Optimal short-circuit current control of the grid-forming converter during grid fault condition

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Abstract
A considerable amount of rotating synchronous machines are being replaced by the increasing capacity of converter-based resources, which has stimulated a demand for grid-forming converters (GFCs) for grid supporting. The inertia and frequency responses of GFC are remarkably similar to those of synchronous generator (SG), but the inadequate capability of sourcing short-circuit current of GFCs during grid fault can lead to several serious consequences. The low short-circuit current level fails to trigger protection relays and cannot provide sustained voltage support during the fault or more effectively support the recovery of voltage after fault clearance. The short-term overcurrent capability of GFC can be promoted either from the point of view of the power devices or from the topology of it. The overcurrent capability of converter is hard-earned, so full use of it should be made. This paper proposes an optimal control strategy of short-circuit current of GFC, which can enable the GFC to source the short-circuit current with an optimal angle within the allowable magnitude. A detailed simulation model of the proposed method here is set up in PSCAD/EMTDC. The simulation results show that the proposed method can achieve better voltage supporting results compared with the traditional reactive support control.

1 | INTRODUCTION

Converter-based resources (CBRs) represented by wind power and photovoltaic have developed rapidly in recent years, and the worldwide electric power grids are undergoing a big change in generation mix [1, 2]. It is critically important for the CBRs to provide grid support functionality. Historically, the grid support requirements started from low voltage ride through (LVRT) control [3] and then developed into inertia and frequency responses [4]. Most recently, the penetration level of the CBRs continue to increase, and considerable amounts of rotating synchronous machines are being replaced by the CBRs, which have stimulated the demand for grid-forming converters [5].

Several grid-forming control strategies have been investigated, including virtual synchronous generator (VSG) [6–8], synchronous power controller (SPC) [9], and power synchronization control (PSC) [10]. The grid-forming converter (GFC)-based resources combined with the energy storage system can act similar to that of the conventional SG during a normal steady state, that is providing inertia, damping and voltage regulation. Despite numerous researchers have identified the inherent merits of the GFC control during normal operating conditions, little efforts have been devoted into analysing and understanding its transient characteristics and behavior during grid fault condition. It is infeasible for the power electronic converter with current sensitive semiconductor devices to replicate the short-circuit behavior of SG, which can tolerate a short-circuit current of 3–10 p.u. over a short time scale. Hence, the lack of short-circuit current has occurred in the grid with high penetration level of the CBRs, which will lead to several serious consequences [2, 11]. For example, the low short-circuit current fails to trigger protection relays and cannot provide sustained voltage support during the fault or more effectively support the recovery of voltage after fault clearance. Therefore, it is very meaningful to promote the short-term overcurrent capability of GFC either from the point view of the power devices [12] or from the topology of it. To that end, Shao et al. integrated phase-change materials internally in the device to hamper the temperature rise...
in the literature [12], where experiment and simulation results both suggested that it was realistic for a converter to achieve 3.0 p.u. overcurrent for 3 s and 1.5 p.u. overcurrent for 30 s. The optimal control of short-circuit current is equally important with promoting the short-term overcurrent capability of GFC. For the optimal control of short-circuit current, two key issues are faced by the GFC during grid fault condition. The first one is how to limit the short-circuit current magnitude below a tolerable value properly and precisely without causing instability problem and wind-up in the outer power loop [11]. This issue will be discussed in detail in Section 3. The second one is the optimal power factor control of GFC’s short-circuit current, which is rarely involved in the available literatures. The short-circuit current power factor of GFC can be inductive, capacitive, or resistive based on converter control and system conditions. The angle of short-circuit current (with respect to grid voltage) would vary depending on regional or interconnected power system requirements, such as LVRT and reactive support requirements during system disturbances for which the converter controls are required to support [2]. It is worth noting that to source the short-circuit current according to LVRT and reactive support requirements is not necessarily the best choice for the voltage support and recovery. Since the overcurrent capability of a converter is very precious, we should make full use of it, that is to source the short-circuit current with an optimal angle within allowable magnitude.

This paper focuses on the optimal control of GFC’s short-circuit current. The remaining parts of the paper are organised as follows. Section 2 provides a basic description of the structure of GFC and its control strategy. The short-circuit current limiting control is presented in Section 3. Section 4 gives a detailed description of the optimal short-circuit current power factor control strategy. Subsequently, the effect of the proposed optimal short-circuit current control strategy is verified by a simulation model set up in EMTDC/PSCAD in Section 5. Section 6 concludes this paper.

2 | STRUCTURE OF GFC AND ITS CONTROL STRATEGY

Figure 1 shows the basic structure of GFC and its control strategy. As shown in the figure, \( L_f \) and \( C_f \) are the inductor and capacitor filter, respectively; \( i \) is the grid-connected current; \( V_{\text{pcc}} \) is the effective value of the voltage measured at point of common coupling (PCC); \( Z_L \) is the line impedance and \( Z_g \) is the impedance of a Thevenin model grid; and \( Z_f \) is the equivalent impedance from the f bus to the fault point, which depends on the line impedance and load along the line.

As for the grid-forming control strategy, we take VSG control as an example here for a detailed discussion. The GFC under VSG control emulates a conventional SG with virtual mechanical and electrical characteristics. The virtual inertia and damping are used to emulate the mechanical part of SG, which aims to support and stabilise the frequency. The electrical part is emulated by a virtual stator impedance, which defines the power sharing and power exchange with the grid [11]. The VSG control model simulates the basic mathematical equations of SG as shown in the following equation:

\[
\begin{align*}
\frac{d\Delta \omega}{dt} &= T_m - T_e - D_P \cdot \Delta \omega \\
T_e &= \mu i_i \langle i, \sin \theta \rangle \\
e &= \omega \mu i_i \sin \theta \\
Q &= -\omega \mu i_i \langle i, \cos \theta \rangle
\end{align*}
\]

\[ (1) \]

\[
\begin{align*}
\sin \theta &= \left[ \sin \theta, \sin (\theta - 2\pi/3), \sin (\theta + 2\pi/3) \right]^T \\
\cos \theta &= \left[ \cos \theta, \cos (\theta - 2\pi/3), \cos (\theta + 2\pi/3) \right]^T
\end{align*}
\]

\[ (2) \]
where \( J, T_m, T_e, D_p, \omega_s \), and \( \theta \) are the virtual inertia, mechanical torque, electromagnetic torque, droop coefficient for the active power, virtual angular velocity, and rotor phase angle of the VSG, respectively; \( \Delta \omega \) is given by \( \Delta \omega = \omega - \omega_N \), where \( \omega_N \) is the nominal frequency; \( i_t \) and \( M_f \) are the excitation current and mutual inductance between virtual stator and rotor; \( e \) is the induction electromotive force of VSG; \( Q \) is the output reactive power of VSG; \( P_{\text{set}} \) and \( Q_{\text{set}} \) are the external set points of active and reactive power; \( V_N \) are the nominal grid voltage; \( D_t \) is the droop coefficient for the reactive power; and \( K \) is the inertia coefficient for the reactive power.

The detailed derivation of Equation (1) can be found in [7], and we avoid repetition here. A pre-synchronisation unit is also necessary for the VSG model, and the pre-synchronisation method described in [8] is adopted in this paper.

\( R_v \) and \( L_v \) are the virtual stator resistance and inductance, respectively. Implementing the virtual stator impedance has the following positive roles: (1) to limit the short-circuit current to some extent and (2) to function as a vital link between the internal electric potential of VSG and the current reference of the current loop. The current reference in the two-phase stationary frame is given by

\[
\dot{i}_{\alpha\beta}^* = \frac{e_{\alpha\beta} - i_{\alpha\beta}^*}{R_v + sL_v}
\]

(3)

where \( e_{\alpha\beta} \) and \( i_{\alpha\beta} \) are the internal electric potential of VSG and the voltage measured at PCC in the stationary frame. The virtual impedance can be implemented by the way presented in [11]. The cascaded current control loop after the grid-forming control strategy plays an important role in short-circuit current limiting control, a detailed presentation is given in Section 3.

### 3.1 The issues of the existing short-circuit current magnitude limiting control of GFC

At present, there are mainly two methods which account for the short-circuit current magnitude limitation of GFC without causing stability problem during grid fault, that is implementing the virtual short-circuit current limiting impedance [13, 14] and switching the grid-forming control into the grid-following control strategy [15, 16].

Several issues are faced by implementing the virtual current limiting impedance. First of all, the value of the short-circuit current depends on a variety of factors described before, and the endurable current value of the power devices is with certainty. And we hope the GFC can generate the maximum allowable short-circuit current during grid fault, so it is difficult to implement a virtual impedance suitable for all kinds of fault scenarios. The virtual impedance also increases the output impedance of GFC, which will decrease the synchronising power and impose a negative effect on the stability of GFC. Moreover, the introduction of a pure inductive virtual impedance will lead to increase of the total inductance of GFC, which will result in a longer decay time constant of DC-bias that exists in the short-circuit current. The DC-bias of the short-circuit current is inevitable because the inductor current cannot instantaneously change its value. An AC current signal with a slow attenuated DC component, which wastes the precious overcurrent capability of GFC for the voltage support, is not desired. On the other hand, the introduction of the pure resistive virtual impedance will also lead to the change of coupling relationship between the output power and the voltage’s amplitude and phase angle.

Except for implementing virtual current limiting impedance, switching the grid-forming control mode into the grid-following control mode can also make the short-circuit current under control by limiting the current reference of the current loop directly. However, the GFC will lose all the functionalities of grid-forming control during grid fault in this way. Moreover, a backup phase-locked loop (PLL) is necessary, which has its own instability problem when exposed to the weak grid [17]. The smooth switching between the two different control modes is also a challenge. Though we can implement a proportional-resonant (PR) controller in the stationary \( \alpha\beta \) reference frame without a PLL, the mode switch and lose of functionalities of grid-forming control are also inevitable.

### 3.2 Our proposed short-circuit current magnitude limiting control of GFC

As mentioned before, since the introduction of virtual current limiting impedance and the control mode switch all have their own problems in current limiting, it is necessary for us to propose a novel short-circuit current magnitude limiting control without causing the above-mentioned problems. The grid-forming control strategy is incapable of controlling the short-circuit current, so a cascaded current control loop after it is essential as shown in Figure 1. It is worth noting that the output variable of grid-forming control is the reference voltage,
which cannot be directly provided for the current loop. And this is one of the reasons for introducing the virtual stator resistance and inductance, which function as a vital link between the output reference voltage of grid-forming control and the current reference of the current loop. Then, the current reference of the current loop in the two-phase stationary frame is given by Equation (3). During the grid fault condition, a cascaded current limiter is needed to introduce after the calculation of the current reference. We can operate on the current reference of the current loop directly through the current limiter. However, an instantaneous hard current limiter will clip the peak of the sinusoidal signal with which the current loop operates. And this will result in distortion output currents. To address this problem, a circular current limiter is implemented as shown in Figure 2. The current reference depends on Equation (4):

\[
\begin{align*}
    i_{\alpha\beta_{c}}^* &= \begin{cases} 
        i_{\alpha\beta}^* - \frac{\mu_{\text{max}}}{\sqrt{(\mu_{\alpha})^2 + (\mu_{\beta})^2}} & \text{if } \sqrt{(\mu_{\alpha})^2 + (\mu_{\beta})^2} \leq I_{\text{max}} \\
        i_{\alpha\beta}^* & \text{otherwise}
    \end{cases} 
\end{align*}
\]

where \(I_{\text{max}}\) is the maximum endurable current value of the power device and \(i_{\alpha\beta_{c}}^*\) is the reference for the current loop after current limiting.

However, the output power of the GFC would be much lower than the reference power of grid-forming control because of the voltage dip and current limiting. If we do not adjust the high reference power of outer power loop in grid-forming control, it will undoubtedly result in wind-up of the outer power loop, which would exert an adverse influence on fault response. The integrator wind-up would particularly lead to an elongated unsatisfactory post-fault response [11]. It is more than necessary to implement reference power adjustment while adopting current limiting control. During the grid fault condition, the short-term new apparent capacity of GFC should be adjusted according to the voltage dip and the maximum allowable current value \(I_{\text{max}}\), as shown in Equation (5):

\[
\begin{align*}
    S_{\text{new}} &= \begin{cases} 
        \sum_{i=1}^{n} V_{\text{PCC}} \sqrt{(\mu_{\alpha_{i}})^2 + (\mu_{\beta_{i}})^2} & \text{if } \sqrt{(\mu_{\alpha_{i}})^2 + (\mu_{\beta_{i}})^2} \geq I_{N} \\
        S_N & \text{otherwise}
    \end{cases} 
\end{align*}
\]

where \(S_N\) is the nominal apparent capacity during normal condition. It is notable that the lifespan of new apparent capacity \(S_{\text{new}}\) depends on the duration time the current \(\sqrt{(\mu_{\alpha_{i}})^2 + (\mu_{\beta_{i}})^2}\) can hold, which is determined by characteristics of the device.

The new reference reactive power \(Q_{\text{new}}^*\) during a fault can be determined according to the voltage sag, as shown in the following equation:

\[
Q_{\text{new}}^* = \begin{cases} 
    Q_{\text{set}} + D_q \cdot (V_{N} - V_{\text{PCC}}) & \text{if } \frac{V_{\text{PCC}}}{V_{N}} \geq 0.9 \\
    2S_{\text{new}} \cdot (1 - \frac{V_{\text{PCC}}}{V_{N}}) & \text{if } 0.5 \leq \frac{V_{\text{PCC}}}{V_{N}} < 0.9 \\
    \delta_{\text{new}}^* & \text{otherwise}
\end{cases}
\]

where \(V_{N}\) is the nominal grid voltage. The new reference active power can be calculated by Equation (7). This control method during the grid fault condition is called reactive support control:

\[
P_{\text{new}}^* = \sqrt{(S_{\text{new}})^2 - (Q_{\text{new}}^*)^2}
\]

The recalculation of the new reference active and reactive power complies with the grid codes. In this way, the wind-up of outer power loop of grid-forming control can be avoided, which would guarantee a satisfied fault response.

### 4.1 The Optimal Power Factor Control of GFC Short-Circuit Current

As shown in Figure 1, a symmetrical fault occurs near the \(v_f\) bus. Sensibly, the short-circuit current phasor is composed of two parts according to the superposition principle, among which one part is sourced from the grid and the other is sourced from the GFC. A simplified diagram of the system during a fault is shown in Figure 3. The short-circuit current phasor \(i_f\) is presented by

\[
\vec{i}_f = \vec{i}_g + \vec{i}_{GFC}
\]

where \(\vec{i}_g\) is the grid current phasor and \(\vec{i}_{GFC}\) is the GFC current phasor. The voltage magnitude of the \(f\) bus closed to the fault point can be described as

\[
V_f = |\vec{i}_f| \cdot |Z_f|
\]

where \(|\vec{i}_f|\) is the amplitude of short-circuit current and \(|Z_f|\) is the amplitude of equivalent impedance from the \(f\) bus to the fault point.
We have to notice that once the fault occurs, the impedance $Z_f$ is determined and the amplitude of $\vec{i}_f$ is the only variable in determining the values of $V_f$. During the fault condition, the converter should generally limit the short-circuit current below the endurable value, which is usually 1.2–1.3 p.u. if not improved, to protect the current sensitive devices. Then low short-circuit current level has resulted from the low short-term
overcurrent capability of the converter, which would lead to failure in sustained voltage supporting during the fault, recovery of voltage after fault clearance and triggering protection relays, as mentioned above. As such, how to promote the short-term overcurrent capability of GFC is valuable. Some useful attempts have been made in the literature [12]. It is equally important to make full use of the hard-earned overcurrent capability of GFC.

If we do not take GFC into consideration, the power factor of the short-circuit current sourced from the grid is determined by the line impedance and load along the line. However, the new reference power of GFC during grid fault, that is the power factor of the short-circuit current sourced from GFC, is commonly determined by the voltage dip and the new apparent capacity of GFC, as presented by Equations (5), (6), and (7). In this case, the power factors of $i_g$ and $i_{GFC}$ are not necessarily the same, then the additive effect of the GFC current and grid current is not the best, that is the magnitude of $i_f$ is not optimal for the voltage support. Figure 4 shows such a scenario where the power factors of $i_g$ and $i_{GFC}$ are not the same. Assuming a constant magnitude for the GFC current during fault, its effect on the total fault current magnitude then depends on the power factor, that is its phase angle. Since the low short-circuit level has resulted in the grid with high penetration level of the CBRs, we should do everything possible to increase the magnitude of the short-circuit current for voltage support during fault. The power factor of GFC current can be flexibly controlled. When the power factor of GFC current is controlled the same with $i_g$, the magnitude of $i_f$ reaches a maximum, as shown in Figure 5.

Figure 6 shows the phasor illustration of optimal power factor control of GFC current. The points O and O’ represent the...
starting point and ending point of the grid current phasor \( \vec{i}_g \), respectively. As shown in the figure, a series of black arrows represents the GFC fault current phasors with different phase angles and the blue arrows represent the corresponding fault current phasors after superposition. The endpoint for the fault current phasor \( \vec{i}_f \) (such as point A, B, C, and D) can only fall on the circumference of the circle centered around point O’ with a radius of \( |\vec{i}_{GFC}| \). When the endpoint for the fault current phasor falls on the point D, the magnitude of the fault current reaches a maximum. So, the point D is called the optimal point and the corresponding power factor of \( i_{GFC} \) is called the optimal power factor, which is the same with that of \( i_g \).

When implementing the proposed optimal power factor control in practice, how to get the reference phase angle for GFC short-circuit current is an issue faced by us. Nowadays, transition of the existing centrally controlled electric power systems to smart grids enables the continuous monitoring and control of power system elements [18]. Real-time current and voltage information including the magnitudes and phase angles from all system buses, which are available to control different assets of the power system, can be obtained from the advanced metering and communication infrastructure of smart grids. It is possible to detect the abnormal conditions and take the necessary control actions according to the available information from
The switching between the normal operation and the optimal power factor control depends on the value of $V_{pcc}$, which enables the optimal power factor operation during fault condition. And the threshold value is chosen as 0.9 p.u. It is worth noting that the switching between the normal operation and the optimal power factor control can be realised by only changing the reference power of the grid-forming control strategy rather than switching the control mode. The reference power of the outer power loop can be calculated by the current and voltage phasor information communicated between the smart meters and the control units during fault condition. The reference power factor of GFC short-circuit current can be obtained from the smart meter measured the grid current and the magnitude of it is obtained from the circular current limiter. A combination of the two provides the current reference of GFC during fault, which is used to calculate the reference power of GFC. Based on the received data, the reference power of GFC during fault is shown by Equation (10):

$$\begin{align*}
P_{op}^* &= \frac{\sqrt{6}}{2} V_{PCC} \sqrt{\left( i_{\alpha}^* \right)^2 + \left( i_{\beta}^* \right)^2 \cos (\varphi_v - \varphi_i)} \\
Q_{op}^* &= \frac{\sqrt{6}}{2} V_{PCC} \sqrt{\left( i_{\alpha}^* \right)^2 + \left( i_{\beta}^* \right)^2 \sin (\varphi_v - \varphi_i)}
\end{align*}$$

(10)

where $Q_{op}^*$ and $P_{op}^*$ are the reference active and reactive power of outer power loop under optimal power factor control during fault. $\varphi_v$ is the phase angle of the voltage measured at PCC and $\varphi_i$ is the phase angle of the grid current during fault. The overall control structure of the proposed optimal short-circuit current control of GFC during fault is shown in Figure 7.

5 | SIMULATION RESULTS

Our proposed optimal short-circuit current control has been verified with simulation set-up in PSCAD/EMTDC. The parameters of the GFC and the grid in the simulation model are shown in Table 1. For the sake of comparison, our proposed optimal short-circuit current control method and the method without optimal power factor control, that is the reactive support control described in Section 3 are simulated, respectively. It is worth noting that the two simulation models are the same everywhere except for with or without the optimal power factor control of the short-circuit current.

The two simulation models were carried out according to the following sequence of actions:

1. starting the system and using the pre-synchronisation algorithm adopted in [8], which is not discussed in this paper;
2. completing the synchronisation at $t = 1$ s and turning the circuit breaker on at the same time, $P_{set} = 0, Q_{set} = 0$;
3. enabling the voltage droop mechanism at $t = 1.2$ s;
4. issuing the power instruction at $t = 2$ s, $P_{\text{set}} = 20$ kW, $Q_{\text{set}} = 2$ kVAR;
5. symmetrical fault occurring at $t = 5$ s;
6. fault clearing at $t = 6$ s.

We assume that 1.5 times of the nominal current value can be achieved by the power devices during a short time. Figure 8 shows the current waveforms of the GFC under our proposed optimal short-circuit current control. Figure 9 shows the current waveforms of the GFC without optimal short-circuit current control. As we can see from the two figures, the circular current limiter can guarantee that the magnitude of GFC’s short-circuit current would not exceed the maximum allowable value. The DC component of the short-circuit current is suppressed by the current loop. During grid fault condition, the magnitude of short-circuit currents under the two control methods, that is the optimal control and reactive support control are almost the same, but their phase angles are not the same with each other, as shown in Figure 10. Our proposed optimal short-circuit current control method can make the GFC short-circuit current operate at an optimal phase angle, which is more effective for voltage support during grid fault. And the following simulation results can prove this point. However, there is no difference between the two methods during a normal steady state, as shown in Figures 8 and 9.

Figures 11 and 12 show the power setting and the actual output power of the GFC under the two control methods, respectively. As we can see from the two figures, the power settings during the fault are different.

Figure 13 shows the voltage of the f bus during operation. As we can see from the figure, the voltage of the f bus during the grid fault condition under the optimal control is about 4% higher than that under reactive support control in this case. We have to notice that the magnitude of the short-circuit current
under optimal control is the same with that under reactive support control. This means that we can make full use of the overcurrent capability of the power device and improve the voltage supporting capability of the grid with high penetration level of the CBRs without increasing cost by only changing the control method of the converter during grid fault. Though one converter under the optimal short-circuit current control makes little contribution to the voltage support during fault due to its limiting capacity, the additive effects of the numerous converters should be noticeable.

Figure 14 shows the voltage of the f bus during operation with two GFCs connecting parallelly to the f bus. As we can see from the figure, the voltage of the f bus during the grid fault condition with two GFCs is higher than that with one GFC. The voltage support effect provided by the two GFCs under the optimal control during the sags is more remarkable in this case. And the f bus voltage during fault under the optimal control is around 7%-8% higher than that under reactive support control with two paralleled GFCs.

6 | CONCLUSION

An optimal short-circuit current control of the grid-forming converter during grid fault condition is proposed in this paper, which can not only suitably and precisely limit the magnitude of the short-circuit current below an endurable value without causing instability problem but also make full use of the hard-earned overcurrent capability of power devices and make the short-circuit current operate at the optimal power factor for grid voltage support during the fault. The GFC under our proposed optimal short-circuit current control can achieve a better voltage support effect with the same overcurrent capability and no additional cost compared with that under reactive support control. The simulation results verify the feasibility and validity of our proposed optimal short-circuit current control method.

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