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Novel high performance DC reactor type fault current limiter

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ABSTRACT

This paper presents a novel structure for DC reactor type fault current limiter (DRFCL), which can suppress the fault current in distribution networks. The proposed DRFCL is composed of a DC reactor, a bridge rectifier, and anti-paralleled IGBTs power electronic (PE) switch. The DC reactor contains main and supplementary windings. The main winding has a high inductance and acts as a DC reactor. The supplementary winding is used as a control means for fast FCL operation. The fast response allows the cost, weight and volume of the DC reactor to be reduced. The proposed DRFCL reduces the overvoltages on the devices and it has lower number of components, therefore, it can be economic. Analytical solutions, to describe the performance of the proposed DRFCL are presented and the proposed model is simulated via MATLAB software. Finally, a one-phase prototype structure is built and experimental results are studied to show the capability of the proposed DRFCL.

1. Introduction

It is well known that distribution network's power quality, reliability and protection are important for utility and customers. Limiting the fault current amplitude reduces the stress on devices, improves the PCC voltage level, decreases the voltage drop on elements, etc. When a fault occurs, the result is a fault current flow, PCC and load voltage drop and other severe insulation problems. Such transient phenomenon will shorten the lifetime of distribution network equipments, and may damage circuit breakers or electromagnetic switches. Moreover, the fault current may cause an abnormal operation of transformers and sensitive loads, and results in lower power quality [1–4]. Various approaches have been proposed for limiting the fault current and preventing the insulation failure problems, such as employing single-use fuse [5–7], series current limiting reactor [8], series transformer [9], and also superconductive limiter [10–12]. These solutions may cause other problems such as series resonance, need for an additional control circuit, and more power losses during the steady state operation mode, and complexity of control strategy. Hence, solid state fault current limiters (SSFCLs) have been commonly studied and suggested for distribution networks to provide a better equipment protection. Besides the SSFCLs, DC reactor type FCLs have been suggested with different control approaches [13]. For example, single-phase DC reactor-type FCL has been studied in [14]. But this FCL needs a DC bias power supply and the inductance of the FCL winding is low as compared with the suggested DRFCL winding. The size of the FCL winding and DC bias power supply of [14] increases the FCL cost and also weakens the FCL response to the first peak of the fault current. Other improved topologies have been studied in [15–18] but in these FCLs, the mentioned problems have not been solved. A single-phase FCL employing IGBT bidirectional switch has been reported in [19]. The switch has been realized using a stack of IGBT and anti-parallel diode. Also, varistors have been used in parallel with switches as a voltage clamping element. The main disadvantages of this FCL are high conduction loss of the IGBT switch in normal operation mode and the switch overvoltage which is higher than the line peak voltage. Also, the varistor is required to dissipate a rather significant power. A transformer inrush current limiter based on DC reactor has been studied in [20]. The bridge-type FCLs with reduced number of controlled devices for inrush current limitation has been given in [21]. In order to reduce the magnitude of inrush current, a bidirectional impedance-type inrush current limiter (BIT-ICL) is proposed in [22]. Application of new control strategy to improve the fault ride through capability of doubly fed induction generator (DFIG) during the symmetrical and asymmetrical grid faults is studied in [23]. The smart fault current mitigation solutions and voltage sag analysis are given in [24]. Fault level consideration is an important factor for the interconnection of distributed generation (DG) to the electrical network [25]. In this paper, the calculation of the resulting fault level in medium and low voltage distribution networks with DG is discussed. Using FCL as a constraint for properly dispatch of active power in the power

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system is given in [26]. Employing a new family of zero-energy sag correctors to realize protection against voltage sag has been presented in [27,28] and the design guidelines for such sag correctors for the new dynamic voltage restorer (DVR) system have been provided. The DVR, as a means of series compensation for mitigating the effect of voltage sags, has been established as a preferred approach for improving power quality [29] and also, the combination of FCL and DVR for decreasing the requested power rating and time response of abnormal variations at DVRs have been proposed. In [30], the DVR and resistive type high temperature superconducting fault current limiter (HTS-FCL) have been designed and implemented as a series grid interface topologies for enhancing the fault ride-through (FRT) performance of doubly fed induction generator (DFIG)-based wind turbines (WTs).

In order to overcome the shortcomings of the DC reactor response problem and decrease the FCL cost, this paper proposes a DC reactor type FCL to increase the FCL response to the first peak of the fault current while the inductance of the DC reactor is high as compared with other conventional DRFCLs [14–18]. The fast response allows the inductance, cost, weight, and volume of the DC reactor to be accordingly reduced. This paper has been organized as follows: in Section 2, the proposed distribution network configuration including DRFCL and its operation principles has been presented. The analysis of the proposed DRFCL has been developed in Section 3, and Section 4 discusses the simulation results and Section 5 includes experimental results of the built prototype. Finally, last section gives the conclusion and highlighted merits of the proposed DRFCL.

2. Distribution network configuration and operation principles

2.1. Distribution network and DRFCL configurations

The single-line diagram of a two feeders power system including DRFCL is shown in Fig. 1. It is assumed that the feeder F1 supplies a sensitive load and the feeder F2 delivers power to other loads. After fault occurrence in F2, the rapidly increased fault current causes a voltage sag at the PCC. For controlling the fault current and maintaining the PCC voltage at an acceptable range, a novel DRFCL is proposed, which is composed of a DC reactor with two windings, an anti-paralleled IGBT switch, a single-phase bridge rectifier, a DC voltage source (V_b) for compensation of DRFCL power losses and a simple control circuit.

The suggested FCL employs a DC reactor with two windings that act as a transformer. The main winding has a relatively high inductance and the second one (supplementary winding) has less winding turns. In usual DC reactor based FCL, it can be saturated by the induced DC voltage on the DC reactor during normal operation mode. The saturated DC reactor shows negligible impedance and FCL has negligible effect on the system voltage, current and power quality. However, the size of the DC reactor is a great challenge because high inductance DC reactor has a considerable delay in the instant of the circuit breaker energization. Furthermore, we suggest a novel DC reactor based FCL with high inductance and good current limiting capability. During normal operation mode, the supplementary winding is short-circuited via antiparallel IGBTs. Furthermore, the short-circuited supplementary winding bypasses the main winding and FCL inductance does not cause any delay in the system energization instant. Other DRFCL stray inductances are saturated via induced DC voltage form DRFCL rectifier bridge. Therefore, during normal operation mode, the DRFCL losses are negligible and the stray inductances are saturated and are short-circuited completely. Finally, the DRFCL main and supplementary windings are short-circuited via connected IGBTs but they are not saturated. Therefore, the DRFCL employs a DC reactor with high inductance and fast performance. The saturated inductances include main and supplementary stray inductances.

The first winding of the DC reactor (main winding) is placed between PCC and the electrical load, and its main function is to insert high impedance into the line at the instant of fault occurrence. Moreover, the DC reactor short circuit rate and the fast response of the DRFCL are related to the secondary winding (supplementary winding) operation and can be changed by adjusting its turns ratio. So, it provides best electrical isolation and a fast performance for the DRFCL as well. The main winding of the DC reactor has a high inductance and its core is made of silicon steel, without any air gap, which short-circuits in normal operation mode and reduces the voltage drop across the DRFCL. In normal operation mode, for reducing power losses, the IGBT switches turn-on and after transient removal, the output voltage of the bridge rectifier short-circuits the remains inductances and these switches turn-off automatically.

2.2. Operation principles

To explain the operating principles in normal and fault conditions, the proposed DRFCL can be simplified to the circuit shown in Fig. 2.

According to the DC reactor charging and discharging behavior, its operation modes are described as follows:

Normal operation mode: After closing the CB, the diode pairs D_1–D_2 and D_3–D_4 conduct in positive and negative half cycles respectively. So the output DC current of the bridge charges the DC reactor up to the AC current level. Prior to start-up, the control circuit of the anti-paralleled IGBTs turns the switches on. Therefore, the supplementary winding is short-circuited which bypasses the main winding. Furthermore, the linkage inductance of the DC reactor is short circuited by the high flowing DC current and the DRFCL is invisible during normal operation mode. Then the short-circuited DC reactor turns off IGBTs in next interval. During this period, the DC reactor voltage freewheels and acts as a short circuit presenting low impedance. The DRFCL has direct connection to the voltage source with a negligible voltage drop, and the current of the line flows through the diodes shown in Fig. 2(a).

Fault current limiting mode: This mode can be divided into the following two sub-modes:

(a) Limiting sub-mode: When a downstream short-circuit fault occurs, the rising AC fault current reaches the DC reactor current level and the diodes, which are carrying the fault current, remain in ON state and other two diodes are in OFF state at zero current. When a pair of diodes (D_1 and D_2 or D_3 and D_4) conduct at the instant of fault occurrences, the fault current flows through the DC reactor. In this case, the supplementary winding of the DC reactor is open-circuited because its supply voltage is fed from node n, and voltage of this node is near zero. Therefore, the IGBTs driver circuit is bypassed and these switches are turn-off during the fault, as shown in Fig. 2(b). Due to increase in the DC reactor reactance, the magnitude of the fault current will be limited below the expected value and the CB can take protective action.

(b) Freewheeling sub-mode: After suppressing the fault current, voltage of node n back to the pre-fault value and the supplementary winding is again short circuited via IGBT switches. In this mode, the DC reactor discharges via the diode rectifier rapidly. Then, all diodes (D_1–D_4) turn on simultaneously. In this mode, the DC reactor freewheels and acts as a short circuit. The load has a direct connection to the line, and the current of the line flows through the diodes as shown in Fig. 2(a). Because of the supplementary winding of the DC reactor and IGBT switches operation, the DC reactor is charged