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Ground fault location analysis on transmission lines using MATLAB/Simulink environment

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Abstract

With the continued expansion of the power systems, the accuracy of fault diagnosis on power transmission lines is crucial to ensure their safe and stable operation. A single-phase-to-ground fault can occur anywhere along an overhead transmission line. The amplitude of the fault current and its variation over time depend on the distance between the transformer substation and the fault location. This paper introduces a MATLAB/Simulink programmatic modelling framework for a faster simulation of fault scenarios in a given power system. It also presents the single-phase-to-ground fault current signal features for various fault locations. Both the amplitude of the current and the voltage decreases when the distance from the busbars of the station increases, with the current declining steeper than the voltage.

Keywords: ground fault, overhead transmission lines, fault location, Matlab, Simulink

1. Introduction

The synergy between power systems theory with the tools provided by MATLAB-Simulink environment continues to push the boundaries of power transmission networks analysis. MATLAB and Simulink are both software tools developed by MathWorks [1]. Using the MATLAB/Simulink environment, many models have been implemented for the design of a power transmission network, the assessment of different power quality problems, or for the analysis of faults in power systems. Its extensive simulation capabilities allow extensive modelling and in-depth analysis of different types of faults. For example, the „Single-Pole Reclosing of a Three-Phase Line" [2] model simulates a 735 kV line experiencing a phase-to-ground fault and demonstrates how selective protection isolates only the faulted phase, allows the arc to extinguish, and then automatically recloses it, with shunt reactors stabilizing voltage and preventing restrikes. Similarly, the „Three-Phase Series Compensated Network" [3] represents a 2100 MVA power plant delivering energy through 600 km of 735 kV lines segmented into 300 km sections. In this model, series capacitors reduce line reactance to increase transmission capacity, while shunt reactors maintain voltage stability during normal operation and faults. The „IEEE 13 Node Test Feeder" [4] illustrates an unbalanced distribution network composed of 13 nodes, allowing users to modify phase voltages, amplitudes, and phase angles, as well as inject active or reactive power, to study the impact of unbalanced loads. The „Unified Power Flow Controller

(UPFC) Phasor Model” [5] shows how a UPFC with two 100 MW IGBT converters can balance power flow in a looped transmission system and eliminate transformer overloads, demonstrating flexible control under low- to medium-flow conditions. The „Initializing a 5-Bus Network with the Load Flow Tool of Powergui” [6] example models a 125 kV system supplied by a 9 MW wind farm and a 150 MW plant. The wind farm connects through a 25 kV distribution line with two transformers, a dynamic load, and grounding, while the larger plant feeds the high-voltage grid via a 13.8/125 kV transformer. Using Powergui’s Load Flow tool, users can adjust block parameters and observe power flow and node voltages across the five-bus network. Larger networks are represented in the „29-Bus, 7-Power Plant Network” [7], combining seven hydro turbines and a 9 MW wind farm feeding 29 buses, where users can introduce faults and calculate load flow for each bus to analyze system responses. For cable systems, the „Four Coupled 66-kV Cables / Power Cable Parameters” [8] model calculates R, L, and C parameters for four parallel underground cables feeding two 66 kV loads over 30 km, comparing PI-section and frequency-dependent line models to show how cable placement and modeling choices affect induced voltages. The „STATCOM Phasor Model” [9] simulates a device STATCOM that regulates voltage by controlling active and reactive power in a 500 kV transmission line. Installed at the midpoint of a 600 km line, it can vary its output by ±100 MW, significantly improving voltage stability compared to when it is off. A STATCOM unit is also used in the „Flickermeter on a Distribution STATCOM” [10] model, where a flickermeter—a standardized instrument based on the lamp-eye-brain response—measures voltage fluctuations that cause light flicker. The „Performance of Three PSS for Interarea Oscillations” [11] model represents a four-generator, two-area power system where the areas are interconnected by two 230 kV transmission lines of about 220 km each. It is designed to study low-frequency electromechanical oscillations in large networks and to compare the damping provided by three different Power System Stabilizers (PSS). By applying the PSS variants to this benchmark system, the simulation highlights how each controller improves the stability of inter-area oscillations.

A single-phase-to-ground fault can occur anywhere along an overhead transmission line. The amplitude of the fault current and its time variation depend on the fault location, i.e., the distance from the substation to the fault location. The accurate estimation of ground fault currents is essential for the design of grounding installations in electrical transmission and distribution networks, therefore this topic has been the subject of extensive research, with numerous analytical methods published [12], [13], [14], [15], [16], [17], [18], [19]. When a single-phase-to-ground fault occurs on an overhead transmission line in a three-phase power network with grounded neutral, the fault current returns to the grounded neutral through the tower structures, ground return path and ground wires, respectively. In our previous works, analytical methods have been presented to estimate the distribution of ground-fault currents in effectively grounded power networks for a ground fault located along the transmission line. It was shown that the ground fault splits the transmission line into two sections, each spanning from the fault to one end of the line. Depending on the number of towers between the faulted tower and the stations, and the span length, these two line sections can be considered either infinite, in which case the distribution of the ground-fault current is independent of the network end; or as finite, in which case the distribution of the ground-fault current may be highly dependent on the network end [13], [14], [15].

In this paper, the facilities offered by the MATLAB-Simulink environment are exploited. Thus, the Simulink environment serves as a visual platform for developing and testing models. Using the *Simscape Electrical toolbox*, it is possible to simulate various faults, including single-phase-to-ground faults, in an electrical network, by using the *Three-Phase Fault block* [20]. To analyse the influence of the fault location on the values of voltages and currents it is necessary to move the fault block in Simulink after each quadripolar electrical schematic modelling the overhead transmission line. For a complex network structure, this method is time-consuming. In this case, in order to reduce the required manual workload, a MATLAB program will be created to autmatically move the fault block to the targeted distance from the end of the power line. In this way, it is possible to estimate the distribution of the single-phase-to-ground-fault currents, by considering the location of the fault at, practically, any tower of the transmission line. Then, using the MATLAB-Simulink environment (version R2024b), the influence of the fault location on the values of voltages and currents is assessed. The analysis of the influence of the fault location provides a deeper understanding of the behaviour of three-phase power network during faults and facilitates the design of protection systems.

2. The Simulink model of the considered power system

To study the impact of ground fault location on the single-phase-to-ground fault current using the blocks from *Simscape Electrical toolbox*, a Simulink model is proposed. To build a valid test feeder, a power system available in the literature [21] was modelled. The single line diagram of the power system is presented in Figure 1 and includes the following components:

- the power plant G1 equipped with three generators, each with a power of 100 MW;
- the power plant G2 equipped with four generators, each with a power of 100 MW;
- the transformer stations TR1, TR2, TR3 and TR4;
- the double-circuit overhead power lines L1 and L4;
- the single-circuit overhead power lines L2 and L3;
- the consumer C1, considered the main consumer;
- the consumer C2, representing a medium-sized city;
- the consumer C3, representing an industrial zone and a large town.

The power plant G1 ensures the supply of electricity via the 220 kV busbars of the network. The power plant G2 supplies the local consumer C2 through the 10 kV busbar, directly connected to its terminals, and, through the transformer station Tr3, the system on the 220 kV busbar.

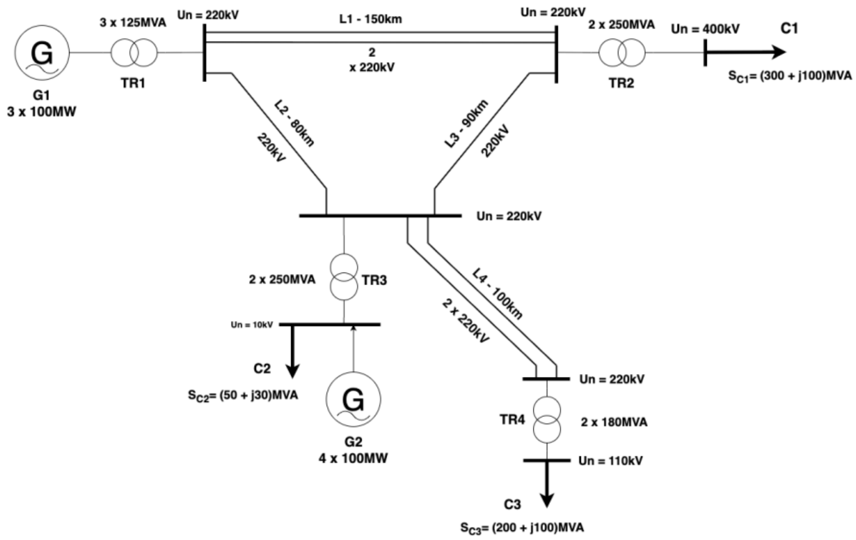

Figure 1 The Power system

MATLAB/Simulink provides specific blocks in its libraries, that enable the modelling of power system elements. The *Simscape Electrical toolbox* provides prebuilt blocks for generators, transmission lines, transformers, loads, faults, and relays. The data presented in Tables 1, 2 and 3 were used to calculate the parameters of the power system components [21], [22], [23]

Tabel 1 Characteristics of generators [21]

Power Plant	Type	Number of generators	Nominal power P_n (MW)	Nominal voltage U_n (kV)	Nominal power factor cosρ	Synchronous reactance X	Transient reactance X	Surge reactance X
G1	TB2-100-2	3	100	15.75	0.85	1.803	0.203	0.138
G2	TB1-100-2	4	100	10.5	0.85	1.795	0.283	0.183

Tabel 2 Characteristics of transformers [21]

Station	No. of transformers	Nominal power S_n (MVA)	Nominal primary voltage U_{np} (kV)	Nominal secondar y voltage U_{ns} (kV)	Short-circuit voltage u_{sc} (%)	Short-circuit active power losses p_c (kW)	No-load power losses p_j (kW)	No-load current i_0 (%)	Primary/ secondary connection
TR1	3	125	15	242	11	380	135	3	Δ/Y_0
TR2	2	250	220	420	13	700	250	1	Y_0/Y_0
TR3	2	250	10	242	14	650	240	2.5	Δ/Y_0
TR4	2	180	121	220	12	760	320	3.2	Y_0/Y_0

Tabel 3 Characteristics of transmission lines [21]

Line	No. of circuits	Nominal voltage U_n (kV)	Length km	Resistance			Inductive reactance			Capacitive susceptance		
				Ω/km	of circuit Ω	of line Ω	Ω/km	of circuit Ω	of line Ω	μS/km	of circuit μS	of line μS
L1	2	220	150	0.07	10.5	5.25	0.432	64.8	32.4	2.63	394.5	789
L2	1	220	80	0.07	5.6	5.6	0.421	33.68	33.7	2.71	216.8	216.8
L3	1	220	90	0.07	6.3	6.3	0.421	37.89	37.9	2.71	243.9	243.9
L4	2	220	100	0.07	7	3.5	0.432	43.2	21.6	2.63	263	526

Using specialized blocks available in the MATLAB-Simulink libraries, the model shown in Figure 2 was built.

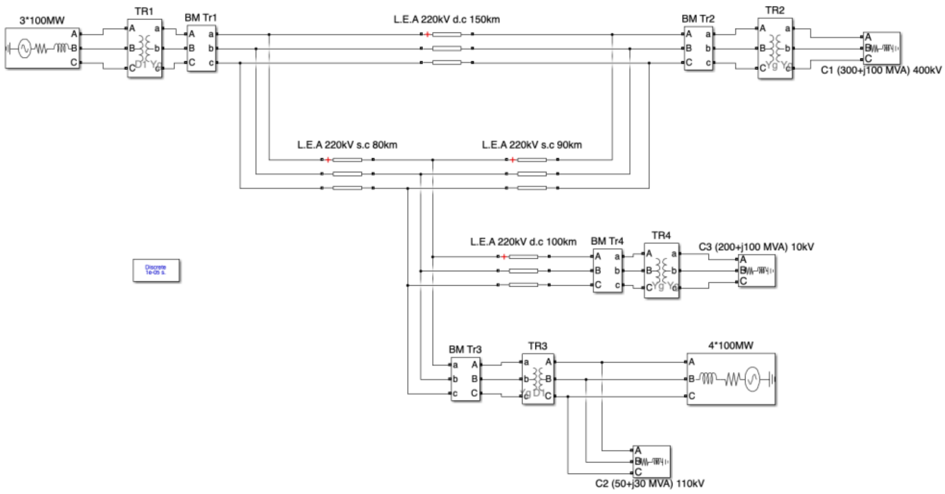

Figure 2 The MATLAB/Simulink model

The validation of the numerical model was done by analysing the normal operating regime. Thus, the values of the voltages and currents in the normal operating mode from the Simulink model were compared against those presented in the literature [21]. The results obtained from the simulations show minimal errors (relative current error: 0.052 %; relative voltage error: 0.183 %).

3. Program implementation in MATLAB/Simulink

The working method implemented in this article is presented in Figure 3.

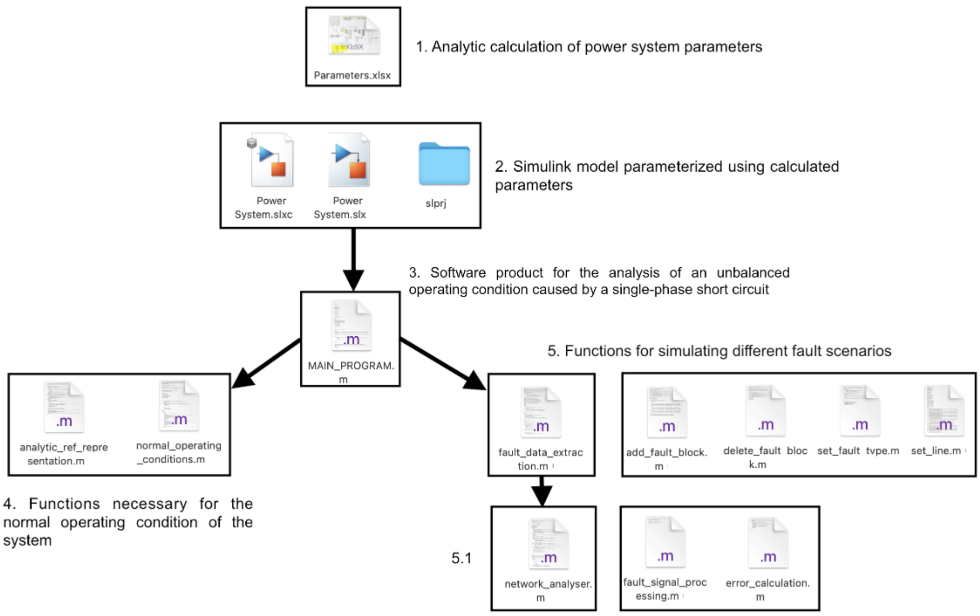

Figure 3 Workflow implemented in the project

The six stages on which the program was built are described in detail. In the file *Parameters.xlsx*, the necessary calculations were performed to determine the parameters of the equivalent schemes of the power system. The Simulink program, shown in Figure 2, is saved as *Power Systems.slx*. The *MAIN_PROGRAM.m* block defines the program code that contains all the functions subsequently called. The .m files labeled with number 4 define the stage for displaying voltage and current values as graphs under normal operating conditions. The function block labeled with number 5 contains the functions for fault simulation, the definition of fault conditions, and the extraction of data related to the power system during a single-phase fault. In stage 5.1, the .m files are defined to perform fault-signal processing, error calculation, and the graphical representation of voltage and current in the power system under fault conditions.

To analyse the influence of the fault location on the values of voltages and currents, a single-phase-to ground fault along the 220 kV double-circuit transmission line L1 (Figure 1) is considered. For different fault locations along the entire length of the L1 power line, instead of a single quadripolar equivalent scheme the transmission line L1 was modelled by a series of identical quadripolar equivalent schemes, each corresponding to a certain length. Specifically, for L1 having 150 km, 10 quadripolar equivalent schemes were considered, each corresponding to a 15 km stretch of line. In this way, the influence of the fault location can be studied by moving the block modelling the single-phase-to-ground fault (Figure 4).

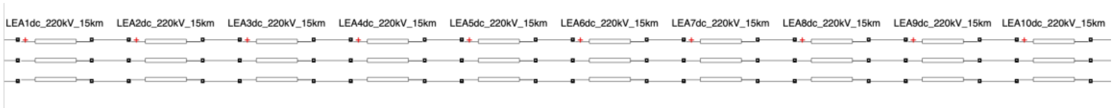

Figure 4 The model of the overhead transmission line L1

The Simulink environment allows the simulation of a single-phase short-circuit in the electrical network using a fault block ("*Three-Phase Fault*") [20]. The classic way of introducing the fault block into the Simulink model is usually done manually by the user, by positioning it in the desired location. To analyse the influence of the fault location on the values of voltages and currents it is necessary to move the fault block in Simulink after each quadripolar equivalent schematic modelling the overhead transmission line. To make this task less time-consuming, a MATLAB program, called *Function „add_fault_block()”*, that automatically moves the fault block after each quadripolar equivalent scheme (Figure 5) was created. The program *Function* "*add_fault_block()*" contains functions that use predefined commands: *"add_block()"* to add the block at the desired location in the modelled system and *"add_line()"* to make connections between the transmission line sections.

```
function [L1,L2,L3,blk]=add_fault_block(nr_block)
% add_fault_block - add fault block...

x=((nr_block-1)*135)+50;
y=300;
% poz=[x,y,width,length];
poz=[x,y,x+50,y+50];

blk=add_block('powerlib/Elements/Three-Phase Fault', ...
    'SEE/Three-Phase Distributed Line/Fault', ...
    'Position',poz);

switch nr_block
    case 1
        connections_out=["LEA1dc_220kV_15km/RConn 1","LEA1dc_220kV_15km/RConn 2","LEA1dc_220kV_15km/RConn 3"];
    case 2
        connections_out=["LEA2dc_220kV_15km/RConn 1","LEA2dc_220kV_15km/RConn 2","LEA2dc_220kV_15km/RConn 3"];
    case 3
        connections_out=["LEA3dc_220kV_15km/RConn 1","LEA3dc_220kV_15km/RConn 2","LEA3dc_220kV_15km/RConn 3"];
    case 4
        connections_out=["LEA4dc_220kV_15km/RConn 1","LEA4dc_220kV_15km/RConn 2","LEA4dc_220kV_15km/RConn 3"];
    case 5
        connections_out=["LEA5dc_220kV_15km/RConn 1","LEA5dc_220kV_15km/RConn 2","LEA5dc_220kV_15km/RConn 3"];
    case 6
        connections_out=["LEA6dc_220kV_15km/RConn 1","LEA6dc_220kV_15km/RConn 2","LEA6dc_220kV_15km/RConn 3"];
    case 7
        connections_out=["LEA7dc_220kV_15km/RConn 1","LEA7dc_220kV_15km/RConn 2","LEA7dc_220kV_15km/RConn 3"];
    case 8
        connections_out=["LEA8dc_220kV_15km/RConn 1","LEA8dc_220kV_15km/RConn 2","LEA8dc_220kV_15km/RConn 3"];
    case 9
        connections_out=["LEA9dc_220kV_15km/RConn 1","LEA9dc_220kV_15km/RConn 2","LEA9dc_220kV_15km/RConn 3"];
end

L1=add_line('SEE/Three-Phase Distributed Line',connections_out(1),'Fault/LConn 1');
L2=add_line('SEE/Three-Phase Distributed Line',connections_out(2),'Fault/LConn 2');
L3=add_line('SEE/Three-Phase Distributed Line',connections_out(3),'Fault/LConn 3');

end
```

Figure 5 Function „add_fault_block()”

The input parameters of the function include the desired position of the fault block and the total number of faults to be simulated. For the automatic definition of the connections, the program uses a *"switch"* structure which sets the appropriate connection pairs for each section. In addition, the function returns variables containing information about the added block, allowing it to be subsequently modified or deleted depending on the simulated scenario. Figure 6 presents the function that changes the position of the fault block along the transmission line L1.

```
for i=1:block_step:nr_blocks
    [L1,L2,L3,blk]=add_fault_block(i);
    set_fault_type(fault_parameters,F_resistance(1),G_resistance(1));
    out=sim('SEE.slx');
    data_current4=out.Trafo1(:,1:3);
    data_voltage4=out.Trafo1(:,13:15);
    for j=1:3
        date_fault_current_location(:,(i-1)*3+j)=data_current4(:,j);
        date_fault_voltage_location(:,(i-1)*3+j)=data_voltage4(:,j);
    end
    delete_fault_block(L1,L2,L3,blk);
end
```

Figure 6 Extraction of three-phase system data of currents and voltages for analysing the influence of the distance between the fault location and the transformer substation TR1

Thus, using the functions *"add_fault_block()"* and *"set_fault_type()"* the defect block is added and set accordingly. The fault block parameters values are given in Table 1.

Tabel 1 Fault block parameters for analysing the influence of the distance from the fault location to the transformer substation TR1

Faulted phases	Fault duration (s)	Fault resistance– F_resistance (Ω)	Ground resistance – G_resistance (Ω)
Phase 1	[0.04 0.25]	0.1	0.1

In Figure 7 the transition of the fault block between those ten sections of the L1 equivalent quadripolar schemes is presented.

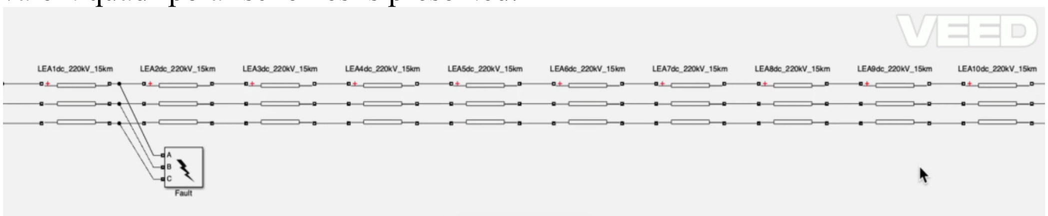

Figure 7 The transition of the fault block between line L1 sections

4. Results

A single-phase-to-ground fault can occur anywhere along a transmission power line. To determine how the fault location influences the amplitude of the single-phase-to-ground fault current, such a fault along the line L1 was simulated. Figure 8 shows the voltages measured on the busbars of the TR1 transformer station in the event of a fault occurring at different distances from it.

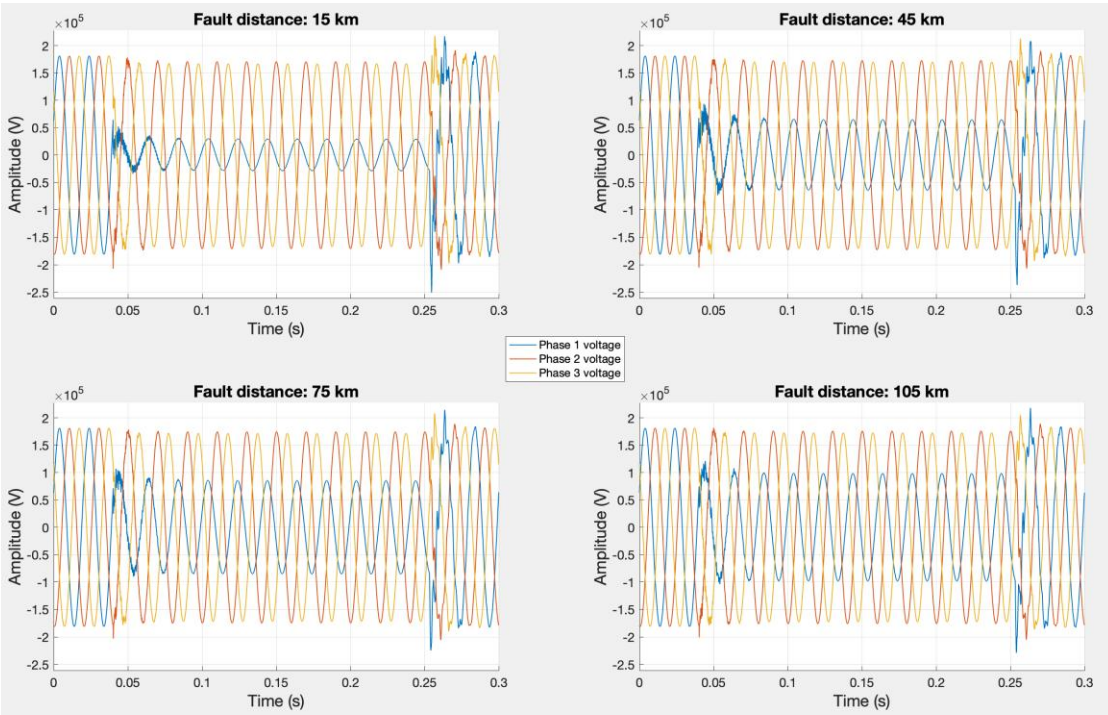

Figure 8 Voltage amplitude as a function of the distance from the fault

Figure 9 presents the currents for the four distances considered.

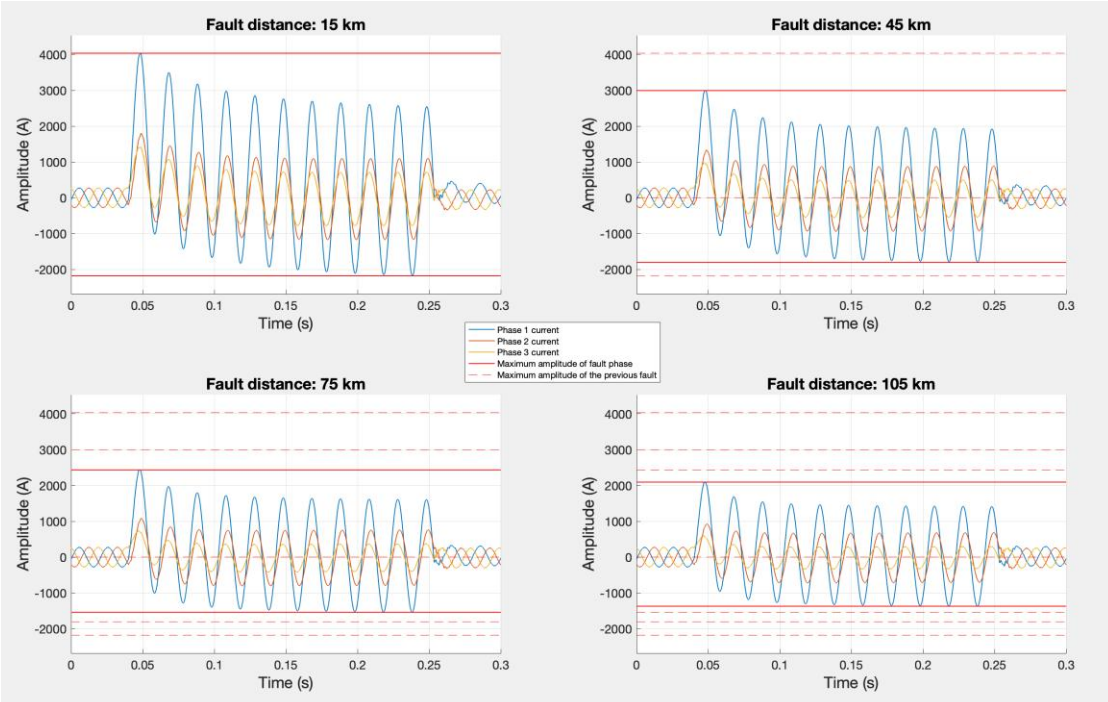

Figure 9 Current amplitude as a function of the distance from the fault

It is observed that the amplitude of the currents decreases with increasing distance from the busbars of the station.

5. Conclusions

MATLAB-Simulink is a widely used platform for power system modelling, simulation, and analysis.

This paper had two main objectives: firstly, the implementation in the MATLAB/Simulink environment of a program for a faster fault simulation, and, secondly, the analysis of the influence of the fault location on the single-phase-to-ground fault current in a power transmission network. The advantage of the proposed MATLAB program is that it makes it possible to estimate the distribution of fault currents considering the influence of various factors on the values of currents and voltages, i.e., the location of the fault at, practically, any transmission line tower.

Realistic fault scenarios were simulated, providing interesting outputs well correlated with other related work [12], [13], [14], [15], [21], [22], [24]. It has been shown that the amplitude of the currents decreases with increasing distance from the station busbars. As the distance between the fault location and the substation increases, the voltage has a more attenuated decrease. This behaviour is explained by the influence of the longitudinal impedance and transverse admittance of the power line. As the values of these transmission lines parameters increase, they influence the ground fault current and voltage amplitude significantly. The transient duration also decreases with increasing distance between the fault location and the transformer substation.

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