Introduction : Basics about power electronic converters in the grid

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The development of the modern civilization has been associated with the use of the energy for centuries. Very long time ago, the men were using the forces from the nature as, the wind, the water to create a mechanical power.

This was a local use of the energy.
During the industrial revolution, the renewable energies have been largely replaced by the coal to create steam and then mechanical power.

Soon, the question arises about the transmission of the power over a long distance.
Brief historical recall

First solution: use of mechanical means to transmit the power.
1896: 10 x 5000 horse power generators in the Niagara power station. A part of the power is transmitted to Buffalo about 30 km away from Niagara Falls with the first 20 kV line.
Let’s suppose the motor produces a given mechanical power $p_{meca2}$

In the figure below, $p_{meca2}$ comes from this mechanical power $p_{meca1}$ of the generator.
5. A mechanical power $p_{meca1}$ is needed to generate $p_{elec1}$

$$p_{meca1} = \frac{p_{elec1}}{\eta_1}$$

4. This power has been converted by a generator $p_{elec1}$

3. This power has been delivered by an electrical grid

2. This motor needs a given electrical power

$$p_{elec2} = \frac{p_{meca2}}{\eta_2}$$

1. Let’s suppose that a given mechanical torque ($T_{meca2}$) is applied on the shaft of a motor. The mechanical power is:

$$p_{meca2} = T_{meca2} \times \Omega_{meca2}$$
If the losses are neglected in the grid:

{\displaystyle p_{\text{elec}}_1 \approx p_{\text{elec}}_2 = \frac{p_{\text{meca}}_2}{\eta}}

In case of a DC grid with a given voltage \( u_{dc} \)

The current can be calculated as:

{\displaystyle i = \frac{p_{\text{elec}}}{u_{DC}}}
Power transmission in case of an AC grid

\[ v(t) = V \sqrt{2} \sin(2\pi f \ t) \]

\[ i(t) = I \sqrt{2} \sin(2\pi f \ t - \varphi) \]

\( V \): Valeur efficace de la tension \( v(t) \)

\( I \): Valeur efficace du courant \( i(t) \)

\( \varphi \): Phase of the voltage respect to the current with

\( \varphi \): depends on the type of load
Power transmission in case of an AC grid

Sinusoidal voltage
frequency $f$

$v(t) = V\sqrt{2} \sin(2\pi f \cdot t)$

Sinusoidal current
frequency $f$

$i(t) = I\sqrt{2} \sin(2\pi f \cdot t - \phi)$

$p(t) = v(t) \cdot i(t)$
Power transmission in case of an AC grid

\[ p(t) = 2V I \cos(\omega t) \cos(2\omega t - \varphi) \]

\[ p(t) = V I \cos(\varphi) - V I \cos(2\omega t - \varphi) \]

The instantaneous power is the sum of:
- a constant component \( V I \cos(\varphi) \)
- a fluctuent component \( V I \cos(2\omega t - \varphi) \)

Only the constant part of the power may have a permanent effect on the load since the other component has a null average value.

The average value of the instantaneous power

\[ = \text{Usefull power} \]
Power transmission in case of an AC grid

The useful power is the average value of the instantaneous power

\[ P_{elec} = \frac{1}{T} \int_{(T')} p_{elec} (t) \, dt \]

This useful power is called active power

In sinusoidal operation, it results in:

\[ P_{elec} = V I \cos(\varphi) \]

It yields:

**For a given active power**, and a given voltage, the current in the grid depends on power factor \((\cos(\varphi))\) in case of pure sinusoidal application
The electromechanical way (« historical way ») of producing the **active power** is to convert the power delivered by a primary source to a mechanical power thanks to a steam, hydro or gas turbine. The mechanical power is converter to active power thanks to a synchronous or an induction machine.

When connected to the grid, the rotating speed cannot be controlled. The turbine is not always operating at its optimal operating point from a technical point of view, no other solution was possible.
Power electronics and the production

At the beginning, wind turbine was using the same type of connection. Due to the small size of the generators, induction machines were using.

Fixed or pitch orientated blades

Multiplier

Transformer

Medium Voltage Grid

Induction machine

Reactive power Compensation
**Pro:** Very simple and cheap connection

**Con:** To avoid the inrush current with the magnetizing of the induction machine, the power is limited to few hundreds of kW

Trip of the electrical machine as soon as a voltage sag occurs

The speed is not controllable: impossibility to optimize the aerodynamic conversion
Power electronics and the production

Con: More complex connection

Con: Soft connection
  Voltage ride through capability
  The speed can be adjusted to optimize the aerodynamic conversion
  Very smooth management of the reactive power
Power electronics and the production

There is a maximum in the $c_p$ curve. To optimize the production, the operating point has to be located at this maximum.

\[ \lambda = \lambda_{max} \quad \Omega = \frac{\lambda_{max} v_{wind}}{R} \]

The rotating speed has to follow the wind speed.

Needs of a variable speed for the wind turbine to optimize the aerodynamic conversion.
Power electronics and the production

Photovoltaic Pannel
DC power

Inverter

AC grid

Need of a DC to AC conversion
In the same time, the PV inverter is optimizing the photovoltaic conversion
Power electronics and the production

The power can be optimized by adjusting the voltage applied on the PV cells

The diagram shows a PV module with its power-voltage (P-V) curves under different irradiance levels. The power can be optimized by adjusting the voltage applied on the PV cells through the use of Transistor Gates, which are controlled by the MPPT (Maximum Power Point Tracking) system. The output is then further processed to achieve active and reactive power control before being connected to the AC grid.
Power electronics and storage of energy

The power electronic converter is controlling the power flow between the storage element and the AC grid.

More over, it can provide a reactive power service.
The integration of power electronics in the power system is also linked with:

1. The development of new ways to transmit electrical power with HVDC
2. Connection of the load
3. Power production with new sources of energy
4. Transmission of power with HVDC

In the future, another component will take an important role: the storage of energy.
Power electronics in the grid: HVDC Link

The integration of power electronics in the power system is also linked with the development of new ways to transmit electrical power with HVDC.

AC/DC conversion
Thyristor converters
Power electronics in the grid: HVDC Link

AC/DC conversion
Transistor converters
2 levels or 3 levels Voltage Source Converters

Modulate Multilevel Converter
Power electronics and the load

The integration of power electronics in the power system is also linked with the loads which are more and more connected with power electronic converters.

Drive of large industrial motors

Household goods

Huge data centers

The load is more and more connected to the grid thanks to power electronic converters.
To sum up:
In any case, there is an AC/DC conversion
It may be bidirectional in power or not
Power electronic and the AC grid

Various ways of connection:

- Single phase or Three phase AC grid
- In many applications, a transformer is making the connection. The leakage inductance is used as the connection impedance in the first scheme
- An LC filter can be included for the grid connection
Basic principles for the control

Let’s take this scheme as a generic AC/DC converter

The main of this converter is to control the power flowing through the converter either on the DC side \( P_{DC} \) or on the AC side (active power) \( P_{AC} \)

Depending on the type of control, a reactive power control or voltage control at the PCC is added

For any kind of control, the way to drive the active power is linked with the modulated voltage \( v_m \)
Different topologies may be implemented for the converter but, in any case, the semi conductors have to be driven by some boolean (on/off) gate signals.

A reference $v_{m\,ref}$ for the average value of the voltage $v_m$ has to be defined in the control. The aim of the low level control is to convert $v_{m\,ref}$ in suitable gate signals.
Basic principles for the control

Different topologies may be implemented for the converter but, in any case, the semi conductors have to be driven by some boolean (on/off) gate signals

A reference $v_{m\,\text{ref}}$ for the average value of the voltage $v_m$ has to be defined in the control. The aim of the low level control is to convert $v_{m\,\text{ref}}$ in suitable gate signals in order to have

$$\left\langle v_m \right\rangle_{T_e} \approx v_{m\,\text{ref}}$$

With $T_e$ : switching period of the converter
Basic principles for the control

Assuming: \[ \langle v_m \rangle_{Te} \approx v_{m \text{ ref}} \]

How to generate \( v_{m \text{ ref}} \) in order to:

- \( \checkmark \) transfer a given amount of power \( P^* \)
- \( \checkmark \) synchronize to the AC grid?

\[ P^* \]
\[ ??? \]
\[ v_{m \text{ ref}} \]
\[ \text{Low level control} \]
\[ P_{DC} \]
\[ P_{AC} \]
\[ u_s \]
\[ v_m \]
\[ v_k \]
\[ L, r \]
\[ i \]
Active power control: 2 different solutions
Let’s define $P$ as the active power at the point of common connection.

$$P = V_g I \cos(\varphi) = V_g I_p$$

$I_{sp}$ : active component of the current

It exists two different types of formulation for $P$

If the resistance is neglected

$$P \approx \frac{V_m V_g}{X} \sin(\theta_m - \theta_g) = \frac{V_m V_g}{X} \sin(\psi)$$

$$\psi = \theta_m - \theta_g$$
\[ P = V_g I_p \]

This first formulation means that the power control is achieved thanks to the active current. Indeed, the voltage \( V_g \) cannot be considered as a means to control the power.

An extremely simple model of the system can be proposed as shown on the block diagram below:

\[ \begin{array}{c}
I_p \\
\rightarrow \\
V_g \\
\rightarrow \\
P
\end{array} \]

It means that the power is controlled by an action on the active current. However, since the VSC is a voltage source, it has to be transformed to a current source thanks to a current loop. A model of the current loop can be introduced:

\[ \begin{array}{c}
I_{p\text{ref}} \\
\rightarrow \\
Model of the Current loop \\
\rightarrow \\
I_p
\end{array} \]

Let’s assume that, in steady state: \( I_p = I_{p\text{ref}} \).
Let’s define $P^*$ as the reference for the active power.
A very simple control can be deduced from this analysis.

If the model is correctly identified: $P \approx P^*$

This kind of control is linked with the grid feeding control.
Another way to control the power is to implement a closed loop control.

If an integrator is included in the controller, it will compensate some possible inaccuracy in the model. In steady state, it yields: \( P = P^* \)

The response time of the closed loop system has to be chosen slower than the current loop.
Active power control with the voltage

\[ P = \frac{V_m V_g}{X} \sin(\psi) \]

This second formulation means that the power control could be achieved by action on \( V_m \) or \( \psi \).

However, an action on \( V_m \) would induce an effect on the reactive power.

The choice is to control the active power thanks to \( \psi \).

An extremely simple model of the system can be proposed as shown on the block diagram below.

To control the power, the phase of the voltage is used. No explicit current control is required, the voltage is directly driven by the Power loop: *grid forming control*
Active power control with the voltage

\[ P = \frac{V_m V_g}{X} \sin(\psi) \]

The second formulation of the active power leads to a **second type** of control.

In theory, we could control the power in open loop:

\[ P^* \rightarrow \text{Arcsin} \left( \frac{X}{V_m V_g} \right) \rightarrow \psi_{\text{ref}} \rightarrow \psi \rightarrow \frac{V_m V_g}{X} \sin(\psi) \rightarrow P \]

**Control**

**Model of the system**

However, this model is not accurate enough, so only the closed loop is used:

\[ P^* \rightarrow \text{Power controller} \rightarrow \psi_{\text{ref}} \rightarrow \psi \rightarrow \frac{V_m V_g}{X} \sin(\psi) \rightarrow P \]

**Control**

**Model of the system**

To control the power, the phase of the voltage is used. No explicit current control is required, the voltage is directly driven by the Power loop: *grid forming control*
Currently, nearly all the power electronic converters are driven with a grid following type of control.

However, this control needs a voltage source to be synchronized.

In the future, the grid forming type of control will be developed since it can operate autonomously and does not need a strong AC grid to operate.