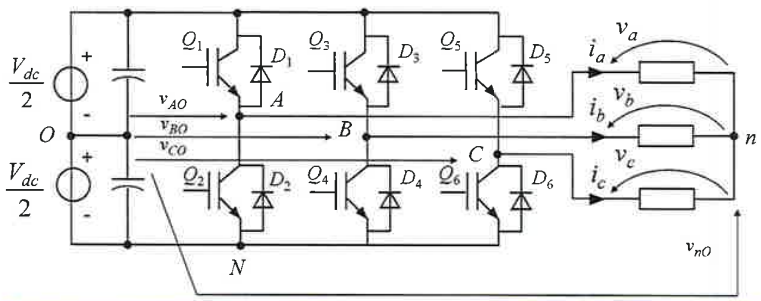
everything is a single phase half bridge inverter

Three phase inverter

- We consider a virtual DC link midpoint O



- Each phase operates as a half-bridge, single-phase inverter that generates its voltage with respect to virtual point O

relationship between V_{AO}, v_a
V_{BO}, v_b
V_{CO}, v_c

Three phase inverter

- We need sinusoidal three-phase commands to generate a three-phase voltage system

voltage command sinusoidal

$$v_{cA}(t)=\frac{\hat{V}^*}{(V_{dc}/2)}\cdot\hat{V}_{tr}\cdot\sin(\omega t)$$

$$v_{cB}(t)=\frac{\hat{V}^*}{(V_{dc}/2)}\cdot\hat{V}_{tr}\cdot\sin\left(\omega t-\frac{2\pi}{3}\right)$$

$$v_{cC}(t)=\frac{\hat{V}^*}{(V_{dc}/2)}\cdot\hat{V}_{tr}\cdot\sin\left(\omega t+\frac{2\pi}{3}\right)$$

$$\Rightarrow \quad \bar{v}_{AO}(t)=\frac{V_{dc}}{2}\cdot\frac{v_{cA}(t)}{\hat{V}_{tr}} \qquad \bar{v}_{BO}(t)=\frac{V_{dc}}{2}\cdot\frac{v_{cB}(t)}{\hat{V}_{tr}} \qquad \bar{v}_{CO}(t)=\frac{V_{dc}}{2}\cdot\frac{v_{cC}(t)}{\hat{V}_{tr}}$$

- Amplitude modulation index $\frac{\hat{V}^*}{(V_{dc}/2)}=m_a$

Three phase inverter

- **Generated voltage with respect to midpoint O**

$$v_{AO}(t),\ v_{BO}(t),\ v_{CO}(t)$$

- **Phase voltages (with respect to neutral point n)**

$$v_a(t),\ v_b(t),\ v_c(t)$$

- The relationship between the inverter voltages and the load voltages is the common mode voltage v_{nO}

$$v_{nO}(t)=\frac{1}{3}\cdot\left[v_{AO}(t)+v_{BO}(t)+v_{CO}(t)\right]$$

Three phase inverter

- **Load phase voltages (with respect to neutral point n)**

$$v_a(t)=v_{AO}(t)-v_{nO}$$
$$v_b(t)=v_{BO}(t)-v_{nO}$$
$$v_c(t)=v_{CO}(t)-v_{nO}$$
$$v_{nO}=\frac{1}{3}\sum_{k=A,B,C}v_{kO}(t)$$

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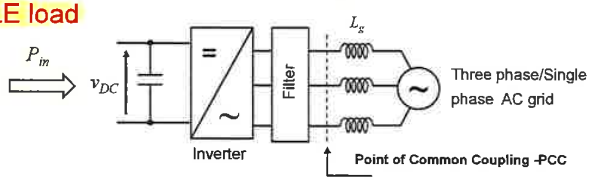
Three phase inverter

- The maximum peak value of the moving average voltage is $0.5 \cdot v_{dc}$
- If the inverter load is the grid ⇒ the grid can be seen as an active LE load



$V_{DC} > 2\hat{V}_{grid}$

- ✓ **For industrial 400Vrms grid ⇒ peak grid phase voltage is 327 V ⇒ $v_{dc} > 654\ V$, typical value 700V**
- ✓ Three-phase LC or LCL filter is needed to inject sinusoidal current into the grid

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Lesson 5
GRID FRONT-END CONVERTERS (II)

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Outline(1/2)

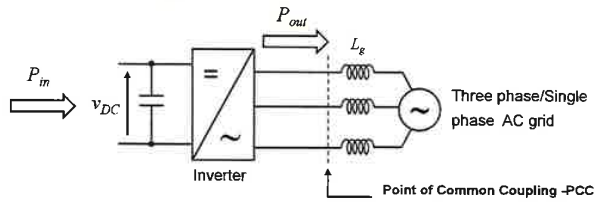
- Fundamental principles of power generation into the grid with electronic power converters
  - Power generation
    - ✓ Operation in parallel with the grid
    - ✓ Power generation to local loads and micro-grids

Outline(2/2)

- Fundamental of vector control of three-phase converters
  - Definition of space vectors
  - Three-phase to bi-phase and rotational transformations
  - Instantaneous power theory
- Standards for converters connected to the grid
- Virtual synchronous generator and smart transformer

Voltage source converters

- **Grid front-end converter = DC/AC converter (inverter) operated as voltage source converters**



- ✓ Capacitive input: DC voltage source v_{dc} (costant or variable)
- ✓ Inductive output: the grid is the converter inductive load (grid inductance L_g)

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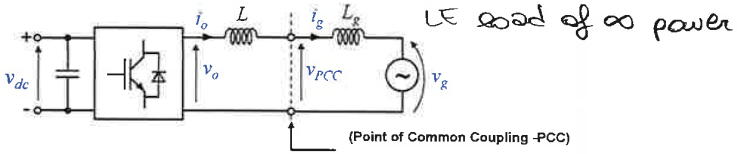
Power generation

(1) Main grid feeding with no grid support

- **For semplicity, we consider a single-phase inverter with output L filter**

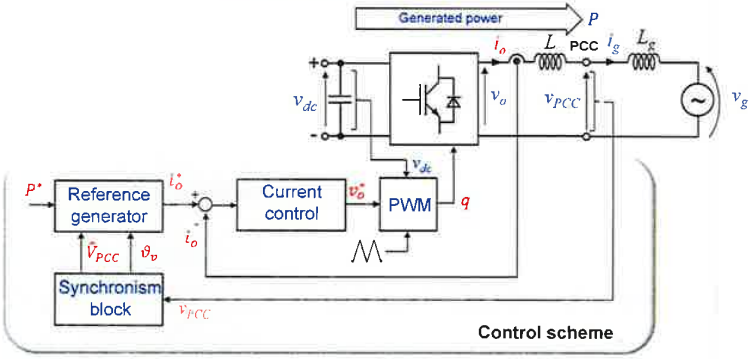


- The grid is of infinite power respect to the converter power ⇒ the grid voltage v_g is constant in terms of amplitude of frequency (stiff grid)

Power generation

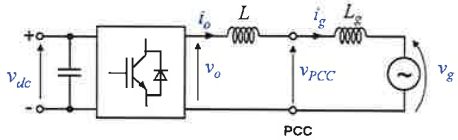
PV inverters can inject only P (tipically)

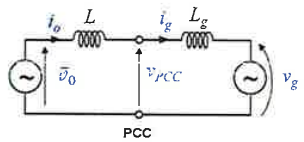
- Main grid feeding with no grid support ⇒ the inverter should behave like a **current source** that injects an active current i_o^* into the grid ⇒ **current control**



Power generation

- If we neglect the converter switching dynamics ⇒ the inverter is a variable mean mobile voltage having an active LE load





✓ The mean mobile voltage $\bar{v}_0(t)$ depends on the DC link voltage and also on the PWM commands

Power generation

- Main elements from the control scheme:
  - **Synchronism block** = obtains the magnitude (peak value) and the phase of the PCC grid voltage
  - **Reference current generator** = computes the active current to be injected into the grid according to a power reference and the PCC grid voltage (as magnitude and phase)
  - **Current control** = current controller (regulator) to generate the desired output mobile mean voltage
  - **PWM modulator** = generates the inverter switching functions according to the desired output voltage and the DC link voltage

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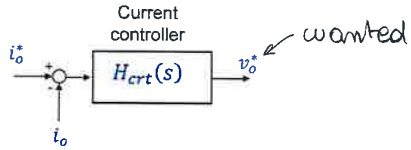
Power generation

❖ **Current control** = current controller whose transfer function in the Laplace domain is $H_{crt}(s)$



- ✓ The reference current i_o^* is sinusoidal
- ✓ The output current is measured with a current sensor
- ✓ The regulator output is the desired (reference) voltage at the inverter output that must be applied to the PWM modulator

Power generation

➢ To generate the necessary output current, the inverter fundamental voltage must be higher than the PCC grid voltage

⇩

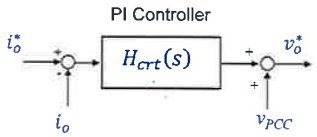
➢ **The current regulation is possible only if the DC link voltage is higher enough to get enough voltage margin**

- ✓ Example: grid rms voltage 220V +10% ⇒ peak grid voltage is 342.2V ⇒ at steady-state, the minimum DC link voltage should be about 380V for a single-phase inverter (typical values 400V)

Power generation

➢ Current controllers used in practice

A) **Proportional-Integral (PI) controllers with feedforward**



control only additional to regulate

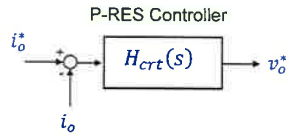
$$H_{crt}(s) = k_{p,crt} + \frac{k_{i,crt}}{s}$$ Transfer function of the current controller

- ✓ $k_{p,crt}$ = proportional gain
- ✓ $k_{i,crt}$ = integral gain
- ✓ Feedforward implemented with the PCC voltage

Power generation

proportional

B) Resonant controllers (P-RES)



$$H_{crt}(s) = k_{p,crt} + \frac{2 \cdot k_{i,crt} \cdot s}{s^2 + \omega_0{}^2}$$ Transfer function of the current controller

- ✓ Has a proportional term and a resonant term tuned on the grid frequency
- ✓ Gets best results when the reference current is sinusoidal with fixed frequency (50 Hz)

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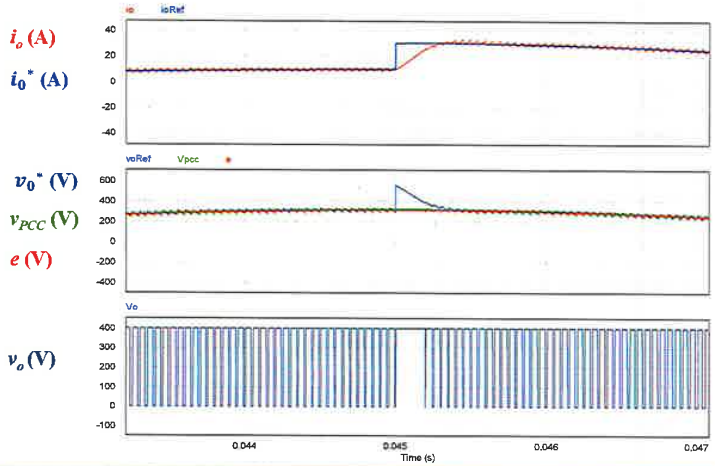
Power generation

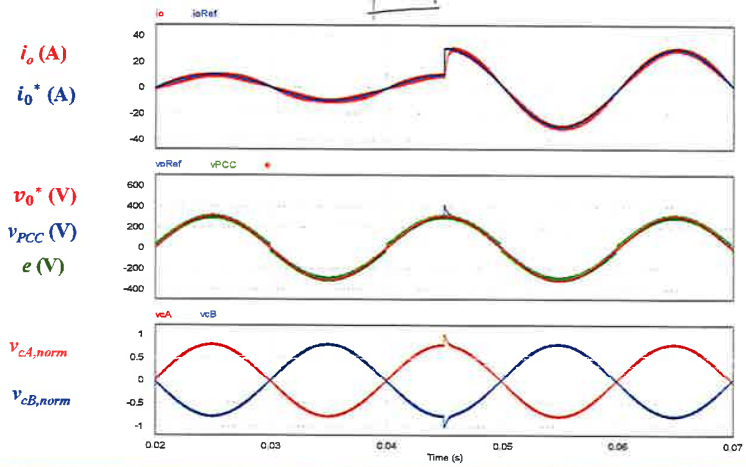
- Step output current $\hat{I}_0$ from 10A to 30A - PI controller (detail)



Power generation

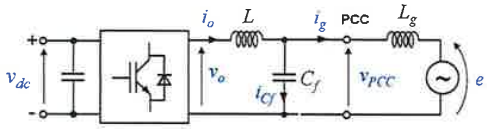
used because of grid is constant

- Step output current $\hat{I}_0$ from 10A to 30A - P-RES controller

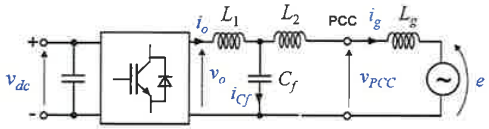


Power generation

- In practice, the PCC voltage becomes distorted due to the converter switching $\Rightarrow$ *LC* or *LCL* filter
  - ✓ Inverter *LC* filter



  - ✓ Inverter *LCL* filter (high power and three-phase systems)



Power generation

- The *LC* e *LCL* filters introduce resonant frequencies that can affect the current control performance

⇩

- The resonance higher than the current control bandwidth and less than the converter switching frequencies

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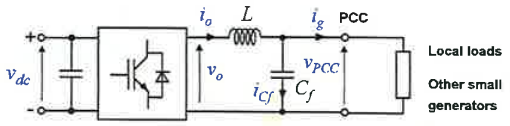
Power generation

2) Stand-alone loads feeding or micro-grid feeding

- **For simplicity, we consider a single-phase inverter with output LC filter**

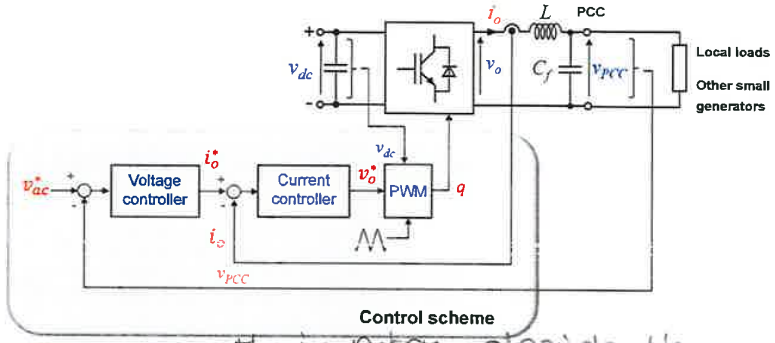


Power generation

- The power is generated only if a local loads discharges the output capacitors
- Cascaded v_{PCC} voltage loop and current loop
  - ✓ Inner current regulation loop must be as fast as possible with highest possible bandwidth
  - ✓ AC voltage regulation loop slow loop with a bandwidth that should be lower than the current bandwidth by at least one decade
- PI controllers or P-RES controllers

Power generation 2° METHOD

- Power generation to local loads ⇒ the inverter is **a voltage generator** that imposes the PCC voltage to the local loads ⇒ **voltage control of the PCC voltage**



the inverter decide the output voltage

Power generation big alternator

- When the inverter is connected in parallel with other small distributed sources in a micro-grid, the load should uniformly distributed among the inverters

⇩

- The inverters should emulate the behavior of big alternators driven by steam/water turbines from big power plants
  - The output frequency must decrease with the increase of the demand of the output power $f_o \downarrow$ $P_o \uparrow$
  - The rms voltage must decrease with the increase of the demand for reactive power $V_o \downarrow$ $Q_o \uparrow$

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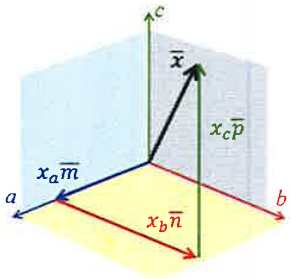
Vector control of three-phase converters

- A three-phase system of generic quantities (x_a, x_b, x_c) can be represented in the cartesian tridimensional space by a space vector
  - ✓ Matrix notation

$$[x]_{abc} = x_a \cdot \begin{bmatrix}1\\0\\0\end{bmatrix} + x_b \cdot \begin{bmatrix}0\\1\\0\end{bmatrix} + x_c \cdot \begin{bmatrix}0\\0\\1\end{bmatrix}$$

  - ✓ Vector notation

$$\overline{x}_{abc} = x_a \cdot \overline{m} + x_b \cdot \overline{n} + x_c \cdot \overline{p}$$

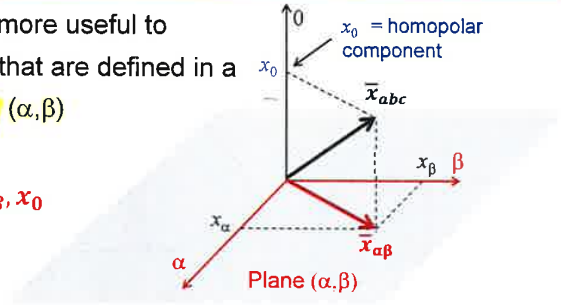


  - ✓ $\overline{m}, \overline{n}, \overline{p}$ are versors along the orthogonal axes (a, b, c)

Vector control of three-phase converters

- In practice, it is more useful to usare employ vectors that are defined in a cartesian plane (α,β)

$$\overline{x}_{abc} \rightarrow \overline{x}_{\alpha\beta}, x_0$$



- A transformation of variables is necessary by mean of a transformation matrix $[T]$

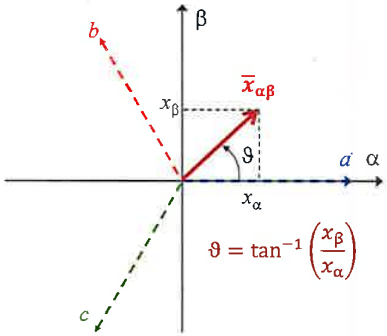
$$\begin{bmatrix}x_a\\x_b\\x_c\end{bmatrix} \underset{[T]}{\Longrightarrow} \begin{bmatrix}x_\alpha\\x_\beta\\x_0\end{bmatrix}$$

Vector control of three-phase converters

- Transformation matrix proposed by Edith Clarke

$$\begin{bmatrix}x_\alpha\\x_\beta\\x_0\end{bmatrix} = [T] \cdot \begin{bmatrix}x_a\\x_b\\x_c\end{bmatrix}$$

$$[T] = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix}$$

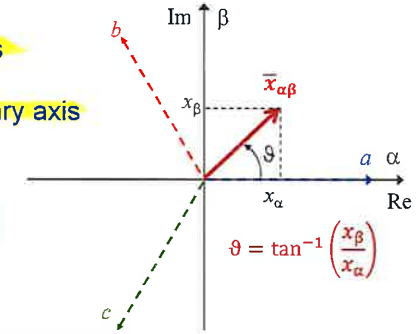


$$\vartheta = \tan^{-1}\left(\frac{x_\beta}{x_\alpha}\right)$$

- ✓ The Clarke matrix is orthogonal $[T]^{-1} = [T]^t$
- ✓ In the (α,β) plane, the projection of the vector lies on the α axis

Vector control of three-phase converters

- The (α,β) plane can be considered as a complex plane
  - ➢ α -axis is the real axis
  - ➢ β - axis is the imaginary axis



$$\overline{x}_{\alpha\beta} = x_\alpha + j \cdot x_\beta$$

$$\Updownarrow$$

$$\vartheta = \tan^{-1}\left(\frac{x_\beta}{x_\alpha}\right)$$

$$\overline{x}_{\alpha\beta} = |\overline{x}_{\alpha\beta}| \cdot e^{j\vartheta} = |\overline{x}_{\alpha\beta}| \cdot \cos\vartheta + j \cdot |\overline{x}_{\alpha\beta}| \cdot \sin\vartheta$$

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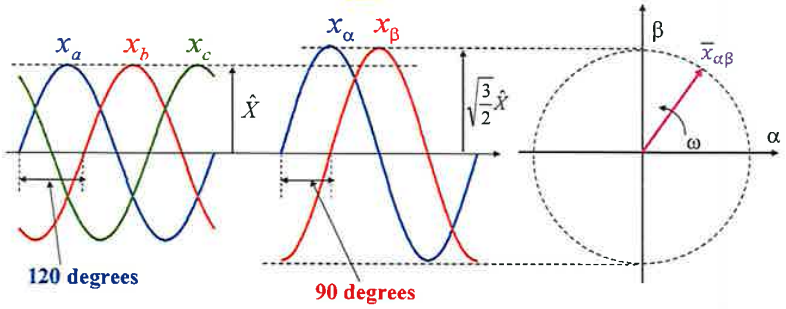
Vector control of three-phase converters

$$x_\alpha(t) = \sqrt{\frac{3}{2}} \cdot \hat{X} \cdot \cos(\omega t)$$

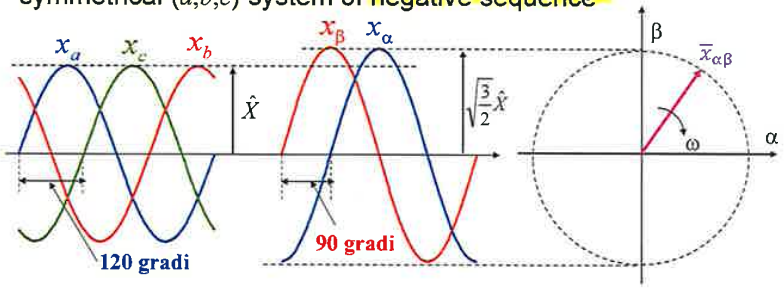
$$x_\beta(t) = \sqrt{\frac{3}{2}} \cdot \hat{X} \cdot \sin(\omega t)$$

➤ The $\overline{x}_{\alpha\beta}$ vector has constant magnitude and rotates counterclockwise in the (α,β) plane with the angular speed ω = pulsations of the three-phase quantities



Vector control of three-phase converters

❑ Similarly, the bi-phase components for a three-phase symmetrical (*a*,*b*,*c*) system of negative sequence



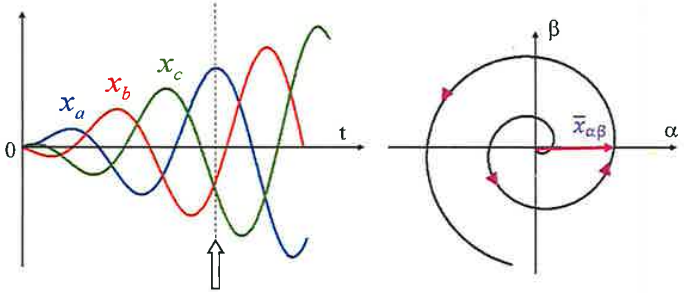
➤ The (α,β) components are phase-shifted by 90 electrical degrees (x_α iags x_β)

➤ The $\overline{x}_{\alpha\beta}$ vector rotates in clockwise direction in the (α,β) plane with the (negative) angular speed equal to the pulsation ω of three-phase quantities

Vector control of three-phase converters

❑ The(*abc*)→ (αβ0) transformation is general and does not depend on the time variation of the three-phase quantities (*abc*)

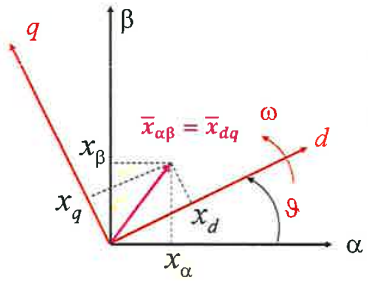
➤ Example of transient sinusoidal operation



✓ At any moment, the instaneous values of the three-phase quantities correspond to an unique $\overline{x}_{\alpha\beta}$ vector in the (α,β) plane

Vector control of three-phase converters

❑ A vector can be defined (referred) in other reference systems, such an orthogonal (*d*,*q*) rotating reference frame with the angular speed ω



$$\overline{x}_{\alpha\beta} = x_\alpha + jx_\beta$$

$$\overline{x}_{dq} = x_d + jx_q$$

➤ ϑ is the position of the *d* axis respect to the α axis (considered as reference)

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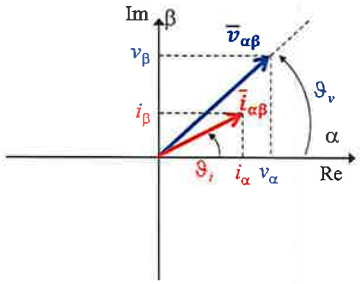
Vector control of three-phase converters

- Voltage and current vectors in (α,β) frame

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = [T]\cdot\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}, \quad \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = [T]\cdot\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$[T] = \sqrt{\frac{2}{3}}\cdot\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

- ✓ The phase quantities may have any time variations
- ✓ At steady-state, the $\bar{v}_{\alpha\beta}$ and $\bar{i}_{\alpha\beta}$ vectors have constant magnitude and rotate at constant speed the voltages and currents form symmetrical three-phase systems



Vector control of three-phase converters

- **p-q Instantaneous Power Theory**

$$\begin{bmatrix} p \\ q \\ p_0 \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta & 0 \\ -v_\beta & v_\alpha & 0 \\ 0 & 0 & v_0 \end{bmatrix}\cdot\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix}$$

d, q component fictitious
p, q real

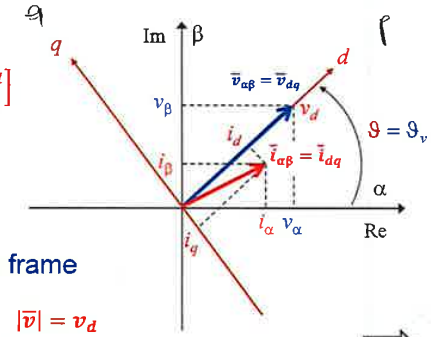
- Instantaneous active power → $p = v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta$ [W]
- Instantaneous reactive power → $q = v_\alpha \cdot i_\beta - v_\beta \cdot i_\alpha$ [VAR]
- Homopolar power → $p_0 = v_0 \cdot i_0$ [W]

Vector control of three-phase converters

- If the vectors are referred in a (d,q) rotating frame,where the *d-axis* is defined by the voltage vector

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{bmatrix}\cdot\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} v_d \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{bmatrix}\cdot\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$



- In the new (d,q) reference frame

$$\bar{v}_{dq} = v_d + j\cdot 0\ , \qquad |\bar{v}| = v_d$$
$$\bar{i}_{dq} = i_d + j\cdot i_q$$

$i_q < 0$
assorbo q dalla rete

Vector control of three-phase converters

- **p-q Instantaneous Power Theory in the(d,q) frame**

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_d & v_q \\ -v_q & v_d \end{bmatrix}\cdot\begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

- If the d –axis is defined by the voltage vector ⇒ v_q=0

⇩

- Instantaneous active power → $p = v_d \cdot i_d$ [W]
  - ✓ i_d = active current [A]
- Instantaneous reactive power → $q = v_d \cdot i_q$ [VAR]
  - ✓ i_q = reactive current [A]

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Standards for grid-connected converters

- The connection to the grid of distributed energy sources by means of power elctronics is subject of standards to get **safe power generation without affecting the existing grid in the wrong way**
- Standards
  - **National used at national levels by the energy operators**
  - **International to be adopted that more countries**

Standards for grid-connected converters

- National and international organizations dealing with the writing and application of standards:
  - **IEEE** (Institute of Electrical and Electronic Engineers) - USA
  - **IEC** (International Electrotechnical Comission) - Switzerland
  - **DKE** (German Commission for Electrical, Electronic and Information Technologies) – Germany → most important market for photovoltaic power plants
  - **EN** (CEN -European Committee for Standardization) – UE
  - **CEI** (Comitato Elettrotecnico Italiano) – Italy

Standards for grid-connected converters

- The standards have a very big impact on the design of power converters for distributed generation
- Today, the operating manual of a power converter must clearly specify which are the standards that are fulfilled with the coonverter
- Therefore, it is important to know which are the main standards that regulate the connection of power converters with the power grid ⇩
- This module will analyze the most important international standards for photovoltaic applications

Standards for grid-connected converters

1) **IEEE Standards**
   a) IEEE 1547-2018 Interconnection of Distributed Generation
   b) IEEE 929-2000 Recommended Practice for Utility Interface of Photovoltaic (PV) Systems
   (Withdrawn, but may be found in existing systems)
   Ritirato
   c) UL 1741 Standard for Inverters, Converters and Controllers for Use in Independent Power Systems
   (Mainly a supplement to IEEE1547-2018)
   d) IEEE519, Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

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Standards for grid-connected converters

(A Distribution Voltage Quality in power networks

- EN 50160 provides the rated voltage values at PCC and the allowed variations for Low Voltage (LV) and Mean Voltage (MV) networks
  - ✓ Maximum imbalance factor for three-phase systems 3%
  - ✓ Rms voltage variation ± 10%
  - ✓ Frequency variation ± 1%
  - ✓ Voltage dips : time length < 1s, voltage variation < 60%
  - ✓ Maximum voltage distortion factor 8%

⟹

Standards for grid-connected converters

✓ Allowed limits for the voltage harmonics

Odd harmonics				Even harmonics	
Not multiple of 3		*Multiple of 3*			
Order h	Relative voltage (%)	Order h	Relative voltage (%)	Order h	Relative voltage (%)
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.5	6 to 24	0.5
13	3	21	0.5		
17	2				
19	1.5				
23	1.5				
25	1.5				

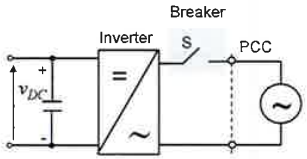
➢ The inverter must be able to operate with high voltage harmonic content at PCC with maximum voltage and frequency variations

Standards for grid-connected converters

(B) Response to Abnormal Grid Conditions

➢ The inverter shall be disconnected form the grid (trip disconnection) by means of **a breaker** in case of abnormal grid operating conditions

- ✓ **Abnormal voltage variations**
- ✓ **Abnormal frequency variations**



➢ The standards must specify:
- ✓ The allowed variations of voltage/frequency and the maximum time after which the inverter must shut off
- ✓ In case of abnormal conditions, which are the conditions that may allow the inverter to re-connect again to the grid to generate power

Standards for grid-connected converters

➢ In case of abnormal conditions (trip), the inverter control must remain active to monitor the grid ⇒ the inverter may reconnect itself and generate power if the grid goes back to normal conditions

➢ Disconnecting times in case of voltage variations (%) respect to the rated value

IEEE 1547		IEC 61727		VDE 0126-1-1	
Voltage range (%)	Disconnection time (s)	Voltage range (%)	Disconnection time (s)	Voltage range (%)	Disconnection time (s)
V<50	0.16	V<50	0.10	110≤V<85	0.2
50≤V<88	2.00	50≤V<85	2.00		
110<V<120	1.00	110<V<135	2.00		
V≥120	0.16	V≥135	0.05		

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Standards for grid-connected converters

- Special care must be taken for direct connection of inverters to the grid (" transformerless inverters")
- The maximum allowed DC current component values are specified by the standards

IEEE 1547	IEC 61727	VDE 0126-1-1
$I_{DC} < 0.5$ % of rated RMS current	$I_{DC} < 1$ % of rated RMS current	$I_{DC} < 1A$ Maximum trip time 0.2 s

- The VDE requires a special devices that must measure the DC current component and it is able to command the breaker; if the injected current exceeds the maximum allowed value, the inverter must be disconnected within 0.2 s

Standards for grid-connected converters

(C2) Current harmonics

- The inverter must not inject current harmonics into the grid
  - The PCC voltage becomes distorted
  - Overload in the transmission lines

⇩

- The standards limit the current harmonics, specified as rms value or percentage value respect to the rated current

Standards for grid-connected converters

- The IEEE1547 and IEC 61727 specify percentage values respect to the rated current

IEEE 1547 and IEC 61727						
Individual harmonic order (odd) *	h<11	11≤h<17	17≤h<23	23≤h<35	35≤h	Total Harmonic Distorsion THD (%)
%	4.0	2.0	1.5	0.6	0.3	5.0

* For even harmonics, the allowed values are ¼ of the values allowed for the odd (dispari) harmonics

Standards for grid-connected converters

- IEC61000-3-2 (grid connected converters having an rms rated current up to 16A) specifies absolute values for odd (dispari) and even (pari) harmonics

IEC61000-3-2 (class A)			
Odd harmonics		Even harmonics	
Order h	Current (A)	Order h	Current (A)
3	2.30	2	1.08
5	1.14	4	0.43
7	0.77	6	0.3
9	0.4	8≤h≤40	0.23×8/h
11	0.33		
13	0.21		
13≤h≤39	0.15×15/h		

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Standards for grid-connected converters

- Islanding operation means that the inverter keeps generating power even if a trip on the distribution line isolates the local line ⇒ S_2 is open

- The islanding operation must be avoided because :
  - ✓ If the grid comes back and S2 becomes closed, a fault condition can occur since the inverter and the grid are no longer synchronized (short-circuit)
  - ✓ Safety issues = the local plant is still fed and becomes dangerous if the line is disconnected for maintanance reasons (human operators can work on the line) ⇨

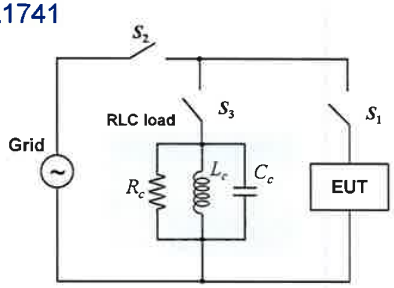
Standards for grid-connected converters

- The standards require the detection of islanding operation and inverter disconnection within a well-defined time interval

- In addition, the standards specify the test procedure to certify the inverter (**Equipment Under Test – EUT**) to check if the inverter control is able to detect the islanding operation

Standards for grid-connected converters

- Test procedure IEEE 1547/UL1741
  - ✓ EUT generates the power P (≅ rated) to the grid having a RLC local load (S_1, S_2 e S_3 are closed)
  - ✓ The LC resonant frequency is the rated grid frequency f_N
  - ✓ The RLC load is designed for the generated power P ⇒



$$R_c = \frac{V^2}{P_N}, \quad L_c = \frac{V^2}{2\pi f_N P_N}, \quad C_c = \frac{P_N}{2\pi f_N V^2}$$

⇨

Standards for grid-connected converters

- ✓ All power provided to the local load is generated by the EUT and the current drawn from the grid must be very low (less than 2% of the EUT generated current)
- ✓ The grid-side breaker is opened (S_2) and the time needed by the EUT control to detect the islanding operation + disconnection time (measured from the moment from which S_2 is opened) must be less than 2 s

- The procedure required by the VDE 0126-1-1 is similar with the one required by the IEEE 1547/UL1741, but the time for islanding detection and disconnection must be less than 5 s

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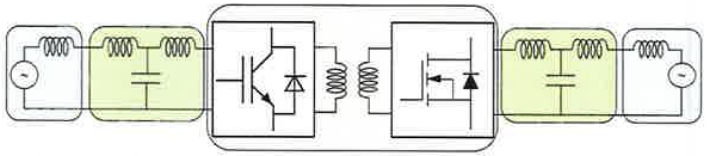
Smart Transformers

- Tomorrow:

Solid State Smart Transformers

- ✓ Small size: transformer for HF ✓
- ✓ Continuous regulation ✓
- ✓ Need for high voltage semiconductors (>10kV) ✗



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Source-side power converters

- Electrical machines that are employed in the distributed generation systems:

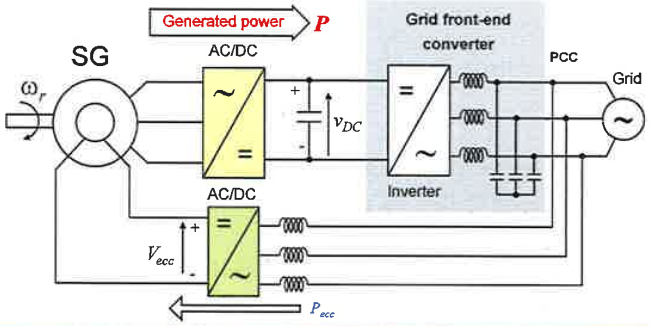
(A) Synchronous machines
- wound excitation
- permanent magnets

(B) Induction machines
- squirrel-cage rotor
- wound rotor (doubly-fed machine)

Source-side power converters

(A) Power converters for synchronous generators

- We consider as the most generic case the synchronous generator with wound rotor



Source-side power converters

- The synchronous generator with wound rotor needs two power conversion units:

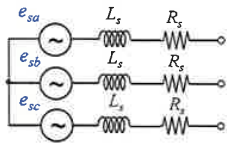
(1) **AC/DC converter** designed for the full power

(2) **Excitation AC/DC converter** that is designed for the excitation power (very low respect to the rated generated power ⇒ reduced power AC/DC converter)

Source-side power converters

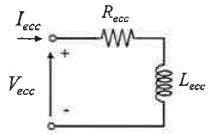
- The synchronous generator is modeled as a three-phase voltage source with internal R-L impedance

✓ R_s is the phase resistance
✓ L_s is the phase inductance (also called as syncronous inductance)



- The excitation winding is a series R-L load fed by a DC voltage source

✓ R_{ecc} is the excitation winding resistance
✓ L_{ecc} is the excitation winding inductance



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Diode rectifiers

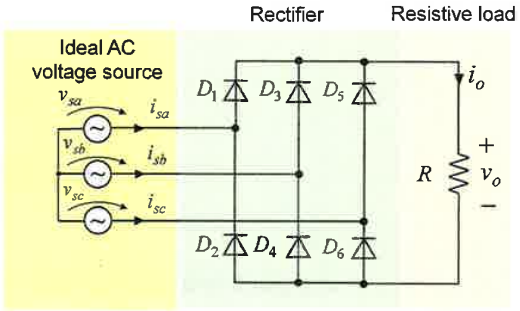
(A1) Diode rectifiers

- Low cost converters
- Unidirectional currents ⇒ irreversible converters
- The output voltage cannot be regulated
- Very robust against overloads

Diode rectifiers

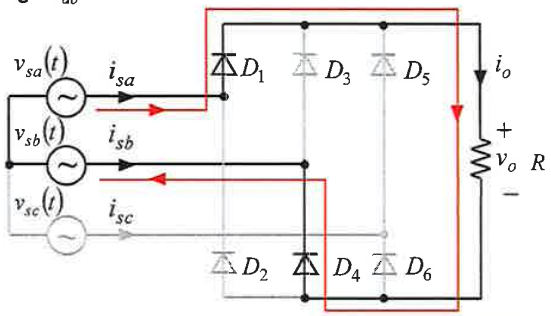
- Ideal three-phase bridge rectifier
  - For simplicity, we consider and ideal generator, while the load is emulated as a resistance

$$v_{sa} = \sqrt{2} \cdot V_s \cdot sin(\omega t)$$
$$v_{sb} = \sqrt{2} \cdot V_s \cdot sin(\omega t - 2\pi/3)$$
$$v_{sc} = \sqrt{2} \cdot V_s \cdot sin(\omega t + 2\pi/3)$$



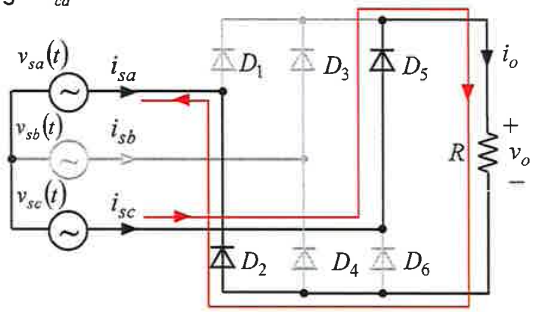
Diode rectifiers

- Any moment, we have two active diodes – one diode from the positive side (D_1,D_3,D_5) and one from the negative side (D_2,D_4,D_6) ⇒ rectifier applies to the load a line-to-line voltage
  - ✓ Example: D_1-D_4 ON ⇒ the output voltage is the line-to-line voltage v_{ab}



Diode rectifiers

- ✓ Example: D_5-D_2 ON ⇒ the output voltage is the line-to-line voltage v_{ca}



- For one period of the input voltage we have six conduction combinations :
  (D_1-D_4, D_1-D_6, D_3-D_6, D_3-D_2, D_5-D_2 e D_5-D_4)
  - ✓ One diode conducts for 120 electrical degrees (1/3 of the period)

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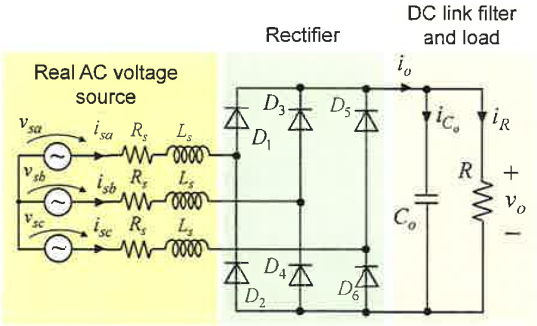
Diode rectifiers

- Three-phase bridge rectifier with real voltage source
  - ✓ For simplicity, the diodes are considered as ideal



$$v_{sa} = \sqrt{2} \cdot V_s \cdot sin(\omega t)$$
$$v_{sb} = \sqrt{2} \cdot V_s \cdot sin(\omega t - 2\pi/3)$$
$$v_{sc} = \sqrt{2} \cdot V_s \cdot sin(\omega t + 2\pi/3)$$

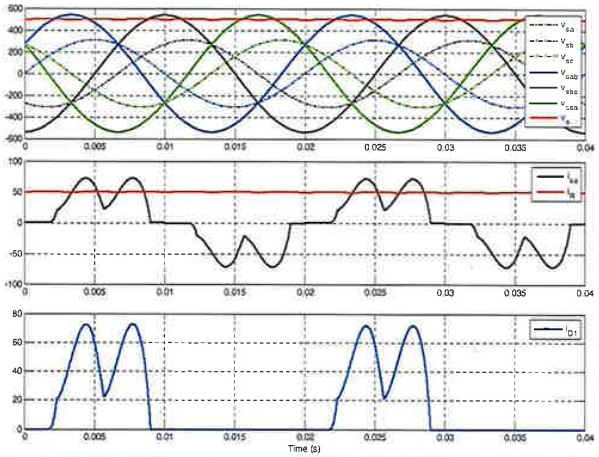
Diode rectifiers

- ✓ Waveforms for V_s = 220Vrms, f = 50Hz, R = 10Ω, R_s=50 mΩ, L_s=0.5 mH, C_o=5000 μF

Input voltages (phase and line-to-line) and output voltage

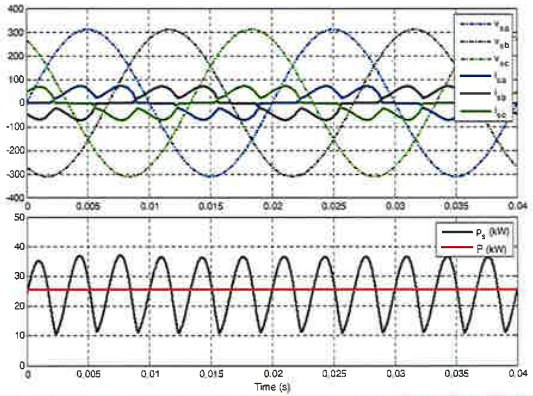
Output current and phase *a* input current

D_1 current



Diode rectifiers

- The phase generator currents are more distorted respect to the case without capacitive filter ⇒ the generator instantaneous power $p_s(t)$ has more oscillations respect to the previous case
  - ✓ The mean value of the instantaneous power is the active power which is equal with the DC power (we neglect the converter losses)
  - ✓ Better results are obtained with generators having trapezoidal back-emf voltages instead of sinusoidal voltages

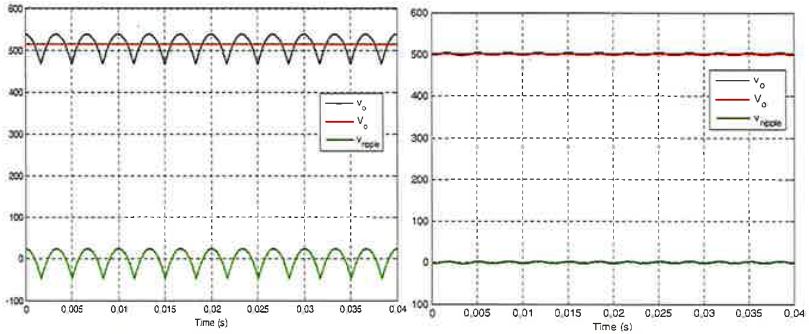


Diode rectifiers

- The output DC link capacitances smoothens the output voltage ⇒ the output voltage ripple can be significantly reduced

No output capacitor

With output capacitor



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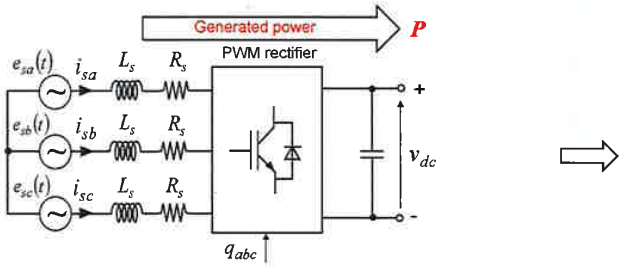
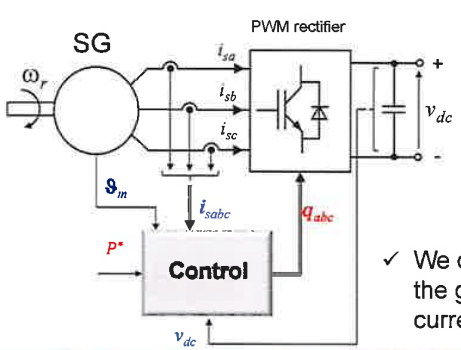
PWM Rectifiers

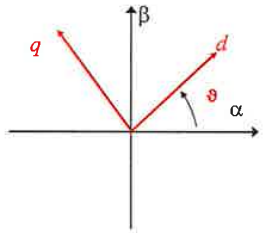
- PWM rectifier = the dual counterpart of the inverter PWM
  - ✓ Inductive input, capacitive output
  - ✓ "Boost" converter = the DC link voltage v_{dc} must be higher than the peak value of the line-to-line voltages



PWM Rectifiers

- The rectifier control is in practice a vector control of the electrical generator
  - ➢ As example, we can implement a current control in a rotating (d,q) frame defined by the rotor electrical position





✓ We define the SG current using the generator convention for the currents signs

PWM Rectifiers

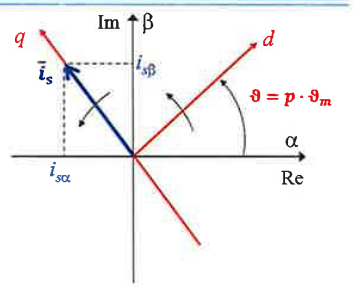
- Measures:
  - ➢ Phase machine currents
  - ➢ Rectifier DC link voltage
  - ➢ Mechanical rotor position ϑ_m that is measured using a position sensor
  - ➢ The d-axis position that is used by the rotational transformations

$$\vartheta = p \cdot \vartheta_m$$

- ✓ p is the generator pole-pairs number
- ✓ ϑ is the rotor electrical position

PWM Rectifiers

- The rotating (d,q) frame defined by the rotor electrical position
  - ➢ d –axis = reactive current (power)
  - ➢ q –axis = active current (power)



- To generate active power, the current vector must be located on the q axis

$$\bar{i}_s = 0 + j i_{sq}$$
$$i_{sq} > 0$$

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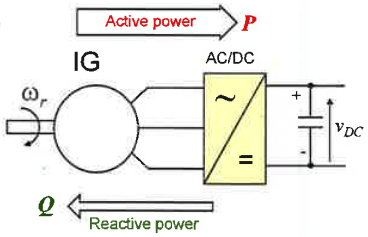
Power converters for induction generators

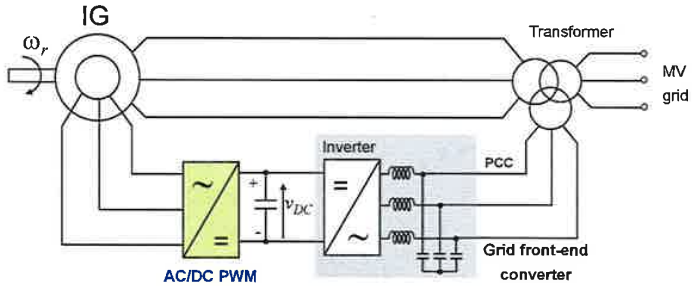
- For the same generator rated power, the PWM rectifier for an IG is designed for a higher power respect to the PWM rectifier for an SG

- The reason is the reactive power needed by an IG to create the magnetic field, while the SG has the excitation



Power converters for induction generators

- The doubly-fed induction generator has the stator that is directly connected to the grid, while the rotor is fed by an AC/DC/AC conversion system
  - Example for a wind generation system with the IG that is connected to the MV grid through a transformer with two secondary windings



Power converters for induction generators

- The stator is directly connected to the grid (transformer) ⇒ the stator frequency f_1 is equal with the grid frequency f_g

- The IG synchronous speed

$$n_s = \frac{60 \cdot f_1}{p} \text{ (rpm)}$$

  - ✓ p is the IG pole-pairs number

- The wound rotor is a three-phase system working at a frequency

$$f_2 = s f_1 \text{ (Hz)}$$

  - ✓ s is the slip computed as $\frac{n_s - n_r}{n_s} = \frac{\omega_s - \omega_r}{\omega_s}$

Power converters for induction generators

- From the power balance viewpoint, the machine operation depends on the relationship between the rotor speed (imposed by the turbine) and the synchronous speed

(1) Oversynchronous operation ⇔ $n_r > n_s$

(2) Undersynchronous operation ⇔ $n_r < n_s$

(3) Operation at synchronism ⇔ $n_r = n_s$

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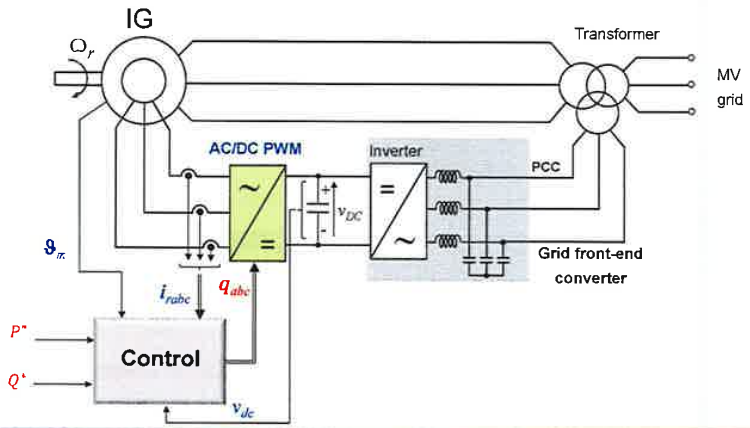
Power converters for induction generators

- The grid front-end converter must regulate the DC link voltage



Power converters for induction generators

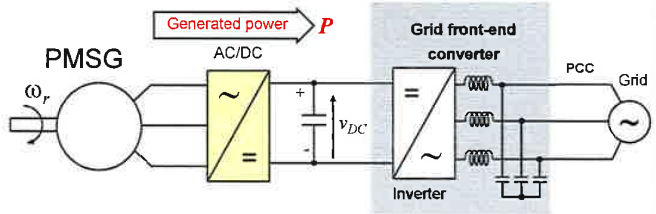
- The rotor-side converter is designed for a power that is about 30% the IG rated power ⇒ the maximum allowed slip is about ± 30%

⇩

- This solution is very convenient for high power wind turbine systems since the power electronics is designed for a power that much less the generated power

DC link voltage limitation

- A power electronic conversion system for distributed generation contains very often two conversion units that share a common capacitive DC link
- Example for a permanent magnet SG



- A common practice is to regulate the DC link voltage with the grid front-end converter

DC link voltage limitation

- If the grid-front end converter is disconnected from the grid from some reason and the source side converter continues generating, then the DC link capacitor will be charged with a voltage that exceed their maximum voltage ⇒ the DC link capacitors explode

⇩

- A damper is necessary on the DC link to dissipate the energy that arrives from the source side converter

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