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Non-Superconducting Fault Current Limiter

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Abstract – Many types of superconducting fault current limiters (FCLs) are proposed but considering their high technology and considerable cost it is not possible using these devices commercially, yet. This paper deals with presentation the designing formulas and characteristics for near zero resistance copper DC reactor type FCL. The device is series with distribution line and it uses a single copper coil with a diode bridge without any other control circuits. The simplicity to be built and its low cost are the main advantageous of analyzed system. 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.

Keywords – Fault current limiter, Non-superconducting

1 Introduction

By growth of interconnections in electrical systems the short circuit capacity increases. This not only affects the reliability of system but also it could result in damaging, degradation, mechanical forces, extra heating and electrical stresses of power apparatus. On the other hand, the increasing demand of electric energy makes these problems more important in future.

The FCLs are useful devices for limiting the fault currents and avoiding upgrading of switchgears during system expansion. An ideal FCL should have the following characteristics [1]:

(a) zero resistance/impedance at normal operation
(b) no power loss in normal operation and fault cases
(c) large impedance in fault conditions
(d) quick appearance of impedance when fault occurs
(e) fast recovery to normal state after fault removal
(f) reliable current limitation at defined fault current
(g) good reliability
(h) low cost

Different structures are proposed for FCLs such as resistive, screening, saturated core and inductive types but superconducting inductive devices have attracted more attention [2-3]. This is due to this fact that it is possible achieving to many of above-mentioned ideal features of FCLs by these devices.

The common power circuit topology of inductive FCLs could be divided into two categories as follows:

a) AC reactor type
b) DC reactor type

The AC reactor type FCL makes use of a parallel resonant circuit that connected in series with line and it poses high resonant impedance during fault condition. A fast solid state switch inserts an inductance in parallel with a capacitor during fault condition. The capacitor remains in circuit for reducing the inductive reactance of line even in normal operation of system. Unfortunately, resonant type FCLs generates transient voltages that could cause in transient oscillations with series L-C circuit formed by power factor correction capacitors and customer step down transformers. This gives rise to unwanted voltage magnification of customer voltages [4].

The DC reactor type FCL uses a diode bridge to rectifying the system current that passes through a superconducting inductor. The inductor could be a saturated or linear inductance [5, 6]. The diode-bridge and DC reactor connect in series with distribution or transmission line directly or by a current transformer. The inductive FCL could have a three-phase or single-phase structure but, in both cases usually it has only one superconducting DC reactor [7].

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.

2 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 ω, 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 would result in power losses and voltage drop which they could be decreased by increasing the cross section area of copper coil.

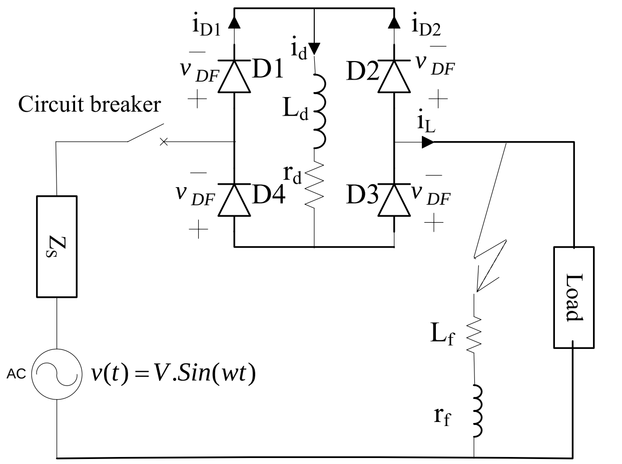

Fig. 1. Power circuit topology of analyzed FCL

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.

3 Circuit Analysis

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

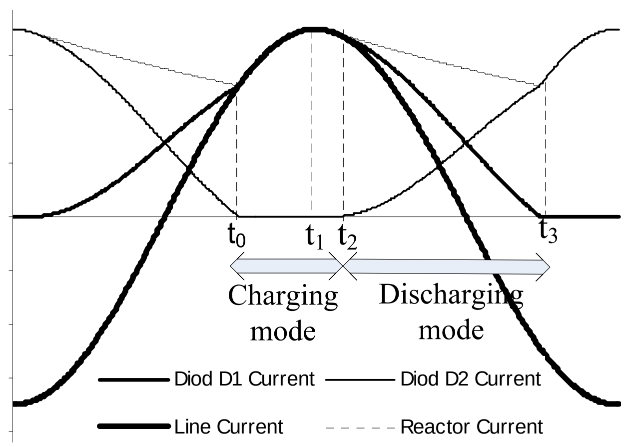

Fig. 2. The Line and FCL current waveforms in normal circuit operation case

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].

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

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.

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

Where

$$v_{Ld}(t_2) = L_d \frac{di_d(t_2)}{dt} \quad (3)$$

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.

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

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

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.

4 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} :

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

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.

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

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

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

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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 $i_{r,p-p}$.

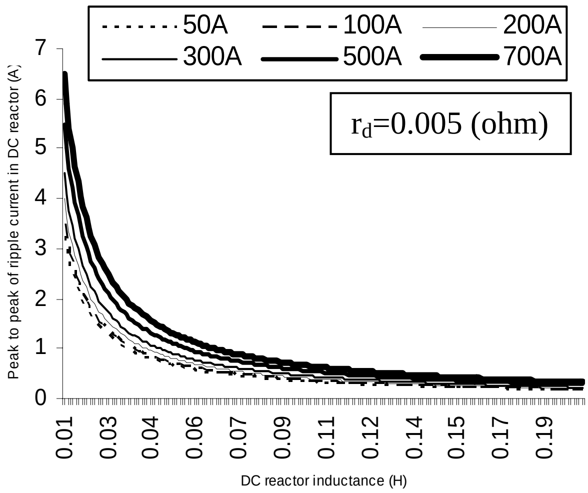

Fig. 3. The $i_{r,p-p}$ vs. the variations of L_d for different values of line current

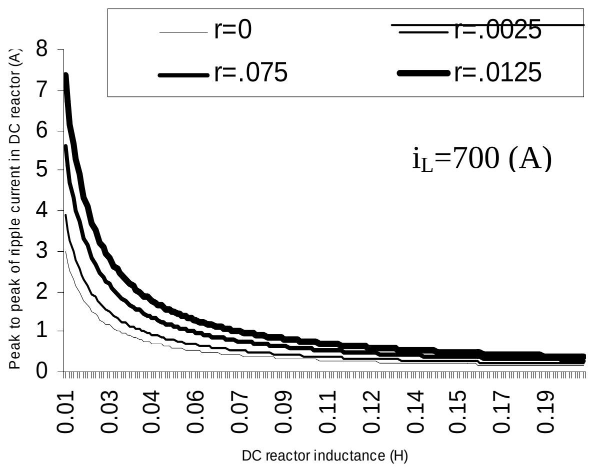

Fig. 4. $i_{r,p-p}$ vs. the variations of L_d for different values of inductor resistance

5 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. 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.

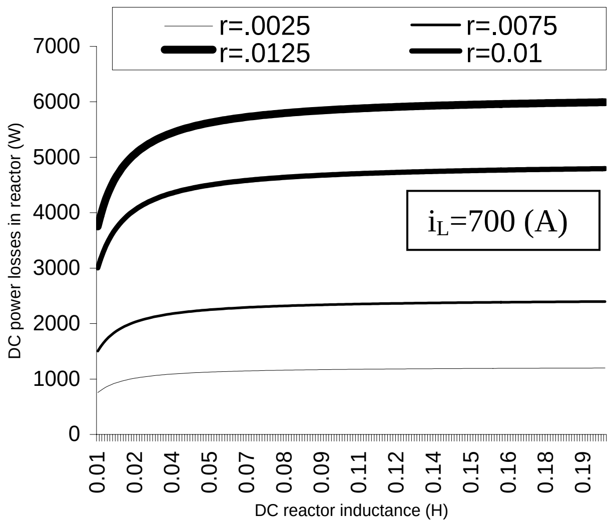

Fig. 5. DC power losses vs. DC reactor inductance for different values of reactors resistance

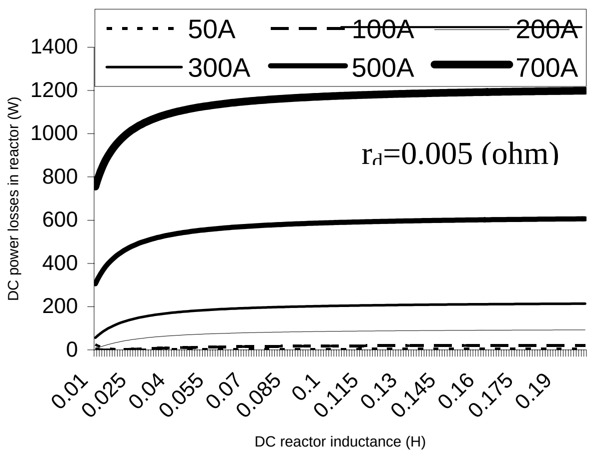

Fig. 6. DC power losses vs. DC reactor inductance for different values of line current

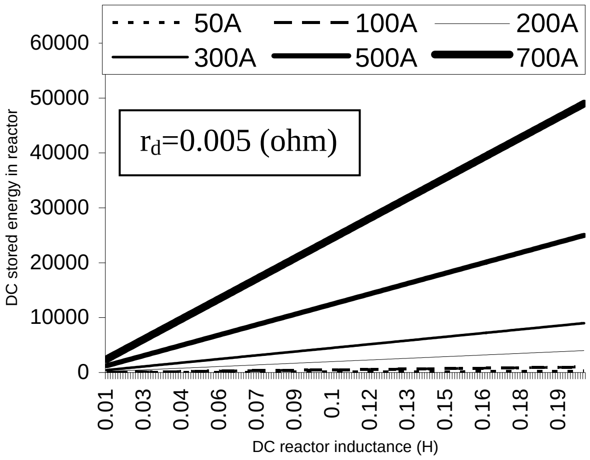

Fig. 7. Storage energy in inductor vs. different values of L_d

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.

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

7 Simulation Results

During fault condition, the line current increases because the fault impedance $z_f = r_f + j\omega L_f$ 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:

$z_L = 9.24 + j\omega\ 0.022$	(Ω)
$z_s = 0.01 + j\omega\ 0.001$	(Ω)
$z_f = 0.01 + j\omega\ 0.001$	(Ω)
$v_s(t) = 3.81 \text{ Sin}(314t)$	(kv)
$V_{DF} = 3$	(v)
$r_d = 0.01$	(Ω)
$L_d = 0.1$	(H)

Fig. (8) shows the line and FCL currents during a fault condition. The fault occurs at $t=t_4$ and the load current begins to increase. As is shown in this figure, before fault condition, the current through inductor is a almost ripple free DC current. The produced voltage across L_d in fault condition has resulted in limiting the fault current as well as distortion of its waveform. At $t=t_5$ a charging mode begins and the line current reaches the inductor current. The operation of FCL has resulted in fault current limiting between t_5 to t_6. At $t=t_6$ a discharging mode starts and it continuous until $t=t_7$.

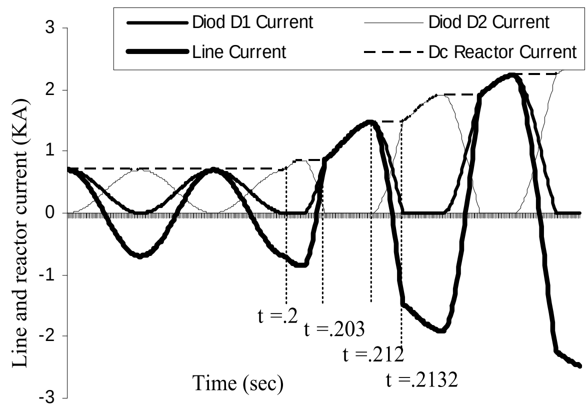

Fig. 8. line and FCL currents during a fault condition

The current equation in charging mode, between t_5 to t_6 is shown by eq. (13) as follows:

$$i\ (t) = e^{-(r/L)(t-t_5)} \left\{ i_5 - \frac{V}{z} \sin(\omega t_5 - \varphi) + \frac{2V_{DF}}{r} \right\} + \frac{V}{z} \sin(\omega t - \varphi) - \frac{2V_{DF}}{r} \tag{13}$$

Where:

$r = r_S + r_f + r_d$

$L = L_S + L_f + L_d$

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

$i_5 = i(t_5)$

Eq. (14) and (15) shows the load and inductor currents during discharging mode, respectively.

$$i_L(t) = e^{-(r/L)(t-t_6)} \left\{ i_6 - \frac{V}{z} \sin(\omega t_6 - \varphi) \right\} + \frac{V}{z} \sin(\omega t - \varphi) \tag{14}$$

$$i_d(t) = e^{-(r_d/L_d)(t-t_6)} \left\{ i_6 + \frac{2V_{DF}}{r_d} \right\} - \frac{2V_{DF}}{r_d} \tag{15}$$

Where, $i_6 = i(t_6)$

Considering the resistance of DC reactor had not so important effect on FCL operation but, Fig. (9) is used to magnify the difference between superconductor and copper coil FCL. This figure shows that existence of resistor had resulted in speed up the discharging of L_d that has not significant effect on FCL operation.

Fig. (10) shows the line and FCL currents after removal of a fault current. The fault has been eliminated at $t=t_8$. This figure shows that the DC reactor current that has been raised to a high value

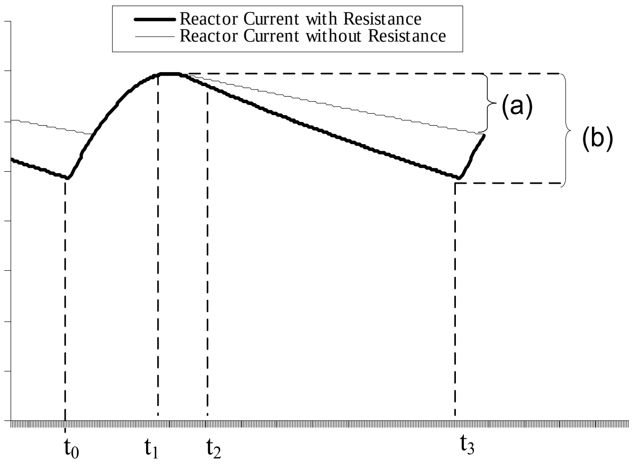

Fig. 9. Magnified charging/discharging modes for superconducting and copper coil FCLs

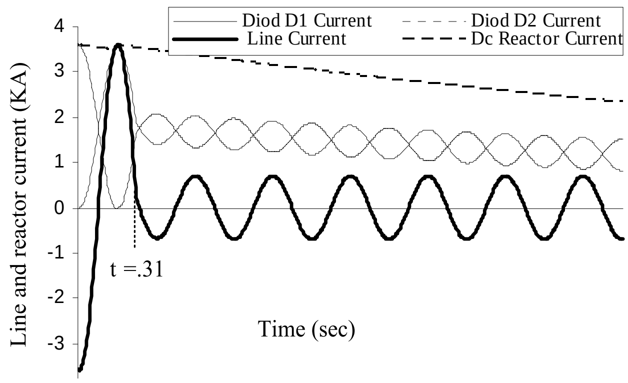

Fig. 10. Operation of copper coil FCL after fault condition

during fault condition, is decreasing gradually to its normal state value. The simulation results show there is not considerable difference between superconducting and copper coil FCLs in limiting the fault current magnitudes.

If the maximum permitted fault time considered to be equal with $\Delta t = t_8 - t_4$ then it is possible writing eq. (16) as fallows:

$$t_8 - t_4 = \frac{L}{r}\ln\frac{ri_8 - V_{DS} + 2V_{DF}}{ri_4 - V_{DS} + 2V_{DF}} \qquad (16)$$

Where; $r = r_S + r_f + r_d$ and $V_{DS} = 2V/\pi$

Using this equation, it is possible calculate the desired value of Ld using eq. (17).

$$L_d = \frac{rKT}{\ln\frac{ri_8 - V_{DS} + 2V_{DF}}{ri_4 - V_{DS} + 2V_{DF}}} - L_S - L_f \qquad (17)$$

8 Conclusion

The analytical analysis and designing characteristics for DC reactor "superconductor" and "copper coil" type FCLs presented. 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.

8 References

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