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Impact of Critical Clearing Time on Over-current Relays Coordination in a Multi-Machine Power System in Presence of Resistive SFCL

Mohammadsaleh Jafaritalarposhti, Saied Hamid Fathi, Hossein Askarian Abyaneh
Department of Electrical Engineering
Amirkabir University of Technology
Tehran, Iran

***Abstract*— Introduction of distributed generations (DG) to electrical networks has many virtues. Nevertheless, by connecting DGs to a network, there might happen some defects in coordination of overcurrent (O/C) relays. In order to eliminate these likely defects and restoration of O/C relays' coordination, a resistive superconducting fault current limiter (SFCL) is used in series with DG. The resistive SFCL also affects the transient stability of a multi-machine power system, and as a result, change the critical clearing time (t_c) of the network. In this paper, the effect of consideration of t_c on the determination of optimal size of resistive SFCL in order to simultaneously satisfy both the coordination of backup and main (B/M) relays and the operation of relays before reaching t_c is studied. The results show that the determination of SFCL size, without consideration of t_c, is not appropriate since after installation of SFCL in the network, the network t_c changes, and the determined size of SFCL causes the operation time of some relays to be more than t_c, although it removes the miscoordination between B/M relays. Ignoring this point makes the network unstable at fault occurrence.**

Keywords- Critical clearing time, distributed generation (DG), overcurrent relay coordination, resistive superconducting fault current limiter (SFCL), transient stability, syncronous generator

I. Introduction

The trend of a power system to develop restoring forces which are equal to or greater than the disturbing forces in order to sustain the state of balance is known as stability [1]. A transient stability is identified if the synchronism of the machines' rotor angle in the network is sustained after a fault occurrence. Occurrence of abrupt disturbances and changes, such as short circuit, causes severe changes in electrical powers, power angles and the speed of synchronous generator's rotors. If these disturbances are not removed very fast, the forces tending to keep generators in synchronism with other generators in the network are not able to do so, and consequently, the network loses its stability. This maximum possible time is called the critical clearing time (t_c) of the network. Superconducting fault current limiter (SFCL) is able to improve the transient stability of the power system by reducing the amount of fault current [2, 3]. FCL is a well- known device which presents a big impedance during fault, in order to deplete the fault current to an acceptable level, having very low impedance and power loss under normal operation conditions [4]. The unique characteristics of high temperature superconductors enable the building of electrical tools with parameters that are not feasible to be built using common materials [6]. Many of research on the stability of an SFCL has been carried out in radial networks. Regarding this fact, investigating the impact of SFCL on the stability of a multi-machine power system with a mesh structure network sounds integral [7]. In order to enhance the reliability and continuity of electrical power in a power network, a mesh structure network is usually used. In such a network, inverse time O/C relays are used as the most common protection implements [8]. These relays are coordinated with each other in order to protect efficiently the network.

Although the introduction of DGs, such as synchronous generators, to the network has some advantages, it causes some defects in the coordination of relays, and changes the value and direction of power flow and short circuit current in the network [8]. In [10] SFCL is used to improve the negative effects of DG on the coordination of O/C relays.

In this paper the effect of the network critical clearing time (t_c) on both the determination of the size of SFCL and restoration of the O/C relays' coordination are investigated. By considering the network t_c, the old size of SFCL is not appropriate anymore because, although it removes the miscoordination between B/M relays, along with installation of SFCL in the network, the network t_c alters, and the operation time of some relays would be more than t_c. Ignoring this point causes the network to be unstable at fault occurrence.

II. Structure of Resistive SFCL

The simple structure of a resistive (noninductive winding) SFCL unit is shown in Figure 1. The unit includes three elements: the stabilizer resistance of the *k*-th unit, called $R_{Ks}(t)$; the superconductor resistance of the *k*-th unit $R_{Kc}(t)$, connected to $R_{Ks}(t)$ in parallel, and the coil inductance of the *k*-th unit, L_k. The subscript *K* indicates the number of units connecting to each other in series [11]. The values of $R_{Ks}(t)$ and $R_{Kc}(t)$ in the pre-fault state are considered zeros since the quantities of $R_{Ks}(t)$ are too small. Nevertheless, these quantities turn to non-zero depending on their unique characteristics during faults. The wound coils identify the value of L_k to have very low inductance. Then, it can be said that the value of L_k is very small and negligible. The total amount of resistance $\left(R_{SFCL}(t)\right)$ can be calculated as follows, during a fault state.

$$R_{SFCL}(t) = R_m(1-\exp(-t/T_{SC})) \quad (1)$$

Where R_m is the maximum resistance of SFCL in the quenching state, T_{SC} is the time constant of SFCL when passing from the superconducting state to the normal state.

III. Transient stability of multi-machine systems

Before starting analysis of transient stability, the initial load flow is solved, and all the initial bus voltage magnitudes (V_k) and phase angles are calculated. After that, a solid three-phase fault at bus *K* in the network is assumed, resulting in $V_k = 0$. It is simulated by omitting the *K*-th row and column from the pre-fault bus admittance matrix. All nodes other than the internal generator nodes are omitted to get the new bus admittance matrix reduced. Excitation voltages of the generators are considered to remain constant during the fault and post-fault states. For machine *i*, the swing equation with damping neglected becomes

$$\frac{H_i}{\pi f_0}\frac{d^2\delta_i}{dt^2} = P_{mi} - \sum_{j=1}^{m}\left|E_i^{'}\right|\left|E_j^{'}\right|\left|Y_{ij}\right|\cos(\theta_{ij}-\delta_i+\delta_j) \quad (2)$$

Where Y_{ij} are the elements of the faulted reduced bus admittance matrix, and H_i is the inertia constant of machine *i* presented on the common MVA base S_B. If H_{G_i} is the inertia constant of machine *i* presented on the machine rated MVA, then H_i is given by (3)

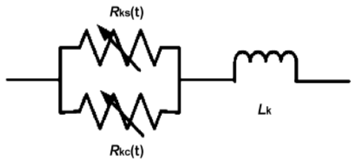

Figure 1: Simple structure of a resistive SFCL

$$H_i = \frac{S_{G_i}}{S_B}H_{G_i} \quad (3)$$

Presenting the electrical power of *i*-th generator by P_e^f and changing (2) into state variable model results in

$$\frac{d\delta_i}{dt} = \Delta w_i \quad i=1,\ldots,m\,, \quad \frac{d\Delta w_i}{dt} = \frac{\pi f_0}{H_i}(P_m - P_e^f) \quad (4)$$

For each generator, there are two state equations with initial power angles δ_{0_i} and $\Delta w_{0_i} = 0$. When removing faults, the bus admittance matrix is recomputed to take into account the variations in the network. Thereafter, the post-fault reduced bus admittance matrix is evaluated, and the post-fault electrical power of the *i*-th generator shown by P_i^{pf} is determined from (5)

$$P_{ei} = \sum_{j=1}^{m}\left|E_i^{'}\right|\left|E_j^{'}\right|\left|Y_{ij}\right|\cos(\theta_{ij}-\delta_i+\delta_j) \quad (5)$$

Using the post-fault power P_i^{pf}, the simulation is continued to determine the system stability or instability by considering the slack generator as the reference generator and calculating the phase angle difference of all other generators with respect to the reference generator. If the phase angle differences do not increase indefinitely, the system is stable; If not, the system loses its stability [1].

IV. Simulation And Results

The case study in this paper is WSCC 3-machine, 9-bus system, shown in Figure 2, which is a multi-machine mesh structure. The network includes 3 machines, 9 buses, 6 lines, 3 transformers, 3 loads and 12 O/C relays. The data of generator, transmission lines and transformers can be obtained from [12]. One synchronous-type DG is added to the network through a transformer. Regarding load demands and the network topology, the location of DG is determined. In this paper the DG is assumed to be connected at bus 5. The data of DG is given in TABLE 1.

A. O/C Relays Coordination Without Consideration of the Network t_c

1) **Before Installation of DG:**

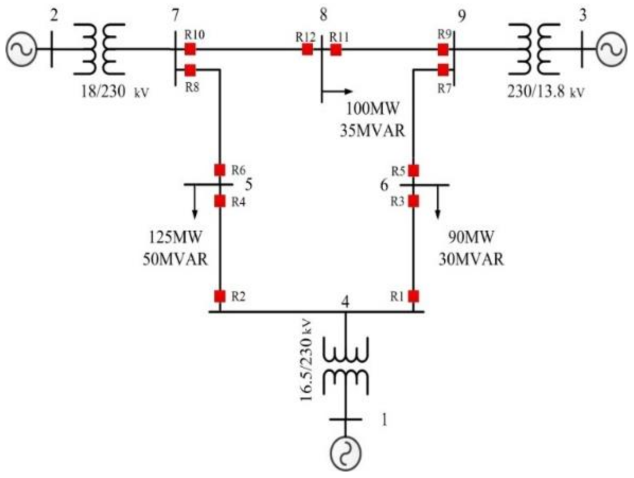

Figure 2: WSCC 3-machine, 9-bus system

TABLE 1: DATA OF DG

Parameter	*X_d (p.u)*	*H (sec)*	*V (kV)*	*S (MVA)*
value	0.7614	2	13.8	30

In the first step, while DG is not in the network, O/C relays have to be coordinated. Genetic Algorithm (GA) was used in several papers to create this coordination between O/C relays [13], [14]. For this purpose, the method presented in [14] is used. As a summary of this method, it defines an objective function used in GA as (6).

$$OF = \alpha_1 \sum t_i^2 + \alpha_2 \sum (\Delta t_{mb} - \beta_1 (\Delta t_{mb} - |\Delta t_{mb}|))^2 ,$$

$$\Delta t_{mb} = t_b - t_m - CTI \tag{6}$$

The first part of (6) is the summation of operation times of O/C relays, when occurring faults at front of each relay, and the second part represents the coordination constraints. α_1, α_2 and β_1 are weighting factors and Δt_{mb} is the discrimination between each backup and main (B/M) relays. Critical time interval (CTI) is chosen regarding the relay over-travel time, the operation time of the breaker, and the safety boundary for relay error which is considered to be 0.2 s in this paper. After each iteration, the new TSMs are set to the GA. After reaching the number of assumed generation, the process is ended.

The operation time of chosen relays in this paper are according to (7) derived from IEC-UIT-10PU.

$$t_d(I) = \frac{K}{(\frac{I}{I_S})^{\alpha} - 1} \times \frac{T}{\beta} \tag{7}$$

Where I_s is the current set point, I is the amount of current flowing through the relay, T is the time setting of relay which can be considered as the time setting multiplier (TSM), and K, α and β are coefficient values which are equal to 315.2, 2.5, 1, respectively. The consequent TSMs of all O/C relays can be seen in TABLE 2.

TABLE 2: TSMs AND OPERATION TIMES OF ALL RELAYS IN ABSENCE OF DG AND SFCL

Relay no.	*TSM*	*Operation time (s)*	*Relay no.*	*TSM*	*Operation time (s)*
1	0.73	0.0591	7	0.18	0.0252
2	0.83	0.0767	8	0.10	0.0232
3	0.89	0.3037	9	0.57	0.0951
4	0.19	0.2090	10	0.20	0.0796
5	0.22	0.1574	11	0.53	0.0839
6	0.10	0.1381	12	0.10	0.2275

2) After Installation of DG:

As it was said previously, with installation of DGs, there might exist some miscoordinations in the network that can be removed with installation of SFCL.

As it can be seen in TABLE 3, after installation of DGs in the network, there appear six miscoordinations among relays in which the miscoordination between relays 1 and 4, as well as relays 7 and 11 are the worst cases since the backup relays operate before main relays. For solving this problem, SFCL is connected in series with DG. As an essential step, the appropriate size of SFCL should be determined that is done in this paper by using the method presented in [8]. First, an amount of SFCL is considered, then the fault calculation is done. This process is repeated until the discrimination between relays 1 and 4, as well as relays 7 and 11 meet, at least, 0.2 s, and also all other discriminations are more than 0.2 s. By using this method, the minimum size of SFCL is attained as 5 pu.

B. O/C Relays Coordination with Consideration of Network t_c

As it was previously mentioned, utilization of resistive SFCL has some influences on the stability of the power system, and consequently, changes network t_c. In this section, it is considered that a fault occurs in front of each relay, and resistive SFCL is appeared in the network as the faulted line's resistive impedance, and the initial load flow is solved by using Newton-Raphson Method. Afterward, all the possible t_cs of the network are calculated by using the method described earlier. The MATLAB function is employed to solve all the 2m first-order differential equations obtained from transient stability analysis. All these obtained t_cs are shown in TABLE 4. In TABLE 5, it is shown that the size of determined SFCL without consideration of the network t_cs is not suitable since the operation times of some relays are not in appropriate intervals. It means that, regarding occurring fault in these locations, relays operate in a time more than corresponding t_c. This delay in removal the fault would cause instability in the network. In order not to occur such an event, the size of SFCL has to be determined again. As it was done before, the size of SFCL increases step by step, and all the operation times of relays and discriminations between B/M relays are calculated. This process is repeated until each operation time of relays becomes less than the corresponding t_c, and also all the discriminations between B/M relays become more than 0.2 s. As it is obvious in Figure 3, the minimum size of SFCL which

TABLE 3: DISCRIMINATION OF B/M RELAYS WITHOUT CONSIDERATION OF THE NETWORK T_C

Main relay no.	*Backup relay no.*	*Discrimination (s) without SFCL*	*Discrimination (s) with SFCL*
1	4	0.1787	0.9483
3	7	0.3741	1.6211
2	3	0.9042	0.9706
4	8	1.3138	0.2812
3	7	1.0044	1.0694
1	4	-0.2015	0.2294
4	8	1.3514	1.0839
2	3	0.5714	0.4782
5	1	0.5206	0.6670
7	11	-0.1343	0.5931
6	2	0.9879	0.7681
8	12	0.6513	0.6077
7	11	0.6594	0.7784
5	1	0.4401	0.5680
8	12	0.6467	0.7230
6	2	3.0974	0.2636
9	5	0.3023	0.4287
11	10	0.1804	0.2200
10	6	0.0297	0.2236
12	9	0.4282	0.4739
11	10	0.4558	0.5374
9	5	0.3881	0.9054
12	9	0.9513	1.0224
10	6	0.1035	0.9119

TABLE 4: CRITICAL CLEARING TIME (t_c) OF THE NETWORK WITH AND WITHOUT DG AND SFCL

Faulted relay no.	*Removed line*	*t_c (s) without DG*	*t_c (s) with DG*	*t_c (s) with DG and SFCL*
1	4-6	0.3280	0.2990	0.2950
2	4-5	0.3190	0.2920	0.2890
3	6-4	0.4240	0.4040	0.3960
4	5-4	0.3420	0.3190	0.3100
5	6-9	0.4710	0.4640	0.4530
6	5-7	0.4110	0.4040	0.3930
7	9-6	0.1720	0.1560	0.1520
8	7-5	0.1830	0.1710	0.1690
9	9-8	0.2760	0.2660	0.2630
10	7-8	0.3050	0.2920	0.2900
11	8-9	0.2410	0.2290	0.2290
12	8-7	0.2200	0.2060	0.2040

satisfies both these two constraints is 8.33 pu.

As it can be also seen in TABLE 5, utilization a new SFCL causes all the new operation times of relays to be less than corresponding t_c of each relay which means regarding occurring faults in front of all relays, relays operate in intervals less than their own corresponding t_cs. For investigation of the accuracy of utilization of the new SFCL in the network, all discriminations between B/M relays in presence of the new SFCL are calculated again, and as TABLE 6 shows, all of them are more than 0.2 s, the assumed amount for CTI in this paper.

V. Conclusion

This paper studied the impact of the network critical clearing time (t_c) on the determination of the size of resistive superconducting fault current limiters (SFCL). In the first part of the study, the WSCC 3-machine, 9-bus system was simulated using MATLAB simulation, and all the fault currents were obtained. Then, all the overcurrent (O/C) relays were coordinated. After the introduction of distributed generation (DG) to the network, in order to eliminate the created defects in coordination of relays, resistive SFCL was used, and like all the previously-done works, its optimal size without consideration of the network t_c was determined. In the second part of the study, in front of each relay, a fault occurring at t=0.08 s was considered, and by using a MATLB code the network t_c was calculated. The result showed that with consideration of network t_c, the old-determined size of SFCL was no longer efficient, and it had to be determined again.

TABLE 5: DISCRIMINATION OF B/M RELAYS WITH NEW SFCL

Main relay no.	*Backup relay no.*	*Discrimination (s) with new SFCL*	*Main relay no.*	*Backup relay no.*	*Discrimination (s) with new SFCL*
1	4	0.9835	7	11	0.7820
3	7	1.6263	5	1	0.5709
2	3	0.9734	8	12	0.7243
4	8	0.2597	6	2	0.2398
3	7	1.0718	9	5	0.4318
1	4	0.2666	11	10	0.2212
4	8	1.0773	10	6	0.2274
2	3	0.4786	12	9	0.4747
5	1	0.6704	11	10	0.5404
7	11	0.6176	9	5	0.9142
6	2	0.7648	12	9	1.0241
8	12	0.6074	10	6	0.9223

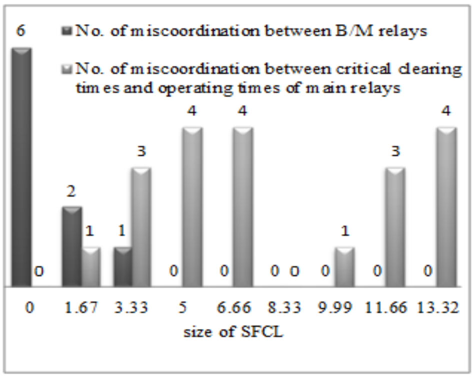

Figure 3: Number of miscoordination vs. size of SFCL

TABLE 6: DISCRIMINATIONS BETWEEN t_c AND OPERATING TIMES OF MAIN RELAYS REGARDING OLD AND NEW SIZES OF SFCL

Relay no.	Network t_c with old SFCL	Network t_c with new SFCL	Operating time with considering old size of SFCL	Operating time with considering new size of SFCL	Discrimination between network t_c and old operating time	Discrimination between network t_c and new operating time
1	0.2950	0.3000	0.1570	0.1579	0.1380	0.1421
2	0.2890	0.2930	0.2904	0.2903	-0.0014	0.0027
3	0.3960	0.4050	0.3161	0.3167	0.0799	0.0883
4	0.3090	0.3200	0.1933	0.1995	0.1157	0.1205
5	0.4530	0.4650	0.2815	0.2829	0.1715	0.1821
6	0.3920	0.4050	0.2042	0.2068	0.1878	0.1982
7	0.1520	0.1560	0.0692	0.0693	0.0828	0.0867
8	0.1690	0.1710	0.1696	0.1697	-0.0006	0.0013
9	0.2630	0.2670	0.2530	0.2534	0.0100	0.0136
10	0.2900	0.2930	0.2202	0.2212	0.0698	0.0718
11	0.2290	0.2310	0.2297	0.2310	-0.0007	0.0000
12	0.2040	0.2070	0.2062	0.2066	-0.0022	0.0004

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