Enhancement of Power System Transient Stability using Superconducting Fault Current Limiters

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Abstract—Transient stability investigations consist in studying the rotor oscillations of generators (electro-mechanic oscillations, 0.1-2 Hz) followed by a fault of large amplitude, e.g. short circuit. The goal is to indicate if the generators are capable to stay synchronous after a fault has occurred. The fault duration is one of the most important factors to be given an answer. In fact, the shorter the fault, the more the maintaining of synchronisation can be guaranteed. Now in case of a fault, a fault current limiter has an extremely fast current transition in comparison with electro-mechanic time constants. This implies a quasi-instantaneous elimination of the fault through a limitation of the current and consequently a better ability to maintain the synchronisation of the system. We recall, in a classic system the elimination of a fault, by opening a circuit breaker, is carried out in two or three cycles in the best case. We have here studied a simple, radial electric network configuration with a machine and an infinite network. The study covers simulations of different faults that can occur in a network and the consequences of the recovery time of the fault current limiter.

I. INTRODUCTION

Due to political and ecological reasons, it is today more and more difficult to obtain authorisations to extend or reinforce a power system in order to respond to the evolution of electric consumption. Consequently, the power system is exploited to the limits of stability maintained by the generators. For a power system in a stable condition, the generators operate in synchronism in order to respect the frequency of the power system. This means that there is an equilibrium between the consumed and produced power in this power system. When a fault such as a short-circuit appears, this situation of synchronous equilibrium may momentarily (damped oscillations) or definitively be lost, depending on the case. The maintaining of power system stability is conditioned by the fault duration, among others. The shorter the duration, the more the return to a stable state after a fault is guaranteed. In fact, during a fault the voltage drop causes a corresponding drop of the power transmitted to the network
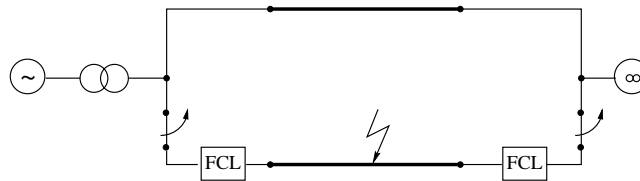
Fig. 1. Simulated system: A generator supplying power to an infinite network via a transformer and two parallel transfer lines. A short-circuit is simulated in one line.

and therefore the generators accelerate and acquire an increase of kinetic energy which is larger with longer fault duration. After the fault has been eliminated and if the power system is capable to suppress this excessive kinetic energy, it will find a state of stable operation. Therefore, it is evident that the kinetic energy surplus must be as small as possible. The elimination of the fault is made by opening circuit-breakers. The fastest circuit-breakers of today permit to interrupt the current in 40 to 60 ms (2-3 50Hz cycles). This duration may prove insufficient depending of the fault location, e.g. at the generator terminal. Now, if a superconducting current limiter is inserted in a power system, the elimination of the fault is accomplished quasi-instantaneously. This is due to the transition from a superconducting to a normal state of the superconducting element when the critical current is exceeded. In theory, one can anticipate that the stability of a power system equipped with a superconducting fault current limiter (FCL) may be maintained independently of the fault severity.

II. SIMULATED CASE AND MODELS

To investigate how well the superconducting FCL can influence the stability of the power system, we have studied a simple power system consisting of a generator supplying power to an infinite network via a transformer and two parallel transfer lines, see Fig. 1. We have simulated a fault in one of the transfer lines at a certain time instant and considered the evolution of the generator angle in presence and absence of a FCL until the current was interrupted by the circuit-breakers in the faulty line.

We have applied classical models for the conventional circuit elements used in stability investigations. In conventional stability simulations, complex ($j\omega$) models are normally utilised since ω does not change significantly. As

the superconducting FCL is a highly nonlinear element, it is not clear how to express its equations in complex variables, and so we have considered all three phases in our simulations.

The *generator's* mechanical behaviour is described by the classical swing equation [1], which relates mechanical power $P_m = 100$ MW, electrical power used by the power system P_e, nominal power $P_0 = 100$ MAV and frequency $\omega_0 = 2\pi \cdot 50$ rad/s, generator inertia $H = 7.5$ s and the generator internal angle δ:

$$\frac{d^2\delta}{dt^2} = \frac{\omega_0}{2H}\frac{P_m - P_e}{P_0} \qquad (1)$$

It is the evolution of the internal angle of the generator that determines whether the stability of the system can return to a stable state after a fault. The electric part of the generator is described by a seven-winding model in state space representation.

The model of the step-up *transformer* at the generator, that we have applied, is an ideal transformer with negligible inductances in primary and secondary windings for each phase.

The modelled *overhead lines* are equally long (50 km) and have a self-inductance L_s of 1.17 mH/km and a mutual inductance between the phases M of 224 μH/km. The short-circuit is simulated to be in the middle of one of the lines.

After the fault, we interrupt the current with *ideal circuit-breakers* on each side of the faulty line. The circuit-breaker models work in such a way that when they are triggered to open 40 ms after the fault has appeared, they await the next zero crossing of the current and then interrupt the current, similar to actual circuit-breakers.

The *infinite network* is a part of the system, that is assumed to be constant. It is therefore modelled as a voltage source with constant amplitude and phase angle.

The *superconducting FCLs* are here supposed to be of resistive type, i.e. they are mainly resistive both in superconducting and normal state, and we ignore their inductive part. The FCL consists of a superconducting material in parallel with a by-pass with constant resistance so that the superconductor transports the main part of the current in superconducting state and so does the by-pass when the superconductor enters the normal state. The voltage-current characteristics of the superconductor are described by a temperature and current dependent relation. In the superconducting state, it is computed as a power-law, where the exponent is chosen close to three. The critical current and the exponent are both temperature dependent. The superconductor enters the normal state at the critical temperature of $T_c = 95$ K.

The temperature of the superconductor T is computed considering the heat diffusion in the combined material of by-pass and superconductor. For simplicity, the heat diffusion is only considered in one dimension, radial, and not along the conductor, as shown in Fig 2. It is supposed that the cooling is made from both sides.

The whole system is now described by the equivalent circuit in Fig. 3.
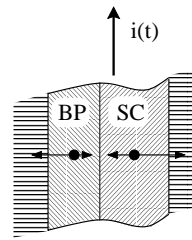

Fig. 2. The heat diffusion is computed in the radial axis only (BP = by-pass, SC = superconductor).
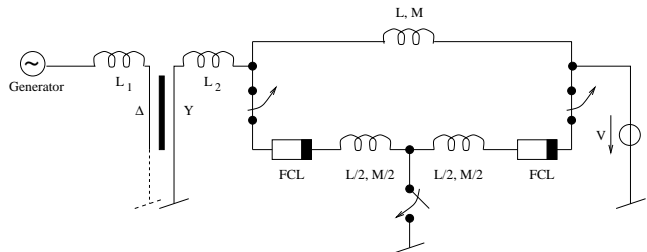

Fig. 3. The equivalent circuit of the simulated system.

III. RESULTS

The differential equations, the heat diffusion equation and (1), have large differences in their time constants. We are therefore dealing with a stiff nonlinear system, which requires a sophisticated solver. We implemented the system in Dymola$^{\text{TM}}$ [2] which takes the whole system into account at each time instant. It is delivered with a number of good solvers.

We simulated two different cases: with and without FCL. The fault was severe enough for the system to become unstable when no FCL was applied. However, when the FCLs were present, the situation became stable. The evolution of the internal angle of the generator δ is depicted in Fig. 4. We see in the figure how the internal angle goes to infinity when no FCL was used. This means that the generator started to accelerate without control. In the same figure we see the influence of the FCLs on the internal angle. The FCLs increase the stability margin of the system, and we notice how the internal angle returns to an equilibrium point. For completion, we also present the current evolutions in the faulty transfer line for the investigated cases. Fig.5 and 6 depict the three phases through the circuit-breaker closest to the generator, where a considerable decrease of the fault current is observed.

The simulations also predict the evolution of the temperatures in the superconductors which are depicted in Fig.7. The long recovery time about 3 s would cause a problem with today's security systems. They reconnect the current already after 2-3 cycles (40-60 ms). If the fault has not disappeared, they break the circuit again. This means that the FCL would not be ready to protect the system after such a short time duration and a second
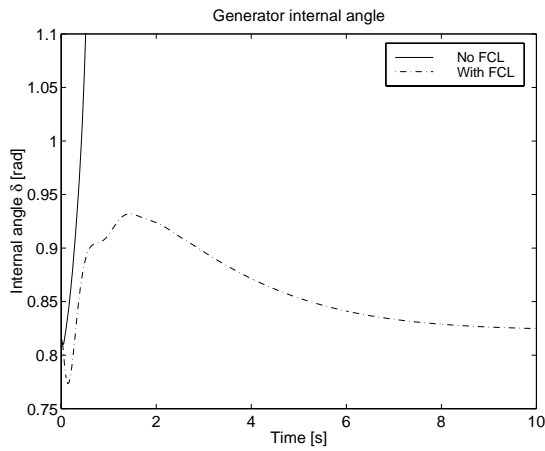
Fig. 4. Evolution of the internal angle δ of the generator due to a short circuit in one of the lines. The system becomes unstable and the generator accelerated uncontrollably when no FCL is used ($\delta \to \infty$). The FCLs stabilises the system to return to a stable state (δ returns to equilibrium point).

Fig. 5. The current through the circuit-breaker closest to the generator when no FCL is used.

parallel FCL might be necessary.

IV. Conclusions

We have considered a simple power system in the perspective of stability. It was shown that the system stability can be increased by introducing superconducting fault current limiters (FCLs) at strategic points, which is due to their fast transition from low to high resistance. A real power system is normally of a much higher complexity. Such a meshed power system would need a larger number of FCLs. A problem is that a short-circuit affects the currents not only in the line with the fault but in neighbouring lines as well. It is undesirable to have all FCLs to react, so more research is required to coordinate the FCLs in the system and to optimise their position. By such investigations, large systems must be considered. It
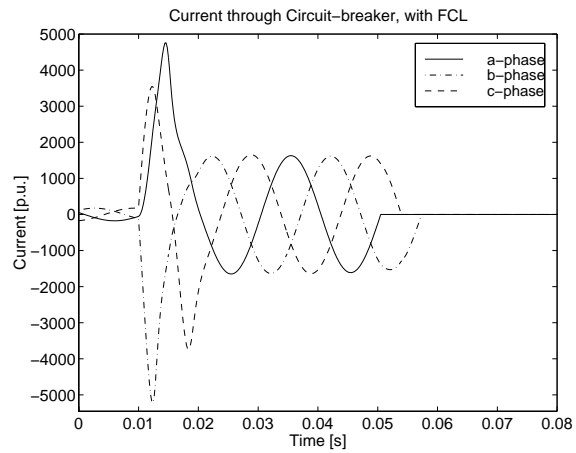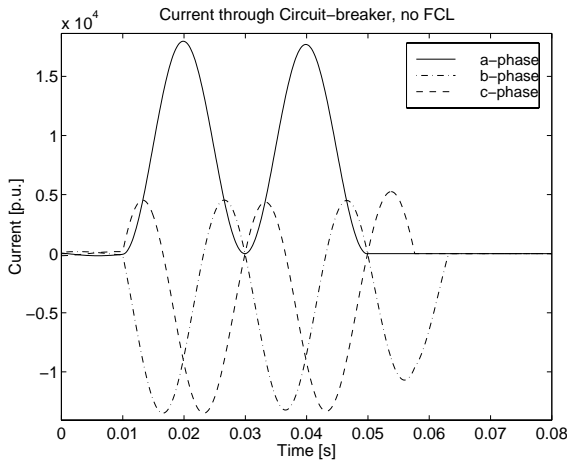

Fig. 6. The current through the circuit-breaker closest to the generator when a FCL is used. The FCLs reduce the amplitude considerably.
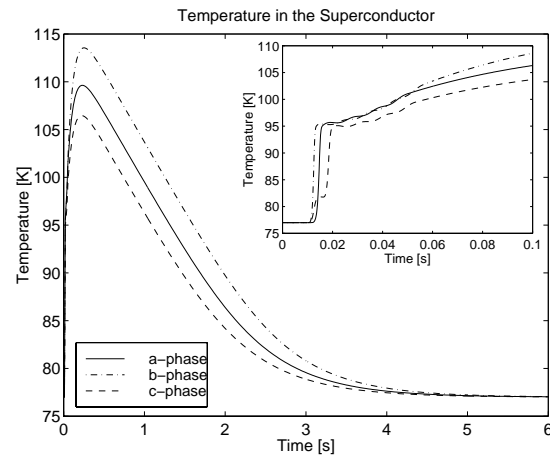

Fig. 7. Temperature in FCL closest to the generator. The recovery time is too long for todays security systems which reconnect after 2-3 cycles (40-60 ms). The inset shows the temperature evolution just after the short-circuit at $T = 0.01$ s.

is therefore desirable to use simplified models to speed up simulations. The FCL model presented here can then be somewhat simplified without loss of generality. The simulations also show that the recovery time of a superconducting FCL is too long for todays security systems.

References

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[2] H. Elmquist, D. Brück and M. Otter , *Dymola - Dynamic modelling laboratory*, Dynasim AB, Sweden, 1996.