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Effect of the Series Resonance LC Tank on the Mitigation of Fault Current in Radial Distribution Networks

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Abstract

This paper proposes a novel Fault Current Limiter (FCL) for the application on power systems to control voltage sags at the Point of Common Coupling (PCC) during faults. This new FCL is a resonance transformer, whose primary side is connected to a series capacitor and transmission line. Also, the secondary side of the transformer is switched by a semiconductor device to change the impedance of the primary side of the transformer. The main control component is a fast-closing switch connected in parallel with the secondary side of the transformer, which is driven by the power electronic switch. It can respond within 1 msec. When a fault occurs, the switch closes and bypasses the transformer secondary side and fault current is limited by the reactor. So, by increasing the existing resonant frequency, the fault current is limited. The simulated and experimental results show that it is feasible to develop the FCL with low cost and high reliability. The experimental results show the capability of the proposed FCL, too.

Keywords: Fault Current Limiter (FCL), Point of Common Coupling (PCC), Power Quality, Resonance Transformer

1. Introduction

The fault current in the power system tends to increase over time for different reasons; e.g., electric power demand increase (load growth) and subsequent increase in generation, new parallel conducting paths, new interconnections within the grid and new distributed generation units. The fault currents, flowing from the source to the fault, lead to high dynamical and thermal stresses being imposed on equipments like overhead lines, cables, transformers and switchgears[1–4]. Therefore, there is a considerable interest in devices, which are capable of limiting fault currents. Also, various types of Superconducting Fault Current Limiters (SFCLs) have been presented[5–7]. A Fault Current Limiter (FCL) can limit the fault current passing through it within the first half cycle. The simplest way to limit the short-circuit current would be the use of an impedance (Z_S) in series with the current path. The drawback of this solution is that it also obviously influences the system during normal operation, i.e. it results in considerable voltage drops at high load currents[8–10]. The concept of FCL is limited to the fault current before its first peak, although the response speed is of greatest importance. Since the 1970s, several types of scheme have been applied in power systems such as the fuse with fault-current limitation and superconducting FCL[11–13]. In recent years, power electronic based FCLs have been proposed[6], which has the features of a series compensation under normal conditions. A new hybrid FCL has been proposed for primary distribution systems, which is a high temperature superconducting element in parallel with two other branches[14]. Superconducting Fault Current Limiters (SFCL) can limit

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the prospective short-circuit currents to lower levels, so that the underrated switchgears can be safely operated[15]. The necessity and procedure for the application of FCL and bus sectionalizing system have been discussed in[14]. A rectifier SFCL with non-inductive reactor has been presented in[16]. In normal operation mode, the impedance of the FCL is much less, while in the current limiting mode, the impedance is higher than the impedance of the network[17]. There are different FCL technologies that have been suggested by researchers such as: purely resistive SFCL, hybrid resistive SFCL, saturable core SFCL, shielded-core SFCL, solid-state (SSFCL-CB), fuses and bridge type FCL. The combination of the bridge type FCL and power converter for voltage quality improvement has been suggested in[18], where common diode bridge Fault Current Limiter and power converter have been linked by a common DC link in the power system. Fast-closing switch based FCL with series compensation has been investigated in[19]. Also, in[20], it is mentioned that a DC reactor type FCL in series with a downstream circuit breaker can be a solution to control fault current levels in electrical distribution systems. System studies show that the DC reactor type FCL can not only limit the fault current to an acceptable value, but also can mitigate the voltage sag. In this paper, the FCL structure, presented in[21] is carefully investigated and its problems are solved in a new scheme of FCL, which has a fast-closing switch. Its effectiveness is verified by simulations and measurements. It is shown that the fast-closing switch based FCL has more advantages, lower cost and higher reliability in comparison with other FCLs. It can improve the system stability by its fast response after fault occurrence and series compensation after fault clearing. The results are compared with the FCL proposed in[21] too.

2. Proposed FCL

In this section, a None-Superconducting Fault Current Limiter (NSFCL) based on resonant structure is investigated and results are compared with[21]. In[21], the impedance of the series reactor is very low, so it cannot control the fault current. The FCL controlled the fault current and decreased it to 50% of its initial value, which is not enough and the transient response of the voltage and current of the capacitor can cause the dielectric failure and damage of devises. Advantages of the proposed FCL to the FCL introduced in[21] are listed as follows:

The magnitude of the limited current in[21] is 0.65 time of the fault current, while the limited current, in this paper, is 0.015 time of the fault current. This means that the suggested FCL can effectively control the fault current. Switching delay is 3 msec in[21], while in current paper, this delay is decreased to 2 msec. In[21], the peak current and spark of voltage on the switch is high and causes damage to the capacitor, but in this paper there are no spark and surge current. During the fault, the current of the switch is considerable and can result in switch failure. Also, the fault overvoltage on the metal oxide surge arrester can cause its failure. In this paper, all of the problems are solved using the proposed FCL. During normal operation mode of power system, the impedance of the resonance circuit includes series capacitor and the primary winding of a series transformer. When the fault is happened, the semiconductor switch is closed in the secondary side of the transformer and causes an increase in the impedance of the resonant circuit and as a result the fault current limitation. As shown in Figure 1, in the parallel feeder, which is connected to the Point of Common Coupling (PCC), the downstream fault of the faulty feeders could result in large fault current flow, which not only might damage the series equipments but also can cause voltage drop at PCC. This voltage drop can affect other loads on parallel feeders connected to PCC.

A significant advantage of FCL technologies is their ability to remain virtually invisible to the grid under nominal operation, introducing negligible impedance in the power system until a fault event occurs. Ideally, once the limiting action is no longer needed, an FCL should quickly return to its nominal low impedance state. Also, an ideal FCL should have the following characteristics: low impedance at normal operation, a very short recovery time, large impedance in fault conditions, fault current limitation before the first peak, properly respond to any fault magnitude and/or phase combinations and finally high reliability and low cost. The suggested FCL is shown in Figure 2. There are

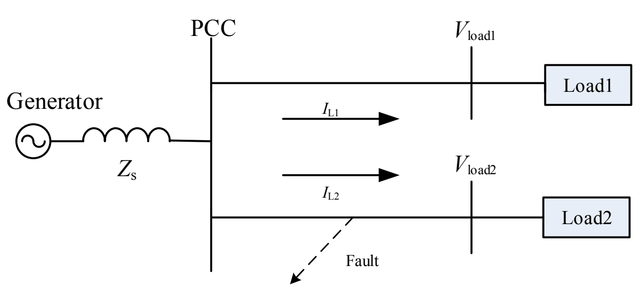

Figure 1. System with loads connected to PCC through parallel feeders.

three FCLs, installed in each phase of the transmission line for controlling the over current of each phase separately, where C_s is series capacitors. Also, transformers are presented by T_1 and connected in series with the transmission line. In addition, the semiconductor switch, T_s, is connected in series with the secondary of transformers.

In the normal operation mode of the power system, the series capacitor and primary winding of the transformer have resonance frequency the same as the power system frequency, while the secondary side of the transformer is open. So, the transformer works as an AC reactor and the impedance of the FCL, i.e., C_s and AC reactor is near to zero. In order to decrease the flux linkage of the transformer and voltage of the secondary, this equipment is designed by lowest turn of winding up to possible value. When the fault occurs, the semiconductor switches instantly on and the transformer secondary side is short circuited. In this mode, the impedance of the inductor decreases suddenly, so series capacitor limits the fault current and controls the voltage of PCC.

3. FCL Control Circuit

During fault, the voltage of PCC and the voltage of the downstream buses decrease suddenly. The fault detector circuit is connected to the point n_1 as shown in Figure 3.

It consists of one bridge circuit, capacitor and a resistor. In this circuit, the voltage on the capacitor is compared with the DC reference voltage. In the case of decrease of the voltage of the capacitor from the reference voltage, the fault detector switch turns on the FCL switch. Using this control circuit, FCL can successfully control and limit the fault current as will be shown in simulation and experimental results.

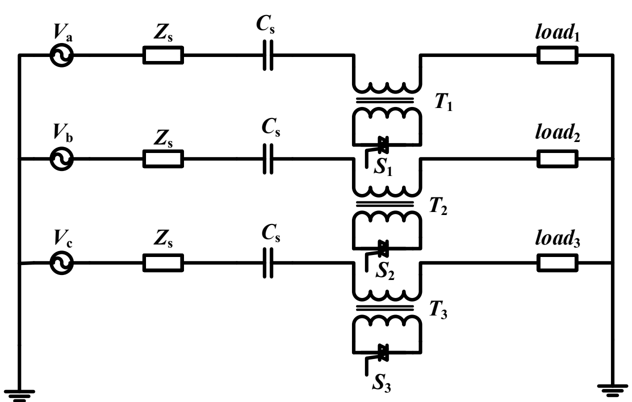

Figure 2. Proposed FCL and system equivalent circuit.

4. Dynamic Modeling of Proposed FCL

In the proposed FCL, the semiconductor switch, T_s, is assumed to be an ideal switch. Also, the turn's ratio of the transformer, T_1, is equal to 10/1. The proposed FCL transformer model is shown in Figure 4.

The impedance of the load and source is listed in Table 1 and we have:

$$z_s = R_s + j\omega L_s \tag{1}$$

$$z_L = R_L + j\omega L_L \tag{2}$$

4.1 The FCL Normal Operation Mode

In the secondary winding of the transformer is open circuit and the current of the semiconductor switch is equal to zero. By applying Kirchhoff's Voltage Law (KVL) to the equivalent circuit shown in Figure 3, the nonlinear dynamic equation of the power system can be written, as follows:

$$\sqrt{2}\sin\omega t = Ri_L + L\frac{di}{dt} + \frac{1}{C}\int i_L dt \tag{3}$$

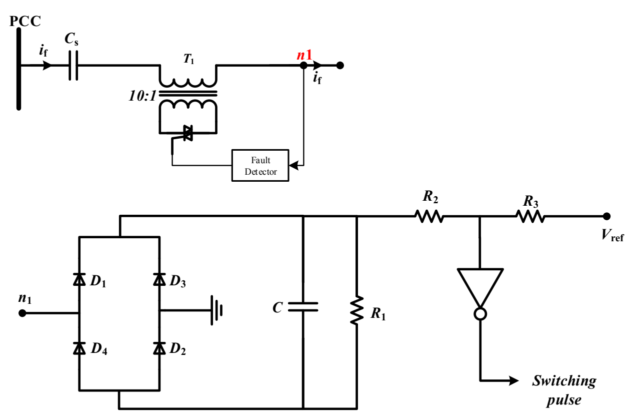

Figure 3. **a)** FCL structure and **b)** Controlling circuit diagram.

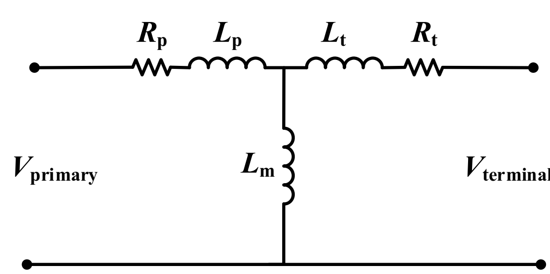

Figure 4. Transformer model.

Table 1. Electrical network parameters

Parameters	Value	Description
R_s	0.5 Ω	Source resistance
L_s	0.009 H	Source inductance
C_s	50μf	Series capacitor
L_p	0.02 H	Primary inductance of transformer
L_m	0.18 H	magnetization inductance of transformer
L_t	0.002 H	secondary inductance of transformer
Rp	20 Ω	Primary resistance of transformer
Rt	20 Ω	secondary resistance of transformer
R_L	1200Ω	Load resistance
L_L	0.01H	Load inductance
N1	300	Primary turns ratio
N2	30	secondary turns ratio

Then, we have:

$$\omega\sqrt{2}\cos\omega t = R\frac{di_L}{dt} + L\frac{d^2 i}{dt^2} + \frac{i_L}{C} \tag{4}$$

By solving Equation (4), the line current (i_L) can be written, as follows:

$$\omega\sqrt{2}\frac{s}{s^2+\omega^2} = \left(Rs + Ls^2 + \frac{1}{C}\right) i_L \tag{5}$$

$$i_L = \left(\omega\sqrt{2}\frac{s}{s^2+\omega^2}\right) \Big/ \left(Rs + Ls^2 + \frac{1}{C}\right) \tag{6}$$

Where, the equivalent resistance is $R = R_s + R_L + R_p$ and the equivalent inductance is $L = L_s + L_L + L_p + L_m$.

5. Simulation Results of proposed FCL

By solving Equation (6), the line current, i_L, can be determined. In the fault operation mode, the secondary winding of the transformer is short-circuited by the semiconductor switch. In this mode, the current of the secondary side is equal to the line current; in other word, $i_T = i_L$ and $i_L = i\ (t=t_1)$. This equivalent circuit is shown in Figure 5.

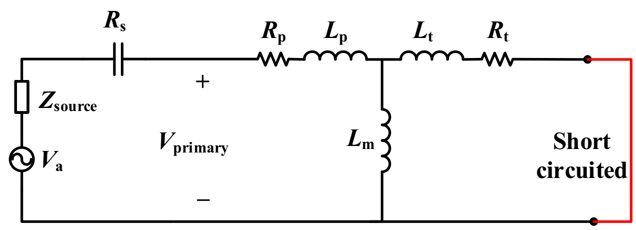

Figure 5. Equivalent circuit of system considering transformer model.

According to Figure 5, Equations are written, as follows:

$$R_p = \left(1 + Q_s^{\ 2}\right) R_t \tag{7}$$

$$x_p = \left(\frac{1 + Q_s^{\ 2}}{Q_s^{\ 2}}\right) x_t \tag{8}$$

$$Q_s = \frac{x_t}{R_t} \tag{9}$$

By using above mentioned Equations, the right hand side series branch of Figure 5 is changed to parallel branch. Now, L_m in Figure 5 is paralleled with L_p. The reduced equivalent circuit can be driven by changing the parallel branch to the series branch, as follows:

$$R_{tt} = \frac{1}{1 + Q_p^{\ 2}} R_{pp} \tag{10}$$

$$x_{tt} = \frac{Q_p^{\ 2}}{1 + Q_p^{\ 2}} x_{pp} \tag{11}$$

$$Q_p = \frac{x_{pp}}{R_{pp}} \tag{12}$$

Where, $x_{pp} = x_p \| x_m$ and $R_p \| R_{pp}$. By solving the Equation (13) we have:

$$\omega\sqrt{2}\cos\omega t = R_{eq}\frac{di_L}{dt} + L_{eq}\frac{d^2 i}{dt^2} + \frac{i_L}{C_s} \tag{13}$$

Where,

$$R_{eq} = R_s + R_p + R_{tt} \tag{14}$$

and then,

$$L_{eq} = L_p + L_{tt} \tag{15}$$

In this study, the fault occurs at t = 400 msec. The simulation results indicate that there is no voltage sag during the fault. After fault occurrence, the voltage of the load decreases to zero and because of very low impedance of semiconductor switch in on state, the voltage of the secondary winding of the transformer almost reaches to zero. There is no any unwanted phenomenon and the system is working under normal operation mode. Figure 6 shows the simulated load voltage. In this figure, the fault is occurred at 400 msec and the amplitude of the load voltage reached to zero.

Figure 7 shows the line current during normal and fault operation modes. Figure 7(a) represents the line current when there is no installed FCL in the line. Figure 7(b) shows the line current while the suggested FCL is utilized in the line. The fault current amplitude depends on the operation of the FCL component. According to this figure, the amplitude of the fault current reduces from 4 kA to 60 A.

When the fault occurs, FCL limits the fault current and the voltage on the Point of Common Coupling (PCC) remains in an acceptable level as shown in Figure 8. In this application, FCL can successfully control the faults current and limit the transient overvoltage.

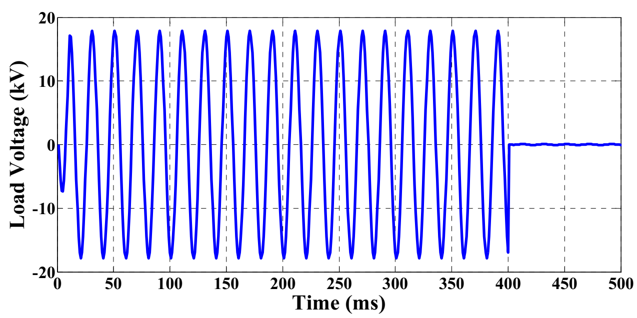

Figure 6. Voltage of load during normal and fault operation conditions.

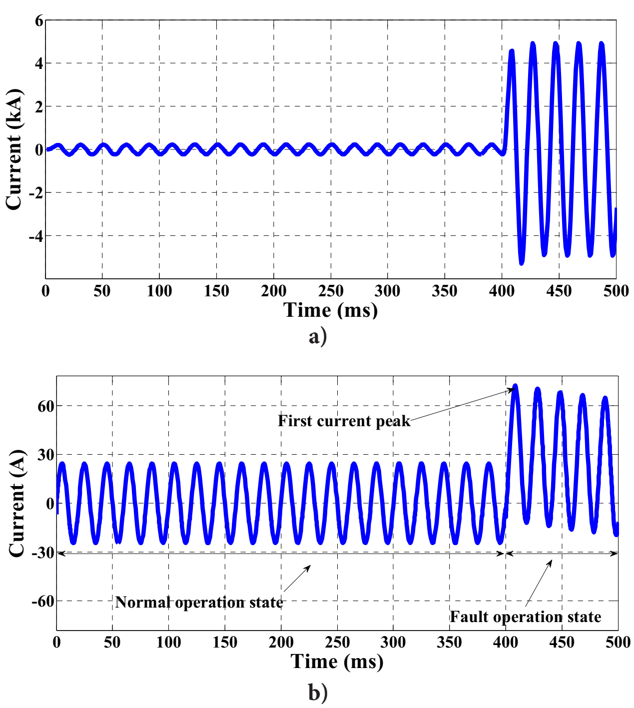

Figure 7. Line current during the normal and fault operation modes **a)** Without FCL effect and **b)** With FCL effect.

6. Experimental Results

In order to verify the FCL effectiveness on the fault current, a low voltage ($220V_{rms}$) laboratory prototype is built as shown in Figure 9. To verify the simulation results, the limited fault current and the voltage of the PCC are measured in the prototype for normal and fault operation modes.

Figure 10 shows the line current (lower waveform) and load voltage (upper waveform) before and after fault

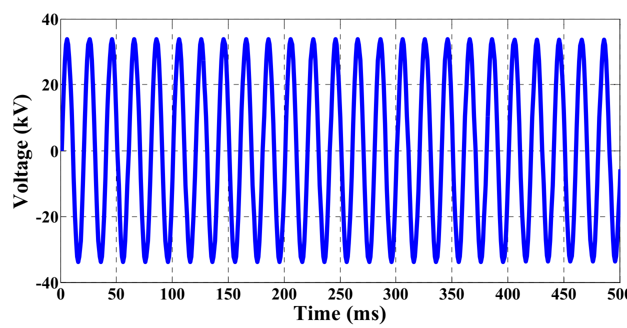

Figure 8. PCC voltage during the normal and fault operation modes while FCL is connected in series with the line.

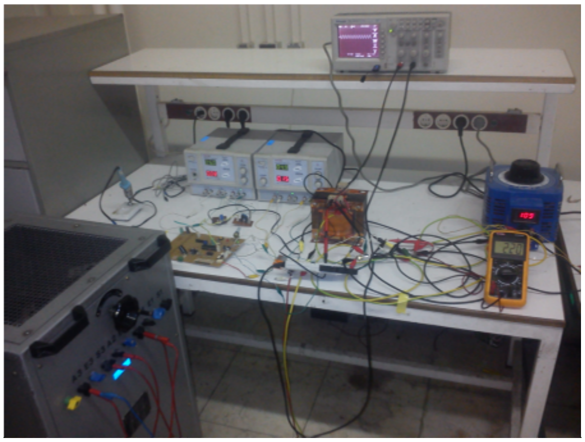

Figure 9. Laboratory test setup.

occurrence. Before the fault occurrences, the line current amplitude is 1 A and the load voltage is 220 V. The load voltage and line current are sinusoidal and system works under normal operation mode. In this case, power electronic switch is in off state and the voltage drop on FCL is near zero. In the instant of the fault inception, the power electronic switch drivers change the gate signal and this switch is turn on. So, the series transformer is bypassed and the series capacitor is connected in series with the line and fault current is decreased to 2 A as shown in Figure 10. It is assumed that the fault duration is 3 sec and then the fault is removed. In this case, the fault current is decreased to the normal current and again switches turn off simultaneously. After fault removal, the FCL voltage drop is zero and the system can work under normal operation mode.

Figure 11 shows the PCC voltage during the normal and fault operation modes. This figure clearly shows

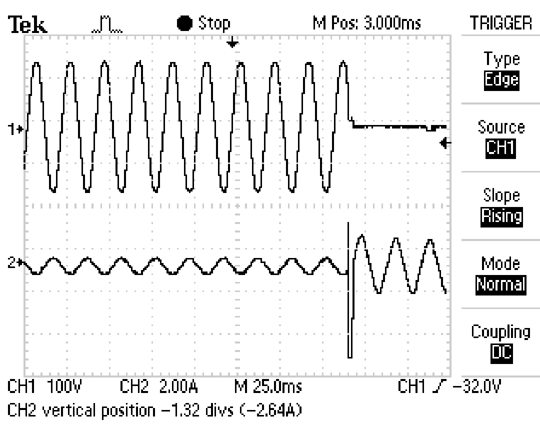

Figure 10. Line current (lower waveform) and load voltage (upper waveform) during the normal and fault operation modes.

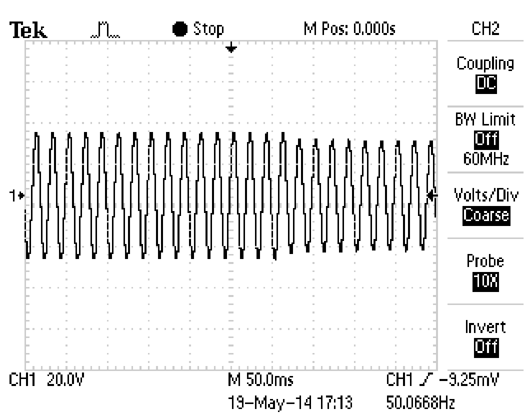

Figure 11. PCC voltage during the normal and fault operation modes.

the FCL effect on the fixing the PCC voltage level to an acceptable level during the fault.

In the steady state condition, the voltage drop of the FCL is equal to zero. During fault, the voltage drop is equal to the source voltage. The voltage drop of the component during the fault depends on the structure and topology of the FCL. During fault, the semiconductor switch turns on and the secondary side of the transformer is short circuited. This switch can limit the fault current, control the voltage of the PCC and keep the amplitude in the acceptable range.

7. Conclusion

In this paper, a new FCL topology has been proposed, modeled and simulated. It has been shown that the proposed FCL can limit the fault current and adjust the voltage of PCC. The time delay of this FCL operation is very low, the fault detection circuit delay is less than one msec. So, FCL can limit the fault current before its first pick. The simulation results have been compared with simulation results. The good agreement between the simulation and measurement results verifies the effectiveness the proposed FCL.

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