Engineering and Technology Journal e-ISSN: 2456-3358

Volume 09 Issue 08 August-2024, Page No.- 4724-4734

DOI: 10.47191/etj/v9i08.17, I.F. – 8.227

Investigating the Impact of Ground-Return Parameters on Transitional Voltages at Switching-Off Unloaded Power Transmission Lines

E. A. Saafan

Department of Electrical Engineering, Faculty of Engineering, University of El-Mansoura, Mansoura, Egypt, 35516

ABSTRACT: The electrical parameters calculations of the overhead transmission lines are very important to the areas concerned to electromagnetic compatibility and transitional processes in power systems. Therefore, accurate calculations of these parameters were performed in this research, taking into account the ground-return parameters (Carson correction factors). The return parameters of the homogenous ground (one-layered ground) the overhead transmission line passes over were taken into consideration via using the actual value of the ground resistivity. In this research, the effect of ground-return parameters on transitional voltages at switching-off an unloaded transmission line using SF_6 circuit-breaker was recorded and clarified. As a result, when the ground-return parameters are taken into account, the overall transmission line inductance increases. This has an obvious impact on the rate of rise of recovery voltage for the SF_6 circuit-breaker inter-contact space that consequently affects the transitional voltages during switching-off process.

KEYWORDS: Transmission Line Parameters, Ground Resistivity, Ground-Return Parameters, Carson Correction Factors, Rate of Rise of Recovery Voltage (RRRV), Dielectric Strength Restoration, Stiff Differential Equations

1. INTRODUCTION

For studying transitional processes, the calculating method of the electrical parameters of overhead power transmission lines is crucial. Based on some assumptions about the geometry of the overhead transmission line and the physical properties of its conductors, these parameters were estimated using well-known equations [1-4].

The ground effect may not be taken into account when calculating the electrical parameters of the overhead power lines. This implies that, these parameters might not match those calculated when the ground dielectric properties were taken into account [3, 4].

It is well known that; the ground permittivity and ground resistivity are the dielectric properties of the ground that influence its ground-return parameters [4, 5]. Only the ground resistivity is taken into account in this research because the ground permittivity has no significant effect at power frequency (50 Hz).

J. R. Carson proposed a creative method to solve the ground-return parameters problem in 1926 [5]. It was based on the presumption that, the ground had not perfect conductive, and the power voltage and current propagated along the overhead line like waves.

Carson took into consideration the basic system, which consists of two parallel wires with a ground return, and created equations to calculate the return parameters of the homogeneous ground (one-layered ground). Consequently, the obtained solution of the two parallel wires system can be extend to multi-wired systems [3, 5].

Two components make up the impedance of the double-wired overhead line that passes over the homogeneous ground: one is essentially geometric in nature, while the other is computed using Carson integration [5-8]. The geometrical spacing of the overhead line conductors were used to determine the first component. This component considers that, the double-wired overhead line passing over a superconductive homogeneous ground. As a result, this component has no ground contribution to the two-wired overhead line's electrical parameters [5, 7]. The second component that considers how the ground resistivity affects the two-wired overhead line parameters is the ground-return impedance. This consequently have an impact on the propagation of electromagnetic waves and transitional voltages in high-voltage power systems [6, 8].

Besides the transmission line electrical parameters, there are other parameters that affect the transitional voltages during switching processes. These parameters are concerned to high-voltage circuit-breaker modeling that must be taken into consideration. The most significant parameters required for circuit-breaker modeling are dielectric strength restoration, chop current and full operation time [9-12]. These parameters are very important in order to model the electric arc phenomenon in the inter-contact spaces of the high-voltage circuit-breakers.

It is known that, the differential equations that formalized voltages and currents during switching processes in electrical networks belong to the class of so-called “stiff” differential equations. Therefore, the numerical solution of such equations requires paying special attention [13-16].

This research discusses how the ground-return parameters affect the overhead transmission line parameters via using the actual value of ground resistivity and, in turn, how those parameters affect the transitional voltages. PSCAD/EMTDC program was used to create the simulated results at switching-off three-phase unloaded transmission line using an auto-compression circuit-breaker (SF_6 CB). Keep in mind that the ground the transmission line passes over is considered as homogeneous ground (infinite one-layer ground).

2. ELECTRICAL PARAMETERS CALCULATIONS OF OVERHEAD POWER TRANSMISSION LINE

In this section, the resistance, inductance, and capacitance of three-phase power transmission line (110 kV) were calculated. According to [8], the conductor of a 110 kV transmission line has an AC resistance equals 0.1181 Ω/km per phase at frequency 50 Hz when the ground considered as superconductive. This value of resistance takes the correction factor due to skin effect into consideration as given [17, 18].

The geometric configuration described in [8] for the three-phase overhead transmission line (110 kV) that passing over a homogeneous ground is considered in order to compute the transmission line inductance and capacitance. This geometric configuration is shown in figure (1) that presents an unsymmetrical spacing between the transmission line conductors.

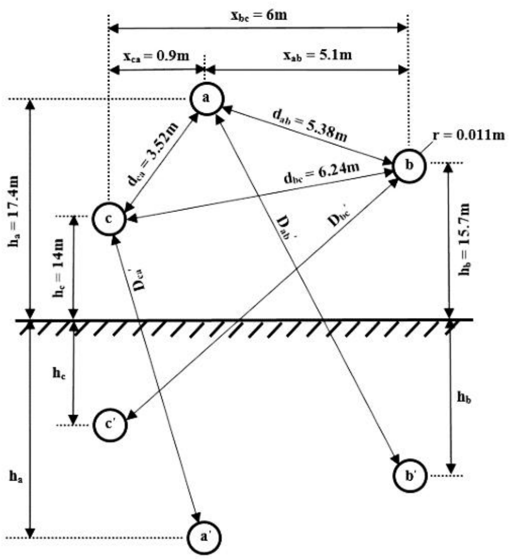


Figure 1. Geometric configuration of the three-phase power transmission line (110 kV) under study

As shown in figure (1), the second electrode (ground) is replaced by a conductor in the ground below the real electrode, at a depth equal to the height of the conductor above the ground, in order to compute the line inductance and capacitance [19–23].

where,

h_a, h_b, h_c: are correspond to mean heights of conductors; [m]
x_{ab}, x_{bc}, x_{ca}: are horizontal distances between conductors; [m]
d_{ab}, d_{bc}, d_{ca}: are distances between the conductors; [m]
$D_{ab'}$, $D_{bc'}$, and $D_{ca'}$: are distances between the conductors and images of conductors; [m]
a', b', and c': are images of the conductors a, b, and c.

When the ground is assumed to be perfectly conductive, the transmission line inductances (self and mutual) are computed using the following formulas,

$$L_{ii} = \frac{\mu_o}{2\pi} \ln\frac{2h_i}{r_i'} \tag{1}$$

$$L_{ij} = \frac{\mu_o}{2\pi} \ln\frac{D_{ij'}}{d_{ij}} \tag{2}$$

where,

L_{ii}, L_{ij}: are self and mutual inductances for overhead transmission line; [H/m]
$D_{ij'}$, d_{ij}: are distances determining the overhead line's mutual inductance; [m]
$r_i' = r_i e^{-\mu_r/4}$: is effective radius of conductor (i); [m]
μ_o: is magnetic permeability for air; [H/m]
μ_r = 1.0: is relative permeability for non-magnetic ground.

In early researches the ground is thought to be perfectly conductive (ground resistivity is equal to zero Ω.m), but the conductivity of the ground actually varies depending on the type of soil in the homogenous ground [7, 24]. Therefore, it is crucial to adjust the transmission line electrical parameters using the Carson correction factors.

In 1926, Carson assumed the earth is not perfect conductive and took into account the exact value of the ground conductivity in his integration method [5]. It should be noted that, Carson integration method only considers the calculations of the ground-return parameters. In other words, only the resistance and inductance have correction factors (ΔR^{gr}, ΔL^{gr}). According to [5, 25, 26], the following formulae present the Carson correction factors for the power line resistance and inductance (self and mutual);

$$\Delta Z_{ii}^{gr} = \Delta R_{ii}^{gr} + j\Delta X_{ii}^{gr} = \Delta R_{ii}^{gr} + j\omega\Delta L_{ii}^{gr} \tag{3}$$

$$= j\frac{\omega\mu}{\pi}\int_0^\infty \frac{exp[-2h_i\lambda]}{\lambda + \sqrt{\lambda^2 + j\omega\mu/\rho}}\, d\lambda$$

$$\Delta Z_{ij}^{gr} = \Delta R_{ij}^{gr} + j\Delta X_{ij}^{gr} = \Delta R_{ij}^{gr} + j\omega\Delta L_{ij}^{gr} \tag{4}$$

$$= j\frac{\omega\mu}{\pi}\int_0^\infty \frac{exp[-(h_m + h_n)\lambda]}{\lambda + \sqrt{\lambda^2 + j\omega\mu/\rho}} cos(x_{ij}\lambda)\ d\lambda$$

where,

ΔZ_{ii}^{gr}, ΔZ_{ij}^{gr}: are self and mutual return impedance; [Ω/m]

ΔR_{ii}^{gr}, ΔR_{ij}^{gr}: are self and mutual return resistance; [Ω/m]
ΔX_{ii}^{gr}, ΔX_{ij}^{gr}: are self and mutual return reactance; [Ω/m]
ΔL_{ii}^{gr}, ΔL_{ij}^{gr}: are self and mutual return inductance; [H/m]
ω: is angular frequency; [rad/s]
$\mu = \mu_o\ \mu_r$: is magnetic permeability of the ground; [H/m]
ρ: is ground resistivity; [Ω.m]
λ: is integration variable.

It is known that, without any expensive geological measurements, it is quite challenging to estimate the accurate resistivity value of the homogenous ground [24, 27, and 28]. Since these measurements are difficult to achieve, approximated values of ground resistivity were used. The selected value of ground resistivity that taken into consideration in this research equals 150 Ω.m.

Tables (1, 2) show the self and mutual values of transmission line resistance and inductance for the selected value of ground resistivity (150 Ω.m). These tables show the geometric parameters, Carson correction factors, and overall parameters of the power transmission line under study.

It is clear from the results shown in tables (1, 2) that, the computed values of the overall transmission line parameters differ significantly from those that ignored the ground effect (geometric parameters). Consequently, this can affect the transitional voltages in high-voltage power systems during switching-off processes.

Table 1. Self and mutual values of transmission line resistance when the ground resistivity equals 150 Ω.m

Item	Resistance [Ω/km]		
	Geometric (R)	Correction (ΔR^{gr})	Overall ($R+\Delta R^{gr}$)
R_{aa}	0.1181	0.04806	0.16610
R_{bb}	0.1181	0.04820	0.16630
R_{cc}	0.1181	0.04835	0.16640
R_{ab}	-	0.04813	0.04813
R_{bc}	-	0.04827	0.04827
R_{ca}	-	0.04820	0.04820

Table 2. Self and mutual values of transmission line inductance when the ground resistivity equals 150 Ω.m

Item	Inductance [mH/km]		
	Geometric (L)	Correction (ΔL^{gr})	Overall ($L+\Delta L^{gr}$)
L_{aa}	1.664	0.7038	2.368
L_{bb}	1.644	0.7239	2.368
L_{cc}	1.621	0.7463	2.367
L_{ab}	0.366	0.7113	1.077
L_{bc}	0.316	0.7308	1.047
L_{ca}	0.438	0.7238	1.162

Normally, for transmission lines have lengths more than 80 km (medium transmission line), it is important to consider the transmission line capacitance due to its effect on the transitional voltages [22, 23]. With the geometric configuration of the transmission line shown in figure (1), the general procedures for calculating self and mutual capacitances are based on the following formulae,

$$P_{ii} = \frac{1}{2\pi\varepsilon_0}\ ln\frac{2h_i}{r_i} \tag{5}$$

$$P_{ij} = \frac{1}{2\pi\varepsilon_0}\ ln\frac{D_{ij'}}{d_{ij}} \tag{6}$$

$$[C] = [P]^{-1} \tag{7}$$

where,
r_i: is conductor (i) radius; [m]
ε_0: is permittivity of free space; [F/m]
P_{ii}, P_{ij}: self and mutual Maxwell potential coefficients; [m/F]
$[P]^{-1}$: is inverse of potential coefficients matrix; [F/m]
[C]: is matrix of transmission line capacitances; [F/m]

By inverting the potential coefficient matrix using formula (7), the matrix of power transmission line capacitances is obtained. Hence, table (3) shows the capacitances values of the three-phase transmission line under study.

Note that, the capacitance has no correction factor. It means that, the capacitance matrix of the power transmission line depends only on the geometric spacing of its conductors.

Table 3. Self and mutual values of transmission line capacitance

Item	Capacitance [nF/km]
C_{aa}	7.714
C_{bb}	7.523
C_{cc}	7.828
C_{ab}	-1.400
C_{bc}	-1.124
C_{ca}	-1.869

3. SEQUENCE PARAMETERS CALCULATIONS OF OVERHEAD POWER TRANSMISSION LINE

From the results shown in tables (1, 2, and 3) it is clear that, the overhead power transmission line under study has unsymmetrical electrical parameters. It means that, this transmission line has unbalance in voltage and current due to the unbalance of its inductive and capacitive reactances. To reduce this unbalance and consequently reduce the system power loss, the transmission lines are transposed [29, 30].

By transposing the power transmission lines, both self or mutual electrical parameters are equal to each other. Hence, transposed transmission lines can be fully represented with its zero and positive sequence parameters. Zero and positive sequences for the geometric configuration shown in figure (1) were calculated according to [31, 32]. The values of these sequences are listed in tables (4, 5) for two different values of ground resistivity (zero Ω.m, 150 Ω.m). Remember that, the transmission line capacitance is not affected by varying the ground resistivity. It means that, zero and positive sequences of the transmission line capacitances are not changing with the ground resistivity.

Table 4. Positive sequence parameters for the transposed transmission line under study

ρ [Ω.m]	Resistance [Ω/km]	Inductance [mH/km]	Capacitance [nF/km]
	$R_1 = R_s - R_m$	$L_1 = L_s - L_m$	$C_1 = C_s - C_m$
zero	0.1181	1.2695	9.1526
150	0.1181	1.2722	9.1526

Table 5. Zero sequence parameters for the transposed transmission line under study

ρ [Ω.m]	Resistance [Ω/km]	Inductance [mH/km]	Capacitance [nF/km]
	$R_0 = R_s + 2R_m$	$L_0 = L_s + 2L_m$	$C_0 = C_s + 2C_m$
zero	0.1181	2.3895	4.7596
150	0.2627	4.5580	4.7596

where,
R_s, L_s, C_s: are average values of line self-parameters,
R_m, L_m, C_m: are average values of line mutual parameters,
R_1, L_1, C_1: are positive sequences of line parameters,
R_0, L_0, C_0: are zero sequences of line parameters.

4. AUTO-COMPRESSION (SF_6) CIRCUIT-BREAKER MATHEMATICAL MODELING

It is well known that; the dielectric strength of the circuit-breaker inter-contact gap starts to rise when the circuit-breaker contacts begin to move away from each other. Furthermore, from the beginning of contacts separation of circuit-breaker, an electric are is formed between them. Due to the formation of that arc, the electric current continues to flow until the next zero crossing.

Successful arc extinction at next zero crossing results in the termination of the electric current conductance and the beginning of the transient recovery voltage (TRV). The TRV rises quickly, and the circuit breaker's dielectric strength is not fully restored yet. Dielectric re-ignition or re-strike happens if the rate of rise of recovery voltage (RRRV) is greater than the recovery rate of the circuit-breaker dielectric strength; otherwise, interruption will occur.

A high-frequency current starts to flow through the circuit breaker in the event of dielectric re-ignition or re-strike occurs, resulting in interruption failure. The TRV then returns to zero and does not rise again until the arc is quenched. So, circuit-breaker's dielectric withstand is considered as an important parameter in switching analysis [10, 11].

Since the dielectric strength restoration is one of the main features of circuit-breakers modeling that define their influence on the switching processes, the following restoration law of dielectric strength in the inter-contact space of SF_6 circuit-breaker according to [9] is used. This law gives an acceptable coincidence with the real law for SF_6 circuit-breakers that presented in [12].

$$V_{str}(t) = 2^{-1}V_m\left\{1 - \cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\} \quad (8)$$

where,
$V_{str}(t)$: is dielectric strength restoration law of SF_6 circuit-breaker,
V_m: is dielectric strength maximum value,
t: is the time,
T_{full}: is full switch-off time of SF_6 circuit-breaker (50 msec),
t_{off}: is initial instant of contacts separation of SF_6 circuit-breaker [9, 12].

It should be noted that, arc repeated ignitions and strikes in the inter-contact spaces of SF_6 circuit-breakers are set according to the following condition;

$$|\Delta V| \geq V_{str}(t) \quad (9)$$

Furthermore, the modelling of SF_6 circuit-breakers takes into account the phenomena of current chopping. In other words, circuit-breakers current interruption is set according to the following condition;

$$|i| \leq I_{ch} \quad (10)$$

where,
ΔV: is recovery voltage between SF_6 circuit-breaker poles,
I: is current passing through SF_6 circuit-breaker during switching-off process,
I_{ch}: is chop current depending on the circuit-breaker type.

5. SWITCHING-OFF UNLOADED THREE-PHASE POWER TRANSMISSION LINE

In this section, numerous simulations were performed to record the values of transitional voltages during switching-off an unloaded power transmission line (transposed).

In some literatures, the medium power transmission lines have lengths between 80 km and 160 km (or 50 and 100 miles) [33]. So, the simulation results were performed in cases of with and without arc repeated re-strikes while changing the transmission line length from 80 km to 160 km (medium line, 110 kV).

The behaviors of phases terminal voltages and recovery voltages across SF_6 circuit-breaker poles during switching-off process will be investigated. All simulations for the system shown in figure (2) were performed while the transmission line is modeled as a pi-section and has no loads (unloaded regime).

Note that, the effect of ground-return parameters is not considered into account in this section. It means that in this section, all simulations were performed for the case of zero ground resistivity (ρ = zero Ω.m).

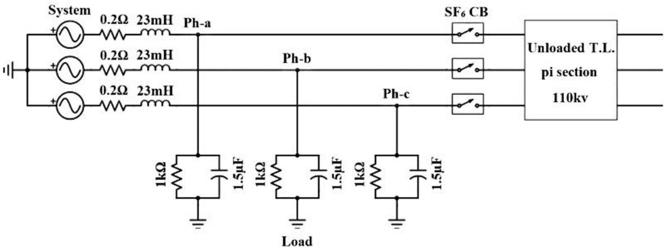


Figure 2. System configuration for switching-off three-phase unloaded power transmission line (110 kV)

5.1 Switching-off without arc re-strikes occurrence

Switching-off unloaded medium transmission line has length more than 80 km is the same as capacitor bank switching-off because of the unloaded transmission line has a dominantly capacitive behavior.

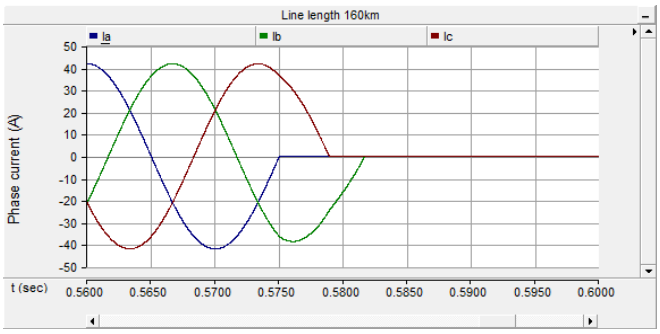
Figure (3) shows the voltage waveforms at switching-off unloaded overhead transmission line with length 160 km. In this case, the effect of ground-return parameters is ignored (ground resistivity equals zero Ω.m) and no re-strikes occurred during switching-off process. As seen in figure (3), phase-a which is firstly switched-off has the highest voltage value. This is due to the electromagnetic coupling of the other phases and due to Ferranti effect. The sequence of switching-off process is explained in details as following,

- To analyze three-phase unloaded transmission lines switching-off, the capacitive coupling between phases and the capacitance to ground are taken into account.
- When the first phase (phase-a) switched-off, it remains connected to the other phases (b, c) through the neutral point. This will occur when the voltage of phase-a is at its peak value. It means that, the input voltage of the neighboring phases (b, c) is coupled into the terminal voltage of phase-a through the neutral point. The voltage of neutral point is then added to phase-a terminal voltage. That is the reason of why phase-a has the highest voltage.
- When the second phase (phase-c) switched-off, the third phase (phase-b) is still at system voltage and this voltage couples into the terminal voltages of the other phases (a, c) through the neutral point. It means that, the voltage of neutral point is then subtracted from phase-c voltage. That is the reason of why phase-c has the lowest voltage.
- When the current in phase-b (last phase) interrupted at next zero crossing, phase-b is now connected to zero voltage of neutral point. So, the terminal voltage of phase-b remains at its maximum value.

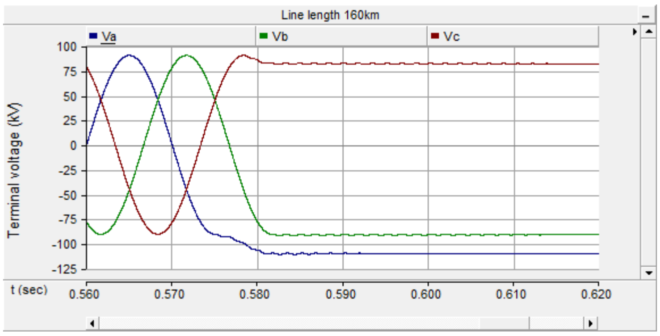
5.2 Switching-off with arc re-strikes occurrence

In this subsection, numerous simulations were performed to have the highest values of transitional voltages in case of the re-strikes occurred. All simulation results were accompanied with a single re-strike in phase-a for all lengths of transmission line under study (80-160) km.

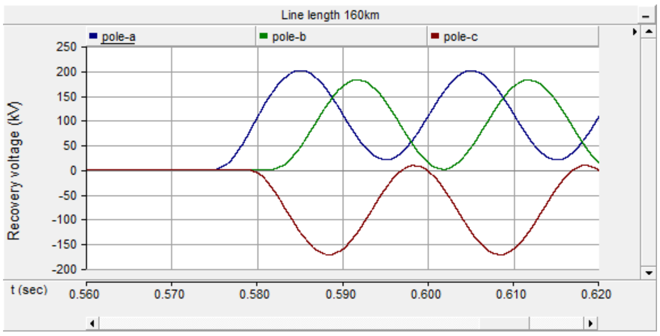
Due to phase-a is the first phase switched-off, it has the highest probability of re-strikes occurrence since the dielectric strength of SF_6 circuit breaker is not enough yet. In contrary, the other phases have lower probability of re-strikes occurrence especially the last phase (phase-b) since they are not switched-off yet. When these phases (b, c) are switched-off, the dielectric strength of SF_6 circuit-breaker will be stronger since it increases as the contacts continue to separate.



(a) switched-off phases currents



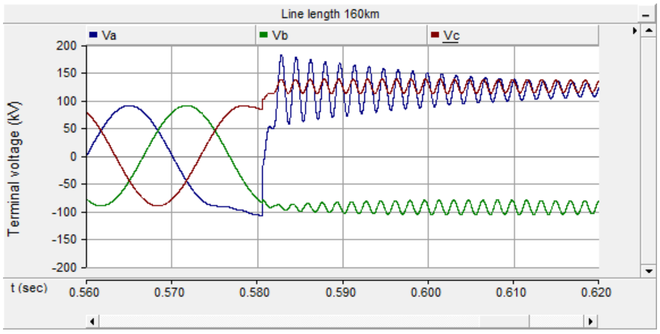
(b) switched-off phases terminal voltages



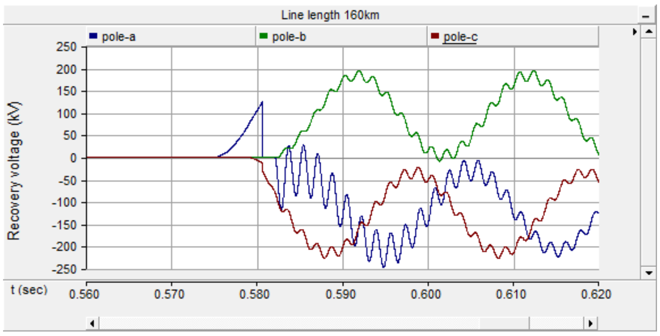
(c) recovery voltages across SF_6 CB poles

Figure 3. Switched-off currents and voltages waveforms with no arc re-strike occurrence when the ground-return parameters are not taken into account

Figures (4, 5) show the waveforms of phases terminal voltages and recovery voltages in case of the effect of ground-return parameters are not taken into consideration (ρ = zero Ω.m) when the transmission line has lengths 160 km and 80 km respectively. As shown, the greatest values of transitional voltages were got for transmission line with length 160 km.

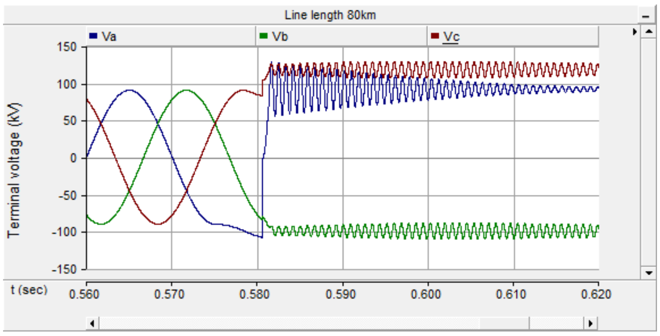


(a) switched-off phases terminal voltages

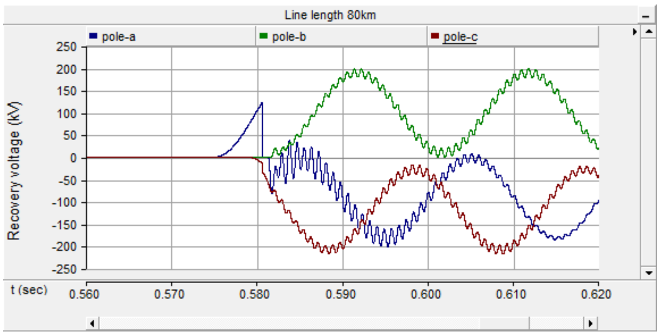


(b) recovery voltages across SF_6 CB poles

Figure 4. Switched-off transitional voltages for 160 km transmission line with arc re-strike occurrence when the ground-return parameters are not taken into account



(a)switched-off terminal voltages



(b) recovery voltages across SF_6 CB poles

Figure 5. Switched-off transitional voltages for 80 km transmission line with arc re-strike occurrence when the ground-return parameters are not taken into account

In order to more clarifying, the ratios of phases terminal voltages (V) and recovery voltages (ΔV) for this line length are shown in table (6). It is evident that, phase-a has the greatest ratios of transitional voltages due to the re-strike that occurred when it compared with other phases (b, c).

Table 6. Ratios of transitional voltages for overhead transmission line with length 160 km when the ground-return parameters are not taken into consideration

phase	V [p.u]	ΔV [p.u]
a	1.99	2.72
b	1.19	2.17
c	1.53	2.52

It should be mention that, the transitional voltages have higher values for longer transmission lines due to the slower rate of rise of recovery voltage (RRRV). To determine RRRV, divide the peak value of transient recovery voltage by the total time elapsed from zero voltage to peak voltage.

It is known that, RRRV depends on both the inductance and capacitance of the system at the instant of switching-off. In other words, RRRV is inversely proportional to the transmission line inductance and capacitance according to the relation ($RRRV\ \alpha\ 1/\sqrt{LC}$). It means that, as the overhead transmission line becomes longer, its parameters (L, C) will be higher that make the RRRV slower. Consequently, the intersection point between recovery voltage and dielectric strength of SF_6 circuit-breaker (dielectric breakdown point) has a longer time delay, that leads to higher transitional voltages. As a result, the time delay increases from 5.45 msec to 5.6 msec when the overhead line length changed from 80 km to 160 km (see figure 12).

Furthermore, switching-off process for longer transmission lines flows smoother due to lower natural free frequencies (transitional voltages have less steepness). In contrary, we face with the possibility of high-frequency current interruption at switching-off shorter lines. As a result, according to the relation $f_{free} = 1/(2\pi\sqrt{LC})$, the natural free frequency is reduced from 1200 Hz to 575 Hz when the transmission line length increases from 80 km to 160 km (see figure 13).

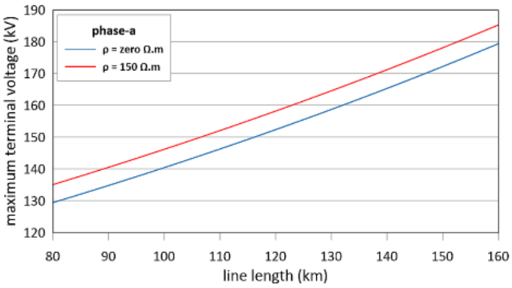
6. EFFECTS OF GROUND-RETURN PARAMETERS ON SIMULATION RESULTS

The actual value of ground resistivity let researchers to take the ground-return parameters into account via calculating Carson correction factors (ΔR, ΔL). This consequently increases the overall transmission line electrical parameters (R, L), that have an impact on the simulation results during switching off processes. Note that, the selected value of ground resistivity used in this study is equal to 150 Ω.m.

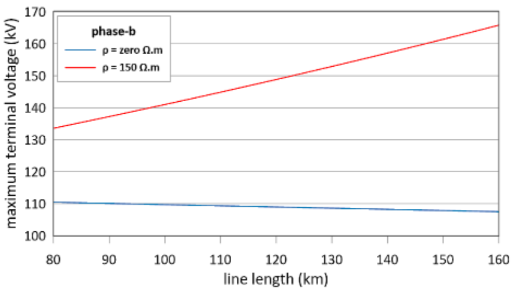
Therefore, in this section numerous simulations were performed for the case of switching-off an unloaded transmission line (transposed, 110 kV) when varying its length from 80 km to 160 km. The simulation results show that, the ground-return parameters can affect the maximum values of transitional voltages. Furthermore, these parameters can affect the dielectric breakdown voltages of SF_6 circuit-breaker inter-contact space, the time required for dielectric breakdown (delay time), and the natural free frequencies of transitional voltages. Each will be discussed in details in the following substations.

6.1 Effect of ground-return parameters on maximum values of transitional voltages

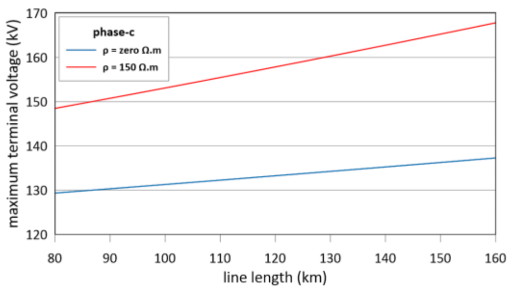
This subsection investigates the transitional voltages behaviors during switching-off the unloaded transmission line under study, taking into account the ground-return parameters. Figures (6, 7) show the maximum values of phases terminal voltages and recovery voltages across SF_6 CB poles respectively against the transmission line length (80 km-160 km). The simulations were performed for two values of ground resistivity (zero Ω.m and 150 Ω.m).



(a) maximum terminal voltages on phase-a



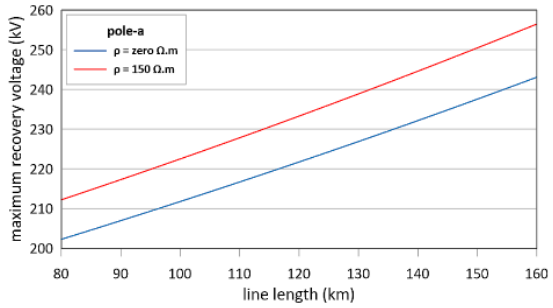
(b) maximum terminal voltages on phase-b



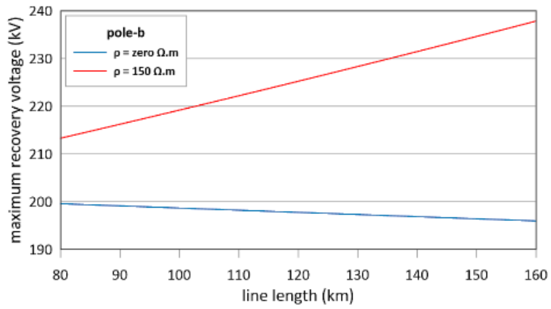
(c) maximum terminal voltages on phase-c

Figure 6. Maximum phases terminal voltages at switching-off using SF_6 circuit-breaker with arc re-strike occurrence for the both cases of ground resistivity

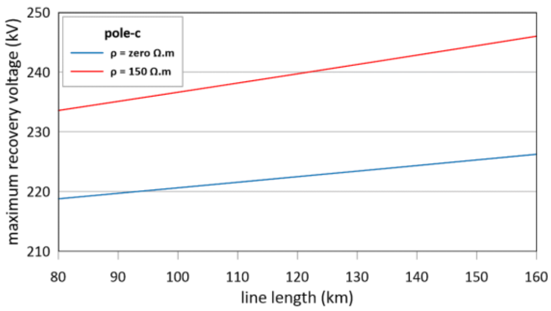
The simulation results show that, the maximum values of transitional voltages are higher for all phases in case of the ground-return parameters were taken into account (ρ = 150 Ω.m). Furthermore, these maximum values are increase as the transmission line length increases. In other words, the overhead transmission line with length 160 km has the highest values of transitional voltages during switching-off processes related to this research.



(a) maximum recovery voltages across pole-a



(b) maximum recovery voltages across pole-b



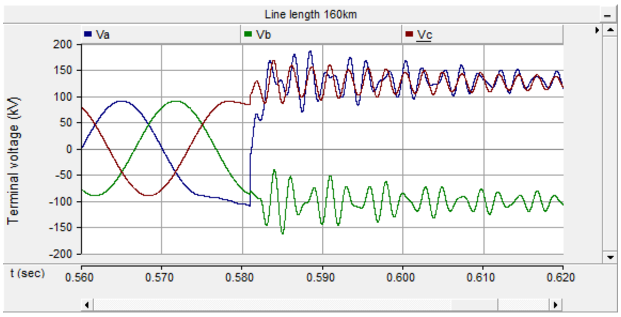
(c) maximum recovery voltages across pole-c

Figure 7. Maximum recovery voltages at switching-off using SF_6 circuit-breaker with arc re-strike occurrence for the both cases of ground resistivity

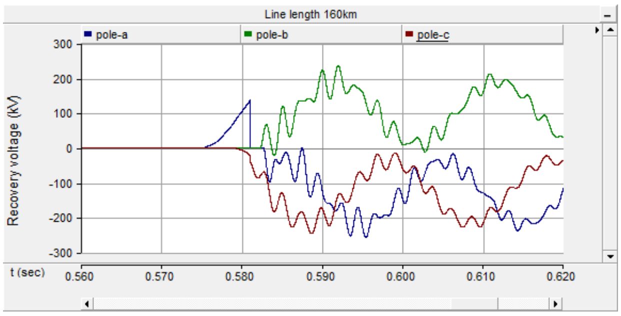
When the ground-return parameters are not taken into account (ρ = zero Ω.m), the same behaviors were got except the behaviors of phase-b (decreasing with line length increases) due to the natural free frequency. It means that, the lower free frequencies and consequently lower voltages correspond to the higher lengths of transmission line.

For more clarifying, figure (8) shows the waveforms of phases terminal voltages and recovery voltages across SF_6 CB poles at taking the effect of ground-return parameters into consideration for 160 km transmission line (worst case in this research). As shown, the simulation results are accompanied with a single re-strike in phase-a.

For easier comparison, the ratios of phases terminal voltages and recovery voltages across SF_6 CB poles for this case are shown in table (7). As shown, phase-a has the greatest ratios when it compared with other phases due to the presence of arc re-strike. Comparing these results with previous results shown in table (6) we can state that, taking the ground-return parameters into account causes higher magnitudes of phases terminal voltages, and inter-contact recovery voltages of SF_6 CB.



(a) switched-off terminal voltages



(b) recovery voltages across SF_6 CB poles

Figure 8. Switched-off transitional voltages for 160 km line length with arc re-strike occurrence when the ground-return parameters were taken into account

Table 7. Ratios of transitional voltages for 160 km transmission line when the ground-return parameters were taken into consideration

phase	V [p.u]	ΔV [p.u]
a	2.06	2.86
b	1.81	2.63
c	1.87	2.74

Although taking the ground-return parameters into consideration overestimate the ratios of transitional voltages, these ratios do not exceed the triple value of the allowable voltage in transitional processes at switching off an unloaded overhead transmission line (see tables 6, 7).

To deeply compare between the results shown in tables (6, 7), figure (9) shows the percentage differences between them. It is clear that, the ground-return parameters have more impact on the phases that not experienced any arc re-strikes (phases b, c). Note that, the last phase switched-off (phase-b) has the greatest percentage differences on phases terminal voltages and recovery voltages when it compared with other phases.

Note that, the same behaviors were got for most lengths of the overhead transmission line under study when the return parameters of the homogenous ground are taken into account.

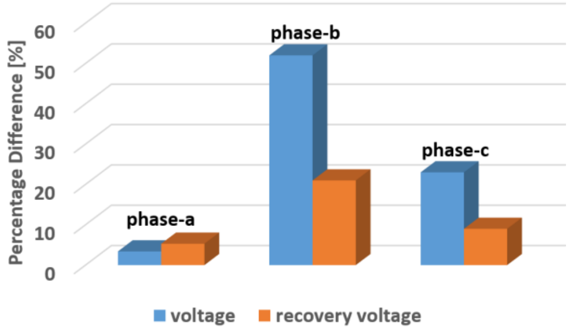
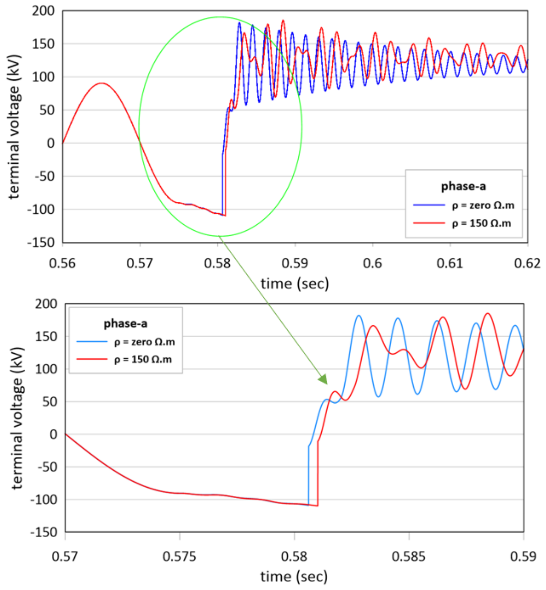


Figure 9. Percentage differences of transitional voltages at switching-off unloaded transmission line (160 km)

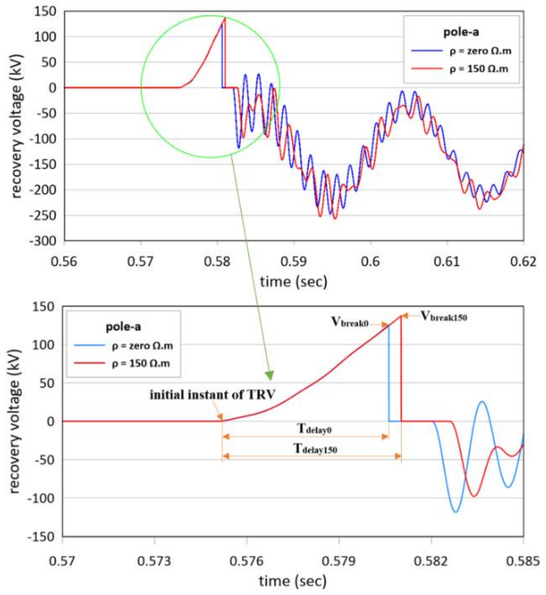
6.2 Effect of ground-return parameters on dielectric breakdown voltage of SF_6 CB and its time delay

The behavior of dielectric breakdown voltage of SF_6 CB inter-contact space taking into account the effect of ground-return parameters is investigated in this subsection. Figure (10) shows the waveforms of terminal voltages and recovery voltages of phase-a at switching-off overhead transmission line with length 160 km for the both cases of ground resistivity (zero Ω.m, 150 Ω.m). This figure clarifies the value of dielectric breakdown voltage of SF_6 circuit-breaker inter-contact space and the time required to reach it (time delay) of phase-a for the both cases of ground resistivity under study. As shown, as the time delay of breakdown increases, the dielectric breakdown voltage becomes higher. As a result, taking into account the effect of ground-return parameters leads to longer time delay ($T_{delay150}$) and consequently higher dielectric breakdown voltage ($V_{break150}$). This leads to higher values of transitional voltages. The reason of this behavior is related to RRRV during switching-off process as discussed before.

For more comprehensive, the maximum values of dielectric breakdown voltage across pole-a of SF_6 circuit-breaker when the transmission line length is changing from 80 km to 160 km are shown in figure (11). As shown, the value of dielectric breakdown voltage increases with the line length due to increasing the transmission line parameters (L, C) for the two cases of ground resistivity under study (zero Ω.m, 150 Ω.m). As a result, the maximum value of the dielectric breakdown voltage increases from 124 kV to 135 kV when the ground-return parameters were taken into account (ρ = 150 Ω.m). The same behavior was got for the case of zero ground resistivity. For this case, the dielectric breakdown voltage increases from 120 kV to 125 kV as shown. Remember that, in this case the ground-return parameters were not taken into account.



(a) terminal voltages on phase-a



(b) recovery voltages across pole-a

Figure 10. Transitional voltages of phase-a at switching-off using SF$_6$ circuit-breaker with arc re-strike occurrence for the both cases of ground resistivity

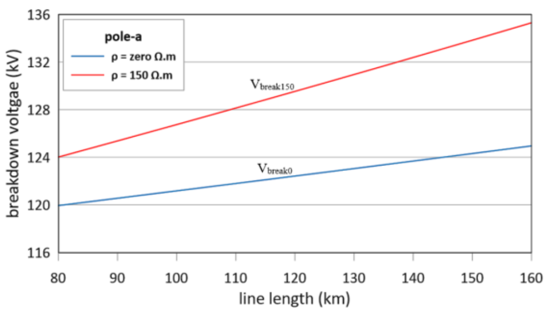


Figure 11. Dielectric breakdown voltages across pole-a of SF$_6$ circuit-breaker at unloaded transmission line switching-off for the both cases of ground resistivity

Since the transmission line capacitance is constant and not changed with the ground resistivity for the selected line length, the main parameter that affects the RRRV when the ground-return parameters are taken into account is the transmission line inductance. In our case study, taking the ground-return parameters into consideration (ρ = 150 Ω.m) increases the overall transmission line inductance which increasing the inductive coupling factor from 23% to 46% ($K_l = L_m/L_s$). This leads to decreasing of the RRRV and consequently increasing the time required for dielectric breakdown occurrence for SF$_6$ circuit-breaker inter-contact space. It other words, taking the ground-return parameters into account leads to higher values of dielectric breakdown voltages and consequently higher values of transitional voltages.

It should be mention that, the time required for dielectric breakdown occurrence of SF$_6$ circuit-breaker inter-contact space becomes higher when the transmission line length increases due to slower RRRV for the two cases of ground resistivity under study as shown in figure (12). As a result, the dielectric breakdown voltage increases from 125 kV to 135 kV for 160 km transmission line when the ground resistivity changed from zero Ω.m to 150 Ω.m (see figure 11). Consequently, the time required to achieve that increases from 5.6 msec to 6 msec (see figure 12).

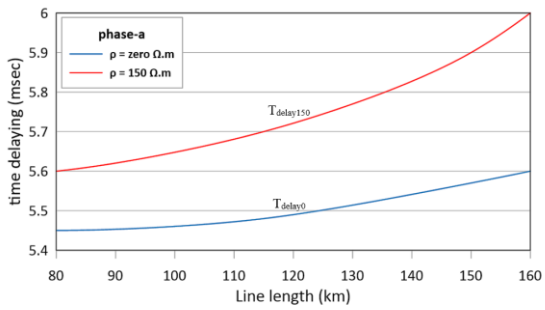


Figure 12. Time delay of dielectric breakdown voltages at switching-off unloaded transmission line using SF$_6$ circuit-breaker for the both cases of ground resistivity

6.3 Effect of ground-return parameters on natural free frequencies of transitional voltages

In this subsection, we will investigate the effect of ground-return parameters on the transitional voltages’ free frequencies when the transmission line length is changing from 80 km to 160 km. Figure (13) shows the behaviors of natural free frequencies of transitional voltages against the transmission line length for the both cases of ground resistivity under study (zero Ω.m, 150 Ω.m). These behaviors demonstrate how the natural free frequencies are affected by the transmission line length and by the ground-return parameters.

As shown, the natural free frequencies of transitional voltages decrease as the transmission line length increases for the both cases of ground resistivity under study. Furthermore, the transitional voltages have lower natural frequencies when the ground-return parameters are taken into account (ρ = 150 Ω.m). As a result, the range of natural free frequencies for the transmission line with lengths (80-160) km is reduced from (1200-575) Hz to (850-450) Hz when the ground-return parameters were considered into account. Note that, the higher frequencies correspond to the lower lengths of transmission line.

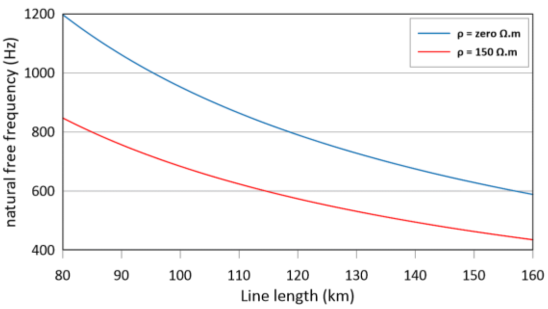


Figure 13. Natural free frequencies of transitional voltages at switching-off unloaded line using SF_6 circuit-breaker for the both cases of ground resistivity

7. CONCLUSIONS

Considering the actual value of ground resistivity into account at unloaded transmission line switching-off, makes it possible to investigate the ground effect on the transitional voltages during the switching-off process.

In general, the rate of rise of recovery voltage for the SF_6 circuit-breaker inter-contact space decreases as the length of overhead transmission line increases due to increasing of transmission line parameters (L, C). So, the transitional voltages (phases voltages, recovery voltages) have higher values for longer transmission lines due to the slow rate of rise of recovery voltage after the electric arc extinction.

Taking the ground-return parameters (Carson correction factors) into account via using the actual value of ground resistivity, increase the overall value of the transmission line parameters (R, L). In other words, considering the effect of ground-return parameters makes the rate of rise of recovery voltage becomes slower due to the higher transmission line inductance. As a result, it increases the time required for dielectric breakdown of SF_6 circuit-breaker inter-contact space, and consequently higher value of dielectric breakdown voltage. This in turn, overestimates the transitional voltages during switching-off processes. Furthermore, it can improve the stability of the differential equations numerical solutions via reducing the free frequency oscillations of the transitional voltages.

REFERENCES

1. Manuel Reta-Hernández, “Electric Power Generation, Transmission, and Distribution,” 3rd Edition, CRC Press, 2012.
2. H. Wayne Beaty, “Handbook of Electric Power Calculations,” The McGraw-Hill Companies, 2000.
3. S. Kurokawa, J. P. Filho, M. C. Tavares, C. M. Portela & A. J. Prado, “Behavior of Overhead Transmission Line Parameters on the Presence of Ground Wires,” IEEE Transactions on Power Delivery, vol. 20, no. 2, pp. 1669–1676, 2005.
4. A. Margitová, M. Kanálik & M. Kolcun, “Impact of Ground Wires on the Series Impedance, Voltage and Current Conditions of Overhead Power Lines,” Acta Electrotechnica et Informatica, vol. 19, no. 1, pp. 11–18, 2019.
5. J. R. Carson, “Wave Propagation in Overhead Wires with Ground Return,” Bell System Technical Journal, vol. 5, pp. 539–554, 1926.
6. F. Pollaczek, “Uber Das Feld Einer Unendlich Langen Wechselstrom Durchlossenen Einfachleitung,” E. N. T., vol. 3, no. 9, pp. 339–359, 1926.
7. Theofilos A. Papadopoulos, Grigoris K. Papagiannis & Dimitris P. Labridis, “A Generalized Model for the Calculation of the Impedances and Admittances of Overhead Power Lines above Stratified Earth,” Electric Power Systems Research, vol. 80, no. 9, pp. 1160–1170, 2010.
8. Anastázia Margitová, Michal Kolcun & Martin Kanálik, “Impact of the Ground on the Series Impedance of Overhead Power Lines,” Transactions on Electrical Engineering, vol. 7, no. 3, pp. 47–54, 2018.
9. T. Lazimov, S. Akhundov, “Modeling of Electrical Strength of High Voltage Circuit-Breakers,” Proceedings of the International Symposium SIEMA’2001, Kharkov, Ukraine, pp. 112-114, Oct. 2001.
10. L. Van der Sluis, “Transients in Power Systems,” New-York, John Wiley & Sons, 2001.
11. Ruben D. Garzon, “High Voltage Circuit Breakers Design and Applications,” New-York, Marcel Dekker, 2002.
12. H. Drebenstedt, W. Rother, F. Paul & P. Schaller, “Support of the Development of High Voltage Circuit-Breakers by a Mathematical Breaker Model,” CIGRE, 13(02), 1986.
13. L. F. Shampine, “Numerical Solutions of Ordinary Differential Equations,” New-York, Chapman and Hall, 1994.
14. E. Hairer, S. P. Norsett & G. Wanner, “Solving Ordinary Differential Equations-Part 1,” Springer-Verlag, Berlin, Heidelberg, 1987. https://www.mathworks.com/help/matlab/math/solve-stiff-odes.html
15. T. M. Lazimov, S. V. Imanov, “On Stability While Simulating Switching-Offs the Capacitive and Small Inductive Currents,” Proceeding of the MEPS’06 International Symposium, Wroclaw, Poland, Sep. 2006.

16. W. A. Lewis, P. D. Tuttle, "The Resistance and Reactance of Aluminium Conductors, Steel Reinforced," Transactions of The American Institute of Electrical Engineers, Part III: Power Apparatus and Systems, vol. 77, issue 3, pp. 1189 – 1214, 1958.
17. Working Group B2.43, "Guide for Thermal Rating Calculations of Overhead Lines," Dec. 2014.
18. E. D. Sunde, "Earth Conduction Effects in Transmission Systems," Dover Publications, New York, 1968.
19. M. Vintan, P. I. Mihu & I.Borlea, "AC Power Lines Impedances Computational Methods," journal of sustainable energy, vol. 2, no. 2, June 2011.
20. Tainá Fernanda Garbelim Pascoalato, Anderson Ricardo Justo de Araújo, Pablo Torrez Caballero, Jaimis Sajid Leon Colqui & Sérgio Kurokawa, "Transient Analysis of Multiphase Transmission Lines Located above Frequency-Dependent Soils," Energies, vol. 14, issue 17, August 2021.
21. J. Duncan Glover, Thomas J. Overbye & Mulukutla S. Sarma, "Power System Analysis & Design," Sixth Edition, Cengage Learning, USA, 2017.
22. William H. Kersting, "Distribution System Modeling and Analysis," 4th Edition, CRC Press, 2018.
23. V. Kasturi, P. Chowdhuri, "Effects of Soil Parameters on the Wave Propagation along Overhead Lines," Journal of the Tennessee Academy of Science, United States, vol. 68, no. 2, 1993.
24. Ivan Krolo, Tonći Modrić & Slavko Vujević, "Definition and Computation of Carson Formulas," Proceeding of 2nd International Multidisciplinary Conference on Computer and Energy Science (SpliTech), July 2017.
25. INSU KIM, "A New Single-Logarithmic Approximation of Carson's Ground-Return Impedances-Part 1," IEEE Access, power & energy society section, vol.9, pp. 103850–103861, July 2021.
26. G. J. Palacky, "Resistivity Characteristics of Geologic Targets," Electromagnetic Methods in Applied Geophysics, vol. 1, January 1987.
27. Jan B. Rhebergen, Henk A. Lensen, Piet B. W. Schwering, Garciela Rodriguez Marin & Jan M.H. Hendrickx, "Soil Moisture Distribution Around Land Mines and the Effect on Relative Permittivity," Proceedings of the SPIE - The International Society for Optical Engineering, vol. 4742, Aug. 2002.
28. Washington Colon Castillo Jurado, Miguel Castro Fernandez, Wilber Manuel Saltos Arauz & Julio Cesar Hernandez Chilan, "Transposition of Medium and Long Transmission Lines," International Journal of Physical Sciences and Engineering, vol. 3, no. 1, pp. 1–9, 2019.
29. Arif M. Gashimov, Aytek R. Babayeva & Ahmet Nayir, "Transmission Line Transposition," Proceedings of the international Conference on Electrical and Electronics Engineering (ELECO 2009), 2009.
30. G. V. B. Chary, K. Roslina, "Comparison of Transmission Line Models by Excluding Frequency Dependence in Complex Power System for Error Estimation," Journal of Operation and Automation in Power Engineering, vol. 12, no. 1, pp. 77–90, 2024.
31. H. H. El-Tamaly, H. A. Ziedan, "Sequence Impedances of Overhead Transmission Lines Carson's Method Versus Rudenberg's Method," Proceedings of the 41st International Universities Power Engineering Conference, Sep. 2006.
32. V. K. Mehta, Rohit Mehta, "Principles of Power System," S. Chand Publishing, 2005.