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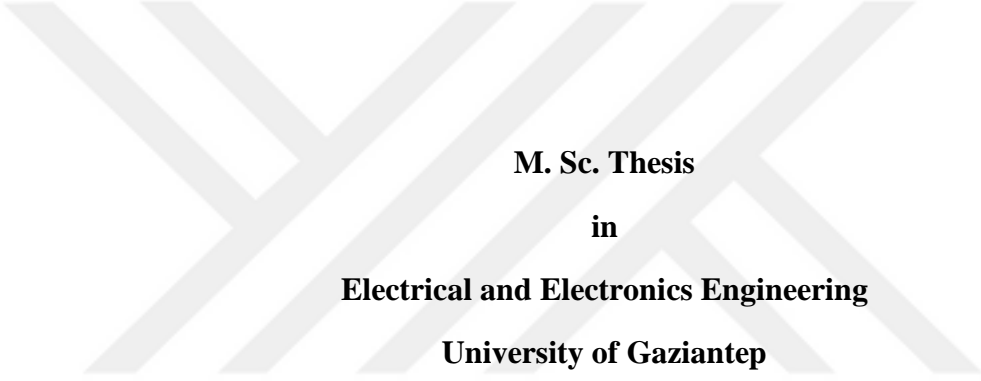**GRADUATE SCHOOL OF**
NATURAL & APPLIED SCIENCE

TRANSIENT VOLTAGE DISTRIBUTION ON THE SINGLE-PHASE

TRANSMISSION LINE UNDER SHORT CIRCUIT FAULT EFFECT

M. Sc. THESIS

IN

ELECTRICAL & ELECTRONICS ENGINEERING

BY

ALAA KOJAH

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Transient Voltage Distribution on The Single-Phase

Transmission Line Under Short Circuit Fault Effect

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Supervisor

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Alaa KOJAH

ABSTRACT

TRANSIENT VOLTAGE DISTRIBUTION ON THE SINGLE-PHASE TRANSMISSION LINE UNDER SHORT CIRCUIT FAULT EFFECT

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M. Sc. In Electrical and Electronics Engineering

Supervisor: Prof. Dr. Arif NACAROĞLU

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Single phase transmission lines are used to transfer data or energy between two users. Transient conditions such as switching operations and short circuit faults cause the generation of the fluctuation on the waveform to be transmitted. Spatial voltage distribution on the single-phase transmission line may change owing to the position and duration of the short circuit fault in the system. In this paper, the state space representation of the single-phase transmission line for short circuit fault and for various types of terminations is given. Since the transmission line is modeled in time domain using distributed parametric elements, the mathematical representation of the event is given in state space (time domain) differential equation form. It also makes easy to solve the problem because of the time and space dependent characteristics of the voltage variations on the distributed parametrically modeled transmission line.

Keywords: Energy transmission, transient effects, transmission line, transient voltage, RLC short circuit, single phase.

ÖZET

TEK FAZLI SİSTEMLERDE KISA DEVRE HATALARI NEDENİYLE OLUŞAN GEÇİŞ HAREKETLERİNİN İNCELENMESİ

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Danışman: Prof. Dr. Arif NACAROĞLU
Kasım 2018
42 sayfa

Bilgi ve enerjinin iletimi için genellikle çok veya tek fazlı iletim sistemleri kullanılmaktadır. İletim sistemlerinin herhangi bir noktasında oluşabilecek kısa devre ve anahtarlamadan kaynaklanan hatalar iletilen voltaj şekli üzerinde dalgalanmalara sebep olmaktadır. Boyutsal olarak uzanan iletim hattının üzerinde oluşacak kısa devre hatasının süresi ve yeri dalga şeklini doğrudan etkilemektedir. Bu çalışmada, tek fazlı iletim hattının uzay-durum denklemleri kullanılarak elde edilen modeli üzerine uygulanacak değişik senaryoların dalga şeklini ne şekilde etkileyeceğine ilişkin bir model oluşturulmuş ve değişik sonlandırma elemanları (yük) için sonuçlar elde edilmiştir.İletim hattının tamamı uzay durum denklemleri ile modellendiğinden dağınık parametre metodu kullanılarak modellenebilecek iletim hatları birbirini takip eden doğrusal sıradan difransiyel denklemleri zaman domeyni kullanılarak modellenmiştir. Bu yaklaşım aynı zamanda denklemlerinin modellenmesini ve çözülmesini de kolaylaştırmıştır.

Anahtar kelimeler: Enerji iletimi, geçiş etkileri, iletim hattı, geçiş voltajı, RLC kısa devre, tek fazlı.

ACKNOWLEDMENTS

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CHAPTER 1

INTRODUCTION

Transmission lines are widely used in any kind of data transmission at various frequencies. Depending on the frequency of data to be transmitted physical structures of transmission medium may change. Generally, the waveguides [1] are used for microwave levels while the optic mediums [2] are preferred for shorter wave lengths. For lower frequencies the copper wires are used although their loss and inductive effects many cause the loss of energy to be transmitted [3].

At relatively lower frequencies generally copper wires are used for any kind of energy. Because of their high internal resistances, some of the transmitted energy is converted into heat during the transmission depending on the level of the current flowing in the line [4]. In some amounts it may be acceptable but fortunately it does not cause the change on the shape of the waveform. But more than that, owing to the length of the medium, the inductive and capacitive behavior of the medium changes the shape of the voltage in some levels and it directly effects the quality of the voltage waveform. The high inductance and high capacitance equivalents of the structure not only the reason of the loss of the energy but also the change of the wave shape of the voltage and current in the line [5].

In general, the energy in the worldwide systems are transmitted at 50 or 60 Hz sinusoidal form at different voltage levels. To decrease the copper losses in the systems the only way is to increase the quality of the material (use of super conductors, etc.) and it will cause the high cost in the system. Comparing to power loss due to copper effect and the cost of better systems, the copper lost is unfortunately accepted as not primary problem in the energy transmission. At high voltage applications, since the energy is generated in 3-phase form as 3 independent voltage coils, the optimum number of the line which is enough to

transfer 3 sources changes with respect to their connection types. Normally star and delta connections are presented in the literature which are obtained connecting some lines as common nodes. Both connection types have their own advantages and disadvantages.

In normal conditions, the time domain modelling of the transmission lines is easy and to compute the source [6], transmission and load relations, simple circuit equations are sufficient. In these models, some assumptions may more increases the simplicity of the model. But under some abnormal conditions, such as short circuit in somewhere in the transmission line between source and load, the circuit models should be more complicated.

Due to single or multi short circuit faults happening in different points on the transmission line with different durations, the waveform of the output is different than the transmitted waveform [7], [8]. Although the transmission line is modeled generally as distributed parametric form, it is also possible to cut the line into small RLC circuit form which are cascaded. In this model each part is time invariant and the values of the elements R, L, and C depends on the length of the line. During the transmission, because of any and many reasons, the transmission may be cut due to the short circuit fault between two lines. And the left and right side of the line may behave two different lumped circuit. The schematic view of the simulated structure is given in subsequent chapters. Since the transmission line considered in this work is single phase, the wires have internal resistances, inductances (efficient for high frequencies) and capacitance between two wires.

The duration of the short circuit fault affects the part of the circuit between source and fault and between the fault and load in a different way. Since, generally, the equivalent circuit values for transmission lines vary from manufacturer to manufacturer, and material to material. To pass the short circuit fault to normal conditions, the speed of the variation of the voltage on the transmission line which is the transient time affects the minimum necessary number of the cascaded sections [9]. The simulation is designed to be adaptive to variations in these values. The model is a continuous time invariant system model and for the solution, the conventional state space formulation and solution can be used.

Electromagnetic transients may be simulated in a transmission line and this process is usually done caring its distributed characteristics and the speed dependence of the parameters through the line [12]. For each part (section) of the transmission line, since the circuit is modeled by RLC components, the voltage of each capacitor and current of each inductor can be written in the differential equation form in the time domain. These equations are first order two dimensional sets of differential equations [13]. The time domain formulation modulated for transient analysis is very commonly applied method which is used for the analysis of the linear circuits. The correctness and the quality of the result highly depends on the number of the lumped sections. More lumped section gives better result but it costs the calculation time. The above mention case is valid for single and three phase systems but without losing the generality of the method, an only single-phase transmission lines will be taken into consideration.

Single phase transmission line has two wires. One of the wires is used as ground wire. In some applications of the equivalent model representation the ground wire may be also simulated by the conductance which is namely the explicit representation. Otherwise the value of the ground line is hidden into the phase conductor [14]. In either case the mathematical modulization and its solution is not changed.

In [15], transmission line is simulated using many RLC lumped circuits which are connected in the cascade form and the general distributed characteristics of the line is kept in the model. The number of the sections in the lumped model can easily be decided if the acceptable error range for lumped parameter approximation is initially known. The highest limit for the number of the section is controlled by the speed of the calculation. More section means better and correct result as if the system is solved using the distributed parametric representation.

But more sections mean not economical because of longer computer run time, and an unwanted error may be collected owing to the large number of numerical calculations.

Although the analytical solutions of the state space model are possible for only distortion less and lossless transmission lines with resistive loads, the distributed parametric model may be used using the numerical differentiation such as Runge-Kutta method for more realistic cases.

CHAPTER 2

LİTERATURE REVİEW

The flow of energy and current demand by simply are the power, when the value of flow is increased also the value of power is going to increase that's related by current, voltage and frequency. So, the performance of the quality range of the power is connected to the efficiency of the electronic components, directly.

The electric transmission and electric distribution to the end user of the electric power by move the electric through the wiring system until it reaches the load with variations in generation, weather, demand, distance, and other factors provide many reasons effect to the quality of electric that move to the load.

Voltage surges are becoming more important if fluctuations are nearly instantaneous or occurs for longer time duration, when the voltage is 110% [5], 220% or more above normal. when heavy electrical equipment and other high tech equipment being turned off can exposed to kind of risk and wrongs in its electric parts such as equipment shutoff, flickering lights, errors or memory loss and others of risk. So many engineers see the solution is adding uninterruptable power supplies, surge suppressors, voltage regulators and resistances to prevent the voltage reaching to above the normal limit.

After the end of the fault the line voltage repairement after a short period of time and a drops in the supply voltage magnitude being called short time duration under-voltages or voltage dips. The fault on the electric system is the main reason of the voltage drops on the source that a voltage stops will not be happen and therefore the serious point is triggering of the sensitive loads such as electronic structures and infact the electrical motors.

Power transmission line generally are used as continuous systems but many times the switching processes are needed in the systems. Not only the swtiching but also the short circuit faults cause the generation of the waves on the power transmission lines. These waves are generally the travelling waves. Immediate variations in the transmission line system parameters due to the faults and/or switching phonomenas cause travelling waves on the transmission line and cause the time domain variations in the voltage and current waveforms. A travelling wave starts at the point where the short circuit is happened and travels through the transmission line. The travelling wave reflects and refracts at the load side through the load altough it is short circuit or open circuit (no-load). This situation can take a place in the line for a several seconds. Duration depends on the line loss and load parameters.

Transmission line quantities such as transient voltages and currents are important values which should be considered for correct operation of power transmission systems. A more complicated current and voltage shapes of the power transmission line is necessary for reaching a cheaper system insulation range, protection devicet design, checking and development of switching algorithms and quick fault detection.

In energy and data transmission, the most popular wire shapes are two wire parallel transmission line and coaxial structure. Owing to their structures each shows different capacitive and inductive equivalents. Therefore the transmission lines are not only the resistances but also the capacitances and inductances and some times more due to the other parameters such as voltage level, frequency, etc.

2.1 Two-wire parallel transmission line

The Kirschoff's current law says that the same amount of current should enter and leave the node or region. To satisfy this rule the energy may only be transmitted by using at least two conducting wires located at some optimum distance and isolated by using any insulator materials. The simple structure of the two-wire paralel transmission line is given in Figure 2.1.
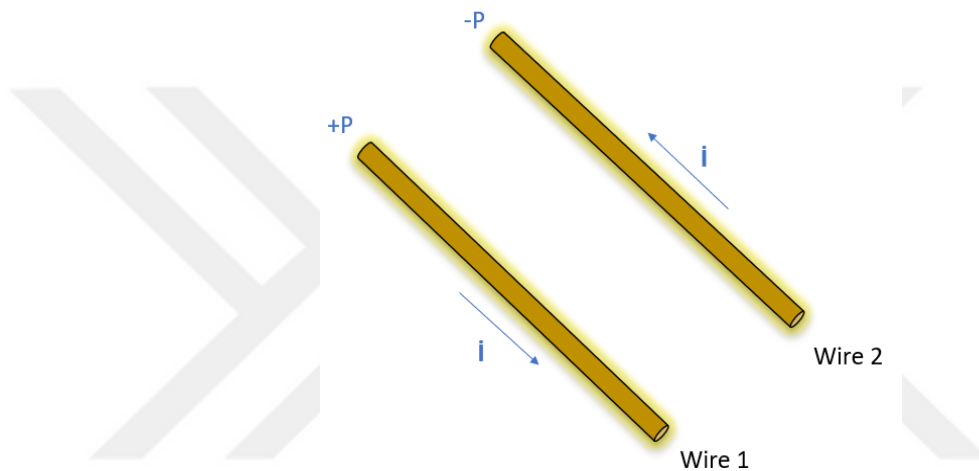
Figure 2.1 Two wires parallel transmission line.

One end of the transmission line is called as sendingend while the other terminal is receiving end or as source and load sides, respectively.

The material is generally copper and the resistance of the wire per meter depends on the cross sectional area of the wire as,

$$\frac{R}{m} = \frac{\rho}{A}$$

(2.1)

where ρ is the resistivity of the material and A is the cross sectional area. To increase the cross sectional area causes less energy losses and more current capacity but it increases the cost of the overall system.

On the another hand the capacitance of the two-wire parallel transmission line per meter on which the parameters are defined in Figure 2.2 is calculatedusing the electrostatic equations as
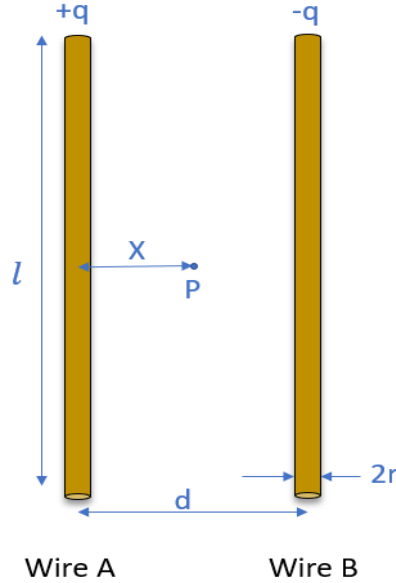

Figure 2.2 Parameters in two wire parallel transmission line.

We can use superposition to find the electric field at point x in Figure 2.2, and compute the value of capacitance C between positively charged and negatively charged of the two wires of the paralleltransmission line as,

$$C = \frac{q}{V_A - V_B} \quad , \qquad |E| = \frac{2K\lambda}{x} + \frac{2K\lambda}{d-x} \quad , \qquad \lambda = \frac{q}{l} \tag{2.2}$$

where K is $1/4\pi\varepsilon_0$.Then the potential difference is calculated to be

$$\Delta V = V_A - V_B = \int_{r}^{d-r} \vec{E} \cdot \vec{dr} \;=\; 4K\lambda \ln\frac{d-r}{r} \tag{2.3}$$

$$\Rightarrow C \;=\; \frac{q}{4K\left(\frac{q}{l}\right)\ln\frac{d-r}{r}} = \frac{\pi\varepsilon_0 l}{\ln\frac{d}{r}} \;\; \text{(Farad/meter)} \tag{2.4}$$

We see that the capacitance C between two wires of the parallel transmission line depends only on the geometrical factors, d, r, l.

On the other hand the inductance of the wire is calulated by using Ampere's law and Faraday's induction law.

$$\oint \overrightarrow{B} \ \overrightarrow{dl} = \mu_0 I \quad , \qquad \oint \overrightarrow{E} \ \overrightarrow{ds} = -\frac{d\Phi}{dt} \tag{2.5}$$

The source of the magnetic field is generally the current passing through the conductor. The magnetic field which has the direction found using the right hand rule passes throgh any surface surraounded by the conducting wire is called as magnetic flux. Right hand rule is like if the thumb of the right-hand shows the flow of current then the rotation of the fingers shows the flux lines. The wisa versa is also true. If current turns in circular conducting wire, fingers show the direction of the current while the thumb shows the direction of the magnetic lines. The shape oft he magnetic field is as same as the shape of the current creating it. The magnetic field flux density value at x distance from the source wire is given as

$$B = \mu_0 H_X = \frac{\mu_0 I}{2\pi r^2} x \tag{2.6}$$

where μ_0 is the permeability of the free space and It is estimated as

$$4\pi \times 10^{-7} \text{Henry/ meter}$$

The flux density is integrated through the area of the any surface enclosed by the another conducting wire with length l becomes

$$\Phi = \iint_S B.ds = \frac{\mu I l}{\pi} \ln\left(\frac{d-a}{a}\right) \tag{2.7}$$

Therefore, the inductance per unit length is

$$L = \frac{\mu}{\pi} \ln\left(\frac{d-a}{a}\right) \approx \frac{\mu}{\pi} \ln\left(\frac{d}{a}\right) \text{Henry/ meter} \tag{2.8}$$

The flux flowing through the inside of the area is created owing to the current magnitude in the conductor. The flux at the outside of the area of the conductor is because of its self current and the current of the neighbour conductors located around the conductor. The calculation of the total inductance should consider all internal (self) and neighbour magnetic fluxes (mutual).

Now, it is considered two cylindrical conducting wires (single phase line). The one of the line is for phase and the other wire is neutral (ground). Consider the radius of these cylindrical conducting wires are same as r. They are located such as the distance between the centers of the lines is D meters. The paralel 2 wires conducting wire cross section is given in Figure 2.3 below.
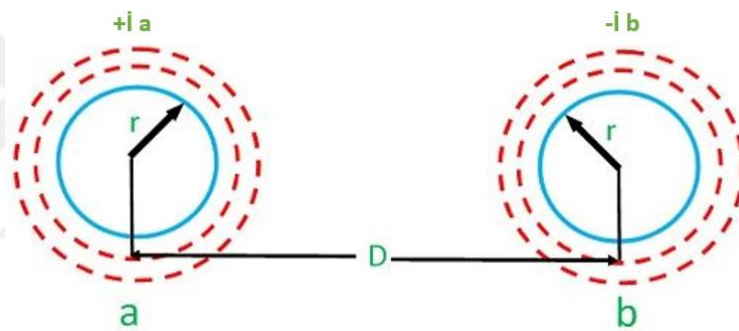

Figure 2.3 Two wire parallel transmission line.

In normal operation conditions the current in the one of the conductor flows in one direction while the other current is in the opposite direction in the other wire. Then the flux of wire (a) becomes

$$\lambda_a = 2 \times 10^{-7} \left[I_a \ln\frac{1}{r} + I_b \frac{1}{D} \right]$$ (2.9)

where $I = I_a = -I_b$,

Replacing these values in equation (2.9)

$$\lambda_a = 2 \times 10^{-7} I \ln\frac{D}{r}$$ (2.10)

For wire b we can use same way to find λ_b and it will has same result in equation (2.10).

The inductance of one wire of Figure 2.3 is

$$L_b = L_a = \frac{\lambda_a}{I} = 2 \times 10^{-7} \ln\frac{D}{r} \tag{2.11}$$

The inductance of two-wire parallel transmission line is

$$L_{loop\ inductance} = L_a + L_b = 4 \times 10^{-7} \ln\frac{D}{r} \quad \text{henry/ meter} \tag{2.12}$$

Therefore, the inductance of one-wire parallel transmission line is the half of the total inductance of a two wire line.

2.2 Coaxial Cable

Especially for the transmission of the higher frequency and lower voltage data, the coaxial cables have more advantages compared to the two wires parallel transmission lines.

The coaxial cables are more generally preferred to transmit the large number of short duration pulses (wide spectrum) without any deformation. In high bit data transmission the number may increase to a few millions (Megabits). In ideal transmission line model we offcourse prefer minimum inductance value to decrease the filtering effect of the transmission lines but unfortunatelly we are limited by the phsical structure of the transmission line and the material used in the construction. Therefore less inductance is possible by the careful design of the coaxial cables. The structure and the parameters of the coaxial cable is given in Figure 2.4.
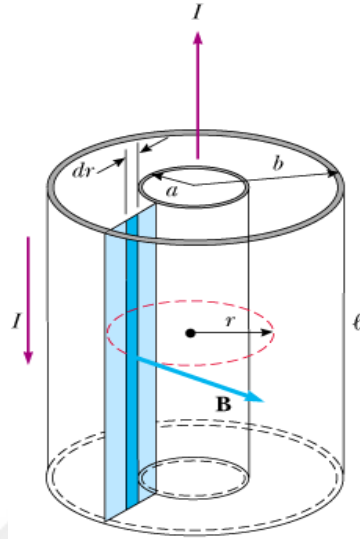
Figure 2.4 Structure and the parameters of the coaxial cable.

We can use equation (2.5) (Faraday's equation) to find the inductance of the coaxial cable

$$L = \frac{\Phi_\beta}{I} \tag{2.13}$$

Because the electrons moving (current) through the inside conductor of the coaxial cable and comes back through the outside conductor, for the flux ϕ_β through the coaxial transmission line magnetic field should be intagrated through the are given in Figure 2.4.

Ampere's law gives the magnitude and the direction of the magnetic field in the inner conductor of the coaxial cable as zero $(B_{in} = 0)$. Between two conductors of the coaxial cable, the magnetic field density becomes $B = \frac{\mu_0 I}{2\pi r}$, and outside the cable $B_{out} = 0$. The integration of the B in the given area gives the total flux as

$$\phi_\beta = \int B \, dA = \frac{\mu_0 Il}{2\pi} \int_a^b \left(\frac{l}{r}\right) dr = \left(\frac{\mu_0 Il}{2\pi}\right) \ln\frac{b}{a} \tag{2.14}$$

The energy stored in the cables is $U = \frac{1}{2}LI^2$ and therefore,

$$L/l = \left(\frac{\mu_0}{2\pi}\right) \ln \frac{b}{a} \quad \text{(Henry/meter)} \tag{2.15}$$

The capacitance between two wires of the cable is calculated using the electrostatic equations of the Electromagnetic theory such as Coloumb's Law and Gauss's Law.

Regarding to Figure 2.4 assume that inner cylinder is full of positive charge λ(col/m) and outer one with nigative of the same amount. Then the electric field between the cylinders is calculated by using Gauss's law as

$$\int E.ds = \frac{q_T}{\epsilon_0 \epsilon_r} \tag{2.16}$$

$$E = \frac{\lambda}{2\pi\epsilon_0 \epsilon_r \rho} \tag{2.17}$$

where ϵ_r is the relative permeability of the material used between two cylindric conductor to isolate them. The potential between the conductors of the coaxial cable becomes

$$V_a - V_b = \frac{\lambda}{2\pi\epsilon_0\epsilon_r} \ln \frac{a}{b} \tag{2.18}$$

Using the relation $q_t = C(V_a - V_b) = \lambda l$, we obtain the capacitance of coaxial cable per unit length as

$$\frac{C}{l} = \frac{2\pi\epsilon_0\epsilon_r}{\ln\frac{a}{b}} \quad (F/m) \tag{2.19}$$

2. 3 Distributed Parametric Representation

In this section the mathematical model of the single phase (2-wires) transmission line will be derived using the Maxwell´s equations. The model of the transmission line with corresponding parameters is shown in Figure 2.5.
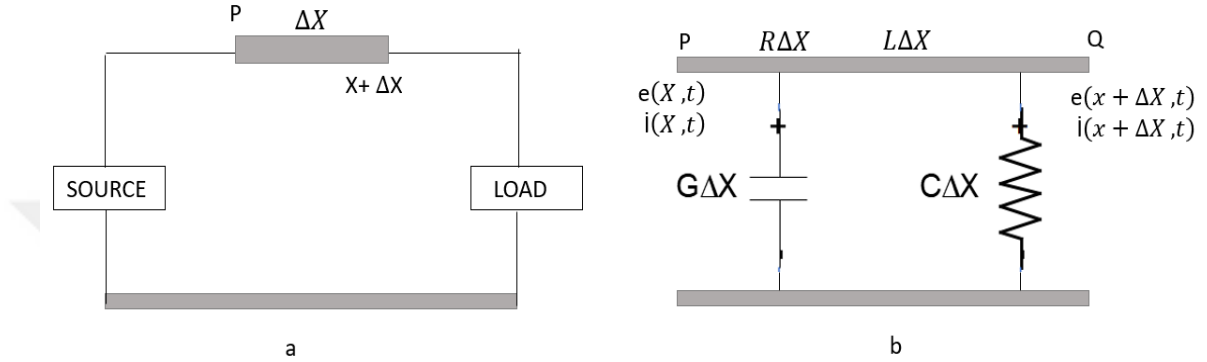

Figure 2.5 The model of the transmission line with corresponding parameters.

In this model the distance between the points p and q can be a several kilometers as well as an infinitesimal. In either case the equation relating the potentionals (e) at points p and q at any time and current (i) will be

$$e(x + \Delta x, t) = e(x, t) - (R\ \Delta x)i - (L\ \Delta x)\frac{\partial i}{\partial t} \qquad (2.20)$$

If we divide the right and left sides of the equation (2.12) by Δx and using the definition of tangent of line the continuous partial diffrential equation is obtained as

$$\frac{\partial e}{\partial x} = -Ri - L\frac{\partial i}{\partial t} \qquad (2.21)$$

By using the Kirshoff `s Current Law at point q, the current at q is written as

$$i(x + \Delta x, t) = i(x, t) - (G\ \Delta x)e - (C\ \Delta x)\frac{\partial e}{\partial t} \qquad (2.22)$$

and for Δx approaching to zero it becomes

$$\frac{\partial i}{\partial x} = -Ge - C\frac{\partial e}{\partial t} \qquad (2.23)$$

Derivating Eq.(2.22) and Eq (2.23) for x and t, respectively we get,

$$\frac{\partial^2 e}{\partial x^2} = -R\frac{\partial i}{\partial x} - L\frac{\partial^2 i}{\partial x \partial t} \qquad (2.24a)$$

$$\frac{\partial^2 i}{\partial t \partial x} = -G\frac{\partial e}{\partial x} - C\frac{\partial^2 e}{\partial t^2} \qquad (2.24b)$$

If we substitute Eq $(2.24a)$ and $(2.24b)$ into each other the second order partial differential equations for voltage and current are obtained as

$$\frac{\partial^2 e}{\partial x^2} = LC\frac{\partial^2 e}{\partial t^2} + (RC + GL)\frac{\partial e}{\partial t} + RGe \qquad (2.25a)$$

$$\frac{\partial^2 i}{\partial x^2} = LC\frac{\partial^2 i}{\partial t^2} + (RC + GL)\frac{\partial i}{\partial t} + RGi \qquad (2.25b)$$

These two equations generally can be solved using numerical techniques but after some assumptions such as some parameters are negligable they are simplified further and their analytical solution becomes possible. But in many applications these equations are preffered to be used for relatively high frequencies and microwaves. For lower frequencies, for example for power transmission at 50 or 60 Hz. the lumped parametric structure is thought to be more efficient compared to distributed parametric presentation and it will be discussed in the following section.

2.4 Lumped parametric approximation

The lumped parametric approximation is the modification of the distributed parametric representation assuming the long transmission line is the cascaded form of RLC structures of shorter parts of the transmission line. Figure 2.6 shows the equivalent configuration.
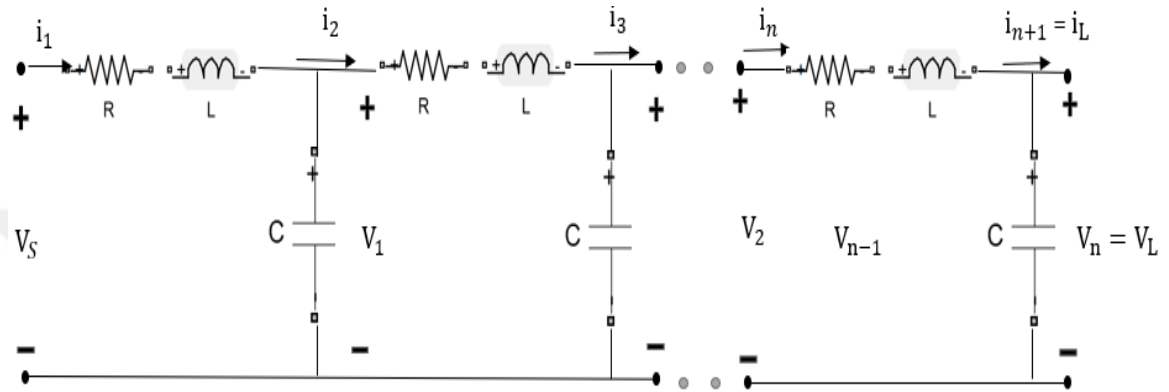

Figure 2.6 Model of single phase lumped parameter transmission line.

The values of R, L and C of each segment is calculated considering the geometry and material used in the transmission line as it is explained in Sec. 2. 1. Each segment of the cascaded structure can be mathematicaly modelled either in time or in frequency domain. The segment representation of the transmission line makes the calculation of the fault effects such as short circuit, open circuit easier. This method will be discussed in the following chapter in more detail. In the modelling and analysis the time domain is preferred.

CHAPTER 3

MODELLING OF TRANSMISSION LINE

The distributed parametric form of the two-wire single phase transmission line which is given in Figure 3.1 is simplified as a two-stage circuit in T-form. The receiving end of the transmission line is open circuit (load end) and the series resistance and inductance in the last lumped equivalent circuit will not be embedded in the time domain differential equation model (state space representation); hence, some part of the line will not be included in the model. This simplification will reduce the correctness of the RLC lumped parameter model. The model given here is not only valid for high voltage transmission, but also short duration pulse transmission in the digital (computer) communication. In this study, we will simulate the power transmission and short duration pulse transmission giving some practical examples in the following section [16]. In either case, the state space model is unique and may be formulated as:

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t), \qquad x_0 = x(t_0) \tag{3.1a}$$

$$y(t) = Cx(t) + Du(t) \tag{3.1b}$$

In Equations (3.1a) and (3.1b), the vector x covers all equivalent capacitor voltages and all inductor currents. u is the input vector and it is normally a scalar quantity for the single input. y is the output vector. In our application we have single output and y also is a scalar quantity.

The coefficient matrices A, B, C, and D contains the values of the resistances, capacitors and inductors of the equivalent lumped model. The coefficient matrices are defined in Equations (3.1c) -(3.1f). x(t$_0$) is the values of the voltages and the currents of the capacitors and inductors, respectively, at the initial time t$_0$.

$$A = \begin{vmatrix} \dfrac{-R_1}{L} & \dfrac{1}{L} \\ \dfrac{-1}{C} & \dfrac{-1}{(C.R_2)} \end{vmatrix} \tag{3.1c}$$

$$B = \begin{vmatrix} \dfrac{1}{L} \\ 0 \end{vmatrix} \tag{3.1d}$$

$$C = |0 \quad 1| \tag{3.1e}$$

$$D = |0| \tag{3.1f}$$

Since the system with short circuit fault is represented as cascaded 2-stages circuits, in the solution of the equation (3.1a), the system is solved in time domain for both side of the short circuit fault considering the final value of the short circuit case is the initial value of the following time interval. Since the element values in the matrices are not same for both side of the fault because of the arbitrary position of the fault in the line, the systems to be solved in cascaded form are not same. On the other hand, if pi-sections were used, this problem would not occur. However, then, the source parameters (R and L) would not be combined with the line parameters and this would increase the total number of state variables.

3. 1 State Space Simulation

For the T-shape equivalence of the transmission line, the state space model of the system is given in Eqs. (1a)-(1f). For some specific load termination, it will be convenient to use a specific lumped parameter transmission line model. For example, if the receiving end of the transmission line is short circuited, using L-sections for lumped parameter modeling removes the effect of the shunt capacitance and conductance at the last node [10]. A similar situation arises if pi-sections are used. Hence,L- or pi-sections are not preferred for the representation of a transmission line with a short circuit end [11].
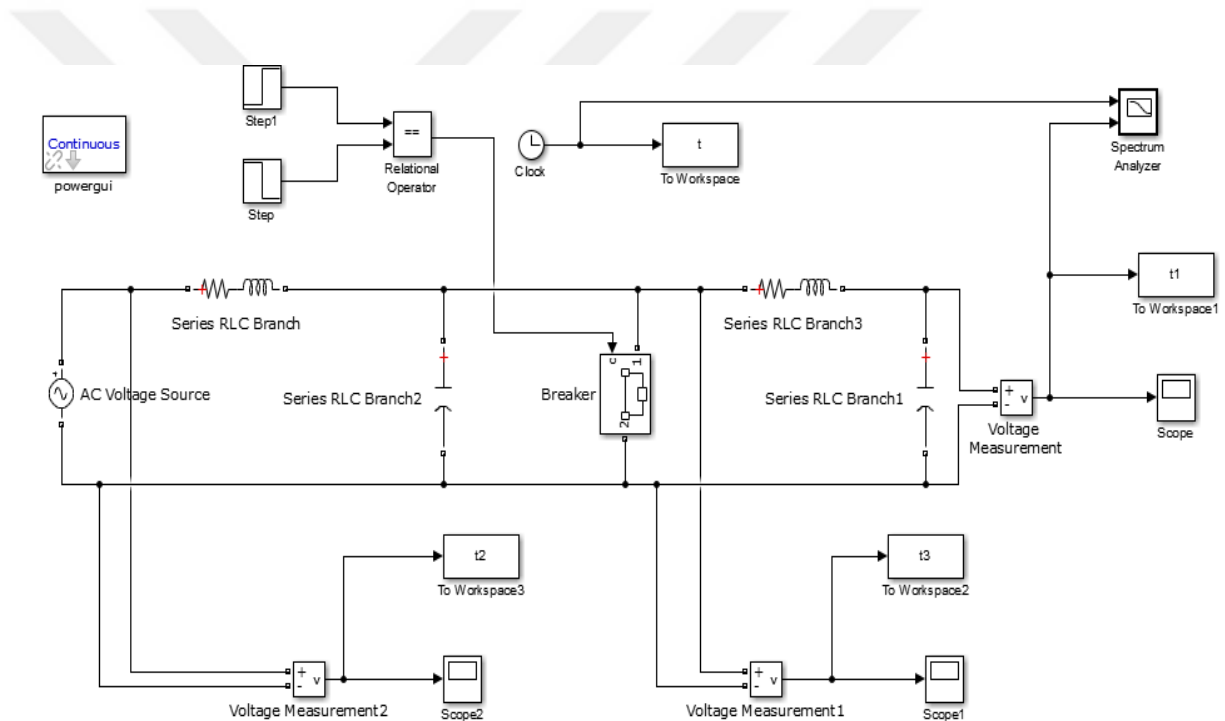
Figure 3.1 RLC equivalent of transmission line modeled using Simulink.

The short circuit fault model described above is used for lumped parameter representation of the line; hence the notation given above and the definitions of the state vector, x, as well as the coefficient matrices A and B given in (1.c) and (1.d).

Hence, the state variables are defined as:

$$x = \begin{vmatrix} i_1 & v_1 \\ i_2 & v_2 \end{vmatrix} \qquad (3.2)$$

where i_i and v_i's are the current and voltages of the inductors and capacitors in the circuit model, respectively.

The state equations can be solved using numerical integration method, but these methods are time consuming if the integration step is chosen to be small enough to increase the level of the accuracy. The solution of Eq. (3.1a) for a sinusoidal excitation is:

$$x(t) = Re\{e^{A(t-t_0)}x_0 + (pI - A)^{-1} \times (e^{pt}Bu - e^{A(t-t_0)}BUe^{pt_0})\} \qquad (3.3)$$

where u is the peak value of the sinusoidal excitation. This equation gives the complete response of a lumped parameter system. The steady state solution, defined by limit time, goes to infinity in the equation and is written as:

$$x_{ss}(t) = Re\{(pI - A)^{-1}Be^{pt}u\} \qquad (3.4)$$

CHAPTER 4

SIMULATION BY MATLAB

4. 1 Application examples

As a first example, the values of the inductances, resistances and capacitors for each kilometer are given for 50 Hz. For higher frequency applications (data transmission for digital systems for example), the distributed values may be changed easily as we will do in the next example.

The response of the system, under the short circuit fault instant and after, is obtained by using a closed form solution of the state space equations formulated from the lumped parameter equivalent of the distributed transmission system model and shown in Figure 4.1a. The model is simulated in Simulink and the equations are solved by using MATLAB. The spectrum is controlled by timer as shown in the block diagram given in the figure 4.2.
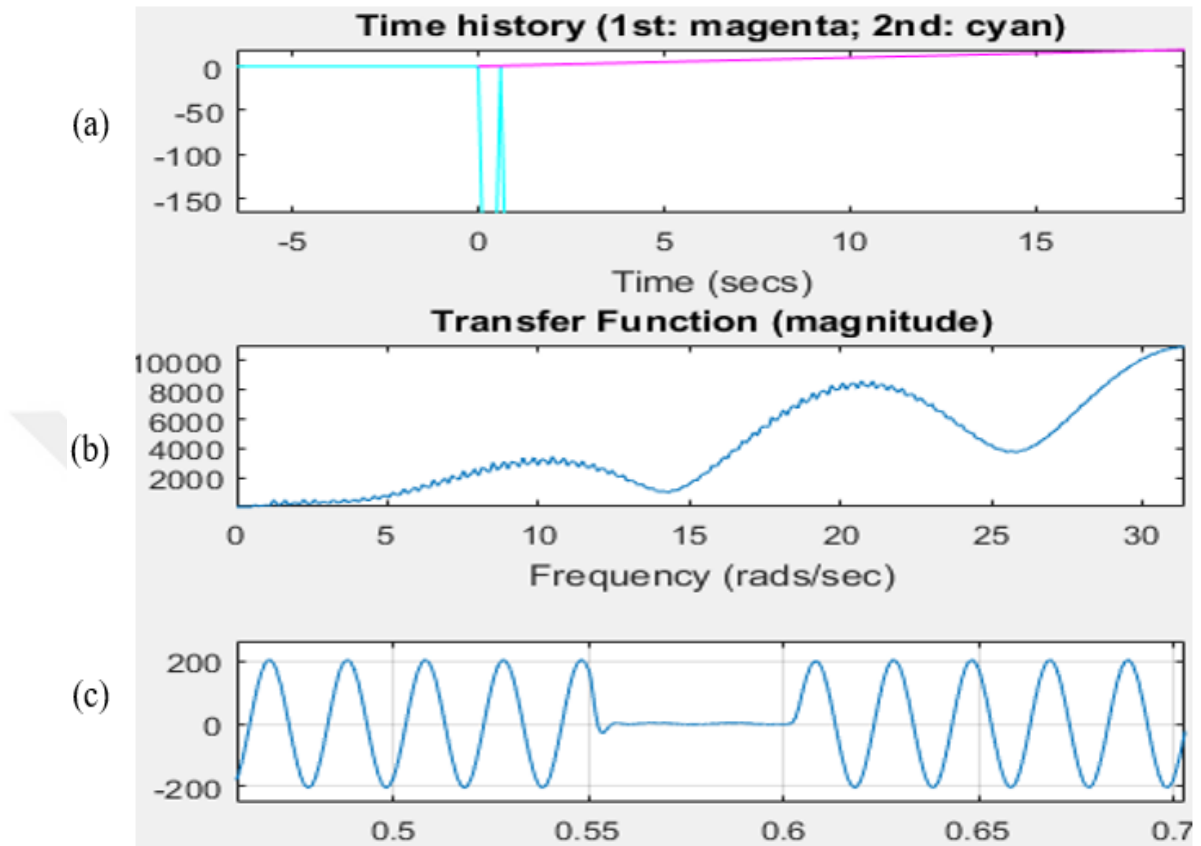
Figure 4.1 Spectrum results of RLC equivalent with short circuit fault by Simulink

The frequency interval (band) of the frequency spectrum analyzer is controlled by the history of the timer. The measurement of the voltmeter in Figure 4.2 is also given in Figure 4.1c and as it is obvious from the figure, the output voltage is affected as not only the short circuit (zero volt) but also the fluctuation in the magnitude. The duration of the short circuit is taken as 0.05 sec.
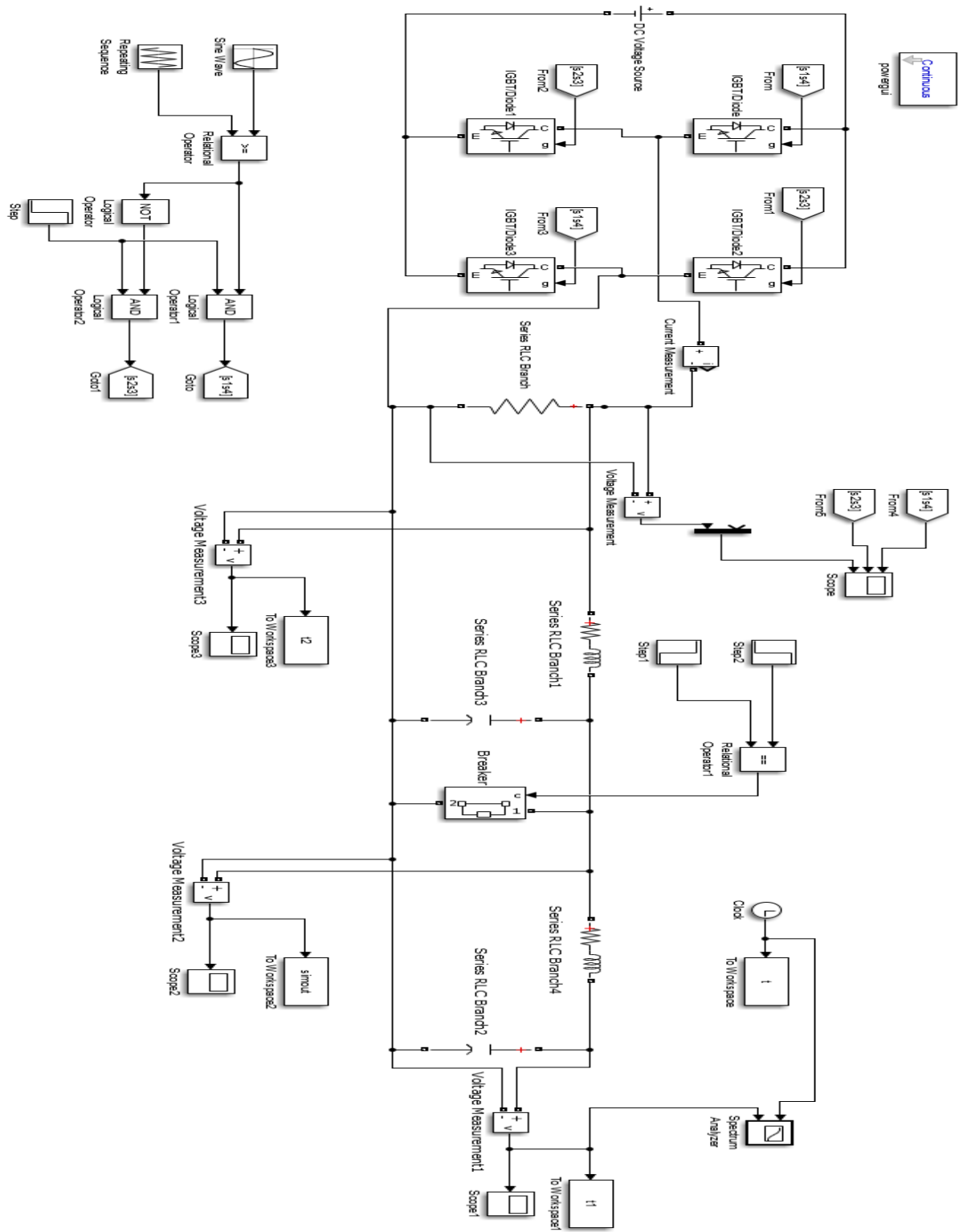
Figure 4.2 The Simulink model of the line using pulse generation.

Figure 4.3 shows the output voltage of the transmission line under the short circuit affect which happens at the middle of the transmission line (50th kilometer from the source) for 0.1 sec. The short circuit fluctuation is enlarged and shown in the same Figure. The same situation is also masticated by using MATLAB and the results for input and output voltages are shown in the Figure 4.4 (a) and (b).
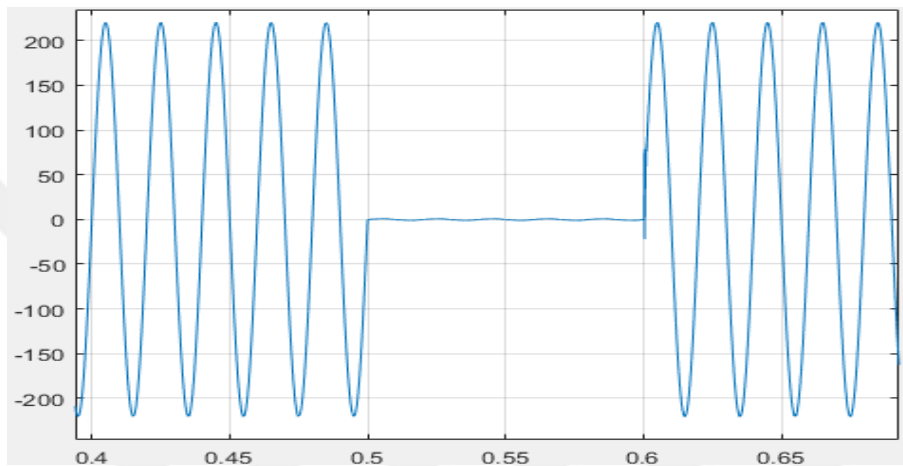

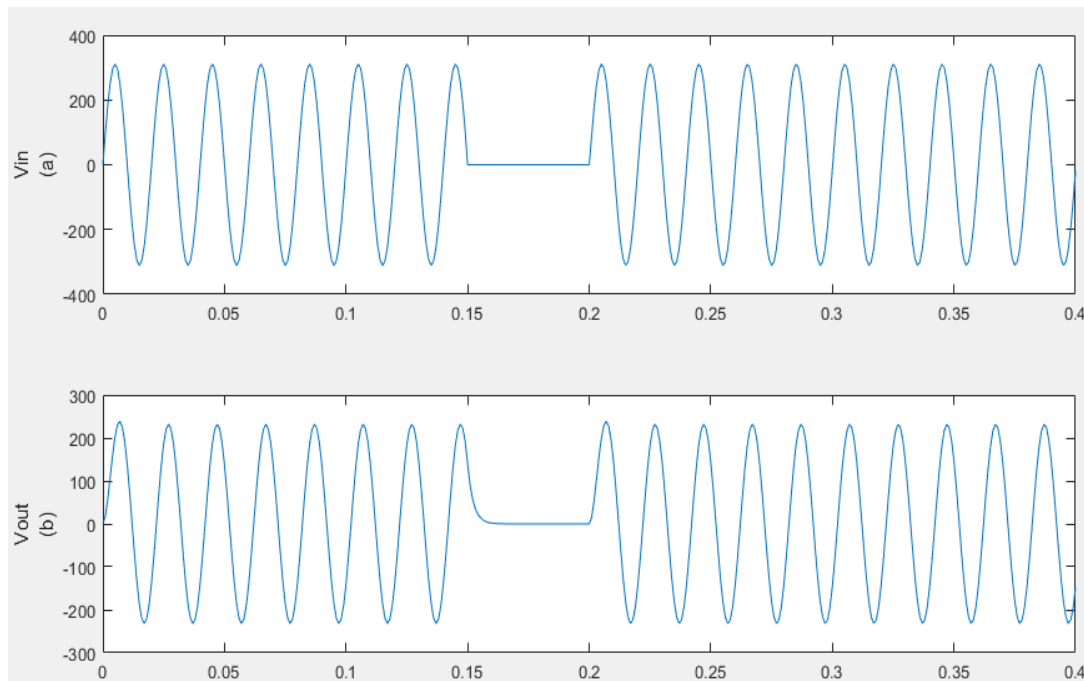**Figure 4.3** Output result of RLC equivalent with fault by Simulink

Figure 4.4 The results of the RLC equivalent with fault by MATLAB

As a second example, bipolar binary pulses are applied to the transmission line. The line parameters are replaced by the real values used in the data transmission.

The Simulink model of the line and pulse generation is given in Figure 4.5 and the case of a short circuit fault in the transmission line is generated and the waveforms at the input and output of the transmission line are given in Figure 4.5.

The input is generated by the pulse generated in the Simulink model Figure 4.2. The duration of each rectangular bipolar pulses is approximately 6.6 m. sec (Figure 4.5a) the shape of the pulses after short circuit fault is as given in Figure 4.5b.
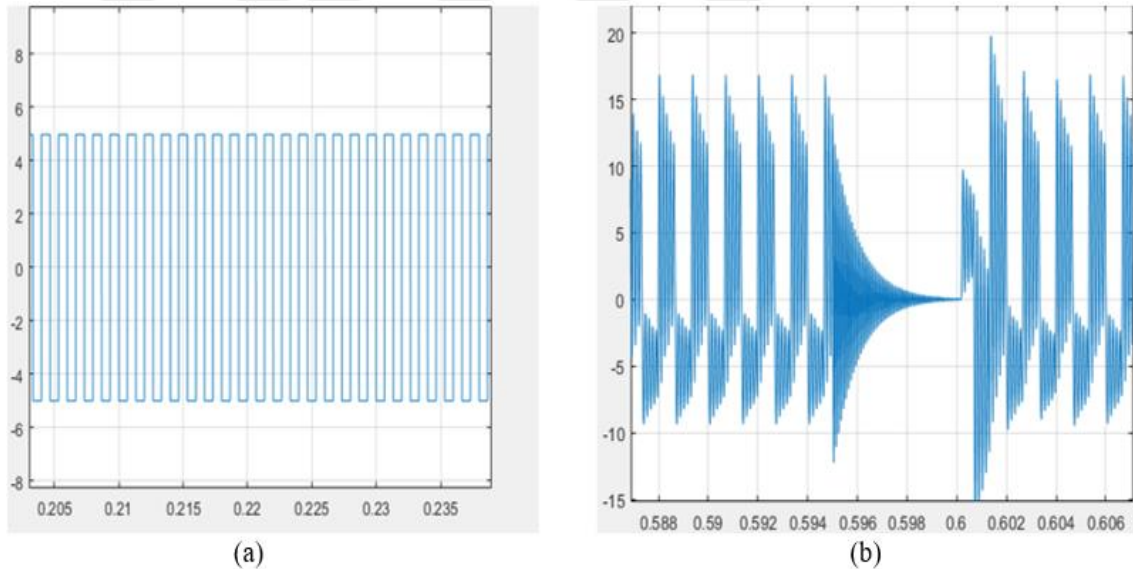

(a)

(b)

Figure 4.5 Comparison between the input (a) and output (b) voltage signal in the Simulink model of the line using pulse generation.

4. 2 MATLAB Codes of the Solution

Equations (4.1a) and (4.1b) are used for a single-phase transmission line with parameters $r = 0.03\ ohm/km$, L= 1 mH/km and c = 10 nF/km. The MATLAB program is given in Figure 4.6. In this program the values of the parameters can be changed easily and the position and duration of the short circuit fault can be input to the program changing the values of x and the limits of t(i).

```matlab
1 -     clc;
2 -     clear all;
3 -     close all;
4 -     x=50;
5 -     R1 = 0.03*x;
6 -     R2 = 20;
7 -     L = 1e-3*x;
8 -     C = 10e-9*x;
9 -     A = [-R1/L -1/L;1/C -1/(C*R2)];
10 -    B = [1/L;0];
11 -    C = [0 1];
12 -    D =0;
13 -    [num den] = ss2tf(A,B,C,D);
14 -    t = 0:0.001:0.4;
15 -    H = tf(num,den);
16 -    for i=1:length(t)
17 -     if t(i)>0.2 || t(i)<0.15
18 -     Vin(i) = 311*sin(314*t(i));
19 -     else
20 -     Vin(i) = 0;
21 -     end
22 -    end
23 -    subplot(2,1,1);
24 -    plot(t,Vin);
25 -    ylabel('Vin');
26 -    [Vout t] = lsim(H,Vin,t);
27 -    subplot(2,1,2);
28 -    plot(t,Vout);
29 -    ylabel('Vout');
```

Figure 4.6 MATLAB code of RLC equivalent with fault.

MATLAB is run again for different duration and position of the short circuit fault and the input and output voltage are sketched as in the Figure 4.6. In this example the position of the short circuit is taken as x=30 and the duration of the short circuit is taken as t(i) > 0.3 || t(i) < 0.25.
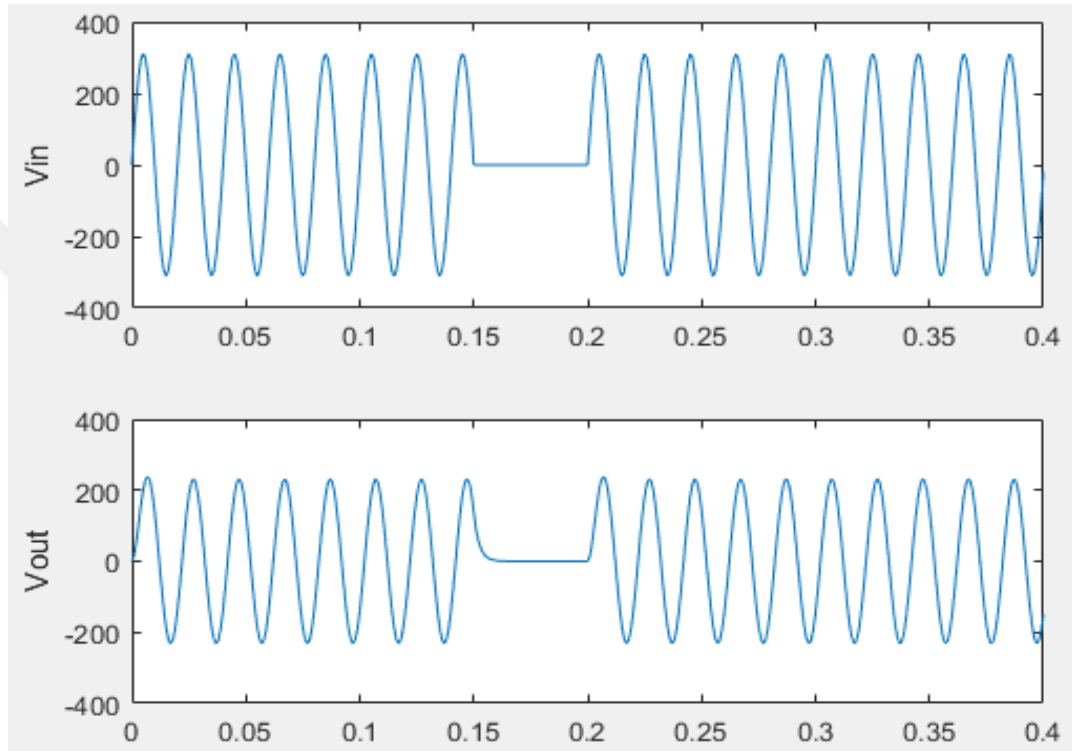

Figure 4.7 The results of MATLAB code of RLC equivalent.

4.3 Short Circuit Fault Under Load Condition

In the previous section the model of transmission line is given as cascaded LC structures assuming no-load condition and the transients (fluctuations) of voltage at input and output are obtained and sketched in the related figures.

In this section the several different types of load such as resistive (for heating processes), inductive (for electromechanical systems and electrical motors), capacitive (energy distribution system) loads are connected to the load side of the transmission line and the short circuit fault effect is observed at source side, load side, and any point in the transmission line.

As a first case $R_L = 3\ \Omega$ is assumed to be connected to the output and similar short circuit position and duration (middle of the transmission line for 0.1 sec.) are applied to the system. In this case, RLC equivalent of transmission line modeled using Simulink and the output voltage are given in Figure 4.9 and 4.10, respectively.
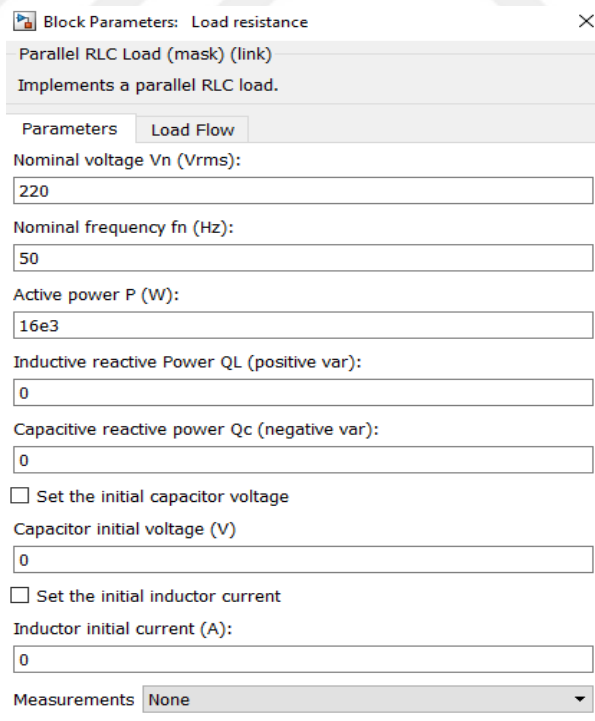

Figure 4.8 Block parameters of load resistance in the Simulink model.
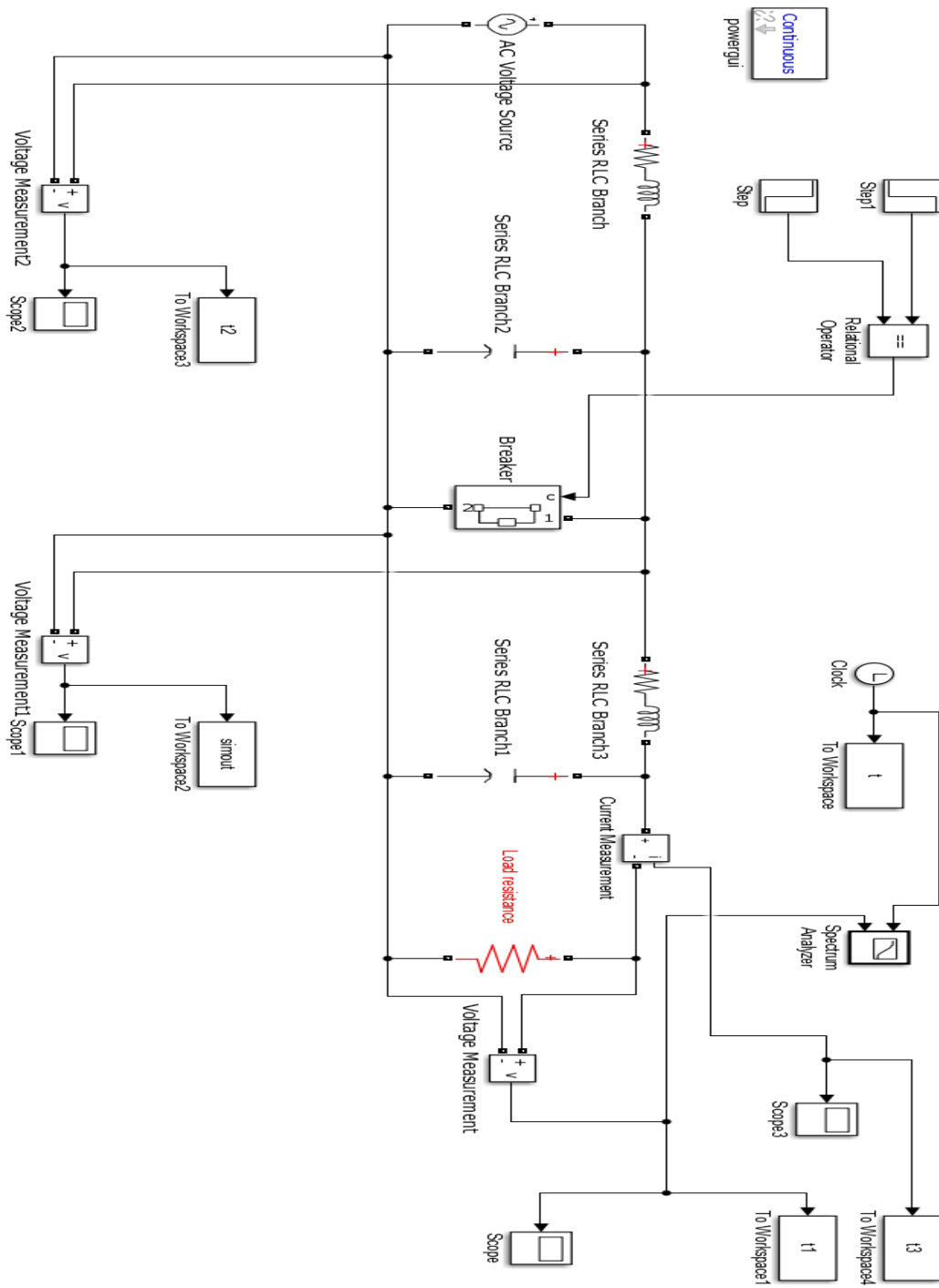
Figure 4.9 RLC equivalent of transmission line modeled using Simulink with resistive load.
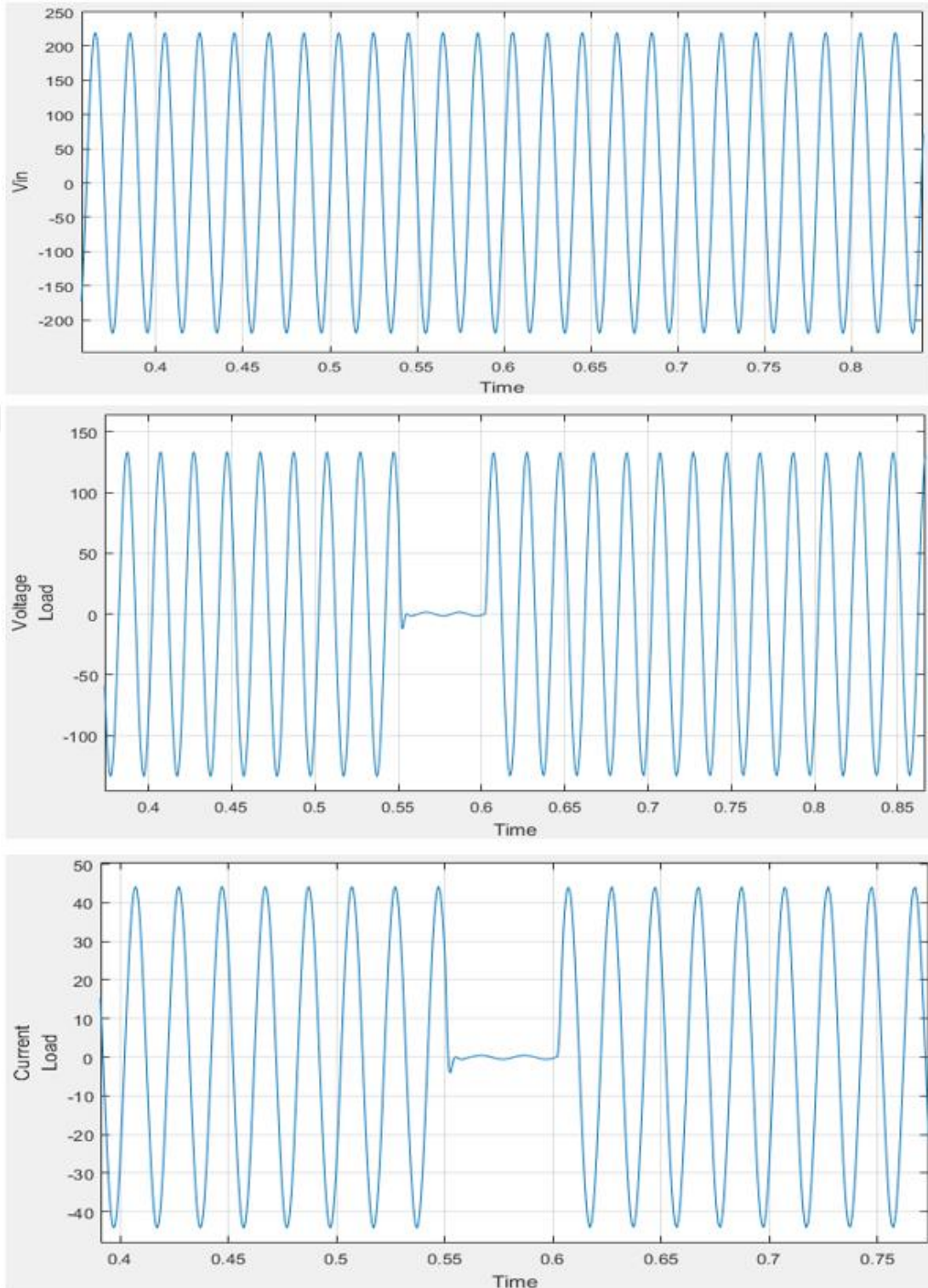
Figure 4.10 The results of transmission line for V_{out}, V_{in} and I_{load} for resistive load.

As a second case load is replaced by the series resistance and inductance which represents the electrical motor equivalent. The values are taken as $R_L = 3\,\Omega$, $L_L = 10\,mH$ is assumed to be connected to the output and similar short circuit position and duration (middle of the transmission line for 0.1 sec.) are applied to the system. In this case, RLC equivalent of transmission line modeled using Simulink and the output voltage are given in Figure 4.12 and 4.13, respectively.
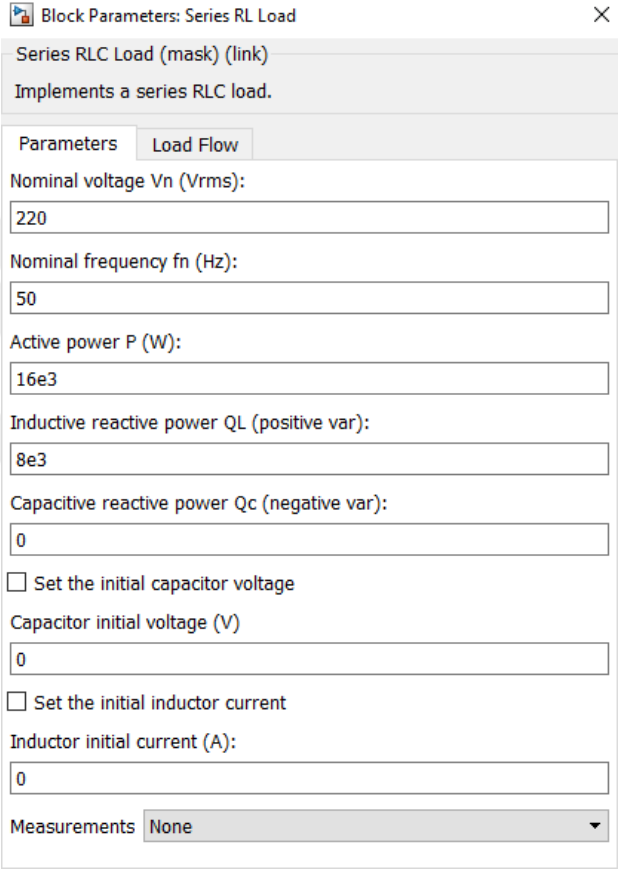

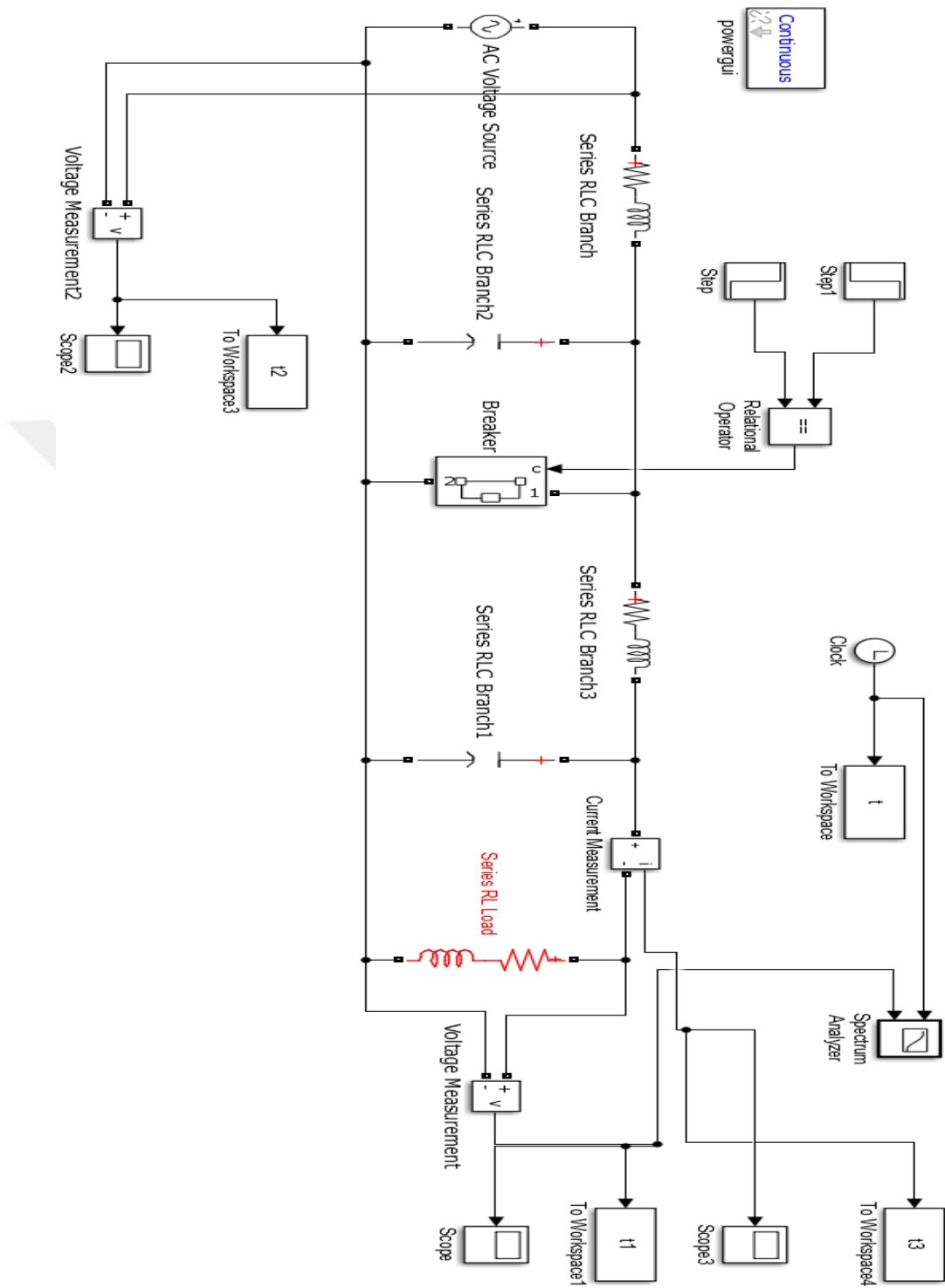**Figure 4.11** Block parameters of the series resistance and inductance in the Simulink model.

Figure 4.12 RLC equivalent of transmission line modeled using Simulink with inductive load.
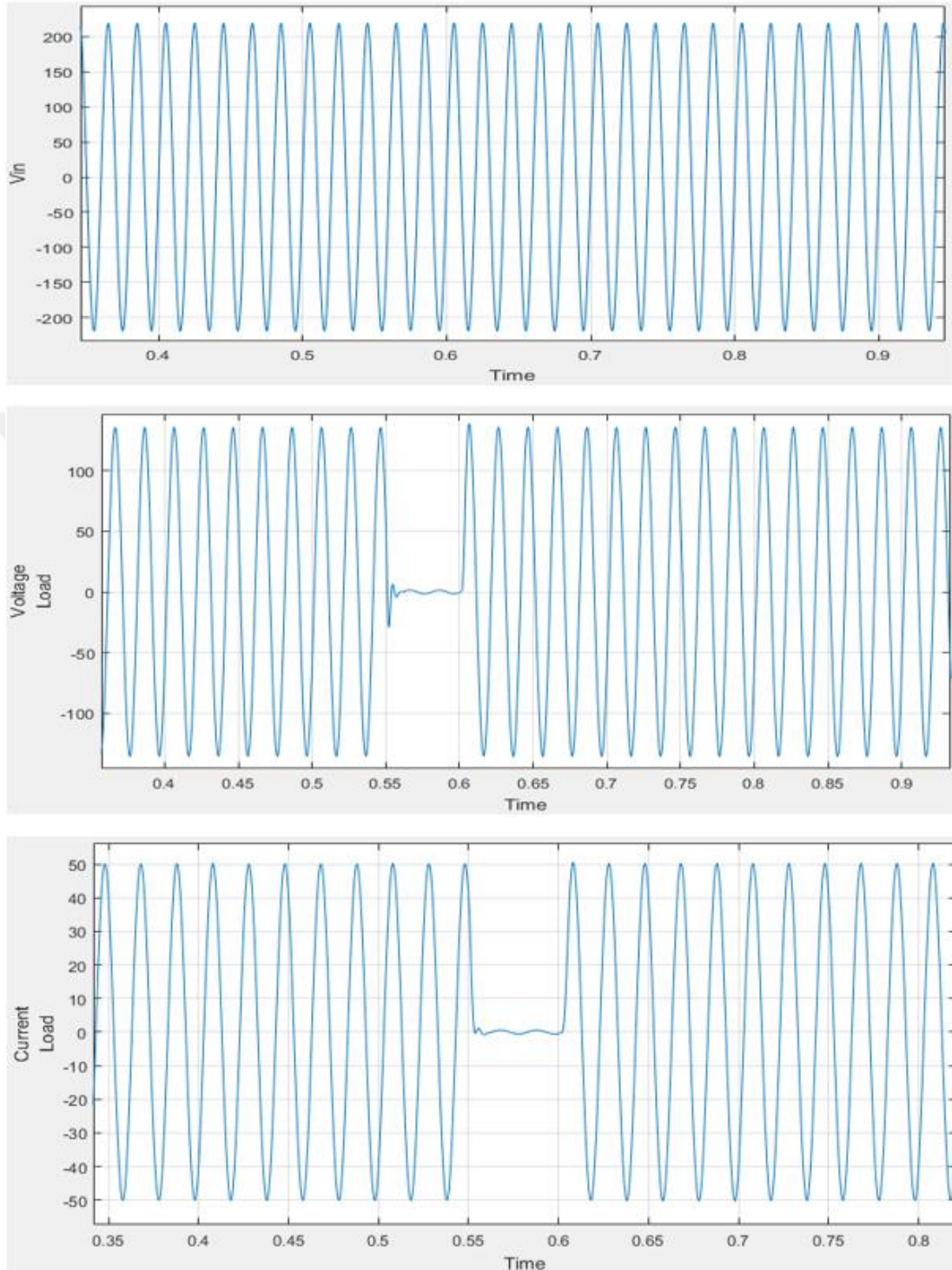
Figure 4.13 The results of transmission line for V_{out}, V_{in} and I_{load} for inductive load.

As a third case the load is replaced by the parallel resistance and capacitance which represents the distribution system equivalent. The values are taken as $R_L = 3\,\Omega$, $\quad C_L = 500\,\mu F$ is assumed to be connected to the output and similar short circuit position and duration (middle of the transmission line for 0.1 sec.) are applied to the system. In this case, RLC equivalent of transmission line modeled using Simulink and the output voltage, input voltage and load currents are given in Figure 4.15 and 4.16, respectively.
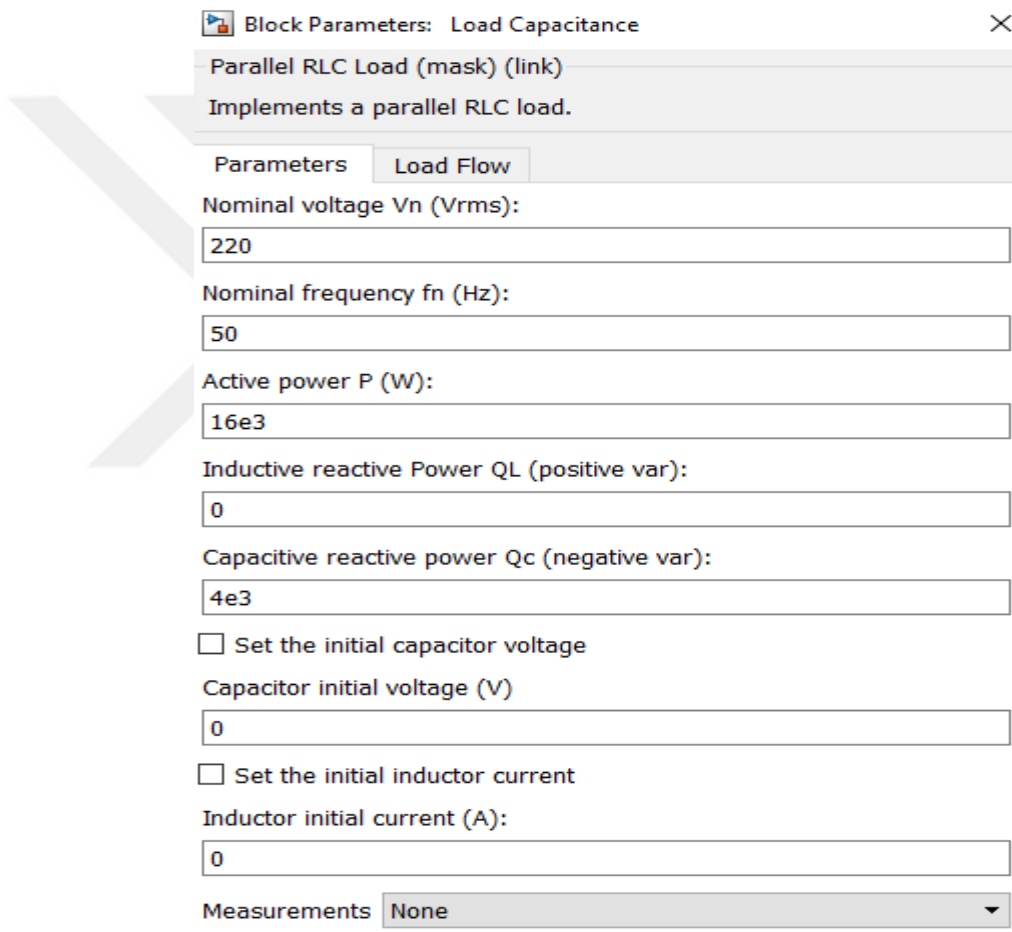

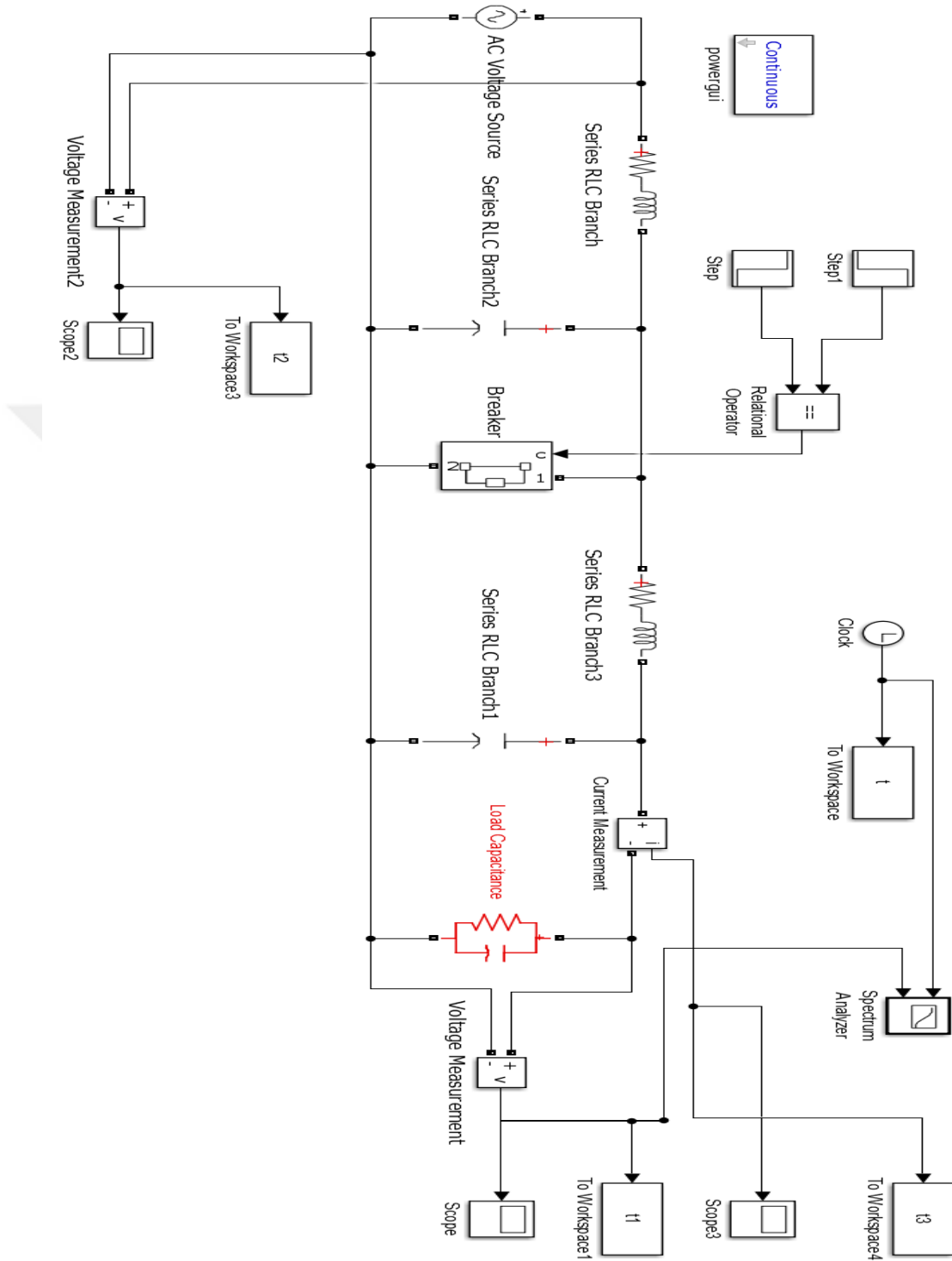**Figure 4.14** Block parameters of the parallel resistance and capacitance in the Simulink model.

Figure 4.15 RLC equivalent of transmission line modeled using Simulink with capacitive load.
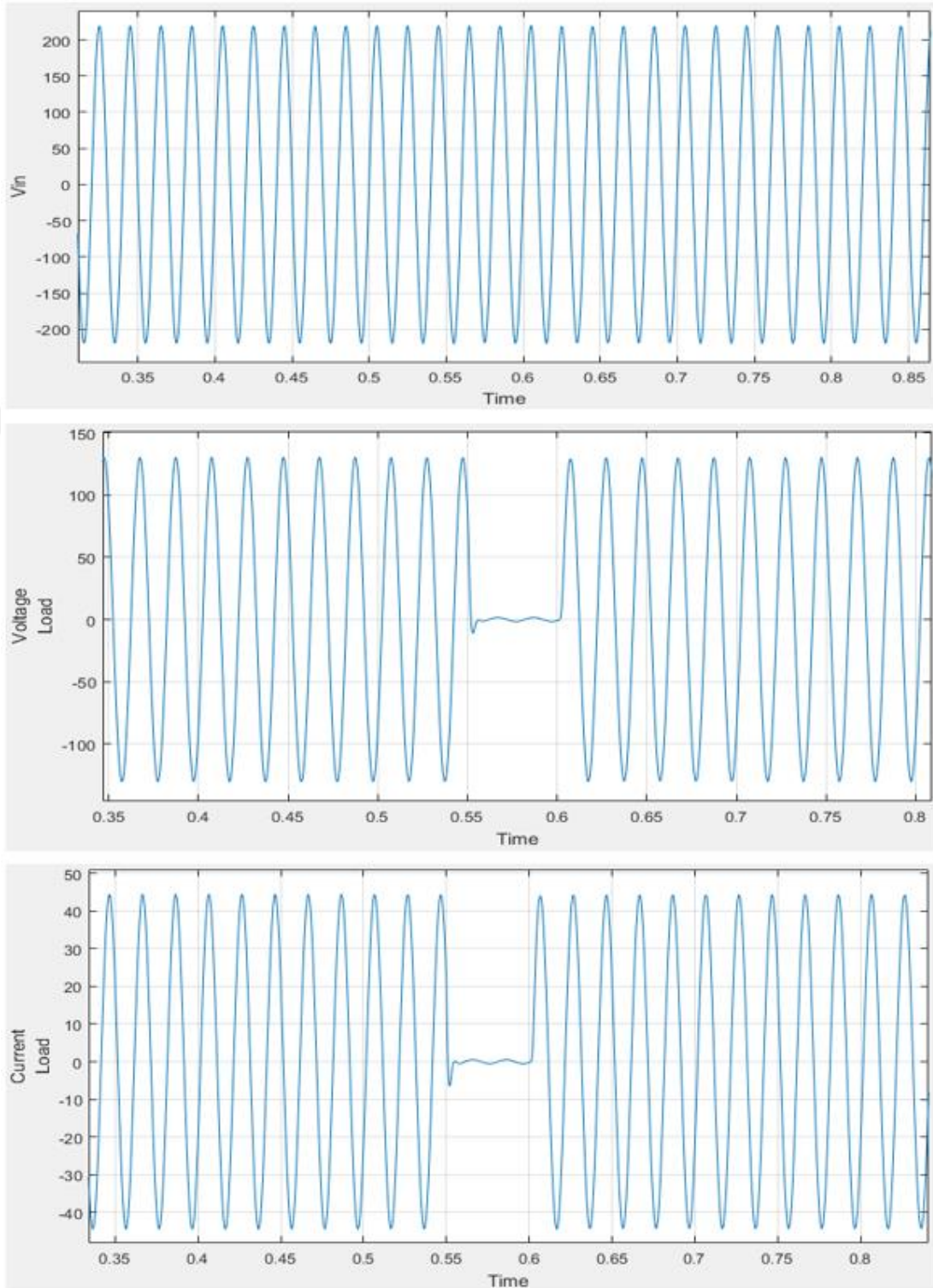
Figure 4.16 The results of transmission line for V_{out}, V_{in} and I_{load} for capacitive load.

4.4 Pulse Transmission Under Short Circuit Fault Effect with Resistive Load

In the previous sections, the Simulink model of the transmission line for very high bit rate data transmission under short circuit fault is given for no-load condition.

Generally, the data transmitted from the source is used by the computers which show the resistive load behavior. The Figure 4.18 shows the Simulink model with load value.
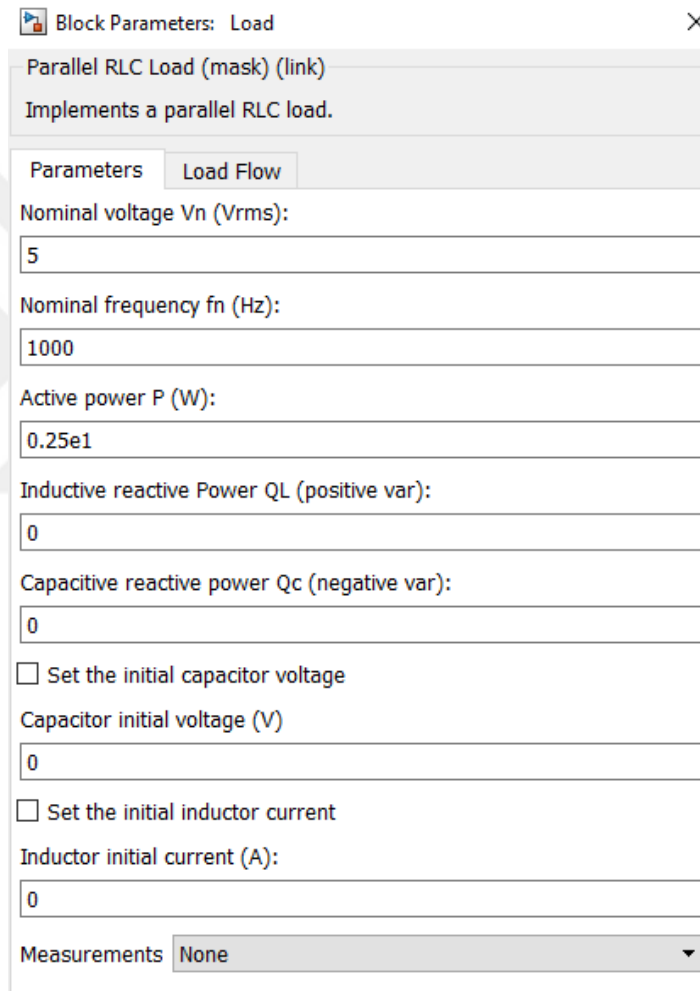

Figure 4. 17 Block parameters of load resistance in the Simulink model (Pulse transmission).
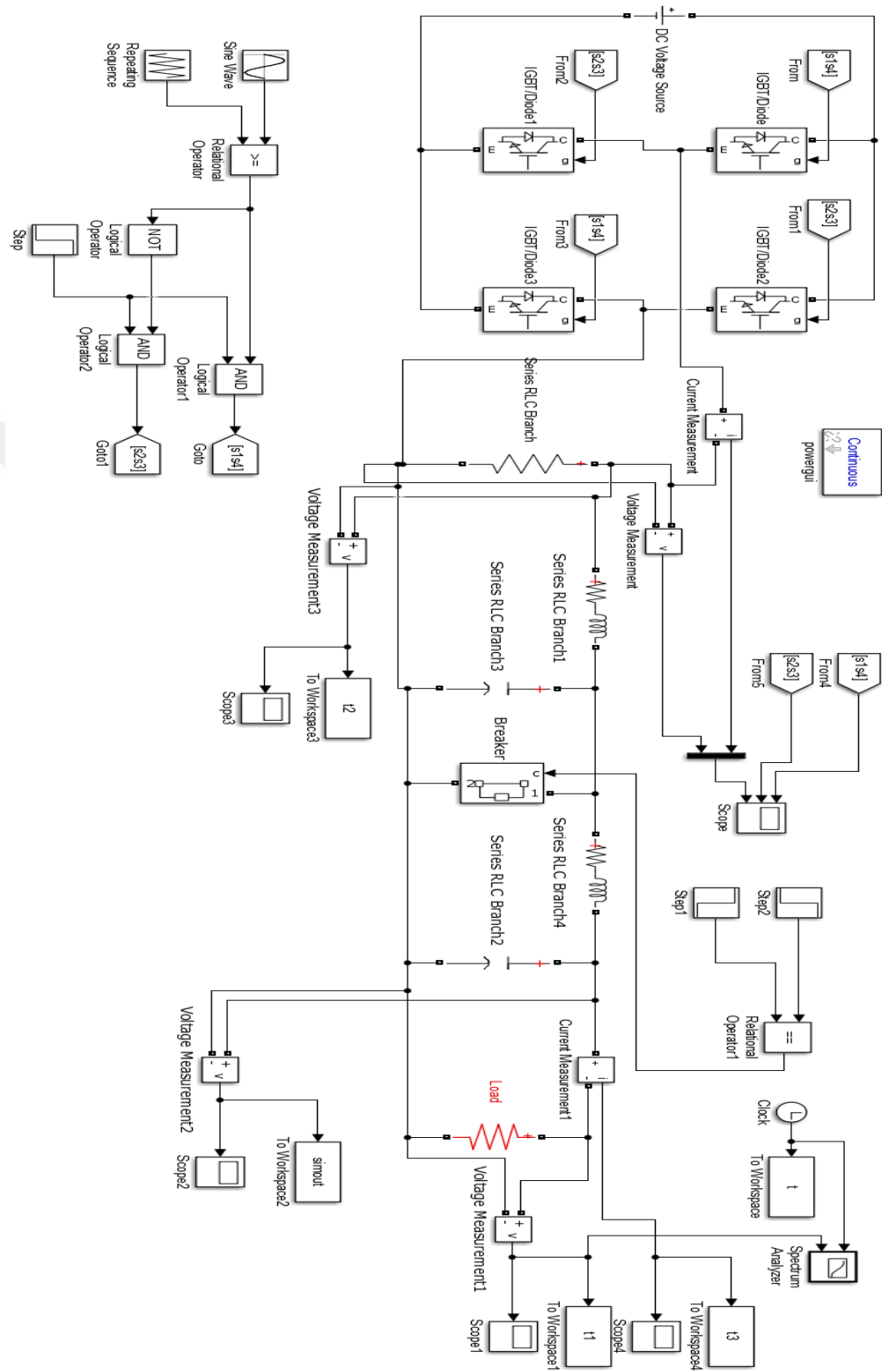
Figure 4. 18 The Simulink model of the line using pulse generation with load.
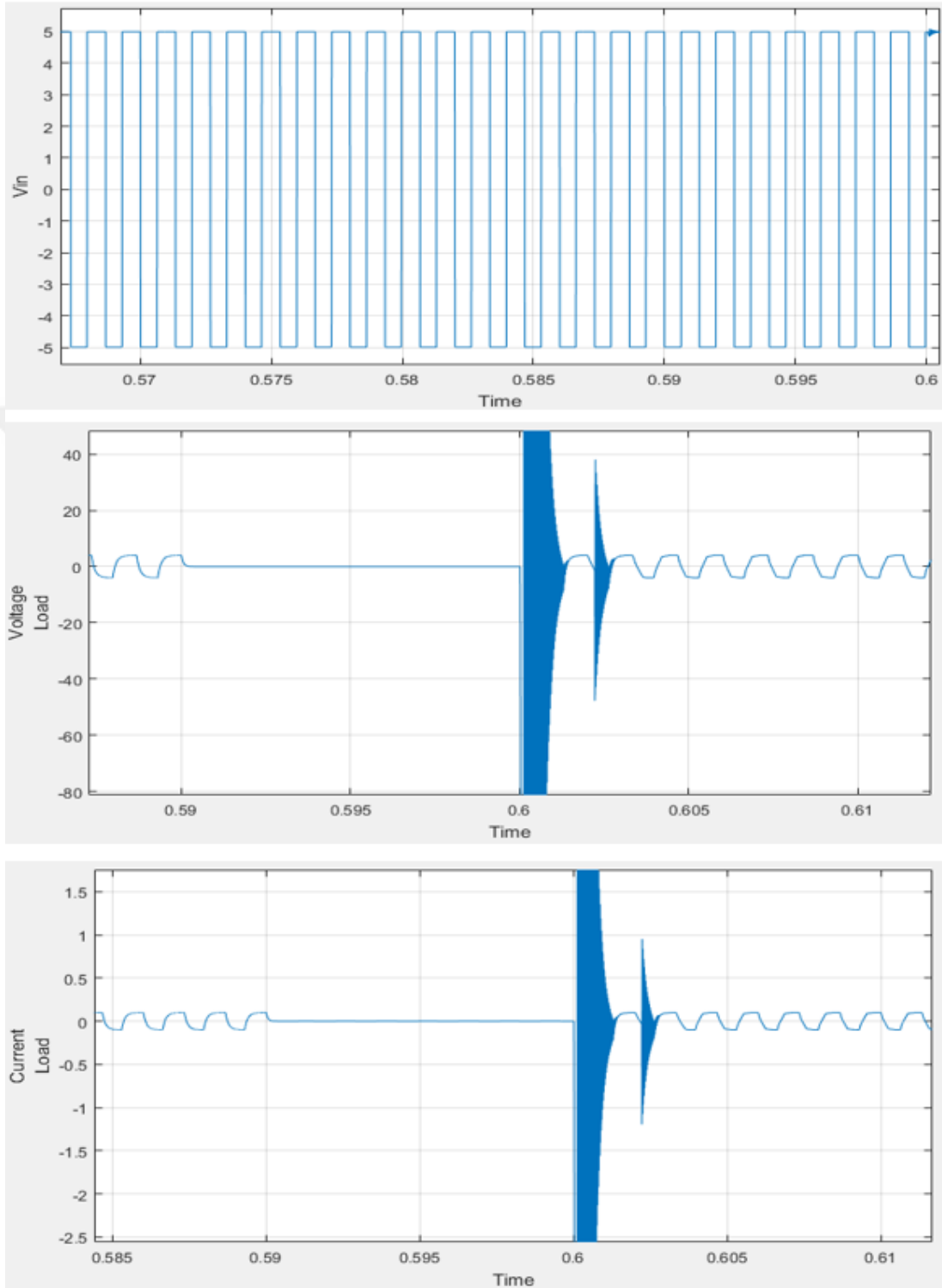
Figure 4. 15 Comparison between the input (a) and output (b) voltage signal in the Simulink model of the line using pulse generation with load.

CHAPTER 5

CONCLUSION

In this study, a transmission line is modeled as a lumped parameter circuit and the effect of the short circuit fault in between input and output is applied to see the change in the output waveform for sinusoidal input for energy transmission and pulse input for data transmission. The system is modeled using Simulink and solved by MATLAB.

In either application, the position and the duration of the short circuit is changed and its effect owing the distance of the fault and source (and load) is observed. Since the input source is real 50 Hz, 220-volt rms waveform, the fluctuation of the waveform during the short circuit fault case is sketched. The MATLAB program preplaced to find output in time domain using state space model of the system and hence the transient phonemes are exactly observed.

The verification of the results is done by solving the same problem is Simulink. In MATLAB and in Simulink it is easy and practical to set the position and duration of the fault. The overall transmission system is not limited for the energy transmission in the form of the pulse. To observe this event the pulse generator is designed in Simulink and the short circuit fault effect on pulse shape is also measured. This work way be easily extendable to 3-phase systems.

The model has capacity of solving the short circuit faults for not only the no-load case but also for resistive, inductive and capacitive loads.

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