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Power loss and Ripple Current Analysis of a DC Reactor Type Fault Current Limiter

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Abstract: This paper proposes the use of non-superconducting DC reactor type FCL (NSFCL) instead of superconducting fault current limiter which has high cost and technology. The device is connected in series with distribution line and it has almost no effect on the normal operation of the utility. It is not necessary to use a control circuit and it has a simple and cheap power circuit. Design characteristics, analytical analysis and overall transient and steady state performance of NSFCL in normal and fault conditions are presented in this paper. The results show that the power loss is a very small percentage of protected load power. The analytical and simulation results are presented and the overall operation is compared with superconductor FCLs.

Key word: FCL, DC Reactor, Ripple Current, Power Loss, Non-superconducting

INTRODUCTION

Occurring of faults in power systems results in unwanted effects such as damaging, degradation, huge mechanical forces, extra heating and electrical stresses on power system apparatus. High temperature superconductor fault current limiters (SFCLs) due to their efficient fault current limiting performance and competitive cost could be a good candidate to reduce the mentioned problems. Diode bridge type high-TC SFCL because of its simplicity and low cost has attracted a great deal of attention during the last years (Wanmin Fei *et al*, 2009), (Imparato *et al*, 2010), (Morandi *et al*, 2010), (Sharifian *et al*, 2009), (Hui Hong *et al*, 2009), (Jing Shi *et al*, 2008), (WanMin Fei *et al*, 2008), (Salim *et al*, 2004), (Muta *et al*, 2004), (Kameda *et al*, 2002).

As mentioned before, using superconductors is because of their no-loss during normal and fault conditions. Unfortunately, due to high technology and cost of these devices those are not commercially available. There are many attempts to realize using superconducting coils for example in high temperature but most of proposed methods results in more complicated technology and cost. On the other hand, it is interesting to analytical analysis and comparison of using near zero resistance copper coils with superconductors in FCL structure. Obviously, using copper coils for making FCLs is very easy and initial cost would be much lower than superconductors. But, there will be power losses during normal and fault conditions using copper coils so we should pay for power loss cost. This paper deals with analytical analysis of DC reactor type superconductor and non-superconductor type FCLs. Designing formulas and useful characteristics are used to compare the mentioned FCLs. Ours studies show that power losses of near zero resistance copper coils which have enough copper cross section area, have less than 1% power loss of their protected loads power. On the hand, it would be interesting to present new methods for recovery of generated heat by copper coil FCLs for example to warming up of their cooling water. It seems, using copper coil FCLs could be a suitable way for less-developed countries especially those with low electrical energy cost such as middle-east area.

Power Circuit Topology:

Fig. 1 shows the power circuit topology of analyzed copper coil DC reactor type FCL. The utility voltage is a sinusoidal waveform with angular frequency w, and rms value V, and its impedance consists of series connection of resistor r_s, and inductor L_s. There is a switchgear SW, that could disconnect the utility from load after a small time delay after fault current occur that should be determined by protection relay setting time. The proposed FCL consists of a diode-bridge that rectifies the system current that passes through a copper coil DC reactor. The system has no control circuit. The resistance of DC reactor is modeled with a small series resistor R_d while its inductance is shown by L_d in Fig. 1. By choosing appropriate value for inductor L_d, it is possible to achieve an almost DC current with small ripple i_d, that results in short circuit of inductance L_d during normal operation of system. Obviously, increasing the inductance of L_d, results in decreasing the ripple currents of i_d and the DC reactor will have almost no effect on normal operation of system. Existence of r_d

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Corresponding Author: Mir Mahmood Hosseini, Abhar Branch, Islamic Azad University, Abhar, Iran would result in power losses and voltage drop which they could be decreased by increasing the cross section area of copper coil.

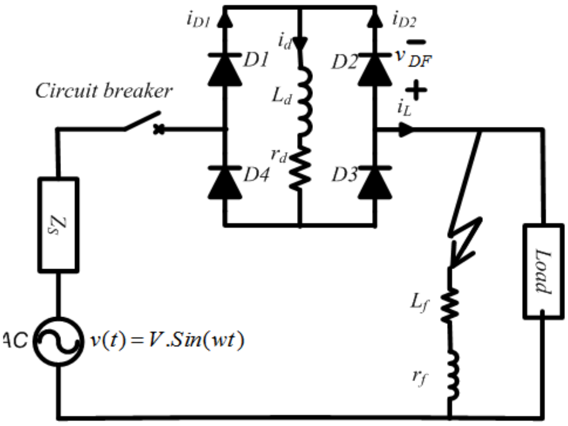

Fig. 1: Power circuit topology of analyzed FCL

There would be a forward voltage drop across rectifier diodes v_{DF}, too. The load is assumed to be a R-L load with r_L and L_L as its resistor and inductor, respectively.

During fault condition, the fault current increases and this time varying current passes through DC reactor that increases voltage drop and decreases the fault current magnitude. In this way, the power rating of switchgear could be determined for lower fault current magnitude. The fault current will pass through DC reactor for only some milliseconds due to the operation of switchgear.

Circuit Analysis and Simulation Result:

Fig. 2 shows the line and FCL current waveforms in circuit normal operation case. The line current is a sinusoidal waveform while the reactor current i_d, is a rectified current. The reactor current is periodic with time interval between t_0 to t_3. The circuit has two modes of operation a follows:

(a)Charging mode
(b)Discharging mode

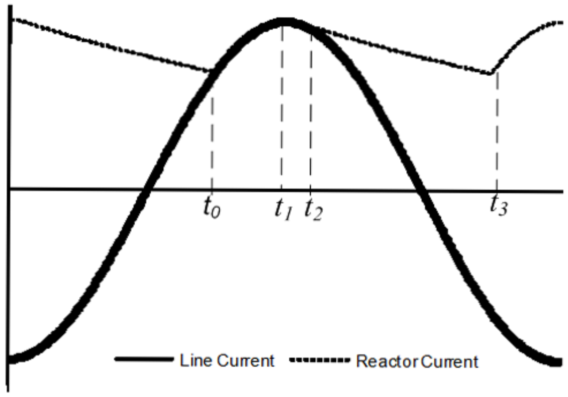

Fig. 2: The Line and FCL current waveforms in normal circuit operation case

During fault condition, the line current increases because the fault impedance $z_f = r_f + jwL_f$ is substituted to load impedance z_L. The power circuit topology of Fig. 1 is used for analyzing the fault condition. The simulation parameters are as follows:

$z_L = 9.24 + j\omega\ 0.022$ (W)
$z_s = 0.01 + j\omega\ 0.001$ (W)
$z_f = 0.01 + j\omega\ 0.001$ (W)
$v_s(t) = 3.81\ \mathrm{Sin}(314t)$ (kv)

$v_{DF} = 3$ (v)
$r_d = 0.01$ (W)
$L_d = 0.1$ (H)

Charging mode begins at t_0 and it continues until t_2. At t_0 the diodes D1 and D3 turns ON and DC reactor connects in series with utility.

Eq. (1) shows the system current formula in charging mode [6].

$$i(t) = e^{-(r/L)(t-t_0)} \left\{ i_0 - \frac{V}{z}\sin(\omega t_0 - \varphi) + \frac{2V_{DF}}{r} \right\} + \frac{V}{z}\sin(\omega t - \varphi) - \frac{2V_{DF}}{r} \tag{1}$$

Where:

$$i_L(t) = i_d(t) = i(t)$$

$$r = r_S + r_L + r_d$$

$$L = L_S + L_L + L_d$$

v_{DF} is the forward voltage drop of the diodes that is assumed to be constant

$$i_0 = i(t_0)$$

$$z = \sqrt{r^2 + (L\omega)^2}$$

$$\tan\varphi = L\omega/r.$$

It is interesting to notice that the current waveform in charging mode is not sinusoidal due to transient of insertion of DC reactor. Obviously, the resistance of DC reactor is not so important in this subject because it is much more less than sum of line and load resistors. So, using inductive FCLs would result in distortion of line current.

Discharging mode begins at t_2 and it continuous until t_3. At $t=t_1$, due to changing the direction of current through L_d, the polarity of its voltage $v_{Ld}(t)$, changes and between t_1 to t_2 its magnitude begins to increase. It is possible to write eq. (2) at $t=t_2$ in which $v_{Ld}(t)$ equals $v_{rd}(t)$ with opposite polarity and the diodes D2 and D4 turns ON because of their forward biasing.

$$\begin{aligned} &[v_{Ld}(t_2) + v_{rd}(t_2)] = [v_{DF1}(t_2) + v_{DF4}(t_2)] \\ &= [v_{DF2}(t_2) + v_{DF3}(t_2)] = 0 \end{aligned} \tag{2}$$

Where

$$v_{Ld}(t_2) = L_d \frac{di_d(t_2)}{dt}$$

During discharging mode, the inductor current free-wheels through the diodes D3-D2 and D4-D1. The line current iL flows both the upper and lower diodes of rectifier bridge. Eq. (4) and Eq. (5) show the line current and DC reactor current formula during discharging mode, respectively.

$$i_L(t) = e^{-(r/L)(t-t_2)} \left\{ i_2 - \frac{V}{z}\sin(\omega t_2 - \varphi) \right\} + \frac{V}{z}\sin(\omega t - \varphi) \tag{4}$$

$$i_d(t) = e^{-(r_d/L_d)(t-t_2)} \left\{ i_2 + \frac{2V_{DF}}{r_d} \right\} - \frac{2V_{DF}}{r_d} \tag{5}$$

Where:

$r = r_S + r_L$

$L = L_S + L_L$

$i_2 = i(t_2)$.

The inductor current decreases because of resistor r_d and diode forward resistors. So, the superconducting coil current will decrease in slower rate because of existence of only rectifier diodes resistors. The current of D1 and D3 which are similar, decreases in discharging mode because of decreasing the line current. At t=t_3 the current of these diodes reaches to zero and they turn OFF naturally. On the other hand, the current of D2 and D4 which are similar, increases during discharging mode. At t=t_3, the current through these diodes begins to increase the current of DC reactor, so the charging mode begins again. Obviously, the sum of currents of diodes in each diode-bridge arm is equal with line current, instantaneously.

Ripple Current:

Eq. (1) and eq. (5) show the charging and discharging current formulas of DC reactor, respectively. Obviously, these currents consist of a DC value in addition to a ripple current. Existence of ripple current, results in voltage drop across L_d during normal system operation case. So, it is appropriate to decrease the ripple currents as much as possible. Eq. (6) is used for definition of DC value of inductor current, I_{DC}:

$$I_{DC} = i_{Max} - \frac{i_{r,p-p}}{2} \tag{6}$$

Where i_{Max} stands for the maximum current of reactor and it is equal with i_1 and $i_{r,p-p}$ stands for the peak to peak of ac ripple current of reactor and it is equal with $(i_1$-$i_3)$. Eq. (7) shows the formula of DC value of inductor current.

$$I_{DC} \cong i_{\max}(1 - \frac{r_d T}{4L_d}) - \frac{V_{DF}T}{2L_d} \tag{7}$$

The $i_{r,p-p}$ could be obtained using eq. (8) as follows:

$$i_{r(p.p)} \cong \frac{T}{L_d}(\frac{r_d i_{\max}}{2} + V_{DF}) \tag{8}$$

Where T is $(t_3$-$t_0)$ and it equals 10 (ms) for power frequency of 50 Hz.

By considering the inductor resistor r_d equal with zero it is possible getting eq. s (9) and (10) which show the DC value and the peak to peak of ac ripple current of a superconducting FCL, respectively [6].

$$I_{DC} \cong i_{\max} - \frac{V_{DF}T}{2L_d} \tag{9}$$

$$i_{r(p.p)} \cong \frac{T}{L_d} V_{DF} \tag{10}$$

Comparison of eq. (8) with eq. (10) shows that existence of resistance in copper coil FCL would result in increasing of $i_{r,p-p}$ through inductor. On the other hand, increasing of L_d could decrease the $i_{r,p-p}$ in addition to increasing of DC value of current through inductor. Fig. s (3) and (4) show the variations of $i_{r,p-p}$ versus DC reactor inductance for different values of line current and inductor resistance. Considering these figures, it seems choosing the DC reactor inductance near to 0.02 (H) would result in acceptable value of $i_{r,p-p}$.

Power Losses:

The main objective for using superconductors in FCLs is their zero resistance and no power loss in normal operation case as well as fault condition. Eq. (11) shows the magnitude of DC power losses in reactor considering this fact that $i_{r,p-p}$ is very small compared with I_{DC} as follows:

$$P_{dc} = r_d I_{DC}^{\,2} = r_d \left\{ i_{\max}\left(1-\frac{r_d T}{4L_d}\right) - \frac{V_{DF}T}{2L_d} \right\}^2 \tag{11}$$

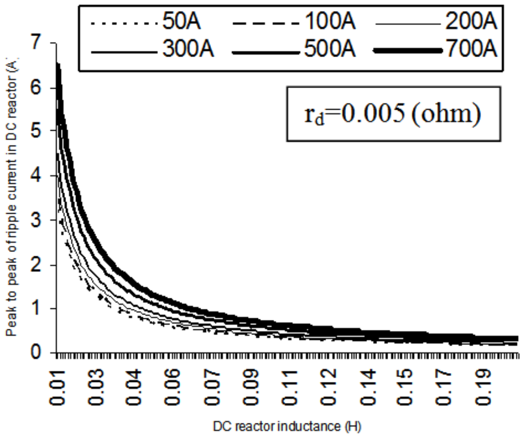

Fig. 3: The $i_{r,p\text{-}p}$ vs. the variations of L_d for different values of line current

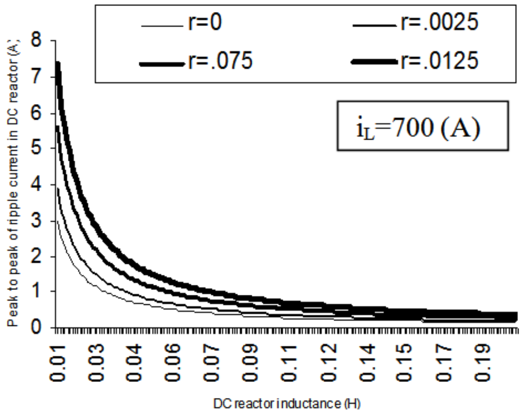

Fig. 4: $i_{r,p\text{-}p}$ vs. the variations of L_d for different values of inductor resistance

Fig. s (5) and (6) show DC power losses variations versus DC reactor inductance where its resistor and line current is as the parameter of curves. This figures show that the power loss in resistance of reactor is less 1% of its protected load power.

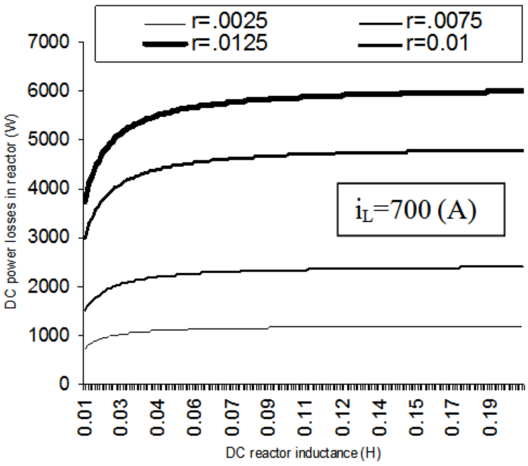

Fig. 5: DC power losses vs. DC reactor inductance for different values of reactors resistance

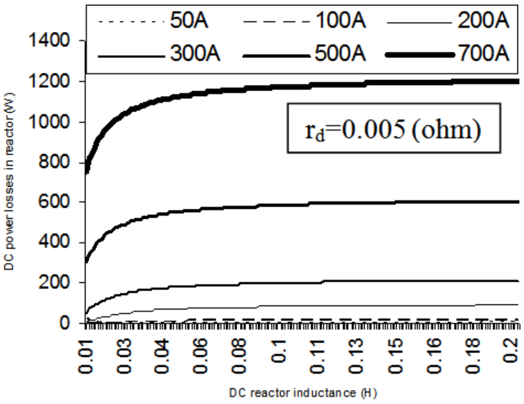

Fig. 6: DC power losses vs. DC reactor inductance for different values of line current

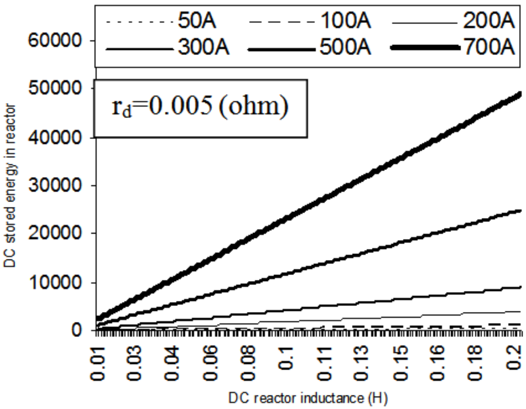

Fig. 7: Storage energy in inductor vs. different values of L_d

The energy stored in inductor can be obtained using eq. (12). Fig. (7) show the storage energy value versus different values of L_d. This figure shows that the stored energy is a function of Ld in almost linear form.

$$W_{DC} = \frac{1}{2} L_d \left\{ i_{\max} (1 - \frac{r_d T}{4L_d}) - \frac{V_{DF} T}{2L_d} \right\}^2 \qquad (12)$$

Conclusion:

The overall operation of mentioned FCLs in normal and fault cases studied, carefully. The results show the power loss of copper coil FCL is less than 1% of its protected load power. On the other hand, the simulation results show that there is not significant difference between superconductor and copper coil FCLs operation in limiting the fault currents magnitude. It seems the lower initial cost and simpler technology for building and using the copper coil FCLs in addition to the possibility for recovering of its heat energy could make this kind of FCLs a good alternative for more researches in this field.

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