Impact of Voltage Controlled by TCVR on Ground Fault Parameters

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Abstract* - The control of voltage and reactive power is a major issue in power systems control and operation. Because of the topological differences between distribution and transmission systems, different strategies have evolved. Flexible AC Transmission Systems (FACTS) controllers, such as the Thyristor Controlled Voltage Regulator (TCVR), employ the latest technology of power electronic switching devices in electric power transmission systems to control voltage and improve voltage regulation. This paper presents an impact study of using TCVR on the fault current calculations in case of a ground fault. The case study is a high voltage transmission line in the Algerian power network. The analysis is based on symmetrical components method which includes symmetrical components of current and voltage as well as the transmission line currents and line voltages, without and with TCVR in the presence of fault resistance. In this research work, the obtained simulation results match the presented theoretical analysis.

***Index Terms* - Power Systems, Voltage Control, Flexible AC Transmission Systems (FACTS), Thyristor Controlled Voltage Regulator (TCVR), Ground Fault, Pre-Fault Conditions.**

I. INTRODUCTION

In power systems, fault current calculations are made at the system design stage to determine the short-circuit ratings of new switchgear and substation infrastructure equipment to be procured and installed. System reinforcements may be triggered by network expansion and/or the connection of a new generating plant to the power system. Routine calculations are also made to check the continued adequacy of existing equipment as system operating configurations are modified [1]. Fault current calculation approach is formulations which are normally used to analyse faults in power systems that estimate the during-fault system state. These approaches and algorithms can be used to provide the settings and coordination of protection relays. In addition, calculations of minimum fault currents are made and these are used in the calculation of protection relay settings to ensure accurate and coordinated relay operations. In transmission systems, fault currents must be quickly cleared to avoid loss of synchronism of generation plant and major power system blackouts. Maximum fault current calculations are carried out for the design of substation earth electrode systems.

Considered fault calculations due to multiple faults at different locations in power systems, as in [2], presented a canonical model for the study of faults in power systems in [3], presented a method to calculating the effects of mutual coupling in multi faults and the incorporation of the zero sequence mutual coupling effects among multi parallel routes in [4], investigated the calculation of simultaneous faults on power systems in [5], presented a systematic short circuit analysis method for unbalanced distribution systems based on exact three phase models and two relationship matrices of distribution systems in [6], described a generic approach to the analysis of faulted power systems in three phase coordinates in [7], investigated the influence of mutual coupling between parallel transmission lines on single line-to ground and double line-to-ground faults in [8], presented detailed analysis of the apparent impedance as seen from the relaying point due to faults on parallel transmission lines in [9], new calculation method of the ground fault current distribution along non-uniform multi-section line and cable in [10], presented a piecewise solution procedure for fault studies using large change sensitivity concept in [11], and proposed a systematic approach to applying the three terminal Thevenin's equivalent circuit to three terminal elements in [12].

Under steady-state conditions, high loading and low voltage can be a limiting factor. The proper corrective action is to supply reactive power so as to correct the load power factor and to compensate for the reactive losses in lines and transformers. Traditionally, mechanically switched shunt capacitors and reactors were used for voltage control. In fact, heavy use of these devices is responsible, at least in part, for some voltage control problems today. FACTS devices are a family of high-speed electronic devices, which can significantly increase the power system performance by delivering or absorbing real and/or reactive power as in [13]. There are many types of FACTS controllers available in power systems.

This paper deals with the impact of the voltage controlled by the FACTS device denoted by Thyristor Controlled Voltage Regulator (TCVR), given by V_{TCVR}, on ground fault parameters; mainly in the presence of phase (A) to ground fault at the end of a high voltage transmission line compensated by a TCVR at its midpoint. The case study is for a 400 kV transmission line in the Algerian power network. The line connects two 400/200 kV substations, namely Salah Bey (Sétif) and Bir Ghbalou (Bouira) in Algeria. This research study investigates the impact of voltage controlled by TCVR on ground fault parameters, which are symmetrical current components (I_1, I_2 and I_0), transmission line currents (I_A, I_B and I_C), voltage symmetrical components (V_1, V_2 and V_0), and transmission line voltages (V_A, V_B and V_C) in the presence of fault resistance.

II. Voltage Controlled by the Thyristor Controlled Voltage Regulator

In dynamic stability studies, the rapid speed of FACTS offers several benefits to systems' operation and control. In particular, they are capable of increasing the synchronizing torque, damping oscillations at various frequencies below the rated frequency, supporting dynamic voltage or controlling power flows.

Moreover, FACTS devices may have benefits in case of fault, by limiting the fault current [14]. Another advantage of FACTS devices is considered in the ability of this technology to extend the current transmission line limits in a step-by-step manner with incremental investment when required. Furthermore, it offers the possibility to move an installation when it becomes not useful anymore. Different types of devices have been developed and there are various ways to classify them in terms of the technology of the used semiconductor, the possible benefits of the controllers, and the type of compensation. Figure 1 shows the active power flow equation between two buses 1 and 2 and the variables that can be modified by each FACTS device [15].

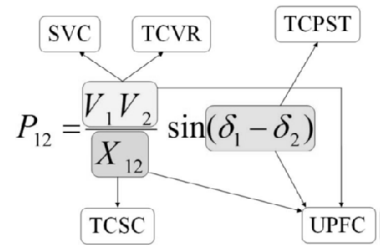


Fig. 1. Impacts of FACTS devices on active power equation.

Where, V_1 and V_2 are the voltage magnitudes at bus-bars 1 and 2, X_{12} is the reactance of the line and (δ_1 - $\delta_2 = \delta$) is the difference angle between V_1 and V_2 phasors. TCVR operates by inserting an in-phase voltage to the main bus voltage to change its magnitude.

To model TCVR, an ideal tap changer transformer can be used without series impedance as shown in Figure 2. The value of the turns ratio is given by the ratio of the additional transformation relative to the nominal transformation and its values range from 0.9 to 1.1, where 1.0 corresponds to no additional transformation [14].

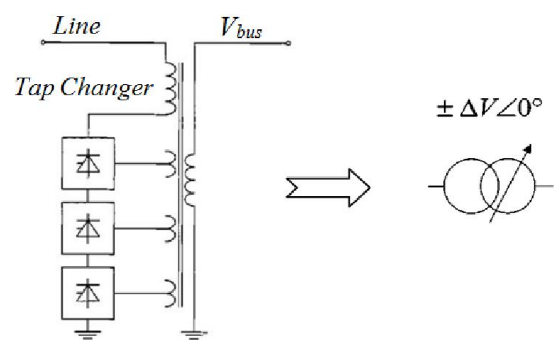


Fig. 2. Model of TCVR.

Therefore, TCVR can be modeled as an ideal tap changer transformer without series impedance [14, 16]. The TCVR coefficient K_{TCVR} has the following ranges, presented as equations:

$$V_{TCVR} = K_{TCVR} . V_{bus} \quad (1)$$

$$-0.15 \leq K_{TCVR} \leq +0.15 \quad (2)$$

$$-0.15 \times V_{bus} \leq V_{TCVR} \leq +0.15 \times V_{bus} \quad (3)$$

III. Ground Fault Calculations in The Presence of TCVR

Figure 3 shows the equivalent circuit of a transmission line compensated by TCVR in case of a phase to ground fault (F) with a fault resistance R_F and fault location n_F at bus-bar B.

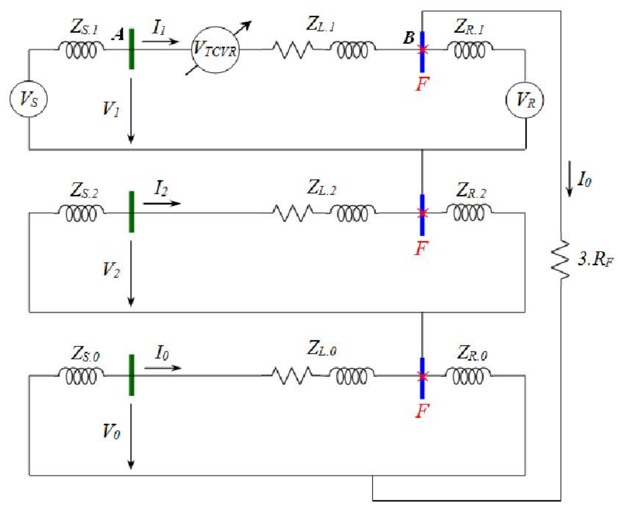


Fig. 3. Ground fault equivalent circuit with TCVR.

The basic equations for this type of fault [16-19] are:

$$I_B = I_C = 0 \quad (4)$$

$$V_A = V_1 + V_2 + V_0 = R_F \times I_A \neq 0 \quad (5)$$

The symmetrical components of currents are [1, 19]:

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

From equation (4) and matrix (6), the symmetrical components of the currents take the following form:

$$I_1 = I_2 = I_0 = \frac{I_A}{3} \quad (7)$$

The symmetrical components of the voltages are:

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

From equation (5) and the matrix in equation (8), the direct voltage component becomes:

$$V_1 = -\left(V_0 + V_2\right) + \left(R_F \times I_A\right) \quad (9)$$

Hence,

$$V_s \pm V_{TCVR} - M_1 = -\frac{1}{3}\left(-M_0\right) - \frac{1}{3}\left(-M_2\right) + \left(R_F \times I_A\right) \quad (10)$$

Where,

$$\begin{cases} M_1 = Z_{L.1} \times I_1 \\ M_0 = Z_{L.0} \times I_0 \\ M_2 = Z_{L.2} \times I_2 \end{cases} \quad (11)$$

$$\Rightarrow V_s \pm V_{TCVR} = \frac{I_A}{3}\left(Z_{L.1} + Z_{L.2} + Z_{L.0}\right) + \left(R_F \times I_A\right) \quad (12)$$

From equations (12), the current at phase (A) in the presence of a TCVR device on transmission line is given by:

$$I_A = \frac{3 \times \left(V_S \pm V_{TCVR}\right)}{Z_{L.1} + Z_{L.2} + Z_{L.0} + \left(3 \times R_F\right)} \quad (13)$$

From equations (7) and (13), the symmetrical components of the currents in the presence of a TCVR are:

$$I_1 = I_2 = I_0 = \frac{V_S \pm V_{TCVR}}{Z_{L.1} + Z_{L.2} + Z_{L.0} + \left(3 \times R_F\right)} \quad (14)$$

The direct component of the voltage is defined by:

$$V_1 = V_S \pm V_{TCVR} - M_1 \quad (15)$$

$$V_1 = \frac{\left(V_S \pm V_{TCVR}\right) \times \left[Z_{L.2} + Z_{L.0} - \left(2 \times Z_{L.1}\right) + \left(3 \times R_F\right)\right]}{Z_{L.1} + Z_{L.2} + Z_{L.0} + \left(3 \times R_F\right)} \quad (16)$$

The inverse component of voltage is defined by:

$$V_2 = -M_2 \quad (17)$$

$$\Rightarrow V_2 = -\frac{\left(V_S \pm V_{TCVR}\right) \times Z_{L.2}}{Z_{L.1} + Z_{L.2} + Z_{.L0} + \left(3 \times R_F\right)} \quad (18)$$

The zero component of the voltage is:

$$V_0 = -M_0 - \left(R_F \times I_0\right) \quad (19)$$

$$\Rightarrow V_0 = -\frac{\left(V_S \pm V_{TCVR}\right) \times \left(Z_{L.0} + R_F\right)}{Z_{L.1} + Z_{L.2} + Z_{L.0} + \left(3 \times R_F\right)} \quad (20)$$

The coefficients are defined as:

$$A_a = a^2 - a \quad (21)$$

$$A_b = a^2 - 1 \quad (22)$$

$$A_c = 3 \times a^2 - 1 \quad (23)$$

$$A_d = a - a^2 \quad (24)$$

$$A_e = a - 1 \quad (25)$$

$$A_f = 3 \times a - 1 \quad (26)$$

From equations (16), (18), (20) and matrix (8), the three phase voltages of the line in presence of TCVR are:

$$V_A = \frac{3 \times R_F \times \left(V_S \pm V_{TCVR}\right)}{Z_{L.1} + Z_{L.2} + Z_{L.0} + \left(3 \times R_F\right)} \quad (27)$$

$$V_B = \frac{(V_S \pm V_{TCVR}).[A_a \times Z_{L.2} + A_b \times Z_{L.0} + A_c \times R_F]}{Z_{L.1} + Z_{L.2} + Z_{L.0} + (3 \times R_F)} \quad (28)$$

$$V_C = \frac{(V_S \pm V_{TCVR}) \times [A_d \times Z_{L.2} + A_e \times Z_{L.0} + A_f \times R_F]}{Z_{L.1} + Z_{L.2} + Z_{L.0} + (3 \times R_F)} \quad (29)$$

Hence, fault calculations are only related to the TCVR parameters: voltage controlled V_{TCVR} and operation mode.

IV. Case Study and Simulation Results

The case study of this research work is the 400 kV line in the north part of the Algerian power network as shown in Figure 4 [20]. The TCVR is installed in the mid of this transmission line that connects bus-bar *A* at Salah Bey (Sétif) substation with bus-bar *B* at Bir Ghbalou (Bouira) substation. The TCVR data and transmission line parameters are given in the Appendix. The impact of the voltage controlled by V_{TCVR} on the ground fault parameters is studied in the presence of a fixed fault resistance of 20 Ω in case of a single phase to ground fault of phase A at bus-bar *B*.

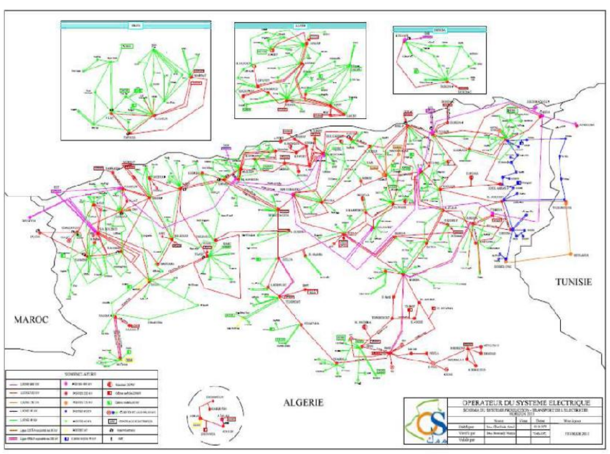


Fig. 4. Algerian power transmission network.

Figure 5 shows the impact of the voltage controlled by TCVR (positive and negative modes) on the active power P_L variation when the line angle δ varies from 0° to 180°. As shown in Figure 5, in the presence of TCVR at the mid of the transmission line, the active power P_L will be increased in case of having positive injected voltage by TCVR and it will be reduced in case of a negative TCVR injected voltage.

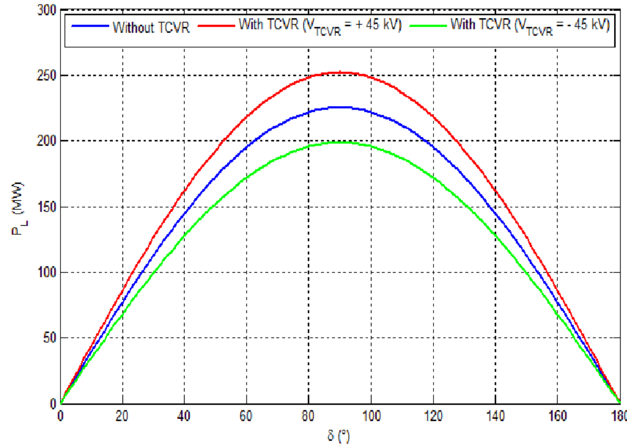
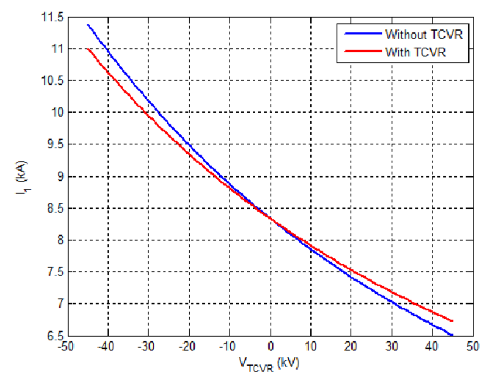
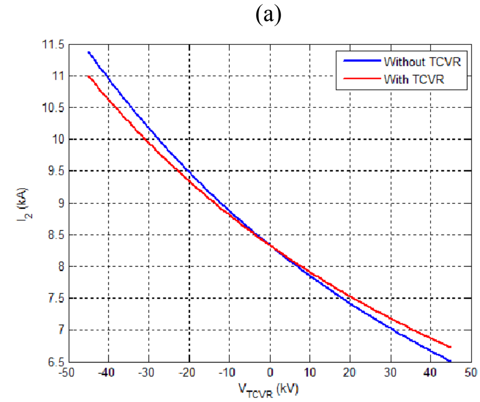


Fig. 5. Impact of V_{TCVR} on P_L.

Figures 6.a, b, c represent the variation of the current symmetrical components I_1, I_2 and I_0, respectively and Figures 7.a, b, c represent the variation of the line currents I_A, I_B and I_C, respectively as a function of the V_{TCVR} with/without using TCVR. Figures 8.a, b, c represent the variation of the voltage symmetrical components V_1, V_2 and V_0 respectively and Figures 9.a, b, c represent the variation of the line voltages V_A, V_B and V_C respectively as a function of the V_{TCVR} in case of using TCVR and without.



(a)



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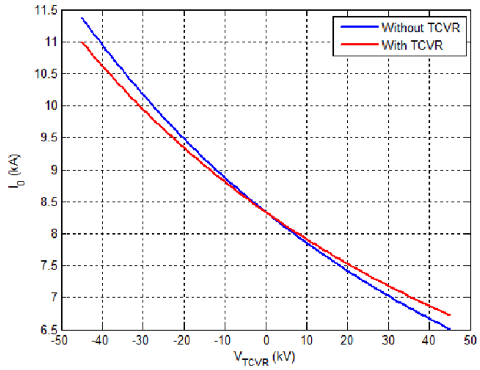
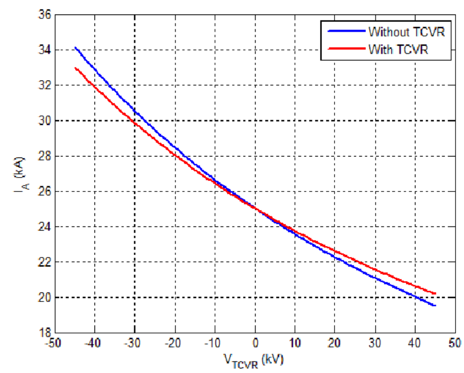
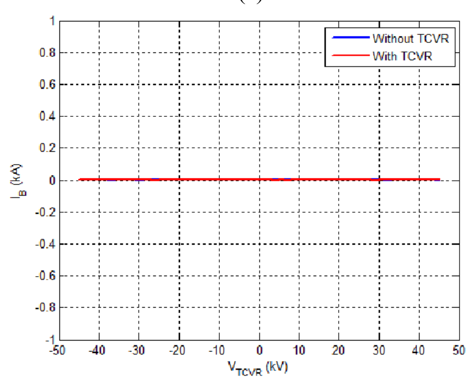


(c)

Fig. 6. Impact of V_{TCVR} on the transmission line currents: a). $I_A=f(V_{TCVR})$, b). $I_B=f(V_{TCVR})$, c). $I_C=f(V_{TCVR})$.



(a)



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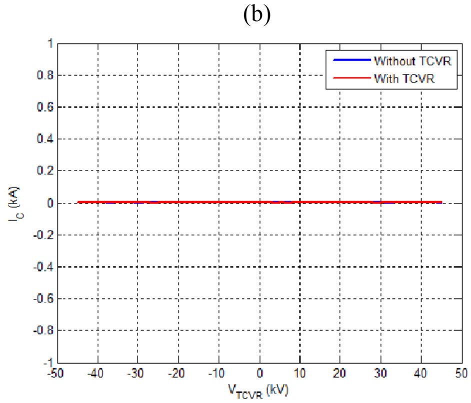
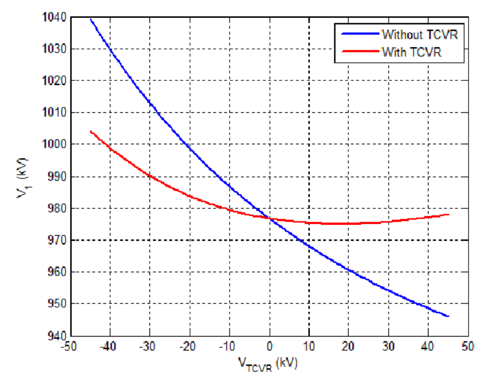


(c)

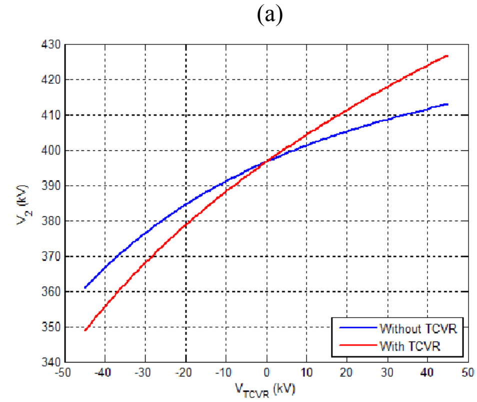
Fig. 7. Impact of V_{TCVR} on the transmission line currents: a). $I_A=f(V_{TCVR})$, b). $I_B=f(V_{TCVR})$, c). $I_C=f(V_{TCVR})$.

Figures 6.a, b, c, shows that the three symmetrical currents are equal, in case of using TCVR on transmission line or not, which matches equation (7). It is also clear that increasing the value of V_{TCVR} leads to decreasing the value of the three current symmetrical components. For example, in case of negative injected voltage, the value of each of the three current symmetrical components is higher in the absence of TCVR than its value in the presence of TCVR. In case of positive injected voltage, the value of each of the three current symmetrical components is higher in the presence of TCVR than its value without TCVR.

In Figures 7.a, b, c, it is noticeable that the line currents of phases B and C are always zero which is confirmed by equation (4). However, increasing the value of V_{TCVR} shows a reduction in the line current of the faulty phase (A), whether TCVR is present or not. In case of negative injected voltage, the value of the line current of the faulty phase (A) is higher in the absence of TCVR than its value in the presence of TCVR. In case of positive injected voltage, the value of I_A is higher in the presence of TCVR than its value without TCVR.



(a)



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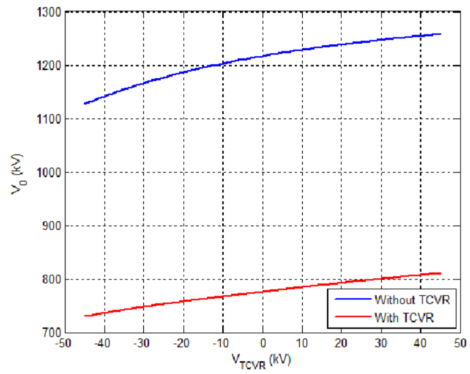
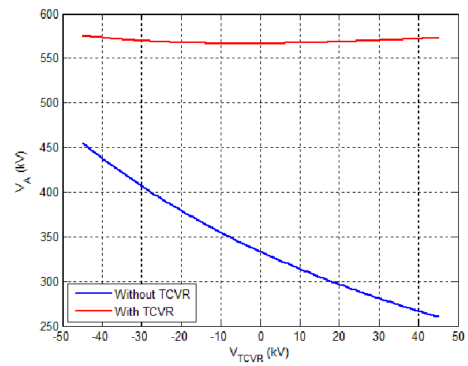
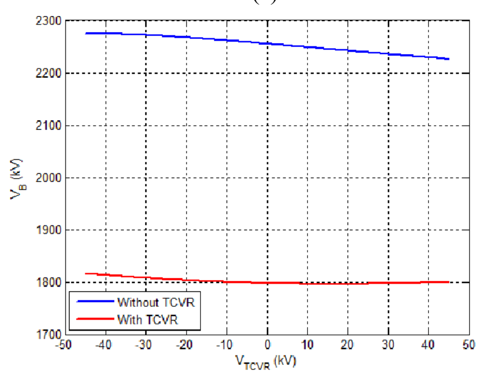


(c)

Fig. 8. Impact of V_{TCVR} on the voltage symmetrical components: a). $V_1=f(n_F)$, b). $V_2=f(V_{TCVR})$, c). $V_0=f(V_{TCVR})$.



(a)



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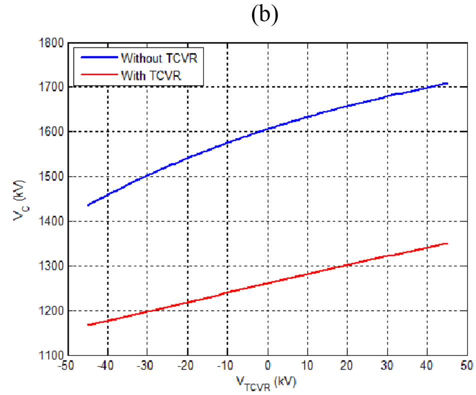

(c)

Fig. 9. Impact of V_{TCVR} on the transmission line voltages: a). $V_A=f(V_{TCVR})$, b). $V_B=f(V_{TCVR})$, c) $V_C=f(V_{TCVR})$.

In Figures 8.a, b, c in case of negative V_{TCVR}, the increase of V_{TCVR} value leads to a decrease in the value of the direct voltage symmetrical component and an increase in the value of the inverse voltage symmetrical component. This applies to both cases of whether using TCVR or not which is confirmed by equations (16), (18) and (20). In this case of negative voltage, it is also noticeable that the values of the direct and inverse voltage symmetrical components in the absence of TCVR are higher than their corresponding components while using TCVR. On the other hand, in the case of positive V_{TCVR}, the values of the direct and inverse voltage symmetrical components in the presence of TCVR are higher than their corresponding components exhibited while not using V_{TCVR}. Across the whole range of V_{TCVR}, the zero voltage component in the absence of TCVR exhibits a higher value than its corresponding value when using TCVR.

In Figures 9.a, b, c**,** it is obvious that the increase of V_{TCVR} value leads to a decrease in the value of the line voltages of phases *A* and *B*, compared with the voltage phase *C* which is increased with the increase of V_{TCVR} for the studied cases. Across the whole range of V_{TCVR}, the values of line voltages of phases *B* and *C* in the absence of TCVR are higher than their corresponding values while using TCVR where the opposite is exhibited for the line voltage of phase *A*.

V. CONCLUSION

This research work highlights the impact of using TCVR on the short-circuit parameters of a ground fault for a high voltage transmission line installed between two substations in the Algerian power system, in the presence of a fault resistance.

This research is focused on studying the impact of the voltage controlled by TCVR on the following parameters: symmetrical current components, transmission line currents, voltage symmetrical components, and transmission line voltages. Analytical results based on symmetrical components method are presented and verified by detailed simulations which show the great impact of the voltage controlled by TCVR on the value of the parameters in case of a ground fault which varied between minimum and maximum values as a function of the positive and negative operation modes of the installed V_{TCVR}.

For the continuity of this work, an off-line setting and coordination of relays considering various values of V_{TCVR} are proposed for meshed power systems using artificial neural network and heuristic methods. It is also suggested to develop an automation system based on the adaptive relay settings and according to the V_{TCVR} value using optimization algorithms. This system can be adopted for determining the optimum settings of protection device and hence improve the quality of its operation.

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APPENDIX

A. Transmission Line

$U_n = 400\ kV$, $f_n = 50\ Hz$, $l = 205\ km$,
$Z_1 = 0.0291 + j\ 0.3081\ \Omega/km$, $Z_0 = 0.0873 + j\ 0.9243\ \Omega/km$.

B. TCVR System

Type: series FACTS device,
$V_{min} = -45\ kV$, $V_{max} = +45\ kV$.