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Influence of fault type on the optimal location of superconducting fault current limiter in electrical power grid

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ABSTRACT

This paper presents a novel approach to determine the optimal location of a resistive superconducting fault current limiter (SFCL) to improve the transient stability of an electric power grid (EPG). The presented method use the angular separation of the rotors of synchronous machines present in the power system to select the optimal location of SFCL. The selection of this optimal location is coordinated with the corresponding optimal resistive value to improve transient stability in case of short-circuit fault. To obtain a global study on the optimal placement of SFCL in case of fault, various types of short-circuits are considered (single phase grounded fault, two phases grounded fault, etc.). To evaluate the effectiveness of the proposed method, the IEEE benchmarked four-machine two-area test system is used to carry out several case studies. It is shown that the optimal location of SFCL as well as its optimal resistance value are not the same for each fault studied. A global analysis of EPG stability is presented in the paper to select only one location of the SFCL in the EPG. Results show that the optimal location of SFCL combined with its optimal resistive value reduces the angular separation of the rotors that improves effectively the stability of the EPG for any type of short-circuit.

1. Introduction

In modern networks, levels of short-circuit current can reach very high values (several tens of kA), which imposes severe mechanical and thermal stresses on the network equipment (transformers, lines, generators, circuit breakers, etc.) [1]. Without adequate protection systems, these fault currents can easily cause significant repair costs in a very short time (the duration of a short-circuit is about a few ms).

Traditional approaches to limit the short-circuit current always operate to the detriment of their reliability (separation of busbars, adding limiting inductances, etc.). Therefore, the introduction of devices that can limit the short-circuit current with more flexibility becomes increasingly imperative. There are a number of technologies that can do the job, at least in principle [2] but in practice, either the costs are too high, or physical clutter prevents the solution to be applicable, particularly in urban areas, where space for new equipment in substations is very limited.

Superconducting materials with high critical temperature (i.e. at 77 K, which is the temperature of liquid nitrogen) is one of the most promising technologies in this regard. Superconducting fault current limiters (SFCLs), in particular, through their intrinsic non-linear resistivity, can be seen as natural fault current limiter (no equivalent standard) [3–6]. This technology opens the way to more reliable network architectures, such as mesh networks [7]. Indeed, in normal operation, this device is entirely transparent to the network, whereas under short-circuit, it introduces a high impedance in the faulty line to reduce the short circuit current of the order of 20–50%. A reduction of 30% is often sufficient to ensure adequate safety margin for the network equipment.

In addition to the short-circuit current limitation, studies have shown that the use of SFCL in EPG allows to increase the transient stability of generators and consequently the global stability of the network [8–10]. When a SFCL is introduced in an EPG, three important factors should be considered:

1. Optimal resistive value of SFCL.
2. Optimal location of SFCL in the power grid.
3. Protection-coordination between other existing devices (circuit breaker, recloser, sensors, etc.).

The presented paper focuses on factors 1 and 2. Several studies advise on the optimal selection of the SFCL resistance to reduce the impact on existing protection schemes [11–13], to minimize the power exchanged between regions of an EPG during a fault [14] or to improve the transient stability of induction machines [10,15,16]. Concerning the power stability problem, some works deal on the subject but all of them use a SMIB (Single Machine

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Infinite Bus) to evaluate the impact of the SFCL on the power system stability [9,17]. So far, the remaining open question is the selection of this optimal location in a large-scale power system to improve its transient stability. In addition, the optimal location of SFCL is studied only for a three-phase short-circuit. No works deals with the fact that the most common fault is the single phase grounded fault. The three phase short-circuit is certainly the most destructive fault for equipments but it is one of the faults which appears less often in an EPG. In this paper we consider a multi-generators system and we use their rotor angular difference to define a sensitivity index, which leads to find the best location of the SFCL in the grid. This sensitivity index is calculated with respect to the resistive value of the SFCL. We have take into account all type of short-circuit that can appears in EPG (single phase fault, two phases fault, grounded or not, three phase fault) to select the optimal location of the SFCL. The effectiveness of the proposed method is evaluated on the IEEE benchmark four-machines two-area test system. The toolbox SimPowerSystems of MATLAB/SIMULINK software is used to carry out simulations studies (in the mode "phasor simulation"). Simulation results show that the optimal location selected by the proposed method improves the transient stability of the power system when a fault occurs. The advantage of the method is that the selected location takes into account the fact that a fault can occur any where in the studied grid. In addition, it is important to specify that the proposed method can be used for any type of superconducting limiters.

2. Superconducting fault current limiter model

We can represent the SFCL by impedance, which depends on current and/or temperature [18,19], or by resistance, which varies with time [14,20,21]. The second representation is more simpler than the first and allows to decrease the time simulation. In case of fault, the time necessary to recover a stability point in an EPG is equal to several seconds, consequently, it is not necessary to have a precise SFCL model in our case. The SFCL used in simulation can be represented by a resistance which varies with times as follows:

$$R_{SFCL}(t) = R_{SFCL}(1 - e^{-t/T_t}) \quad (1)$$

where R_{SFCL} and T_t represent respectively the maximum resistance that the SFCL can introduce in the transmission line and the time of transition from the superconducting state to the normal state, which is assumed, in this study, equal to 1 ms [14]. Concerning simulations, the SFCL model is introduced in the hight voltage (HV) lines because the level of the fault current is less important than in low voltage (LV) (the ratio between these two line currents is defined by the ratio of the primary and secondary voltages of transformers). In fact, the SFCL units (placed in parallel in the line) necessary to limit the fault current will be less important in HV than in LV [22]. Consequently, the SFCL would be easier to design in HV.

3. Determination of the sensitivity index

Concerning the selection of the optimal location of the SFCL, technicals constraints impose a specific location in the EPG. Generally, the SFCL is placed at a position where the current level can be very important in case of fault (depending of the short circuit power). However, its influence on the EPG stability is often overlooked. In [10], authors have shown that the transition of the SFCL to its superconducting state to its normal state (resistive state) can induce instability in the EPG in case of three phase short circuit if this later is not positioned correctly in the EPG. Therefore, from the point of view of the network, the location of the limiter must be determined in order to provide the best protection possible, both in fault limitation that its influence on the transient stability, for any type of short circuit.

It is in this context that the presented paper was conducted, find the optimal location of SFCL in an EPG to limit the fault current and improve the system stability in case of short-circuit. For an EPG with more than one generator, a necessary condition for satisfactory system operation is that all synchronous machines remain in synchronism when a severe transient disturbance appears (loss of transmission line, important increase of load, three phase short-circuit). This aspect of stability is influenced by the dynamics of generators rotor angle and power-angle relationships [1]. When a fault occurs in the system, the operating point of generators suddenly changes. Owing to inertia, the angular separation δ between the rotor position of each generator is modified until the fault is cleared. At the beginning of the perturbation, this angular separation increases with a magnitude that depends on the time necessary to clear the fault. If the fault clearing time is small, the power system is perturbed but a stable point is finding again after a few seconds. Otherwise, the synchronism of the power system is lost.

Fig. 1 presents the evolution of the angular separation δ of a simple power system (2 generators and 1 load) when a three phase short-circuit occurs at 1 s near a generator. In the presented Figure, the angular separation δ represents the difference between the angular position of the rotors of the two generators. If the fault is cleared at 1.2 s, the power system remains stable and the angle δ oscillates a few seconds to find, finally, a constant value, indicating a return to a stable state. On the other hand, if the fault is cleared at 1.3 s, the kinetic energy gained during the time of fault has not been yet completely expended to the system. The angle δ continues to increase after the fault cleared. The power system is not capable to return to a stable position, leading to loss of synchronism.

Sung et al. in [17] have demonstrated theoretically that the presence of a resistive SFCL in a SMIB (Single-Machine Infinite-Bus) allow to increase the fault clearing time. In terms of angular variation, the presence of a SFCL reduces the two boundary markers (δ^{MAX} and δ^{MIN}) of the angular separation of the rotors of the generators when a fault occurs. Consequently, the transient stability of the system is increased. Starting from this observation, we propose a method to select the optimal location of the SFCL in an

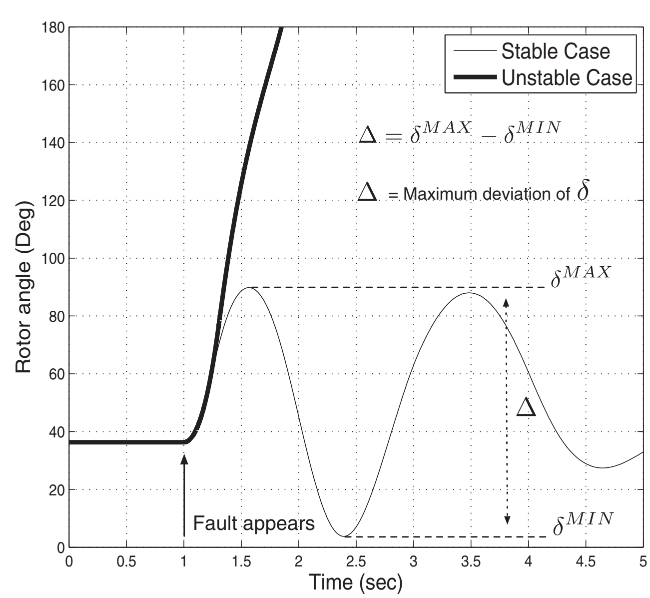

Fig. 1. Evolution of the angular separation δ of the rotors with a fault cleared at 1.2 s (stable case) and a fault cleared at 1.3 s (unstable case).