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Phase to Ground Fault Analysis of a High Voltage Transmission Line Equipped with Resistive and Inductive SFCL

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Abstract. Advanced technologies in power electronics have always been a prominent factor in the development of new devices in power systems. Superconducting Fault Current Limiter (SFCL) can be regarded as a key component for future electric power systems. It is capable of eliminating the hazards during faults by increasing the short-circuit power of the network. SFCL devices can be either resistive (R-SFCL) or inductive (I-SFCL). They show negligible resistance or reactance, respectively, under normal operating conditions and they reliably switch to a high impedance state in the case of a high current. This paper studies the use of R-SFCL and I-SFCL by investigating their impacts on the short-circuit calculations of a high voltage line. The case study is for a 220 kV transmission line in the northern transmission network of Algeria which is subjected to a phase to ground fault in the presence of a fixed fault resistance. The impact of SFCL impedance (Z_{SFCL}) of R-SFCL and I-SFCL on short-circuit parameters (symmetrical current components, transmission line currents, voltage symmetrical components, and transmission line voltages) is presented using a developed MATLAB program. Analysis and comparison of the obtained simulation results lead to the conclusion that using R-SFCL offers a better system performance than I-SFCL for the system under study.

Keywords: Power systems, Superconducting fault current limiter, Short-circuit calculations, Symmetrical components, Ground fault.

Analiza napak faza ozemljitev pri visokonapetostnih daljnovodih v prisotnosti uporovnih in induktivnih SFCL

Superprevodni tokovni omejevalnik (SFCL) je lahko ključen gradnik pri bodočih elektroenergetskih sistemih, saj omogoča izločitev rizičnih dejavnikov pri kratkostičnih tokovih. SFCL je lahko ali uporovni (R-SFCL) ali induktivni (I-SFCL). Ti gradniki izkazujejo zanemarljivo upornost in induktivnost pri pravilnem delovanju in visoko impedanco v primeru kratkostičnega toka. V prispevku analiziramo uporabo R-SFCL in I-SFCL ter njun vpliv na izračun kratkostičnih tokov na visokonapetostnih vodih. Izvedli smo študijo na primeru 220 kV napetostnega voda v Alžiriji. Vpliv impedance SFCL na parametre kratkostičnega toka je predstavljen s pomočjo računalniškega programa MATLAB. Na podlagi dobljenih rezultatov ugotavljamo, da za analizirano visokonapetostno omrežje R-SFCL zagotavlja boljšo uporabnost kot I-SFCL.

1 INTRODUCTION

Short-circuit analysis has always been a vital research topic that has been frequently addressed by researchers in the power engineering field. Nowadays, short-circuit calculations are being investigated particularly in the presence of rapidly growing loads and highly complicated networks which are frequently subjected to various types of faults. As an electrical power system continues to expand in size, generation capacity and transmission network expansion may be restricted by the fault current limit which can affect the reliability of the power system adversely [1]. Nowadays, options available for utility companies to reduce fault currents in a power grid are not only few but they also have some significant drawbacks. For example, using high impedance transformers and earthing reactors will compromise the efficiency and increase the cost. Splitting existing networks to reduce fault currents has an adverse effect on the grid stability and efficiency [2].

The Superconducting Fault Current Limiter (SFCL) has been used in power systems in order to reduce fault currents. A decreased fault current results mainly in the need for a change in the settings of overcurrent relays, coordination and nuisance trip.

SFCL is basically a variable impedance that is installed in series with a circuit breaker. In the case of a fault, the impedance rises to a value at which the fault current is correspondingly reduced to a lower level that the circuit breaker can cope with [3, 4]. SFCL can offer cost-effective means to limit the high level fault currents to lower levels which allow circuit breakers contact to

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open quickly and safely [5]. In [6], effects of different types of SFCL on the successful interruption of circuit breakers are investigated using the Transient Recovery Voltage (TRV), where the simulation results showed that the TRV can be damped in the presence of the resistive and bridge type SFCL during fault clearing period.

An existing medium voltage network in the United Kingdom is considered in [7]. It incorporates a distributed generation capacity and the performance of overcurrent and distance protection schemes in the presence of SFCL. In [8], based on the structure and theory of voltage compensation in SFCL, the effect of the SFCL on the current relay is studied in details, and a solution was proposed and applied to 10 kV isolated neutral distribution network system. In [9], dynamic characteristics of hybrid SFCL are studied for short-circuit test considering a simple coordination of relays in distribution networks. A study on correction of protective devices settings in a power distribution system with a Distributed Generation (DG) using SFCL is represented in [10]. Another study on the coordination of protection relays between primary feeder and interconnecting transformer grounded by SFCL in wind farms is presented in [11]. In [12], the application of multiple resistive solid state SFCL for fast fault detection in highly interconnected distribution systems, based on current division discrimination, is proposed as a potential cost-efficient candidate to minimize the effect of exposing DG to the distribution system. A genetic based algorithm is employed to obtain SFCLs optimum number, location and size [13].

In this paper, the effect of using resistive and inductive SFCL devices on short-circuit calculations is studied and compared by varying the device impedance (Z_{SFCL}). A practical case study is considered for a 220 kV transmission line which connects two 220/60 kV substations in Algeria, namely Batna and Biskra. The line is subjected to a phase to ground fault while maintaining a fixed fault resistance. System modeling and simulations obtained from the developed program are presented. Finally, the results are compared to demonstrate the difference between using R-SFCL and I-SFCL devices on system performance under short-circuit states.

2 MODELING OF SFCL

There are several types of SFCLs but they fall into two basic categories of either resistive or inductive. The simplest superconducting limiter concept in both categories exploits the nonlinear impedance of superconductors (Z_{SFCL}) in a direct way. A superconductor is inserted in the circuit. Many models or SFCL device have been developed as resistor, reactor, and transformer type, etc.

In this paper, the model used for resistive and inductive SFCL is based on [14, 15]. This represents the experimental side for the superconducting elements of SFCL as well as the quench and recovery characteristics. Impedance of SFCL as a function of time t is given by:

$$Z_{SFCL}(t)=\begin{cases}0 & (t<t_0)\\ Z_n\left[1-e^{\left(-\frac{t-t_0}{T_F}\right)}\right]^{1/2} & (t_0\le t<t_1)\\ a_1(t-t_1)+b_1 & (t_0\le t<t_2)\\ a_2(t-t_2)+b_2 & (t\ge t_2)\end{cases}\qquad(1)$$

Z_n and T_F are the convergence impedance being saturated at normal temperature and the time constant respectively. t_0, t_1 and t_2 denote the starting time of the quench, starting time of the first recovery, and starting time of the second recovery, respectively. a_1, a_2, b_1 and b_2 are the coefficients of the first-order linear function used for representing the experimentally obtained recovery characteristics of SFCL [16].

3 PHASE TO GROUND FAULT CALCULATIONS IN THE PRESENCE OF SFCL DEVICES

Figure 1 shows the equivalent circuit of a transmission line of impedance Z_L that connects between bus-bars A and B in the case of a phase to ground fault occurring at phase (A). The fault location is denoted by n_F which takes the value of zero if the fault occurs at bus-bar A and 100% if it occurs at bus-bar B.

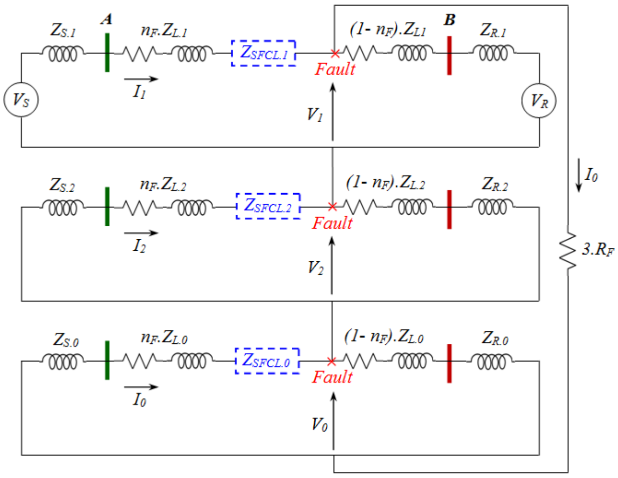


Figure 1. Phase to ground fault equivalent circuit with SFCL.

As shown in the figure, the line is equipped with either R-SFCL or I-SFCL of impedance Z_{SFCL} which is connected in series with the line impedance. A fault resistance (R_F) is also used as shown in the equivalent circuit diagram while the internal impedance of the generator Z_s is ignored due to its small magnitude.

While having the SFCL device installed, the new impedance of the transmission line (Z_{L-SFCL}) becomes:

$$Z_{L-SFCL} = Z_L + Z_{SFCL} \tag{2}$$

where;

$$Z_{SFCL} = \begin{cases} R_{SFCL} \text{ for resistive SFCL (R-SFCL)} \\ jX_{SFCL} \text{for inductive SFCL (I-SFCL)} \end{cases} \tag{3}$$

Basic equations for this type of fault at phase *A* are given by, [16-21]:

$$I_B = I_C = 0 \tag{4}$$

$$V_A = V_0 + V_1 + V_2 = R_F.I_A \tag{5}$$

The symmetrical components of line currents are given by [16, 21]:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \tag{6}$$

From equations (4) and (6), the current symmetrical components take the following form:

$$I_0 = I_1 = I_2 = \frac{I_A}{3} \tag{7}$$

The voltage symmetrical components are given by [16, 21]:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \tag{8}$$

From equation (5), the direct voltage component is given by:

$$V_1 = R_F.I_A - V_0 - V_2 \tag{9}$$

The impedances symmetrical components are given by [16, 21]:

$$\begin{bmatrix} Z_0 \\ Z_1 \\ Z_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} Z_A \\ Z_B \\ Z_C \end{bmatrix} \tag{10}$$

Therefore, the symmetrical components of the transmission line impedance Z_L and the apparent impedance of the SFCL device Z_{SFCL} are defined according to equation (10) as follows:

$$Z_L = Z_{L.0} + Z_{L.1} + Z_{L.2} \tag{11}$$

$$Z_{SFCL} = Z_{SFCL.0} + Z_{SFCL.1} + Z_{SFCL.2} \tag{12}$$

From Figure 1, V_1 , V_0 and V_2 take the following form:

$$V_1 = V_s - \left(n_F.Z_{L.1} + Z_{SFCL.1}\right).I_1 \tag{13}$$

$$V_2 = -\left(n_F.Z_{L.2} + Z_{SFCL.2}\right).I_2 \tag{14}$$

$$V_0 = -\left(n_F.Z_{L.0} + Z_{SFCL.0}\right).I_0 \tag{15}$$

Substituting by the above equations (13), (14) and (15) in equation (9) using equation (7) yields:

$$V_s = \frac{I_A}{3}\left(n_F.Z_L + Z_{SFCL} + 3.R_F\right) \tag{16}$$

From equation (16), the current of phase (*A*) in the presence of a SFCL device is given by:

$$I_A = \frac{3.V_S}{\left(n_F.Z_L + Z_{SFCL} + 3.R_F\right)} \tag{17}$$

From equations (7) and (17), the current symmetrical components in the presence of a SFCL device take the following form:

$$I_0 = I_1 = I_2 = \frac{I_A}{3} = \frac{V_S}{\left(n_F.Z_L + Z_{SFCL} + 3.R_F\right)} \tag{18}$$

Substituting by I_1 from equation (18) into equation (13) while using equations (11) and (12), the direct voltage component takes the following form:

$$V_1 = \frac{V_S.\left[n_F.(Z_{L.0} + Z_{L.2}) + (Z_{SFCL.0} + Z_{SFCL.2}) + 3.R_F\right]}{\left(n_F.Z_L + Z_{SFCL} + 3.R_F\right)} \tag{19}$$

Similarly, using equations (14) and (18), the inverse voltage component becomes:

$$V_2 = -\frac{V_S.\left[n_F.Z_{L.2} + Z_{SFCL.2}\right]}{\left(n_F.Z_L + Z_{SFCL} + 3.R_F\right)} \tag{20}$$

Using equations (15) and (18), the zero component of the voltage becomes:

$$V_0 = -\frac{V_S.\left[n_F.Z_{L.0} + Z_{SFCL.0}\right]}{\left(n_F.Z_L + Z_{SFCL} + 3.R_F\right)} \tag{21}$$

In order to obtain the phase voltages at the fault point in the presence of SFCL device and fault resistance, the following equation is used [16, 21]:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \tag{22}$$

Substituting equations (19), (20) and (21) into equation (22) yields:

$$V_A = \frac{3.R_F.V_S}{\left(n_F.Z_L + Z_{SFCL} + 3.R_F\right)} \tag{23}$$

$$V_B = \frac{V_S.\left[\left(a^2 - a\right)Z_2' + \left(a^2 - 1\right)Z_0' + 3.a^2.R_F\right)\right]}{\left(n_F.Z_L + Z_{SFCL} + 3.R_F\right)} \tag{24}$$

$$V_C = \frac{V_S.\left[\left(a - a^2\right)Z_2' + \left(a - 1\right)Z_0' + 3.a.R_F\right)\right]}{\left(n_F.Z_L + Z_{SFCL} + 3.R_F\right)} \tag{25}$$

Coefficients Z_2' and Z_0' are defined as:

$$Z_2' = n_F Z_{L.2} + Z_{SFCL.2} \tag{26}$$

$$Z_0' = n_F Z_{L.0} + Z_{SFCL.0} \tag{27}$$

This analysis shows that short-circuit calculations in this case are mainly related to the impedance of used SFCL (Z_{SFCL}), fault location (n_{F}) and fault resistance (R_{F}). Below, the effect of changing Z_{SFCL} on short-circuit parameters is studied in the case of using either R-SFCL or I-SFCL, while both fault location and fault resistance are maintained at constant values.

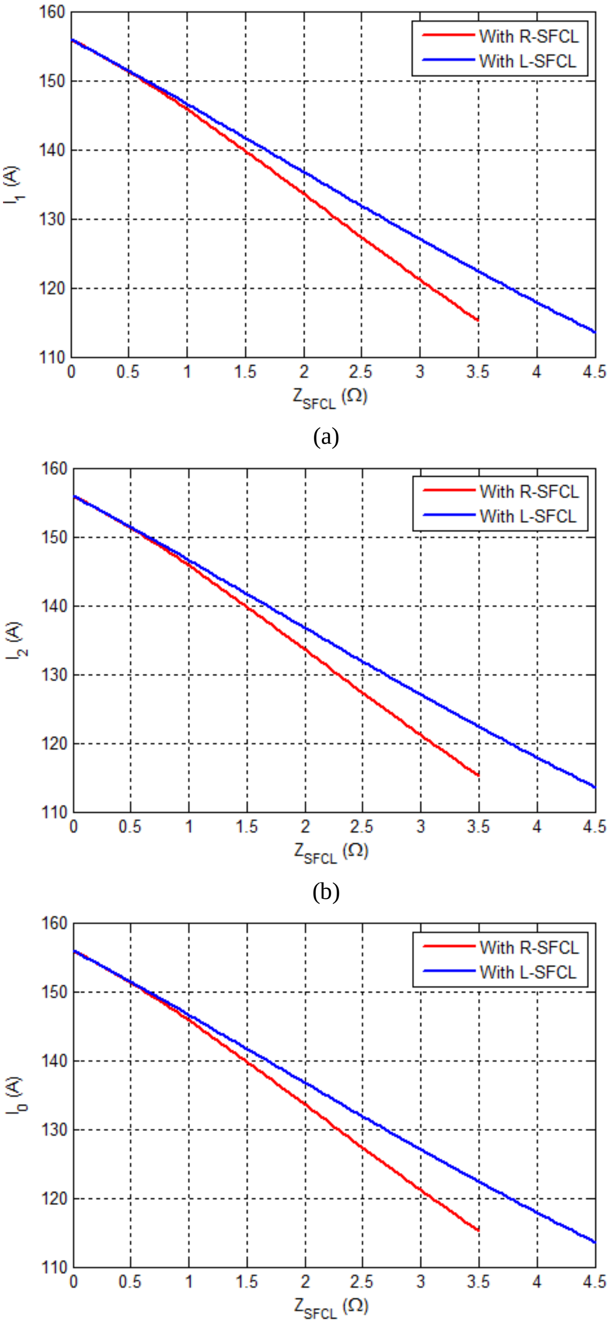
4 CASE STUDY AND SIMULATION RESULTS

In this paper, the selected case study is for a 220 kV transmission line in the Algerian transmission network, Sonelgaz group [22]. The line connects bus-bar *A* at Batna and bus-bar B at Biskra. The relay measuring the fault current is located at Batna to protect the line. The system is modeled using MATLAB where obtained simulation results are presented and discussed.

Transmission line parameters are given as follows: length = 113 km, frequency = 50 Hz, direct and inverse sequence impedances $Z_{L.1} = Z_{L.2} = 0.121 + j\,0.421$ Ω/km and zero sequence impedance $Z_{L.0} = 0.361 + j\,1.263$ Ω/km. The ranges of R-SFCL and I-SFCL impedances are given by 0 - 3.5 Ω and 0 - 4.5 Ω, respectively. These ranges are determined based on practical considerations related to the understanding of the system operation.

For the given results, the fault location is assumed to occur at bus-bar *B* (n_F = 100 %) in the presence of a fixed fault resistance R_F which takes the value of 30 Ω.

Figures 2.a, b, c represent the variations in the current symmetrical components, I_1, I_2 and I_0, as a function of Z_{SFCL} while using either R-SFCL or I-SFCL. It is noticed that the three symmetrical current components are equal for each case, according to equation (7). It is also noticed that increasing Z_{SFCL} leads to a decrease in the current components which is expected whenever using SFCL devices. When comparing the magnitudes of the two cases, it is clear that the magnitudes of the current symmetrical components in the case of using R-SFCL are less than those obtained when using I-SFCL.

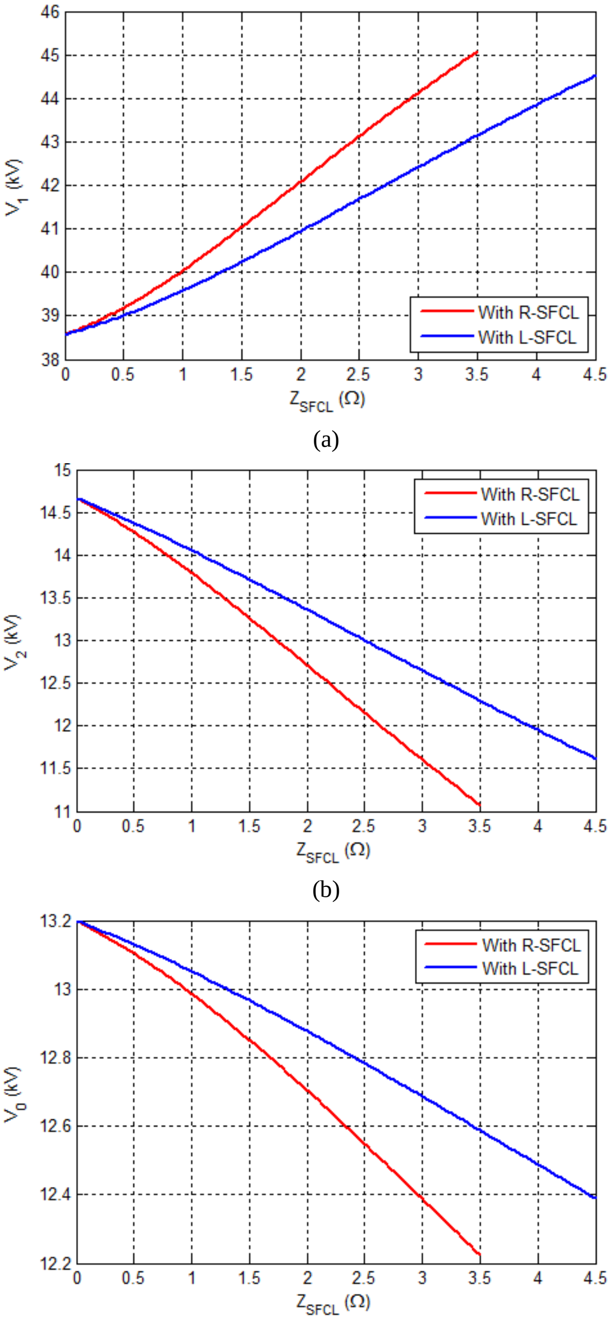


(a)

(b)

(c)

Figure 2. Impact of Z_{SFCL} on current symmetrical components: (a). $I_1 = f\,(Z_{SFCL})$, (b). $I_2 = f\,(Z_{SFCL})$, (c). $I_0 = f\,(Z_{SFCL})$.



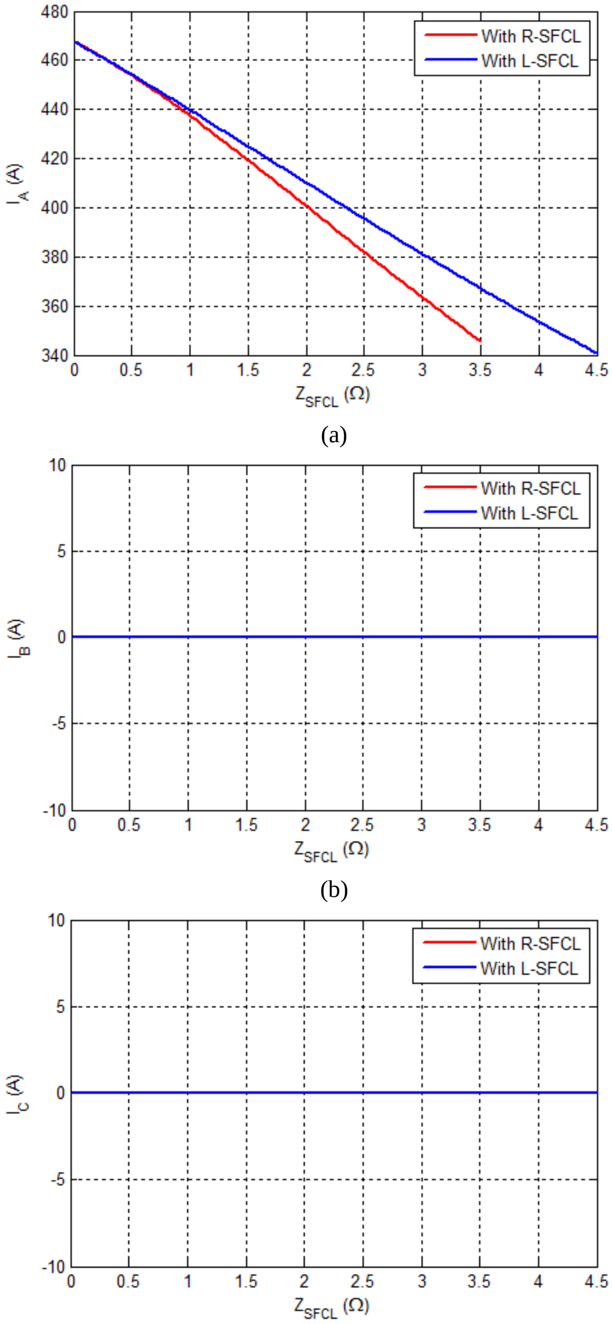
(a)

(b)

(c)

Figure 3. Impact of Z_{SFCL} on voltage symmetrical components: (a). $V_1 = f(Z_{SFCL})$, (b). $V_2 = f(Z_{SFCL})$, (c). $V_0 = f(Z_{SFCL})$.

Figures 3.a, b, c represent the variations in the voltage symmetrical components, V_1, V_2 and V_0, as a function of Z_{SFCL} for both cases. Increasing Z_{SFCL} leads to an increase in the direct voltage component and a decrease in the inverse and zero voltage components for both cases, as in equations (19), (20) and (21). This reflects an improvement in the system performance when using SFCL. Results obtained for the voltage symmetrical components when using R-SFCL are shown to be better than those obtained when using I-SFCL. This is represented in the larger voltage magnitudes exhibited by the direct sequence component and the smaller voltage magnitudes exhibited by both the indirect and zero sequence components in the case of using R-SFCL and when compared with their corresponding values when using I-SFCL, for the same Z_{SFCL}.



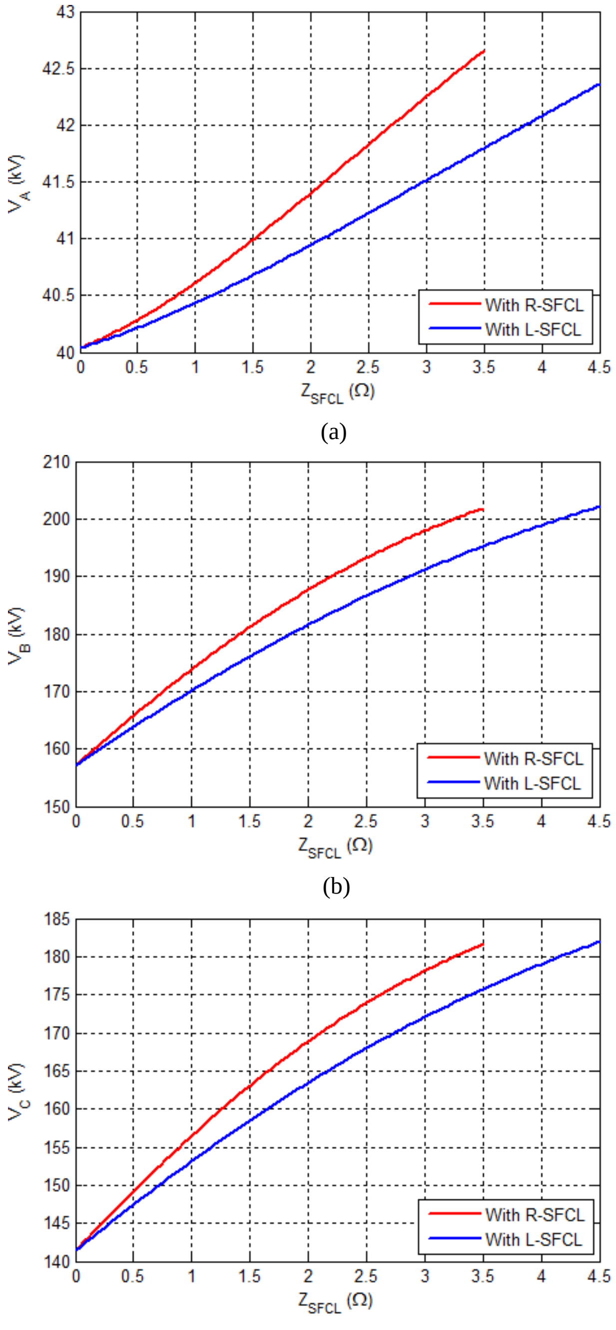
(a)

(b)

(c)

Figure 4. Impact of Z_{SFCL} on transmission line currents: (a). $I_A = f(Z_{SFCL})$, (b). $I_B = f(Z_{SFCL})$, (c). $I_C = f(Z_{SFCL})$.

Figures 4.a, b, c represent the variations in the line currents, I_A, I_B and I_C, as a function of Z_{SFCL} for both cases. The line currents of phases B and C are always zero since the phase to ground fault occurs at phase A, as in equation (4). While using R-SFCL or I-SFCL, the increase of Z_{SFCL} leads to a reduced magnitude of the line current of the faulty phase (A) which is an advantage gained from using SFCL devices. Comparing the magnitudes of the fault current in both cases, it is shown that less magnitude is exhibited when using R-SFCL than that obtained when using I-SFCL for the same Z_{SFCL}, particularly for significant values of Z_{SFCL}. This means that R-SFCL leads to a reduced magnitude of fault current.



(a)

(b)

(c)

Figure 5. Impact of Z_{SFCL} on transmission line voltages: (a). $V_A = f\,(Z_{SFCL})$, (b). $V_B = f\,(Z_{SFCL})$, (c) $V_C = f\,(Z_{SFCL})$.

Figures 5.a, b, c represent the variations in the voltages, V_A, V_B and V_C, as a function of Z_{SFCL} for both cases. It is clear that the increase in Z_{SFCL} leads to an increase in the system phase voltages under fault conditions. R-SFCL shows better performance than I-SFCL which is represented in the exhibited higher magnitudes of the system three phase voltages under short-circuit.

5 CONCLUSIONS

This research work investigates the effect of using two Superconducting Fault Current Limiters (SFCL), one resistive and the other inductive (R-SFCL and I-SFCL), on short-circuit calculations of a 220 kV transmission line operating in the Algerian power network in the case of a phase to ground fault and a fixed fault resistance.

The presented theoretical analysis shows that the short-circuit calculations for this type of fault are directly related to the magnitude of the impedance of the used SFCLs device, whose effect was explored in this research work, as well as to the fault location and fault resistance which are both maintained at fixed values in this paper.

The simulations results obtained by using the developed MATLAB program, highlight the advantages of using both SFCL devices presenting from their reducing the fault current and increasing the system phase voltages under fault conditions while increasing the impedance of the device.

Furthermore, it was concluded that R-SFCL offers a better system performance under fault than I-SFCL for the considered case. Increasing the impedance of R-SFCL was met by a less magnitude of the fault current and higher magnitudes of the system phase voltages than those noticed when using I-SFCL for the same device impedance. This can be mainly attributed to the direct effect of using pure resistance in controlling the magnitude of the fault current.

Further research studies are currently conducted towards determining an optimal location of SFCL devices using suitable optimization algorithms in meshed and radial power systems.

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