GENERALISED GRID-FORMING VSC CONTROL FOR GRID CONNECTION AND ISLAND NETWORK

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Abstract

This study proposes a generalised grid-forming VSC control for grid connection and island network for distributed generations. The proposed control scheme is based on grid-forming direct voltage control to establish the AC voltage and frequency for island network, while it works as a controlled AC voltage source to regulate the active and reactive power flowing to the local load and AC grid during grid-connected operation. Strategy for fault current limiting is also proposed to overcome the overcurrent problem brought by the grid-forming direct voltage control. Simulation results during three-phase AC fault and transition from grid-connected operation to islanding operation are presented to confirm the feasibility and effectiveness of the proposed control strategy.

1 Introduction

The concept of environmental protection and sustainable development has drawn more attention due to serious issues brought by traditional power generation. This leads to the increased focus on the development of renewable energy and distributed generation. Since renewable energy is naturally dispersed and has large power variation, the utilisation and integration of renewable energy has become a prevalent topic in the field of electrical power generation [1], [2]. Considering the characteristics of renewable energy, distributed generation is becoming an optimal solution to utilise and integrate the renewable energy to ensure the reliability, quality and security of electricity supply [2], [3]. Many distributed generations largely use voltage source converters (VSC) for interfacing the prime energy source to the network [4].

Most power converters for connecting renewable generation and energy storage system use inner current control due to its fast response and effective fault current limiting during large external transient [5], [6], [7]. However, VSC using inner current control is only suitable when it is interfaced with a strong AC grid with a low grid impedance. In fact, the equivalent grid impedance will increase with higher penetration of inner current control based VSCs in the network, and consequently the inner current based VSCs interfaced power generations could become unstable when connected to a weak grid [8], [9], [10], [11], [12], [13]. A power synchronisation control is proposed to provide a fast response with good dynamic performance when the converter is connected to a weak grid [9]. However, the power synchronisation control based converter cannot limit the fault current without switching in the inner current control. In [13], a current error based compensation control for PLL angle and voltage magnitude is proposed. The investigated method can significantly improve the stability of control system and limit the fault current without control mode switching. However, this kind of control strategy cannot handle islanded operation, which is increasingly becoming important for converters connected to distributed networks.

This study presents a generalised VSC control method which provides grid-forming ability with direct voltage control and has the ability to work on both grid connection and island network. To overcome the overcurrent problem brought by the adoption of grid-forming operation, an extra fault current limit control is combined with the grid-forming direct voltage control without the need for control model switching.

This rest of the paper is organised as follows. Section 2 presents the considered system configuration. The control objectives and strategies are described in Section 3. Simulation results relative to two case studies are expressed in Section 4. Lastly, conclusions are drawn in Section 5.

2 System Configuration

The system configuration is shown in Fig. 1 for grid connection example where the VSC is rated at 400kVA and the normal local load demand is set at 200kW.

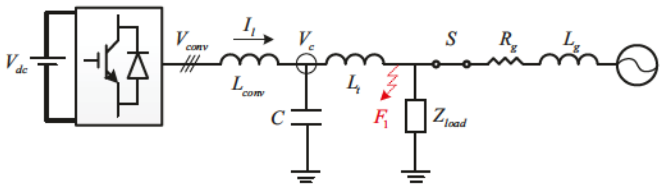

Fig. 1 Simplified circuit of system configuration

The system is consisted of a VSC (with a fixed DC source), and an AC LCL filter, local load and an AC grid with a SCR of 5 (on 400kVA base). V_c is the output voltage at the filter bus and I_l represents the converter output current. Switch S is connected between the AC grid and VSC to connect and disconnect the VSC from the grid to perform grid connection and islanding operations. F_1 is the location of AC fault for the simulation test of fault.

3 Control Objectives and Strategies

3.1 Control Objectives

During grid-connected operation, the VSC works as a controlled voltage source synchronised to the grid to regulate its active and reactive power flowing into the local load and AC grid. On the other hand, it operates as a grid-forming converter which regulates the voltage magnitude and frequency when the network becomes islanded. The overall control objectives are as follows:

- Active and reactive power control. During grid-connected operation, the active and reactive power is controlled according to the set values.
- Synchronisation of the VSC with AC grid. When the converter is working on grid connection network, it is essential to synchronise the converter to the grid for accurate and stable operations.
- Voltage magnitude and frequency control. On islanding operation, the VSC needs to establish the voltage and frequency for the island network to maintain a stable operation.
- Fault current limit control. The VSC needs to limit the current effectively when there is a large transient in the external network, such as AC faults.

3.2 Control Strategies

Fig. 2 illustrates the overall structure of the control system. The filter bus voltage and converter output current, V_{cabc} and I_{labc}, in three-phase frame are transformed into the dq-frame by the modified phase-locked loop (PLL) which will be discussed in detail late in the section. The generalised grid-forming VSC control system is based on direct voltage control with frequency regulation, as well as power droop control to balance the delivered power from the VSC to the local load and AC grid. A current-voltage droop controller is then used to limit converter current during fault since there is no current control loop during normal operation.

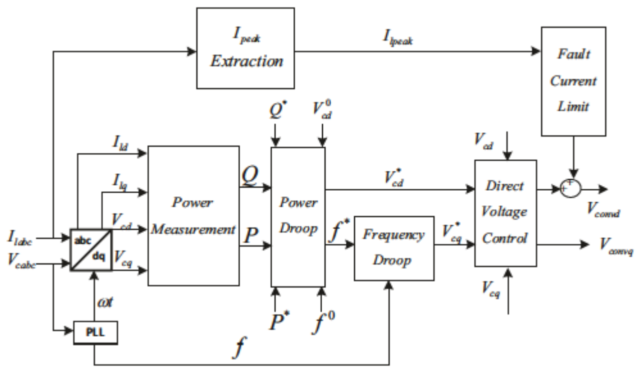

Fig. 2 Overall structure of the control system

3.2.1 Direct Voltage Control

The circuit shown in Fig. 1 can be expressed in the dq frame as

$$
\begin{aligned}
V_{convd} &= L_{conv}\frac{dI_{ld}}{dt} - \omega I_{lq}L_{conv} + V_{cd} \\
V_{convq} &= L_{conv}\frac{dI_{lq}}{dt} + \omega I_{ld}L_{conv} + V_{cq}
\end{aligned} \tag{1}
$$

where ω is the angular frequency of the network; L_{conv} is the reactance; I_{ldq} , V_{cdq} and V_{convdq} are the converter output current, filter bus voltage and converter voltage in the dq frame, respectively. $L_{conv}\frac{dI_{ldq}}{dt}$ is negligible on steady state, and the disturbance from I_{ldq} and V_{cdq} can be compensated by using PI regulator to control the measured voltage to match voltage order. Hence, the VSC direct voltage control dynamics in the dq frame can be described in (2) and Fig. 3.

$$
\begin{aligned}
V_{convd} &= k_P(V^*_{cd} - V_{cd}) + k_I\int (V^*_{cd} - V_{cd})dt \\
&\quad -\omega I_{lq}L_{conv} + V_{cd} \\
V_{convq} &= k_P(V^*_{cq} - V_{cq}) + k_I\int (V^*_{cq} - V_{cq})dt \\
&\quad +\omega I_{ld}L_{conv} + V_{cq}
\end{aligned} \tag{2}
$$

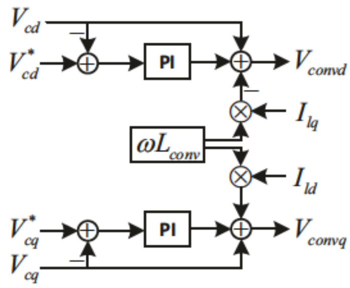

Fig. 3 Direct voltage control loop

where V^*_{cdq} and V_{cdq} are the voltage order and measured voltage in the dq frame, respectively. k_P and k_I are the proportional and integral gains of the PI regulator, respectively.

3.2.2 Power Droop Control

Power droop control is used to control the active and reactive power flowing into the local load and AC grid such that the system can operate at both grid-connected and islanding modes. The key concept of the power droop control is mimicking the operation of a synchronous generator governor whose frequency reduces when the generated/output active power increases and vice versa. The characteristic between the generated reactive power and voltage magnitude is similar. By following this characteristic, the VSC works as a controlled AC voltage source while its active and reactive power are adjusted to enable the frequency and voltage magnitude order to match the network when it operates on grid-connected operation. When the converter is working on island operation, the VSC works as a grid-forming converter and establishes the frequency and voltage magnitude for the island network according to the demand of the local load. The power droop control can be expressed in (3) and Fig. 4.

$$V^*_{cd} = V^0_{cd} - k_{QQ}(Q^* - Q)$$
$$f^* = f^0 + k_{PP}\left(P^*\frac{V_{cd}}{V^0_{cd}} - P\right) \tag{3}$$

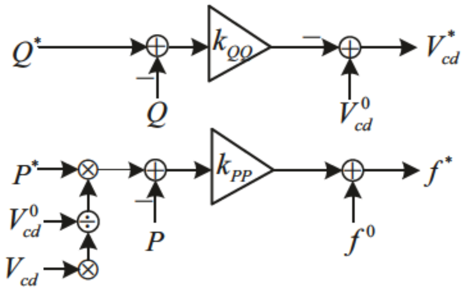

Fig. 4 Power droop control loop

where P and Q are the measured active and reactive power, respectively; f is the measured frequency of the system; k_{QQ} and k_{PP} are the reactive and active droop coefficients, respectively. Symbols with superscripts * and 0 represent the reference and system nominal values, respectively. As seen, the active power droop control is used to produce the frequency order f^* for frequency droop control, while the reactive power droop control produces the d-component voltage order V^*_{cd} that will be fed to the aforementioned direct voltage control. For the active power droop control, the setting point P^* is multiplied by the quotient between V_{cd} and V^0_{cd} to produce a dynamic active power reference according to the measured voltage level. Compared to conventional power droop control, this control strategy has the ability to avoid the error between P and P^* when there is a large external transient, such as AC faults.

3.2.3 Modified PLL

Phase-locked loop (PLL) is used widely to synchronise converters to network [14], [15]. The PLL controller takes the filter bus V_{cq} as the input and forces it to be zero through the regulation of the tracked voltage angle. However, when the system is subject to an AC severe fault that causes the system voltage at the converter connection point (filter bus in this example) to zero, the PLL controller has no external voltage to lock to, so the frequency could diverse by any control or measurement error. Once the fault is cleared, the system frequency will recover which will be significantly different to the value calculated by the PLL controller. This potential can cause large transient current during the recovery stage. To tackle this issue, the adopted PLL control is modified as shown in Fig. 5. As seen, if the AC voltage drops below a set value, 0.15pu in this example, the modified PLL control will lock the AC frequency to the value 0.2s prior to the AC voltage drop and the PI regulator stops calculation. Once the AC voltage recovers to a higher value, say above 0.25pu, the PLL controller will switch back to its normal operation mode. The modified PLL can maintain a smooth transient during zero network voltage caused by severe external AC fault.

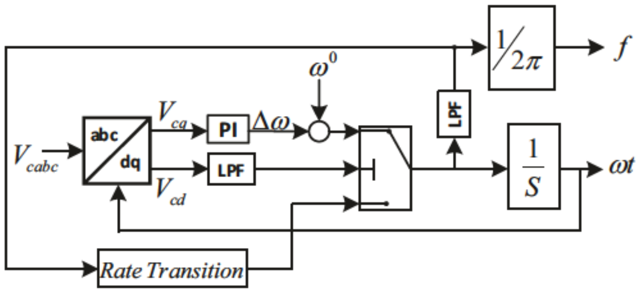

Fig. 5 Modified PLL control

3.2.4 Frequency Droop Control

For a stable islanding operation, it is essential for the VSC to establish the voltage and frequency for the island network which forms the concept of 'grid-forming'. According to the control diagram in Fig. 5, the frequency produced by the PLL controller can be illustrated as

$$f = f^0 + k_{Ppll}V_{cq} + k_{Ipll}\int V_{cq}dt \tag{4}$$

where k_{Ppll} and k_{Ipll} are the proportional and integral gains of the PI regulator in the modified PLL control, respectively. The relationship between the frequency f and q -axis component voltage V_{cq} is depicted in Fig. 6.

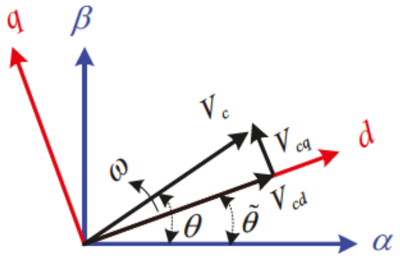

Fig. 6 Filter bus voltage vector in the dq frame

As aforementioned, the PLL controls V_{cq} to be 0. If V_{cq} is greater than 0, the detected voltage angle ($\tilde{\theta}$) lags the system voltage angle θ and thus, the system angular speed is faster than the detected speed and vice versa. The PI controller in the PLL will then increase the frequency so as to reduce the angle error between $\tilde{\theta}$ and θ. This principle is adopted in the frequency droop control as expressed in (5) and Fig. 7.

$$V^*_{cq} = k_f \cdot (f^* - f) \tag{5}$$

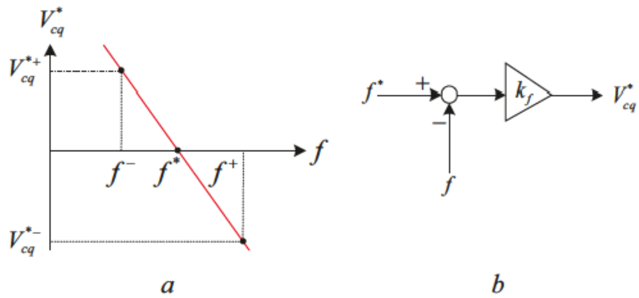

Fig. 7 (a) Characteristic of frequency droop control, (b) Diagram of frequency droop control where k_f is the frequency droop coefficient. When the measured system frequency f (f^+ in Fig. 7 (a)) is greater than the frequency order f^* produced by the active power droop control, this means the system frequency needs be reduced. The frequency droop controller will then produce a negative q-axis voltage order V_{cq}^{*-} to be fed to the direct voltage control. This negative V_{cq} is detected by the PLL and the system frequency is thus reduced. Therefore, the direct voltage control combined with the frequency droop makes a smooth transition for the VSC from grid-connected operation to islanded operation without control mode switching.

3.2.5 Fault Current Limit Control

The direct voltage control with grid-forming ability ensures satisfactory converter control during weak grid connection and island operation. However, the absence of fast inner current control loop means that it lacks the capability of fault current limiting. During an external AC fault, the d-axis PI regulator will saturate due to the error between the voltage order and the measured voltage. Consequently this could result in a very large fault current. To solve this issue, the fault current limit controller uses a current-voltage droop control illustrated in Fig. 8.

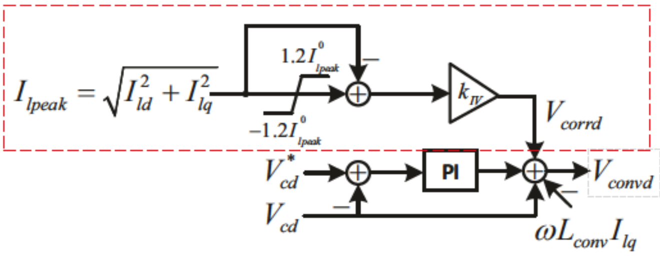

Fig. 8 Fault current limit control

During an external AC fault, the measured current magnitude will hit the upper limit of $1.2I_{lpeak}^0$ (I_{lpeak}^0 is the nominal peak output current of the VSC). The controller will produce a correction voltage V_{corrd} through a proportional gain k_{IV} to effectively reduce the VSC output $d-$axis voltage V_{convd} for fault current limiting. Once the converter output current drops below the maximum level, the fault current limit control will stop working. The transition between the normal operation and AC fault ride through operation can be smooth without control mode switching.

4 Simulation Results

The proposed control strategy of the generalised grid-forming VSC is tested using Matlab/Simulink simulations in using of the circuits shown in Fig. 1. As way of example, two cases have been illustrated including an external balanced AC fault during grid-connected operation and the transition from grid-connected operation to islanding operation. The DC side of the VSC is connected to a constant DC voltage source, and a VSC switching model is used. The detailed parameters of the VSC system and control system are listed in Table 1 and Table 2, respectively.

Table 1 Parameters of the VSC system

DC voltage source V_{dc}		1200V
AC grid voltage V_{abc}		690V
SCR of AC grid		5
VSC power rating		400kVA
Normal local load demand P_{load}		200kW
System nominal frequency f^0		50Hz
IGBT switching frequency		2.5kHz
AC LCL filter	L_{conv}	0.2pu
	C	0.15pu
	L_t	0.06pu

Table 2 Parameters of the control system

Active power droop coefficient k_{PP}	1.25×10^{-6}Hz/W
Reactive power droop coefficient k_{QQ}	0.71×10^{-4}V/Var
Frequency droop coefficient k_f	18
Direct voltage controller proportional gain k_P	0.9
Direct voltage controller integral gain k_I	150
PLL proportional gain k_{Ppll}	125
PLL integral gain k_{Ipll}	3947
Fault current limit droop coefficient k_{IV}	2.9

4.1 External Three-phase AC Fault

The simulation waveforms of the system are shown in Fig. 9 where the pre-fault active and reactive power setting points are 400kW (1pu) and 0 (0pu) respectively. The three-phase AC fault with a fault resistance of 0.01Ω is induced into the system during 2.0-2.3s at the location of F_1 shown in Fig. 1. As shown in Fig. 9, the converter filter bus voltage drops to almost 0 due to the fault, while the fault current is largely limited to the pre-set level of 1.2pu with a transient highly peak of 1.4pu at the inception of the fault. The frequency remains at 1pu due to the effective operation of the modified PLL controller, while the active and reactive power are 0 during the fault. After the fault cleared, the converter output voltage and current, frequency and delivered power quickly recovers back to 1pu. As shown in Fig. 9 (e) and (f), the active current goes to 0.66pu while the reactive current is limited at -1pu during the fault. The simulation results prove that the proposed control strategy provides a good fault ride-through operation and can restore normal operation automatically after fault clearance.

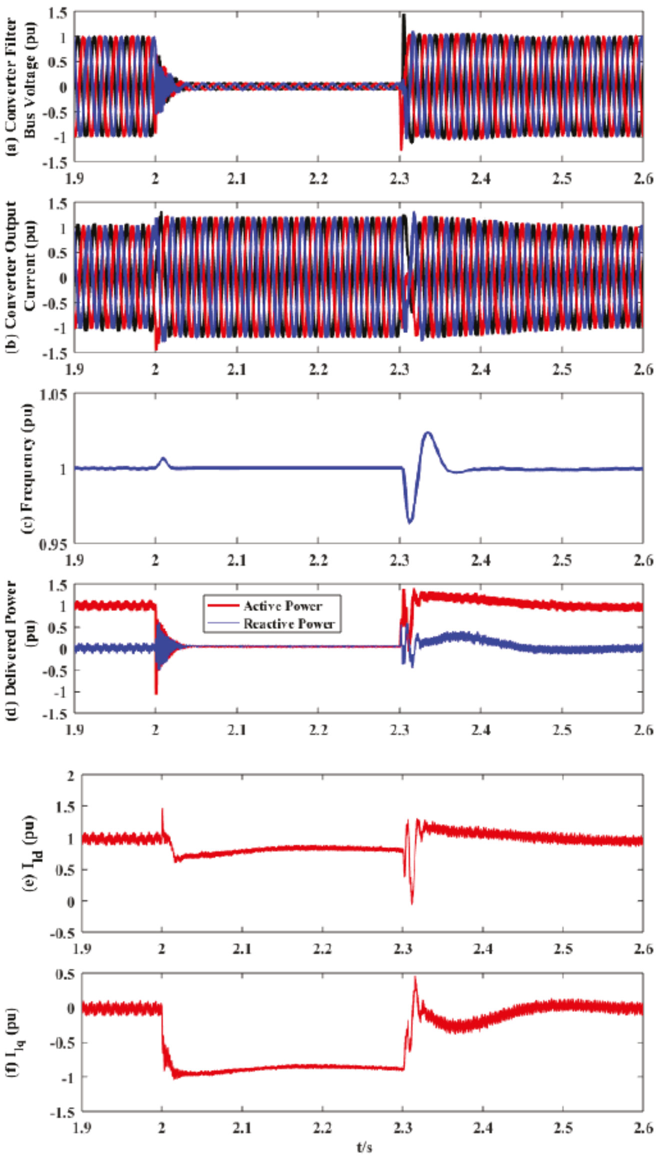

Fig. 9 (a) Converter filter bus voltage, (b) Converter output current, (c) Frequency, (d) Delivered Power, (e) Active current, (f) Reactive current

4.2 Transition from Grid-connected Operation to Islanded Operation

In this simulation, the system shown in Fig. 1 is disconnected from the AC grid by opening the Switch S at 3s, and the simulation results are depicted in Fig. 10 and Fig. 11. As can be seen from Fig. 10 (a), the converter filter bus voltage remains well-controlled during and after the transient. During islanded operation, all the generated power is fed to the local load (200kw or 0.5pu), so the active power, converter output current and active power current drops to 0.5pu from 1.0pu. Considering the characteristics of the active power droop control, the dip of the measured active power can lead to a slight rise of the frequency. According to the waveform (c) shown in Fig. 10, the frequency increases to 1.005pu after islanding. From the simulation study, it can be seen that the proposed control strategy provides good operation on both grid connection and island network.

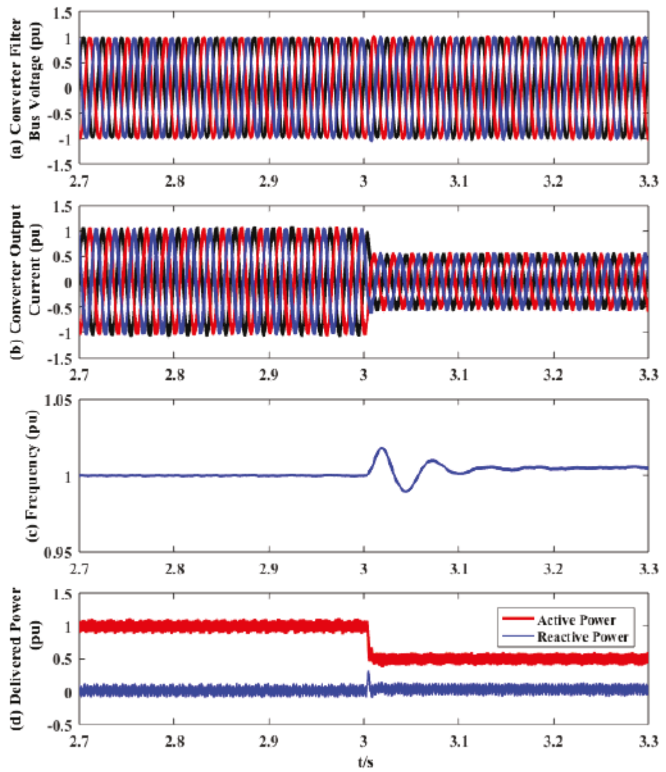

Fig. 10 (a) Converter filter bus voltage, (b) Converter output current, (c) Frequency, (d) Delivered Power

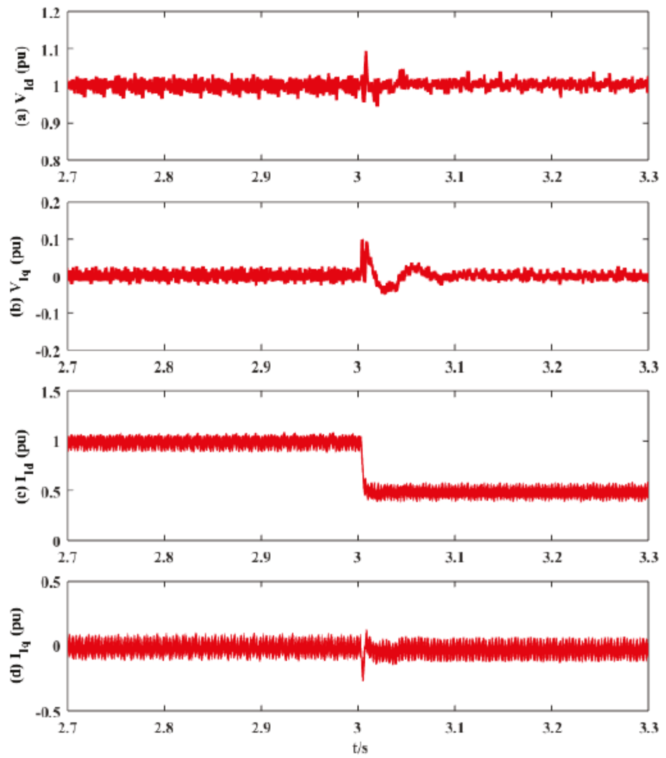

Fig. 11 (a) Converter filter bus d-component voltage, (b) Converter filter bus q-component voltage, (c) Active current, (d) Reactive current

5 Conclusion

In this paper, a generalised grid-forming VSC control is proposed for grid connection and island network with effective fault current limit control. On grid-connected operation, the generalised VSC works as a controlled AC voltage source synchronised to the grid by a PLL controller to regulate the active and reactive power flowing into the local load and AC grid with power droop control. On islanded operation, the generalised VSC establishes the voltage and frequency for the island network with direct AC voltage and frequency control to provide stable islanding operation. The transition from the grid-connected operation to islanding operation is smooth without control mode switching. During external AC faults, the fault current limit control produces correction response to compensate the d-axis voltage for fault current limiting, while the modified PLL controller ensures the frequency remains at a set value to avoid large current transient after fault clearance.

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