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Optimal Placement of a Resistive Superconducting Fault Current Limiter in a Multimachine Power System

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***Abstract*—This paper presents a method to find the optimal position of resistive superconducting fault current limiter (SFCL) for transient stability enhancement of multi-machine power system. The method is based on minimization of rotor angle separation of synchronous machines present in the system. The SFCL can have different impacts (positive and negative) according to its resistance value and location in the power system when a fault occurs. The studies are carried out on the loop electrical power system based on the Western System Coordinated Council (WSCC) three machines, nine-bus system to evaluate the effectiveness of the method by using MATLAB. The optimal location of SFCL combine with its resistive valve reduces the angular separation of the rotors that improve effectively the system stability during fault.**

***Index Terms*— Superconducting fault current limiter (SFCL); rotor angle deviation; transient stability; optimal location; multi-machine power system.**

I. Introduction

With the increased demand of electric power the power systems are becoming larger and more interconnected day by day. As a result the fault current increases and transient stability problems have become significant. Excess in fault current causes instability and security problems to the electric network. The development of superconducting fault current limiters (SFCL) offers one of the most attractive alternative to solve the above problems. Resistive SFCL is the simplest form of SFCL. They are placed in series with the line. Resistive SFCLs operate on the principle that passing a current, which is greater than the superconductor's rated critical current, through a superconducting wire initiates quenching and results in a transition to a resistive state. Hence, virtually there are no electrical losses in the SFCL during normal operation and SFCL inserts impedance into the fault current path during a fault. When an SFCL is introduced in an electric power system, the important factors to be considered are:

1) Optimal location of the SFCL.
2) Optimal resistive value of the SFCL.

In a power system single or multiple SFCL can be placed. But multiple SFCL in a micro grid are not only costly but also less efficient than strategically located single SFCL [1]. The effects of the SFCL on the overall system during a fault vary with the different locations depending on the amount of transmitted powers

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[2]. The effect of SFCL will also vary with the type of system in which it is installed. The optimal resistive value for a single machine infinite bus system can be found easily with the transient stability study based on the equal-area criterion [3]. In a large multi machine power system the probability that a fault appears at a specific location is very low and hence the placing of SFCL is complex compared to a single machine infinite bus system. So a detailed analysis is necessary to place it optimally in a large scale power system. We can determine suitable location and design the smallest capacity of SFCL simultaneously in a loop power system using different optimization algorithms [4].

In this work 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 studies are carried out on the loop electrical power system based on the Western System Coordinated Council (WSCC) three machine, nine-bus system to evaluate the effectiveness of the method by using MATLAB. 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 method is that the selected location of the SFCL takes into account the fact that the fault can occur anywhere in the studied power system.

II. Superconducting Fault Current Limiter

The operation of an SFCL is based on the natural transition of the superconducting state to normal state by exceeding the critical current of the material. Materials used for making SFCL are Bismuth-Strontium-Calcium-Copper Oxide (BSCCO), Yttrium Barium-Copper-Oxide (YBCO). Following are the advantages of SFCL:

- Zero resistance during normal operation.
- Reduction of online power loss.
- Provides sufficiently large resistance under fault conditions.
- Provides rapid initiation of limiting action.
- Provides immediate recovery of normal operation after clearing fault.
- Fully automatic.
- Does not need a trigger to activate.
- Improvement of transient stability and voltage sag [5].

The SFCL used in simulation is represented by a resistance which varies with time as follows:

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

where R_m represents the maximum resistance that the SFCL can introduce in the lines of the power system and T_C is the time of transition from the superconducting state to the normal state.

III. Optimal Placement Method

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 G1 is taken as reference, the angular separation of the rotors of generators G2 and G3 (relative to G1) can be noted as δ_{21} and δ_{31}. The variation of each is depending on the fault severity introduced in the electric power system. 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, we can determine the optimal location of the SFCL in electric power system by the analysis of a transient stability index.

To obtain the value of index with respect to the resistive value of the SFCL noted, we determine in advance an index by considering the sum of the maximum deviations given by when a fault appears at different positions in the system. The maximum value of k is equal to N.

$$\Delta_{i1}=\partial_{i1}^{max} - \partial_{i1}^{min} \qquad (1)$$

$$\Delta_k=\sum_{i=1}^{2}\Delta_{i1} \qquad (2)$$

$$SMD_m=\sum_{k=1}^{N}\Delta_k \qquad (3)$$

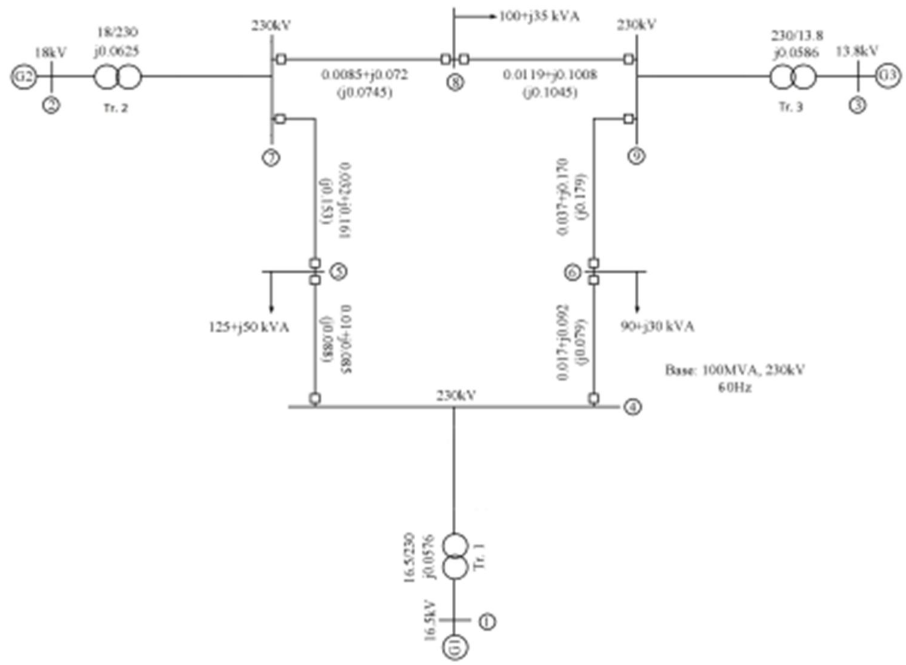

Fig 1. Western System Coordinated Council (WSCC) 3 machine, 9 bus system

$$TSI_m = \frac{\partial SMD_m}{\partial RSFCL} \qquad (4)$$

The value of indices SMD_m and TSI_m will give us an accurate information to find the optimal location of the SFCL if a fault occurs in the system. And these indices reflect the contribution of the SFCL in the system in terms of stability when a fault occurs. To determine SMD_m and TSI_m, the angular deviation Δ_{i1} (Δ_{21} and Δ_{31}) during each fault has to be found.

According to the variation of the resistance of SFCL, the reduction of index SMD_m means that the SFCL increases the system stability in case of fault. When index TSI_m presents a negative value, the SFCL contributes to increase the global rotor angle variations of generators. Consequently, the selected location weakens the transient stability of the power system. And when the value of index is positive which means that the presence of SFCL increases the transient stability of electrical power system in case of three-phase fault by reducing the variation of separation angle between the rotors. Therefore, if the value of TSI_m is greater for a given resistive value, the corresponding location becomes more optimal.

IV. Simulation Results

A. Determination of sensitivity indices

The network considered for the test is a multi-machine power system. Hence there are many options for installing the SFCL. Twelve fault locations and nine SFCL locations are considered as shown in fig.2. Therefore, it is necessary to identify the stability effect of the SFCL on the network on a case-by-case basis. The simulation process used to evaluate the stability of the installation of the SFCL is as follows.

For a given position $L_m$of the SFCL (*m*=1 to 9), a 100-ms three-phase short-circuit is applied at each location Lk (*k*=1to 12). For each case the maximum deviation Δ_{i1} *(i*=2 and 3) of generators are calculated to obtain Δ_k. In a second time, 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 is positioned at each location Lk , the study of indices SMD_m and TSI_m will give us the best location of the SFCL in the system in case a three-phase fault appears at any position k in the system. Before performing simulations with SFCL, it is necessary to obtain the value of index SMD when a three-phase short-circuit is introduced at each location Lk when no SFCL is used.

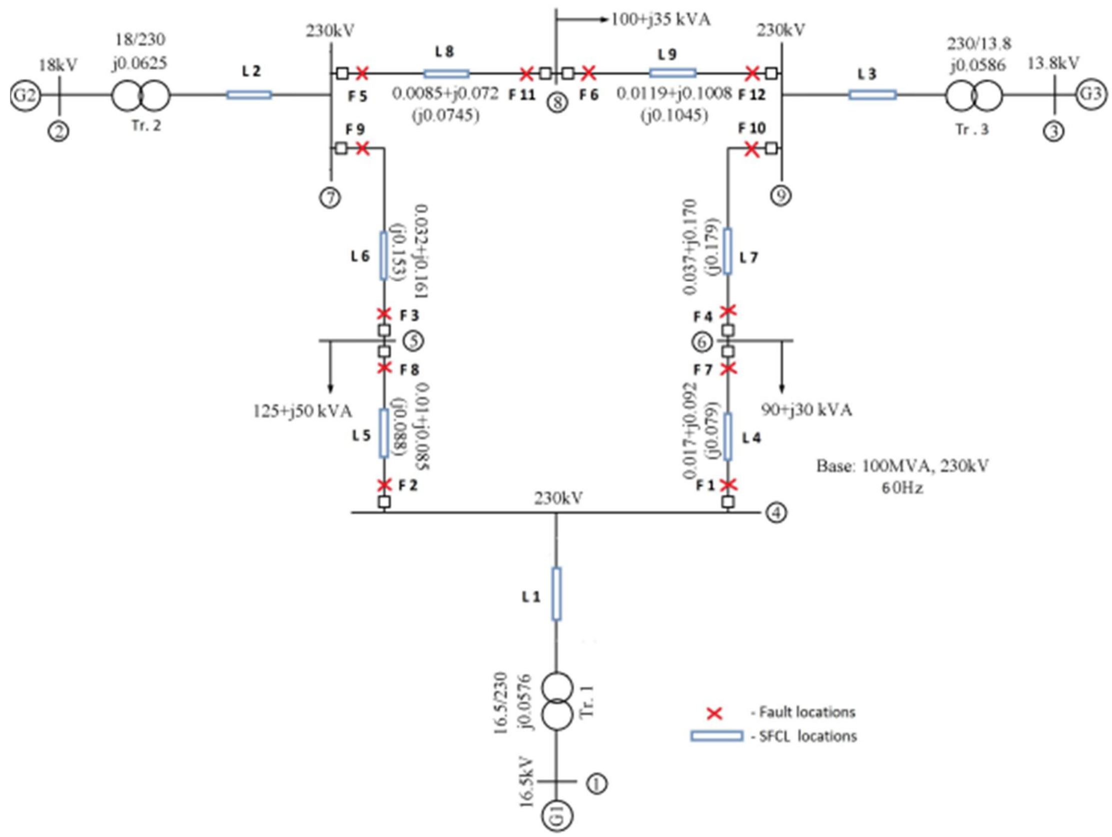

Fig 2. Western System Coordinated Council (WSCC) 3 machine, 9 bus system with fault and SFCL locations

B. Study of indices SMD_m and TSI_m

When no SFCL is used the test gives an SMD of 1262° (The subscript m is not indicated on this index because no SFCL is used.). In different cases studied, when SFCL is placed in the lines 4-5, 4-6 and 8-9(L5, L4 and L9), the value of SMD_m with SFCL is less than that of the case without SFCL. Also at those positions the value of TSI_m is positive, which means that the presence of SFCL increases the transient stability of electrical power system in case of three-phase fault by reducing the variation of separation angle between the rotors. When SFCL is placed at other locations it gives a negative TSI_m and will increase the instability of the system in case of fault. When SFCL is placed at location L4 with different values of SFCL the value of SMD_m is seemed to be less compared to other locations. Also the value of the index TSI_m is greater for all the given resistive values at L4. Hence the line 4-6 is the optimal location for the given SFCLs. Fig. 3 shows the variation of rotor angle separation versus time when a three-phase short-circuit occurs at F9 when simulations are made without the SFCL, and Fig. 4 with an SFCL of 1pu (529 ohm) at location 4-5 (All the graphs show the variation from fault to post fault condition.). It is found that the rotor angle separation with SFCL (157°) is less than the case without the SFCL (163°). From the analysis of SMD_m and TSI_m following results are obtained:

- The SFCL cannot be placed at the locations L1, L2, L3, L6, L7 and L9 since it gives a negative TSI_m and will increases the instability of the system in case of fault.
- When SFCL is placed at the locations L5, L4 and L9 (lines 4-5, 4-6 and 8-9) it increases the transient stability of electrical power system in case of a three phase fault by reducing the variation of separation angle between the rotors.
- Line 4-6 is the optimal location for the given SFCLs since the value of SMD_m is less and TSI_m is greater compared to other locations.

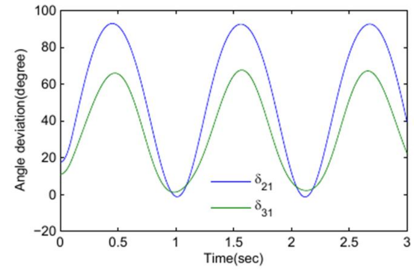

Fig 3. Angle deviation without SFCL

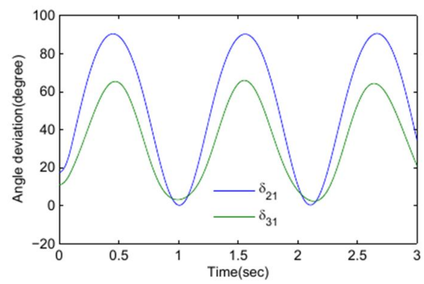

Fig 4. Angle deviation with SFCL

C. Study of index Rsd_{wi}

If SFCL is placed at location 4-6, the value of SMD_m (1142°) remains the same for all the given resistance values. The SFCL resistance is an important parameter in the case of electric power system stability study. An SFCL with a resistance of 1pu is easier to manufacture and implement than an SFCL with a resistance of 2pu. Another point to be considered could be the damping improvement of generators speed introduced by the SFCL. When an SFCL of 1pu is placed at location L4 and L9 respectively, when a 100 ms three phase short circuit is applied at each location Fk the rotor speed deviation of the i^{th} generator is given by:

$$Rsd_{wi} = \frac{(w_{imax} - w_{imin})with\ SFCL}{(w_{imax} - w_{imin})without\ SFCL} \text{ at Fk} \qquad (5)$$

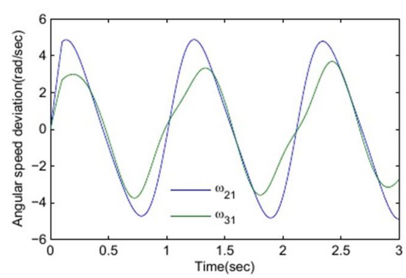

Fig 5. Angular speed deviation without SFCL

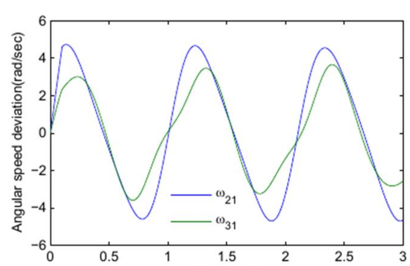

Fig 6. Angular speed deviation with SFCL

Fig.5 shows the variation of angular speed versus time when a three-phase short-circuit occurs at F9 when simulations are made without

$$W = (w_{21}^{max}\text{-}w_{21}^{min}) + (w_{31}^{max}\text{-}w_{31}^{min}) \qquad (6)$$

the SFCL, and Fig.6 with an SFCL of 1pu (529 ohm) at location 4-5. It is found that the angular speed deviation W(6) with SFCL (17.19 rad/sec) is less than the case without the SFCL (16.68rad/sec). Hence the presence of SFCL of 1pu resistance at location 4 can enhance the transient stability of the WSCC three machine, nine bus system by reducing the angular speed deviations.

If the SFCL is placed at location L4 (in line 4-6), its influence on Rsd_{wi} is more significant if the fault occurs at locations F1, F2, F3, F4, F7, F8, F10 or F12. Hence the rotor speed deviations can be reduced if fault occurs at locations F1, F2, F3, F4, F7, F8, F10 or F12. However, the presence of SFCL at this location increases the ratio if the fault occurs at F5, F6, F9 or F11. The ratio Rsd_{wi} for a particular position remains almost same for all the given resistance values. If the SFCL is placed at location L4, we obtain a reduction of the low frequency oscillation of the rotors speeds equal to 5.75 % and if the SFCL is placed at location L9, the reduction of the low frequency oscillation of the rotors speeds is only 2.72 % (The value is found by taking mean of the ratio, by considering all locations and all generators.).

The damping performance is a function of the location of SFCL. It is found that the damping performance is more effective when SFCL is placed at the location L4. Hence the optimal location of SFCL in the considered system is L4 and the maximum value of optimum resistance of SFCL is found to be 1pu on considering the manufacturing, easiness of implementation, improvement of angular deviations and the improvement of speed deviations introduced by the SFCL.

V. Conclusion

The presence of SFCL increases the transient stability of the system in case of three-phase fault by reducing the variation of separation angle between the rotors. The applied method is based on the study of the angular separation between the rotors of the generators present in the power system. This approach allows to find the optimal location of SFCL when the power system studied presents several generators. It is found that the optimal location of SFCL selected by the method, in accordance with the resistance, 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 optimal location decreases the low frequency oscillation of the generators speed when a severe damage is introduced. The main advantage is that the optimal location of the SFCL determined by the analysis of indices takes into account that the three-phase short-circuit can appear anywhere in the system.

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