Operation of Unified Power Flow Controller as Virtual Synchronous Generator

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ABSTRACT The continuous growth of Renewable Energy (RE) in the grid reduces system inertia and damping, impacting the overall stability of power systems. To alleviate this issue, “virtual” inertia can be provided by power electronics converters. Under this functionality they are controlled to emulate the behavior of rotating machines, operating as Virtual Synchronous Generators (VSGs). However, grid-connected inverters are susceptible to voltage and frequency disturbances which negatively affect their performance. Therefore, this paper introduces a Unified Power Flow Controller (UPFC) with VSG functionality that can compensate for voltage variations at the point of common coupling and provide a constant voltage reference for the connection of remote RE systems. The detailed controlled strategy together with the small-signal analysis are also developed in this work. The UPFC-VSG is compared with an equivalent Static Synchronous Compensator (STATCOM) with centralized energy storage also under VSG control to illustrate the major benefits of the UPFC-VSG. Validation of the analysis and the proposed control method is provided through simulation of a UPFC-VSG and a STATCOM-VSG supporting the grid-connection of a 100-MVA RE system.

INDEX TERMS Unified Power Flow Controller (UPFC), virtual synchronous generator (VSG), inertia emulation, renewable energy, power reference variations, grid disturbances, Static Synchronous Compensator (STATCOM).

NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| Jp     | Virtual inertia coefficient |
| kV     | Voltage regulation coefficient |
| kvp, kvi | PI in excitation voltage generator |
| kω     | Frequency regulation coefficient |
| P      | Output active power |
| Pset   | Active power reference value |
| PSTATCOM | Active power of STATCOM |
| PST_PCC1 | Active power at PCC in STATCOM-VSG |
| PUPFC_PCC1 | Active power at PCC in UPFC-VSG |
| PUPFC_SEC | Active power of SEC in UPFC-VSG |
| PUPFC_SHC | Active power of SHC in UPFC-VSG |
| Q      | Output reactive power |
| Qset   | Reactive power reference value |
| QSTATCOM | Reactive power of STATCOM |
| QST_PCC1 | Reactive power at PCC in STATCOM-VSG |
| QUPFC_PCC1 | Reactive power at PCC in UPFC-VSG |

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Penetration of Renewable Energy (RE) in the modern power grid is increasing rapidly. Power electronics-dominated power networks are exhibiting high vulnerability to resource intermittency. Such issues are further exacerbated by grid disturbances such as voltage swells/sags and frequency or phase angle variations caused by transmission line outages, generator outages and other faults [1], [2]. In networks with high proportion of renewables, the observed stability issues will extend beyond a single converter or a station into larger-scale frequency and voltage stability issues.

Grid-connected inverters with Battery Energy Storage Systems (BESSs) controlled as Virtual Synchronous Generators (VSGs) imitate the behavior of traditional Synchronous Generators (SGs). The concept of an inverter operating as an SG was developed in [3], where the mathematical expressions that define the operation of a synchronous generator have been incorporated into the controller of the inverter. The emulated operation as VSG demonstrates all the major properties of an SG which include virtual inertia and damping coefficients. Furthermore, these parameters can be flexibly designed according to the specific requirements of the power system or even changed in an adaptive manner [4]–[8]. Therefore, they can provide functionalities such as oscillation damping and inertia to a modern power system [9], [10].

Typically, grid-connected RE systems such as wind or solar adopt a more conventional grid feeding current control strategy [11]. One approach for enabling virtual inertia into wind turbines or solar systems is with the addition of localized BESS [12], [13]. This solution, that is referred to as ‘Unit’-VSG in this paper, is shown in Fig. 1(a). However, this solution means that all units of a wind or solar power station should have a corresponding independent BESS so that the grid-connected inverter has sufficient virtual inertia to ensure frequency stability.

Flexible AC Transmission Systems (FACTS) devices such as Static Synchronous Compensators (STATCOMs) and the Unified Power Flow Controllers (UPFCs) can play a critical role in the modern power grid due to their contributions to reactive power compensation and active power flow control [14], [15]. Both of these FACTS devices can be configured with BESS on the common dc-link to allow
an aggregate response from the solar and wind farm that emulates the response of a large SG with programmable inertia and damping parameters consistently (referred to as ‘Station’-VSG [16]–[18]).

At present, VSG control strategies have been applied to STATCOMs with capacitors [19] or BESS [20], as shown in Fig. 1(b) and (c), respectively. The STATCOM-VSG with centralized BESS of Fig. 1(c) is connected in parallel to the RE station provides local voltage support. On one hand, frequent power fluctuations will lead to VSG voltage variations, which further affect the operation of grid-connected inverter as disturbances of RES. However, the output voltage of power electronic inverters (such as STATCOMs), either current-controlled, voltage-controlled or controlled as a VSGs, is susceptible to variations because of variable power references or random and unpredictable grid disturbances. These variations will further affect each independent wind turbine or PV system of the RES degrading the performance of the whole station. Grid-connected power electronic converters are sensitive to these sudden voltage variations, which can lead to local oscillations with the risk of evolving into a large-scale of tripping incidents [21]. Parameter design for improving the stability of grid-connected inverters was analyzed in [22]. However, individual differences between the converters strengthen the challenges of implementing such a method at scale [23]. Alternatively, the stability of the RES can be improved by reducing voltage disturbances seen by the grid-connected inverters of the station. A STATCOM is unable to eliminate the impact of large voltage variations on the RES under either power reference changes or grid disturbances. On the other hand, the VSG should have a larger voltage range due to the larger line impedance under weak grid conditions. The higher VSG output voltage means that the grid-connected inverters in RES should be configured with a larger voltage or current margin. The lower VSG output voltage may also cause grid-connected inverters to operate beyond the normal range, and further lead to grid-connected inverters in RES operating in low voltage ride-through more frequently.

The UPFCs with BESS can provide frequency and voltage support. Compared to a STATCOM, the UPFC requires higher expenditure and a more complex control strategy. However, it can maintain the voltages of the shunt converter and RES constant, through its series converter that can compensate any voltage amplitude variations. This approach is effective in reducing the impact of power reference variations and grid disturbances on RES. In addition, a UPFC can provide further benefits in the operation of the power system through oscillation suppression [24]. The frequency VSG control strategy was attempted to apply to UPFC/BESS [25], which supplies virtual inertia and damping to eliminate the impact of active power fluctuations on the point of common coupling (PCC). However, the proposed approach does not include contributions to voltage droop and regulation of reactive power control of VSG algorithm [3].

This paper develops a VSG control strategy applied to UPFC with the aim of assisting RES integration through inertia and damping characteristics provided by the UPFC. The key contributions of this work are: i) the VSG control strategy applied to UPFC is developed and its comparison object-STATCOM/BESS-VSG is also reviewed, ii) the series converter of the UPFC-VSG can compensate such voltage amplitude variations, ensuring that the voltages of the shunt converter and RES are kept constant, thus improving the overall performance of the grid-connected system, and iii) validation of the analysis through simulations and comparison between the proposed UPFC-VSG and an equivalent STATCOM. The proposed approach provides an integrated solution for handling frequency and voltage disturbances, improving the transient stability of the power system.

The rest of this paper is organized as follows. In Section II, the proposed VSG control strategy for UPFC is analyzed. In Section III, the small-signal model of VSG is developed and a detailed comparison between the proposed UPFC-VSG and the STATCOM-VSG is given. Both devices also include a BESS. The simulation of Section IV provides verification of the control strategy and the theoretical comparisons developed in this work. Finally, Section V concludes this work.

II. PROPOSED UPFC-VSG STRATEGY AND STATCOM-VSG STRATEGY

A. PROPOSED UPFC-VSG CONTROL STRATEGY

The proposed UPFC-VSG applied in RES power transmission system is shown in Fig. 1(d). The UPFC consists of the series converter (SEC), the shunt converter (SHC) and the BESS connected to the common dc bus. Modular Multilevel Converters (MMCs) [26] can be adopted in both SEC and SHC; similarly, the bidirectional DC/DC [27] which is used to integrate the BESS in the dc-bus can also utilize modular structures.

The conventional swing equation can be given by (1).

$$J_p \frac{d\omega_m}{dt} = \frac{P_{set}}{\omega_n} - \frac{P}{\omega_n} - D_p(\omega_m - \omega_n) \tag{1}$$

Existing VSG methods have so far been implemented in single converters. However, the dual converter structure of the UPFC provides a circuit topology in which the SEC and SHC can be seen as connected in series from the ac-side. Thus, the voltage at PCC1 is determined by both converters. Operation as a VSG is achieved by controlling the phase angle and voltage amplitude at PCC1 to track their corresponding references, $\theta_m$ and $E_m$. The modulation signal of the SEC and SHC are determined by the phase angle $\theta_m$ and voltage amplitude reference $E_m$ of the VSG controller. The proposed control structure is shown in Fig. 2.

The SHC is connected in parallel with RES and provides voltage support. Here the voltage at PCC2 is the same with the SHC output voltage. Thus, in order to regulate the RES voltage at PCC2, the voltage reference value of the SHC is set to a constant value. The voltage difference between PCC1 and PCC2 is compensated by the SEC. The voltage compensated
by the SEC will be minimum for the same percentage voltage variation, if the phase difference between the series compensated voltage and the shunt converter voltage is equal to 0 or $\pi$ [28], [29]. Therefore, the required voltage reference and phase angle of SHC and SEC are given by (2) and (3).

$$
\begin{align*}
\theta_{\text{ref},\text{sh}} &= \theta_m \\
E_{\text{ref},\text{sh}} &= U_n \quad (2) \\
\theta_{\text{ref},\text{se}} &= \begin{cases} 
\theta_m, & U_n < E_m \\
\theta_m - \pi, & U_n \geq E_m
\end{cases} \\
E_{\text{ref},\text{se}} &= |E_m - U_n| \quad (3)
\end{align*}
$$

The modulation signals can be generated by the phase angle $\theta_{\text{ref},i}$ and the voltage amplitude value $E_{\text{ref},i}$ (where $i$ represents $se$, $sh$ or $st$). According to Fig. 2, the SHC is controlled as a voltage source with constant amplitude $U_n$ and phase angle $\theta_m$. The compensation of the voltage difference between PCC1 and PCC2 reduces the voltage variations seen by the RES. The voltage synthesized by the SEC and SHC shows the dynamic and steady-state droop characteristics of a conventional SG, but also the provision for power control and inertia by the UPFC-VSG. As mentioned earlier, because of SHC and SEC, a UPFC-VSG also has the ability to limit voltage variations in RES, so that the normal operation of the RES can be maintained at a fixed point. The control strategy of the BESS ensures that the dual control goals of maintaining the dc voltage and regulating power transfer between SHC and SEC are achieved [30].

**B. STATCOM-VSG CONTROL STRATEGY**

As a comparison for the proposed UPFC-VSG controller of Section II. A, a STATCOM-VSG with centralized BESS is also considered. Such a comparison will illustrate the commonalities and differences between the two implementations and the benefits provided by the UPFC-VSG.

The configuration of an equivalent STATCOM-VSG is shown as Fig. 1(c) and the control structure for the converter, based on the controller developed in [20] is shown in Fig. 3.

In STATCOM-VSG, the STATCOM is connected in parallel with the RES at a single point of common coupling, thus the voltage at PCC1 and PCC2 become identical and equal to the STATCOM output voltage. The required voltage reference and phase angle of the STATCOM, when operating in VSG mode, is given by (4).

$$
\begin{align*}
\theta_{\text{ref},\text{st}} &= \theta_m \\
E_{\text{ref},\text{st}} &= E_m \quad (4)
\end{align*}
$$

**III. ANALYSIS AND COMPARISON OF UPFC-VSG AND STATCOM-VSG**

**A. COMPENSATION ABILITY COMPARISON**

Due to their similar control structure, the UPFC-VSG and STATCOM-VSG will display identical static and dynamic characteristics. When $X_{\text{line}} \gg R_{\text{line}}$, the active and reactive power injected to the grid can be written as [31], [32]:

$$
\begin{align*}
P &= \frac{3U_gE_m}{X_{\text{line}}} \sin \theta_m \\
Q &= \frac{3U_gE_m}{X_{\text{line}}} \cos \theta_m - \frac{3U_g^2}{X_{\text{line}}} \quad (5)
\end{align*}
$$

Adding superimposed small variations to the operating point of (5), and according to the control structures shown in Fig. 2 and Fig. 3, the VSG closed-loop small-signal control block of active power and reactive power is shown in Fig. 4. The transfer functions from $\Delta P_{\text{set}}, \Delta \omega_g, \Delta Q_{\text{set}},$ and $\Delta U_g$ to $\Delta \theta_m$ and $\Delta E_m$ can be written as:

$$
\begin{align*}
\Delta \theta_m(s) &= A_1 \Delta P_{\text{set}}(s) + A_2 \Delta \omega_g(s) + A_3 \Delta Q_{\text{set}}(s) + A_4 \Delta U_g(s) \\
\Delta E_m(s) &= B_1 \Delta P_{\text{set}}(s) + B_2 \Delta \omega_g(s) + B_3 \Delta Q_{\text{set}}(s) + B_4 \Delta U_g(s) \\
\end{align*}
$$

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where $A_1, A_2, A_3, A_4, B_1, B_2, B_3$ and $B_4$ are the corresponding transfer functions are given in (7).

$$
A_1 = \frac{T_p}{1 - T_p T_q H_p E_q H_\delta} \\
A_2 = \frac{k_\omega}{1 - T_p T_q H_p E_q H_\delta} \\
A_3 = -T_q H_p E_q H_\delta \\
A_4 = (k_V - H_{qu} + H_{pu} T_q H_p E_q H_\delta) T_p \\
B_1 = -T_p H_q H_\delta \\
B_2 = -k_\omega T_p H_q H_\delta \\
B_3 = -T_q H_q H_\delta \\
B_4 = (k_V - H_{qu} - H_{pu} T_q H_p E_q H_\delta) T_q \\
H_p = \frac{H_J}{1 + H_J H_p^\delta} \\
H_q = \frac{1}{1 + H_V H_q^\delta} \\
H_\delta = \frac{\omega_n s (J s + D)}{X_{line}} \\
H_{pu} = \frac{3 U_g E_0 \cos \theta_{n0}}{X_{line}} \\
H_{qu} = \frac{3 E_0 \sin \theta_{n0} - 6 U_g}{X_{line}} \\
H_{pE} = \frac{3 U_g \sin \theta_{n0}}{X_{line}} \\
H_{qE} = \frac{3 U_g \cos \theta_{n0}}{X_{line}} \\
$$

Eqs. (6) and (7) indicate that power reference variations or grid disturbances will cause variations in the phase angle reference and voltage amplitude reference generated by VSG. Furthermore, the phase angle variation $\Delta \theta_m$ and voltage amplitude variation $\Delta E_m$ generated by UPFC-VSG and STATCOM-VSG are identical.

In UPFC-VSG, the phase angle reference and voltage amplitude reference of the SHC and SEC, according to (2) and (3), will change as follows:

$$
\theta_{ref.sh} = \theta_{n0} + \Delta \theta_m \\
E_{ref.sh} = U_n \\
\theta_{ref.se} = \theta_{n0} + \Delta \theta_m \\
E_{ref.se} = |(E_{n0} + \Delta E_m) - U_n| \\
$$

(8)

Considering that the shunt converter is responsible for phase angle and voltage support for RES and simplifying (8), we get:

$$
\Delta \theta_{ref.sh} = \Delta \theta_{ref.se} = \Delta \theta_m \\
\Delta E_{ref.sh} = 0 \\
\Delta E_{ref.se} = \Delta E_m \\
$$

(9)

When the system returns to stable operation conditions, the output phase angle and voltage amplitude of SEC and SHC will be identical with their reference value. Then, (9) can be rewritten as:

$$
\Delta \delta_{RES_UPFC} = \Delta \delta_{UPFC_SHC} = \Delta \delta_{UPFC_SEC} = \Delta \theta_m \\
\Delta U_{RES_UPFC} = \Delta U_{UPFC_SEC} \approx 0 \\
\Delta U_{UPFC_SEC} \approx \Delta E_m \\
$$

(10)

It is shown that the amplitude variation $\Delta E_m$ will affect the output voltage amplitude variation $\Delta U_{UPFC_SEC}$ of the series converter, so that the output voltage amplitude $U_{UPFC_SEC}$ of the shunt converter and the voltage $U_{RES_UPFC}$ of the RES will be kept constant, $U_n$. The detailed small-signal variations in UPFC-VSG system are shown in Fig. 5(a).

Similarly, the phase angle reference $\theta_{ref.ST}$ and voltage amplitude reference $E_{ref.ST}$ of STATCOM will also be affected. The small-signal variations relationship can be expressed as (11).

$$
\Delta \delta_{RES_ST} = \Delta \delta_{STATCOM} = \Delta \theta_{ref.ST} = \Delta \theta_m \\
\Delta U_{RES_ST} = \Delta U_{STATCOM} = \Delta E_{ref.ST} = \Delta E_m \\
$$

(11)

The detailed small-signal variations of the STATCOM-VSG circuit is shown in Fig. 5(b). Here, the voltage amplitude reference variations generated by the VSG will cause the output voltage variation of STATCOM, so that the grid-connected converters of the RES will operate in a voltage changing state as well.
TABLE 1. Comparison of the three VSG systems.

|                      | UPFC/BESS-VSG | STATCOM/BESS-VSG | Centralized BESS-VSG |
|----------------------|---------------|-------------------|----------------------|
| SM Quantity          | 10*6^2 - 120  | 10*6 - 60         | 0                    |
| IGBT Quantity        | 10*6^2*2 - 240| 10*6^2 - 120      | 8*6 - 48             |
| Transformers         | 3*single step-up transformer | 0 | 8*5MVA step-up transformer |
| Voltage compensation | 0.3pu         | 0                 | 0                    |

B. ECONOMIC COMPARISON

Beyond the above aspects that are demonstrated in this paper, the costs and economics are also important.

It is assumed that three VSG method (UPFC/BESS-VSG, STATCOM/BESS-VSG and centralized BESS-VSG) should be configured the power capacity margin of 40 MVA to provide identical compensation requirements:

i) Both series and parallel converters of UPFC-VSG have a capacity of 40MVA. The MMC is adopted for the high dc voltage (20kV); its SM voltage is equal to 2000V. The series converter is connected to the transmission line through the single-phase transformer (3:1), which can compensate up to 30% voltage drop.

ii) The MMC topology with 40MVA is adopted in STATCOM/BESS-VSG, and the SMs of the system are the same as (i).

iii) The centralized BESS-VSG adopts the 5MVA low-voltage converter. There are 8 converters that should be configured in order to achieve the same compensation ability.

It can be found that the quantity of IGBTs required by UPFC-VSG is twice of STATCOM-VSG, as we have already commented on the paper. However, this configuration can provide 30% voltage compensation for large-scale transmission line voltage drop under high voltage, high current, weak grid conditions.

IV. CASE ANALYSIS AND SIMULATION RESULTS

In order to verify the effectiveness of the proposed VSG control strategy based on UPFC-VSG and to provide a thorough comparison between the two FACTS devices, a 100 MVA transmission system, based on the models of Figs. 1(c) and (d) was developed and simulated using Matlab/Simulink. The output power of the RES is kept at a constant 100 MW. An average model consisting of the controlled-voltage source is used instead of the SHC and the SEC converter in UPFC as well as in the STATCOM. Identical controller parameters for the VSG as well as grid voltage/frequency standards are adopted, so that the two VSG cases can be accurately compared. The design standard principles are shown in Fig. 6 and are as follows:

a) the required active power variation $\Delta P$ is 30% ($S_{\text{rate}} = 100$ MVA) if the grid angular frequency variation $\Delta \omega_g$ by 1%;

b) the required reactive power variation $\Delta Q$ is 0% (0 MVar) with the normal operating voltage range of the power grid (90% $U_n \sim 110% U_n$);

c) the required reactive power variation $\Delta Q$ is 20% (20 MVar) if the voltage amplitude variation $\Delta U_g$ by 10% with 70% $U_n \sim 90% U_n$ or 110% $U_n \sim 130% U_n$.

Based on the above principles, the maximum active power and the maximum reactive power to be compensated by the UPFC and STATCOM is 30 MW and 40 MVar, respectively. Thus, the rated capacity of the SHC and SEC in the UPFC and the STATCOM is selected as 40 MVA. In addition, there are [33]:

\[
\frac{\Delta P_{\text{max}}}{\Delta \omega_{\text{g,max}}} = D_p \omega_n + k_\omega = 0.3 S_{\text{rate}} \omega_n \\
\frac{\Delta Q_{\text{max}}}{\Delta U_{\text{g,max}}} = k_V = 0.2 S_{\text{rate}} \frac{1}{0.1 U_n} 
\]

(12)

The transfer function from $\Delta P$ to $\Delta \omega_g$ or $\Delta P_{\text{set}}$ can be obtained as:

\[
\begin{align*}
\Delta P_{\text{set}} &= \frac{H_{p \omega}}{(\omega_n J_p)} \\
\Delta P &= \frac{H_{p \omega}}{s^2 + (D_p \omega_n + k_\omega)\omega_n J_p + H_{p \omega}} \\
\Delta \omega_g &= \frac{k_\omega H_{p \omega}}{s^2 + (D_p \omega_n + k_\omega)\omega_n J_p + H_{p \omega}} \\
\end{align*}
\]

(13)

The damping ratio $\xi_{Gr}$ is set to satisfy (9) [34], so the inertia coefficient $J_p = 125$ kg·m². To obtain satisfactory performance, the phase margin of (13) should be between 30° ~ 60°, and the amplitude margin of (13) should be than 6 dB [35]. For the system studied in this paper, the angular frequency coefficient $k_\omega = 0.3$, the damping coefficient $D_p \approx 30396$. The other parameters of the VSG system are
listed in Table 2.

\[
\xi_{Gr} = \frac{0.5(D_p \omega_n + k_\omega)}{\sqrt{H_p \omega_n I_p}} = 0.707
\]  

(14)

A. OPERATION UNDER CONSTANT FREQUENCY AND CONSTANT VOLTAGE

1) ACTIVE POWER REFERENCE VARIATIONS

A change in the active power reference \( P_{set} \) will cause the voltage amplitude reference \( E_m \) variations according to (6). The RES voltage will change in STATCOM-VSG, while the RES voltage amplitude will be regulated to a constant value in UPFC-VSG. In order to verify the proposed UPFC-VSG control strategy and RES voltage stability during active power variations, the following scenario has been considered: When \( t < t_1 \), the grid operates at its rated frequency \( f_g = 50 \) Hz and \( U_g = U_n \). The initial setpoints for active and reactive power are \( P_{set} = 100 \) MW and \( Q_{set} = 0 \) MVar. At \( t_1 = 1s \), \( P_{set} \) is set to 70 MW, and then at \( t_2 = 2s \), \( P_{set} \) is increased to 130 MW. The simulation results variations are shown in Fig. 7.

Fig. 7(a)-(d) show the voltage, frequency and power characteristics at PCC1 of UPFC-VSG and STATCOM-VSG. There are identical voltage and frequency support characteristics at PCC1 point in UPFC-VSG and STATCOM-VSG. The active power at PCC1 can track its reference of 0.7 pu (70 MW) and 1.3 pu (130 MW) at \( t_1 = 1s \) and \( t_2 = 2s \) well.

Fig. 7(e)-(i) show the voltage amplitude, phase angle and power for the SHC, SEC and the STATCOM based on the control of Section II. The active power variation leads to a change in the voltage amplitude reference generated by UPFC-VSG and STATCOM-VSG at \( t_1 = 1s \) and \( t_2 = 2s \). Because the voltage amplitude reference variations caused by active power variation are small for the SEC voltage, the active power is mainly absorbed or released through the shunt converter in UPFC-VSG.

Figs. 7(j) and (k) show the RES output current components in the case of the UPFC-VSG and STATCOM-VSG. As shown in Fig. 7(f), the series converter can compensate for the voltage difference to ensure that the shunt converter can output a constant amplitude voltage. Therefore, the voltage and current of the RES in UPFC-VSG also can be controlled as the constant value, meaning that the active power variations do not affect the operation of RES. However, in the case of the STATCOM, the output of the RES leads to changes as observed at \( t_1 = 1s \) and \( t_2 = 2s \). The RES voltage variations caused by the active power variations can be regarded as the disturbances and affect the stable operation of RES in STATCOM-VSG.

2) REACTIVE POWER REFERENCE VARIATIONS

A similar analysis is presented for changes in the reactive power reference \( Q_{set} \) which will cause the voltage amplitude reference \( E_m \) variations according to (6). The RES voltage will change in STATCOM-VSG, while the RES voltage amplitude can be maintained as a constant value in UPFC-VSG. In order to verify the proposed UPFC-VSG control strategy and RES voltage stability during reactive power variations, the simulation has been finished as follows: Similarly to the steady-state case of Section IV.A.1, at \( t < t_1 \), the grid operates with frequency \( f_g = 50 \) Hz and \( U_g = U_n \). At \( t_1 = 1s \), \( Q_{set} \) is set to 40 MVar, and then \( Q_{set} \) decreases to -40 MVar at \( t_2 = 2s \). The simulation results of \( Q_{set} \) changes are shown in Fig. 8.
FIGURE 8. Simulation results of reactive power variations. (a) D-axis voltage on PPC; (b) Grid frequency and VSG response frequency; (c) Active power on PPC; (d) Reactive power on PPC; (e) D-axis voltage of SHC and STATCOM; (f) D-axis voltage of SEC; (g) Phase angle of SEC, SHC and STATCOM; (h) Active power of SEC, SHC and STATCOM; (i) Reactive power of SEC, SHC and STATCOM; (j) D-axis voltage of RES; (k) D-axis current of RES.

Figs. 8(a)-(d) show the voltage, frequency and power characteristics at PPC of UPFC-VSG and STATCOM-VSG during reactive power variations. The reactive power at PPC can track its reference 0.4 pu (40 MVar) and -0.4 pu (-40 MVar) at t = 1s and t = 2s.

Figs. 8(e)-(i) show the voltage amplitude, phase angle and power in the SEC, SHC and STATCOM. The voltage amplitude reference generated by VSG changes due to reactive power variations leading to an increase in the voltage that needs to be compensated by the SEC. In addition, when the active power reference remains constant at t_1 = 1s, the phase difference between the series converter voltage and the shunt converter voltage is equal to 0, the active power flows out from the series converter. Correspondingly, the active power flows into the shunt converter. When the phase angle difference between the series converter voltage and shunt converter voltage is π, the active power exchange status of two converters in the UPFC-VSG changes as seen during the transition at t_2 = 2s.

Figs. 8(j) and (k) are the simulation results of RES voltage and current. At t_1 = 1s and t_2 = 2s, the voltage amplitude reference generated by STATCOM-VSG changes resulting in RES voltage and current variations. For the same conditions, the voltage amplitude reference E_m also changes in UPFC-VSG, however, this variation ΔE_m is compensated by the SEC, keeping the voltage of the RES supported by the SHC constant. It can be noticed that the RES voltage U_{RES,UPFC} and current I_{RES,UPFC} do not change in UPFC-VSG during the interval 0.5-3s.

3) ACTIVE POWER REFERENCE AND REACTIVE POWER REFERENCE VARIATIONS SIMULTANEOUSLY

To verify the performance of UPFC-VSG during simultaneous active and reactive power reference variation, the following case is considered: For t < t_1, the initial simulation condition is the same as before. At t_1 = 1s, P_{set} is set to 120 MW, Q_{set} is set to 40 MVar. At t_2 = 2s, P_{set} is set to 70 MW, Q_{set} decreased to -30 MVar. The simulation results of this case are shown in Fig. 9.

Figs. 9(a)-(d) show the voltage, frequency and power characteristics at PPC of UPFC-VSG and STATCOM-VSG. Following the results of the previous section, when P_{set} and Q_{set} changes at t_1 = 1s and t_2 = 2s, the active power and reactive power at PPC track their reference, which conforms to the theoretical analysis of UPFC-VSG. Figs. 9(e)-(i) show the voltage amplitude, phase angle and power in the SHC, SEC and STATCOM. The results demonstrate the compensation voltage amplitude and phase angle of series converter during voltage at PPC changes, and further keeping the shunt converter voltage at a constant point. Finally, Figs. 9(j) and (k) show the RES voltage and current. UPFC-VSG can still control the voltage and current of RES to a constant value when the active and reactive power reference change simultaneously. Compared with STATCOM-VSG, UPFC-VSG has the ability to reduce the RES voltage disturbances under power reference variations.

B. GRID DISTURBANCES

1) GRID FREQUENCY VARIATIONS

Changes in the grid frequency ω_g will cause voltage amplitude reference E_m variations according to (6). The RES voltage will change in STATCOM-VSG, while the RES voltage amplitude can be maintained as a constant value in UPFC-VSG. In order to verify the proposed UPFC-VSG control
strategy and RES voltage stability during grid frequency variations, the following scenario is considered. When $t < t_1$, the grid operates steadily with frequency $f_g = 50$ Hz and $U_g = U_n$, the initial $P_{set} = 100$ MW and $Q_{set} = 0$ MVar. The grid frequency $f_g$ increases to 50.5 Hz at $t_1 = 1$s, and then decreases to 49.5 Hz at $t_2 = 2$s. The simulation results for these frequency variations are shown in Fig. 10.

The voltage, frequency and power at PCC$_1$ of UPFC-VSG and STATCOM-VSG which is shown in Figs. 10(a)-(d) demonstrate that both UPFC-VSG and STATCOM-VSG can track the grid frequency variations and active power responses at PCC$_1$ well. The frequency variations lead to a change in the voltage amplitude reference $E_m$, there is only a small voltage that needs to be compensated by the series converter, as shown in Figs. 10(e)-(i). While the UPFC-VSG can still provide a constant amplitude voltage to the RES when grid frequency changes, ensuring the RES operating state is not affected (Figs. 10(j) and (k)).
2) GRID VOLTAGE AMPLITUDE VARIATIONS

The grid voltage $U_g$ change will cause the voltage amplitude reference $E_m$ variations according to (6). Here at $t = 0.97\, s$, the grid voltage amplitude $U_g$ begins to decrease by 0.3 pu in 0.03 seconds and kept at 0.7 pu from $t = 1\, s$; then from $t = 1.94\, s$, $U_g$ rises to 1.3 pu within 0.06 seconds. The simulation results of $U_g$ variations are shown in Fig. 11.

The results of Figs. 11(a)-(d) show that both the UPFC-VSG and the STATCOM-VSG provide voltage and reactive power support at PCC$_1$. As shown in the small-signal analysis of Fig. 4, the voltage disturbance will also affect the VSG frequency and active power in a transient manner. This is due to the transfer function $H_{pu}$ and the coupling between $\Delta U_g$ and $\Delta P$ in (7). This is only a transient effect as both variables eventually return to their steady-state value. The SEC in the UPFC is responsible for compensating the grid voltage variations, so that the SHC will not be affected as shown in Figs. 11(e)-(i).

The large fluctuations in the RES voltage and current of STATCOM-VSG during grid voltage variations are shown...
in Figs. 11(j) and (k). However, UPFC-VSG can still maintain a constant voltage at PCC$_2$, connected to the RES, ensuring that the RES operating state is not affected. Frequent voltage variations are detrimental to the stable operation of RES. The series converter in UPFC-VSG can compensate for a large voltage range within its rated voltage, thus eliminating the negative impacts of grid voltage variations. The shunt converter can provide a constant amplitude voltage support to ensure that active power generated can still be transmitted to the grid.

3) GRID FREQUENCY AND VOLTAGE AMPLITUDE VARIATIONS SIMULTANEOUSLY

A combined transient operation is also shown for the two systems. At $t_1 = 1$s, the grid voltage amplitude $U_g$ begins to decrease to 0.85 pu with $f_g = 49.75$ Hz; then, the grid voltage rises to 1.1 pu and the grid frequency is 50.5 Hz at $t_2 = 2$s. The simulation results of this case are shown in Fig. 12.

It is shown that the UPFC-VSG can support the RES voltage when the under variations in the grid frequency and voltage amplitude, while the voltage of RES in STATCOM-VSG will be negatively affected, confirming the overall analysis of the proposed approach.

V. CONCLUSION

This paper introduced a UPFC with VSG functionality that can compensate for grid voltage variations at the point of common coupling and provide a constant voltage reference for the connection of remote RE systems. The proposed UPFC-VSG was compared with an equivalent STATCOM-VSG. The work presented in this paper demonstrates that:

1) The shunt converter of the UPFC-VSG can operate as a voltage source with a constant voltage amplitude, while the series converter of the UPFC-VSG is designed to compensate for the voltage difference between the grid and the RES.

2) The proposed UPFC-VSG can emulate the behavior of SGs providing inertia and damping during power reference variations or grid disturbances.

3) Power reference variations and grid disturbances will affect the output of the VSG controller. This is shown through small-signal analysis of the proposed UPFC-VSG as well as the STATCOM-VSG.

4) Although a solution based on a UPFC leads to a higher cost and more complex control, compared to with a STATCOM, the compensation of voltage disturbances provided by the series converter, ensuring that the shunt converter voltage and RES voltage is not affected, improves the overall stability and performance of large-scale grid-connected renewable energy systems.

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