Evaluation on power system transient stability with resistor type SFCL and parameter design

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With the development of high temperature superconducting fault current limiter (SFCL), it is necessary to investigate its effects on the power system with SFCL installed. In this paper a theoretical analysis of power system transient stability with resistor type SFCL using Lyapnov energy function is presented, and a guideline for SFCL's parameter design is given. Digital simulation was also made. Both theoretical analysis and simulation results demonstrate that resistor type SFCL could improve the transient stability of power system.

INTRODUCTION

SFCLs as the devices for limiting fault currents have been progressing thanks to the development of superconducting technology [1]. Power system transient stability with resistor type SFCL was already studied [2,3], but it still needs deep investigation. In this paper, we put forward a detailed theoretical analysis of transient stability with resistor type SFCL using Lyapnov energy function. In order to investigate the effects of SFCLs on the power system, we propose a simple single-machine infinite-bus power system with SFCL, a generator, and transformers being mathematically modeled. Digital simulation is made to observe the transient performance of the circuit. In view of improving transient stability, the parameter of the resistor type SFCL is also designed.

MODEL SYSTEM

OMIB system

The one machine and infinite bus system (see Figure 1) consists of one generator supplying power to an infinite network via a transformer and double-circuit transmission lines. The generator is a salient pole synchronous machine, and its mechanical behavior is described by the classical swing equation.

SFCL model

Here we use the resistor type SFCL with YBCO thin film, which is one of the most promising current limiting devices for its effective operation in the power system. In case of short circuit fault, when excess current flows in the YBCO film, the superconducting film changes to the resistive state and generates the joule heating. In this condition, the weakest zone becomes resistive and heats firstly. Then the heat generation expands the zone by thermal propagation, and the expansion is limited at the millisecond time scale because the conductivity is low. It is possible that the voltage-current characteristics of superconductor rise exponentially to a stable value within some dozens of milliseconds during the fault [2]. The SFCL has an extremely fast current transition in comparison to electro-mechanic time constants.
When the transport current exceeds the critical current under the condition that the temperature of the superconductor is above the critical temperature, the resistance of the superconductor reaches its normal state resistance. When the transport current is below the critical current, the resistance of the superconductor keeps zero. Considering that the S/N transition of the superconductor can be completed in one or two steps during the transient stability simulation, the resistor type SFCL could be modeled as a

resistor with a shunt switch (see Figure 2). If the current of the circuit exceeds the critical current of the superconductor, the shunt switch is open. Otherwise the shunt switch is closed. The SFCL is installed at the Y-side of transformers T-1.

ANALYSIS OF TRANSIENT STABILITY WITH SFCL

Direct method and energy function

Lyapnov direct method solves the problem of nonlinear systems stability based on the structure of differential equations and initial values. For autonomous differential equations:

$$\dot{X} = F(X),\ X(0) = X_0,\ X \in R^N,\ F \in R^N$$

if we can find a positive scalar v(x) and a region D, which satisfy:

$$V(X) > 0, V(0) = 0,\ X \in D \tag{1a}$$

$$\mathring{V}(X) \le 0,\ X \in D \tag{1b}$$

Then, for any $x_0 \in D$, solution of differential equations (1) is stable. We could get the Lyapnov energy function of one machine infinite bus system by means of first integrals [4]. Considering that the power system is conservative, we get:

$$V(\delta,\omega) = \frac{1}{2}M\omega^2 + \frac{1}{M}\int_0^{\delta}(p_e \sin(u+\delta^s) - p_e \sin\delta^s)du = V_k(\omega) + V_p(\delta) = constant \tag{2}$$

Assessment

When the power system is in stable state, the kinetic energy V_k is zero because the warp of synchronous rotor speed $\omega = 0$. When the fault occurs, energy is injected into the power system. Assuming that potential energy reference point is set at $\delta_c(t_c)$ (t_c is the time when the fault is cleared), the total transient energy V after disturbance is:

$$V_c = V_k\big|_c + V_p\big|_c = \int_{\delta_0}^{\delta_c} M\frac{d\omega}{dt}d\delta = \int_{\delta_0}^{\delta_c}(p_m - p_{\mathrm{II}}\sin\delta)d\delta \tag{3}$$

The maximal energy that the system can endure is $V(0,\delta^u)$, where δ^u is the saddle point given by $\delta^u = \pi - \delta^s$. $V(0,\delta^u)$ is the critical transient energy:

$$V_{cr} = \int_{\delta^c}^{\delta^u}\{P_{\mathrm{III}}\sin\delta - p_e\sin\delta^s\}d\delta = \frac{E_q U}{X'_{d\Sigma}}(\cos\delta^c - \cos\delta^u) - P_m(\delta^u - \delta^c) \tag{4}$$

if $V_c \le V_{cr}(\delta^u,\delta_c)$, the system keeps stable; if $V_c > V_{cr}(\delta^u,\delta_c)$, the system loses synchronization. If the resistor type SFCL works at the fault beginning without time delay and we neglect the quench time of the superconductor, the transient energy when the fault is eliminated is:

$$V_c = \frac{1}{2}M\omega_c^2 = \int_{\delta_0}^{\delta_c} M\frac{d\omega}{dt}d\delta = \int_{\delta_0}^{\delta_c}(p_m - p'_{\mathrm{II}}\sin\delta)d\delta \tag{5}$$

It could be obviously seen that $V_c - V'_c = Area(b'bcc') > 0$, which means that the SFCL decreases the initial energy injected into the power system. The recovery time of resistor type SFCL is relatively long (about a few seconds). Taking the recovery characteristics into consideration, the critical transient energy with SFCL applied is:

$$V'_{cr} = \frac{E_q^2}{|Z|}\sin\alpha(\delta^{b-o} - \delta^c) + \frac{E_q U}{|Z|}\{\cos(\delta^c - \alpha) - \cos(\delta^u - \alpha)\} + \frac{E_q U}{|Z|}(\cos\delta^{b-o} - \cos\delta^u) - P_m(\delta^u - \delta^c) \tag{6}$$

Compare the critical transient energy with SFCL installed and without SFCL installed, we could see that: $V'_{cr} - V_{cr} = Area(mefh) > 0$. With SFCL installed, the initial transient energy injected into power system is reduced. Meanwhile, the maximal energy that the power system can endure is enlarged taking recovery characteristics of the SFCL into account.

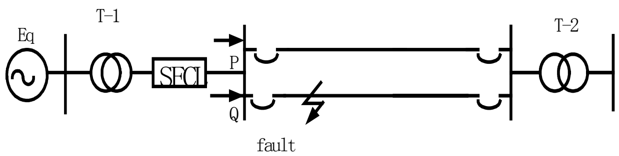


figure1 One machine and infinite bus system

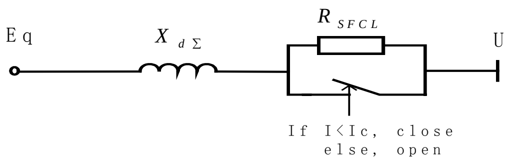


figure2 Equivalent circuit

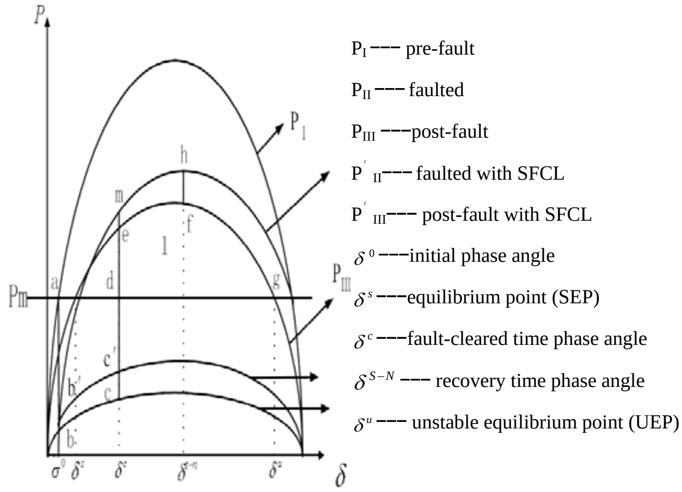


figure3 Power-angle curves with SFCL

<u>Parameter design</u>

The analysis above shows that it is good to the power system transient stability if the SFCL do not quit immediately after the fault clear. The SFCL is put at the side of transformer in order to avoid its influence on the transmission line auto-reclosed brake. Thus the resistor type SFCL functions like breaking resistors except that the recovery time of the SFCL could not be controlled. But if the resistance of SFCL is too large, the power system will lose synchronism after the second swing. When energy is concerned, the resistance value of SFCL should be restricted by the equation: $V_{k2} = V'_{p1} < V_{cr}$.

$$\int_{\delta^c}^{\delta^u}\{P_{III}'(\delta) - p_e\sin\delta^s\}d\delta \le \int_{\delta^c}^{\delta^u}\{P_{III}(\delta) - p_e\sin\delta^s\}d\delta \tag{7}$$

We can approximately get:

$$R_{SFCL} \le X'_{d\Sigma}\tan\left(\frac{\pi}{2} - \arcsin\frac{U(\cos\delta^s - \cos\delta^c) - P_m(\delta^u - \delta^s)X'_{d\Sigma}}{E_q(\delta^u - \delta^c)}\right) \tag{8}$$

Where $X'_{d\Sigma} = X_d + X_{T-1} + X_L + X_{T-2}$. Thus, there are three factors we should take into consideration when we design the parameter of SFCL: affects on protection relay, switching off ability of circuit breaker and enhancement of power system stability.

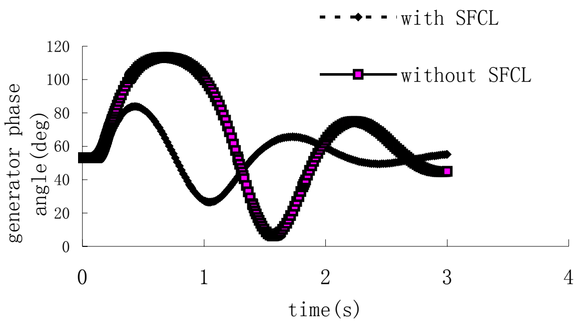
SIMULATION RESULTS AND DISCUSSION

System simulation parameters are shown in Table 1. A short circuit fault occurred on one of the transmission lines. After 100ms the circuit breaker operated, and cut off the faulted single line. Two cases, SFCL being applied or not, were simulated using Matlab simulink. Fig.4 and Fig.5 show that the swing curve with SFCL applied is lower than the curve without SFCL, and the same for the rotor angular velocity. This demonstrates that the resistor type SFCL can protect the synchronism of the generator.

When the resistance value of SFCL is too large, that is the value exceeds the restriction of equation, the power system lost synchronism. The simulation results are shown in Fig.6 and Fig.7. The resistance value of SFCL is 2 per unit.

Table 1 Model system parameters

Generator					Transformer	Transmission line
S_N	P_0	δ_0	M	X'_d	X_T	X_L
500MVA	385.2MW	49.34deg	3.7.p.u	0.238.p.u	0.13.p.u	2.93.p.u



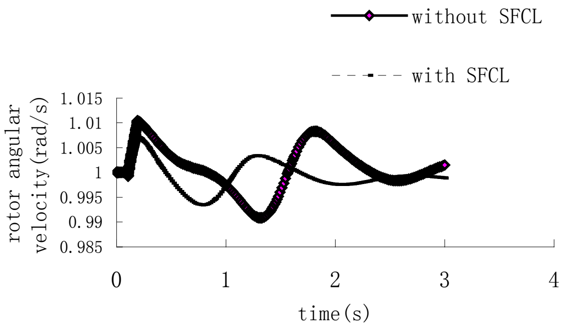
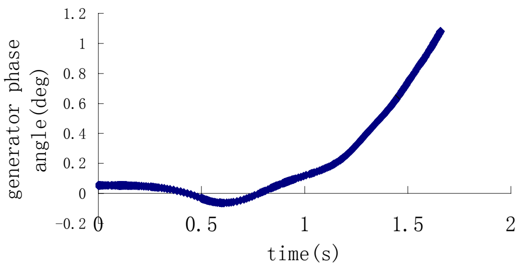


Figure 4 Generator swing curve with and without SFCL

Figure 5 Gnerator rotor angular velocity curve with and without SFCL



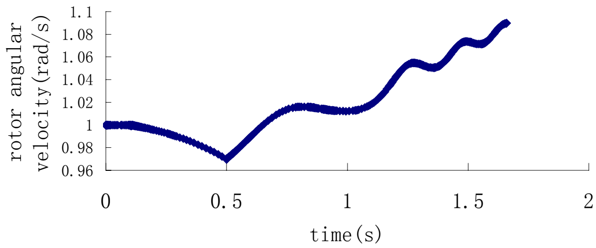


Figure 6 Swing curve with R_{SFCL}= 2 .p.u

Figure 7 Angular velocity curve with R_{SFCL}= 2 .p.u

CONCLUSION

Through theoretical analysis and digital simulation, it is found that the resistor type superconducting fault current limiters not only limit fault current but also protect synchronization of generators. The SFCL can decrease the initial transient energy V_c injected into the power system and increase the critical transient energy V_{cr}, which enhances the transient stability. Considering the second swing stability, the resistance value of SFCL cannot be too large, and should be restricted.

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