Control Structures Implementation to Allow High Penetration of a VSC within an Isolated Power System

D Curto, S Favuzza, R Musca, M Navarro Navia, and G Zizzo

Department of Engineering, Università degli Studi di Palermo, Palermo, Italy.

Abstract: Recently, the increasing occurrence of power instability caused by alternative energy sources has attracted the possibility of implementing Energy Storage System (ESS), capable of supplying the energy necessary to improve the energy quality within the grid. Therefore, the attention of researchers has been drawn on the behaviour that has the connection of the ESS, based on internal controllers such as Virtual Synchronous Machine (VSM) and a Classical Control Cascade (CCC), for different ESS power ranges. In this context, this paper deals with the implementation of an ESS represented by a Voltage Source Converter (VSC) employing control techniques of VSM and CCC simulated in PScad environment in three cases: in the first case, the power system in the steady-state is seen during the description of the controls; in the second case, the power system in the presence of a fault; in the third case, the power system with a load at the PCC. Finally, a fusion CCC-VSM using a grid impedance estimator is implemented with different current reference controls considering Short Circuit Ratio (SCR) values that represent the weak and robust grid.

1. INTRODUCTION

From the last decade, Renewable Energy Sources (RES) are increasing the rated power capacity concerning the Conventional Power Plants (CPP), generating a deficit in the energy quality and grid stability [1]. Due to the intermittent and aleatory RES production, the electrical grid can be exposed to sudden changes of active and reactive power flowing [2][3][4]. To limit this issue, the adoption of Energy Storage System (ESS) was proposed as active power support for the grid. In [5], the possibility to incorporate the ESS through a Voltage Source Converter (VSC) was investigated, considering flexible AC transmission systems devices such as a Static Synchronous Compensator (Statcom) [6]. Some authors reported valuable studies on Statcom connected to energy storage units [7],[8]. In the following, the integration of a Statcom and an ESS is expressed as E-Statcom. As examples, the E-Statcom topology is investigated to support energy production from wind turbines [9] and photovoltaic panels [10]. Traditionally, VSC is used for applications that involve sinusoidal voltage with a variable output. In [11], a VSC generates a set of alternating voltages that can be controlled in amplitude and phase as it happens for the synchronous machines but, unlike them, E-Statcom has no inertia, since it has a virtually instantaneous response and it does not alter the system impedance significantly.

The control topology plays an essential role in the robustness of the converter formation. A Classical Control Cascade (CCC) is an internal loop that feedbacks among themselves. In [13], a Virtual Synchronous Machine (VSM) is proposed and fused to a classical CCC. Control algorithms for grid-connected converters in a simulated grid environment are validated considering a load connected to the Point of Common Coupling (PCC). Besides, the grid information is implemented by the algorithms; a grid impedance used to give stability and quality for the energy produced at the VSC output. To make the control model real, delays are introduced through delay compensation techniques to increase the quality power and reduce the output current oscillations. The relation between the grid and the VSC is expressed by the Short Circuit Ratio (SCR), that is the ratio between the grid short...
circuit power and the converter rated power. The SCR, the grid characteristics and the voltage value are part of the facility's control requirements [14]. In this paper, the proposed controls are tested on an ideal grid representing an isolated power system of a small island. The simulations are carried out in the presence of a fault and a load at PCC for different values of SCR, to study both cases of weak and strong grids. The control is examined in the case of voltage regulation and power quality, as a function of the active power regulation, is also assessed by considering the effect of the ESS; simulations are performed in the PScad software. The remaining part of the paper is organised as follows: Section 2 gives the working principle of the power system model; Section 3 reports the control design of CCC, VSM and the fusion CCC-VSM; Section 4 provides the results obtained from the models implemented in PScad and, finally, Section 5 contains the conclusion of this paper.

2. MODEL OF THE POWER SYSTEM

In [15], an E-Statcom regulates the PCC voltage within the specified limit with reactive power support. A simple model is represented in Figure 1 with two VSC: the first is E-S.1, based on VSM, using controls that provide virtual inertia and damping; the second is E-S.2, based on CCC, using feedback current control through coordinate transformation. The controllers have as the main goal to generate an AC-voltage \( V_{vsc} \) through internal control loops. These are connected at the PCC through an RL-filter, composed of a resistance \( R_f \) and an inductance \( L_f \), connected with a grid impedance \( Z_g \), modelled by a resistance \( R_g \) and inductance \( L_g \) (see Figure 1).

![Figure 1. Model of the power system.](image)

The CPP is modelled as an ideal grid with a total rated power of 24.5 MVA, a rated phase to phase voltage of 10 kV, rated frequency of 50 Hz and an E-Statcom, having the characteristics of a VSC. On the other hand, the power delivered by the transmission line is studied for the following reference active power of E-Statcom: 0.2, 0.5, 0.7, 1 p.u. based on E-S.1/E-S.2 internal controls. The relation between the ideal-grid and the VSC is expressed by the Short Circuit Ratio \( SCR = S_{sc}/S_{vsc} \) where, \( S_{vsc} \) is the grid short circuit power and \( S_{sc} \) is the converter rated active power. Therefore, varying the SCR value from 1 to 10 it is possible to analyse the behaviour of \( Z_g \).

| SCR | \( L_g \) [H] | \( R_g \) [Ω] |
|-----|--------------|--------------|
| 1   | 0.0001       | 0.041        |
| 3   | 0.0003       | 0.122        |
| 5   | 0.0005       | 0.204        |
| 7   | 0.0008       | 0.286        |
| 10  | 0.00108      | 0.408        |

3. CONTROL DESIGN

This section provides a brief overview of the controls.

3.a VSM-Structure: This control allows a compatible grid integration of E-Statcom even in a weak, isolated grid since it mimics a Synchronous Generator (SG) [16] [17]. The goal is to create the VSM-
angle phase $\theta_{vsm}$ from Equation (1) allowing the choice of the oscillation damping and the inertia support that will be used by the converter [18] [19].

$$2H_{vsm} \frac{d\omega_{vsm}}{dt} = P_{ref} - P_{vsc} - D\omega_{vsm}$$

(1)

In Equation (1), $P_{ref}$ is the input active power, $P_{vsc}$ is the VSC output active power, $H_{vsm}$ is the virtual mechanical time constant (measured in seconds), $D$ is the virtual mechanical damping, $\omega_{vsm}$ is the VSM angular frequency, $\delta\dot{r}$ is the power angle of VSM and $\omega_0$ is the rated angular frequency.

Simulations are performed for VSC active power references of 20% and 100% (dashed line). The following parameters are considered: constant inertia levels $H$ 0.5 s (red line), 3 s (light blue), 7 s (medium blue), 10 s (raised blue), damping levels (D= 30, 50, 100).

![Figure 2. VSM response for different H and D values at the VSC power step equal to 20% and 100%.](image)

Figure 2 shows that waveform improves with high damping values. Note that the damping is opposed to the inertial response. Therefore, the mean value of inertia is a good compromise.

Below, in Table 2 the analysis of overshoot $Se\%$ and settling time $T_{\alpha\varepsilon}$ is shown. Indeed, Table 2 verifies the similarity of the dynamic response of VSM with an average $D$ between 50 to 100. It is possible to obtain a low power fluctuation. Therefore, the phase of the oscillatory component is estimated 70, thus providing active damping.

| Reference | VSC Active Power |
|-----------|------------------|
|           | 20%  | 50%  | 100% |
| $Se\%$    |       |      |      |
| 30        | 60.50%| 60.50%| 60.50%|
| 50        | 42%  | 42%  | 42%  |
| 100       | 13.90%| 13.90%| 13.90%|
| $T_{\alpha\varepsilon}$ |       |      |      |
| 30        | 2.9  | 1.9  | 1.1  |
| 50        | 2.9  | 1.9  | 1.1  |
| 100       | 2.9  | 1.9  | 1.1  |
According to the preliminary results from simulations, the average value of inertia 7s is adopted. In the following, the paper is mainly focused on optimal strategy from the mix of active power $P_{\text{vsc0}}$ from Equation (2) in steady-state and Equation (1).

$$P_{\text{vsc0}}^0 = \frac{v_{\text{vsc}} v_{\text{g}} \sin \delta_{\text{v0}}}{\nu}$$

(2)

In Equation (2), $v_{\text{vsc}}$ and $v_{\text{g}}$ are respectively the magnitude voltage of the converter and of the grid in p.u., $X_f$ is the converter reactance in p.u. The input and output ratio of the power imbalance transfer function is named $V_{\text{Dvsm}}$. To find this, it is necessary to study the response of the controller after a small variation of the reference power $\Delta P_{\text{ref}}$ around the steady-state condition, based on Equations (1) and (2) can be expressed as:

$$2H_{\text{vsm}} \frac{d\Delta w_{\text{vsm}}}{dt} = \Delta P_{\text{ref}} - \frac{dP_{\text{vsc}}}{d\delta} \Delta \delta - D \Delta w_{\text{vsm}}$$

(3)

$$\frac{d\Delta \delta}{\nu} = \frac{v_{\text{vsc}} v_{\text{g}} \cos \delta_{\text{v}}}{\nu} = K_{\text{p-vsm}}$$

(4)

after some mathematical passages:

$$V_{\text{Dvsm}} = \frac{\Delta P_{\text{vsc}}}{\Delta P_{\text{ref}}} = \frac{w_0 K_{\text{p-vsm}}}{2H_{\text{vsm}}} = \frac{w_0 K_{\text{p-vsm}}}{s^2 + \frac{D}{\nu} S + w_0^2}$$

(5)

where the poles from Equation (5) are: $-2\omega n \pm \omega n \sqrt{2}-1$, where $\omega$ is the damping ratio and $\omega n$ is the natural frequency. Next, the VSM improvement is simulated as a function of a disturbance, considering that a step active power of 0.7 p.u. at the instant $t = 5$ s is activated. Virtual inertia of 7 s, it would be a good compromise among the three possibilities of inertia previously studied. The small-perturbation is a double-phase short circuit applied at the instant $t = 10$ s with values of short-circuit resistance $R_{\text{sc}}=0.5 \Omega$.

![Figure 3. Damping Control Loop.](image)

Figure 3. Damping Control Loop.

E-S.2 improvement from Figure 3 the E-Statcom's active power trend is constant in steady-state, then when is present the step-fault, it increases the E-Statcom's active power to 30 times. So far, E-S.2 is not capable of guarantee overcurrent protection to the VSC.

3.b CCC-Structure: Cascaded loops comprise the integration of an inner loop involving the secondary loop and secondary outer loops involving the primary loop [20-22]. These are a Phase-Locked Loop
(PLL) to track the grid voltage angle [23-25]; a Current Vector Control (CVC) used to protect the converter from overcurrent [26] [27]; a Reference Control (RC) used to obtain the converter input of the CVC and coordinate change control abc/dq and dq/abc [28] [29]. Figure 4 shows the electrical circuit of the power system.

![Electrical Circuit Diagram](image)

**Figure 4.** The classical cascade control scheme.

Where \(v_{vsc}\) is AC-voltage source represents the VSC and \(v_g\) is grid voltage. The dynamic Equation that describes Figure 4 can be given in the stationary reference frame by

\[
\begin{align*}
\dot{\mathbf{v}}_{g} & = \mathbf{if}(dq) \\
\mathbf{R}_f \cdot \mathbf{i}_f & = \omega_0
\end{align*}
\]

where subscript \(dq\) represent the multi-system variability due to two inputs and two outputs. \(v_g\) represents the grid voltage. \(\mathbf{i}f(dq)\) represents the current output of the VSC in \(dq\) coordinates. \(R_f\) and \(L_f\) are the filter resistance and inductance, respectively. \(\omega_0\) represents the natural frequency. Equation 6 in terms of the Laplace domain as

\[
\begin{align*}
\mathbf{G}(s) & = \mathbf{Y}(s) = \mathbf{G}(s)\mathbf{U}(s) \\
\mathbf{G}(s) & = \frac{\mathbf{Y}(s)}{\mathbf{U}(s)}
\end{align*}
\]

where \(\mathbf{ec}\) represents the inputs. Equation (7) is resolved through the following transfer matrix.

Assuming that:

\[
\mathbf{Y}(s) = \mathbf{G}(s)\mathbf{U}(s)
\]

Figure 5 represents the block diagram, where \(\mathbf{G}(s)\) is a transfer function. Respectively, the structure has input reference denominated as \(\mathbf{ec}\) and output denominated as \(\mathbf{yt}\). It is doesn't see but \(\mathbf{ec}\) is formed from references currents in \(dq\) and \(\mathbf{yt}\) is given in terms of voltage in \(dq\). Respectively, \(\mathbf{G}(s)\) is an internal transfer function parallel to the system controller \(\mathbf{G}(s)\).
Figure 5. The current classical control without decoupled.

In other words,

\[ CV_{CPI}(s) = \frac{C(s)}{s} \]  \hspace{1cm} (10)

Applying matrix properties

\[ CV_{CPI}(s)(1 + C(s)\hat{G}(s))(I + C(s)\hat{G}(s))^{-1} = (I + C(s)\hat{G}(s))^{-1}C \]  \hspace{1cm} (11)

where \( I \) is the identity matrix of \( C(s) \); \( G(s) \) and \( \hat{G}(s) \) are internal transfer functions. Figure 6 is necessary to maintain the entire closed-loop stable, which means that all transfer functions must be permanent. On the other hand, to avoid the errors in steady-state should be used as an integral action; therefore, it is necessary that \( \hat{G}(s) = G(s) \). In [30] a calculation method of \( C(s) \) through an H2 optimisation procedure is proposed to achieve the condition of stability according \( Gc(s) = G(s)C(s) \). In this case \( C(s) = G(s) - I \), giving \( G(s) = I \). This result should be readjusted adding a detune for the optimal controller with a low-pass filter represented as \( L(s) = (\alpha_{cvc}s + \alpha_{cvc}) \), where \( \alpha_{cvc} \) represents the CVC bandwidth. The \( L(s) \) is used in all diagonal elements of the matrix. Then, considering matrix properties maybe select \( L(s) = (\alpha_{cvc}s + \alpha_{cvc})I \). \( L(s) \) represents replaced in Equation (9).

\[ CV_{CPI}(s) = \left( I + \frac{\alpha_{cvc}}{s} \right)^{-1} \frac{\alpha_{cvc}}{s} \frac{\alpha_{cvc}}{s} = \frac{\alpha_{cvc}}{s} G(s) \]  \hspace{1cm} (12)

\[ \frac{\alpha_{cvc}}{s} \begin{bmatrix} sL_f + R_f & 0 \\ 0 & sL_f + R_f \end{bmatrix} = \begin{bmatrix} \frac{\alpha_{cvc}L_f}{s} + \frac{\alpha_{cvc}R_f}{s} \\ \alpha_{cvc}R_f \end{bmatrix} \]

Feedback controllers are based on PI controllers [31].

\[ v_{\text{dq}}^{\text{ac}}(t) = v_{\text{pcc}}(d) + w_{\text{o}}l_{\text{f}}^{\text{dq}} + CV_{CPI}\left(t_{\text{dq}}(t) - i_{\text{dq}}^{\text{pcc}}(t)\right) \]

\[ v_{\text{dq}}^{\text{sc}}(t) = v_{\text{dq}}(d) + w_{\text{o}}l_{\text{f}}^{\text{dq}}(t) + \alpha_{cvc} l_{\text{f}}^{\text{dq}}(t) - i_{\text{dq}}^{\text{pcc}}(t) \]

\[ + \alpha_{cvc} R_f \int_{t}^{t} \left(i_{f}^{\text{dq}}(t) - i_{\text{dq}}^{\text{pcc}}(t)\right) \hspace{1cm} (13) \]

In [28], [29], two block diagrams represent the dq input of the CVC: the first one is an active power close loop with the RC tuning in Equation (14), and the latter is a reactive power close loop with the RC tuning in Equation (15).
where $P_{PI}$ is a first-order low-pass filter with a cutoff frequency $k_i-p$; therefore, the bandwidth will be represented as $\propto P=ki-p$. To improve the system dynamically, it is necessary a $\propto P$ value like $10\, acvc$. On the other hand, $Q_{PI}$ is a first-order low-pass filter with a cutoff frequency $ki-Q=\propto QXf$. It is essential to know that $Xf$ is evaluated on the greatness of the grid. Therefore, it is necessary to choose a value within the range of oscillations required by the controls. The fast-responding feedforward power controller assumes that the PLL angle always aligns with $vpcc$.

\begin{align}
    P_{PC} &= \frac{P_{vsc}}{P_s} = \frac{P_{PI}}{P_{PI} + 1/v_{pcc}} \\
    Q_{PC} &= \frac{v_{pcc}}{v_s} = \frac{Q_{PI}}{Q_{PI} + 1/(-X_f)}
\end{align}

Figure 6. CVC response for different active power step.

3c) CCC-VSM: [32] proposes a fusion between VSM and CCC as shown in Figure 7. The block diagram has seven internal controllers, which are: a swing equation denominated as SC, used to create $\theta_{vsm}$; a damping controller denominated as DC, used to improve the response of active power of the VSC as function of the pole transfer function; a current control denominated as CVC, used to protect the converter from overcurrent; a reference control denominated as RC, used to obtain the converter input of the current control and coordinate change controls abc / dq and dq / abc. On the other hand, according to the diagram $P_{pcc}$, $i_{pcc}$, $V_{pcc}$ are firstly measured. The input of controls abc/dq and dq/abc are consequently evaluated. Note that these controllers use $\theta_{vsm}$ for generate $idq$ and $Vdq$, which are the input of CVC. Moreover, $P_{pcc}$ is used as input of SC. Therefore, in the diagram, two types of variables are observed. First, variables denominated as complementary, are: $Xf$, $If$ and $w_0$. Secondly, variables denominated as reference are: $Pref$, $Href$.
4. RESULTS AND DISCUSSIONS

4.a No load at the PCC: A perturbation is applied to the grid, represented by a double-phase short circuit at the instant $t = 15s$, with a short-circuit resistance $R_{sh}=10 \, \Omega$. The following assumptions are made:

- A step reference active power of 0.7 p.u. is active at the instant $t = 5 \, s$. In this context, it would be a good compromise among the three possibilities examined in Section 3.
- $V_{pcc}$ and frequency: a step reference of 1 p.u. is active at the instant $t = 5 \, s$.
- E-S.2 is analysed with the inclusion of a compensation angle $\theta_{comp}$ introduced by PWM using synchronous sampling [32]. The $\theta_{comp}$ is given by $w_0T_d$, where the time delay is $T_d=1.5T_s$ and $T_s$ represents a sampling time.
- E-S.1 is analysed with VSM-CCC with $H_{vsm}=7s$, $\alpha=0.707$, $D=70$. The initial active power reference is zero and at the instant $t = 0.5 \, s$.
- The following delays are introduced: one sample delay between the calculation and the VSC-Voltage sending values; half sample between the calculation and VSC active power transmitting values. Regarding the delay values, they depend on the sampling rate of the converters: the modern converters for E-Statcom work with a sampling rate of about 1 or 5 kHz.
- Both controllers are analysed in the case of a robust grid (SCR = 10) and weak grid (SCR = 5).
- In both controllers, to improve power oscillation, a lead-lag is added to the measure of $P_{pcc}$.
Figure 8. Controllers response.

Figure 8 shows that:

- E-S.2 control has the same VSC’s active power trend for different SCR values.
- E-S.1 control has a variable VSC’s active power trend that depends on grid condition SCR.
- E-S.1 control response speed is slower than E-S.2.
- E-S.2 is the best choice for an ideal-grid.
- The power responses at the time of failure are E-S.2. an overshoot of 0.2 p.u., while E-S.1 an overshoot of 200 p.u.
- PCC-voltage is 12% over the allowed range for the E-S.1 with SCR = 5. For the rest of the simulations, it remains without a problem during the small-disturbance.
- In the case of SCR, E-S.1 is not capable of supporting a weak grid. Therefore, PCC voltage is more significant than 1.15 p.u.

4.b Load at the PCC: in this case, the scheme in Figure 1 is assumed, considering a shunt load connected at the PCC through a grid impedance $Z_{TH}$ composed by a resistance $R_{TH}$ and an inductance $L_{TH}$. Then, Equation (11) in continuous time is

$$v_{dc}^{dq}(t) = v_{dc}^{dq}(t) + w_{rad}i_{dc}^{dq}(t) + C_{PI}(t) - i_{dc}^{dq}(t)$$

(16)

where $idq*$ is the reference current calculated with Equations (14) and (15); $i_{loaddq}$ is the measures of current in dq coordinates; $CPI-th$ is a transfer function of a proportional-integral PI circuit where, $kp-th = \alpha cvc(th)I_{TH}$ is the proportional gain and $kI-th = \alpha cvc(th)R_{TH}$ is the integrator gain, indicating $\alpha cvc(th)$ as the closed-loop bandwidth of the CVC. Based on these criteria, the simulation is carried out in the presence of a perturbation located between the R-L filter and $Z_{th}$. The setting parameters are: a step active power of 0.7 p.u., activated at the instant $t = 5$ s, $H_{vsm}$ is set to 7 s, D to 70 p.u., and $\alpha cvc-th$ to 1215 rad/s, with a perturbation of a double-phase short circuit applied at the instant $t = 15$ s, with $R_{sh}=0.5 \Omega, 0.10 \Omega$ and SCR=10.

Figure 9. Controllers response.

Figure 9 shows the VSC's output active power with a Grid-TH, demonstrating worse performance for both controllers. It would be from at least two perspectives:
first, the increase in the impedance seen by the VSC opposes the passage of currents;
second, an effect on the power imbalance given at the time of the small-perturbation is that the d-axis inductance variation is small. However, cross-saturation may affect the q-axis inductance; as a consequence, the voltage grid had a variation of about 30%. It causes the d-axis current a variation of 3% in the q-axis and of about 5% in the d-axis. Because of this, efforts should be made to improve the dynamic robustness of CVC and RC.

4.c Controller performance utilising a Grid Impedance Estimator GIE: The grid impedance estimator $Z_{GIE}$ consists of an indirect modification of the PCC that adds greater dynamic stiffness near the synchronous frequency. On the other hand, it is shown in Subsection 3b that the VSC’s output power deteriorates due to coupling in the dq coordinates. In search of a solution, Equation (13) is rewritten in terms of an equivalent impedance $Z(t) = (R, L(t))$ where $L(t)$ is the sum of the VSC filter inductance $L_f$ and the estimated grid inductance $L_g$ and $R(t)$ is the sum of the VSC filter resistance $R_f$ and the estimated grid resistance $R_g$ [13]. For the improvement of control with VSM-CCC is proposed to change RC for RC-2 as a function of Equation (6).

$\nu = \nu_{vsc} \pm (GIE - C)$

(17)

where $\nu_{vsc}$ is VSC voltage, $\nu_{pcc}(dq)$ is the measured VSC output voltage in dq-frame, $GIE\_PI$ the transfer function based on Equation (17). A simulation to test the internal control utilising GIE with an RC2 is proposed in Figure 10. The fault is located between $R_{th}$ and $L_{th}$ in this case. The setting parameters are the same as in Figure 9.

The trends in Figure 10 reveal the following aspects:
• The settlement time $T_{a\epsilon}$ of the PCC-voltage trend was evaluated as the time taken by the response to definitively enter a band between $\pm 3\%$ of the steady-state value after the step voltage; in this case, it is set $e\% = 0.3$ of the steady-state value that corresponds to 0.3 kV. These values are not placed in tables because after the fault the voltage is within this range.
• The controller response in the previous Sections shows that the mix between E-S1 and E-S2 with the strategy based on virtual impedance is an exciting proposal because it allows implementing virtual inertia and damping in the isolated micro-grid leading to advantages for grid stability.
• The simulation results show that the virtual impedance has a visible improvement. System stability and current sharing ability are strongly enhanced.
• The controls require almost 15 s to stabilise in the event of extreme failure resistance.
• E-S.2 allows the VSC to produce only 78% of the reference at 26 s means that it is slower than E-S.1.
5. CONCLUSION

The dynamic response of the two controls is good at steady state. In particular, CCC is faster than VSM. Below, Table 3 reports a comparison of the two internal controls within the VSC.

| Description                                      | CCC | VSM |
|--------------------------------------------------|-----|-----|
| Possibility of high-frequency instabilities      | x   | x   |
| Increased RoCof                                   | x   |     |
| Emulates inertia                                 |     | x   |
| Provides synchronising power and voltage reference|     | x   |
| No capability of regulating voltage              |     | x   |
| Control succeeds considering delays, even in case of low SCR |     | x   |
| Possibility of modelling in RMS system studies   |     | x   |
| Contributes to RoCof                             |     | x   |

In case of a short-circuit, when an overcurrent is observable within the grid, it is necessary to implement a new control strategy. Therefore, various CRs, current limiters and some low-pass filters are studied to obtain the best internal collegiate controls. Considering the above results, the second RC option is chosen for the VSM-CCC model with the Load on the PCC, because it allows implementing virtual inertia and damping in the isolated micro-grid leading to advantages for grid stability.

The results of this study will be used for facing the issue of enhancing the penetration of RES-based generators in small islands, a very hot topic, as demonstrated by the recent literature [33]-[36].

REFERENCES

[1] J. Dakovic, M. Krpan, P. Ilak, T. Baskarad, I. Kuzle "Impact of wind capacity share, allocation of inertia and grid configuration on transient RoCoF: The case of the Croatian power system”, *International Journal of Electrical Power and Energy Systems*, Volume 121, October 2020.

[2] E. Bargiacchi, S. Frigo, G.SpaZZafumo "Energetic and energetic analysis of an innovative plant for the production of electricity and substitute natural gas", *Energy Procedia*, Vol. 148, 2018, Pages 312-319.

[3] J. A. Sa'ed, S. Favuzza, M. G. Ippolito, F. Massaro, "An Investigation of Protection Devices Coordination Effects on Distributed Generators Capacity in Radial Distribution Systems". Proceedings of 4th IEEE International Conference on Clean Electrical Power - ICCEP 2013, Alghero (Italy), June 11-13, 2013, pp. 686-692, Print ISBN: 978-1-4673-4430-2, CD ISBN 978-1-4673-4429-6, DOI 10.1109/ICCEP.2013.6586928.

[4] J. A. Sa'ed, S. Favuzza, M. G. Ippolito, F. Massaro "Investigating the Effect of Distributed generators on Traditional Protection in Radial Distribution Systems". Proceedings of IEEE Powertech 2013, Grenoble (France), June 16-20, 2013, pp. 1-6, Print ISBN: 978-1-4673-5667-1, DOI 10.1109/PTC.2013.6652100

[5] Huang Yuhui, Liu Dong, Liao Huaiqing "Site and Size Selection Strategies of Energy Storage System Based on Power Supply and Storage Capability Index", International Conference on Renewable Power Generation (RPG 2015), 2015.

[6] L. S. Xavier, W. C. S. Amorin, A. F. Cupertino, V. F. Mendes, W. C.do Boaventura and H. A. Pereira "Power converters for battery energy storage systems connected to medium voltage systems: a comprehensive review", *BMC Energy*, 2019.

[7] K. Sundararaju, A. Nirmal Kumar "Cascaded Control of a Multilevel STATCOM for
Reactive Power Compensation”, International Journal of Innovative Research & Development, vol 3, July 2014.

[8] A. Bharadwaj and S. Maiti "Modular Multilevel E-STATCOM using Supercapacitor Based Energy Storage System", International Conference on Power, Energy and Environment: Towards Smart Technology (ICEPE), 2018.

[9] A. Bharadwaj and S. Maiti "Analysis and control of modular multilevel converter-based E-STATCOM to integrate large wind farms with the grid", IET The Institution of Engineering and Technology, 2019.

[10] S. M. Muyeen, R. Takahashi, T. Murata, J. Tamura, M. H. Ali "Stabilisation of Wind Farms Connected with Multi-Machine Power System by Using STATCOM/BESS", Electrical Machines and Systems, 8 October 2007.

[11] S. Kharjule "Voltage Source Converter", International Conference on Energy Systems and Applications (ICESA), 2015.

[12] A. Bharadwaj and S. Maiti "Modular Multilevel Converter based Hybrid Energy Storage System", IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2017.

[13] J. A. Sa'Ed, D. Curto, S. Favuzza, R. Musca, M. Navarro Navia, Gaetano Zizzo "A Simulation Analysis of VSM Control for RES plants in a Small Mediterranean Island", 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EECIC / I&CPS Europe), Madrid (Spain), 9-12 June 2020.

[14] R. P. Rodriguez, A. V. Timbus, R. Teodorescu, M. Liserre, F. Blaabjerg, "Flexible Active Power Control of Distributed Power Generation Systems During Grid Faults”, in IEEE Transactions on Industrial Electronics, vol. 54, no. 5, pp. 2583-2592, Oct. 2007.

[15] S. Feng, X. Wu, P. Jiang, L. Xie and J. Lei, "Mitigation of Power System Forced Oscillations: An E-STATCOM Approach", IEEE ACCESS, Vol. 6, 2018.

[16] H. P. Beck, and R. Hesse, "Virtual Synchronous Machine" 2007 9th International Conference on Electrical Power Quality and Utilisation, pp. 1-6, 2007.

[17] O. Mo, S. d Arco and J. A. Soul "Evaluation of Virtual Synchronous Machines with Dynamic or Quasi-Stationary Machine Models“ IEEE transitions on Industrial Electronic, Vol. 64, No. 7, 2016.

[18] M. Torres, L. A. C. Lopez "A Virtual Synchronous Machine to Support Dynamic Frequency Control in a Mini-Grid That Operates in Frequency Droop Mode” Energy and Power Engineering, May 2013.

[19] S. d Arco and J. A. Soul "Equivalence of Virtual Synchronous Machines and Frequency-Droop for Converter-Based MicroGrids" IEEE transitions on Smart Grid, January 2014.

[20] Yi Zhou, Zhixin Miao, Yin Li, Lingling Fan "Design Robust Cascade Control Structure for Voltage Source Converters", North American Power Symposium (NAPS), 2017.

[21] Seborg, D.E., Edgar, T.F., Mellichamp, D.A.: "Process dynamics and control" (Jhon Wiley & Sons, 2010, 3, edn).

[22] Ali Akbar Jamshidifar, Dragan Jocvic "3-Level Cascaded Voltage Source Converters Controller with Dispatcher Droop Feedback for Direct Current Transmission Grids", IET Generation, Transmission & Distribution, 10 October 2014.

[23] Siyu Gao, M Barnes "Phase-Locked Loops for Grid-Tied Inverters: Comparison and Testing”

[24] Jim Ogren "PLL design for Inverter Grid Connection, Simulations for ideal and non-ideal grid conditions", UPPSALA Universitet, 2011.

[25] Rutvik Desai, Smit Patel, Priyanka Patel "PLL Based Method for Control of Grid-Connected Inverter for Unbalanced Grid Frequency”, Chhotubhai Gopalbhai Patel Institute of Technology, 2017.

[26] J. Wei, "Review of Current control strategies in Modular Multilevel Converter”, Master Thesis at Norwegian University of Science and Technology, Department of Electric Power Engineering.

[27] L. Harnefors, L. Zhang and M. Bongiorno "Frequency-domain passivity-based current
controller design”, in IET Power Electronics, vol. 1, no. 4, pp. 455-465, December 2008.

[28] F. Guo, T. Zheng, Z. Wang "Comparative Study of Direct Power Control with Vector Control for Rotor Side Converter of DFIG", 9th IET International Conference on Advances in Power System Control, Operation and Management (APSCOM 2012).

[29] Elena-Daniela, Iona Fagarassan "Voltage - Reactive Power Control in Renewables Power Plants", IEEE, 2016.

[30] H. Kwakernaak "H2-optimization — Theory and applications to robust control design", Annual Reviews in Control, Vol. 26, No.1, 2002, Pages 45-56.

[31] S. d’Arco, J. A. Suul, O. B.Fosso "Automatic tuning of Cascaded Controllers off Power Converters Using Eigenvalue Parametric Sensitives", IEEE transactions on Industry Applications, Vol, 51, N.2, 2015.

[32] Anil Bharadwaj and Suman Maiti "Modular Multilevel Converter based Hybrid Energy Storage System", IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2017.

[33] D. Curto, S. Favuzza, V. Franzitta, R. Musca, M. A. Navarro Navia, G. Zizzo "Evaluation of the optimal renewable electricity mix for Lampedusa island: The adoption of a technical and economical methodology", Journal of Cleaner Production, Vol. 263, 2020, article 121404.

[34] M. Bongiorno, S. Favuzza, M. G. Ippolito, R. Musca, G. Zizzo. "Inertial response of isolated power networks with wind power plants", 2019 IEEE Milan PowerTech, 23-27 June 2019, Milan (Italy), DOI: 10.1109/PTC.2019.8810574.

[35] S. Favuzza, M. G. Ippolito, R. Musca, M. Navarro Navia, E. Riva Sanseverino, G. Zizzo, M. Bongiorno. "An Analysis of the Intertial Response of Small Isolated Power Systems in Presence of Generation from Renewable Energy Sources", 2018 IEEE 4th International Forum on Research and Technology for Society and Industry (RTSI), pp. 1-6, 10-13 September 2018, Palermo (Italy), DOI: 10.1109/RTSI.2018.8548401.

[36] S. Favuzza, M. G. Ippolito, R. Musca, M. Navarro Navia, E. Riva Sanseverino, G. Zizzo, M. Bongiorno. "System Stability of a Small Island's Network with Different Levels of Wind Power Penetration", 2018 IEEE 4th International Forum on Research and Technology for Society and Industry (RTSI), pp. 1-6, 10-13 September 2018, Palermo (Italy), DOI: 10.1109/RTSI.2018.8548355.