Exploitation of Synchronverter Control to Improve the Integration of Renewable Sources to the Grid

The grid integration of large-capacity renewable energy sources opens operational issues into power system stability and control. This paper investigates the impact of the synchronverter control strategy on renewable sources integration. The study proposes an improved control scheme for the integration of variable-speed wind generators and solar photovoltaic systems into the power grid. The control strategy based on the synchronverter technology, applied to the grid-side converter for the connection of wind and photovoltaic systems. The parameters of the converter regulator are tuned based on a specific residues method. The proposed control performances were evaluated in comparison with the conventional voltage oriented control (VOC) in terms of accordance with Grid Code Requirements (GCR). Dynamic performances tested include low voltage ride through, frequency ride through, and fault critical clearing time. The results show that the synchronverter control ensures better performances, complies better with the GCR of power system operator and enhances additional reactive power supply.

Keywords: Photovoltaic systems; Wind Energy generation; Synchronverter; GCR; Voltage oriented control

1. Introduction

Modern power grids are characterized by large scale penetration of renewable energies and less reliance on fossil fuels [1]-[2]. The most exploited renewable energies are hydroelectric, photovoltaic (PV), and wind. The share of renewable in global electricity production is steadily increasing. The world’s renewable energy production share will be increased to 20% by the year 2020 [3]. However, 16% is due to hydroelectric energy production; hence, wind and PV (the most promising renewable sources) energy production is still very modest [3]. However, these two most promising renewable energies have different requirements. Compared to hydraulic power, wind and PV energies are Variable Renewable Energy (VRE) sources, and their integration into power grids open operational issues in power grid [4]-[5]. Indeed, VRE has direct implication on system operation and stability. Their integration is achieved using power electronic converters and hence, the control design of power converter-fed units connected to the grid has become a major issue in control and power research communities. These generator concepts differ significantly from conventional sources in terms of performances during grid faults, emission of harmonic currents or inherent response to frequency changes.

The current trend is that renewable sources must comply with the system operators ancillary services, such as voltage and frequency controls. Grid codes provide the rules for the power system and energy market operation, ensuring operational stability and security of power supply [5]. The function of a grid connection code covering VRE is to
provide technical requirements for wind and PV plants when connecting to a utility electricity grid.

In response to these technical requirements, power electronic devices and control systems have undergone a fast evolution. Voltage source converters (VSC) have been developed offering new capabilities for dynamic voltage support, independent controls of active/reactive power and easier integration of wind farms. Several control schemes are used for the control of the power converters for renewable sources integration [6]-[7]. These controls must assure maximum power extraction from the renewable, and be able to withstand grid disturbances such as voltage sags, frequency disturbances and short-circuits. The main control methods are the Oriented Control (VOC), Virtual Flux Oriented Control (VFOC) and Direct Power Control (DPC). In state of the art systems, cascaded voltage oriented control is often implemented in order to control the grid-side converter of renewable energy sources. Nevertheless, traditional controllers lack of inertia highly dependent on the connected AC network conditions and when applied to the increasing number of renewable connected to the grid, they directly affect the stability of the power network [8].

To this end, virtual synchronous generators (VSGs) have been proposed in the literature, the idea of operating inverters in a grid-friendly manner in order to mimic the complete dynamic behaviour of synchronous generators was developed as the concept of synchronverters [9], [10]. Its controls emulate the mathematical model of a synchronous generator along with it active and reactive power controls. The controller involves frequency, and voltage control loops instead of conventional current and voltage loops. The synchronverter concept offers some advantages over the conventional converter control strategies as it introduces emulated inertia and controlled frequency dynamics, whereas in the conventional VSC, frequency dynamics cannot be controlled directly. The synchronverter represents a promising technology in various applications, such as HVDC transmission [11], [12], [13] and STATCOM [14]. In [11]-[12], the authors developed an analytical method which takes into account, at the tuning stage, the neighboring AC zone of the HVDC link. As a consequence, dynamic performances of DC interconnected systems were enhanced in addition to power transfer capacity.

In this paper, an original control strategy based on the synchronverter technology is proposed for grid-side converters in PV and variable-speed wind power applications. We therefore propose a more general structure of VSC power converter of renewable generator integration, as schematized in Fig. 1. The effectiveness of the tuning method mentioned above is used for the case of power converter in wind/PV integration.

The proposed controller tests dynamic performances included low voltage ride through (LVRT), frequency ride through (FRT), and fault critical clearing time (CCT). The study shows that the synchronverter control yields better performances compared to the conventional VOC, and complies with the Grid Code Requirements of power system operators, such as [15].

The rest of the paper is organized as follows: in Section 2, the synchronverter control strategy is recalled. An analytic method to tune the parameters of VSC converter for renewable sources integration is given in Section 3, while validation tests are presented in Sections 4 and 5.
2. Control schemes for grid-side converter

Various control methods are used to control power converters based VSC in renewable energy applications. In this Section, we recall the synchronverter control and the standard voltage oriented control in order to control the grid-side converter of renewable energy sources.

2.1 Synchronverter Control

Figure 2 depicts the power circuit of a three-phase inverter with the block diagram of the synchronverter control [7]. The latter has been derived based on the mathematical model of the three-phase round rotor synchronous machine [16]. The equations are summarized as

\[
\dot{\theta} = \frac{1}{J} (T_m - T_e - D_p \dot{\theta}),
\]

\[
T_e = M < i_{abc}, \tilde{\sin} \theta >,
\]

\[
e_{abc} = Ms \theta \tilde{\sin} \theta,
\]

\[
P = Ms \theta < i_{abc}, \tilde{\sin} \theta >,
\]

\[
Q = -Ms \theta < i_{abc}, \tilde{\cos} \theta>.
\]

where \(T_m\) and \(T_e\) model the mechanical and electrical torques, respectively, \(e\) is the three-phase inverter’s generated voltage and \(i\) is its current (see Fig. 2), \(P\) and \(Q\) are the real and reactive powers at the \(e\) terminals, \(\theta\) is the voltage angle, \(J\) is the moment of inertia, and \(M\) models the field excitation. The variable \(\dot{\theta}\) is the angular speed of the machine and also the frequency of the control signal \(e_{abc}\) sent to the pulse width modulation (PWM) generator.

The equations of \(\tilde{\sin} \theta\) and \(\tilde{\cos} \theta\) are defined as

\[
\sin \theta = \begin{bmatrix} \sin \theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix}^T,
\]

\[
\cos \theta = \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \end{bmatrix}^T.
\]

The operator \(<,.,.>\) denotes the conventional inner product in \(\mathbb{R}^3\).

In the synchronverter control of Fig. 2, the torque \(T_{m,ref}\) is generated by the PI controller that regulates the DC-link voltage. The control strategy involves two parts: one channel to regulate the real power and another to regulate the reactive power. The real power channel, shown in Fig. 2, has three cascaded control loops. The inner loop is the frequency regulation loop (with the feedback gain \(D_p\)), the middle loop is a torque loop (with the feedback coming from the current \(i\) via the electromagnetic torque \(T_e\)) and the outer loop is the DC-link voltage loop (with the feedback coming from the DC voltage \(V_{dc}\)).
The real and the reactive power of converters in Fig. 2 are based on a frequency and a voltage droop control loop, respectively. In steady-state, assuming the asymptotic stability of the system, the following relationships will hold

$$\omega = \omega + \frac{1}{D_p}(T_{m_{inf}} - T_e)$$  \hspace{1cm} (6)

$$V = V_n + \frac{1}{D_q}(Q_{set} - Q)$$  \hspace{1cm} (7)

The reactive power set-point is linked to the derivative of the voltage magnitude as shown in Fig. 2 by the lower portion of the block diagram. Moreover, a droop term \(D_q(V_n - V)\) is included in it where \(V\) and \(V_n\) are the magnitudes of the measured output voltage and its nominal value, respectively. Equation (6) is the static frequency droop control loop of the synchronverter. Equation (7) describes a drooping characteristic of the conventional output voltage magnitude versus the reactive power while (7) relates the internal inverter frequency to the real power through a droop characteristic.

2.2 Voltage Oriented Control

Usually, the main trends in control techniques for renewable generators are based on the well-established voltage oriented control (VOC) scheme. The latter uses an outer DC voltage control loop and an inner current control loop to achieve fast dynamic response. Voltage and current synchronization with the network grid are assured by a phase locked loop (PLL) [6]-[7]. The PWM pulses are generated to the converters through a PI cascaded control structure for the current converter output. The performances of the power flow depend largely on the quality of the applied current control strategy. The VOC strategy guarantees fast transient response and high static performance via internal current control loops.
3. Control model of renewable sources

The inverter parameters in Fig. 2 are tuned with a specific residues method. The latter developed in [10-11] is used to control grid-side converter of renewable sources based synchronverter emulation. In order to guarantee better dynamic performance compared to the VOC, oscillatory modes must be taken into account at the design level. Consequently, synchronverter control is exploited to improve renewable sources integration into grid. More precisely, synchronverter control yields better dynamic performances and complies better with the grid code requirements: LVRT, LFT and CCT.

A feedback control presented in Fig. 3 is applied on the system in Fig. 2 in order to meet the mentioned control objectives. In Fig. 3, $H(s)$ is the linear approximation of the system in Fig. 2. The following diagonal matrix includes all control parameters:

$$K(s,q) = \text{diag}(D_p, D_q, K_{p,vdc}, K_{i,vdc})$$

where $D_p$ and $D_q$ are respectively, the frequency and voltage droop coefficients of the synchronverter. $K_{p,vdc}, K_{i,vdc}$ are the DC voltage PI control parameters. These parameters are tuned via a pole placement approach given in Section 3.1.

The inputs control vector $u$ and the output vector $y$ are:

$$u = [T_m, Q, T_{m-ref, kp}, T_{m-ref, ki}]^T, \quad y = [\omega_s - s\theta, V_{ref} - V, V_{dc-ref} - V_{dc}, \frac{V_{dc-ref} - V_{dc}}{s}]^T.$$ 

3.1 Parameters and residues of the Regulators

The tuning of the control parameters is based on the poles sensitivity to the regulators parameters. Each closed-loop of the feedback system in Fig. 3 corresponds to the $i^{th}$ input $u_i$ and output $y_i$. More specifically, $H_{ii}(s)$ and $K_{ii}(s)$ are the $(i,i)$ transfer functions of $H(s)$, respectively. The sensitivity of a pole $\lambda$ of the closed-loop in Fig. 3 with respect to a parameter $q$ of the regulator $K_{ii}$ is given by [17]:

$$\frac{\partial \lambda}{\partial q} = r_{ii} \frac{\partial K_{ii}(s,q)}{\partial q}$$

where $r_{ii}$ is the residue of $H_{ii}(s)$ at pole $\lambda$.

For our case the parameters $K_{ii}$ given in (8). Hence, $\left.\frac{\partial K_{ii}(s,q)}{\partial q}\right|_{s=\lambda} = 1$.

3.2 Coordinated Tuning of the synchronverter parameters

From [10], [11], the contribution of each control gain in the shift of the pole is:

$$\lambda_i = \lambda_i^0 + \sum_{j \in \Lambda} r_{ij} K_j,$$

where $\lambda_i^0$ is the open-loop mode and $r_{ij}$ is the residue of $H_j(s)$ in $\lambda_i$. The pole placement is the solution of the following optimization problem:

$$\{K_j^*, j = 1...4\} = \arg \min_{k_j} \sum_j \|\lambda_j^* - \lambda_j\|,$$

where $\lambda_j$ is given by (10).
4. Photovoltaic System Integration

4.1 System Modeling

The structure of the Photovoltaic system under study system under with its entire components is as depicted in Fig. 4. Each device in the system is presented below. It consists of a photovoltaic farm of 100 kW power. The panels output into the network through a chopper "Boost" DC-DC, and a three-phase voltage PWM inverter of three levels. A photovoltaic cell is represented by a simplified model of a current source in parallel with a diode. Fig. 5 shows the synchronous boost converter for MPPT tracking of the PV module. Single-stage topology with incremental conductance (INC)-based MPPT for PV arrays has been used. INC-based MPPT algorithm was used to track the maximum power from the designed PV module. Finally, the inverter converts the DC power after the chopper Boost into AC power transited to the distribution network.

4.2 PV System Simulations

The system specifics and controller constants have been listed in the Appendix, whereas the system configuration is shown in Fig. 4. The PV source considered in this paper for the simulation study has a rating of 100 kW at a maximum operating DC voltage of 500 V and current of 200 A. The switching frequency of the system was chosen as 2000 Hz. The grid was assumed to be strong with a short-circuit capacity of 500 MVA.

The simulations performed are intended to test dynamic performances of the three-phase grid-connected PV-based synchronverter. Simulations tests use Matlab/Simulink toolbox.

A. MPPT Evaluation

The power delivered by the PV system depends on the irradiance, temperature, and the current drawn from the cells. Maximum Power Point Tracking (MPPT) is used to extract the maximum power. An algorithm is implemented based on the INC technique. With varying incident irradiation (Fig.5.a), the PV system should be capable of supplying the required real power as per command from the grid.

Column 3 of Table 1 presents the desired mode location $\lambda^*$ for each dynamic of interest. The parameters of the diagonal matrix $K(s,q)$ are tuned via the pole placement explained in Section 3. These parameters K are obtained using (11) (see appendix). Dynamics of the neighbor zone are taken into account at the synthesis stage via the oscillatory modes in Table I. The gains of the controllers are computed to damp these modes and thus to have better dynamic performances with the proposed controller. Hence, transient oscillations with the PV system based synchronverter control are more damped.

The responses of the PV system-based synchronverter control for the test power system with these tuned parameters are given in Fig. 5. The latter shows the response of the active power injected into the network following various temperature and irradiation profiles. We may note a good tracking of maximum generated power assuring by the MPPT function and the synchronverter control.
Fig. 4. Grid-connected PV system

Fig. 5 MPPT for variable temperature and irradiation

Table 1: Desired modes

<table>
<thead>
<tr>
<th>Dynamics of interest</th>
<th>$\lambda_i^0$</th>
<th>$\lambda_i^1$</th>
<th>$r_{\lambda_i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage $V_m$</td>
<td>-5.36</td>
<td>-10</td>
<td>-0.18</td>
</tr>
<tr>
<td>Active Power $P_m$</td>
<td>1.69±5.07i</td>
<td>-21±21.42i</td>
<td>-0.08±0.06i</td>
</tr>
<tr>
<td></td>
<td>-2.78±18.89</td>
<td>-21±21.42i</td>
<td>-0.02±0.07i</td>
</tr>
<tr>
<td>Reactive Power $Q_m$</td>
<td>-5.36</td>
<td>-10</td>
<td>-0.18</td>
</tr>
</tbody>
</table>
B. Low Voltage Ride Through (LVRT)

The performances of the PV system-based synchronverter are tested for reactive power sharing, and LVRT capabilities. This case study showcases the ability of the proposed control to respond for the voltage deviations at the PCC grid voltage. To this end, the reactive power demand is increased of 100 kVAR at \( t = 2 \) s. Fig.6a depicts that the grid voltage was stepped down from its nominal value to 94\% of the nominal. The voltage variation has negligible impact on the real power as in Fig.6b, whereas the voltage droop-based reactive power loop supplies the volt-ampere reactive (VAR) power in accord to droop ‘\( D_q \)’ as shown in Fig. 6c. With the Q–V droop control loop, the reactive power output of the inverter varies with variation in voltage thereby providing responsive operation in support of the grid voltage.

From Fig. 6 and 7, it is noted that the grid voltage decrease with the synchronverter control is less than the voltage decrease for the VOC controlled power factor (CPF).

Dynamic performances are further tested for short-circuit of increased duration (50-500 ms) applied at the point of common coupling. The critical clearing time (CCT) is used as a transient stability criterion. After a series of simulations, the CCTs are determined for the synchronverter and the VOC controls, respectively 500 ms and 50 ms.

Fig. 8 compares the transient responses of the powers for the two control schemes, following a 500 ms short-circuit. This CCT value complies with power system operator requirements for solar photovoltaic power integration in the Tunisian distribution network (STEG, required CCT=250 ms) [15].

C. Frequency Ride Through (FRT)

In order to observe the PV system based synchronverter response to frequency disturbances, the infinite bus is replaced by a controllable generator, which frequency is varied following a ramp down of 2 Hz/sec. The PV system should deliver its maximum power for frequencies above 47 Hz [15]. The active power response for both control strategies is shown in Figs. 9-10. Active power support lasted up to \( f=44 \) Hz and \( f=48 \) Hz, respectively under synchronverter control and VOC. The synchronverter control scheme complied with the operator requirements.

5. Wind power Integration

5.1 System modeling

Wind turbine converts the wind power to a mechanical power, which in turn, runs the generator to generate electrical power. The mechanical power generated by wind turbine can be expressed as:

\[
P = \frac{\rho}{2} A_r V_w^3 C_p(\lambda, \beta)
\]  

(12)

where \( \rho \) is the air density, \( A_r \) is the swept area, \( \beta \) is the pitch angle, \( C_p(\lambda, \beta) \) is the wind turbine power coefficient, \( V_w \) is the wind speed (m/s). The term \( \beta \) is the blade pitch angle, and \( \lambda \) is the tip speed ratio. The latter is the ratio of the blade-tip linear speed to the wind speed which is defined by \( \lambda = \frac{R \omega}{V_w} \) with \( R \) the rotor radius and \( \omega \) the rotor speed [18].
Fig. 6: Performances of PV systems based synchronverter for grid voltage variation

Fig. 7: Responses of PV systems based VOC for grid voltage variation
5.2 System Control

The wind energy conversion system is depicted in Fig.11. It features a variable speed wind-turbine-driven Permanent Magnet Synchronous Generator (PMSG) a diode bridge rectifier, a boost DC/DC converter, a battery bank, and a PWM DC/AC inverter. This configuration corresponds to a direct drive wind turbine; the grid-converter side control is based on the synchronverter strategy.

The decoupling between the generator and the grid through power converters presents a very important solution to comply with the G.C.R [15]. The whole control strategy of the wind system is shown in Figure 11. Normally, the maximum power extraction MPPT from the wind is achieved by controlling the rotor-side converter, and the DC link voltage is controlled by the grid-side converter.
5.3 Wind system Performances

In this section, the wind system performances of Fig. 11 are analyzed and evaluated in term of accordance with the STEG GCR. Different case studies were performed. The system response was analyzed taking into consideration the normal operation mode, and the degraded operation mode.

A. Behavior of MPPT

Figs. 12 and 13 depict the wind generator rotor speed, generated power and the pitch angle $\beta$, for a variable wind profile with two control strategies. We may note the maximum power point tracking by the MPPT controller: for wind speeds higher than nominal (11 m/s), the active power is maintained at 1 p.u, due to the pitch angle control. For wind speeds lower than nominal, the blade's pitch angle is maintained at 0° to maximize of the generator rotor speed.

B. Low Voltage Ride Through (LVRT)

The same LVRT disturbances as for the PV system are tested. Fig. 14 shows the responses of the voltage, active power and reactive power injected to the grid following a step reactive load increase of $\Delta Q=10\text{MVAR}$ at $t= 20 \text{ sec}$. The voltage drop is about $\Delta V = 770 \text{ V}$ under the VOC and only under the synchronverter control. This is explained by the presence of a voltage control loop imbedded in the synchronverter control scheme.

Dynamic performances are further tested for short-circuit applied at the PCC. After a series of simulations, the CCT is estimated at $CCT = 700 \text{ ms}$ (Fig. 15). This CCT value complies with power system operator requirements for wind power integration in the Tunisian distribution network (STEG, required CCT=250 ms) [15].

C. Frequency Ride Through (FRT)

This capability implies active power sharing of wind generators following frequency deviations. Figs 16 and 17 depict the response of active power following a frequency ramp (-0.5 Hz/s), respectively with the synchronverter and the VOC controls. Active power support lasted up to $f=42.5 \text{ Hz}$ and $f=47 \text{ Hz}$, respectively under synchronverter control and VOC. The synchronverter control scheme exhibits better active power support and complies system operator requirements, with better operating margins (see appendix).
Fig. 12 MPPT for variable wind speeds based on vector control

Fig. 13 MPPT for variable wind speeds based on synchronverter control

Fig. 14 System responses following a step reactive load increase
Fig. 15 Transient responses for short circuit of 700 ms

Fig. 16 System responses following a frequency ramp of (-0.5 Hz/s) under synchronverter control

Fig. 17 System responses following a frequency ramp of (-0.5 Hz/s) under VOC
6. Conclusion

This paper proposes the exploitation of synchronverter control for the integration of variable-speed wind generators and solar photovoltaic systems into the power grid. The synchronverter control strategy is applied to the control the grid-side converter. It involves angle, frequency, and power control loops instead of conventional current and voltage loops. The dynamic performances tested are low voltage ride through, frequency ride through, reactive loading, and fault critical clearing time. The results prove that the synchronverter control yields better performances compared to the conventional voltage oriented control and complies better with the Grid Code Requirements. The results aim at scaling up variable renewable integration, with compliance to power system operators technical requirements.

The method proposed in this paper presents an alternative strategy of controlling PV/wind power systems with improved performance under both normal and grid fault conditions. A further investigation of the synchronverter operation with the dynamics of the complete wind power system will definitely strengthen and support the proposed approach. This provides an interesting topic for future research.

7. References


8. Appendices

Tuned Synchronverter parameters for the PV system (Fig. 4)

K = [55; 28.5; 65.64; 58.069].

<table>
<thead>
<tr>
<th>FREQUENCY RANGE</th>
<th>AVAILABLE POWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.0 – 49.5</td>
<td>90% - 100%</td>
</tr>
<tr>
<td>49.5 – 50</td>
<td>50% - 100%</td>
</tr>
<tr>
<td>50 – 50.2</td>
<td>50% - 100%</td>
</tr>
<tr>
<td>50.2 – 51.5</td>
<td>15% - 100%</td>
</tr>
<tr>
<td>51 – 52</td>
<td>0%</td>
</tr>
</tbody>
</table>

Fig.18 STEG Grid Code: Wind farm Low Voltage Ride Through – LVRT
Fig.19 STEG Grid Code (P>10MW) Wind farm Frequency ride through