The Migrate project: the challenges of operating a transmission grid with only inverter-based generation. A grid-forming control improvement with transient current-limiting control

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Abstract: Renewable generation is mainly connected through converters. Even if they provide more and more ancillary services to the grid, these 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 behaviour will dramatically change, but stability will still have to be ensured with the same level of reliability as today. To reach this ambitious goal, the control of inverters will have to be changed radically. Inverters will need to move from following the grid to leading the grid behaviour, both in steady state and during transients. This new type of control brings additional issues on converters that are addressed in this study. A solution is proposed to allow a stable operation of the system together with a limited solicitation of inverters during transients.

1 Introduction

Renewable generation is providing a larger and larger share of electrical energy production in the European system. Many studies have been performed concerning the impact of renewable generation on the electrical system, some of them focusing on load adequacy, and increasingly others are investigating technical issues associated with the operation and stability of the grid. Most of the new renewable generation such as wind and solar power are connected to the grid using inverters, whose behaviours are completely dictated by their control, as compared with the classical synchronous machines.

To address this evolution of the transmission grid, the European Union (EU) has recently funded, through the Research and Innovation programme Horizon 2020, a project focused on maximising the penetration of power electronics (PEs) devices in the electrical grid. This project, named Migrate for ‘Massive InteGRATion of power Electronic devices’, decomposes the expected issues in subtasks as shortly described in this paper. Amongst the subjects of the overall Migrate project, this paper focuses on one particular aspect, namely the operation of a grid with only PE devices. Assuming there is locally enough electricity production to satisfy the demand, the transmission system operators would like to operate the full-inverter-interfaced transmission AC system with the same reliability or better than nowadays.

This feasibility question is analysed to raise some technical challenges associated with parallel operation of grid-forming inverters subject to transient events on transmission grid.

Full-inverter-interfaced systems are already operating in microgrids for low or medium voltage, uninterruptible power supply, or offshore wind farms [1, 2]. However till now, few studies have been applied on transmission system applications. For transmission applications, differences with smaller networks lie in power ratings level of converters, grid topological uncertainties, and stressful grid operations (as large load connection or line tripping). If some studies focused on transient disturbances on microgrids [3, 4], the consequences are even more challenging at the transmission level [5] and must be addressed specifically.

For proper operations on the AC side of inverters interconnected through a transmission grid, three conditions have been identified here and detailed further:

• Autonomous and flexible operation of each device regardless the topological structure of the rest of the grid.
• Supply of the connected loads under nominal conditions and in accordance with their own rating.
• Stability during the parallel operation with other inverters, even after sudden events.

These combined three functions will be referred as parallel grid-forming capability, and must be fulfilled by the inverters control. Although controls for autonomous synchronisation [6, 7], flexible operation [8, 9], or fault-ride-through capabilities in [10–12] have been treated separately in the literature, a specific implementation based on a threshold virtual impedance (TVI) for current limitation is proposed here to combine all these functions in a stable manner.

After an introduction to the Migrate project in Section 2, Section 3 identifies differences between synchronous machines and inverters as a power source for electrical transmission systems and proposes a synthesis of some fundamental needs of a grid, regardless of the type of connected generation. Section 4 describes how the inverter-based generation can fulfill these needs by implementing a grid-forming control strategy at the expense of new constraints such as high-transient overcurrent sensibility. Section 5 illustrates the transient overload issue following line opening between two parallel grid-forming sources. The last section depicts the proposed approach to alleviate transient overcurrent, with a TVI, without loss of synchronisation between units.
Although, the compatibility of new solutions from WP3 with traditional synchronous generators could be an interesting outcome and will be validated at the end of the project. The rest of this paper focuses on the problematic analysis of WP3 to answer with a possible solution.

### 3 Needs of large transmission systems

A synchronous machine consists of a rotor, rotating with an electromagnetic force, and a stator that is connected to the electrical grid (Fig. 2). The mechanical equation of rotating machines is given as

$$J \frac{d\Omega}{dt} = T_m - T_{em}$$  \hspace{1cm} (1)

where $T_m$ and $T_{em}$ are the mechanical and electromechanical torques and $\Omega$ is the mechanical rotational speed of the rotor, proportional to the electrical frequency of the rotor electromagnetic force (depending on the number of pole pairs of the rotor) [13], and $J$ is the inertia of the rotational masses.

Other characteristics of synchronous machines are that short-term energy stored as rotational energy (of generator and associated turbine), and the short-term overload capability of such machines is very high, up to 6 pu. Indeed, high currents create heat through the Joule effect, but the thermal inertia of both the rotor and stator smooths out any heat ramp transients.

Owing to their overload capacity, the (relatively) slow controls of synchronous machines are not constrained by overcurrent limits. In addition, the rotational energy stored in the machine rotors is immediately available for balancing the grid, and provide damping, before any control response.

Equation (1) also highlights a fundamental intrinsic property of synchronous machines, namely the coupling between the frequency and the imbalance between electrical and mechanical torques, whereby a physical (local) property of one device reflects an operational ‘property’ of the entire grid. Moreover, the coupling of the rotating mass equation with the power flow transit on an inductive line creates a synchronising torque between interconnected synchronous machines, which results in the system being stable for most cases [13].

In the case of inverters, the situation is different. There is no mechanical rotating part in the inverters and no rotational energy is stored. Energy is instead stored in the capacitors of the DC bus, but the quantity involved is several orders of magnitude smaller than the rotational energy stored by synchronous machines (see Fig. 3).

There is no inherent link between an active power imbalance and the frequency of the electrical values generated by inverters. On the positive side, very fast controls can be implemented on inverters

$$\frac{CdV_{DC}}{dt} = I_{received} - I_{grad}$$  \hspace{1cm} (2)

In most cases, energy stored in C in respect with the nominal power of the unit, is ranging from several milliseconds to several hundreds of milliseconds of nominal power.

From a system point of view, rotational inertia is not a requirement. It is only a consequence of the presence of many synchronous machines on existing power systems. Traditional power system operation, based on the ‘slow’ controls of synchronous machines, relies on the assumption of a large amount of inertia. All else being equal, a reduction in system inertia is challenging, because of the smaller time scale available to react to disturbances. The real concern is stability, and with new and faster controls implemented on inverters power systems could, in theory, remain stable with low or even no inertia.

Some of the transmission system requirements to be fulfilled by the electrical generators for secure operation of a grid are:

- Stable terminal voltage regulation.
- Stable synchronisation of all generators (without critical real-time telecommunication).

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**Fig. 1** Two approaches of the Migrate project

**Fig. 2** Traditional energy conversion system

**Fig. 3** Typical scheme of an inverter connecting a DC bus to an AC tri-phase network
found in the deliverable 3.1 ‘Description of system needs and test system needs listed in the previous section requires the inverters to that transmission systems must be able to withstand. It will be used

From grid-following to parallel grid-forming devices only, for which the classical definition of stability may not

synchronous generators through their physical properties and slow acting control, whereas inverter control strategies still need to be defined accordingly. A detailed list of the fundamental requirements that must be fulfilled by a transmission system can be found in the deliverable 3.1 ‘Description of system needs and test cases’ of the Migrate project [14]. It also includes a list of events that transmission systems must be able to withstand. It will be used in the project to assess the stability of systems with inverter-based devices only, for which the classical definition of stability may not be relevant.

4 From grid-following to parallel grid-forming strategy: new challenge for inverter controls

In the case of a 100% PE system, fulfilling the large transmission system needs listed in the previous section requires the inverters to change their control paradigm. Almost all inverters connected to the transmission grid are presently controlled in a grid-following mode, which means that they measure the amplitude, phase, and frequency of the grid voltage and adapt their injected current to

For a power system based only on inverters, grid-following controls cannot be used for all devices. If there are no synchronous machines connected to the network, there will be no voltage to synchronise to.

Moreover, on large transmission grids, the load is not known from the generating units’ point of view. Without synchronous machines present, the controlled set point of the inverters should therefore not be the active power, but the steady-state voltage.

Some of the inverters will need to be operated as synchronised voltage sources, namely in parallel grid-forming mode. For a load, being supplied with a determined amplitude and frequency sinusoidal voltage waveform is necessary to operate in nominal conditions. If inverters are operated as voltage sources, they can persist in a system without synchronous machine regardless of the characteristics of the connected loads. Presently, some high-voltage DC converters offer ‘black start capability’ to feed a passive grid in grid-forming mode. However, no commercial solutions exist for parallel grid-forming devices. Including grid-forming inverters in a system fundamentally changes its behaviour.

As an example, one can compare two inverters providing frequency control with droop, one being grid forming and the other being grid following. The grid-following inverter first needs to measure the frequency of the grid, and then if the frequency decreases (increases), it will increase (decrease) its active power setpoint to restore balance. The link between the active power unbalance and the frequency is performed by the grid, and the dynamic transients resulting from the underlying disturbance may mean that the grid frequency measurement takes some time to stabilise (Typical frequency measurement is about 100 ms.) (Fig. 4).

In the case of a parallel grid-forming inverter, if the load increases, the active power delivered to the grid also increases, and therefore the frequency of the delivered voltage decreases due to the implemented control (Fig. 5). In this case, the dynamics of the frequency variation only depends on the controls (in this simple case, the frequency variation is not limited, but more complex regulation could limit the frequency rate of change).

In the meantime, the reader will have noted that providing such control creates a link between the inverter output voltage angle and the active power. This link recreates a synchronising torque on the inverter voltage angle, similar to that affecting the rotor voltage in synchronous machines.

Parallel grid-forming inverters can fully replace synchronous machines for secure operation in large transmission system. Similar conclusions have been drawn in [15]. However, a new challenge emerges for the following reasons:

- Owing to the poor thermal inertia in semiconductors, the inverters have limited overload capability compared with synchronous machines.
- Grid-forming controls are much more sensitive to grid variations than grid-following controls.

Fig. 6 illustrates the impact of voltage angle shifts due to grid transients on the current generated by grid-following and grid-forming inverters. Fig. 6a is an illustration of the value of the current for a grid-following inverter, whose expression is:

\[
I_P = I_\text{set} \cos(\phi) \\
I_Q = I_\text{set} \sin(\phi) \\
I_\text{set} = \sqrt{I_P^2 + I_Q^2} = I_\text{set} = \alpha \cdot I_\text{max}
\]

with \( \alpha \leq 1 \)

In such a situation, a grid voltage \( V \) angle shift leads to a transient shift between the active and reactive powers (as the angle \( \Phi \) will shift), but the total current is constant and limited to \( I_\text{max} \), given by (3).

Fig. 6b depicts the value of the current for a grid-forming inverter. \( V_2 \) being the grid voltage, \( V_1 \) being the inverter voltage and \( X \) the impedance of the connection to the grid. An angle shift

\[
\begin{align*}
\text{Fig. 4 Frequency control from a grid-following inverter} \\
\text{Fig. 5 Frequency control from a grid-forming converter} \\
\text{Fig. 6 Expression of the output current of} \\
(a) \text{Grid-following inverter, (b) Grid-forming inverter} \\
\end{align*}
\]
of the voltage $V_i$ also has an impact on the generated current given by (4)

$$I_p = \frac{V_i \sin(\theta)}{X}$$

$$I_q = \frac{V_i - \cos(\theta)V_i}{X}$$

$$I_{tot} = \sqrt{I_p^2 + I_q^2} = \frac{1}{X} \sqrt{V_i^2 \sin^2(\theta) + (V_i - V_t \cos(\theta))^2}$$

However, the value of the current only depends on the impedance of the grid, the voltage amplitude, and the angle shift.

This high sensitivity to angle shifts of grid-forming inverters may necessitate a new form of stability to be defined, which was not previously necessary for synchronous machines that are less sensitive to such high currents. These voltage shifts are very common and can be created by different events, line switching, connection of a large load close to an inverter, and disconnection of an inverter.

In the first deliverable of WP3 of Migrate, a list of events that the system needs to be able to withstand has been issued. The list provides test cases for the controls of inverters in a wide variety of events. The next section illustrates the transient overload of parallel grid-forming sources in the typical case of a line switching on the transmission grid.

5 Parallel grid-forming ideal sources behaviour during line switching

This section considers first two ideal grid-forming inverters, modelled as voltage sources, with frequency references provided by a conventional droop control to ensure parallel operation capability [5]. The transient response following a typical line switching on transmission grid exhibits the needs of a specific current-limiting strategy.

5.1 System description and modelling assumptions

As shown in Fig. 7, the elementary system considered here contains two parallel grid-forming inverters interfaced by two parallel transmission lines. The chosen modelling assumptions are:

- Inverters are controlled in grid-forming mode and thus are represented as ideal voltage sources with controllable frequency, behind transformer inductances.
- Frequency references are provided by a conventional droop control to ensure parallel operation capability.
- Inverters are connected to the transmission grid, and will be classified to different voltage levels depending on their sizing. To simplify, here is considered that inverters are connected to a 400 kV bus, where the largest unit has a rated power of 1 GW and smallest unit, 250 MW [16].
- Inverters are transmission sized, above 100 MW, with a dynamic limited by the switching frequency of $f_{sw} = 5$ kHz. This limitation is conservative as smaller inverters usually have a higher bandwidth.
- Inverters have an overload capability of 20% above their rated current. This assumption is probably conservative, but it ensures that there is limited risk of actually exceeding the maximum current limit.

5.2 Power–frequency-droop control description

As stated previously, inverters must be synchronised without the need for (real-time) telecommunication, whereby measurement of local electrical values must be sufficient. Amongst other techniques, the frequency-droop control is linear and allows a simple synchronisation process between parallel grid-forming inverters by defining a frequency reference based on active power measurement. The droop control ensures necessary and sufficient conditions for the existence of a consensus frequency of all interconnected units [17, 18]. Also, droop control provides a smooth migration path from traditional grid with existing synchronous generators to a full voltage-source converter (VSC)-interfaced transmission grid.

The frequency-droop control is based on the dependency of the quasi-static power transfer (5) between two inverters controlled as voltage sources, and their output voltage angle difference

$$P_{1 → 2}(t) = U_1U_2 \sin(\theta_1(t) - \theta_2(t))$$

$$X_{1 → 2}$$

The instantaneous voltage angles are defined by the integration of their frequency reference

$$\theta_i(t) = \int f_o(t) dt$$

Moreover, the frequency reference $f_o$ is given by the droop law (7), knowing the nominal frequency $f_o_n$ and the desired active power setpoint $P_{set}$ of each inverter

$$f_o = f_o_n + k_{droop} \left( P_{set} - \frac{f_o_n}{s + f_o_n} \right)$$

where $k_{droop}$ and $f_o_n$ are the droop gain and the power filter cut-off frequency.

Hence, adjusting the frequency references following active power variation from the initial power setpoint tends to bring back the active power, and the voltage difference to their initial values.

Combining (5)–(7), droop control provides closed-loop control of frequency, based on local measurement of the output active power. The control principle is known as the conventional inverter droop control [1]. The active power is usually filtered by $f_o_n$ to damp out the resonances of the grid [19], the high-frequency component in case of imbalance [20], to avoid fast frequency reference transients [12], and to decouple the faster inner inverter controls [21].

Droop-controlled inverters have proven their effectiveness to remain synchronised and to share the load in small microgrid systems [1, 6, 21]. More recently, their synchronisation stability under small and large disturbances has been analytically demonstrated for large and meshed systems [7, 17, 18] under the condition that droop control provides sufficient power damping, and that the grid can carry the power transfers. The droop control parameters are chosen, so that the power filter damps the frequency response, and that the droop gain $k_{droop}$ limits the maximum expected frequency deviation on the system [5].

5.3 Transient overload following a line switching

Owing to the above criteria on droop parameters selection, droop control response to an instantaneous active power demand is not fast enough to adjust the inverter voltage angle in the first cycle following transient disturbances. Consequently, the output current might reach high value for few cycles before the droop control brings back the inverter to its power setpoint. The typical transmission grid event of a line tripping is applied on the system of Fig. 7. Note that the two droop-controlled inverters have different ratings.

When the inverters are modelled as perfect voltage sources behind transformer inductances, and controlled using power-frequency-droop control, the instantaneous load share following the line trip is unequal during 200 ms. As shown in [5], the
transient load share just following the event depends only on the reactances that separates the inverters. This transient unequal load share has consequences for the magnitude of the output currents for both inverters, as illustrated in Fig. 8. The closest inverter to the load has the lowest rating of 250 MW and thus experiences the larger overcurrent. The overcurrent limit, fixed at 1.2 pu is exceeded up to 1.4, during more than one cycle, resulting in whether the destruction or the disconnection of the device. Regarding the transient load sharing issue, the following requirements must be observed by inverters during severe transients:

- To limit the output current below the inverter maximum value to avoid any risk of disconnection.
- To remain synchronised to the other inverters.
- To have a smooth transition between normal mode and current-limiting mode without control switching for reliability reasons.

**6 Proposition of a new current-limiting approach during transients for inverters controlled in parallel grid forming**

To deal with current-limiting strategies, the full model of a grid-forming inverter must be considered including its voltage regulation. This section takes into account a pulse-width modulation inverter output inductor–capacitor (LC) filter and its voltage regulation by cascaded loops of capacitor voltage (e) and converter output current (i) flowing in the filter inductance. The controls are implemented in the dq-frame (see Fig. 9). The inner control parameters have been chosen to limit the bandwidth of voltage control loop for flexibility reasons, i.e. to ensure stability in a standalone situation or when connected to a strong grid [8] or to another inverter [9]. VSC-based inverters parameters and the tuning procedure can be found in these references. In the following, the concept of TVI is suggested to modify the inner control only when the current exceeds its limit.

**6.1 Grid-forming inverters current-limiting solution based on a TVI**

To protect a grid-forming inverter against transient overcurrents, Guerrero et al. [22] suggested enhancing the droop control by adding a derivative compensator on the power measurement, but at the risk of compromising the system stability [23]. Alternatively, saturation of an inner control reference is not desirable as it prevents the droop control synchronisation process based on power measurement, and can lead to instabilities as demonstrated in [12, 24].

The TVI concept is more suited to limit the overcurrent in a grid-forming converter because it avoids saturating the reference of output current to keep the controllability of the external loops. The concept is to increase the output impedance of the VSC by a virtual value $Z_{vi}$ when the VSC output current magnitude exceeds a defined threshold. As the transient current depends on the grid reactances [5], increasing the output impedance of the inverter reduces its post-fault current raise.

Current limitation using voltage reference modification is already presented in [10, 11] and more recently in [12]. These authors propose introducing a voltage drop signal $\Delta V_{\text{c,dq}}$, given by the TVI module to be subtracted from the voltage control reference, as (8)

$$e_d^c = E^c - \Delta V_{\text{c,dq}}$$

$$e_q^c = -\Delta V_{\text{c,dq}}$$

where the voltage drop $\Delta V_{\text{c,dq}}$ represents the voltage across the virtual impedance. $V_{\text{c,dq}}$ equals 0 when the output current magnitude is beneath a defined limit $I_{\text{threshold}}$ and is dependent on the measured output current during overcurrent conditions

$$\Delta V_{\text{c,dq}} = R_{\text{c,dq}} i_{\text{c,dq}} - X_{\text{c,dq}} i_{\text{c,dq}}$$

Modification of the voltage reference (8) by simple TVI approach is, however, of limited effectiveness in transmission grid applications as shown on the dashed curve in Fig. 10. Indeed, the internal control developed for transmission grid applications has limited bandwidth for flexibility and robustness reasons [8] and cannot react fast enough to lower the output voltage and limit the current. Consequently, the output current will not be limited sufficiently quickly if the TVI signals are applied only to the voltage reference.

To overcome the inner bandwidth limitation, the TVI reference signals $\Delta V_{\text{c,dq}}$ should be applied as close as possible from the VSC modulation, in order to speed up the response to the overcurrent condition. In the present implementation, $\Delta V_{\text{c,dq}}$ signals from TVI are subtracted directly from the VSC modulation reference $(v_{\text{c,dq}}^*)$ given by the current control output, to form the reference $(v_{\text{c,dq,eff}}^*)$ effectively applied to the converter modulation.
The signals $\Delta V_{\text{TVI}}$ are still subtracted from the voltage control tracking reference; otherwise, the inner voltage control attempts to compensate the TVI action. Implementation of TVI in the internal multi-loop control is summarised by the scheme of Fig. 9. The scheme represents a three phases VSC with its LC output filter, the inner voltage control by cascaded loop in dq-frame gives the inverter reference to ensure the filter output voltage to be at the right magnitude $E^*$, aligned with the direct axis. The voltage drop calculated by the TVI is applied both to the output voltage reference and to the inverter reference.

For a smoother transition between normal operation and current-limiting operation, the resistance and reactance values of the virtual impedance are chosen to be proportional in respect with the overcurrent

$$R_{\text{vi}}(I_{s}) = k_R d_{\text{heusal}}$$
$$X_{\text{vi}}(I_{s}) = \rho_R d_{\text{heusal}}$$

(11)

The two TVI parameters to be defined are the gain $k_R$ and the ratio $\rho_{VR}$ of the reactive part to the resistive part of TVI. The gain $d_{\text{heusal}}$ is fixed after the desired maximal value of $I_s$ during the worst-case scenario of a solid three-phase short circuit at the connection bus [10], so that as long as the short circuit is present, the output current $I_{s, \text{sc}}$ will be limited by the virtual impedance magnitude

$$I_{s, \text{sc}} = \frac{E_0}{\sqrt{X^2 + Z_V(I_{s, \text{sc}})}} < I_{\text{max}}$$

(12)

$Z_V$ represents the transformer series impedance. With a maximum short-circuit current defined at $I_{\text{max}} = 1.2 \text{ pu}$, the TVI gain is $k_R = 0.27$.

The ratio $\rho_{VR}$ must be high enough to ensure that the output impedance, augmented by the TVI is always dominated by its reactive part from the droop control perspective [11]. The resistive part of the TVI, nevertheless, provides necessary damping at high frequencies [12]. A trade-off $\rho_{VR} = 5$ is chosen. A full small-signal stability analysis has been conducted using the linearised state-space model developed in [6] to prove the small-signal stability of the system including the inner controls and the droop controls, even when the TVI is activated. The results are not included for brevity.

6.2 Effectiveness of the TVI current-limiting action during line switching

The line trip in the system of Fig. 7 is simulated using EMT software, considering the whole control of the inverters including the droop control, the inner voltage control, and the TVI. The response of the magnitude of the out of the inverter 1 is plotted in Fig. 10. The two curves show a comparison of the basic TVI approach proposed by He and Li [11] and Paquette and Divan [12] against the improved TVI, adapted to the inner control of grid-forming converters for a transmission system. The dashed curve indicates the response of the basic current-limiting TVI. Compared to the response of an ideal VS controlled by a droop plotted in Fig. 8, the basic TVI reduces the current magnitude of the inverter 1 to be under 1 pu slightly faster. The first peak is, however, still present, and is even higher due to the inner control attempting to correct the output voltage.

Besides, oscillation of the inner control in the presence of the TVI is not acceptable. In the case of the improved TVI, the instantaneous magnitude of the output current is effectively contained under 1.1 pu after the line trip, respecting the 1.2 limit. Note that the droop control is still effective, even if the presence of the TVI, as the inverters stay synchronised. Although, the TVI induces a sluggish response of the droop control because of the larger output reactance introduced during the overcurrent mode.

7 Conclusion

To face the increasing share of PE-interfaced generation at the transmission level, the Migrate project has been funded to follow two complementary approaches, first, by determining the penetration limits of actual inverters, second by investing the challenges and solutions for 100% inverters systems. In the second approaches, the prerequisite, and the challenges of 100% PE systems are already identified. These papers showed the need to rely on parallel grid-forming converters that must be autonomous and robust against grid topology variation and transient events.

A linear solution to control the future parallel grid-forming inverters based on classical droop control is proposed to tackle these challenges. To improve the transient behaviour of the grid-forming inverters following sudden grid events, a TVI current-limiting solution is suggested. The advantage of the TVI is to avoid the disturbance of the inner control and the droop control during normal operation and to guarantee the small-signal stability of the whole system, even when activated.

The large-signal stability of the system including the TVI, however, has not been formally demonstrated, especially on large transmission grid with multiple devices. More advanced synchronisation controls based on non-linear could also be assessed on the test cases defined in the Migrate ‘system needs’ and presented in these papers. These future works are part of the objectives of the Migrate WP3.

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