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Application of a modified flux-coupling type superconducting fault current limiter to transient performance enhancement of micro-grid

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ABSTRACT

Concerning the application and development of a micro-grid system which is designed to accommodate high penetration of intermittent renewable resources, one of the main issues is related to an increase in the fault-current level. It is crucial to ensure the micro-grid's operational stability and service reliability when a fault occurs in the main network. In this paper, our research group suggests a modified flux-coupling type superconducting fault current limiter (SFCL) to enhance the transient performance of a typical micro-grid system. The SFCL is installed at the point of common coupling (PCC) between the main network and the micro-grid, and it is expected to actively improve the micro-grid's fault ride-through capability. And for some specific faults, the micro-grid should disconnect from the main network, and the SFCL's contribution is to make the micro-grid carry out a smooth transition between its grid-connected and islanded modes. Related theory derivation, technical discussion and simulation analysis are performed. From the demonstrated results, applying the SFCL can effectively limit the fault current, maintain the power balance, and enhance the voltage and frequency stability of the micro-grid.

1. Introduction

Recently interests in the micro-grid have been growing as a new eco-friendly energy system because it can be designed to accommodate renewable resources, improve energy efficiency and provide ancillary services for the bulk electric power system. It is anticipated that many micro-grids will penetrate into power grids, especially electrical distribution systems [1–3]. However, one of the main issues regarding the micro-grid's development is related to an increase in the fault-current level. It is crucial to ensure the micro-grid's operational stability and service reliability when a short-circuit fault occurs in the main network, and the methods which can alleviate the short-circuit current and consequently prevent the disconnection of the micro-grid from the main network are advantageous [4,5].

From the point of view of enhancing an electrical system's robustness against a fault, a feasible solution is to introduce superconducting fault current limiter (SFCL), which has the potential abilities of suppressing fault current, improving voltage sag and providing critical protection to relevant power equipment [6–10]. Since the protection range of a SFCL will be different when it is placed at various locations, this kind of device may also be used to protect a micro-grid system. In [11], the application of a hybrid SFCL in a simplified micro-grid system has been preliminarily estimated, and in [12,13], the positioning of resistive SFCLs in DC and AC micro-grids has been respectively discussed. From the aforementioned literature, the effectiveness of using a SFCL to limit the fault currents provided by the generation units in the micro-grid has been verified.

Actually, in the case of that a SFCL is applied in the micro-grid, the promising effects can be approximately classified as two kinds in accordance to the severity (or specificity) of a fault. One is to improve the micro-grid's fault ride-through (FRT) capability, and the other is to make the micro-grid carry out a smooth transition between its grid-connected and islanded modes when some specific or serious faults occur. Aiming at these technical issues, this paper introduces a modified flux-coupling type SFCL to enhance the transient performance of a micro-grid system. The article is organized in this manner. Section 2 introduces the SFCL's structure as well as principle, and theoretically discusses the SFCL's influence mechanism to the micro-grid's performance under different fault conditions. Section 3 is devoted to the simulation analysis of an integrated micro-grid system including the SFCL, energy storage

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device, wind farm and loads. In Section 4, conclusions are summarized and next steps are suggested.

2. Theoretical analysis

2.1. Structural principle of the modified flux-coupling type SFCL

The schematic configuration of the modified flux-coupling type SFCL is shown in Fig. 1 [14]. This SFCL is mainly composed of a coupling transformer (CT), a controlled switch S_1 and a superconducting coil (SC). The controlled switch S_1 and the superconducting coil are respectively connected in series with the CT's primary and secondary windings, which are wound in reverse directions. The metal oxide arrester (MOA), which can be used to suppress switching overvoltage, is connected in parallel with the CT's primary winding. L_1, L_2 are the winding self-inductances, and M is the mutual inductance. In addition, Z_s is the circuit impedance and S_{load} is the circuit load. R_{SC}/R_{moa} is recorded as the SC/MOA's normal-state resistance. Below the SFCL's operating principle is introduced in brief.

In normal (no fault) condition, the controlled switch S_1 is closed and the SC is maintained in the zero-resistance/superconducting state. The non-inductive coupling between the CT's two windings can be achieved, and as the MOA is connected in parallel with the CT, it can be identified that the MOA is "short-circuited". As a result, the modified SFCL will not affect the main circuit.

After the fault happens, S_1 will be opened rapidly. Since the flux between the CT's two windings can no longer cancel out each other, the non-inductive coupling will be destroyed, and the superconducting coil will quench to its high-resistance state. Right now the SFCL will play the role, and its current-limiting impedance can be calculated as $Z_{SFCL} = [R_{SC} + j\omega L_2 + (kn\omega L_2)^2/(R_{moa} + n^2 j\omega L_2)]$ [15]. In view of $R_{moa} \gg n^2\omega L_2$, $Z_{SFCL} \approx R_{SC} + j\omega L_2$ can be obtained.

Compared to the original flux-coupling type SFCL which is purely inductive [16,17], the modified SFCL is a resistive–inductive type (hybrid type) SFCL, which absorbs the merits of the two types of SFCLs and can theoretically enhance the transient performance of a power system more efficiently [18].

2.2. Influence of the modified SFCL to the transient performance of a micro-grid system

As shown in Fig. 2, it indicates the SFCL's application in a typical micro-grid system, which is consisting of an energy storage device, a wind farm, a synchronous generator as well as two loads. From this figure, most of the distributed generation (DG) units are connected to the micro-grid through the inverters, and this type of DG unit can be identified as the inverter-interfaced-distributed-generation (IIDG).

Note that, the wind power generation will adopt the maximum power point tracking (MPPT) control, and the energy storage device will be served as a master-control DG, which is used for stabilizing the micro-grid's voltage and frequency under the islanded condition. In general, the master DG has two control modes, namely the active power–reactive power (P–Q) control as well as voltage–frequency (V–f) control, and they will be activated in accordance with the micro-grid's grid-connected and islanded statuses.

The SFCL is installed at the point of common coupling (PCC) and theoretically provides two kinds of contributions, which are respectively stated in terms of different fault locations.

(a) When the fault happens at the K1 point, the SFCL's contribution is to improve the micro-grid's fault ride-through capability as far as possible. Under this fault, it is not necessary to trip off the micro-grid, in particular when the power exchange between the main network and the micro-grid is considerable. Installing the SFCL can help to limit the fault current provided by the micro-grid, and meantime compensate the PCC's voltage sag. As long as the micro-grid is still connected to the main network, each of the DG units will adopt the original P–Q control.

(b) When the fault occurs at the K2 point, the current protection configurated at the connecting line will actuate the static switch's trip operation after several power-frequency cycles, and the micro-grid should disconnect from the main network. Herein the SFCL's contribution is to make the micro-grid carry out a smooth transition between its grid-connected and islanded modes. Considering that the controlled switch can be quickly operated to decouple the coupling coils (less than several milliseconds), the suggested SFCL also has the responsibility of restraining the fault current from the micro-grid to the fault location. In addition, the SFCL's action message/status will be sent to the master DG through an information communication link, and further be used for activating the master DG's control switching (from the P–Q control to the V–f control).

Concerning how to effectively implement the master DG's control switching, a feasible way is presented as follows. Fig. 3 indicates the basic control block diagram of the master DG in consideration of the SFCL's action status. From this figure, the specialized current-input and voltage-output channels are arranged. The channels G1 and G3 are used for realizing the P–Q control [19,20], and the current-input references (i_{Ldref}, i_{Lqref}) can be expressed as:

$$\begin{cases} i_{Ldref} = \frac{2}{3}\frac{P_{gref}u_{gd}+Q_{gref}u_{gq}}{u_{gd}^2+u_{gq}^2} \\ i_{Lqref} = \frac{2}{3}\frac{P_{gref}u_{gq}-Q_{gref}u_{gd}}{u_{gd}^2+u_{gq}^2} \end{cases} \quad (1)$$

where P_{gref} and Q_{gref} are the given power references; u_{gd} and u_{gq} are the d-axis and q-axis components of the network-side voltage, respectively.

Accordingly, the P–Q control's output-voltage signals (u_d, u_q) can be computed in:

$$\begin{cases} u_d = \left(K_p + \frac{K_i}{s}\right)(i_{Ldref} - i_{Ld}) - \omega L_f i_{Lq} + u_{gd} \\ u_q = \left(K_p + \frac{K_i}{s}\right)(i_{Lqref} - i_{Lq}) + \omega L_f i_{Ld} + u_{gq} \end{cases} \quad (2)$$

where ω is the fundamental angular frequency; K_p, K_i are the proportional and integral parameters of the current regulator; L_f is the filter inductance; i_{Ld} and i_{Lq} are the d-axis and q-axis components of the energy storage converter's output current, respectively.

On the other side, the channels G2 and G4 are used to achieve the master DG's V–f control. Based on the network-side voltage references (u_{gdref}, u_{gqref}), the V–f control's current-input references (i_{Ldref}, i_{Lqref}) can be calculated as [21]:

$$\begin{cases} i_{Ldref} = \left(K_{p1} + \frac{K_{i1}}{s}\right)(u_{gdref} - u_{gd}) - \omega C_f u_{gq} + i_{gd} \\ i_{Lqref} = \left(K_{p1} + \frac{K_{i1}}{s}\right)(u_{gqref} - u_{gq}) + \omega C_f u_{gd} + i_{gq} \end{cases} \quad (3)$$

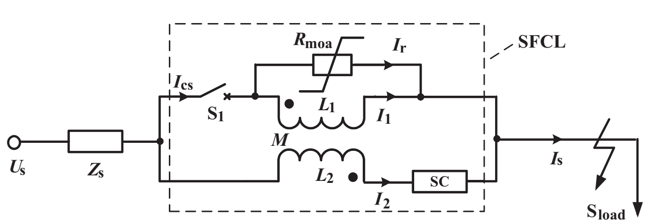

Fig. 1. Schematic configuration of the modified flux-coupling type SFCL.