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Analysis of the Short-Circuit Capacity of Power Systems Considering Changes in Network Topology

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ABSTRACT: This paper presents an analysis of the short-circuit capacity (SCC) of power systems when changes in the network topology are performed. The value of the nodal short-circuit capacity depends on the Thevenin equivalent impedance as seen from each substation of the system, which is directly related to the topology of the network, since any change in the topology causes a change in the Thevenin impedance, therefore, the SCC is a function of the topology of the power system. In many studies, reactive compensation of lines is analyzed using different methodologies to increase their transmission capacity, but most of these studies do not analyze the effect of line compensation on the SCC of the system. For this reason, in the present work, series reactive compensation is performed in transmission lines to change the network topology and analyze how such changes affect the Thevenin equivalent impedance and, consequently, the SCC value. To perform the analysis, a computational algorithm based on systematic fault analysis is implemented, which uses the bus impedance matrix to obtain the Thevenin impedance as seen from each substation of the power system. The results of this work are obtained through several numerical examples, which are carried out to determine whether changes in the network topology are detrimental or beneficial to the value of the SCC. The results show that with changes in the network topology there is a considerable change in the Thevenin equivalent impedance and short circuit capacity, so that when series reactive compensation is carried out the Thevenin impedance decreases and the SCC increases. According to the results obtained, it is concluded that, with the series compensation of transmission lines, the SCC of the power system substations increases, especially in the substations close to the compensated line, which requires a resizing of both the primary equipment and the infrastructure of the electrical substations of the system.

KEYWORDS: Short Circuit Capacity (SCC), Network topology, Series Compensation, Thevenin Impedance.

I. INTRODUCTION

Around the world, electric power supply companies must ensure the operation of power systems, taking into account aspects such as safety, economy, and environmental impact. Of these aspects, safety is a fundamental characteristic in the reliable operation of power systems, since the network must be able to continue operating under fault conditions and with minimal or no loss of load [1, 2].

To guarantee the safe operation of power systems under the occurrence of a fault, electric power supply companies increase the installed generation and transmission capacity; however, this does not guarantee one hundred percent the safe operation of the system and, in addition, it is very costly. For this reason, it is necessary to carry out a detailed evaluation of the safety of the system to adequately manage possible failures, their consequences, and remedial actions [2, 3, 4].

The proper handling of faults in the network consists of isolating them, in an adequate and fast way, the area where the fault occurred from the rest of the power system, to avoid unnecessary tripping of the protection devices. For this purpose, a short-circuit study and a coordination study are required to provide an electrical protection scheme that guarantees the safety and reliability of the power system [5]. In short-circuit studies, several parameters are determined, such as short-circuit current at the fault point, fault current in transmission lines, nodal voltage magnitude during the fault, and short-circuit capacity [6, 7].

The analysis of the short-circuit capacity and the pre-fault studies are necessary to select the circuit-breakers, protection relays, and trip times, as well as to dimension the size and electrical robustness of the primary equipment of the power substations [5, 6]. The SCC undergoes considerable changes when there are changes in the network topology; among these changes, the following can be mentioned: increase in the capacity and type of generation, increase in energy

demand, and changes in the transmission network infrastructure [8]. Changes in the transmission network infrastructure are mainly due to the construction of new lines, installation of flexible transmission devices, or increase in the transmission capacity of the lines. In power systems it is common to carry out series reactive compensation of lines to increase their transmission capacity, avoiding the costly investment that represents the construction of new lines, however, when this type of compensation is carried out there are very few papers in the open literature where the effect that such compensation has on the capacity and short circuit level is reported, which directly affects the safety and reliability of the power system [9].

The series compensation of transmission lines causes changes in the network topology and consequently causes variations in the short-circuit capacity and fault level of the system so that the protection scheme and electrical robustness of the primary equipment of power substations could be incapable and obsolete to protect the power system [10]. For this reason and in the aforementioned context, in this work an analysis of the short-circuit capacity considering the changes in the topology of the network is carried out, this to have information that allows resizing the circuit breakers and primary equipment of the power substations, which guarantee the safe and reliable operation of the power system.

The paper is organized as follows: Section II describes the electric model of transmission lines, the concepts of short-circuit capacity are described in Section III. Section IV presents the study cases where the SCC is determined considering the changes in the network topology. Finally, the conclusions of this paper are presented in Section V.

II. TRANSMISSION LINE MODELING AND REACTIVE COMPENSATION

The transmission lines are represented by the equivalent model π shown in Fig. 1, where the terms I_j and E_j are the current and voltage phasors at the j nodes ($j=k,m$), respectively. R and L are the series resistance and inductance of the line, and B_C is the parallel susceptance [11].

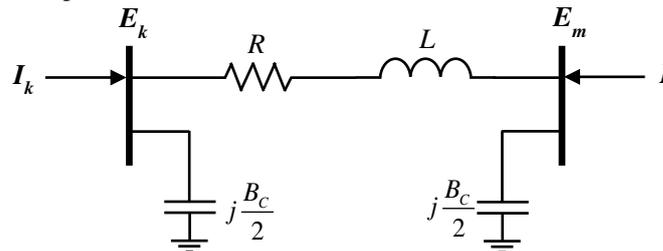


Fig. 1. Equivalent model π of the transmission line.

The active power flow in transmission lines depends on the voltages and mostly on the phase angles at the nodes where they are connected. The equation of the active power flow through the transmission line is,

$$P_{km} = \frac{|V_k||V_m|}{|X_{km}|} \sin(\delta_{km}) \tag{1}$$

According to the above equation, the active power flow in a transmission line can be controlled by varying its series reactance, which is known as series reactive compensation. If X_{km} increases the power flow P_{km} decreases and vice versa. In the past, banks of capacitors were used in series to vary the reactance X_{km} and increase the active power transmission capacity of the lines, but nowadays, the most common way to compensate in series is using devices based on power electronics, also known as FACTS devices. A scheme of the reactive series compensation using FACTS devices is shown in Fig. 2.

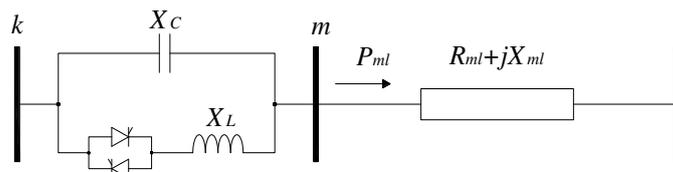


Fig. 2. Compensated transmission line by TCSC.

In this figure, the FACTS device used to compensate the transmission line is the Thyristor Controlled Series Compensator (TCSC), which is one of the most common active power flow control devices that allow fast and continuous compensation of line impedance [12, 13, 14, 15, 16].

III. BUS IMPEDANCE MATRIX AND SHORT-CIRCUIT CAPACITY

The topology of the power system depends on how generators, transformers, loads, and transmission lines are connected; and it can be represented by the bus impedance matrix [6]. This impedance matrix, given by Equation (2), is a square matrix of size $n \times n$, which represents the network topology and is formed by the equivalent impedance of the power system [6, 7].

$$Z_{bus} = \begin{bmatrix} Z_{11} & \dots & Z_{1k} & \dots & Z_{1n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ Z_{k1} & \dots & Z_{kk} & \dots & Z_{kn} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ Z_{n1} & \dots & Z_{nk} & \dots & Z_{nn} \end{bmatrix} \quad (2)$$

In this matrix, the diagonal contains the Thevenin impedance as seen from each substation of the power system and is used to calculate the short-circuit level and the SCC. The subscripts k and n represent, respectively, the node at which the fault occurs and the number of buses or electrical substations in the power system.

The system topology changes mainly due to changes in the transmission lines, which in turn causes variations in the SCC. The short-circuit capacity at a bus is a common measure of its electrical robustness and it is defined as the product of the magnitudes of the rated voltage and the fault current. The short-circuit capacity is used to determine the size of a bus bar and the interrupting capacity of the circuit breakers. The SCC is also known as short-circuit MVA and at a bus k of the power system it can be determined as [6, 17],

$$CCC = \sqrt{3} V_{Lk} I_{Fk} \times 10^{-3} \text{ MVA} \quad (3)$$

Where the line-to-line voltage V_{Lk} is expressed in kV and the symmetrical fault current I_{Fk} is expressed in Amps. The symmetrical fault current in per unit is calculated as follows,

$$I_{Fk, pu} = \frac{V_k}{X_{kk}} \quad (4)$$

In Equation (4), V_k is the pre-fault bus voltage and X_{kk} is the Thevenin reactance in per unit as seen from the bus where the fault occurs.

The system resistance is neglected and only the inductive reactance of the system is considered, which provides a lower impedance in the system and a maximum fault current which helps to increase the safety of the system. The base current is given by,

$$I_B = \frac{S_B \times 10^3}{\sqrt{3} V_B} \quad (5)$$

Where S_B and V_B are base MVA and line-to-line base voltage in kV, respectively. In this way, the fault current in Amps is,

$$I_{Fk} = I_{Fk, pu} I_B = \frac{V_k}{X_{kk}} \frac{S_B \times 10^3}{\sqrt{3} V_B} \quad (6)$$

Substituting (6) in (3) and considering that the base voltage is equal to the nominal voltage $V_B = V_{Lk}$, then the expression for the short-circuit capacity is,

$$SCC = \frac{V_k S_B}{X_{kk}} \quad (7)$$

The pre-fault bus voltage is usually assumed to be 1 pu, therefore Equation (7) is rewritten as,

$$SCC = \frac{S_B}{X_{kk}} \text{ MVA} \quad (8)$$

Equation (7) is the approximate equation commonly used to determine the short-circuit capacity at a node k of the power system. It should be mentioned that S_B is considered to be 100 MVA and X_{kk} is the value of the Thevenin reactance of the bus impedance matrix at position $Z_{bus}(k,k)$, i.e., $X_{kk} = X_{bus}(k,k)$.

The fault current on a bus k of the power system, I_{FK} , and the fault current flowing in the transmission lines, $I_{F,ij}$, are given by (9) and (10), respectively, as follows.

$$I_{Fk} = \frac{V_k}{Z_F + Z_{kk}} \quad (9)$$



$$I_{F,ij} = \frac{V_{F,i} - V_{F,j}}{Z_{ij}} \tag{10}$$

Where Z_F is the fault impedance and Z_{ij} represents the series impedance of the line. The terms $V_{F,i}$ and $V_{F,j}$ are the voltage magnitude on the sending and receiving side of the transmission line, respectively. According to this equation, it is possible to observe that changes in the network topology also affect the fault current in the buses and lines of the power system, since there are changes in the Thevenin equivalent impedance and the bus voltage during the fault.

IV. NUMERICAL EXAMPLES

In this section, several study cases with the 9-node test power system are presented [18]. To carry out these study cases, the imaginary part of the bus impedance matrix is extracted to obtain what the authors call the bus reactance matrix. This matrix is determined before and after the compensation of the transmission lines to visualize the changes in the network topology, and consequently the variations in the short-circuit capacity.

The 9-node power system consists of 6 transmission lines, 3 transformers, and 3 generators. To visualize the effect of changes in the network topology, the line connected between nodes 6-9 is selected for reactive compensation since this transmission line is strategic for system security because it supplies power to the largest load. In the study cases, the transmission line 6-9 is first compensated in series with capacitor banks and later with reactor banks. The reactance of the transmission line 6-9 without compensation is to be $X_{6,9}=0.17$ pu, when the compensation of capacitor banks is carried out the series reactance of the line decreases to $X_{6,9}=0.017$ pu, while when the line is compensated with reactors in series the reactance increases to $X_{6,9}=0.27$ pu.

Table 1 shows a comparison of the short-circuit capacity when the reactive compensation mentioned above is performed, while the SCC profile obtained with such compensation is shown in Fig.3.

Table 1. Comparison of SCC results with changes in network topology.

Short-circuit capacity in MVA			
Node	$X_{6,9}=0.17$ pu	$X_{6,9}=0.017$ pu	$X_{6,9}=0.27$ pu
1	783.26	834.16	765.76
2	590.12	590.57	589.96
3	797.7	843.66	781.75
4	726.68	802	701.99
5	587.35	604.7	581.1
6	595.14	785.19	545.67
7	648.16	648.87	647.9
8	619.97	630.59	616.09
9	747.31	817.02	724.17

Both in the table and the figure, it is possible to observe that when the transmission line is compensated with capacitor banks in series, there is an increase in the short-circuit capacity in all substations of the system, especially in the substations that are electrically closer to the compensated line. This is because with capacitor banks there is a reduction of the effective reactance of the line, which results in a decrease of the values of the diagonal of the bus reactance matrix (Thevenin's equivalent reactance), and consequently an increase in the SCC of the system.

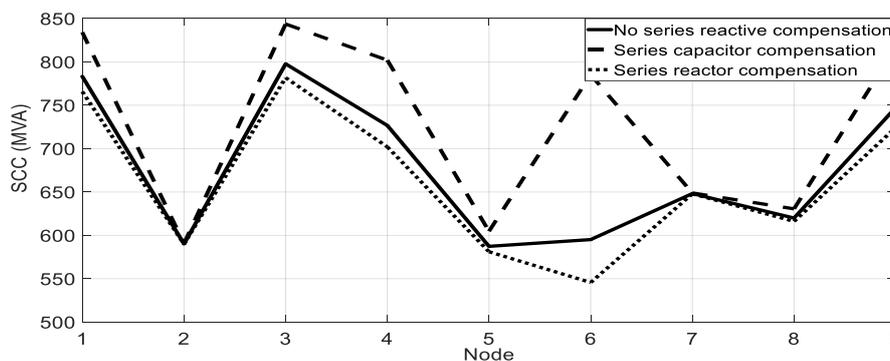


Fig. 3. SCC profile with changes in the network topology.



On the other hand, when the transmission line compensation is carried out with series reactors, a decrease in SCC occurs due to the increase in the effective reactance of the transmission line, which causes an increase in Thevenin equivalent reactance in each substation of the system.

Changes in the network topology also cause changes in some parameters that are important for the safety of the power system, such as fault current or short-circuit level, fault voltages, and fault currents in the transmission lines. Table 2 shows the fault current at each bus of the power system throughout a fault impedance $Z_f=0.16j$ pu. The results of the fault current presented in this table correspond, both for the case without series compensation and for the cases with series reactive compensation cases.

Table 2. Fault current with changes in the network topology.

Node	Fault current (pu)
1	-3.4413j
2	-3.0349j
3	-3.4732j
4	-3.3063j
5	-3.0114j
6	-2.9132j
7	-3.1812j
8	-3.1026j
9	-3.3547j

Regarding the voltages and currents flowing in the transmission lines during the fault, Fig.4 shows that the fault current in the lines increases when compensation is performed with series capacitors, while the opposite occurs with series reactors.

Fig. 5 shows the bus voltage profile of the system during the fault. In this figure, it is possible to observe that when series compensation is performed with capacitors and reactors the voltage decreases and increases, respectively. This is mainly due to the increase or decrease of the voltage drops in the transmission lines, which are caused by the variation of the current flow through the lines during the fault.

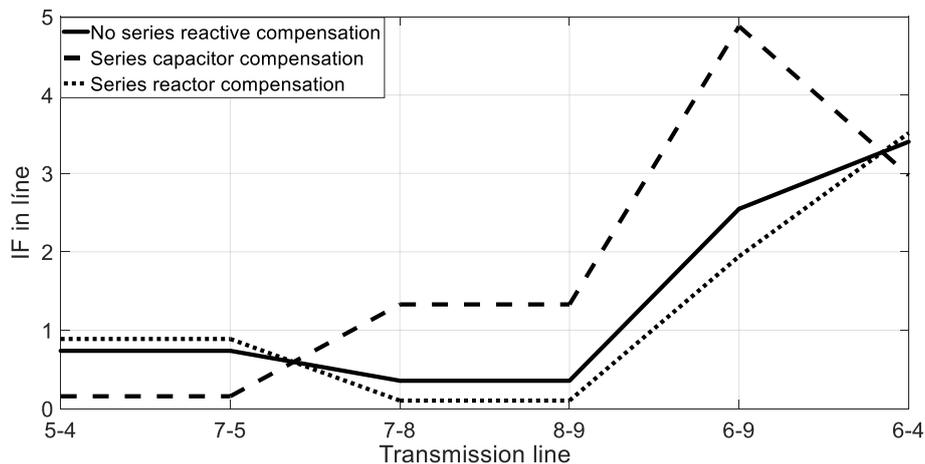


Fig. 4. Fault current in transmission lines with changes in network topology.

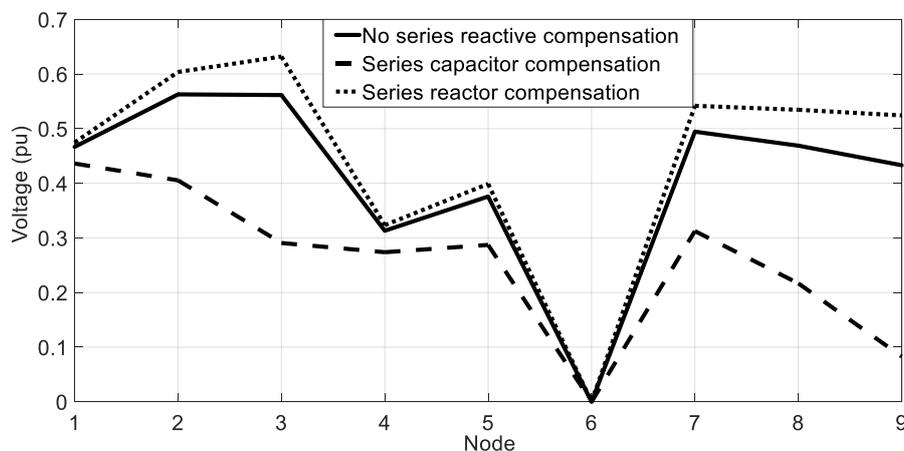


Fig. 5. Bus voltage profiles during the fault with changes in network topology.

It should be mentioned that the utilities carry out the compensation with series capacitors is performed to increase the transmission capacity of the line, however, in this work compensation with reactors is performed only to visualize its effect on the value of the short-circuit capacity in the power system. It should also be mentioned that the value of the capacitor and reactor banks, used in the line compensation, was chosen in such a way that it only decreased or increased the series reactance of the transmission line, so it was not calculated to obtain a specific value of the reactance $X_{6,9}$.

V. CONCLUSION

An analysis of the short-circuit capability (SCC) of power systems considering changes in the network topology has been presented. Several case studies using a test power system were carried out to visualize the impact of changes in the network topology on the SCC. The results obtained from the study cases show that the series compensation of transmission lines the SCC of the power system substations increases, especially in substations close to the compensated line. With the increase of the short circuit capacity in all the substations of the system, a resizing of the primary equipment of each substation is required, as well as a reconfiguration and conditioning of the infrastructure of the electrical substations of the system, this to guarantee the safety and reliability of the power system. In addition, changes in network topology also lead to important changes in parameters such as fault current in power lines and substations, as well as variations in the bus voltages during the fault. Series compensation with capacitors causes increases in fault currents and decreases in bus voltage profile during the fault, while compensation with reactors causes the opposite effect.

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