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Active Fault Current Limitation for Low-Voltage Ride-Through of Networked Microgrids

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Abstract—With the continuously increasing penetration of networked microgrids (MGs) on the local utility grid (UG), MGs face the challenge to avoid increasing system fault currents during low-voltage ride-through (LVRT). To solve this challenge, an active fault current limitation (AFCL) method is proposed with three parts: 1) a novel phase angle adjustment (PAA) strategy is conducted to relieve the impact of MGs output fault current on system fault current; 2) the current injection (CI) strategy for LVRT is formulated to fit the function of PAA; 3) a novel converter current generation (CCG) strategy is developed to achieve a better voltage support ability by considering network impedance characteristics. The proposed AFCL method is applied to the back-to-back converter, as a connection interface between MGs and UG. Extensive tests and pertinent results have verified the improvements of proposed AFCL method with better LVRT performance, while the networked MGs output fault current does not increase the amplitude of system fault current.

Index Terms—Networked microgrids, back-to-back converter, low-voltage ride-through, fault current limitation.

NOMENCLATURE

Abbreviations

LVRT  Low-voltage ride-through
AFCL  Active fault current limitation
PAA  Phase angle adjustment
CI  Current injection
CCG  Converter current generation
BTB  Back-to-back
PCC  Point of common coupling
GSC  Grid side converter in BTB
MSC  Microgrid side converter in BTB

Parameters and variables

Indices and superscripts

*  Reference value
^  Amplitude value
N  Rated value
+ , −  Positive/negative sequence
α , β  Variables in stationary reference frame
q , p  Reactive/active current/power
I^ 1 , m , M  1th , mth , Mth MGs

Indices and variables

I^ 1 , I^ m  Injected/reactive current for LVRT
U^ 0 , U^ g , U^ N  Pre-fault voltage, post-fault voltage, rated voltage
I^ m, i N  Converter’s maximum/rated current
k^ cLVRT , k^ rLVRT  Adjustable coefficients for grid code of LVRT
δ^ U , δ^ PCC  PAA for mth MG fault current
δ^ UG , δ^ PCC  Voltage phase angle difference from UG and MGs to fault branch
R m , X m  Network impedance from mth MG to fault bus
R UG , X UG  Network impedance from UG to fault bus
U^ + , U^ −  Positive/negative sequence voltage amplitude
ω  UG angular frequency
I^ m, i q f r, r f r  Reactive/active current in stationary reference frame
k^ p , k^ q , k^ r , k^ s  Positive and negative sequence adjustable coefficients for CCG strategy
u^ dc  DC voltage in BTB converter

I. INTRODUCTION

MICROGRIDS (MGs) are commonly regarded as an efficient platform to aggregate a cluster of geographically close distributed generators (DGs) and loads [1]. With increasing integration level of distributed energy resources, MGs are interconnected as a networked MGs system, forming a promising solution for refining energy and providing ancillary services in the local distribution networks [1]. Among these services, the LVRT of networked MGs, which requires MGs to maintain connected with UG during voltage sags, plays a more crucial role than ever before, since the numbers and capacity of MGs have been continuously increasing [2]-[3].

Most of the existing LVRT practices are applied for DGs (e.g., wind farms and photovoltaic arrays) [4]-[6]. It is meaningful to study the LVRT of networked MGs since its unplanned islanding mode will cause some serious problem: 1) There will be an un-ignored capacity reduction of UG, which
may lead to the invalidity of the original dispatch plan [7]; 2) There will be a further deterioration of UG voltage amplitude and frequency fluctuations if networked MGs are disconnected suddenly [8]; 3) The power supply of critical load in MGs will not be guaranteed if the power generation in MGs is insufficient [9]; 4) The excessive power generation in MGs will be wasted when the power cannot be delivered to UG; besides, the energy storage system might be fully charged [10]; 5) After fault is cleared, the reconnection of MGs would cause large inrush current and synchronization problems [11].

The LVRT of MGs is essentially necessary. However, this LVRT ancillary service will bring a serious challenge of monotonically increasing system fault current because MGs will contribute fault current to fault branch along with the UG [12]. Considering that MGs fault current is an additional and adverse current, it is imperative to reduce the impact of MGs fault current, in order to keep the system fault current level unchanged [12]. Otherwise, the increased part of fault current will cause serious consequences when system fault current exceeds the maximum endurance of electric equipment [12]-[13]. First, the injection of MGs fault current will lead to the costly upgrades of grid components, such as transmission lines, transformers, circuit breakers, and fuses [14]. Second, the additional MGs fault current will increase the difficulty of relay protection, even causing protection failure and catastrophic damage, which would threaten grid security and stability [15]. Third, the high-level fault current will increase the electromagnetic interference to fault surrounding area, and severely affect personal and equipment safety [16].

Numerous studies have been developed to conquer DGs’ and MGs’ impact on system fault current during its LVRT. One is passive methods. The advanced protection equipment, such as inverse time admittance relay, are equipped and upgraded to accommodate the increase of fault current [17]. Considering protection communications problem, the phasor measurement unit (PMU) strategy and agent-based protection strategy are also proposed in [18]. To avoid large-scale updates of protection devices and communication equipment, fault current limiters are adopted to attenuate the impact of DGs fault currents [13], [19]. The others represent active methods. Initially, based on IEEE Std 1547–2003 and IEEE Std 929–2000, the DGs and MGs are disconnected once UG faults occur [20]. Then, the capacity threshold strategy with the consideration of the size and location of DGs is studied to limit the DGs output fault current [21]. After that, since the voltage sags will increase the peak value of inverter output current under the same power injection, the peak current limitation strategy is proposed for DGs to avoid sudden tripping of grid-tied inverter [22]. However, the core essence of above active methods is to protect the grid-tied inverter itself, since inverter can only withstand 2–3 times rated current [23]-[24]. Based on superposition theorem of sinusoidal current, the DGs will inevitably increase system fault current, when phase angles of different injected fault current are basically the same or with small difference.

More than focusing on inverter protection, the increasing fault current in system level becomes a challenge. Recently, in order to weaken the influence of DGs on system fault current during its LVRT, the phase angle adjustment of DGs fault current is proposed to make DGs and UG fault currents have a certain phase angle difference [23]-[25]. However, although the system fault current amplitude will be lower than the sum of DGs and UG fault current amplitude, it is still significantly larger than UG fault current amplitude [23]-[25]. Why system fault current cannot be equal to UG fault current is the inaccurate phase angle adjustment. In practical systems, the fault occurs arbitrarily, while the voltage/current sampling points of PCC and UG are generally fixed based on PMU or the other sensor detection devices. Considering the long line distances from MGs and UG to fault branch, one of the most critical factors for phase angle adjustment is to comprehensively consider the phase angle differences on the realistic line impedance. Therefore, a novel PAA strategy is conducted to completely eliminate the impact of MGs fault current by considering voltage’s phase angle differences from UG to fault branch and from MGs to fault branch.

In practice, most of the existing MGs/DGs interact flexibly to UG via the simple PCC connection interface, such as electro-mechanical circuit breakers and solid-state switches [26]. Although these interfaces require a simple structure and less investment, the BTB converter becomes more attractive, since it can not only achieve a flexible and reliable bidirectional power flow, but also isolate the frequency and voltage fluctuation between UG and MGs [27]. In industrial distribution networks, with the high demand for power quality of both UG and MGs, the BTB converter is widely used to meet customers’ requirements that have a large proportion of sensitive loads, such as chemical plants and semiconductor devices [9]. Therefore, the reason why we apply BTB converters to connect MGs and UG is to deal with these special scenarios with high demand power quality. The inverter dominated MGs that are equipped by BTB converter can be considered as a centralized power source. In order to achieve the trade-off between LVRT and the active fault current limitation, the CI strategy for the grid code requirement of LVRT is conducted to fit the function of the PAA strategy.

The key of LVRT is to control PCC voltage, which relates to the output current of the BTB converter and the network impedance. This impedance is respectively assumed as pure inductive, pure resistive, and resistive-inductive in medium/high voltage network, low voltage network, and the complex network [2]-[3], [13]. The network impedance can greatly affect the amplitude/phase angle of PCC voltage [2]-[3], [19]-[20], [23]-[25]. Numerous studies have been developed to improve CCG by considering network impedance [28]-[30]. What they have in common is to consider impedance as feedforward/feedback control loops in CCG, such as (virtual) impedance control, and harmonic resonant regulator [28]-[30]. Different from feedforward/feedback loops [28]-[30], directly embedding impedance to CCG controller will be interesting. For the purpose of achieving a better PCC voltage support ability during the LVRT of networked MGs, a novel CCG strategy is developed by embedding the network impedance characteristics.
The motivation of this paper is to avoid monotonically increasing system fault currents during the LVRT of networked MGs. To solve this challenge, an AFCL method is proposed to relieve the impact of MGs fault current. The major contributions are outlined as: 1) a novel PAA strategy is conducted for MGs output fault current with considering voltage’s phase angle differences from UG to fault branch and from MGs to fault branch, in order to keep the amplitude of system fault current unchanged; 2) the CI strategy is conducted to fit the function of PAA under the requirement of LVRT grid code; 3) a novel CCG strategy is developed to improve the LVRT performance by embedding network impedance characteristics.

The remainder of this paper is organized logically. The fault current requirements during LVRT is formulated in Section II. An AFCL method consists of PAA, CI, and CCG strategies are conducted in Section III. Comparative tests with AFCL during LVRT of networked MGs are developed in Section IV. The conclusion is provided in Section V.

II. FAULT CURRENT REQUIREMENTS DURING LVRT OF NETWORKED MGs

Before fault current limitation, it is necessary to analyze the fault current requirements during LVRT of networked MGs.

A. System Fault Current Flow

The PCC connection interface of networked MGs is designed as a BTB converter, which consists of grid side converter (GSC) and MG side converter (MSC). The UG and MGs are considered as uniform power sources. During LVRT of networked MGs, all MGs inject fault current into fault branch along with UG [23]-[25]. The structure of networked MGs and the flow path of fault currents are shown in Fig. 1.

![Fig. 1. Structure of networked MGs and the corresponding fault current flow.](image1)

Based on Fig. 1, \( Z_{UG} \) is the network impedance from UG to fault bus, \( Z_I \) and \( Z_M \) are the impedance from \( I^th \) and \( M^th \) MG to fault bus. \( Z_F \) is the impedance in fault branch. The \( I_{UG} \), \( I_I \), \( I_M \) and \( \theta_{I/UG} \), \( \theta_I \), \( \theta_M \) are the amplitude and phase angle of UG fault current, \( I_i \) and \( M_i \) MG fault current. The \( I_F \) and \( \theta_F \) are the amplitude and phase angle of system fault current.

During LVRT of networked MGs, the system fault current is described as

\[
I_F = \frac{Z_I}{Z_F} I_{UG} + \frac{I_{UG}}{Z_F} (I_I + \ldots + I_M) + \frac{Z_{UG}}{Z_F} (I_I + \ldots + I_M + \ldots + I_M). 
\]  
(1)

For the low-impedance fault \((Z_F << Z_I/\ldots/\ldots/Z_M, Z_F << Z_{UG})\) [25], then, the \( I_F \) is further approximated as

\[
I_F = I_{UG} + (I_I + \ldots + I_M + \ldots + I_M). 
\]  
(2)

According to (2), the system fault current amplitude is much greater than that in case without MGs \((I_F = I_{UG})\).

B. Fault Current Injection by Grid Code Requirement

The grid code requirement for the LVRT operation is shown in Fig. 2. In Fig. 2(a), different countries have different grid code requirements to withstand voltage sags during LVRT. After comparison, the German’s E.ON Netz code is adopted, due to its strict requirements [2]-[3]. Once PCC voltage sags below the red curve, MGs are allowed to disconnect from UG [2]-[3]. Otherwise, MGs should remain connected by injecting a certain reactive current. In Fig. 2(b), when the PCC voltage falls below 90% of rated voltage, each 1% positive sequence voltage sag requires to inject at least \( k_{LVRT} \) increment of positive sequence reactive current. If needed, it is required to inject 1 p.u. of reactive current. Thus, the requirement of positive sequence reactive current for the \( m^{th} \) MG is estimated as

\[
I_{eq}^+ = \begin{cases} 
0, & U_F^+ \in (0.9U_N, 1.2U_N) \\
U_N^+ - \frac{U_F^+ - U_N^+}{U_N^+} I_N^+, & U_F^+ \in (0.5U_N, 0.9U_N), \\
0 & U_F^+ \in (0.5U_N, 0.9U_N). 
\end{cases} 
\]  
(3)

However, there is still no unified mechanism about negative sequence reactive current requirement. In unbalanced fault voltage sag, in order to provide a satisfactory LVRT and system protection, the negative sequence reactive current can be consistent with the positive sequence. When the voltage drops low (e.g., lower than 0.5 p.u.), the requirements of positive sequence reactive current should be satisfied first based on grid code, while negative reactive current is set to be zero. That is, the LVRT should give priority to PCC voltage support, rather than voltage balance. When the fault voltage ranges from 0.5–0.9 p.u., similar to (3) and based on the analysis in [31], the negative sequence current is injected in proportion to negative sequence voltage. Thus, the negative sequence reactive current can be estimated as

\[
I_{eq}^- = \begin{cases} 
0, & U_F^- \in (0.9U_N, 1.2U_N) \\
U_N^- - \frac{U_F^- - U_N^-}{U_N^-} I_N^-, & U_F^- \in (0.5U_N, 0.9U_N), \\
0 & U_F^- \in (0.5U_N, 0.9U_N). 
\end{cases} 
\]  
(4)

where \( k_{LVRT} \geq 2 \), according to German grid code [2]-[3], [32].

![Fig. 2. Grid code requirements. (a) LVRT protocols of different countries for the tolerance of voltage sags, (b) Positive sequence reactive current requirement by Germany.](image2)
III. ACTIVE FAULT CURRENT LIMITATION METHOD FOR LVRT OF NETWORKED MGs

The behavior of LVRT of networked MGs is determined by the performance of the BTB converter. To relieve the contribution of MGs fault current on system fault current, an AFCL method is proposed with PAA, CI, and CCG strategies.

A. PAA Strategy

Based on Fig. 1, system fault current is formed by adding UG fault current and MGs fault current. The UG fault current is synchronous and non-adjustable, while the MGs fault current can be controlled through the BTB converter. Based on the GSC, the MGs fault current has the controllable variables, including amplitude and angle. Based on the same amplitude, the contribution of MGs fault current on system fault current depends on its phase angle [23]-[25]. Taking one of MG as an example, the vector analysis of fault voltage/current depends on its phase angle [23]-[25]. Taking one of MG as an example, the vector analysis of fault voltage/current during LVRT of MG's fault current on system fault current is relieved by the PAA strategy no matter what kind of scenarios.

Based on the analyses of Fig. 3, the key of PAA is to calculate and determine the feasible phase angle of \( m \)th MG current \((I_m)\) during LVRT of networked MGs. Considering the long line distances from MGs to UG, there is a non-negligible angle between \( V_{PCC} \) and \( V_{UG} \). However, the phase angles of \( V_{PCC} \) and \( V_{UG} \) are simply assumed to be the same in the existing method [23]-[25]. To improve the mitigation ability of MG fault current, we propose a novel PAA strategy by considering voltage’s phase angle differences from UG to fault branch \((\delta_{UG})\) and from MGs to fault branch \((\delta_{PCC})\).

As shown in Fig. 3, the system fault current with PAA strategy is expressed as

\[
\vec{I}_{m}^{' PAA} = \vec{I}_{m}^{PAA} = \vec{I}_{m}^{PAA} \cdot \sin(\theta_{m})
\]

The amplitude relationship is described as

\[
\vec{I}_{m}^{PAA} = \vec{I}_{m}^{PAA} \cdot \sin(\theta_{m})
\]

According to (6), the (5) can be rewritten as

\[
\vec{I}_{m}^{PAA} \cdot \cos(\theta_{m}) + \vec{I}_{m}^{PAA} \cdot \sin(\theta_{m}) = \vec{I}_{m}^{PAA} \cdot \cos(\theta_{m})
\]

Then

\[
\theta_{m}^{PAA} = 180^\circ - \theta_{m}^{PAA} - \cos^{-1}\left(\frac{\vec{I}_{m}^{PAA} \cdot \cos(\theta_{m})}{2\vec{I}_{m}^{PAA}}\right)
\]

Based on Fig. 3(b)-(c), considering the voltage’s phase angle difference of \( \delta_{UG} \) and \( \delta_{PCC} \) under scenario 1 and scenario 2, the feasible phase angle of \( I_m \) is expressed as

\[
\theta_{m}^{PAA} = \begin{cases} \theta_{m}^{PAA} - (\delta_{UG} - \delta_{PCC}) & \delta_{UG} > \delta_{PCC} \\ \theta_{m}^{PAA} - (\delta_{UG} - \delta_{PCC}) & \delta_{UG} < \delta_{PCC} \end{cases}
\]

Considering the nature of \( \theta_{m}^{PAA} \), there exists

\[
\theta_{m}^{PAA} = \frac{\vec{I}_{m}^{PAA} \cdot \cos(\theta_{m})}{2\vec{I}_{m}^{PAA}}
\]

Based on (10)-(11), the (9) is rewritten as

\[
\sin(\theta_{m}^{PAA}) \cdot \cos(180^\circ - \theta_{m}^{PAA} - \delta_{PCC}) = \frac{\vec{I}_{m}^{PAA} \cdot \cos(\theta_{m})}{2\vec{I}_{m}^{PAA}}
\]

Then, the (12) is rewritten as

\[
\sin(\theta_{m}^{PAA}) \cdot \cos(180^\circ - \theta_{m}^{PAA} - \delta_{PCC}) = \frac{\vec{I}_{m}^{PAA} \cdot \cos(\theta_{m})}{2\vec{I}_{m}^{PAA}}
\]

Based on the mathematical transformation of (12), under scenario 1 and scenario 2, the novel PAA strategy with considering voltage’s phase angle differences from UG to fault branch and from MGs to fault branch is proposed as

\[
\theta_{m}^{PAA} = \begin{cases} \frac{1}{2}[180^\circ - \theta_{m}^{PAA} + (\delta_{UG} - \delta_{PCC})] + \sin^{-1}\left(\frac{\vec{I}_{m}^{PAA} \cdot \cos(\theta_{m})}{2\vec{I}_{m}^{PAA}}\right) \\ \frac{1}{2}[180^\circ - \theta_{m}^{PAA} + (\delta_{UG} - \delta_{PCC})] - \sin^{-1}\left(\frac{\vec{I}_{m}^{PAA} \cdot \cos(\theta_{m})}{2\vec{I}_{m}^{PAA}}\right) \end{cases}
\]

in case without PAA, the \( I_m \) is much larger than \( I_{UG} \), while, in the case with PAA, the \( I_m \) is equal to \( I_{UG} \). Thus, the contribution of MG’s fault current on system fault current is relieved by the PAA strategy no matter what kind of scenarios.

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B. CI Strategy

In order to adjust the phase angle of BTB converter output current to fit the PAA strategy, the active current should be injected with a certain angle ($\theta^*$). Based on (3) and (11), the requirement of active current for the $m^{th}$ MG is proposed as

$$I_{\text{out}}^{\alpha\beta} = \frac{1}{U_o^+} \left[ I_{\text{desired}}^{\alpha\beta} \tan(\theta^*) \right],$$

where $U_o^+ \in (0,9U_o/\sqrt{3},2U_o/\sqrt{3}]$. Based on (3) and (15), to avoid tripping of BTB converter during LVRT. The BTB converter output current is limited as

$$I_{\text{peak}} = \frac{2}{3} \sqrt{(I_{\text{max}})^2 + (I_{\text{ref}})^2 + I_{\text{ref}}^2},$$

where $I_{\text{max}}$ is the maximum current, which is limited to 2–3 times $I_{\text{th}}$ in silicon devices [23]-[24].

According to [13], and based on (3)-(4) and (15), ignoring oscillatory terms of instantaneous active/reactive power, the reference injected active/reactive power is obtained as

$$P_n^* = \frac{3}{2} (U^+ I_{\text{out}} - U^- I_{\text{out}}),$$

$$Q_n^* = \frac{3}{2} (U^+ I_{\text{out}} - U^- I_{\text{out}}).$$

C. CCG Strategy

The active/reactive powers of $m^{th}$ MG is injected as

$$\begin{bmatrix} P_n^* \\ Q_n^* \end{bmatrix} = \begin{bmatrix} 3/2 & 0 \\ 0 & 3/2 \end{bmatrix} \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} I_{\text{ref}}.$$

Based on (18), and ignoring active/reactive power oscillations, the BTB converter output current is

$$I_{\text{out}} = \frac{2}{3} [u_\alpha^2 + u_\beta^2 + (u_\alpha + u_\beta)^2] P_n^*$$

$$I_{\text{inj}}^{\alpha\beta} = \frac{2}{3} [u_\alpha^2 + u_\beta^2 + (u_\alpha + u_\beta)^2] Q_n^*$$

In existing mainstream CCG strategy, the coefficients $k_0$, $k_1$, $k_2$ are embedded in (19) to achieve flexible active/reactive current injection [32].

$$I_{\text{out}}^{\alpha\beta} = \frac{2}{3} \begin{bmatrix} k_0 u_\alpha + k_1 u_\beta + k_2 u_{\text{ref}} \\ k_0 u_\beta + k_1 u_\alpha + k_2 u_{\text{ref}} \end{bmatrix} P_n^*$$

$$I_{\text{inj}}^{\alpha\beta} = \frac{2}{3} \begin{bmatrix} k_0 u_\alpha + k_1 u_\beta + k_2 u_{\text{ref}} \\ k_0 u_\beta + k_1 u_\alpha + k_2 u_{\text{ref}} \end{bmatrix} Q_n^*$$

In existing strategy in (20), the network impedance, which has a great influence on the phase angle and amplitude for PCC voltage, has often been overlooked [32]. In order to improve the MG’s LVRT ability, a novel CCG strategy is proposed by considering the network impedance as

$$I_{\text{out}}^{\alpha\beta} = \frac{2}{3} \begin{bmatrix} k_0 u_\alpha + k_1 u_\beta + k_2 u_{\text{ref}} \\ k_0 u_\beta + k_1 u_\alpha + k_2 u_{\text{ref}} \end{bmatrix} P_n^*$$

$$I_{\text{inj}}^{\alpha\beta} = \frac{2}{3} \begin{bmatrix} k_0 u_\alpha + k_1 u_\beta + k_2 u_{\text{ref}} \\ k_0 u_\beta + k_1 u_\alpha + k_2 u_{\text{ref}} \end{bmatrix} Q_n^*$$

To avoid tripping of BTB converter, the peak current limiting in (16) is achieved as

$$\left| I_{\text{out}} \right| = \frac{1}{2} \left( I_{\text{out}}^{\alpha\beta} + I_{\text{out}}^{\alpha\beta} \right) = \frac{1}{2} \left( I_{\text{out}}^{\alpha\beta} + I_{\text{out}}^{\alpha\beta} \right).$$

Various proportional-integral (PI) control methods and proportional-resonant (PR) control methods have been studied to improve the quality of closed-loop current control [33]-[34]. Generally, there are three reference frames for power electronic control: synchronous reference frame (dq), stationary reference frame (abf), and natural frame (abc). To achieve zero steady-state current tracking error, the PI control in dq frame is the conventional popular technique to hold an infinite gain for tracking dc reference [33]-[34]. However, it is not well suited for ac reference (e.g., current control in single-phase inverter or three-phase inverter in abf frame), due to the steady-state error caused by finite gain [33]-[34]. In addition, the dq frame controller is more complex than the abf frame controller, since the significant computational effort is required to realize several transformations from abf to dq frame [33]-[34]. A viable alternative to dq frame PI controllers are abf frame PR controller, for achieving zero steady-state error tracking of ac reference [33]-[34].
between CC and VC mode [10]. Thus, the core essence of AFCL method can also applied to VC mode [10].

D. MSC Control

The MGs generally contain energy storage inside, thus, MGs are regarded as dispatchable power sources. In BTB converter, the GSC injects active/reactive power into the UG based on the requirement of LVRT, while the MSC injects the reference power into the GSC. The function of MSC is to extract the reference power from MGs and maintain the stability of dc voltage \( \left( v_{dc} \right) \) [27]. The stability of dc voltage is essential for BTB converter, since it plays important role in active power balance between GSC and MSC.

The dc link capacitor current is described as

\[ i_{dc} = \frac{dc}{dt} = i_{MSC} - i_{GSC}. \]  

where \( i_{MSC}, i_{GSC} \) are current in MSC and GSC side of dc link.

During normal operation, \( i_{MSC} \) and \( i_{GSC} \) are equal, and the dc link voltage remains constant. During fault condition, the PCC voltage sags will cause over-voltage across dc link capacitor. The chopper converter switch is triggered based on dc link voltage [35]. The duty cycle of dc chopper switch is described as

\[ D = \frac{R_{chop}}{u_{dc}} \left( P_{GSC} - P_{MSC} \right). \]  

where \( P_{MSC} \) and \( P_{GSC} \) are the active power in MSC and GSC side of dc link, and their reference value is \( P_{ref} \).

Based on (23)-(24) and considering the stability control of dc voltage, the MSC power injection and the dc chopper action is carried out, which is detailed in Fig. 4.

E. Design of Adjustable Coefficients

1) Design for LVRT

The key to LVRT operation relies on the effective execution of the grid code requirement, which needs the precise coefficients design in (3)-(4). Considering PCC voltage amplitude compensation, the reference of positive/negative sequence reactive current in (3)-(4) is described as

\[ I^{*+}_{mq} = \frac{X_m}{\sqrt{R_m^2 + X_m^2}} \left( U^{**} - U^* \right), \]  

\[ I^{*+}_{mn} = -\frac{X_m}{\sqrt{R_m^2 + X_m^2}} \left( U^* \right). \]

Divide (25) and (26) by (3) and (4), the coefficients for the grid code requirement are obtained as

\[ k^{LVRT}_{+} = \frac{X_m}{\sqrt{R_m^2 + X_m^2}} \frac{U^{**} - U^*}{U_U - U_P} \frac{U_N}{U_N}, \]  

\[ k^{LVRT}_{-} = -\frac{X_m}{\sqrt{R_m^2 + X_m^2}} \frac{U^*}{U_U - U_P} \frac{U_N}{U_N}. \]

2) Design for AFCL

The key of the AFCL method relies on effective control for the active/reactive current injection of BTB converter. In order to fit the PAA function to relieve the impact of MGs fault current on system fault current, the coefficients for CCG strategy in (21) are constrained as

\[ I^{+}_{m} = \begin{bmatrix} k^{U+}_{1}U^{**} + k^{U+}_{2} \frac{R_m}{\sqrt{R_m^2 + X_m^2}} (U^* - U) \end{bmatrix} + \begin{bmatrix} \frac{k^{Q+}_{1}U^{**} + k^{Q+}_{2}}{\sqrt{R_m^2 + X_m^2}} \frac{R_m}{\sqrt{R_m^2 + X_m^2}} \frac{U^*}{U_U - U_P} \frac{U_N}{U_N} \end{bmatrix} = I^{+}_{m} \]  

\[ I^{-}_{m} = \begin{bmatrix} k^{U-}_{1}U^{**} + k^{U-}_{2} \frac{R_m}{\sqrt{R_m^2 + X_m^2}} (U^* - U) \end{bmatrix} + \begin{bmatrix} -\frac{k^{Q-}_{1}U^{**} - k^{Q-}_{2}}{\sqrt{R_m^2 + X_m^2}} \frac{R_m}{\sqrt{R_m^2 + X_m^2}} \frac{U^*}{U_U - U_P} \frac{U_N}{U_N} \end{bmatrix} = I^{-}_{m} \]

where \( k^+_{1}, k^+_{2}, k^-_{1}, k^-_{2} \) are designed as

\[ k^+_{1} = \frac{k^{U+}_{1}X_m}{U_U - U_P} \frac{U_N}{U_N}, \]  

\[ k^-_{1} = \frac{k^{U-}_{1}X_m}{U_U - U_P} \frac{U_N}{U_N}. \]

F. AFCL Method for the LVRT of Networked MGs

According to the analyses of Section III.A-E, the LVRT of networked MGs is combined with GSC control and MSC control. In GSC, the AFCL consists of PAA, CI, and CCG.
strategies to relieve the impact of MGs fault current. The LVRT of networked MGs with BTB converter is illustrated in Fig. 4. The red variable is the sampling and input signals.

IV. CASE STUDY

A. System Data

The effectiveness of the proposed AFCL method for the LVRT of networked MGs is validated based on Matlab/Simulink. For the sake of analysis, the networked MGs consist of two MGs with the same capacity and network impedance. The performance of the proposed AFCL method is tested with three-phase unbalanced voltage sag, as shown in Fig. 5. The fault occurs at 0.05s and is cleared at 0.20s. The system and control parameters are given in Tables I and II, respectively.

![Fig. 5. The fault voltage amplitude of fault bus.](image)

<p>| TABLE I. THE SYSTEM NETWORK PARAMETERS |</p>
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network impedance of UG</td>
<td>RCG / \text{LCG}</td>
<td>0.2 / 1</td>
<td>\Omega / mH</td>
</tr>
<tr>
<td>Network impedance of GSC for MG#1</td>
<td>R1 / L1</td>
<td>1.5 / 3</td>
<td>\Omega / mH</td>
</tr>
<tr>
<td>Network impedance of GSC for MG#2</td>
<td>R2 / L2</td>
<td>1.5 / 3</td>
<td>\Omega / mH</td>
</tr>
<tr>
<td>DC capacitor</td>
<td>Cdc</td>
<td>40</td>
<td>\mu F</td>
</tr>
<tr>
<td>GSC side impedance of ICL filter</td>
<td>R / L</td>
<td>0.01 / 0.5</td>
<td>\Omega / mH</td>
</tr>
<tr>
<td>MSC side impedance of ICL filter</td>
<td>R / L</td>
<td>0.01 / 0.5</td>
<td>\Omega / mH</td>
</tr>
<tr>
<td>Capacitor of ICL filter</td>
<td>Cpar</td>
<td>40</td>
<td>\mu F</td>
</tr>
<tr>
<td>UG nominal voltage</td>
<td>U_G</td>
<td>311</td>
<td>V</td>
</tr>
<tr>
<td>DC voltage</td>
<td>udc</td>
<td>800</td>
<td>V</td>
</tr>
<tr>
<td>Resistance of dc chopper</td>
<td>Rdc</td>
<td>1.5</td>
<td>\Omega</td>
</tr>
<tr>
<td>Nominal frequency</td>
<td>f</td>
<td>50</td>
<td>Hz</td>
</tr>
<tr>
<td>Cutoff angular frequency</td>
<td>\omega_c</td>
<td>70</td>
<td>rad/s</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>f_c</td>
<td>10</td>
<td>kHz</td>
</tr>
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</table>

<p>| TABLE II. THE CONTROL PARAMETERS |</p>
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid code coefficients with existing FCL [2]</td>
<td>\kappa_{CG} / \kappa_{CG}</td>
<td>2.2 / 3</td>
</tr>
<tr>
<td>Grid code coefficients with proposed AFCL</td>
<td>\kappa_{CG} / \kappa_{CG}</td>
<td>2.5 / 3.5</td>
</tr>
<tr>
<td>Adjustable coefficients with existing FCL [23]-[25]</td>
<td>\kappa_0 / \kappa_0</td>
<td>-0.08 / -0.7</td>
</tr>
<tr>
<td></td>
<td>\kappa_0 / \kappa_0</td>
<td>-0.04 / -1.2</td>
</tr>
<tr>
<td></td>
<td>\kappa_0 / \kappa_0</td>
<td>0.1 / -0.8</td>
</tr>
<tr>
<td></td>
<td>\kappa_0 / \kappa_0</td>
<td>0.04 / 6</td>
</tr>
</tbody>
</table>

B. PAA Strategy

Taking positive sequence component as an example, the phase angles of MGs fault current are shown in Fig. 6. With existing PAA [23]-[25], since the phase angle in proposed PAA is updated and shifted with a more precise value by further considering the voltage’s phase angle difference from UG to fault branch and from MGs to fault branch.

![Fig. 6. Phase angle of MG#1 and MG#2 fault current without [2]-[3], with existing [23]-[25] and with proposed PAA strategy.](image)

C. CCG Strategy

The coefficients (\kappa_p and \kappa_q) are tested and verified to illustrate the effectiveness of the proposed CCG strategy in (21), which considers the characteristics of output current and network impedance together. As shown in Fig. 7, compared with [22], [32], it is evident that the proposed CCG strategy is more helpful for the recovery of positive sequence voltage and the reduction of negative sequence voltage. Therefore, the proposed CCG strategy can improve the voltage support ability during the LVRT of networked MGs under fault conditions.

![Fig. 7. Comparison of proposed and existing CCG strategy in [22], [32].](image)

D. AFCL Method for LVRT of Networked MGs

The LVRT of networked MGs is tested based on the UG fault voltage in Fig. 5. In order to keep the networked MGs stay in the grid-connected state, the PCC voltage should be supported, as shown in Figs. 8-9. As can be seen, under the same fault, both existing and proposed method can support the PCC voltage to the rated value within the allowable error. The proposed AFCL method has a better voltage recovery ability during LVRT operation, and can support PCC voltage more balanced and has less fluctuation. This is mutually corroborated with the proposed CCG strategy in the analyses of Fig. 7. During LVRT, the MGs fault currents with existing and proposed AFCL are shown in Figs. 10-11. As can be seen, once UG fault occurs, the phase angle and amplitude of MG#1 and
MG#2 fault currents are different due to the different phase angle adjusted by PAA in Fig. 6. With considering voltage’s phase angle differences from UG to fault branch and MGs to fault branch, the MGs fault current in the case with existing FCL [23]-[25] lags that with proposed AFCL. The power injections for the LVRT of networked MGs with existing and proposed AFCL are shown in Figs. 12-13. The active/reactive power is injected by MG#1 and MG#2 with different phase angles. Due to the presence of PAA, the amount of active/reactive power would be much larger than it is in cases with existing FCL for the same goal of PCC voltage support.

The dc voltage of BTB converter with existing and proposed AFCL is shown in Fig. 14. The $u_{dc}$ is stabilized at a reference value, 800V, which is helpful for the active power flow between GSC and MSC. When considering dc chopper, the dc voltage is more stable by proposed AFCL method. The $u_{dc}$ has fluctuation during LVRT operation. The active power fluctuation in Figs. 12-13 is also corroborated by the fluctuation of $u_{dc}$. The UG fault current under the condition of existing FCL and proposed AFCL is shown in Fig. 15. The UG fault current with existing and proposed AFCL is almost the same because the fault bus voltage is almost the same in these two cases.

The system fault currents with existing and proposed AFCL are shown in Figs. 16-17 and Table III. The system fault current is the sum of UG and MGs fault current. It can be found that the amplitude/angle of system fault current with existing FCL and proposed AFCL are different. In the case with existing FCL, the amplitude of system fault current is larger than UG fault current. In the case with proposed AFCL, the amplitude of system fault current is almost the same as in UG fault current. These results are also summarized in Table III. In the existing FCL without (with) existing PAA strategy, the MG#1 and MG#2 can contribute 48 A (40 A), 25 A (21 A) and 25 A (21 A) to system fault current in phase-a, phase-b, and phase-c, respectively. In the proposed AFCL method, the MG#1 and MG#2 will not contribute fault current to system. The fault current contribution rate, which refers to the ratio of system fault current increments to MG output fault current, is also analyzed in Table IV. Therefore, based on the proposed AFCL, the MGs fault current is more effectively relieved and has no influence (=0% contribution) on system fault current.

### Table III. Comparison of Existing and Proposed AFCL

<table>
<thead>
<tr>
<th>Fault current</th>
<th>Phase-a</th>
<th>Phase-b</th>
<th>Phase-c</th>
</tr>
</thead>
<tbody>
<tr>
<td>UG fault current (A)</td>
<td>330</td>
<td>144</td>
<td>144</td>
</tr>
<tr>
<td>MG#1 and MG#2 fault current by existing FCL without PAA [2],[21]-[22] (A)</td>
<td>55 / 55</td>
<td>35.2 / 35.2</td>
<td>35.2 / 35.2</td>
</tr>
<tr>
<td>MG#1 and MG#2 fault current by existing FCL with existing PAA [23],[25] (A)</td>
<td>60 / 60</td>
<td>37.5 / 37.5</td>
<td>37.5 / 37.5</td>
</tr>
<tr>
<td>MG#1 and MG#2 fault current by proposed AFCL (A)</td>
<td>62 / 62</td>
<td>40 / 40</td>
<td>40 / 40</td>
</tr>
<tr>
<td>System fault current by existing FCL without PAA [2],[21]-[22]</td>
<td>378</td>
<td>169</td>
<td>169</td>
</tr>
<tr>
<td>System fault current by existing FCL with existing PAA [23],[25]</td>
<td>370</td>
<td>165</td>
<td>165</td>
</tr>
<tr>
<td>System fault current by proposed AFCL (A)</td>
<td>330</td>
<td>144</td>
<td>144</td>
</tr>
</tbody>
</table>

### Table IV. Contribution Analyses of Existing and Proposed AFCL

<table>
<thead>
<tr>
<th>Fault current</th>
<th>Phase-a</th>
<th>Phase-b</th>
<th>Phase-c</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG#1 and MG#2 fault current contribution rate by existing FCL without PAA [2],[21]-[22]</td>
<td>87.3%</td>
<td>71%</td>
<td>71%</td>
</tr>
<tr>
<td>MG#1 and MG#2 fault current contribution rate by existing FCL with existing PAA [23],[25]</td>
<td>66.7%</td>
<td>56%</td>
<td>56%</td>
</tr>
<tr>
<td>MG#1 and MG#2 fault current contribution rate by proposed AFCL</td>
<td>≈0%</td>
<td>≈0%</td>
<td>≈0%</td>
</tr>
</tbody>
</table>

### E. Multiple Operation Performance Analyses

The operation performances of existing and proposed method are compared in Fig. 18. During pre- and post-fault conditions, both unbalanced voltage factor (UVF) and relative error of phase voltage are similar due to the normal operation. During fault condition, in Fig. 18(a), the UVF of PCC voltage supported by proposed method is lower than that by existing method, which verifies a stronger voltage support ability of proposed method. In Fig. 18(b)-(d), the relative error of PCC phase-abc voltage supported by proposed method is also lower than that by existing method. These can further indicate that the proposed method can make voltage more balance and precise. Although the maximum UVF and relative error are within allowable error by 2% and 8% respectively, the proposed method provides a better performance.

### Table III. Comparison of Existing and Proposed AFCL

<table>
<thead>
<tr>
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<th>Phase-c</th>
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<tbody>
<tr>
<td>UG fault current (A)</td>
<td>330</td>
<td>144</td>
<td>144</td>
</tr>
<tr>
<td>MG#1 and MG#2 fault current by existing FCL without PAA [2],[21]-[22] (A)</td>
<td>55 / 55</td>
<td>35.2 / 35.2</td>
<td>35.2 / 35.2</td>
</tr>
<tr>
<td>MG#1 and MG#2 fault current by existing FCL with existing PAA [23],[25] (A)</td>
<td>60 / 60</td>
<td>37.5 / 37.5</td>
<td>37.5 / 37.5</td>
</tr>
<tr>
<td>MG#1 and MG#2 fault current by proposed AFCL (A)</td>
<td>62 / 62</td>
<td>40 / 40</td>
<td>40 / 40</td>
</tr>
</tbody>
</table>

### Table IV. Contribution Analyses of Existing and Proposed AFCL

<table>
<thead>
<tr>
<th>Fault current</th>
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<td>MG#1 and MG#2 fault current contribution rate by proposed AFCL</td>
<td>≈0%</td>
<td>≈0%</td>
<td>≈0%</td>
</tr>
</tbody>
</table>

### F. Time Delay Analysis

The impact of communication time delay on the amplitude of system fault current in phase-a is shown in Fig. 20. When there...
is no time delay, the AFCL can be activated immediately. Otherwise, the execution of AFCL is delayed after fault information data is received. During the delay period, the system fault current is larger than UG fault current. After the delay, the system fault current is almost the same to UG fault current, and the system fault current increasing problem is solved. The length of time delay does not influence the nature of AFCL method. In practice, the AFCL is activated once the time delay ends. During communication delay period, the LVRT can be first conducted by traditional method in the MG local controller once PCC voltage drops below 0.9 p.u. Then, when the remote UG fault information data are transmitted to the MG local controller, the AFCL strategy can be operated to relieve the impact of MG fault current on system fault current.

**Fig. 20. Time delay analysis for system fault current amplitude in phase-a.**

### G. Additional Discussions and Analyses

1) Practical application of proposed method

a) In terms of fault location: The main contribution of proposed AFCL is the novel PAA strategy, which considers the practical voltage’s phase angle differences from UG to fault branch and from MGs to fault branch. In practical system, it is important to know fault branch location, in order to determine the precise voltage’s phase angle differences. Fortunately, there are many relatively mature technologies to know fault branch and amplitude/phase angle of voltage/current and the phase angle differences, according to the equipped sensors, GPS-based MPUs, intelligent electronic devices (IEDs) and phasor data concentrators (PDCs), et al [36]-[37].

The real-time synchronized phasor (phase angle) data and synchronized voltage/current waveform data provided by PMUs and IEDs are helpful for power system supervision and the protection relay applications including fault location [36]-[37]. Numerous PMU-based fault location techniques or algorithms for two- or three-term homogeneous or nonhomogeneous lines have been proposed in [36]-[37]. The fault location can be determined based on three-phase currents/voltages which is sampled from the bus equipped with fault locators or sensor detection devices [36]. In addition, the sampling rate has reduced from 20 kHz to 1 kHz, and the detecting time of fault location has reduced to less than 7 ms in two-terminal lines system [37]. On the one hand, our paper mainly focuses on the AFCL to keep system fault current amplitude unchanged, rather than a specific fault location determination method. On the other hand, there are many ready-made and state-of-the-art technologies for fault location, which provide significant support of practical application of proposed AFCL method. Therefore, the proposed AFCL method can be applied to the actual power systems.

b) In terms of network impedance: In practical power system, the network impedance is important for the proposed CCG strategy. This network impedance is variable for different faults. Fortunately, the determination of network impedance between different node is already a very mature technology, which has been widely calculated in [38]. These ready-made technologies can also support the practical application of proposed CCG strategy in AFCL.

c) In terms of hardware: 1) Sensors and PMUs are needed to detect the amplitude/phase angle of UG/UG fault current/voltage, and the phase angle differences; 2) The related communication lines are required for the transmission of fault information data; 3) Converters need more input/output (I/O) interface to receive the fault information data from UG; 4) To relieve MG fault currents, the PAA module is required in inverter controller for phase angle calculation; 5) The CI module is also required in inverter controller to match the PAA function for LVRT.

2) Improvements of proposed method

According to the modeling, mathematical analyses, parameter designs, and multiple scenarios analyses, the proposed method provides the following improvements,

a) Suitable for applications with more stricter power quality. Compared with [2], [22], [23]-[25], due to the BTB converter application, the proposed method is more suitable for industrial distribution networks with a large proportion of sensitive loads, such as chemical plants and semiconductor devices. The proposed method can be also applied to other devices, such as wind and photovoltaic inverter, AC/DC microgrids, and HVDC.

b) System fault current increasing challenge is solved more thoroughly. More than just focusing on inverter protection by peak current limiting [2], [21]-[22], a novel PAA strategy is proposed to avoid the increasing of system fault current by relieving the contribution of MG fault current on system fault current. Compared with [23]-[25], the adjusted phase angle of MG fault current is more precise by considering the voltage’s phase angle differences from UG to fault branch and from MGs to fault branch. The existing methods will inevitably increase system fault current [2], [21]-[22], [23]-[25], while the proposed method can keep the system fault current level unchanged.

c) LVRT performance is improved. Compared with [22], [32], by directly embedding network impedance characteristics, the proposed CCG strategy is more helpful for positive sequence voltage recovery and negative sequence voltage reduction, and the UVF and relative error of PCC voltage is lower, leading to a better voltage support performance for LVRT of MGs.

d) Further reduce reliance on protective equipment. Compared with [17]-[18], the system fault current limitation will not need to install additional protection devices, such as fault current limiters [17]-[18], since system fault current amplitude is kept unchanged by proposed AFCL method.

e) Further reduce reliance on relay protection. Compared with [2], [21]-[22], the relay protections (e.g., over-current amplitude protection and coordination control between primary and secondary protection) will be disturbed, since system fault current will increase with the penetration of MGs.
proposed AFCL method, the relay protection devices do not need to be updated even if the MGs are integrated in the future.

f) Time delay is analyzed. Compared with [2], [21]-[22], [23]-[25], the communication time delay is considered during fault current limitation.

V. CONCLUSION

Under the UG fault condition, in view of the high-level system fault current during the LVRT of networked MGs, an AFCL method is proposed to avoid monotonically increasing system fault current during the LVRT of networked MGs. In this method, in order to improve the voltage control ability of LVRT, the CCG strategy is proposed by embedding the network impedance characteristics. Then, in order to achieve a better fault current limitation by relieving the impact of MGs fault current, the PAA strategy is proposed with considering voltage’s phase angle difference from UG and MGs to fault branch. Meanwhile, the CI strategy is conducted to fit the feature of PAA. Numerous simulation results have validated the improvements of the proposed AFCL method with a successful fault current limitation by relieving the impact of MGs fault current during the LVRT, the networked MGs fault current does not increase the system fault current amplitude.

Considering the fields with a high proportion of sensitive load, the BTB converter is widely used for the PCC connection point of DGs and MGs to provide high power quality. To reduce the fault current level, the AFCL method can be applied to the BTB converter, and can be also used to the other inverter products, such as wind and photovoltaic inverter, AC/DC microgrids, and HVDC transmission system.

VI. REFERENCES

430074, China. His research interests include fault ride-through, fault voltage support, fault current limitation, frequency regulation, self-healing control, power electronics control, and energy management system of smart grid.

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