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On-state Loss Analysis of Diodes on Superconducting Fault Current Limiter

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Abstract: The on-state loss of diodes in a diode bridge type high-TC superconducting fault current limiter (SFCL) is the main part of losses in mentioned system. Considering the on-state losses of diodes in diode-bridge, would result in discharging of DC reactor and it would results in utility current and load voltage distortion. This paper treats investigations on exact analytical analysis of on-state losses in a diode bridge type high-T_C SFCL. In addition, the detail analytical analysis of voltage and current characteristics of superconductor coil is given. The relation between diode losses and superconductor inductance is determined. Simulation results are used to show the utility current and load voltage distortion in addition to instantaneous power of superconductor coil and diodes.

Key word: Power Loss, Superconducting Fault Current Limiter, Loss Estimation, Diode Rectifier, Voltage Distortion

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, 2009), (WanMin Fei et al, 2008), (Salim et al, 2004), (Muta et al, 2004), (Kameda et al, 2002). Loss calculation of diodes under normal utility operation case is an important subject due to their high current ratings. There are three kinds of losses in the diodes which are: turn-on, on-state and turn off. Among these, the on-state loss is the main part of diode losses (Joo, M., 2004). On-state loss depends on forward voltage drop of diodes, utility current and high-TC superconductor inductance. So far, in different articles it has been assumed that superconducting coil carries DC current and it has not any effect on utility current and load voltage waveforms (Joo, M., 2004). But, because of existing of ripple current, there would be a utility current distortion and load voltage dip that their study could be an important subject.

This paper deals with detail analytical analysis of power losses on diodes and voltage drop on superconductor coil of a diode bridge type high-T_C SFCL. However, the diode losses could be calculated with simple relations (Joo, M., 2004), but this paper is focused on the effects of diode losses on utility current and load voltage distortions. The instantaneous power of superconductor coil and diodes are calculated. Also the effect of inductance value of superconductor coil on diode losses has been studied. The magnitude of these losses and its effect on line current and load voltage is critical on operating cost of the SFCL. Simulation and analytical results are used to explain the instantaneous power in charging and discharging modes. The loss estimation model, analysis of the diodes operation at different modes and current and voltage characteristics of superconductor coil are presented, too.

Analytical Analysis of Circuit Operation:

The power circuit of three phase diode bridge type fault current limiter is shown in Fig. 1.

The circuit consists of a 3-phase coupling transformer, six diodes and a high-T_C superconducting coil. The utility voltage is a sinusoidal waveform with angular frequency ω, peak value V, series connected resistor r_s, and inductor L_s. There would be a forward voltage drop across rectifier diodes V_{DF}, too. The load is assumed to be a balance three phase series R-L load with r_L and L_L as its resistor and inductor in each phase,

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respectively. Table 1 shows the main data of power circuit.

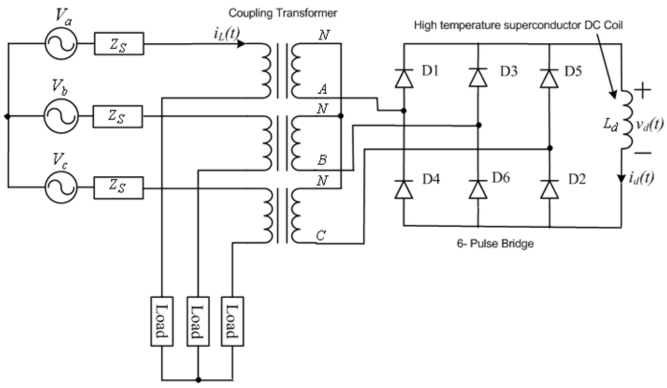

Fig. 1: Power circuit topology of analyzed SFCL

Table 1: Diode Bridge Type SFCL Data

Voltage drop on the diodes[V]	3
Inductance of Superconductor coil[H]	0.04
load current rating[A]	700
Load resistance[ohm]	6.24
Load inductance[H]	0.015
Utility voltage (rms, L-L, kV)	6.6
Utility frequency (Hz)	50
Turns ratio of ideal transformer	1

Fig. 2 shows the line and SFCL current waveforms in normal operation case of circuit.

The reactor current is periodic with time interval between t_0 to t_2. It has assumed that in t_0 the magnitude of current in phase "a" is more than two other phases in all part of this paper.

The circuit has two modes of operation as follows:

(a)Charging mode
(b)Discharging mode

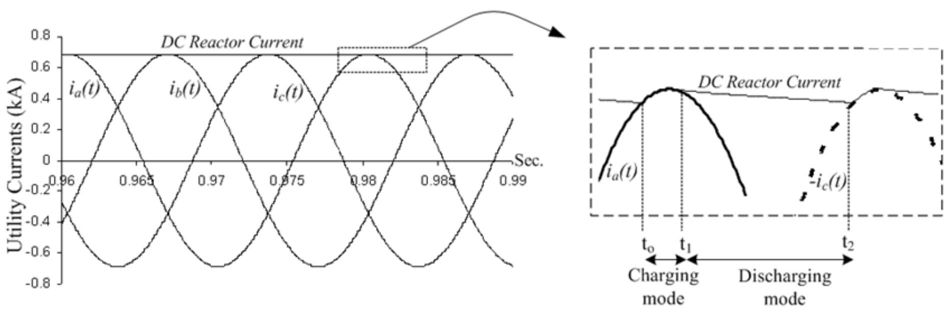

Fig. 2: The Line and Superconductor coil current waveforms in normal circuit operation case

A. Charging Mode:

This mode begins at t_0 and it continues until t_1. At t_0 the diodes D1, D6 and D2 turns ON and superconductor coil connects in series with utility as shown in Fig. 3.

In this case we have:

$$V\sin(\omega t) = ri_L(t) + L\frac{di_L(t)}{dt} + 2V_{DF} \tag{1}$$

Where it results in eq. (2) that shows the line current formula in charging mode.

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

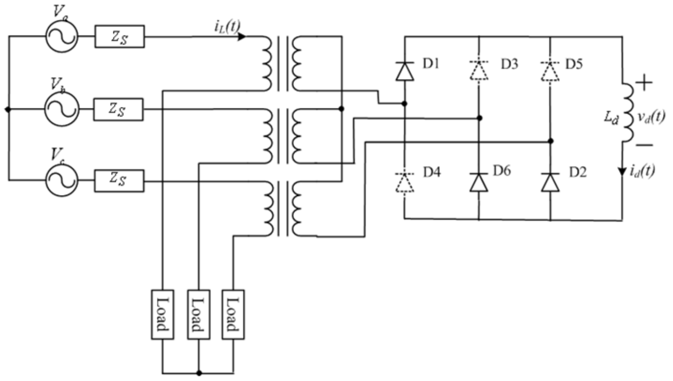

Fig. 3: Circuit diagram at charging mode of Superconductor coil

Where: $r = r_S + r_L$, $L = L_S + L_L + L_d + L_t$, V_{DF} is the forward voltage drop of the diodes that is assumed to be constant, $i_0 = i(t_0)$, $z = \sqrt{r^2 + (L\omega)^2}$ and $\tan\varphi = L\omega/r$, L_d is the inductance of superconductor coil and L_t is the leakage inductance of coupling transformer in each phase. Obviously, in charging mode we have:

$$i_d(t) = i_L(t) \quad (3)$$

Eq. (4) shows the voltage drop on superconductor coil in charging mode.

$$v_d(t) = L_d \frac{di_d(t)}{dt} \quad (4)$$

Substituting eq.s (2), (3) and (4) will yield to eq (5)

$$v_d(t) = (\frac{-rL_d}{L})e^{-(r/L)(t-t_0)}\left\{ i_0 - \frac{V}{z}\sin(\omega t_0 - \varphi) + \frac{2V_{DF}}{r} \right\} + \frac{VL_d\omega}{z}\cos(\omega t - \varphi) \quad (5)$$

B. Discharging mode:

During discharging mode, the inductor current freewheels through the diodes D1, D2, D3 and D6 as shown in Fig. 4.

In this mode the line current i_L, flows through the diodes D1, D3, D6 and D2 as shown in Fig. 4. (a). In this case we have:

$$V\sin(\omega t) = ri_L(t) + L\frac{di_L(t)}{dt} \quad (6)$$

Eq. (7) shows the line current formula in discharging mode:

$$i_L(t) = e^{-(r/L)(t-t_1)}\left\{ i_1 - \frac{V}{z}\sin(\omega t_1 - \varphi) \right\} + \frac{V}{z}\sin(\omega t - \varphi) \quad (7)$$

Also for superconducting coil current we have:

$$L\frac{di_L(t)}{dt} = 2V_{DF} \quad (8)$$

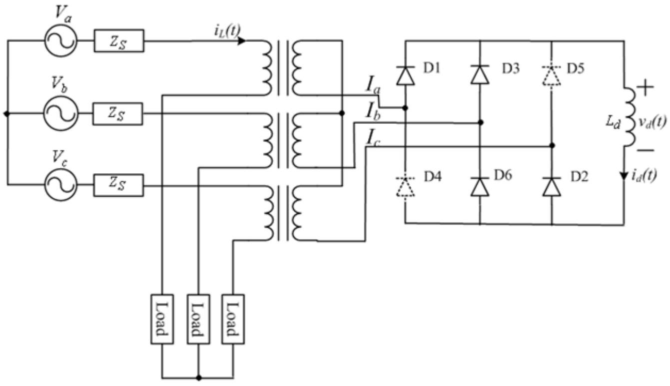

Fig. 4: Circuit diagram at discharging mode of superconducting coil

Eq. (9) shows the superconducting coil current formula in discharging mode:

$$i_d(t) = i_1 - \frac{2V_{DF}}{L_d}(t - t_1) \tag{9}$$

Where: $r = r_S + r_L, L = L_S + L_L + L_t, i_2 = i(t_2).$

Also voltage drop on superconducting coil terminals is given in discharging mode as follows:

$$v_d(t) = -2V_{DF} \tag{10}$$

Fig. 5 show the voltage waveform on superconducting coil in charging and discharging mode and Fig. 6 shows the instantaneous power of superconductor coil.

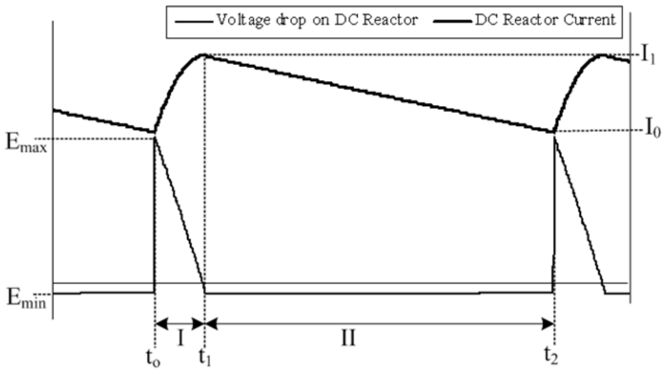

Fig. 5: Superconducting coil current and voltage waveform at charging and discharging modes

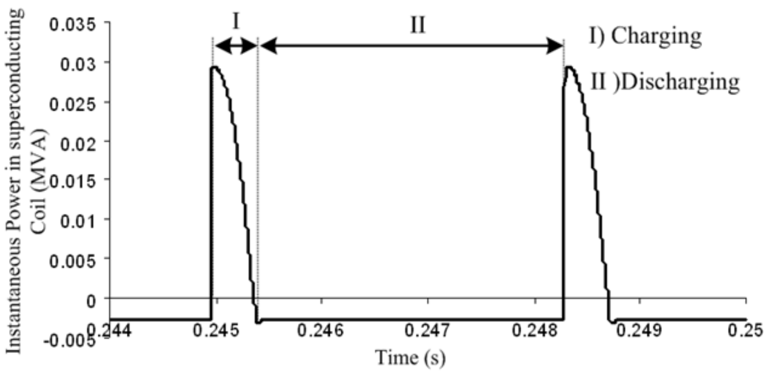

Fig. 6: Instantaneous power of superconductor coil

These results are obtained by simulation of operation of circuit in Fig. 1. The circuit parameters of table 1 are used in this simulation by PSCAD/EMTDC software. The positive instantaneous power shows the absorption of active power from utility and vice versa. The area under positive values of instantaneous power is equal with its negative values that show constant average energy storage in superconductor coil.

On-State Diode Bridge Loss Calculation:

As mentioned in last part, the circuit has two modes of operation as follow which are shown in Fig. 5:
(1) Charging mode (from t_0 to t_1)
(2) Discharging mode (from t_1 to t_2)

Fig. 3 shows the circuit diagram at charging mode and eq. (2) shows the current passing through D1 and (D2 & D6). Considering a constant on-state voltage drop across diodes, it is possible to calculate the instantaneous power of mentioned diodes as follows:

$$P_1(t) = V_{DF} \times i_{D1}(t) = V_{DF} \times i_d(t) \tag{11}$$

$$P_2(t) = V_{DF} \times i_{D2}(t) \tag{12}$$

$$P_6(t) = V_{DF} \times i_{D6}(t) \tag{13}$$

Where eq. (11), (12) and (13) show the instantaneous power of diodes D1, D2 and D6, respectively. Total instantaneous power loss of conducting diodes in charging mode is obtained by eq. (14)

$$P_{D(ch)}(t) = P_1(t) + P_2(t) + P_6(t) \tag{14}$$

On the other hand, during charging mode we have:

$$i_d(t) = i_{D2}(t) + i_{D6}(t) \tag{15}$$

Substituting eq.s (11), (12), (13) and (15) in eq. (14) will yield to eq. (16) as follows:

$$P_{D(ch)}(t) = 2V_{DF} \times i_d(t) \tag{16}$$

Now, substituting eq. (2) in eq. (16) the instantaneous power loss of diode-bridge is given by eq. (17):

$$P_{d(ch)}(t) = 2V_{DF}\left[K_1 e^{-(r/L)(t-t_0)} + \frac{V}{z}\sin(\omega t - \varphi) - K_2\right] \tag{17}$$

where:

$$K_1 = \left\{ i_0 - \frac{V}{z}\sin(\omega t_0 - \varphi) + \frac{2V_{DF}}{r} \right\} \tag{18}$$

$$K_2 = \frac{2V_{DF}}{r} \tag{19}$$

Average conducting diodes power loss in charging mode is given by eq. (20) as follows:

$$\begin{aligned} P_{av(ch)} &= \frac{1}{(t_1 - t_0)}\int_{t_0}^{t_1} P_{d(ch)}(t)dt \\ &= \frac{2V_{DF}}{(t_1 - t_0)}\left[\frac{V}{z\omega}\left\{\cos(\omega t_0 - \varphi) - \cos(\omega t_1 - \varphi)\right\} + K_1\frac{L}{r}\left\{1 - e^{-(r/L)(t_1 - t_0)}\right\} - K_2(t_1 - t_0)\right] \end{aligned} \tag{20}$$

In eq. (20), the charging current is approximated as a straight line as is shown in Fig. 7. On the other hand, eq. (9) shows that discharging current is a straight line, too.

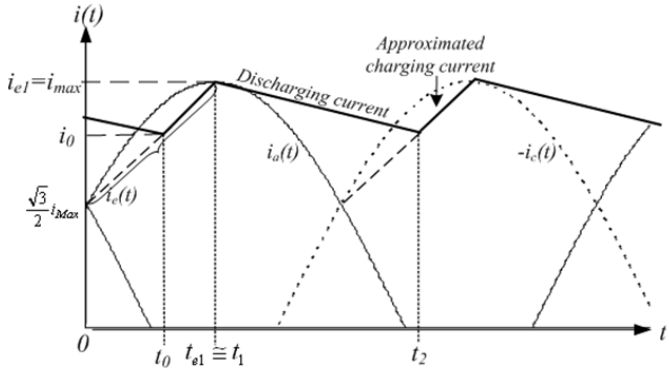

Fig. 7: Estimated current waveform

Obviously, it is easy to write the eq. (21) which i_{e1} is the current values in t_{e1}.

$$i(t=0)=\frac{\sqrt{3}}{2}i_{\max},\ i_{e1}=i_1=i_{\max} \tag{21}$$

Where i_{max} is the maximum current in line and superconducting coil.

The current waveform in time interval between t=0 and t_1 can be estimated by eq. (22).

$$i_e(t)=(\frac{(1-\sqrt{3}/2)}{(T/12)}t+\frac{\sqrt{3}}{2})i_{\max} \tag{22}$$

Consequently the charging current in time interval between t_0 and t_1 can be estimated by eq. (23):

$$i_d(t)=(\frac{(1-\sqrt{3}/2)}{(T/12)}t+\frac{\sqrt{3}}{2})i_{\max} \tag{23}$$

Therefore the average power losses of diode-bridge in charging mode are obtained by eq. (24):

$$P_{av(ch)}=2i_{\max}V_{DF}\left\{\frac{(2-\sqrt{3})L_d i_{\max}+\sqrt{3}(T/6)V_{DF}}{(2-\sqrt{3})L_d i_{\max}+2(T/6)V_{DF}}\right\} \tag{24}$$

In discharging mode, the stored energy of superconductor coil supplies the diodes losses and there is not any energy absorption from utility. Therefore, it is possible to consider the average power of superconductor coil as the average power losses of diodes. In this mode reactor current freewheels through the diodes which are modeled by a constant voltage source equal with V_{DF}. So, the reactor current decreases linearly and the voltage on reactor terminals is $-2V_{DF}$. Instantaneous power of superconductor coil is given by eq. (25) as follows:

$$P_{d(disch)}(t)=\left\{-2V_{DF}i_1+\frac{4V_{DF}^{\ 2}}{L_d}(t-t_1)\right\} \tag{25}$$

Average power of superconductor coil in discharging mode is given by following equations:

$$P_{av(disch)}=\frac{1}{(t_2-t_1)}\int_{t_1}^{t_2}P_d(t)dt \tag{26}$$

$$P_{av(disch)}=\frac{2V_{DF}^{\ 2}}{L_d}(t_2-t_1)-2V_{DF}i_1 \tag{27}$$

Which i_1 is the superconductor coil current at t_1 and it can be considered as i_{max} ($i_1 \approx i_{\max}$). Duration of discharging mode is calculated using eq. (9) as follows:

$$(t_2-t_1)=\frac{L_d(i_{\max}-i_2)}{2V_{DF}} \tag{28}$$

Using intersection point of eq. (28) and eq. (22) it is possible to determine the duration of discharging mode as follows:

$$t_2 - t_1 = \frac{(2-\sqrt{3})(T/12)L_d i_{\max}}{(1-\sqrt{3}/2)L_d i_{\max} + (T/6)V_{DF}} \tag{29}$$

In witch *T* is the time period of utility current. The average power of superconductor coil in discharging mode is obtained by eq. (30):

$$P_{av} = 2 i_{\max} V_{DF} \left\{ \frac{(2-\sqrt{3})L_d i_{\max} + \sqrt{3}(T/6)V_{DF}}{(2-\sqrt{3})L_d i_{\max} + 2(T/6)V_{DF}} \right\} \tag{30}$$

As mentioned before, the amplitude of average power in superconductor coil is equal with average power losses of diodes during discharging mode.

Comparison of eq. (24) with eq. (30) shows that average power in charging mode and discharging modes are equal with each other. It is because of equal average currents of superconductor coil in charging and discharging modes. So, it was enough to calculate the average power loss of diodes in one of circuit modes of operation. Fig. 8 shows the relation between average power losses of diode-bridge versus the value of SFCL coil using eq. (30).

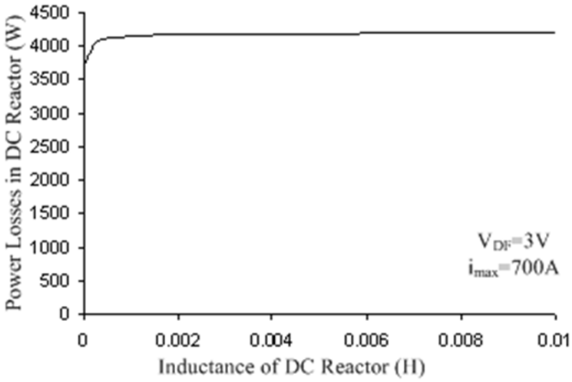

Fig. 8: Average power losses in diode-bridge as a function of inductance value of superconductor coil

This figure shows that the power loss is almost exponentially dependent to L_d in its low values. By increasing the value of L_d, the average power losses of diode-bridge reaches to a constant value that is given by eq. (31).

$$P_{av,Max} = 2 V_{DF} i_{\max} \tag{31}$$

Another interesting subject that obtains from Fig. 8 is that changing the value of L_d changes the power losses of diode bridge. For example, for i_{max}=700 (A), increasing of L_d from 0.0 to 0.01 (H) has changed the power losses about 13% of $P_{av,Max}$. This figure shows that the lower values of L_d results in lower average power loss of diode bridge. The voltage drop on each diode in this study has been *3* (V).

Current and Voltage Distortions Due to SFCL:

The existence of SFCL would result in some utility current and load voltage distortions. Fig. 9 shows the utility current and load voltage due to existence of a superconducting FCL. The phase angle j, is determined by following equation, using the load parameters and the frequency of utility.

$$\tan \varphi_L = \frac{L_L \omega}{r_L} \tag{32}$$

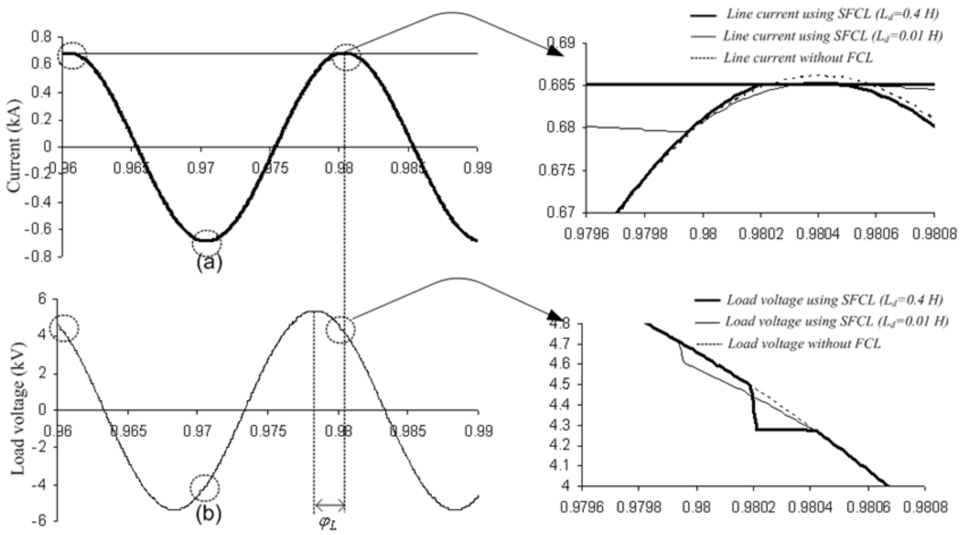

Fig. 9: Utility current and Load voltage due to existence of a superconducting FCL (a) Load Current , (b) Load Voltage

The current distortion will be near to its peak value, while the power factor of load determines the place of voltage distortion in voltage waveform. The current distortion is because of charging of DC reactor. When the utility current reaches to DC reactor current, the utility begins to charging the DC reactor and this result in some current distortions. During discharging mode, the DC reactor current wills free-wheel through the diodes to feed the power losses of them. Obviously, without considering the on-state losses of diodes in diode bridge, the DC reactor would not discharges and there would not be any utility current or load voltage distortion. It is easy to notice that, the distortion on load voltage is a function of utility current distortions and load parameters. Fig. 9 shows that the higher values of L_d, increases the voltage dip and decreases its duration. On the other hand, higher values of L_d, affects the utility current waveform by decreases the charging time. It should be noticed that these distortions will exist in superconductor FCL as well as non-superconducting FCL but, non-superconductor FCL would result in more distortions because of longer charging time of DC reactor. Fig. 10 compares the load voltage distortion by using superconductor and non-superconductor FCLs. This figure shows deeper voltage distortion for non-superconductor FCL. The results of this part have been obtained using the parameters and power circuit topology of Fig. 1.

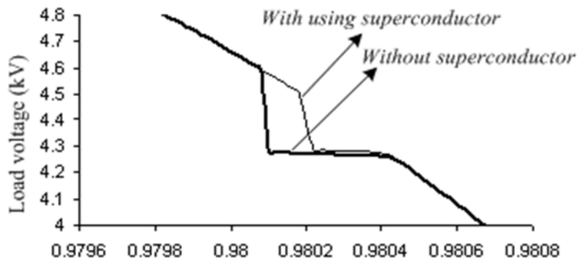

Fig. 10: Load voltage distortion using superconductor and non-superconductor FCLs

Conclusion:

On-state loss calculation of diode-bridge type high-temperature superconducting fault current limiter at normal operation is studied in this paper. Also the effect of superconductor coil inductance on diode bridge losses, utility current waveform and load voltage distortion has been studied. The results show that, higher inductance of SFCL increases the load voltage distortion and it results in higher power loss of diode bridge but obviously, it would result in better performance of SFCL in limiting of short circuit current.

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