Improvement of Power System Stability Using SFCL in Electric Power Grid under Voltage Unbalance conditions

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Abstract—**This paper presents a novel approach to determine the power system stability using resistive superconducting fault current limiter (SFCL) of an electric power grid (EPG). In addition, the electric railway system has rapidly changing load characteristics in time. An unbalance is generated owing to the rapidly changing large single-phase loads. Subsequently, the unbalanced load causes an unbalanced transmission line. A voltage unbalance in the source influences the power equipment by causing a reduction in the power generation capacity of the generator and a decrease in the output of the other facilities in the transmission line. In addition, many flexible ac transmission systems are applied to transmission lines to compensate for and control electric power. A voltage unbalance causes a control error in these systems. In addition, we analyzed the effects of the proposed method using transient simulations. The angular separation of the rotors of synchronous machines present in the power system is introduced. It is shown that the SFCL can have different impacts (positive and negative) in function of its location in the EPG when a fault occurs. 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. The results show that the transient stability using SFCL combined with its optimal resistive value reduces the angular separation of the rotors that improves effectively the system stability during a fault.**

Index Terms—**Damping performance, electric power grid, superconducting fault current limiter, transient stability.**

I. INTRODUCTION

WITH the increasing of system capacity, fault occurrence probability becomes higher, that can induce severe damages in electrical power system [1]. For example, the high value of the short circuit current can damage the insulation strength of electrical devices, synchronous generators, protective relays, lines transmission, and loads. In addition, the electrical power needed by the system when a fault occurs is modified and induced instable state of the power generators [2]. Recently, the development of superconducting fault current limiters (SFCL) offers one of the most attractive alternatives to solve the fault current problems [3]–[5]. Thanks to their fast transition from a low to a high impedance, superconducting devices can limit, in a very short time, the value of any fault current. What is attractive is that the transition is due to an intransit behavior of the material itself [6]–[9].

The presence of the SFCL in a power system can increase the system stability and distributed energy quality [10]–[15]. When an SFCL is introduced in an electric power grid (EPG), three important factors must be considered:

1) optimal location of the SFCL in the EPG [16];
2) optimal resistive value of the SFCL [17];
3) protection-coordination problem with other existing devices (circuit breaker, OCR, etc.).

This paper focuses on factors 1 and 2. Nowadays, the optimal location of SFCL to improve the transient stability is studied for a simple power system like single machine infinite bus (SMIB) [2], [3], [15]. So far, the remaining open question is the selection of optimal location of the SFCL in a large scale power system to improve its transient stability. In this paper we consider a multi- generator system and we use their rotor angular difference to define a sensitivity index which leads to finding the best location of the SFCL in the grid. This sensitivity index is calculated with respect to the resistive value of the used SFCL. The effectiveness of the proposed method is evaluated on the IEEE benchmark four-machine two-area test system. The toolbox Sim Power Systems of MATLAB/SIMULINK software is used to carry out simulations studies.

The simulation results show the effectiveness of the proposed method. In fact, the optimal location determined for the SFCL improves the transient stability of the power system and decreases the low frequency oscillation of the generators speed when a severe damage is introduced (three-phase fault). The advantage of the proposed method is that the selected location of the SFCL takes into account the fact that the fault can occur anywhere in the studied grid.

II. SFCL MODEL APPLIED TO POWER SYSTEM

The operation of an SFCL is based on the natural transition of the superconducting state to normal state by exceeding the critical current I_c of the material. This transition from the super conducting to the normal state must be done in a very short time, generally, to limit the first current peak to a threshold value not exceeding three to five times the rated current, below the short-circuit current without limitation.

The SFCL is placed in series with a circuit breaker. During the fault, the current increases up to reach the threshold of transition from superconducting wire. This transition from the super conducting element to normal state causes the development of resistance that limits or triggers the current limit. The time between threshold crossing and the limitation is small (a few microseconds). The circuit breaker isolates the line as soon as possible after the beginning of the limitation. These super conducting fault current limiters use one of the fundamental properties of superconductors.

The qualifications of SFCL are:

1. Very low impedance during normal operation.
   The current limiter must be "invisible" in this mode. Some transients such as those caused during the switching of a transformer should not inadvertently cause a transition of the limiter.
2. High impedance system during short circuit.
   The limiter must perform its function in the case of massive short circuit but also in the case of low short circuit fault.
3. Very good dynamic.
   The system must transit in very quickly (with in millisecond) to effectively limit the value of the short circuit.

There are several types of SFCL; the main ones include:

1. The resistive limiter.
   This is a coil of superconductive material, non-inductive by construction, mounted in series on the line. In case of fault, the winding initially at the superconducting state changes to the normal state. Its impedance appears in the line, which limits the fault current. This limiter can be applied in AC or DC systems.
2. The inductive limiter.
   It consists in its simplest form, two windings connected in parallel. This association is made so that the impedance of all is the lowest possible. In case of fault, one of the coils (made of superconducting material) returns to its normal state. The other winding made either copper or superconducting material limit the current through the inductance.
3. The limiting transformer.
   It consists of a superconducting secondary short-circuit and primary winding of a conventional copper. In normal Operation, the impedance of this transformer is mainly due to the coupling between the windings and may be very low. Under fault, the secondary winding quenches under the effect of fault current and acts as a switch that opens the secondary of the transformer. Therefore, we obtain the no load impedance of a transformer which is very important.

As we said, the first function of an SFCL is to limit the fault current induced in the faulty line. In this case, the passage to its superconducting state to its normal state can only be achieved if the fault appears in the line where the limiter is placed. The probability that a fault appears at a specific location in the power system is very low. Consequently, if the fault appears at a different location in the power system, the SFCL cannot be used for its first function because the current value through the SFCL will be not sufficient to ensure a transition of this last. The originality of the presented work is that the SFCL is used if the fault appears anywhere in the system. In this case, the SFCL can be seen as a rapid switch that introduces a resistance in the power system. The presence of this additional resistance improves the power system stability in case of short-circuit and this, regard-less of the position of the fault. The SFCL is not used to limit the Fault current but to improve the stability of the power system. If the fault appears in the line where the limiter is placed, the two functions of the SFCL are used (limitation of the fault current in the line and improvement of the power system stability). By cons, if a fault appears at a different location, the SFCL introduce its resistance in the power system to improve the transient stability of generators. In this case, the passage to its superconducting state to its normal state will be accomplished by applying a magnetic field superior to its critical magnetic field after the detection of the fault in the EPG. The results presented in this paper show the effectiveness of the proposed method. We can represent the SFCL by impedance, which depends on current, or by a resistance, which varies during time. The SFCL used in simulation is represented by a resistance which varies with time as follows

$$R_{SFCL}(t) = R_m\left(1 - e^{\frac{-t}{Tc}}\right) \quad (1)$$

Where R_m represents the maximum resistance that the SFCL can introduce in the lines of the power system. Also, T_c is the time of transition from the superconducting state to the normal state, which is assumed, in this study, to be 1 ms [16].

III. DESCRIPTION OF THE PROPOSED METHOD

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.

When a fault occurs in the system, the operating point of generators suddenly changes. Owing to inertia, the angular separation δ between the rotor positions 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 found 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 sec near one of the generators. In the presented figure, the angular separation δ represents the difference between the angular positions of the rotors of the two generators. If the fault is cleared at 1, 2 sec, the power system remains stable and the angle δ oscillates between two extreme values. On the other hand, if the fault is cleared at 1,3 sec, 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 [15] have demonstrated theoretically that the presence of a resistive SFCL in a single-machine infinite bus (SMIB) increases the fault clearing time. In terms of angular variation, the presence of an SFCL reduces the two boundary markers of the angular separation of the rotors of the generator

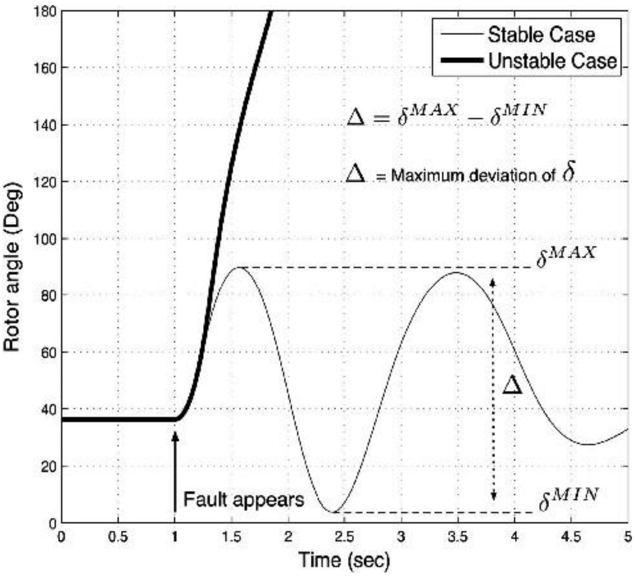

Fig.1. Evolution of the angular separation δ of the rotors with a fault cleared at 1, 2 s (stable case) and a fault cleared at 1, 3 s (unstable case).

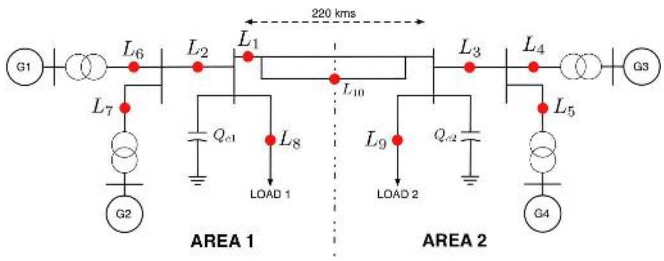

Fig. 2. IEEE benchmarked four-machine two-area test system. When a fault occurs consequently, the transient stability of the system is increased.

Starting from this observation, we propose a method to select the optimal location of the SFCL in EPG based on the study of the angular separation δ of the rotors of synchronous generators in case of fault. Many studies have dealt with the increase of transient stability in power systems thanks to SFCL but most of them have limited the study to a simple power system such as generator, transmission line, and infinite bus. Now, the remaining open questions are the selection of optimal location of the SFCL in a power system with more than 2 generators. We present a method which is not limited to a simple system like an SMIB but extended to the IEEE benchmarked four-machine two-area test system presented in Fig. 2. This power system is composed of four generators, two loads and a long transmission line (220 km), that is a advantage to study the optimal location of an SFCL in a power system in comparison with SMIB.

The details on this system, including the systems parameters, are given in [19]. All generators (G1 to G4) are equipped with power system stabilizers (PSSs).

To determine the optimal location of the SFCL, the method focuses on the angular separation between the rotors of all generators. If the rotor angle of generator G4 is taken as reference, the angular separation of the rotors of generators G1 to G3 (relative to G4) can be noted as $\delta_{11}\ \delta_{21}\ \delta_{31}$. The variation of each i_4 ($i = 1$ to 3) is depending on the fault severity introduced in the EPG. If we consider that subscripts m, k, and N represent, respectively, the position of SFCL in the system, the position of the fault in the system and the number of fault position studied (which will be identical to m in this study), we can determine the optimal location of the SFCL in EPG by the analysis of a transient stability index (TSI_m) given in (3). To obtain the value of index TSI_m with respect to the resistive value of the SFCL, noted R_{SFCL}, we determine in advance an index SMD_m (2) by considering the sum of the maximum deviations of Δi_4 ($i = 1$ to 3) given by Δ_k when a fault appears at position k in the system (the maximum value of k is equal to N):

$$\Delta_{i4} = \delta_{i4}^{MAX} - \delta_{i4}^{MIN}$$

$$\Delta_k = \sum_{i=1}^{N} \Delta_k$$

$$SMD_m = \sum_{k=1}^{N} \Delta_k \quad \ldots\ldots\ldots\ldots \quad (2)$$

$$TSI_m = \frac{\partial SMD_m}{\partial Rsfclm} \ldots\ldots\ldots\ldots \quad (3)$$

Consequently, the value of indexes SMD_m and TSI_m will give us accurate information to find the optimal location of the SFCL if a fault occurs in the system. Indeed, these indices reflect the contribution of the SFCL in the system in terms of stability when a fault occurs.

IV. SIMULATIONS RESULTS

To evaluate the effectiveness of the proposed method, ten locations (L1 to L10 in the middle of each line) are considered in Fig. 2. For a given position of the SFCL (m=1 to 10), a 100ms three-phase short-circuit is applied at each location L_K (k=1 to 10). For each case (k=m and k ≠m), the maximum deviation Δi4 (i = 1 to 3) of generators are calculated to obtain Δ_K. In a second time, index SMD_m and finally, index TSI_m are evaluated with respect to the corresponding value of the SFCL resistance used in simulation. When the SFCL will be positioned at each location, the study of indexes SMD_m and TSIm will give us the best location of the SFCL in the system in case a three-phase fault can appear at any position in the system. The time simulation required until the system is restored to its original steady-state operation point after applying the fault is considered to be equal to 20 s. Before calculating values of index, it is necessary to compute the load flow of the presented power system. The results show that the power generated by generatorsG1 and G2 is mostly consumed by Load 1. In area 2, the power generated by generators G3 and G4 is consumed by Load 2 but it is not sufficient. The rest of the power required by Load 2, i.e., 413 MW, is transferred from area 1 to area 2 by the 220-km transmission line.

Therefore, if the value of TSI_m (3) is greater for a given resistive value, the corresponding location m becomes more optimal. The determination of optimal resistive value of SFCL is presented in the next sub-section.

Resistor-Type SFCL Modeling

In order to limit a fault current, many models for the SFCL have been developed: resistor-type, reactor-type, transformer type, etc. [11]. In this study, we modeled a resistor-type SFCL that is mostly basic and used widely which represents the experimental studies for superconducting elements of SFCL. Quench characteristics and recovery characteristics of a resistor-type SFCL are modeled based on [11] and [12]. An impedance of the SFCL according to time *t* is given as follows:

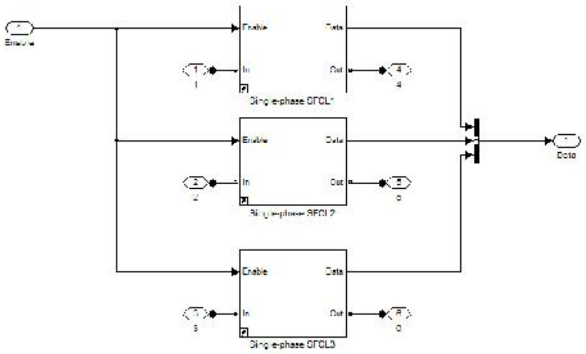

Fig. 3. Three Phase SFCL Model

An SFCL cannot be placed between two areas. The presence of SFCL at location L_1 and L_{10}, i.e., at the beginning or in the middle of a long transmission line, increases the instability of the system in case of fault.

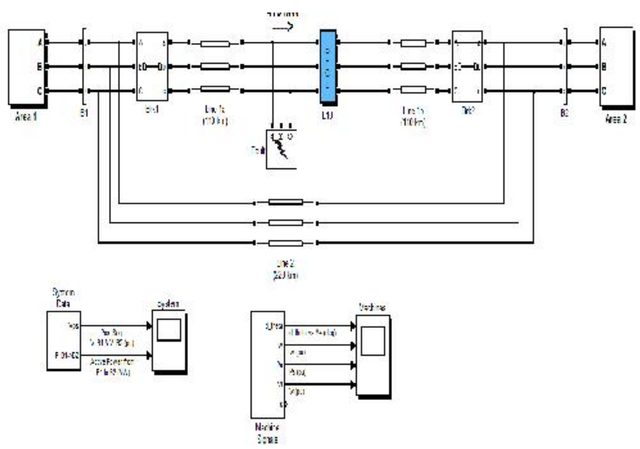

Fig. 4. Simulink model of Two Area Test System

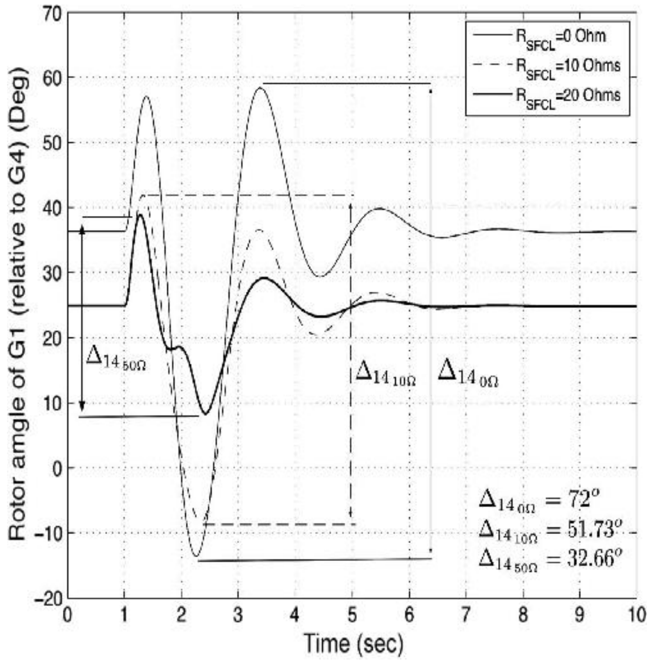

Fig.5 Variation of δ_{14} when the SFCL (with different value of R_{SFCL}) is connected at L_6 when a fault appears at L_2 .

We can note that the presence of the SFCL in EPG reduces the variation of δ_{14} and consequently, the maximum deviation Δ_{14} when a fault occurs in the power system. If a fault occurs in area 2 (for example at location L_1), the evolution of Δ_{14} when the SFCL is placed at location L_6 gives the same results but the reduction of its magnitude is influenced by the length of the transmission line (265 km).

B. Sensitivity Analysis for Optimal Resistive Value of SFCL

The proposed method shows that the optimal location of the SFCL depends on its resistive value R_{SFCL}. We, respectively, present at Figs. 4 and 5 the variation of index SMD_m in function of R_{SFCL} for the two optimal locations L_2 and L_6 determined by the presented method.

If the SFCL is placed at location L_2, the best value of R_{SFCL} is about 10 Ω as we can see in Fig. 4. In the case of location L_6 , it is for a resistance value R_{SFCL} about 50 Ω that the index SMD_6 is the best. This study shows that the SFCL resistance is

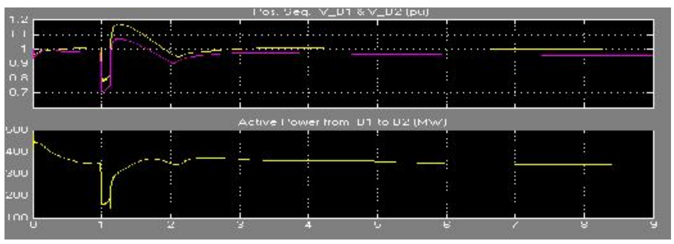

Fig. 6. Positive Sequence voltages and active power flow when the SFCL is placed at location L_2

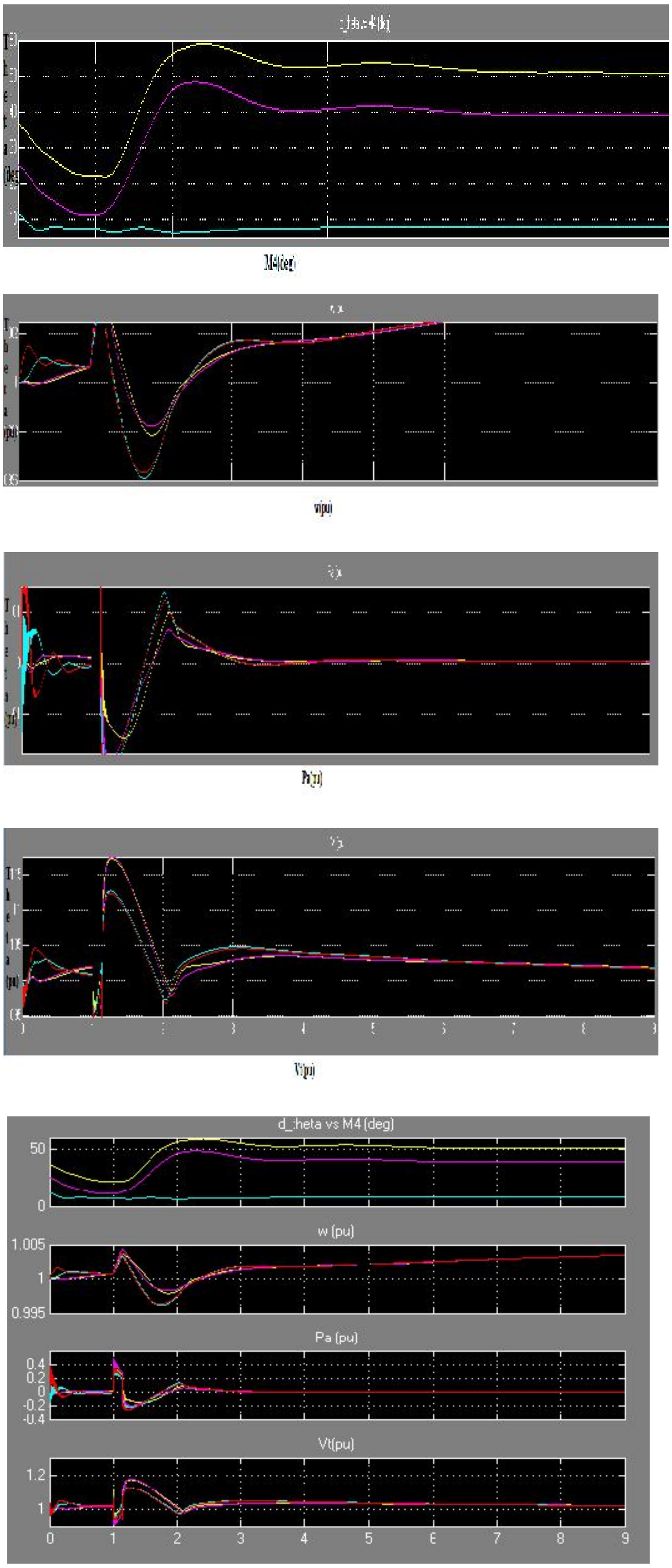

Fig. 7. Angle Deviation (δ), Generator Speed (ω), Voltage Profile (V)

From the above outputs to improve the stability of the system in case of fault. Mainly the stability of the system depends on Angle deviation (δ), Generator speed (ω), Voltage profile (V) values.

To determine the better position between locations L_2 and L_6, we could calculate the mean of the ratio R_{sdwi} by taking into account all locations and all generators. If the SFCL is placed at location L_2, we obtain a reduction of the low frequency oscillation of the rotors speeds equal to 9.17%. If the SFCL is placed at location L_6, the reduction of the low frequency oscillation of the rotors speeds is equal to 19.18%. From the above results, the optimal location L_6 selected by the proposed method is validated to be effective for application of the resistive SFCL to the IEEE Benchmark four-machine two-area test system.

Concerning the coordination of the protective devices present in the power system, You *et al.* in [5] have shown that the recovery time of the SFCL, which depends on its resistive value, can modify the operation of the re closer and the over current relay (OCR) of the faulty transmission line. Two solutions can be considered. The first is to select the resistance of the SFCL to be within the limited range of the protection devices to keep the protection coordination. The second is to modify the setting parameters such as the time dial (TD) and the pickup current of the protective devices.

In our case, the modification of the resistance value of the SFCL is difficult because it has been determined to obtain the best reduction of the rotor angle deviations of generators and an increase of the system damping performance in case of fault. Consequently, in our case, the solution is to modify the setting parameters to ensure the protection coordination of the power system. Recent works have shown that a good coordination of the protective devices with SFCL can be obtained by the modification of the TD [21] or the pickup current [22] of the OCR, these two last parameters being a function of the resistance of the SFCL used in the power system.

Table III gives the ratio of the rotor speed deviation R_{sdi} of the ith generator when the SFCL (with, respectively, a resistance of 10 Ω and 50Ω) is placed at location L_2 and L_6 when a 100-ms three-phase short-circuit is applied at each location L_k:

$$Rsd_{\omega i} = \frac{(\omega i max - \omega i min)/\ WITH\ SFCL}{\omega i max - \omega i min/\ WITH\ SFCL} / Location\ L_k$$

V. APPLICATION OF THE PROPOSED METHOD TO A LARGE-SCALE POWER SYSTEM

If we consider a large- scale power system, it is not possible to use only one SFCL to improve the stability of the system in case of fault. The idea is to split the power system into smaller areas depending on the coherency of the areas when subjected to disturbances. In this case, we will have a number of sub-systems equal to the number of areas. To improve the stability of the power system, an SFCL has to be associated to each sub-system. The optimal location of each SFCL can be determined thanks to the proposed method by considering a three-phase fault at different locations in the considered area. Consequently, the pro-posed method uses only a reduced number of generators to evaluate the optimal location and the optimal resistance of SFCLs.

For example, if we consider the IEEE 39-bus test system (10 generators, 39 bus, and 34 lines) [20], we can divide it into three areas as shown in Fig. 7. For each area (or sub- system), the pro-posed method can be applied to determine the optimal location of the associated SFCL.

VI. CONCLUSIONS

This paper presents a novel approach to select the optimal location of a resistive SFCL in an EPG. The proposed method is based on the study of the angular separation between the rotors of the generators present in the power system. This approach allows finding the optimal location of SFCL when the power system studied presents several generators. We have shown that the optimal location of SFCL selected by the proposed method, in accordance with the own resistive value R_{SFCL}, increases the transient stability of the power system studied by reducing the angular deviation between the rotors of the synchronous machines in case of three-phase fault. In addition, the method takes into account the study of the frequency oscillations of the generator speed in order to select the optimal resistance of SFCL. The main advantage is that the optimal location of the SFCL determined by the analysis of indexes SMD and TSI_m takes into account that the three-phase short-circuit can appear anywhere in the EPG.

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