Simulating the Effect of SFCL on Limiting the Internal Fault of Synchronous Machine

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Abstract. In this paper, we have modelled a synchronous generator with internal one phase to ground fault and then the performance of this machine with internal one phase to ground fault have been analyzed. The results show that if the faults occur in vicinity of machine's terminal, then we would have serious damages. To protect the machine from this kind of faults we have suggested integrating a SFCL (superconducting fault current limiter) into the machine's model. The results show that the fault currents in this case will reduce considerably without influencing the normal operation of the machine.

1. Introduction
In order to enhance the reliability and life time of electric machine, it is necessary to have an accurate analysis of internal faults of machines. In other hand, for designing the protection scheme of the machine, we need to identify the mode and type of the internal fault. Fault current limiters (FCLs) are devices that can limit or eliminate fault current in an electric power system. An ideal FCL would be able to instantly react to a fault, limiting the fault current to a fraction of its unrestrained value. This current reduction, should take place in less than one cycle. Fault current limiter should also be able to intercept and handle a series of faults and they should automatically recover from each fault so that human intervention is not necessary [1].

2. Superconducting Fault Current Limiters
With the recent breakthrough of economical second-generation High-Temperature a superconductor (HTS) wires, the Superconducting Fault Current Limiter (SFCL) has become more feasible. These over current controllers are very effective in limiting fault current without adding any additional impedance to the system during normal operation. However, during a fault, the SFCLs switch into a high-impedance state and it can rapidly respond to a fault.

Superconductor basics are as shown in the figure 1.

The basic idea of superconductivity is that superconductors, when cooled, act as perfect conductors. This means that they have no resistance. However, when their temperature is increased to a given
point, called the critical temperature (Tc) the superconductors revert to normal behavior and show a high level of resistance.

**Figure 1.** Properties of superconductor [1]

3. **Modelling internal one phase to ground fault**

We assume that the winding of phase A of the machine is short circuited, while the two other phases are intact. In order to model the short circuited winding, we decompose the MMF (magnetic motive Force) of that winding in the air gap into two components.

![MMF diagram](image)

**Figure 2.** MMF of machine in case of one phase to ground fault.

The schematic representation of these two components can be shown as follow (fig.3).

Parameters $N_1$, $N_2$, $\gamma_1$, $\gamma_2$ depend on the location where the short circuit has happened. In [2-8], the formulations of these parameters have been derived.

$$N_1 = \frac{N_c}{\pi} \sqrt{\alpha^2 - 2\alpha \sin(\alpha) \cos(\alpha) + \sin^2(\alpha)}$$  \hspace{1cm} (1)

$$\gamma_1 = -\tan^{-1}\left(\frac{\sin^2(\alpha)}{\alpha - \frac{1}{2} \sin(2\alpha)}\right)$$  \hspace{1cm} (2)
Thus it is necessary to take into account the unbalanced model of such machines. In other words, in this case the machine will have unbalanced phases.

Figure 4 shows the schematic representation of one phase to ground fault of the machine. In this case, \( i_n \) and \( i_m \) are the new currents of winding A while \( i_b \) and \( i_c \) are the same as the pre-fault currents. According to the model shown in figure 4, the electric equations governing the machine in this case are as below:

\[
[V] = [R][I] + \frac{d}{dt}[L][I] \quad (5)
\]

In which we have

\[
N_2 = \frac{N}{\pi} \sqrt{(\pi - \alpha)^2 - 2(\pi - \alpha).\sin(\alpha).\cos(\alpha) + \sin^2(\alpha)} \quad (3)
\]

\[
\gamma_2 = -\tan^{-1}\left(\frac{\sin^2(\alpha)}{\pi - \alpha + \frac{1}{2}\sin(2\alpha)}\right) \quad (4)
\]
\[ [V] = [0 \ E_a \ E_b \ E_c \ v_f \ 0 \ 0]^T \]
\[ [I] = [I_m \ i_a \ i_b \ i_c \ i_f \ i_{id} \ i_{iq}] \]
\[ [R] = \text{diag}[R_m \ R_n \ R_h \ R_c \ R_f \ R_{id} \ R_{iq}] \]

\[ L = \begin{bmatrix}
L_m & M_{mn} & M_{mb} & M_{mc} & M_{mf} & M_{mef} & M_{mq} \\
M_{mn} & L_a & M_{ab} & M_{ac} & M_{af} & M_{ae} & M_{aq} \\
M_{mb} & M_{ab} & L_b & M_{bc} & M_{bf} & M_{be} & M_{bq} \\
M_{mc} & M_{ac} & M_{bc} & L_c & M_{cf} & M_{ce} & M_{cq} \\
M_{mf} & M_{af} & M_{bf} & M_{cf} & L_f & M_{fe} & M_{fq} \\
M_{mef} & M_{ae} & M_{be} & M_{ce} & M_{fe} & L_{ef} & M_{ef} \\
M_{mq} & M_{aq} & M_{bq} & M_{cq} & M_{eq} & M_{ij} & L_{iq} \\
\end{bmatrix} \]

In the above equation
\( V = \) stator and rotor voltage matrix
\( I = \) stator and rotor current matrix
\( R = \) diagonal matrix of stator and rotor resistance
\( L = \) inductance of the stator and rotor of the machine

The data of inductances and resistance of the machine are presented in the Appendix. These equations are derived according to the references [3, 4, and 5].

4. Modelling the internal one phase to ground fault while integrating SFCL into the machine's model.
In this section, the SFCL integrated into the machine's model and the behavior of the machine while the machine is under fault condition has been investigated. The parameters of the machine and SFCL are presented in the Appendix. When SFCL's model is integrated into the machine's model, the equations of the machine can be modified as follow.

\[ [V] = [R].[I] + \frac{d}{dt}[L].[I] + V_{FCL} \]  

(6)

In this equation \([R], [L], [I], [V]\) are the same matrix we had in the previous section.
\( [V_{FCL}] \) is defined as below.

\[ [V_{FCL}] = [R_{FCL}][I] \]
\[ R_{FCL} = \text{diag}[0 \ r_{FCL} \ r_{FCL} \ r_{FCL} \ 0 \ 0 \ 0]^T \]
\[ r_{FCL} = r_0 (1 - e^{-(t-t_0)}) \]  

(7)

In the equation of \( r_{FCL} \), \( r_0 \) is the up most resistance of the SFCL and \( t_0 \) is the time when the fault occurs.

5. Simulation
In this section, simulation of internal one phase to ground fault of machine, with and without SFCL in the machine's model has been presented. In \( t = 50 \text{ sec} \), 10\% fault in the winding of phase A has been occurred. The parameters of the machine and SFCL are presented in the appendix. As it is shown in figure 5, when the one phase to ground fault is occurred in the machine without SFCL, the currents
will dramatically increase and other phases are also effected. In this case, the machine will undergo very serious damages.

Figure 6, shows the same currents as in figure 5 except that in this case the SFCL has been integrated into the machine's model. As expected, when the machine is operating in normal condition the SFCL is not seen by the machine (due to zero resistance) but as soon as fault occurs, SFCL will influence the behavior of the machine and will limit the fault current dramatically.

**Figure 5.** $i_a$, $i_b$, $i_c$ and $i_f$ (in pu) of the machine without SFCL while 10% fault in winding of phase A.

**Figure 6.** $i_a$, $i_b$, $i_c$ and $i_f$ (in pu) of the machine with SFCL while 10% fault in winding of phase A has occurred.
6. Conclusion
In this paper we analyzed the performance of the machine under one phase to ground fault. It is shown that if the fault occurs in the vicinity of the machine's terminal, the machine will undergo a very serious damage. We proposed to integrate the model of SFCL into the machine's model. The results are promising and they show that the fault currents in this case will reduce considerably without influencing the normal operation of the machine.

7. Appendices
A) Parameters are in per unit
   \[ L_1 = 0.144 \]
   \[ L_s = 0.54 \]
   \[ L_m = 0.14 \]
   \[ L_f = 0.864 \]
   \[ M_{ad} = 0.686 \]
   \[ L_{ab} = 0.483 \]
   \[ M_{af} = 0.686 \]
   \[ r = 0.4 \]
   \[ r_f = 0.4 \]
   \[ r_e = 0.02 \]
   \[ r_q = 0.04 \]

B) Parameters of SFCL
   \[ t_0 = 50 \text{ Sec} \]
   \[ r_0 = 0.5 \text{ p.u} \]

C) Inductances of the machine
   \[ L_m = \left( \frac{N_m}{N_e} \right)^2 \left[ L_s + L_m \cos(2\theta - 2\gamma_1) \right] \]
   \[ L_n = \left( \frac{N_n}{N_e} \right)^2 \left[ L_s + L_n \cos(2\theta - 2\gamma_2) \right] \]
   \[ L_b = L_s + L_n \cos(2\theta - 120) \]
   \[ L_c = L_s + L_n \cos(2\theta + 120) \]
   \[ M_{ab} = M_{am} = \frac{N_a}{N_e} \left[ -L_s \cos(\gamma_2 + \frac{\pi}{3}) - L_{m0} \sin(\gamma_2 - 2\theta + \frac{\pi}{3}) \right] \]
   \[ M_{ac} = M_{am} = \frac{N_a}{N_e} \left[ -L_s \sin(\gamma_2 + \frac{\pi}{6}) - L_{m0} \cos(\gamma_2 - 2\theta + \frac{\pi}{3}) \right] \]
\[
\begin{align*}
M_{mn} &= M_{m} = \frac{N_u N_u}{N_s^2} \left[ L_N \cos(\gamma_1 - \pi) + L_d \cos(\gamma_1 + \pi) - 2 \theta \right] \\
M_{ab} &= M_{b} = \frac{N_u}{N_s} \left[ L_N \cos(\gamma_1 + \frac{\pi}{3}) - L_d \sin(\gamma_1 - 2 \theta + \frac{\pi}{3}) \right] \\
M_{aw} &= M_{a} = \frac{N_u}{N_s} \left[ -L_N \cos(\gamma_1 + \frac{\pi}{3}) - L_d \cos(\gamma_1 - 2 \theta + \frac{\pi}{3}) \right] \\
M_{ef} &= M_{p} = M_{rd} = M_{a} = M_{sh} = \frac{N_u}{N_s} M_d \cos(\theta - \gamma_1) \\
M_{sd} &= M_{q} = M_{ah} = M_{sh} = \frac{N_u}{N_s} M_d \cos(\theta - \gamma_2) \\
M_{sh} &= M_{k} = M_{ah} = M_{sh} = M_{df} \cos(\theta + \frac{\pi}{3}) \\
M_{sh} &= M_{l} = M_{sh} = M_{sh} = M_{df} \cos(\theta - \frac{\pi}{3}) \\
M_{sh} &= M_{h} = M_{sh} = M_{sh} = M_{df} \cos(\theta + \frac{\pi}{3}) \\
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M_{sh} &= M_{h} = M_{sh} = M_{sh} = M_{df} \cos(\theta - \frac{\pi}{3})
\end{align*}
\]

8. References

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