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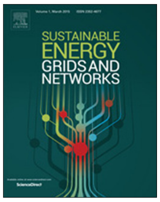

Fault ride through strategy of inverter-interfaced microgrids embedded in distributed network considering fault current management

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ABSTRACT

This paper presents a fault ride through (FRT) strategy specific for a microgrid (MG) with an inverter-based interface (IB-MG) to maintain power exchange with distribution networks during network faults or disturbances. The fault current injected by IB-MG is controlled by its back-to-back converter interface. Besides guaranteeing the power quality of local loads in MGs during faults, the proposed IB-MG FRT could realize the fault current management (FCM) ability – instead of using a fault current limiter – to maintain the short circuit current level in a dense-load network. As the traditional three-phase FRT techniques conducted on the double synchronous reference frame are no longer applicable on IB-MG FRT, especially for unbalanced faults, a newly developed reference current calculation method conducted on the stationary reference frame is adopted and modified. By changing the six control variables – amplitudes and phases of the three-phase currents – based on the information of the fault voltages and the fault currents from the host network, IB-MG FRT could achieve multiple effects: (1) controlling instantaneous energy flow between the MG and the distribution network; (2) limiting the short-circuit current increase; (3) improving the MG system power quality. The application range of the proposed FRT strategy is also discussed. A 27 kV distributed network connected with a 5 MW IB-MG system was built in the MATLAB/Simulink software environment and the proposed IB-MG FRT strategy was demonstrated under the different unbalanced fault scenarios.

1. Introduction

Integrating distributed generation (DG) units into an existing distributed power network is an important feature of active distributed network (ADN) [1–3]. The private-owned DGs usually group with the local loads as a microgrid (MG) and connect to the utility grid through an interconnection switch at the point of common coupling (PCC). The existing implementation methods for the MG grid-connected interface include medium-low voltage (MV/LV) circuit breakers (CB), static power electronic switches and power electronic interfacing inverters [4]. Driven by the fast evolution of power electronic on the fast semiconductor swathes and the real-time computer controllers, the cost-effective and grid-friendly inverter-based interfaces has been adopted by more and more MG manufacturers and system operators [5]. In this paper, the grid-connected interface of IB-MG adopts a back-to-back (B2B) framework, which is made up of two conventional pulse width modulated (PWM) voltage source converters (VSCs) with their DC sides connected through a common center DC-link capacitor [6], to achieve flexible power exchange between the utility and the MG under normal and even abnormal grid conditions.

In the event of faults or voltage sags at the host grid, according to IEEE standard 1547.4 [7], the grid-connected MGs should disconnect from the distributed network and operate as the island systems with the incorporated DGs and local loads [7,8]. In this way, the grid-connected interfaces of the IB-MGs will not be triggered to exchange power with the host grid during the fault. However, for the ADN with a high penetration level of MGs, the large-scale MGs disconnection as well as the MGs re-synchronization for the detected grid disturbances will incur the host grid instability [9,10]. Also, as the temperate utility disturbances occur more frequently, the stability and economic cost for MGs on frequent operation mode transformation at any detected disturbances will be high [11]. In order to overcome those shortcomings, MGs should have the ability to continue the power exchange with utility under the acceptable fault conditions, which is known as the fault-ride-through (FRT) capability [12]. With the development of FRT technique, FRT capability has been included in the standards for

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Nomenclature

α_g, α_{g_abc}	the phase angles of i_g, i_{g_abc}
α_{M_abc}	the FCM-rotated phase angles of i_{M_abc}
μ	the depth of voltage sag
θ_{M_abc}	the phase angles of i_{M_abc}
ADN	active distributed network
B2B	back-to-back
DG	distributed generation
f_L	the local AC bus frequency in IB-MG
FCL	fault current limiter
FCM	fault current management
FRT	fault ride through
I_f, I_{f_abc}	the amplitudes of i_f, i_{f_abc}
i_f, i_{f_abc}	the three phase fault currents at the fault point
I_g, I_{g_abc}	the amplitudes of i_g, i_{g_abc}
i_g, i_{g_abc}	the three phase output currents from the utility
i_L	the local AC bus currents in IB-MG
i_m	the fault current from IB-MG
I_M, I_{M_abc}	the amplitudes of i_M, i_{M_abc}
i_M, i_{M_abc}	the three phase output currents of IB-MG at PCC
i_{L_ref}	the reference currents of i_L
i_{M_ref}	the reference currents of i_M
i_{ref_abc}	the three phase currents of i_{M_ref}
IB-DG	inverter-based distributed generator
IB-MG	inverter-based microgrid
MG	microgrid
MPPT	maximum power point tracking
$P_{0,abc}$	the constant power components of p_{M_abc}
$p_{2\omega,abc}$	the double frequency power components of p_{M_abc}
P_{M_0}	the active power imported by the MG during the fault
$p_{M\_3\phi}$	the total instantaneous output active power of IB-MG
p_{M_abc}	the three phase instantaneous output active power of IB-MG
PCC	the point of common coupling
PLL	phase-locked loop
u_L	the local AC bus voltages in IB-MG
U_M, U_{M_abc}	the amplitudes of u_M, u_{M_abc}
u_M, u_{M_abc}	the three phase voltages at PCC
V_{dc*}	the rated DC-link voltage
V_{dc}	the DC-link voltage
VSC	voltage source converter

distributed resources integration and been required by the distributed system operators. For example, German standards VDE-AR-N 4105 [13] and Chinese standards NB/T 32015-2013 [14] require that FRT capacity is a must for the distributed resources connected with the medium voltage distributed network. In the latest amendment of IEEE standard 1547 [15] released at May 2014, DER is allowed to "ride through" abnormalities of grid voltage and "grid and DER operators can mutually agree to other voltage trip and clearing time settings". Moreover, with an adequate network communication structure, the realization of the automated fault detection and isolation technique has promoted the application of FRT techniques in the modern distributed networks greatly [16].

Different from the existing FRT technology applied on DGs, including the large-scale solar plants and wind plants [17], the FRT strategy implemented on MGs has more requirements on power control. One is eliminating power ripples generated by unbalanced faults because the MG has a local AC bus of which power quality needs to be guaranteed during faults. Also, as the MG is operated as a group with different kinds of loads and DGs, it has a relatively passive way on regulating the output power during faults unlike the solar or wind plants which could decrease their output power timely by the maximum power point tracking control (MPPT) and the wind blade deviation device respectively. The challenges on IB-MG FRT to balance the power flow between the MG and the host network arouse the implementation of the flexible power control on the inverter-based interfaces. The widely-applied FRT power control configuration comprises both positive and negative sequence loops and each sequence loop has the *d*-and *q*-axis frame current control loops to regulate both active and reactive power [18–21]. Such a configuration needs to take the symmetrical components separation and the *dq* transformation on voltages and currents measurements as well as regulate at least four PI controllers. Also, the reference current calculation algorithm based on the double synchronous reference frame cannot adjust the amplitude and phase angle of the current on each phase freely. Kou et al. [17] proposed a new FRT technique to control the output active power under the *abc* reference frame directly without implementing any electrical variable transformations. Its effectiveness is comparable with the double synchronous reference frame vector control.

Once IB-MG have the FRT ability and connect with the ADN during fault, its contribution on the fault current level of the distribution networks should be considered. Especially in places where the old aging grid with fast growing concentrated loads has very little room for additional fault currents from MGs, the substation circuit breakers in the distribution network will be at the risk of exceeding its short-circuit duty limitation because of the extra fault current injection from MGs [22]. As a result, the fault current management ability will be a compulsory requirement for IB-MG FRT in order to get the MG integration permission from the utility operators. More efforts were used to facilitate MGs with fault current management (FCM) ability. One mature solution is fault current limiters (FCLs) [23,24], which are located at PCC and limit fault current contribution from MGs by increasing their impedance rapidly. Installing FCLs renders extra investments on MGs integration and the energy losses, triggering and recovery time, steady-state impedance as well as the installation cost of FCLs all need to be considered by the system operators [25]. Recently, more attention is taken on the inverter-based interfaces of DGs or MGs which could achieve the same effect of FCLs by adjusting the fault currents flexibly. In [26], by using a hard limiter on current references in the *dq* reference frame, the magnitudes of the three-phase output currents could be limited within a desired value. However, it is not a feasible solution in the unbalanced fault conditions in which the three-phase fault currents are coupled and could not be controlled separately. Rajaei et al. [27,28] proposed a FCM technique to maintain the fault current magnitude by changing both amplitudes and phase angles of the inverter-based interface output current. While phase shifting the output current will change the output power at the same time, applying this FCM technique directly on IB-MG will cause the sudden power imbalance at PCC and further affect the inside system operation of IB-MG. The need to promote the IB-MG FRT providing FCM service in different fault situations, especially for unbalanced faults, has motivated the study reported in this paper.

This paper proposes a FRT strategy specific for MG with inverter-based interface to attain power exchange with utility during faults in host grid as well as to maintain the original short circuit current level in the dense-load distributed networks by FCM. FCM service, which involves the phase angle shifting of the MG output current on fault phase, is conducted on the *abc* reference frame. Thus the traditional FRT output current control conducted on the *dq* reference frame is unable to cooperate with the FCM service. In order to overcome this problem, the reference current calculation algorithm for IB-MG FRT adopts the direct

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