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Controllable resistive type fault current limiter (CR-FCL) with frequency and pulse duty-cycle

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ABSTRACT

In this paper a controllable resistive type fault current limiter (CR-FCL) is introduced. The CR-FCL inserts a pre-specified value of resistance based on a pre-defined function, by using a simple switching method, in series with the fault current path. When a fault occurs, a self turn off switch starts switching with a pre-specified frequency and duty cycle. By this switching pattern, the controlled value of resistance enters to the fault current path. So, the CR-FCL limits the fault current to the desired values. In addition, from transient stability point of view, by inserting the optimal resistance value, the CR-FCL is capable to enhance power system transient stability in a good manner. In fact, generation of the controllable resistance that depends on the duty cycle of the self turn off switch is the main idea of the CR-FCL. The variable duty cycle results the variable resistance and the fixed duty cycle results the fixed resistance. Analytical analyses of the proposed FCL are presented in details. Simulation results by power system computer-aided design/electromagnetic transients, including dc (PSCAD/EMTDC) software and corresponding experimental results are studied to validate the effectiveness of the CR-FCL. Considering error analyses, there is the good agreement between the simulation results and the experimental results.

1. Introduction

Interconnection of electric power systems is necessary to increase the reliability of power supply. Therefore, the electric power systems have been getting more complicated. In addition, to achieve more reliability of power networks and proper response for increasing power demand, growth of power generation systems is expected. So, the available fault current levels may exceed the maximum short circuit rating of power system equipments [1–4].

In these conditions, to prevent the bus replacements and changing the switchgears and other equipments to the higher power level, general ways are used to limit the high-level fault currents and their effects on power system such as: splitting the power grid, introducing higher voltage connections (ac or dc), using current-limiting fuses, series reactors, high-impedance transformers, using complex strategies like sequential network tripping and tracking fault location. These ways may cause high power losses and cost in the power systems. So, limiting the fault currents is an important subject, and application of the fault current limiters (FCLs) is one of the promising solutions [5–8].

Considering the structure of FCLs, there are many kinds of the FCLs: superconducting and non-superconducting FCLs, magnetic type FCLs and solid state FCLs. These FCLs can be classified by impedance type: inductive and resistive type FCLs [9–15].

The structure introduced in [14] uses the superconducting dc reactor type FCL to limit the fault current which it has high construction and maintenance costs. In addition, it uses the protection resistor to reduce the current rating of the superconducting dc reactor during the fault. Its resistance is constant and there is not any capability to control fault current level. In [15], the non-superconducting dc reactor type version of [14] has been introduced. It is more practical and is used to keep the magnitude of the fault current in the pre-specified value. But, there is a considerable voltage drop on the large non-superconducting dc reactor. As a result, the power losses on the non-superconducting dc reactor in the normal operation of power system is noticeable. In addition, using the auxiliary circuit of voltage drop compensator for large non-superconductor makes the additional complexity, cost and power losses. This auxiliary circuit produces a constant dc voltage. However, considering load variation in the power system, the constant dc voltage cannot properly compensate the voltage drop.

Considering the impedance type of FCLs, there is another FCL group which is resistive type FCL (R-FCL) [16–18]. Resistive type superconducting FCL (R-SFCL) uses the quenching characteristics

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of the superconductors to generate the limiting resistance. However, the resistance of R-SFCL is not constant during the fault due to its quenching characteristics. So, they are not fully controllable [17,18].

On one hand, R-FCL which is capable to consume the active power can be applied to enhance the power system transient stability by absorbing the accelerating active power of generators during the fault [18–23]. On the other hand, determination of the optimal resistance value and the optimal location of R-FCL are important from transient stability point of view [18–22]. So, the R-FCL which is capable to control the resistance value is necessary to insert the optimal value of resistance to the utility during the fault.

In this paper, a novel approach of the R-FCL is introduced which is fully controlled. Main idea of the controllable resistive type fault current limiter (CR-FCL) is to generate the controllable resistance by the simple switching method for two main applications: (1) limiting the fault current level to the desired value and (2) inserting optimal value of resistance in the power system to reach maximum transient stability along fault current limitation. The proposed structure does not need the large non-superconducting reactor. As a result, it has low losses, low voltage drop and does not need the auxiliary circuit of voltage drop compensator. The analytical analyses in the ac and dc side of the CR-FCL in the normal and the fault conditions are presented in details. The simulation study including the CR-FCL is performed using PSCAD/EMTDC software [24]. Operation of the CR-FCL is experimentally investigated by using of the model FCL and a laboratory scale power system simulator.

2. Power circuit topology and principles of operation

The power circuit topology of the CR-FCL is shown in Fig. 1. This topology is composed of four main parts which are as follows:

1. A three phase transformer in series with the utility that is named "*isolation transformer*".
2. A three phase diode bridge rectifier.
3. A self turn off switch in parallel with a large resistor (R). This is the most important part of the CR-FCL and plays the main current limiting role.
4. A small reactor L_d to prevent sever di/dt on the self turn off switch. Because of small value of L_d, it can be designed with air core to prevent its saturation. In addition, it does not make the considerable voltage drop. Therefore, this structure does not need the additional circuit for compensating its voltage drop compared to [15].

The main idea of the CR-FCL is to make the controllable resistance using the special switching pattern. In the normal operation of power system, the self turn off switch is ON and R is bypassed. In this case, L_d is charged to the peak of line current and operates as a short circuit. Neglecting the small voltage drop on the semiconductor devices, total voltage drop across the CR-FCL is almost zero. So, the CR-FCL approximately has no effect on the normal operation of power system.

Considering a three-phase to ground fault in point F in Fig. 1, $i_L(t)$ starts to increase. When it reaches to a pre-defined value (I_0), the self turn off switch starts switching with a pre-specified frequency f_s and duty cycle D. During the fault, L_d is charged and discharged with f_s (Appendix: Fig. A1). By this switching pattern, the controlled value of equivalent average resistance enters to the dc side of the CR-FCL.

Fig. 2 shows the dc side equivalent circuit of the CR-FCL during the fault. In Fig. 2, R_{dc} is the controllable resistance in the dc side of the CR-FCL. The dc side voltage equation is as follows:

$$V_{Ds} = \frac{6}{\pi}\sin\left(\frac{\pi}{3}\right)aV_m \tag{1}$$

where V_m and a are the peak of source voltage and the isolation transformer ratio, respectively.

For the fixed duty cycle, it is possible to calculate the desired value of R_{dc} by choosing the permissible value of peak of $i_L(t)$ during the fault as follows:

$$R_{dc} = \frac{V_{Ds}}{I_{ss.av}} \tag{2}$$

where $I_{ss.av}$ stands for the steady state permissible value of $i_{dc}(t)$ that is equal to the peak of $i_L(t)$ during the fault.

The value of R_{dc} can be concluded from (3).

$$R_{dc} = (1-D)R \tag{3}$$

Eq. (3) will be discussed in Appendix section in details. So:

$$D = 1 - \left(\frac{R_{dc}}{R}\right) \tag{4}$$

Therefore, for a given constant R and by considering the steady state permissible value of fault current, D can be determined using (2) and (4). Fig. 3 shows the control circuit of the CR-FCL.

By neglecting power losses of the isolation transformer, the diode rectifier bridge and the self turn off switch, ac side and dc side active powers of the CR-FCL are equal. Therefore:

$$3\frac{\left(V_m/\sqrt{2}\right)^2}{R_{ac}} = \frac{\left(\frac{6}{\pi}\sin\left(\frac{\pi}{3}\right)aV_m\right)^2}{R_{dc}} \tag{5}$$

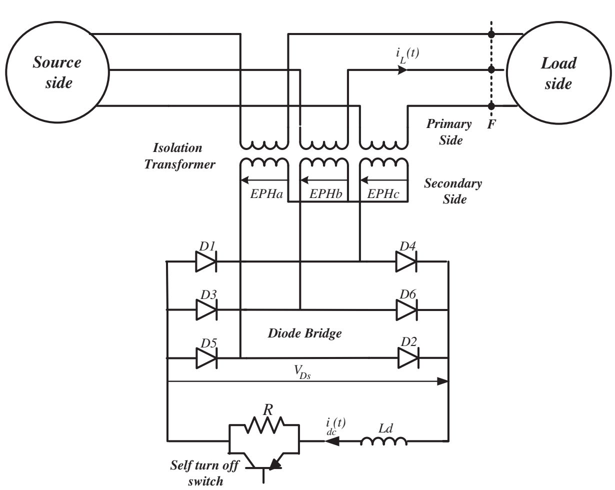

Fig. 1. Power circuit topology of the CR-FCL.

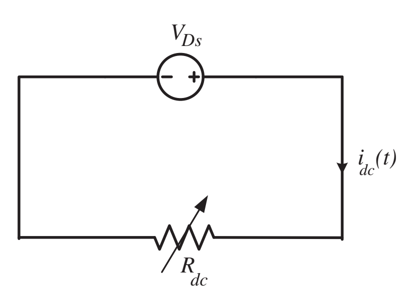

Fig. 2. dc Side equivalent circuit of the CR-FCL during the fault.