GRID-FORMING CONVERTERS – INEVITABILITY, CONTROL STRATEGIES AND CHALLENGES IN FUTURE GRIDS APPLICATION

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ABSTRACT
At the heart of the energy transition is the change in generation technology: from conventional generation based on synchronous machines towards renewable energy sources interfaced with power electronic converters. The accompanying loss of rotational inertia and of the robust synchronization mechanism provided by synchronous machines and their controls is a challenge to the operation, control, and stability of the electric power system. In a future low-inertia power system, these functionalities have to be provided by proper control of so-called grid-forming power converters. This article provides a comprehensive review, a classification, and a critical comparison of different grid-forming converter control strategies in a simulation case study.

Key words — Grid-Forming Converter, Synchronous Generator, Droop Control, Matching Approach, Synchronverter, Virtual Oscillator Control.

INTRODUCTION
In line with recent technological developments increasing the feasibility of renewable energies utilization, one can expect a global transition towards a nearly 100% renewable grid [1]. As a result of massive integration of renewables, we witness a change in generation technology from fossil-fuel based power plants to renewable energy generation. Since renewables generate DC or variable AC output power (e.g., photovoltaics, variable frequency wind generators, etc.), power electronics-based solutions are the most viable energy conversion alternatives [2–4]. This sheds light on the possibility of integrating converters into the power system infrastructure replacing the synchronous generators (SGs). The absence of rotational inertia previously provided by SGs denatures the conventional power grid to a so-called low-inertia system.

The concept of a grid-forming converter (GFC) is fundamental to the operation of a low-inertia power system dominated by non-rotational generation. In such a scenario, grid-forming converters provide the reference for frequency and voltage and regulate these quantities. Furthermore, GFCs need to exhibit load-sharing, drooping and black start behaviors similar to SGs. Unlike SGs, GFCs do not induce any physical synchronization and stabilization mechanisms or provide any physical inertial response. These key features of SGs have to be realized via control of GFCs and separate energy storage elements. On the other hand, the fast response time of GFCs enables control at much faster time-scales than that of SG’s primary control. Different control solutions replicating the SGs system-level functionalities (e.g., frequency/voltage drooping and/or inertial behavior) have been previously proposed in [5–8]; we refer to [9] and [10] for a review. Recently, also alternative promising grid-forming strategies rooted in nonlinear control methods have been proposed relying on matching and duality between power converters and synchronous machines [11–13] or the concept of controlling a converter as a nonlinear virtual limit cycle oscillator [14–17]. Furthermore, various measurement and communication based (i.e., IoT/ICT) solutions have been proposed [18],[19].

This paper aims to provide an updated review and a comparison of GFC control strategies. We classify the vast literature into five major GFC strategies, namely: 1) droop control, 2) synchronverter, 3) matching control, 4) virtual oscillator control (VOC) and 5) IoT/ICT based approaches. We provide a critical, un-biased, and fair comparison of the performance and robustness offered by these strategies by means of a system-level simulation case study. Finally, we list the challenges encountered and future problems to be solved for the different GFC strategies in low-inertia power systems.

REVIEW OF CONVERTER OPERATION AND MODELING
In this section, we present a few fundamental definitions regarding converter operational modes and GFC model configuration. With these preliminaries in place, we discuss GFC control strategies in Section 3.

Grid-Forming and Grid-Following Operation
Previous efforts to classify converter operation modes resulted in a handful of notions, but there is no universally accepted classification to date. Before embarking upon grid-forming control design, the definitions from [3] are presented here. Grid-forming mode refers to the DC/AC converter interaction with a non-stiff power grid or its operation in the complete absence of a power grid with SGs. Thus, GFC exhibits black start capability, frequency and voltage regulation, frequency-power droop and load sharing. Additionally, by transforming energy from a primary source, similar to the SGs, a grid-forming unit can dispatch required amount of power to the network loads. Grid-following
mode, on the other hand, highlights the applications in which the converter frequency is imposed by a stiff AC grid or another grid-forming unit. In this case, the network frequency/phase angle is extracted via a phase locked loop (PLL). Therefore, a grid-following unit locks onto the existing grid and injects (a possibly pre-defined amount of) active/reactive power in order to provide different services, e.g., primary control reserve, self-consumption, or voltage control.

**Two-Level Voltage Source Converter Model**

The two-level voltage source converter model in Figure 1 serves as a common implementation and comparison framework for various grid-forming control approaches. As shown in Figure 1, the converter’s DC energy supply is modelled as a controllable current source $i_d$ in parallel with a resistance $R_f$ (resembling a Norton equivalent circuit) and DC link capacitance $C_{dc}$. The switching stage is represented by a full-bridge three-phase average model including DC/AC side current/voltage source depending on the modulating signal $m_{abc}$. This is cascaded by a three-phase star-connected filter composed of inductance $L_f$ with series resistance $R_f$ connected to the shunt capacitance $C_f$. The filter parameters are assumed to be identical for all the phases. In this setup, DC and AC side losses are modelled by $R_{dc}$ and $R_f$, respectively. Furthermore, the DC link voltage $v_{dc}$ and active power injection at the filter node $p_m$ are measured for the GFC control implementations discussed below.

**EXISTING CONTROL STRATEGIES**

In the sequel, we present a classification of the GFC control strategies into five major categories: 1) droop control, 2) virtual synchronous machine, 3) matching approach, 4) VOC and 5) ICT/IoT based approach. We particularly focus on the closely related first three categories and describe their control structure below. It must be noted that our focus is restricted to converter frequency control, which is the main mechanism that makes a converter grid-forming or grid-following. Thus, we merely control the switching node voltage amplitude to its set-point and disregard other voltage control concepts (such as a voltage droop as a function of active/reactive power) or voltage regulation at the filter node requiring additional inner tracking control loops. Finally, aside from frequency control, we consider the control of active power injection that enables us to look at set-point tracking and load sharing behavior.

**Droop Control**

The baseline solution to GFC control is to mimic the speed droop control of a synchronous machine. Droop control has initially been proposed in [5] as proportional control of active power and frequency, but many modified/improved versions have been reported [8]. Recalling the converter model in Figure 1, the corresponding active power and DC link voltage controllers are depicted in Figure 2 [9]. The proportional droop gain $m_p$ trades off the deviation of the frequency $\omega_f$ from its set-point $\omega_f^*$ with the injected power $p_m$ deviation from its set-point $p_m^*$. Furthermore, the constant AC voltage reference amplitude $v_{dc}^*$ is set such that switching node voltage is nominal when tracking $p_m^*$. Therefore, modulation signal $m_{abc}$ is determined based on the phase angle and the reference AC voltage.

**Virtual Synchronous Machine**

A plethora of control strategies is inspired by virtually emulating the dynamics and control of a SG. The overarching paradigm is to control the converter terminal signals to behave like a SG. The various virtual machine implementations utilize a reduced-order and differential algebraic SG model and heavily rely on the converter AC side current/voltage/power measurement [6],[7],[9], and [10]. Consequently, the SG model encoded in a digital controller imposes an analogy between converter terminal and generator stator voltages. As an example of virtual SGs, the synchronverter control mechanism is shown in Figure 3 [6]. The AC voltage is set to the nominal value by an appropriate choice of a virtual excitation flux $\psi_f$ (assumed to be constant). The generator mechanical swing equation is emulated with
the inertia constant $J$ and the damping gain $D_p$. Note that the relation of frequency $\omega$ and active power $p_m$ is the same as for droop control if $D_p$ is chosen inversely proportional to the droop gain $m_p$ in Figure 2, except that the synchronverter admits one more integrator accounting for the synthetic inertia. The implicit assumption for the synchronverter is similar to droop control: the DC voltage $v_{dc}$ is controlled in a stiff fashion and on much faster time scales. Finally, similar to droop control the synchronverter can be augmented with further inner tracking controllers and outer regulation loops.

We briefly justify our choice of the synchronverter mechanism [6] over other emulation strategies. It has been observed that the emulation of a SG brings with it a few inherent challenges: see e.g., [2], [9], [10]. First, the post-fault response of a SG leads to large over-currents, which are unacceptable and undesired for a power converter. Second, the emulation of a detailed SG model is based on numerically integrating higher order nonlinear dynamics fed by (often filtered, averaged, and PLL-based) AC-side measurements which leads to a significant time delay in the grid-forming control loop. The synchronverter in Figure 3 is the least estimation concept (where all emulated dynamics are algebraic aside from the mechanical ones) for which the aforementioned disadvantageous effects are the least pronounced. Finally, we note the tuning recommendation $J < D_p$ from [6], which (in the limit of vanishing virtual inertia over damping ratio $J/D_p = 0$) effectively reduces the synchronverter control in Figure 3 to the droop control in Figure 2.

Matching Control

Based on the structural similarities between the SG and two-level power converter models different matching approaches are proposed in [11–13]. The dualities between the two models reveal a link between the converter DC link voltage and SG rotor angular frequency (similarly between the electro-static and kinetic energies stored in DC link and rotor respectively). We adopt the matching control from [11] illustrated in Figure 4. The core GFC control strategy relies on a measurement of the DC voltage $v_{dc}$ only, which up to a constant factor $\eta$ then induces the grid-frequency $\omega$. Motivated by the analogy between generator torque and converter DC current, the primary DC energy source, the current source $i_{dc}$ regulates the frequency by controlling $v_{dc}$. Therefore, compared to previously mentioned methods DC side proportional control has a different interpretation. Furthermore, by changing $i_{dc}$, active power set-point tracking is achieved (similar to changing turbine mechanical torque). In this case, it is necessary to compensate the power losses in the DC and AC side of the converter. Lastly, AC side constant voltage amplitude is set in the same way as for the other control strategies.

At this point, we remark that matching control does not require any measurement of AC-side quantities: the modulation signal $m_{ac}$ directly results from the DC voltage measurements. This appealing feature removes time delays encountered by processing AC measurements, and it unmasks the interactions between the converter AC side and the DC side (whereas the previous control strategies all implicitly require a
setting frequency deviation $\Delta f$ droop control gain, synchronverter damping constant and matching DC side proportional gain are selected as

$$m_p = \frac{2\pi \Delta f}{S_b}, \quad D_p = \frac{1}{\omega m_p}, \quad k_m = \frac{\eta}{\nu_m m_p},$$

where $S_b$ is the system base power and $\eta = \omega / v_{dc}$. The controllers parameters are presented in Table 1. Most importantly, as all the GFCs for each method are tuned identically, they all show identical proportional load sharing behavior. For instance, in droop control strategy if $m_p$ is identical for all the GFCs, then

$$P_{m1} - P_{d1} = P_{m2} - P_{d2} = P_{m3} - P_{d3} = 1.$$

The simulation time in each case is 3 seconds including the following three scenarios: 1) For $t = 0$ we consider a black start to pre-defined set-points (1.2, 1 and 0.8 p.u. for GFC 1, 2 and 3, respectively) in a PLL free fashion (with all phase angles initialized at zero); 2) At $t = 1$ the load at bus 9 undergoes a step change from 1 to 1.5 p.u. (increasing the total network load from 3 to 3.5 p.u.) resulting in equal steady-state frequency deviation and load sharing for all three methods. 3) Finally, at $t = 2$, we consider a loss of generation at bus 1. Hence, GFCs 2 and 3 take over the excess load while preserving load sharing and leading to higher frequency deviation. The frequency and active power time series are illustrated in Figure 6.

**Table 1.** Simulation case study parameters.

<table>
<thead>
<tr>
<th>Method</th>
<th>Converter model</th>
<th>Droop control</th>
<th>Synchronverter</th>
<th>Matching</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_b$</td>
<td>100 MW</td>
<td>$0.3 m_p$</td>
<td>$168.87 \times 10^3 J$</td>
<td>0.0156</td>
</tr>
<tr>
<td>$V_b$</td>
<td>345 kV</td>
<td>$1.885 \times 10^{-6} \omega f$</td>
<td>$5 \times 10^3 \omega^3$</td>
<td>$281.69 \times 10^3 \eta$</td>
</tr>
<tr>
<td>$f_s$</td>
<td>50 Hz</td>
<td>$2\pi \times 5$</td>
<td>$2\pi \times 5$</td>
<td>$3.035 \times 10^{-4}$</td>
</tr>
<tr>
<td>$R_{dc}$</td>
<td>0.1 $\Omega$</td>
<td>$C_{dc}$</td>
<td>$v_{dc}$</td>
<td>1035 kV</td>
</tr>
<tr>
<td>$C_f$</td>
<td>0.001 $\Phi$</td>
<td>$L_f$</td>
<td>$C_f$</td>
<td>$10 \mu F$</td>
</tr>
<tr>
<td>$v_n$</td>
<td>$281.69 \times 10^3 \omega^3$</td>
<td>$897.5 \omega^3$</td>
<td>$\eta$</td>
<td>$0.0156$</td>
</tr>
</tbody>
</table>

Notice that droop control results in undesired oscillations due to adverse interactions with the line dynamics. This transient oscillatory behavior can be improved by including appropriate filters for the measured power $P_m$. The synchronverter displays oscillatory behavior and overshoots due to the second-order (virtual) inertial dynamics. These effects are especially pronounced when

**Figure 6.** GFCs 1-3 active power (top) and frequency (bottom) plots. Droop control (D), Synchronverter (S), and Matching (M).
filtering the power measurements and for high $\Delta f$ values. Note that the matching approach achieves a much smoother, albeit slower, transient behavior than the other methods. Its comparatively slow dynamics are related to the fact that the AC and DC regulation are inherently coupled, see Figure 4, and the AC variables are controlled via actuation on the DC side. On the contrary, the droop and synchronverter assume a stringent time-scale separation between AC and DC dynamics and become unstable otherwise. Filtering of active power has no impact on matching control. Finally, we remark that for low $\Delta f$ values (and thus lower $m_p$ and higher $D_p$ and $\epsilon_{dc}$) the convergence speed of all three methods becomes comparable.

**FURTHER CHALLENGES**

As a closing argument on GFC control strategies, we list the critical challenges encountered and problems to be resolved for large-scale GFC application in future low-inertia grids. The main device-level challenges are: 1) counteracting the imperfect measurement (e.g., delay and noise), 2) choice and control of an adequate primary energy source and GFC compatibility with realistic DC energy sources (batteries, photovoltaics and wind generators), and 3) limiting the converter inrush current. Additionally, the system level key issues are: 1) stability/synchronization of interconnected systems of GFCs, 2) backward compatibility with SGs, 3) GFC response to transmission system topology change, and 3) optimal GFC sizing/allocation/planning. These challenges must be thoroughly investigated for GFCs in order to fully replace SGs in low-inertia systems. Moreover, further inner and outer control loops (e.g., for voltage and reactive power) must be integrated to the previously mentioned control structures – thus facilitating their comparison to VOC and ICT/IoT based strategies. Lastly, the case study simulations should be done in higher fidelity environment such as controller/power hardware in the loop.

**SUMMARY AND CONCLUSIONS**

In this paper, we presented an updated review on GFC control strategies followed by a classification of existing methods into five major categories. Consequently, we examined the black start, set-point tracking, and load sharing performance of droop control, synchronverter and matching approach in a system-level simulation case study using IEEE 9-bus test system. Furthermore, a few conclusions regarding controllers tuning, their frequency time-scale and filtering impact have been drawn. Last but not least, we summarized the key challenges to be further investigated prior to large-scale GFC integration into low-inertia grids infrastructure.

**REFERENCES**


