Transfer Function and Z-Transform of an Electrical System in MATLAB/Simulink

Musa Adam Abdullah, Abdel Radi Abdel Rahman Abdel Gadir Abdel Rahman, Anoud Hassan Elzain Ageeb, and Asim Ahmed Babiker Suliman

***Abstract* — This paper presents the transfer function (T.F) and Z-Transform (Z.T) of an Circuits in MATLAB/Simulink. We have dealt with the electrical system, which consists of circuits in which there is a capacitor, resistance, and capacitance. Simulink is useful for obtaining the response of systems to input functions that are more complicated than step, impulse, ramp, or sine functions. The aims of this paper is to describe the solution of the equations of motion with One Degree and Two Degree Freedom of the equations of motion of the circuits by using transfer function equations in MATLAB/Simulink. We followed two applied mathematical methods to obtain the T.F and Z.F of a circuits in MATLAB/Simulink. Different graphics showed a close match result. Using these methods, researchers can effectively solve the RL and RLC circuit problems while presenting the results in excellent graphical form. The numerical approximation provides an acceptable result using the analytical one as a benchmark when we compare simulation results with analytical results.**

***Keywords* —Transfer Function, Z-Transform, MATLAB, Simulink®, RLC Circuits.**

I. Introduction

To estimate the T.F of an electrical system, it is critical to determine the Laplace transform (L.T) of the electrical circuit equations. The three fundamental parts of an electrical system are an inductor, a resistor, and a capacitor. Resistance, capacitance, and inductance as defined for each of these three components are frequently regarded as being combined parameters. The three electrical circuits were used in the investigation. A source v, an inductor L, and two resistors, R_1 and R_2, make up the first circuit. The second circuit is made up of an inductor L, a source v, and a resistance R. A source v, a resistance R, an inductor L, and a capacitor C make up the third circuit. They can function as an electrical resonator, or an electrical equivalent of a tuning fork, when connected together, storing electricity oscillating at the circuit's resonance [1].

Because of recent advancements in microprocessors and microcomputers, discrete-data and digital control systems have gained importance in industry. Working with digital signals has definite advantages over analog ones, as well. The final time response can be calculated using the inverse z-transform after performing algebraic operations in the z-domain first. Similar to the Laplace transform, this is one of the z-primary transform's objectives. An inverse z-transform of a function $P(z)$ typically produces information that only applies to $p(nT)$, not $p(t)$. To put it another way, the z-transform only transmits information during sampling instants. As a result, one of the three methods listed below—the inverse formula, the power-series approach, or the partial-fraction expansion—can be used to do the inverse z-transform [2].

Simulation of Electrical systems with more degrees of freedom is a common issue in engineering. In this paper we found the transfer function.

II. The Z-transformation

Digital control systems are described using difference equations. Similar to how continuous linear data sets are described by differential equations. As we've seen, the Laplace transform is an effective technique

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for resolving differential equations that are linearly dependent on time. Similar to this, the z-transform is a helpful method for solving linearly time-invariant difference equations [2].

To definition of the Z-Transform (Z.T) Let we have the series$p(n)$,n∈R. , where $p(n)$ consider it represent a succession of numbers or occurrences.

The Z.T of a discrete time signal $p(n)$ is defined as:

$$P(z) = z[q(n)] = \sum_{n=-\infty}^{\infty} p(n)z^{-n} \tag{1}$$

The complex variable z had both real and imaginary components.The ability of the Z.T to turn a series of real integers into an expression in the complex z-domain is one of its key characteristics [2].

$$z = re^{-jw}(2) \tag{2}$$

$$P(re^{jw}) \sum_{n=-\infty}^{\infty} p(n)r^{-n}e^{-jwn} \tag{3}$$

When $r = 1$,

$$P(e^{jw}) = \sum_{n=-\infty}^{\infty} p(n)e^{-jwn} \tag{4}$$

The Fourier transform is equivalent to the Z.T when evaluated on the unit circle.
If $p(n) = 0\ for\ n < 0$ $(causal\ sequence\ or$ the $\boldsymbol{Region\ of\ Convergence}$ $(\boldsymbol{ROC}))$

$$P(z) = z[p(n)] = \sum_{n=0}^{\infty} p(n)z^{-n} = p(0)z^{0} + p(1)z^{-1} + p(2)z^{-2} + p(3)z^{-3} + \cdots \tag{5}$$

This expression is referred to as a one-sided z-transform.
Let $p(n) = u(n)$ to find $P(z)$ and the Region of Convergence (ROC) of the causal sequence:

$$P(z) = \sum_{n=0}^{\infty} p(n)z^{-n}$$

$$P(z) = \sum_{n=0}^{\infty} p(n)z^{-n} = \sum_{n=0}^{\infty} z^{-n} = \sum_{n=0}^{\infty} (z^{-1})^{n}$$

$$= 1 + z^{-1} + z^{-2} + z^{-3} + \cdots$$

Then,

$$P(z) = 1 + (z^{-1})^{1} + (z^{-1})^{2} + (z^{-1})^{3} + \cdots \tag{6}$$

Then,

$$P(z) = 1/(1 - z^{-1}) = 1/(1 - (1/z)) \tag{7}$$

By multiplying the numerator and the denominator by z then:

$$P(z) = z/(z - 1) = for\ |z| > \tag{8}$$

III. Electrical Circuits

The resistance, capacitance, and inductance, which are correspondingly defined by the resistor, capacitor, and inductor and are typically regarded as lumped parameters, are the main components of an electrical circuits [1]. Kirchhoff's current rule and voltage rule are fundamental rules governing electrical circuits. The algebraic total of all currents entering and leaving a node is zero, according to Kirchhoff's current law (also known as the node law). Current is the time rate of change of electrons that pass through a specific area, such as the cross section of a wire. The mathematical equation that describes the relationship between current i and charge Q is:

$$i = dQ/dt\ \ or\ Q(t) = \int i\, dt \tag{9}$$

The volt is the unit for measuring voltage, which is the amount of energy needed to transfer a charge between two locations in a circuit (V),

The sign of voltage difference is important The Fig.1 a shows an electrical circuit that contains a voltage, inductor circuit where the electrons are attracted to the positive terminal of the battery, so the positive direction of the current is the direction of the current as indicated by that arrow.

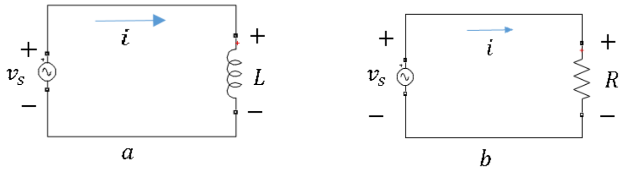

Fig. 1. (a) A voltage, inductor circuit. (b) A resistor, voltage circuit.

Ohm's law explains the linear mathematical relationship between voltage difference, resistance, and current is:

$$v = iR \tag{10}$$

where i is the current, v is the voltage difference, and R(ohm **Ω**) is the resistance.

Fig.1 b shows a circuit containing voltage and resistance connected together. In order to conserve energy, the voltage increase v_s provided by the source must be equal to the energy consumed iR by the resistance. Thus the model of this circuit is:

$$v_s = iR$$

$$i = v_s/R \tag{11}$$

IV. Transfer Functions (T.F) Equations of an Electrical Circuits

The following mathematical relation gives the T.F $G(s)$ for a input(single) $U(s)$ output(single) $Y(s)$ system:

$$G(s) = Y(s)/U(s) \tag{12}$$

or $G(s)$is the ratio of the L.T of the output to the L.T of the input for zeros I.C through Equation (12), we can calculate the dynamic response of the systems in Laplace domain.

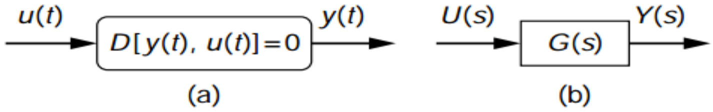

Fig. 2. One-input, One-output system (a) In the time Domain; (b) In the Laplace Domain.

A multiple-input, multiple-output system's transfer function matrix is determined as follow:

$$\{Y(s)\} = [G(s)]\{U(s)\} \tag{13}$$

where [G(s)] is T.F matrix, {Y(s)} is L.T of the output vector and {U(s)} is L.T of the input vector [3].

A. Multiple Degree of Freedom Conservative (DOC) Electrical Systems

There are many ways to find model of equation for conservative circuits with configurations that include multiple degrees of freedom to ascertain their frequency response, such as Kirchhoff's voltage law and the energy method. Also, Analysis techniques can be used or specialized MATLAB commands can be used. Also, analytical methods can be used or specialized MATLAB commands can be used. In the following example, we will use the analytical method to calculate the natural frequencies and corresponding models for a multi-degree-of-freedom electric system. Derive the mathematical models and the transfer function equation$I_1(s)/V(s)$ *and* $I_2(s)/V(s)$ of the circuit in Fig. 3 [3].

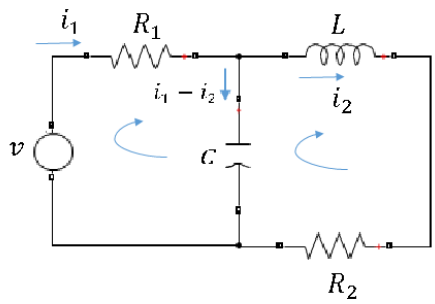

Fig. 3. Two-Mesh Electrical Network.

From the second Kirchhoff's law:

$$R_1 i_1(t) + 1/C \int [i_1(t) - i_2(t)]dt = v(t) \tag{14}$$

$$L\, di_2(t)/dt + R_2 i_2(t) - 1/C \int [i_1(t) - i_2(t)]dt = 0 \tag{15}$$

Equations (14) and equation (15) give a model of the circuit of Fig.3.
A T.F model of the two meshes Electrical Network circuit of Fig.3 can also be obtained as follows:
By taking the Laplace transforms of the equation (14) and equation (15), with $I.C = 0$, we get:

$$R_1 I_1(s) + 1/Cs\, [I_1(s) - I_2(s)] = V(s) \tag{16}$$

$$LsI_2(s) + R_2 I_2(s) - 1/Cs\, [I_1(s) - I_2(s)] = 0 \tag{17}$$

$$(R_1 + 1/Cs)I_1(s) - (1/Cs)I_2(s) = V(s) \tag{18}$$

$$-(1/Cs)I_1(s) + (1/Cs + Ls + R_2)I_2(s) = 0 \tag{19}$$

We can put the tow equations in the matric form:

$$\begin{bmatrix} R_1 + 1/Cs & -1/Cs \\ -1/Cs & 1/Cs + Ls + R_2 \end{bmatrix} \begin{bmatrix} I_1(s) \\ I_2(s) \end{bmatrix} = \begin{bmatrix} V(s) \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} I_1(s) \\ I_2(s) \end{bmatrix} = \begin{bmatrix} R_1 + 1/Cs & -1/Cs \\ -1/Cs & 1/Cs + Ls + R_2 \end{bmatrix}^{-1} \begin{bmatrix} V(s) \\ 0 \end{bmatrix}$$

$$I_1(s) = V(s)(s + CR_2 + CLs)/(R_1 s + R_2 s + Ls^2 + CR_1 + R_2 + CLR_1 s) \tag{20}$$

$$I_2(s) = V(s)s/(R_1 s + R_2 s + Ls^2 + CR_1 + R_2 + CLR_1 s) \tag{21}$$

From the two equations (20), (21), considering that $I_1(s)$ represents the output and $V(s)$ represents the output, we get the following T.F:

$$I_1(s)/V(s) = (s + CR_2 + CLs)/(R_1 s + R_2 s + Ls^2 + CR_1 + R_2 + CLR_1 s) \tag{22}$$

From the two equations (20), (21), considering that $I_2(s)$ represents the output and $V(s)$ represents the output, we get the following transfer function [5]:

$$I_2(s)/V(s) = s/(R_1 s + R_2 s + Ls^2 + CR_1 + R_2 + CLR_1 s) \tag{23}$$

V. Solution of the Electrical System with One Degree of Freedom

To solve the electrical system with first order degree of freedom we applying Kirchhoff's voltage Law [loop or mesh method].

In the following example fig.4 we will illustrate the mathematical molding and the transfer function$G(s) = I(s)/V(s)$of the first order degree circuit RL system by using Kirchhoff's voltage Law [1].

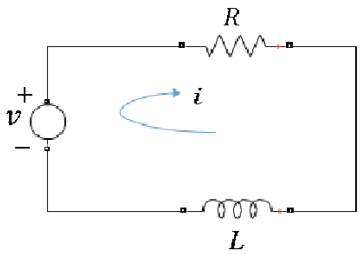

Fig. 4. First order degree Electrical circuit RL.

By application Kirchhoff's second law:

$$Ri(t) + L\, di(t)/dt = v \tag{24}$$

From Laplace transform to the equation (24), $IC = 0$ we have:

$$RI(s) + LI(s)s = V(s) \tag{25}$$

$$(R + Ls)I(s) = V(s) \tag{26}$$

The transfer function is therefore

$$G(s) = I(s)/V(s) = 1/(Ls + R) \tag{27}$$

Or

$$G(s) = I(s)/V(s) = K/(Ts + 1) \tag{28}$$

Since $K = 1/R$ and $T = L/R$
Where T: Time constant, $T > 0$. And$K$: static gain $K > 0$.

A. Transfer Functions to Z-domain of the First Order Degree Electrical (RC) Circuit

Consider that, for the system shown in equation (28), with R = 1Ω, and L = 25 H, let the input $I(s) = Y(s)$ and the output $V(s) = U(s)$. Then the equation (28) be came:

$$G(s) = Y(s)/U(s) = K/(Ls + \mathrm{R}) = 1/(s + 1) \tag{29}$$

For numerical method to solve the differential equations of the First order degree Electrical circuit in s-domain:

$$Y(s)/U(s) = 1/(s + 1) \tag{30}$$

$$Y(s)(s + 1) = U(s) \tag{31}$$

Take the invers of L.T time domain

$$\dot{y}(t) + \mathrm{y}(t) = u(t) \tag{32}$$

$$\dot{y}(t) = u(t) - \mathrm{y}(t) \tag{33}$$

The s-domain T.F for MTLAB

```
%The s-domain transfer function
s=tf('s');
G=1/(25*s+1);
[x,t]=step(G);
plot(t, x,'linewidth',2);
hold on
legend('s-domain function')
hold all
```

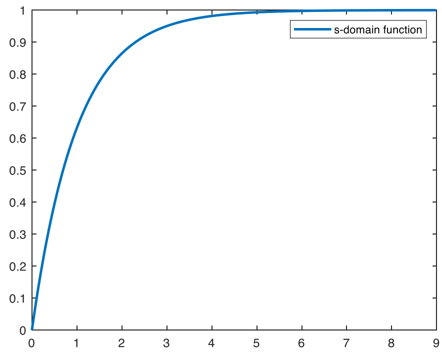

Fig. 5. s-domain T.F for MTLAB to the First order degree Electrical RC circuit.

To find the Transfer Functions to Z-domain of the First order degree Electrical (RC) circuit we use MATLAB Program as follows [4]:

B. MATLAB Program 1

```
>> s=tf('s');
>> R=1;
>> L=25;
>> G=1/(L*s+R);
>>Gz=c2d(G,0.1,'tustin')
Gz =
 0.001996 z + 0.001996
 ---------------------
 z - 0.996
Sample time: 0.1 seconds
Discrete-time transfer function.
>>Gz.variable='z^-1'
Gz =
 0.001996 + 0.001996 z^-1
 ------------------------
 1 - 0.996 z^-1
Sample time: 0.1 seconds
Discrete-time transfer function.
```

C. MATLAB Program 2

```
%build time vector
T=0.02; t=0:T:260;
%Build step input
u=ones(size(t)); u(1)=0;
%Initialize variables
yk_1=0; uk_1=0;
%Step through time and solve the difference equation
fori=1:length(t)
ifi==1
uterms=0.001996*u(i)+0.001996*uk_1;
yterms=0.996*yk_1;
y(i)=uterms+yterms;
elsei==2;
uterms=0.001996*u(i)+0.001996*u(i-1);
yterms=0.996*y(i-1);
y(i)=uterms+yterms;
end
end
scatter(t,y,3)
Legend('z-domain approach')
```

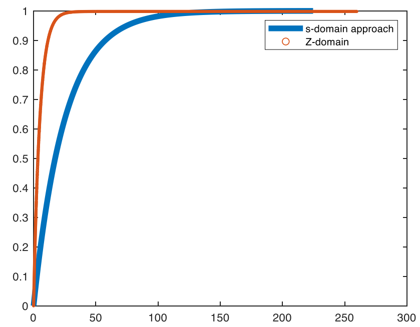

Fig. 6. z-domain approach to the First order degree Electrical RC circuit.

VI. Solution of the Electrical System with Two Degree of Freedom

From Fig. 7, the network analysis method can be used to find the current i model, given the supply voltage v_s [3].

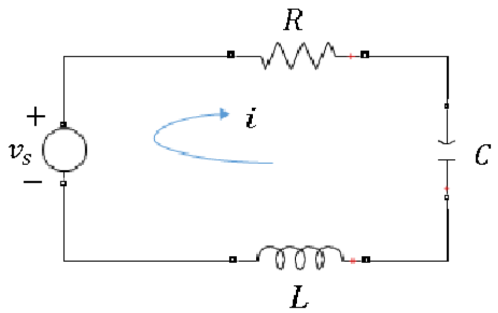

Fig. 7. Electrical System with Two Degree of Freedom (RLC Circuit).

By applying Kirchhoff's second law, we solve the following equations, which represent the mathematical system of equations for current i:

$$v_s = v_R + v_L + v_C \tag{34}$$

$$v_s = Ri(t) + L\,di(t)/dt + 1/C \int i(t)\,dt \tag{35}$$

Or

$$v_s = Ri(t) + L\,di(t)/dt + v_C \tag{36}$$

If the initial conditions are set to zero, Equation (36) can be transformed from the time domain to the s-domain using Laplace transforms.

$$V_s(s) = RI(s) + LsI(s) + V_C(s) \tag{37}$$

where

$$v_L = L\,di(t)/dt \ \ and\ i(t) = C\,dv_c/dt \tag{38}$$

If the initial conditions are set to zero, Equation (38) can be transformed from the time domain to the s-domain using Laplace transforms [4],[5].

$$V_L(s) = LsI(s)\ and\ I(s) = CsV_C(s) \tag{39}$$

Substitution of $V_L(s)$ and $I(s)$ of equation (39) into the equation (37) we have the following equation:

$$V_s(s) = RCsV_C(s) + LCs^2V_C(s) + V_C(s) \tag{40}$$

$$V_s(s) = (RCs + LCs^2 + 1)V_C(s) \tag{41}$$

The necessary transfer function is produced by equation (41) as:

$$V_C(s)/V_s(s) = 1/(LCs^2 + RCs + 1) \tag{42}$$

A. Transfer Functions to Z-domain

Consider that, for the system shown in equation (42), with R = 1Ω, L = 1 H, and C=1 F, let the input $V_C(s) = Y(s)$ and the output $V_s(s) = U(s)$. Then the equation (28) be came:

$$G(s) = Y(s)/U(s) = 1/(s^2 + s + 1)$$

The s-domain to t-domain with Two Degree of Freedom

$$(s^2 + s + 1)Y(s) = U(s)$$

Take invers L.T

$$\ddot{y}(t) + \dot{y}(t) + y(t) = u(t)$$

$$\ddot{y}(t) = u(t) - \dot{y}(t) - y(t)$$

Now we use MATLAB command to find s-domain form $G(s)$ as follows:

```
%The s-domain transfer function
s=tf('s');
G=1/(s^2+s+1);
%step response
[x,t]=step(G);
plot(t, x,'linewidth',5);
grid
legend('s-domain function')
holdall
```

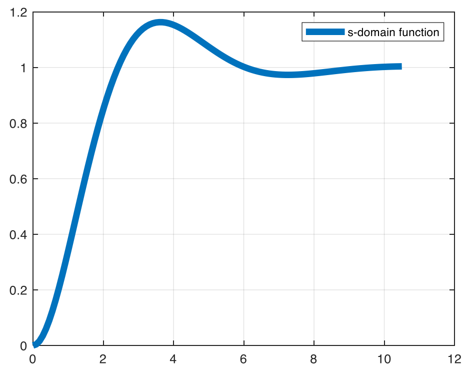

Fig. 8. z-domain approach to the second order degree Electrical RLC circuit.

The s-domain to z-domain of the system with Two Degree of Freedom of equation is determined using MATLAB Program as follows:

B. MATLAB Program 3

```
>> s=tf('s');
>> G=1/(s^2+s+1);
>>Gz=c2d(G,0.1,'tustin')
Gz =
 0.002375 z^2 + 0.004751 z + 0.002375
 ------------------------------------
z^2 - 1.895 z + 0.905
Sample time: 0.1 seconds
Discrete-time transfer function.
>>Gz.variable='z^-1'
Gz =
 0.002375 + 0.004751 z^-1 + 0.002375 z^-2
 ----------------------------------------
 1 - 1.895 z^-1 + 0.905 z^-2
```

Sample time: 0.1 seconds
Discrete-time transfer function.

C. MATLAB Program 4

```
%build time vector
T=0.1; t=0:T:14;
%Build step input
u=ones(size(t)); u(1)=0;
%Initialize variables
yk_1=0; yk_1=0; yk_2=0; uk_1=0; uk_2=0;
%Step through time and solve the difference equation
fori=1:length(t)
ifi==1
uterms=0.002375*u(i)+0.004751*uk_1+0.0075*uk_2;
yterms=1.895*yk_1-0.905*yk_2;
y(i)=uterms+yterms;
elseifi==2
uterms=0.002375*u(i)+0.004751*u(i-1)+0.0075*uk_2;
yterms=1.895*y(i-1)-0.905*yk_2;
y(i)=uterms+yterms;
else
uterms=0.002375*u(i)+0.004751*u(i-1)+0.0075*u(i-2);
yterms=1.895*y(i-1)-0.905*y(i-2);
y(i)=uterms+yterms;
end
end
scatter(t,y,3)
legend('z-domain approach')
```

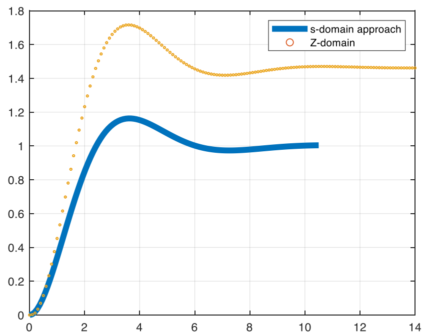

Fig. 9. z-domain approach to the second order degree Electrical RLC circuit.

VII. TRANSFER FUNCTION EQUATION IN MATLAB/SIMULINK

Simulink is especially useful for obtaining the response of systems to input functions that are more complicated than step, impulse, ramp, or sine functions. Simulink is also helpful for computing the response of systems that contain nonlinear elements whose behavior is difficult to analyze by hand and tedious to program in MATLAB. We use several electrical systems to illustrate how to accomplish this.

Solution of the nonhomogeneous system of differential equations of an electrical system with first degree and second degrees of freedom is first done in MATLAB /Simulink using T.F equations [6]-[8]. A graphical addition to MATLAB for system modeling and simulation is called Simulink. One of Simulink's main advantages is that it can simulate a nonlinear system, whereas a T.F cannot. Another advantage is Simulink's ability to take initial conditions into account. When constructing a T.F, the initial conditions (I.C) are assumed to be zero [6].

A. Simulink® Transfer Function (T.F) Model of a First Order Degree Electrical RL Circuit

Now, using the aforementioned examples, we demonstrate how to use the Simulink environment to model and simulate dynamic issues using T.F. Consider the first-order degree electrical circuit in Fig. 4, with $R = 1$ and $L = 25$, and a voltage source of $v = 80\,sin(10t)\,V$. Graph the probably resultant currents for the case where the resistance is purely linear (no saturation) and for the actual resistance, taking into account that the resistor R has a non-linearity of the saturation sort with a saturation voltage of 50 V (both negative and positive) (with saturation). Furthermore, the transfer mechanism that links the input voltage to the output current:

$$I(s)/V(s) = 1/(R + Ls) \tag{43}$$

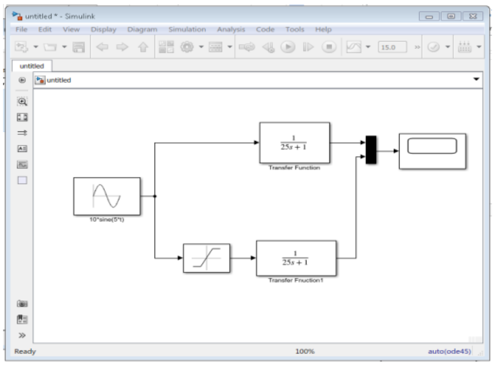

Fig. 10. Simulink of RL electric circuit.

The simulation result is shown in Fig. 11.

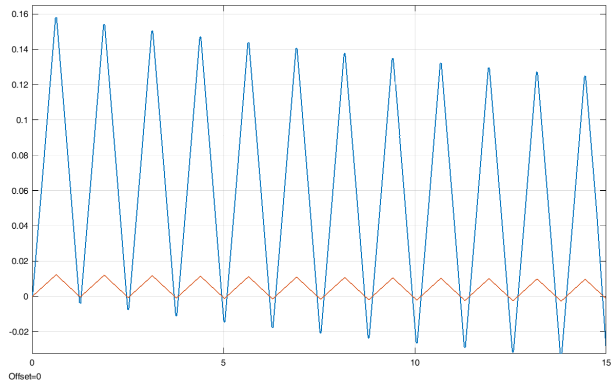

Fig. 11. The result of a circle simulation plot of the RL electric circuit.

B. *Simulink of the Electric Circuit with Two Degree of Freedom Voltage Saturation*

Plot the resulting currents for the electrical circuit with two degrees of freedom and a pure linear resistance (no saturation) and a real resistance (with saturation). The numerical information from equation (44) may be used to calculate the TF that connects the input voltage to the output current[9].

$$V_C(s)/V_s(s) = 1/(LCs^2 + RCs + 1) \tag{44}$$

The voltage-current relationship on a resistor is only proportional (linear) higher than or equal to the saturation voltage value; after that, any growth in the input will maintain the output at the same level. This is known as a saturation-type nonlinearity. Fig. 12 displays the necessary Simulink blocks and their connections[10]. You can enter the saturation voltage values 50 under the Upper limit and 50 under the Lower limit by double-clicking the saturation block in Simulink's discontinuities section of the library. From the sources library, the sine Wave input was chosen; its parameter window calls for an amplitude of 80 and a frequency (rad/sec) of 10. The simulation's output is shown in Fig 13, where it is evident that the saturation effect slices the current peaks including both negative and positive values. The Configuration Parameters' stop time is set to 10 seconds, and the model is then run during that time [11]-[15].

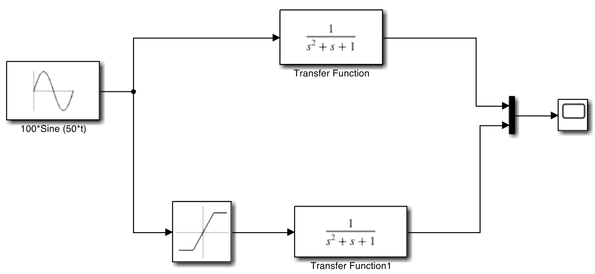

Fig. 12.Simulink of the electric circuit with Two Degree of Freedom Voltage Saturation.

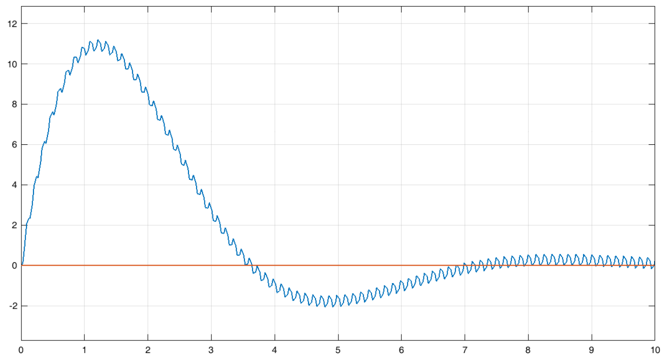

Fig. 13. Simulink Plot of the Simulink of the electric circuit with Two Degree of Freedom Voltage Saturation.

C. Discussion of Results

The results are shown graphically in the above figures. In Fig. 8 we explained the result of numerical solution and transfer function to the z-transfer function of the First order degree Electrical RC circuit between the input and the output of equation is determined using MATLAB Program. In Fig .9 we shown that how transfer function to the z-transfer function of the second order degree Electrical RLC circuit between the input and the output of equation is determined using MATLAB Program. In Fig. 9 we found the Simulink block diagram of the T.F of an Electrical Circuits with Resistor and inductor Voltage Saturation and we investigated in Fig. 10 the simulation results in Simulink with T.F. In Fig. 12 we found the Simulink block diagram of the T.F of an Electrical System with Resistor, capacitor, and inductor Voltage Saturation and we investigated in Fig. 13 the simulation results in Simulink with transfer function.

VIII. Conclusion

The paper, presented T.F Equations of an Electrical System for three circuits with two methods each, using MATLAB and Simulink® to solve the system of Equations of RL and RLC Tuning Circuits. Example problem sets for each of two engineering disciplines have been provided. With the RL and RLC circuits, we were able to demonstrate how MATLAB can analyze these circuits quickly and accurately with little prior programming experience. Additionally, we were able to analyze the circuit using the z-transform and transfer function representation of Simulink. To demonstrate the potential of the Power System in electrical drives studies, two representative examples utilizing the suggested simulation approach have been provided. With less effort and a fantastic graphical representation of the results, these techniques enable scientists to solve the RL and RLC circuits problems. To make sure that the numerical approximation produces an acceptable result using the analytical one as a benchmark, simulation results are compared to analytical results.

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