# Modeling the Effects of PWMSC and Fault Resistance on Ground Fault System in MV Distribution Line

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*Abstract:* A newly developed AC link converter based series compensation is a recent series Flexible Alternating Current Transmission System (FACTS) controller. The Pulse Width Modulated based Series Compensator (PWMSC) exploits the concept of the variable series reactance compensation which can modulate the impedance of a distribution line through applying a variation to the duty cycle ($D$) of a train of pulses with fixed frequency. This paper proposes a new approach for the calculation of short-circuit parameters in the presence of PWMSC. Using PWMSC results in an improvement of the system performance as it provides virtual compensation of distribution line impedance by injecting controllable apparent reactance in series with the distribution line. This work studies the impact of fault resistance ($R_F$) on the fault current calculations in case of a ground fault and a fixed fault location. The case study is for a medium voltage (MV) Algerian distribution line which is compensated by PWMSC in the 30 kV Algerian distribution power network. The analysis is based on symmetrical components method which involves the calculations of symmetrical components of currents and voltages, without and with PWMSC in both cases of maximum and minimum duty cycle value for capacitive and inductive modes. The paper presents theoretical analysis for the case study followed by simulation results which both reflect the improvement of system performance when PWMSC is deployed.

*Key-Words:* Pulse Width Modulated Series Compensator, Duty Cycle, Power System, Distribution Line, Short-Circuit Calculations, Ground Fault, Symmetrical Components Method.

## 1 Introduction

Due to the extremely fast control action associated with FACTS device operations, these devices, through the modulation of bus voltage, phase shift between buses, and transmission or distribution line reactance, can cause a substantial increase in power transfer limits during steady state [1]. Various types of conventional series-FACTS controller's first and second generations, particularly TCSC, TSSC, SSSC, STATCOM, SVC, IPFC and UPFC are now being used in power systems [2]. The conventional series-FACTS devices proposed in the literature can be classified in two major groups. The first group is usually implemented with line commutated thyristors, while the second is based on the force-commutated voltage source converters.

Recently, new FACTS controllers based on Pulse Width Modulated Series Compensator (PWMSC) with AC link convertors have been proposed [3]-[7] demonstrating that it is possible to attain similar control objectives in comparison with conventional FACTS devices. For many years, fixed and controlled series compensators have been used in transmission and distribution lines for compensating the line reactance in order to reduce line voltage drops, influence load flow in transmission and distribution lines, increase transfer capability, and increase voltage stability in power systems [8].

The presence of PWMSC has direct impact on power systems control and operation as it works to regulate the active power flow on the corresponding transmission line [7] and generates low harmonic distortion with the switching frequency of the controlled turn-off switches as low as 400 Hz [9]. A new approach for optimal placement of PWMSC in large power systems is proposed in [10] and a novel tuning strategy for robust PWMSC damping controller inter-area oscillations in power systems based on the Particle Swarm Optimization (PSO) algorithm is available in [11]. A novel current injection model of PWMSC as a means of continuous control of the degree of series compensation through variation of the duty cycle of a train of fixed frequency-pulses is proposed in [12], [13], and a design for an oscillation damping controller for PWMSC to damp low frequency oscillations for different damping controller input-output channels is presented in [14].

Calculation of fault currents is important for power systems design and protection systems. Faults can be symmetric or asymmetric. Symmetric faults can result in large fault currents. Asymmetric faults are more common and cause unbalanced fault currents [15]. In 2014, the 30 kV overhead distribution networks in the Algerian Company of distribution Power had more than 91.62 % of the occurred faults as single phase to ground faults, 5.75% of the faults were phase to phase faults, and 2.63% were three phase faults [16].

This paper deals with the impact of fault resistance ($R_F$) on ground fault parameters; mainly in the presence of phase (*A*) to ground fault at the end of a medium voltage (MV) distribution line compensated by PWMSC. The considered case study is for a 30 kV distribution line in the Algerian distribution network. The line is equipped with PWMSC with a minimum and maximum duty cycle, denoted by *D*, which ranges between 0 and 1.

The line connects two 60/30 kV substations, namely Constantine and Mila. Using the method of symmetrical components, this research study investigates the impact of $R_F$ that varies between 0 to 30 Ω on ground fault parameters. These parameters are symmetrical current components ($I_1$, $I_2$ and $I_0$), distribution line currents ($I_A$, $I_B$ and $I_C$), voltage symmetrical components ($V_1$, $V_2$ and $V_0$) and distribution line voltages ($V_A$, $V_B$ and $V_C$) which are compared in the absence and presence of PWMSC

## 2 Apparent Reactance Controlled by PWMSC

PWMSC offers a method of variable series compensation. It is known that distribution lines loading may be restricted by system dynamics stability. Therefore, PWMSC is a powerful new tool that helps to relieve these constraints.

Furthermore, its controller can be designed to modify the line reactance and provide enough damping to system oscillation modes [12]-[14]. Figure 1 displays a realization of a schematic diagram of PWMSC which it is embedded into a distribution line.

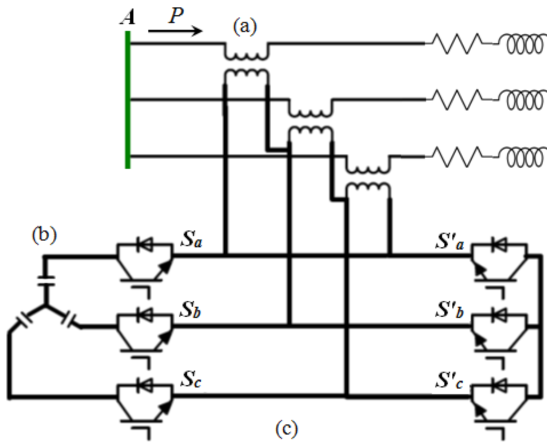



Fig. 1. Block diagram of PWMSC configuration [12-14].

As shown in the figure, PWMSC consists of (a) series injection transformers, (b) compensation capacitors, and (c) PWM controlled switches $S_a$, $S_b$, $S_c$, $S'_a$, $S'_b$ and $S'_c$. The three switches $S_a$, $S_b$, $S_c$ operate with the same switching function in a complementary way to $S'_a$, $S'_b$ and $S'_c$ switches [13-14].

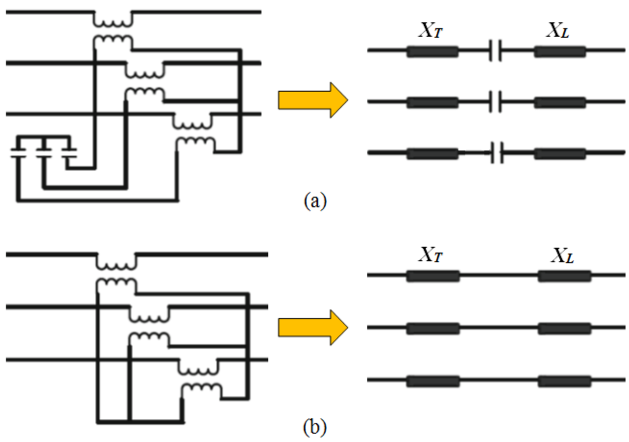



Fig. 2. Equivalent circuit of PWMSC.

The switching period divides the circuit into two switching states. When $S_a$, $S_b$ and $S_c$ are on, the capacitors are connected to the system through a series injection transformer which is represented in Figure 2.a. When $S'_a$, $S'_b$ and $S'_c$ are on, the series injection transformer is shorted and therefore isolating the capacitors from the line as shown in Figure 2.b.

In the illustrated structure, the bank of capacitors is connected in Y to the AC converter and the secondary of the coupling transformer is connected in Δ [3], [4]. The compensator operates as a means for controlling continuously the degree of series compensation ($K_{SC}$) and active power through the variation of the duty cycle ($D$) of a single asynchronous train of pulses with a fixed frequency. The duty cycle of the AC link converter is defined as the ratio of the on-period of switches $S'_a$, $S'_b$ and $S'_c$ to the total switching period.

PWMSC is assumed to be connected onto the distribution line connecting buses $A$ and $B$, as shown in Figure 3. Hence, PWMSC operates like a continuously capacitive controllable reactance. However, for the purpose of developing a control strategy, a proper model representation for PWMSC is developed.

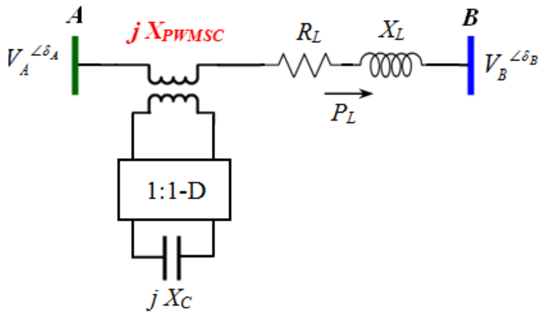



Fig. 3. Single distribution line diagram of PWMSC.

The inserted reactance can vary from being slightly inductive to capacitive, depending on the duty cycle ($D$) of the AC converter [17], [18]. The duty cycle ratio of the converter is defined as the ratio of the on-period of switches $S'_a$, $S'_b$ and $S'_c$ to the total switching period.

The actual transformer is modeled by a leakage reactance ($X_{LT}$) in series with an ideal transformer where leakage losses are neglected. $X_C$ is the reactance of the capacitors in the secondary side. The total and injected impedances of the distribution line can be calculated with state space averaging techniques as follows [10]-[14]:

$$X_{Tot} = X_L + X_{LT} + X_{PWMSC} \tag{1}$$

And,

$$X_{PWMSC} = -n^2 (1-D)^2 .X_C \tag{2}$$

Where, $n$ is the turns ratio of the transformer and $X_L$ is the total reactance of the compensated distribution line. Equations (1) and (2) show that the effective impedance depends on the duty cycle of the AC link switches. Hence, this duty cycle provides a means of realizing the desired controllable reactance and power flow of the line.

From equations (1) and (2), it can be seen that the varying injected apparent reactance can change continuously between two extreme duty cycle values which are 0 and 1.

The active power flow equation between two buses $A$ and $B$ which includes the variables that can be modified by PWMSC is represented by:

$$P_L = \frac{V_A . V_B}{X_L + X_{LT} + X_{PWMSC}} \sin(\delta_A - \delta_B) \tag{3}$$

$V_A$ and $V_B$ are the voltage magnitudes at bus-bars $A$ and $B$ respectively, and ($\delta_A$ - $\delta_B$ = $\delta$) is the difference angle between $V_A$ and $V_B$ phasors.

## 3 Ground Fault System Calculations

System currents cannot change instantaneously when a fault occurs due to the equivalent system impedance at the fault point which results in a decaying DC component. The rate of decay depends on the instantaneous value of the voltage when the fault occurs and the power factor of the system at the fault point. Figure 4 shows the equivalent circuit of a distribution line between bus-bars $A$ and $B$ in case of a phase to ground fault at phase A of the distribution line compensated by PWMSC. The device is deployed in the presence of a fault resistance.

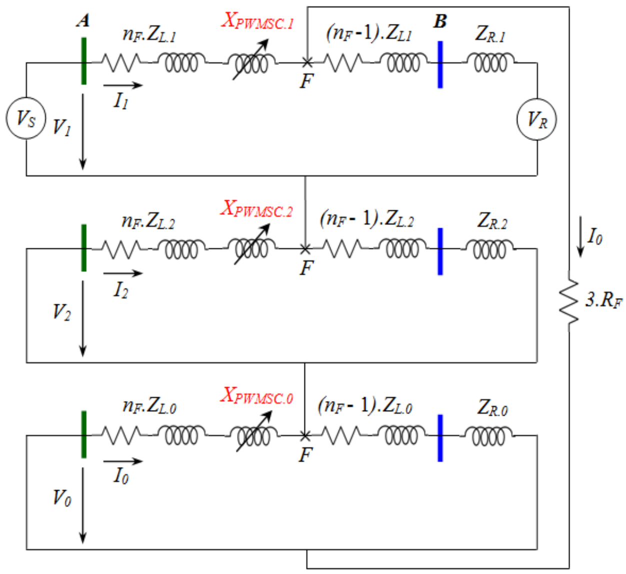



Fig. 4. Phase to ground fault equivalent circuit with PWMSC device.

While having PWMSC device installed, the new impedance of the distribution line ($Z_{L\text{-}PWMSC}$) becomes:

$$Z_{L-PWMSC} = R_L + j(X_L + X_{PWMSC}) \tag{4}$$

The basic equations for this type of fault [19]-[25] are given by:

$$I_B = I_C = 0 \quad (5)$$

$$V_a = V_1 + V_2 + V_0 = R_F.I_A \neq 0 \quad (6)$$

The symmetrical components of currents are given by [20-25]:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} . \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad (7)$$

From equation (5) and matrix (7), the symmetrical components of currents take the following form:

$$I_1 = I_2 = I_0 = \frac{I_A}{3} \quad (8)$$

The symmetrical components of voltages are given by:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} . \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (9)$$

From equation (6) and the matrix in equation (9), the direct voltage component becomes:

$$V_1 = -(V_0 + V_2) + R_F.I_A \quad (10)$$

And,

$$V_s - I_1 \left[ n_F.Z_{L.1} + jX_{PWMSC.1} \right] = \alpha + \beta + \gamma \quad (11)$$

The coefficients $\alpha$, $\beta$ and $\gamma$ are defined as:

$$\alpha = -\frac{1}{3} \left[ -\left( n_F.Z_{L.0} + jX_{PWMSC.0} \right).I_0 \right] \quad (12)$$

$$\beta = -\frac{1}{3} \left[ -\left( n_F.Z_{L.2} + jX_{PWMSC.2} \right).I_2 \right] \quad (13)$$

$$\gamma = R_F.I_A \quad (14)$$

Coefficients $Z_{L-T}$ and $X_{PWMSC-T}$ are defined for simplicity as:

$$Z_{L-T} = Z_{L.1} + Z_{L.2} + Z_{L.0} \quad (15)$$

$$X_{PWMSC-T} = X_{PWMSC.1} + X_{PWMSC.2} + X_{PWMSC.0} \quad (16)$$

$$V_s = \frac{I_A}{3} \left[ n_F.Z_{L-T} + jX_{PWMSC-T} \right] + R_F.I_A \quad (17)$$

From equations (15), (16) and (17), the current at phase ($A$) in the presence of PWMSC device is given by:

$$I_A = \frac{3.V_S}{n_F.Z_{L-T} + jX_{PWMSC-T} + 3.R_F} \quad (18)$$

From equations (8) and (18), the symmetrical current components in the presence of a PWMSC are given by:

$$I_1 = I_2 = I_0 = \frac{V_S}{n_F.Z_{L-T} + jX_{PWMSC} + 3.R_F} \quad (19)$$

The direct voltage component is given by:

$$V_1 = V_S - \left( n_F.Z_{L.1} + jX_{PWMSC.1} \right).I_1 \quad (20)$$

$$V_1 = \frac{V_S.\left[ Z_L' + jX_{PWMSC}' + 3.R_F \right]}{n_F.Z_{L-T} + jX_{PWMSC-T} + 3.R_F} \quad (21)$$

Coefficients $Z_L'$ and $X_{PWMSC}'$ are given by:

$$Z_L' = Z_{L.2} + Z_{L.0} - 2.Z_{L.1} \quad (22)$$

$$X_{PWMSC}' = X_{PWMSC.2} + X_{PWMSC.0} - 2.X_{PWMSC.1} \quad (23)$$

The inverse voltage component is given by:

$$V_2 = -\left( n_F.Z_{L.2} + jX_{PWMSC.2} \right).I_2 \quad (24)$$

$$V_2 = -\frac{V_S.\left( Z_{L.2} + jX_{PWMSC.2} \right)}{n_F.Z_{L-T} + jX_{PWMSC-T} + 3.R_F} \quad (25)$$

The zero voltage component is given by:

$$V_0 = -\left( n_F.Z_{L.0} + jX_{PWMSC.0} \right).I_0 - R_F.I_0 \quad (26)$$

$$V_0 = -\frac{V_S.\left[ Z_{L.0} + jX_{PWMSC.0} + R_F \right]}{n_F.Z_{L-T} + jX_{PWMSC-T} + 3.R_F} \quad (27)$$

Coefficients $Z_2'$ and $Z_0'$ are given by:

$$Z_2' = R_{L.2} + j\left( X_{L.2} + X_{PWMSC.2} \right) \quad (28)$$

$$Z_0' = R_{L.0} + j.\left( X_{L.0} + X_{PWMSC.0} \right) \quad (29)$$

From equations (21), (25) and (27), the three phase voltages of distribution line in the presence of PWMSC are:

$$V_A = \frac{3.R_F.V_S}{n_F.Z_{L-T} + jX_{PWMSC-T} + 3.R_F} \quad (30)$$

$$V_B = \frac{V_S.\left[ \left( a^2 - a \right) Z_2' + \left( a^2 - 1 \right) Z_0' + \left( 3a^2 - 1 \right) R_F ) \right]}{n_F.Z_{L-T} + jX_{PWMSC-T} + 3.R_F} \quad (31)$$

$$V_C = \frac{V_S.\left[ \left( a - a^2 \right) Z_2' + \left( a - 1 \right) Z_0' + \left( 3a - 1 \right) R_F ) \right]}{n_F.Z_{L-T} + jX_{PWMSC-T} + 3.R_F} \quad (32)$$

## 4 Case Study, Results and Discussions

The electrical power system studied in this paper is for the Constantine MV distribution electrical network of Sonelgaz group (Algerian Company of Electrical and Gas) as shown in Figure 5 [26]. The relay measured fault current is located on busbar *A* to protect the 30 kV distribution line connecting busbar *A* at substation 60/30 kV Constantine and busbar *B* at substation Mila.

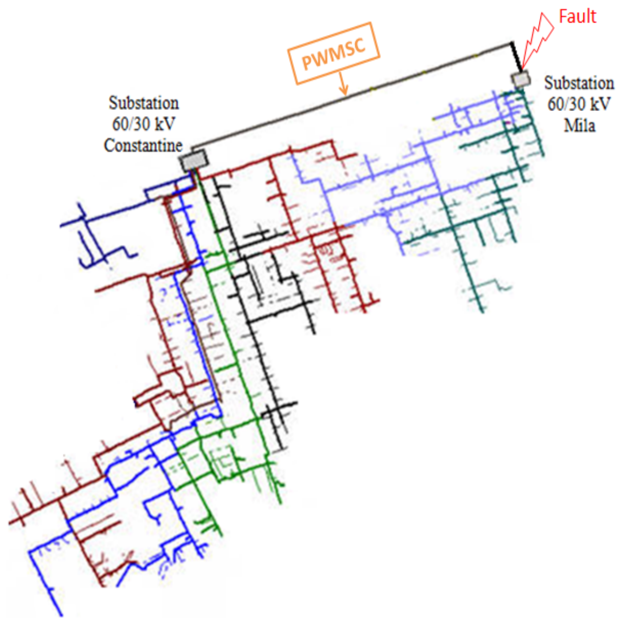



Fig. 5. Algerian MV distribution system (Constantine Region).

Figure 6 represents the impact of duty cycle *D* on the apparent reactance controlled by PWMSC installed on the MV distribution line.

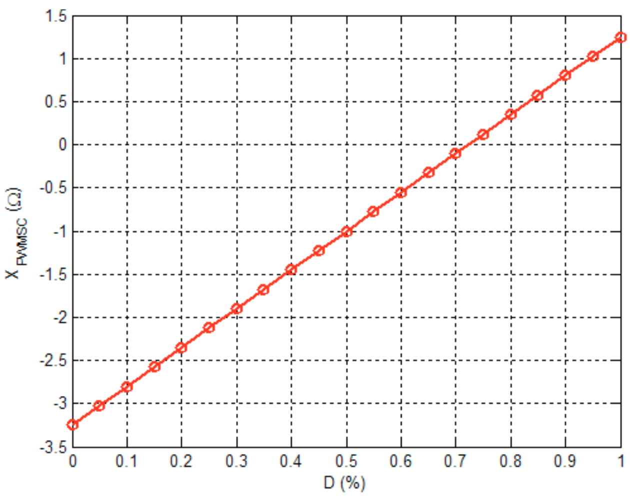
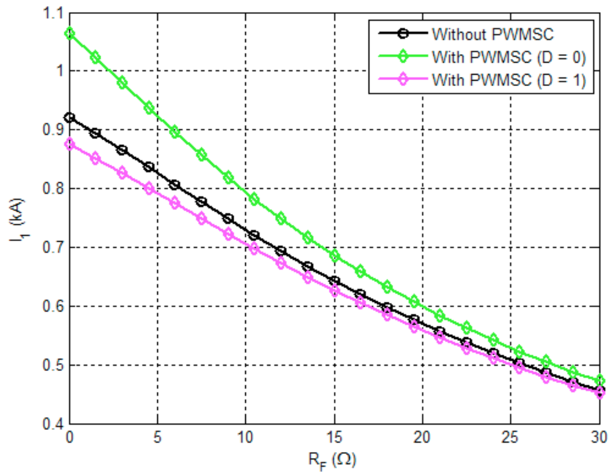



Fig. 6. Impact of duty cycle on the PWMSC apparent reactance.

From Figure 6, it is clear that the apparent reactance $X_{PWMSC}$ is a function of duty cycle. For duty cycle $D$ = 0, the apparent reactance has a negative minimum value and for duty cycle $D$ = 1, the value of apparent reactance has maximum positive value.

Figure 7 represents the variation of the symmetrical current components ($I_1$, $I_2$ and $I_0$) as a function of the fault resistance in the absence as well as presence of PWMSC at minimum and maximum duty cycle.

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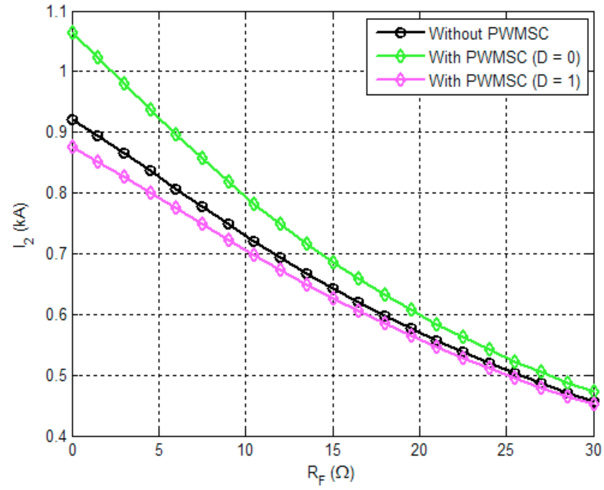


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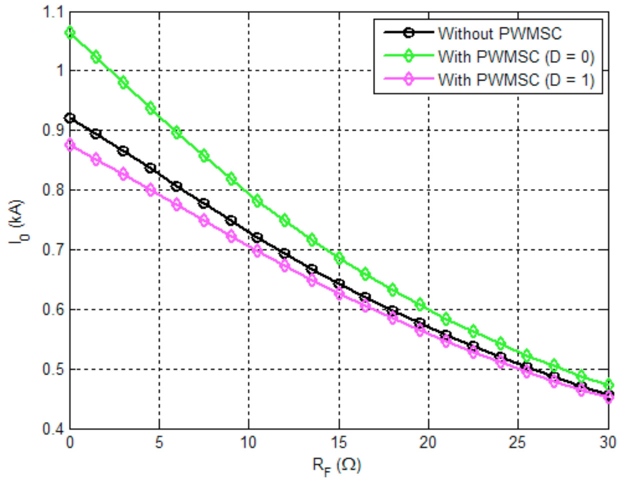
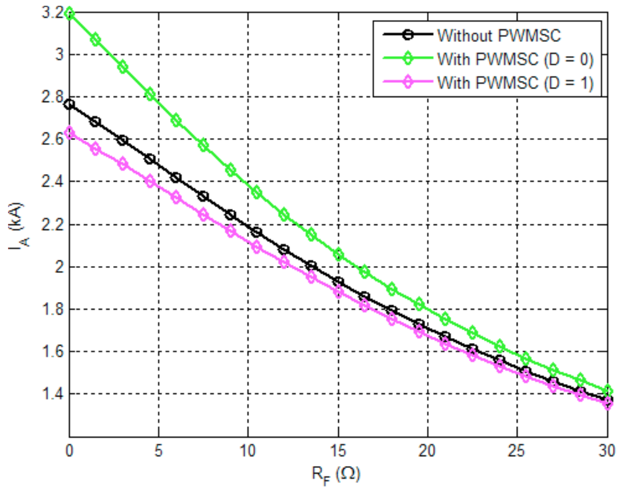



(c)

Fig. 7. Impact of fault resistance on current symmetrical components.

Figure 8 represents the variation of the MV distribution line currents ($I_A$, $I_B$ and $I_C$) as a function of the fault resistance, in the absence and presence of PWMSC at minimum and maximum duty cycle.

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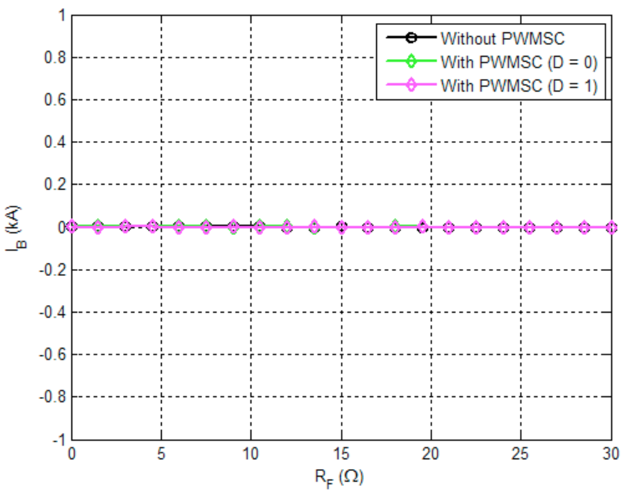


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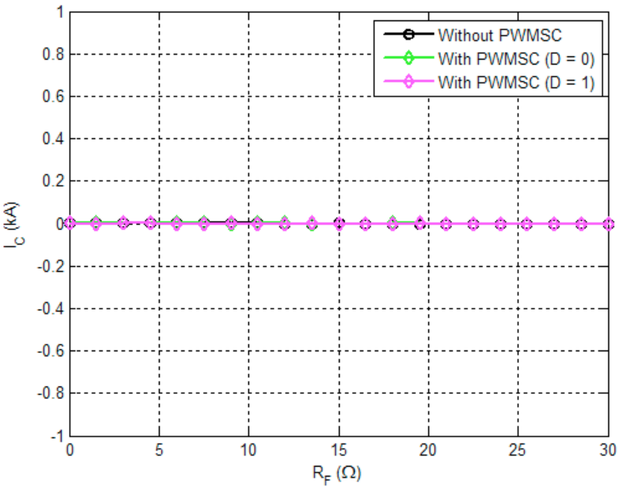


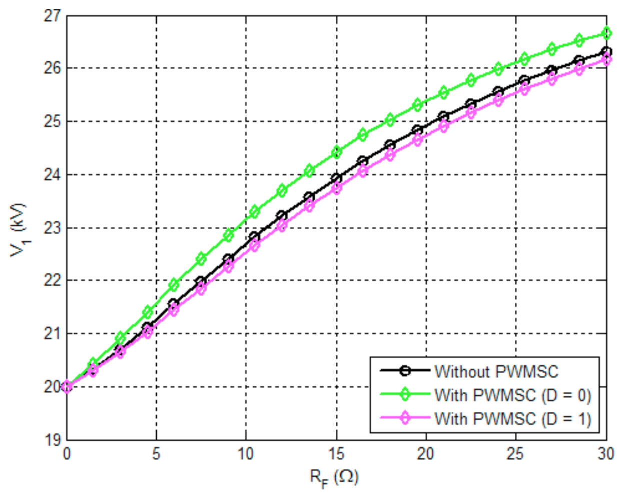

(c)

Fig. 8. Impact of fault resistance on distribution line currents.

Figure 7 shows that the three symmetrical current components are equal to each other in each of the three studied cases; without using PWMSC and in its presence for both minimum and maximum duty cycle *D*. This matches equation (8). It is also clear that increasing the fault resistance leads to decreasing the three studied current components which reflects its importance. However, it is noticed that these three symmetrical current components of the line when compensated by PWMSC with *D* equals 0 are higher when compared with the components obtained for either a non-compensated line or when the line is compensated by PWMSC with *D* equals 1. The least magnitudes are noticed when using PWMSC with *D* equals 1.

In Figure 8, the line currents of phases *B* and *C* are always zero since the fault is assumed to happen at phase A which is confirmed by equation (5). However, increasing the fault resistance shows a reduction in the line current of the faulty phase (*A*) in the absence and presence of PWMSC and for both minimum and maximum duty cycle. Similarly, the least fault current magnitudes of phase *A* are obtained when using PWMSC with *D* equals 1.

Figure 9 represents the variation of the symmetrical voltage components ($V_1$, $V_2$ and $V_0$) as a function of the fault resistance, in the absence and presence of PWMSC for minimum and maximum duty cycle.

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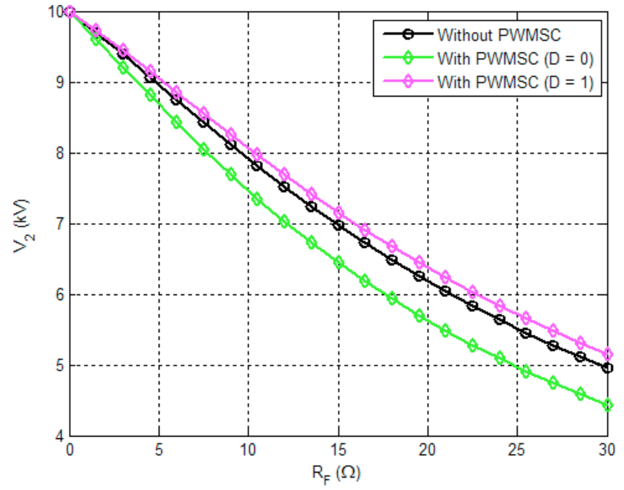


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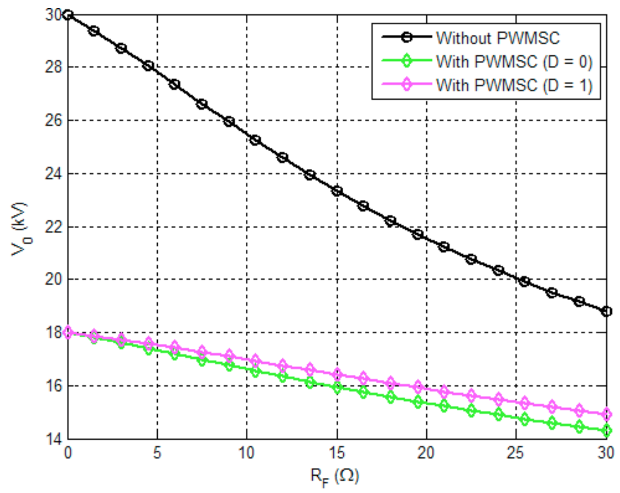


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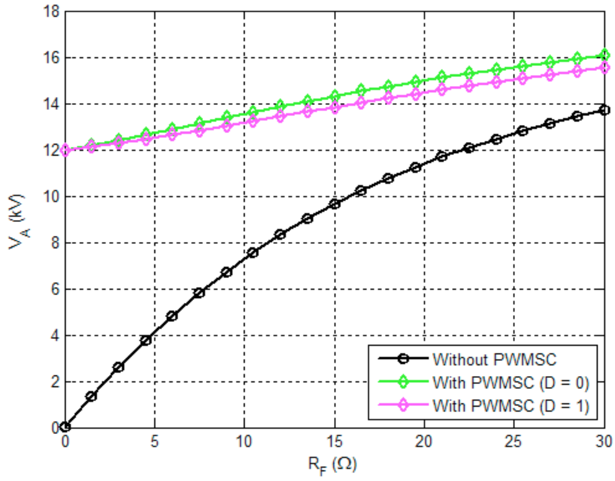
Fig. 9. Impact of fault resistance on voltage symmetrical components.

Figure 10, represents the variation of the MV distribution line voltages ($V_A$, $V_B$ and $V_C$) as a function of the fault resistance, in the absence and presence of a PWMSC for minimum and maximum duty cycle.

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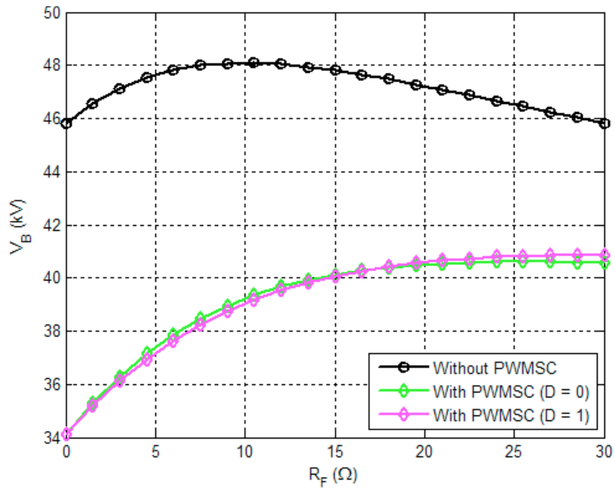


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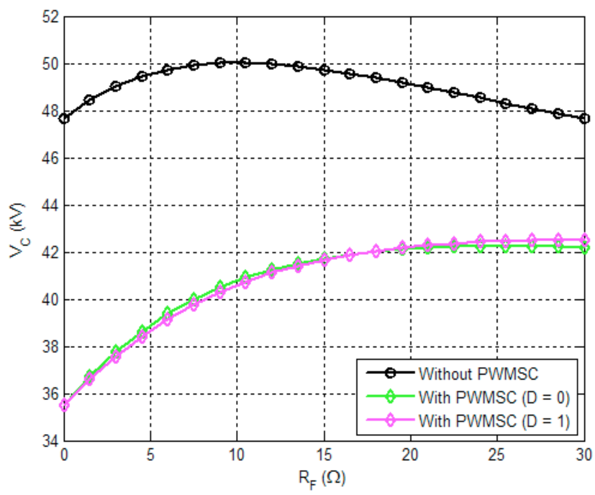


(c)

Fig. 10. Impact of fault resistance on distribution line voltages.

In Figure 9, for the three studied cases, it is noticed that increasing the fault resistance leads to an increase in the value of the direct voltage component and a decrease in the inverse and zero voltage components. These results are confirmed by equations (21), (25) and (27). The highest magnitudes of direct voltage component and the least magnitudes of inverse and zero voltage components are noticed when using PWMSC with duty cycle $D$ equals 0.

In Figure 10, it is obvious that increasing the fault resistance leads to an increase in the three distribution line voltages (phases $A$, $B$ and $C$) in the presence and absence of PWMSC are confirmed by equations (30), (31) and (32). MV distribution line voltages in the presence of PWMSC are very close in magnitude for both minimum and maximum $D$. This is attributed to the small injected apparent reactance of PWMSC.

# 5 Conclusion

In this research work, the impact of fault resistance on short-circuit calculations is investigated for a MV distribution line equipped with PWMSC in the Algerian 30 kV distribution power system.

Fault calculations, considered in current symmetrical components, distribution line currents, voltage symmetrical components, and distribution line voltages, are shown to vary significantly according to the duty cycle which varies between a minimum and maximum value to control the apparent reactance injected by PWMSC.

The presented theoretical analysis using symmetrical components method and the obtained simulations of the proposed model for a ground fault using MATLAB software package showed excellent agreement. The obtained results highlighted the importance of properly selecting the value of fault resistance and duty cycle for the installed PWMSC on ground short-circuits parameters. In order to improve the performance of system protection when using PWMSC, care must be taken mainly concerning the variation of fault current magnitude in distribution power system.

# 6 Appendix

### 6.1. Power transformer data

$U_{TR}$ = 60/30 kV, $f_n$ = 50 Hz,
$X_{TR1} = j\ 0.341\ \Omega$, $X_{TR0} = j\ 0.859\ \Omega$.

### 6.2. Distribution line data

$V_n$ = 30 kV, $l$ = 62 km,
$Z_{L.1} = 0.146 + j\ 0.318\ \Omega$/km,
$Z_{L.0} = 0.438 + j\ 0.954\ \Omega$/km.

### 6.3. PWMSC data

$S_n$ = 1150 KVA, $V_n$ = 30 kV,
$X_{PWMSC.1}\ (D = 0) = -j\ 3.25\ \Omega$,
$X_{PWMSC.1}\ (D = 1) = +j\ 1.25\ \Omega$,
$X_{PWMSC.0}\ (D = 0) = -j\ 9.75\ \Omega$,
$X_{PWMSC.0}\ (D = 1) = +j\ 3.75\ \Omega$.

### 6.4. Fault conditions

$R_F$ = 0 to 30 Ω, and $n_F$ = 100 %.

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