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Maximizing the penetration of inverter-based generation on large transmission systems: the MIGRATE project

M-S. Debry, G. Denis, T. Prevost, F. Xavier
Power System Expertise Department
Réseau de Transport d'Electricité (RTE)
Versailles, FRANCE
Marie-sophie.debry@rte-france.com

Andreas Menze
Offshore HVDC and Control Systems Division
TenneT Offshore GmbH
Lehrte, GERMANY
Andreas.menze@tennet.eu

***Abstract*—Renewable generation is mainly connected through converters. It can provide more and more services to the grid such as voltage support or frequency control. However, these services may not be sufficient for extremely high penetrations. As the share of such generating units is growing rapidly, some synchronous areas could in the future occasionally be operated without synchronous machines. In such conditions, system stability will have to be ensured with the same level of reliability as today. Presently, operation of power systems is based on the presence of synchronous machines. Frequency is linked to the balance between load and generation via the rotating masses equation. This will not be inherently valid for grids without synchronous machines. The matter of operating a network with 100 % power electronics is quite well resolved for small isolated systems. The same doesn't apply for large transmission systems where grid topology and power injections are highly variable and are not known at every moment by all system components or even by a centralized entity. This paper describes the research that needs to be achieved to remove barriers for high penetrations of converters.**

Power electronic, converter, frequency, stability, grid forming, renewable energy, transmission system.

I. INTRODUCTION

The penetration of Power Electronic (PE) devices connected to the network is growing rapidly in Europe. Currently, distributed generation, as wind farms and PV panels is mainly connected through voltage converters. Moreover, many DC link projects (HVDC) are in operation, under construction or planned. Finally, an increasing percentage of loads are themselves interfaced to the grid via static converters. This development impacts power system operation and stability: for example, when connecting offshore wind farms by an HVDC link, constraints as steady state harmonics that deteriorate power quality or interactions between converters [1] appear on the network. In the future, new issues related to these networks could be observed. Whole synchronous areas, like Ireland, or parts of continental Europe, such as the Iberian Peninsula or Germany, whose instantaneous penetration of renewable energy has already reached very high values, could occasionally be operated without synchronous machines directly connected to the AC network. In such conditions, Transmission System Operators (TSO) will have to ensure system stability with the same quality of service as today. Even with a lower penetration of PE devices, in case of an incident leading to a system split, isolated parts of networks could also contain only PE-interfaced devices and not be viable despite a balance between production and consumption.

In a system with mainly synchronous machines, stability, which consists in maintaining an operating equilibrium in every moment with relatively constant voltage and frequency, is clearly defined. It is typically divided into three parts: rotor angle stability, voltage stability and frequency stability [2]. In a system with 100% power electronics, the angular stability for example would make no sense since it refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. As converters are impacted by faults on the network, instabilities specific to 100 % PE-fed grids could also appear. It will therefore be necessary to redefine the various notions of stability for these specific networks.

The paper is organized as follows. Section II presents the modifications and challenges related to 100 % PE-fed grids. In Section III illustrates one specific challenge. A description of the MIGRATE project, which addresses amongst others these challenges is given in Section IV.

II. 100% PE-FED GRIDS: A CHALLENGE FOR TSO

A. Frequency and load-generation balance

Present power system operation is based on the fact that rotating synchronous generators are directly connected to the Alternative Current (AC) network as shown in Fig. 1. The rotational speed Ω of a synchronous generator, which is proportional to the grid frequency, is linked to the difference between the mechanical torque C_m supplied by the turbine and the electrical torque C_e needed by the network according to the classical swing equation (1):

$$\frac{Jd\Omega}{dt} = C_m - C_e \quad (1)$$

where J is the moment of inertia of the synchronous machine.

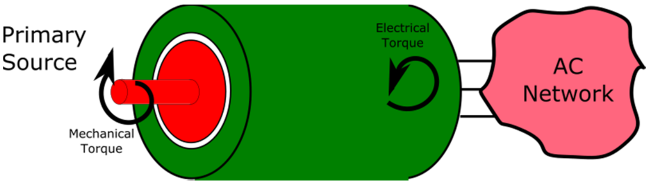

Figure 1: Simplified diagram of a synchronous machine directly connected to an AC system

In an initial stage after a disturbance, e.g. a power plant outage, kinetic energy stored in the rotating masses of synchronous machines is released to instantaneously compensate imbalances between load and generation. Synchronous machines decelerate and the system frequency decreases. In a second stage, regulators of generating units react and adapt the mechanical power depending on frequency deviation.

The availability of a large amount of energy stored in the rotors of synchronous machines gives a certain inertia to power systems: stability is transiently ensured before regulations of generations begin to react. The energy stored in the capacitors associated with PE devices is much lower than the one stored in rotors of synchronous machines [3]. Regulations with time constants similar to the present ones would not ensure the stability of a 100% PE-fed grids because the network would collapse before the action of the regulations.

Beyond this stored kinetic energy in the rotating masses, the physical link between system frequency and load-generation balance is the key element of large power systems operation. For converters, as shown schematically in Figure 2, load-generation imbalance is not reflected on frequency but on DC bus voltage.

$$\frac{CdV_{DC}}{dt} = I_{received} - I_{prod} \quad (2)$$

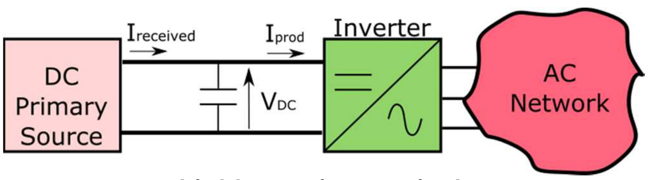

Figure 2: Simplified diagram of a PE-interfaced generating unit

The fundamental difference between the two systems is that frequency is a global parameter for the whole system while DC bus voltage is a local parameter. In 100 % PE-fed grids, if no action is taken to recreate a shared value such as frequency, it will not be possible to have an overview of the network with a local measure.

Two actions can be considered to maintain stability of such a system:

- keep an available energy level similar to the one of present systems and emulate the inertial behavior of synchronous machines with converters used to connect the generation units to the network
- change the network operating strategies and make regulations faster.

Even if it is technically feasible, the first proposition is extremely costly since it requires oversized converters able to transit temporarily extra power equipped with additional storage devices like batteries or supercapacitors. Note also that the present level of inertia has never been defined as a requirement but is only a consequence of the presence of synchronous generators directly connected to the AC network.

The second proposition enables to define a new operating strategy, as it is done for microgrids. The energy level needed to ensure power system stability could then be reduced to a reasonable cost.

B. New converter control strategy

Synchronous machines directly connected to the AC network share a unique and same frequency on the overall system thanks to the synchronizing couple between generators. They create a link between this frequency and load-generation balance via (1). This equilibrium can be ensured by maintaining the frequency at a constant value.

For a converter, frequency is not related to a physical characteristic but it is a set point value of the control system which can be chosen arbitrarily. Today, this value is generally the measured system frequency: converters inject the desired AC current at the adequate frequency. They “follow” the network. Without rotating machines, all converters will no longer be able to remain “followers”. Some of them will necessarily impose grid frequency, which involves a radical modification of their control system [4].

Today, PE systems are controlled as current sources: they measure the voltage at their connection point and inject current with the adequate phase shift compared to network voltage in order to produce the active and reactive power defined by their control system. In a system without synchronous machines, inverters should provide the amount of power needed by the loads. As this value is unknown, the active power produced by inverters cannot be a direct input of the controls.

Inverters will also have to ensure that voltage remains within the admissible range. Today most inverters participate in primary and secondary voltage control, and some are involved in frequency control or provide synthetic inertia. All these features are converter responses: they modulate the active and reactive power they inject according to the variation of an electrical parameter. Voltage control consists in adjusting the reactive power injected on the network while frequency control consists in adjusting the injected active power. Synthetic inertia is equivalent to producing an additional amount of active power during the first few seconds after a frequency drop. As voltage support in the very short term (<100ms) is currently provided by the behaviour of synchronous machines, in future systems based only on PE devices, it will be necessary to control voltage faster. Inverters, which now are mostly voltage sources controlled as current sources, will then be controlled as voltage sources and will themselves create the voltage reference. Today this is the strategy adopted by HVDC links connecting offshore wind farms to the onshore grid or by HVDC links operated in "blackstart" mode.

Maintaining voltage to a value close to its nominal value is the sine qua non condition to ensure that loads consume the required amount of power. Indeed, most loads are sensitive to voltage and operate correctly only for small variations around nominal voltage.

In a meshed network without synchronous machines, a number of issues arise:

- The voltage waveforms created by the different converters connected to the network must be synchronized, because a frequency difference between them would cause very high power flows, and could lead to the destruction of some converters;
- Converters will be much more sensitive to angle or impedance variations: for example, with a converter controlled as a voltage source, if the voltage angle increases, the supplied active power also increases a few moments after. If the converter already provides its maximal active power, protection systems could disconnect it from the grid. Contrary to synchronous machines, converters have low overload capabilities due to current limitations that are closer to the nominal current values.

C. *Different overload capacities*

The overload capacity of synchronous machines allows them to withstand a very high current (about 250% of their nominal current, and even 500% during short-circuit) in the rotor and stator windings for a limited period. Indeed, the main impact of high currents is the heating of the rotor and stator, but the thermal inertia of synchronous machines allows them not to be sensitive to high currents for short periods. For converters, the maximum admissible transient current is limited by the semiconductor capacities. Without costly over-sizing, for high power applications the maximum current is estimated to 110% of the nominal current.

This limitation of the overload capacity impacts the transient behavior of power park modules compared to synchronous machines. In particular, the latter provide a very high current for a short period during short circuits. This current is used by power system protections to detect faults. Today, the behavior of inverters during short circuits can be configured: it is possible to stop the inverter, to operate it at constant power factor while respecting the maximum current criteria or to give priority to reactive current and provide maximum permissible reactive current during faults. All these behaviors quickly modify current injections provided by inverters during faults. But the present protection systems may not operate properly because of these new components which provide a low and limited current during faults [5].

Here again, several solutions are possible:

- slightly change the present protection systems (based on differential protections and distance protections) to ensure their operation in a grid that is in a continuous change;
- take advantage of the specific behaviour of inverters and look for new protection strategies.

It must be pointed out that, although the faults detection may become more complex, lower short-circuit currents will have a positive impact on the design of substation materials that will no longer be subject to intensive electrodynamic stresses.

III. BASIC ILLUSTRATION OF ONE ISSUE WITH 100% PE GRID

The simulation results below illustrate one issue that could happen on 100% PE grid when a line is tripped (no fault in the simulation). The very simplified grid is composed of two inverters feeding a load (see Fig. 3). These two inverters are controlled as voltage sources and to mimic the behaviour of synchronous machines with primary frequency control. This is one of the solutions that have proven their feasibility in microgrids domain.

The network representation is as follow:

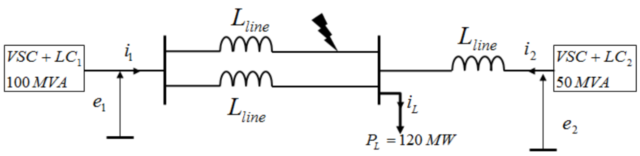

Figure 3: Diagram of the test system

The currents injected on the grid by the two inverters are represented in Fig. 4:

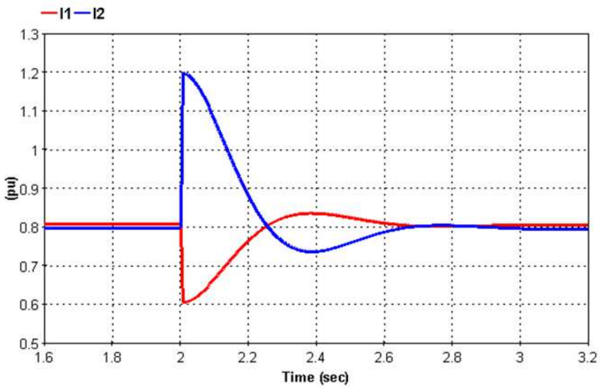

Figure 4: Currents injected by the converters

The smallest unit should be able to withstand a current above its maximum admissible one (considered to be 1.1 p.u). Without a costly oversizing there would be a high risk of disconnection of the unit or even of hardware destruction. Other controls must therefore be developed to withstand the topology changes that can happen at any moment on transmission grids.

IV. THE MIGRATE PROJECT TO ADDRESS THESE ISSUES

The matter of operating a network with 100% power electronics is quite well resolved for small islanded systems, such as microgrids [6], and grids connected to strong AC systems via HVDC, such as offshore grids [7]. In case of offshore grids, the HVDC link inverter is much more powerful than the wind inverters, so it plays a master role (behaviour close to an infinite node) on which the wind farms inverters can synchronize. For small networks (microgrids), the network topology is known and often radial, and load variations are quite limited. Solutions developed for microgrids or offshore grids cannot be applied to large transmission systems, because network topology and power injections are highly variable and are not known at any moment by all components or even by a centralized entity. Distributed control schemes by independent converters are therefore the only viable alternative. Table 1 illustrates the differences between microgrids and transmission networks.

A. *Two complementary approaches*

Challenges raised by the development of converter-interfaced generation will be addressed by the European project MIGRATE, which stands for Massive InteGRATion of power Electronic devices. Its purpose is to analyze the impact of the proliferation of PE devices on system stability through two complementary approaches:

- stability indicators will be defined and a methodology will be proposed to optimize existing control parameters, in order to integrate more PE devices on the current network and to mitigate their impacts on power system stability;
- new control algorithms and new operation rules will be developed to allow power systems to operate with 100% penetration of PE. If hardware changes are required on inverters, specification drafts will be proposed.

The project, coordinated by the German TSO TenneT GmbH, involves a consortium of TSOs, academics and a protection manufacturer. The questions related to the evolution of protection systems and of power quality with PE proliferation will also be addressed. The project began in January 2016 and will last 4 years, with a funding of around 16 million euros by the European Commission.

One of the Work Packages (WP) is dedicated to power system stability of large transmission grids with 100 % converter-interfaced generation. It involves RTE as WP leader, L2EP, ETH Zurich, University College of Dublin and four other TSOs (Eirgrid, REE, TenneT TSO GmbH and Terna). Its objectives are:

- to define requirements about the global behaviour of a system with 100% PE (called “system needs”);
- to develop the necessary controls and management rules ensuring system stability of transmission grids without synchronous machines directly connected to the AC system;
- to check the viability of these controls with real converters on a small scale network mock-up developed for the Twenties project and available in L2EP in order to ensure the validity of modeling, to protect against failures (e.g. of a component) in some operating modes, and to prove the feasibility of the developed solution. Indeed, the physical limitations of inverters are not always precisely defined in digital simulations; the usage of physical mock-ups obviously guarantees that these devices are operated below their physical capacities.
- to infer requirement guidelines for new converter-based generating units, which will facilitate the implementation of these controls and management rules

The viability of such new controls and management rules within transmission grids to which some synchronous machines are connected will be checked so as to enable operation with existing equipment.

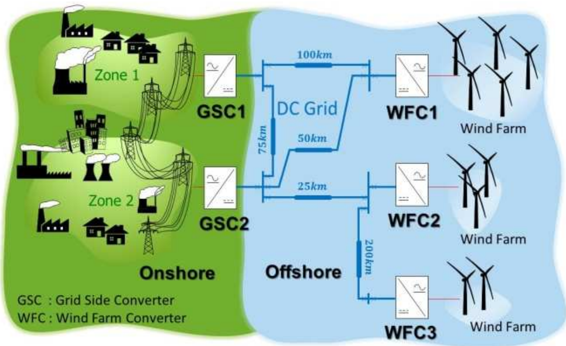

Figure 5: Small scale network mock-up available in L2EP used for the Twenties project – Source: Twenties project

B. *Proposals for new network codes*

The results will be converted into requirements for the connection of PE devices. The purpose of this research is to prepare for future transmission networks based on PE-interfaced devices only. For this, it must quickly be ensured that generating units connected through PE are compatible with the new controls that will be required. The project goal is therefor to define requirements guidelines for new inverters.

The level of details for the future requirements will be one of the outputs. Indeed, requirements at the connection point are sufficient to ensure system stability today. In the future, hardware requirements such as DC bus capacitor or overload capacity of components may be necessary.

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