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Analysis and control of bridge-type fault current limiter integrated with the dynamic voltage restorer

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ABSTRACT

This paper proposes a novel bridge-type solid-state fault current limiter based on dynamic voltage restorer (BFCL-DVR). The new topology uses a DC-link in the back-to-back converter of DVR. The proposed BFCL-DVR is equivalent to the conventional DVR during normal operation mode. At fault inception, the controller deactivates the series converter IGBTs in faulty phase and activates the DC-link semiconductor switches, thus establishing an equivalent bridge-type current limiter to restrict the fault current. The magnitude of the fault current is adjustable by controlling the frequency and duty ratio of the semiconductor switch that is in parallel with the discharging resistance. Moreover, the device is able to quickly recover from the current limiting mode to the normal operation mode. In this study, the operation sequence, optimal value of discharging resistance, duty cycle, and frequency of semiconductor switches are obtained. The design methodology of the proposed BFCL-DVR is fully verified using PSCAD/EMTDC software. Experimental results validate the proposed topology and theoretical analysis.

1. Introduction

Power quality is an important topic in distribution power systems. Specifically, voltage sags, harmonics, and fault current are urgent problems to be solved [1,2]. Voltage fluctuation and harmonics impact the normal operation of sensitive load, whereas a large fault current causes a voltage sag at the point of common coupling (PCC), which may propagate and shutdown sensitive equipment in adjacent industrial plants [3].

Many works were proposed on the control and inhibition of voltage fluctuation and harmonics, such as DVRs and active power filters (APFs) [4–8]. In addition, circuit breakers (CBs) are protective devices, which can be tripped and reset either manually or automatically. However, CBs having a high-current interrupting capability are expensive electromechanical systems [9,10]. On the other hand, a novel scheme called fault current limiter (FCL), which can limit the magnitude of fault current, has been proposed and used as the best solution [11–13]. Different topologies of FCL are introduced in the literature, such as superconducting FCL (SFCL), resonance-type FCL, and solid-state FCL. Resonance-type FCL limits the fault current by using various topologies of series or parallel LC resonant circuits [14–17]. For these topologies, parameter design requires excessive precision and current limiting inductance is in series with the transmission line, producing an inevitable additional loss. The SFCL structure offers a suitable way to control the fault current levels in distribution networks due to inherent low losses of superconductors and limitation of fault current without delay [18–20]. However, given the high cost of superconductors, these devices are not commercially feasible.

To offer simpler and more flexible operation and reduce the complexity of the circuit, the diode bridge-type FCL has been proposed in [2,21–27], which can limit the fault current with almost no delay. However, the power loss under normal operation and the optimal selection of parameters are not described in detail. In [3], a new series transformer-based solid-state FCL with a simple and effective structure is proposed. For this structure, the overvoltage during the IGBT's switching process should be considered, and along with the instantaneous insertion of the large current limiting inductor, which might cause a DC bias in line current.

Overall, FCL devices result in low utilization rate due to their onefold operation. In [28], the suggested topology can limit the fault current and open the faulty line acting as a CB. In [29], a new concept of fault current limiting dynamic voltage restorer (FCL-DVR) is proposed. However, the output filter inductance is relatively small, which causes a lower current limiting efficacy and the DC bias of fault current still exists. Based on the concept of composite system [30], in [31], a crowbar circuit having six

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anti-parallel diodes in the DFIG's rotor-side converter is up-rated to handle short-circuit currents, but the drawback of overheating of the discharging resistance in a short time should be considered.

In this paper, a novel and simple bridge-type solid-state FCL (BFCL) topology based on DVR is presented. This topology overcomes the drawbacks of most FCLs. The proposed BFCL-DVR can solve power quality problems by combining the advantages of the bridge-type current limiter and the high utilization ratio of the DVR, which include real-time dynamic voltage compensation, adjustment of the fault current value, and low DC bias of fault current. In fact, during normal operation mode, the proposed topology is equivalent to the traditional DVR. When faults occur, the BFCL-DVR is able to limit the current rising rate immediately. Finally, after fault recovery, the BFCL-DVR can quickly return to its normal operation condition.

This paper is organized as follows. Schematic diagrams of the BFCL-DVR are proposed in Section 2. In Section 3, the equivalent topology for different operation modes and the control strategy are explained. In Section 4, the operation principle, required mathematical expressions, influence factor of final limiting current, and operation sequence are discussed. Finally, the parameters setting is presented in Section 5, the validation of the proposed BFCL-DVR by simulations and experiments are presented in Section 6, and the conclusions of this work in Section 7 close this paper.

2. System topology

The installation location of DVR is mainly facing the sensitive load side, which likes IT center, precise instruments factories, buildings, and hospitals. Much of the published literature on DVRs using two-level converters for low voltage distribution network, e.g. 400 V [7,8]. This paper is mainly concerned with this application scenario and the location of the proposed BFCL-DVR in distribution system is illustrated in Fig. 1. It is assumed that Feeder 2 supplies a sensitive load, Feeder 1 delivers power to other loads. The BFCL-DVR is located at the downstream of FCB2 in Feeder 2, and close to the sensitive load.

Fig. 2 shows the power circuit topology of the proposed BFCL-DVR; it is composed of DVR, DC-link, and parallel converter modules. The DVR module converts the power from a DC capacitor to compensate voltage fluctuations and mainly comprises three single-phase bridges that are connected to the grid through a series transformer, T, and a LC output filter. The parallel converter module is connected to the grid through a shunt transformer, T_0, with L_2 to eliminate high frequency ripples, transfer the power from the grid to the DC capacitor, restrain harmonics, and compensate reactive power. The DVR and parallel converter modules are connected through the DC-link and DC capacitor C_2. The DC-link is composed of three controllable tubes, freewheeling diode D_5, current-limiting inductance L_d, and discharging resistor r_f.

The major difference between the proposed topology and a conventional DVR is the additional DC-link module. The three controllable tubes of the DC-link for each phase will be deactivated or activated depending on the operation condition.

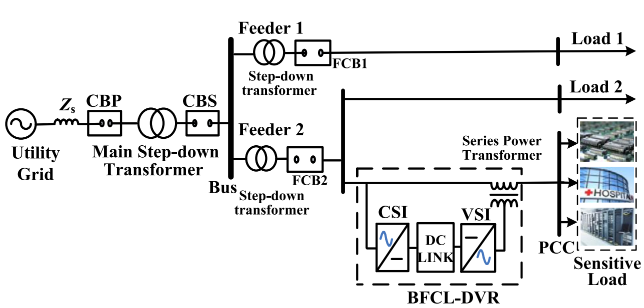

Fig. 1. Installation location of system device.

Under normal operation, the control module turns off the semiconductor switches T_1 and T_2 and turns on T_3, thus operating as a conventional DVR, whereas the parallel converter module provides energy to compensate voltage fluctuation. When a short-circuit fault occurs, the control module turns off the IGBTs of DVR module; T_3 is also turned off, and T_1, T_2 are turned on. Thus, an equivalent bridge-type current limiter is formed, with L and L_d serving to slow down the rising rate of the fault current, by controlling the frequency and duty ratio of the semiconductor switch T_2, which in parallel with the discharging resistance, can control the magnitude of fault current and reduce the overvoltage caused by the switching process. In addition, by combining the BFCL with the DVR, the current ripple that is inevitable in bridge-type FCLs can be eliminated. Some components of BFCL including series transformers and uncontrolled rectifier bridge can also be omitted.

The innovation and advantages of the proposed BFCL-DVR are summarized as follows:

1) In the aspect of topology, the proposed strategy realizes the effective combination of the DVR and BFCL, in contrast to install the BFCL and DVR in the distribution power system separately, the total cost and size of the proposed BFCL-DVR are much smaller. And compare to the FCL-DVR, the fault current is able to active adjusted according to the system relay protection. The limiting effect of the composite system has been greatly improved.
2) In comparison with traditional BFCL, the filter L of BFCL-DVR is able to increase the current limiting effect of BFCL to some certain extent. Furthermore, the power loss and the current ripple process that brought by BFCL can be avoided, which are inevitable to the traditional BFCL during normal condition.
3) Moreover, the influence of different parameters of BFCL on the current limiting effect is analyzed in detail, the optimal value of discharging resistance, duty cycle and frequency of semiconductor switches are obtained. The overvoltage caused by the switching action is reduced, the cooling system can be omitted, and the harmonic content of the fault current also be restrained, which is caused by the uncontrolled rectifier of traditional BFCL. Then, the control logic guarantees the BFCL-DVR is able to properly operate during both normal and fault conditions.

Overall, the proposed strategy not only realizes the effective combination of the DVR and BFCL, but also solves the inherent defects of the BFCL and realizes the self-protection of the whole DVR system.

3. Operation principles

3.1. Normal operation mode

Given that the three phases of BFCL-DVR are independent, consider phase A as an example to elaborate the working principle of BFCL-DVR. As shown in Fig. 3, when the grid voltage fluctuates, the semiconductor switches T_1 and T_2 are turned off and T_3 is turned on, and the control module sends sine-wave pulse-width modulation(SPWM) signal to the DVR module to achieve dynamic voltage compensation, with energy provided by the parallel converter module. Under normal operation, the proposed BFCL-DVR is equivalent to a conventional DVR, whose control principles have been described in detail in [4,29].