A Comprehensive Model of SRM in MATLAB Environment

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Abstract— Nowadays, switched reluctance motors (SRMs) attract more and more attention. Switched reluctance machines have emerged as an important technology in industrial automation. They represent a real alternative to conventional variable speed drives in many applications. It not only features a salient pole stator with concentrated coils, which allows earlier winding and shorter end turns than other types of motors, but also features a salient pole rotor, which has no conductors or magnets and is thus the simplest of all electric machine rotors. Simplicity makes the SRM inexpensive and reliable, and together with its high speed capacity and high torque to inertia ratio, makes it a superior choice in different applications. This research attempts to create a MATLAB model of multiphase SRM using the equations governing the dynamic behavior of linear inductance profile SRM. This simulation model can then be used to see the impact of any control system on SRM behavior. Simulation results also prove the exactness of the model.

Index Term— Switched reluctance motor, linearized inductance profile, multiphase SRM, matlab modeling.

I. INTRODUCTION

The switched reluctance motor (SRM) represents one of the oldest electric motor designs around. A variation of the conventional reluctance machine has been developed and is known as the “switched reluctance” (SR) machine. This development is partly due to recent demand for variable speed drives and partly as a result of development of power electronic drives. The name “switched reluctance”, describes the two features of the machine configuration: (a), switched, the machine must be operated in a continuous switching mode, which is the main reason for the machine development only after good power semiconductors became available; (b), reluctance, it is the true reluctance machine in the sense that both rotor and stator have variable reluctance magnetic circuits or more properly, it is a doubly salient machine. The switched reluctance motor is basically a stepper motor with fewer poles and has been used in many applications as both rotary and linear steppers. The idea of using the SR configuration in a continuous mode (in contrast to a stepper mode) with power semiconductor control is due primarily to [1]-[2], at that time, only thyristor power semi-conductors were available for the relatively high-current, high-voltage type of control needed for SR machines. The switched reluctance motor, which was originally conceived in the early 1800’s [3], recently has gained considerable attention. It has the advantages of being inexpensive and rugged. Its’ simple construction makes it easy to manufacture but rugged enough to be worthy of consideration for powering traction applications such as automobiles [4]. But, it also has its drawbacks. The switched reluctance motor is inherently subject to torque ripple and acoustic noise [5]. This necessitates a more complex means of control. Until recently, it was not considered a viable candidate for traction applications, but with improved methods of control it may be possible to design a method which would allow the use of the reluctance motor where smoother torque is required. Research into this application requires computer simulation and so a computer model is required.

Many researchers worked on switched reluctance motor modeling and control. A general foundation for the basic modes of operation, analysis, design considerations and experimentation from a family of prototype motors can be found in [6]. Authors of [7] has presented a timely review of the different design methods, which have been adopted for the SRM up to 1988 and broadly classified the design methods into 1) linear method; 2) nonlinear method; and 3) finite element method. A superior approach was suggested in [8] which depended on linearizing the inductance that allowed the voltage to be switched at any point in the cycle and enabled control strategies to be examined with sufficient accuracy. An evaluation of the capabilities of the switched reluctance motor drive, particularly in small integral-horsepower sizes, has been presented and was compared with those of typical induction motor drives [9]. Design and development of a single phase 2/2 switched reluctance motor as a cost-effective alternative to multiphase SRM in fan applications is presented in [10]. The finite element method has been used as a suitable technique for electrical design, performance evaluation and device optimization of switched reluctance machine in low frequency applications [11]. A finite element model was successfully used for 2-D magnetic field analysis of SRM to predict the steady state motor performance accurately in [12].

This work presents a simulation model of a multiphase switched reluctance motor created in MATLAB environment. In section II the detail mathematical model of the SRM is presented. Different steps taken to simulate the dynamic model of the SRM is presented in section III. Section IV presents the simulation results for the steady and dynamic behavior of the model. Finally, section V gives the concluding remarks. Detail of the MATLAB coding is included in the appendix.

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II. MATHEMATICAL MODELING

To derive the basic torque equation of the SRM, consider an elementary reluctance machine as shown in fig. 1. The machine is single phase excited; and the excited winding is wound on the stator while the rotor is free to rotate [13]-[14]. From (1), the flux linkage is $\Phi$, $I$ is the current flowing through the stator and $L$ is the inductance. The dependence of the inductance on the rotor position ($\theta$) makes the flux linkage a function of ($\theta$), too.

$$\phi(\theta) = L(\theta)I$$  \hspace{1cm} (1)

A mathematical model of an SRM can be developed based on the electrical diagram of the motor, incorporating phase resistance and phase inductance. The equivalent circuit for one phase is illustrated in fig. 2. The voltage applied to a phase of the SRM can be described as a sum of the voltage drops in the phase resistance and induced voltages on the phase inductance.

$$Vi = i^2R_m + i \frac{d\phi}{dt}$$  \hspace{1cm} (2)

Although SR motor operation appears simple, an accurate analysis of the motor's behavior requires a formal, and relatively complex, mathematical approach. The instantaneous voltage across the terminals of a single phase of an SRM winding is related to the flux linked in the winding as illustrated in (2),

$$V = iR_m + \frac{d\phi}{dt}$$  \hspace{1cm} (2)

where, $V$ is the terminal voltage, $i$ is the phase current, $R_m$ is the motor winding resistance, and $\phi$ is the flux linked by the winding. Because of the doubly salient construction of the SR motor (both the rotor and the stator have salient poles) and because of magnetic saturation effects, in general, the flux linked in an SRM phase varies as a function of rotor position, $\theta$, and the motor current. Thus, (2) can be expanded as:

$$V = iR_m + \frac{\partial\phi}{\partial i} \frac{di}{dt} + \frac{\partial\phi}{\partial \theta} \frac{d\theta}{dt}$$  \hspace{1cm} (3)

where, $\frac{\partial\phi}{\partial i}$ is defined as $L(\Theta,i)$, the instantaneous inductance, $\frac{\partial\phi}{\partial \theta}$ is the instantaneous back EMF. Equation (3) governs the transfer of electrical energy to the magnetic field. Multiplying each side of (2) by the electrical current $i$, gives an expression for the instantaneous power in an SRM:

$$Vi = i^2R_m + i \frac{d\phi}{dt}$$  \hspace{1cm} (4)

The left-hand side of (4) represents the instantaneous electrical power delivered to the SRM. The first term in the right-hand side (RHS) of (4) represents the ohmic losses in the SRM winding. If power is to be conserved, then the second term in the RHS of (4) must represent the sum of the mechanical power output of the SRM and any power stored in the magnetic field. Thus,

$$\frac{dW_m}{dt} + \frac{dW_f}{dt} = \frac{dW}{dt}$$  \hspace{1cm} (5)

where $\frac{dW_m}{dt}$ is the instantaneous mechanical power and $\frac{dW_f}{dt}$ is the instantaneous power stored in the field. Because power, by its own definition, is the rate of change of energy, $W_m$ is the mechanical energy and $W_f$ is the magnetic field energy. It is well known that mechanical power can be written as the product of torque and speed. So, from (5) we have,

$$\frac{dW_m}{dt} = T\omega = T\frac{d\theta}{dt}$$  \hspace{1cm} (6)

where $T$ is the torque, and $\omega$ is the rotational velocity of the shaft. Substitution of (6) into (5) gives,

$$i \frac{d\phi}{dt} = T \frac{d\theta}{dt} + \frac{dW_f}{dt}$$  \hspace{1cm} (7)

Solving (7) for torque yields the following equation,

$$T(\theta,\phi) = i(\theta,\phi) \frac{\partial\phi}{\partial \theta} - \frac{dW_f(\theta,\phi)}{dt}$$  \hspace{1cm} (8)

For constant flux, (8) simplifies to,
\[ T = -\frac{dW_f}{dt} \]  (9)

Since it is often desirable to express torque in terms of current rather than flux, it is common to express torque in terms of co-energy \( W_c \), instead of energy. To introduce the concept of co-energy, first consider a graphical interpretation of field energy.

For constant shaft angle \( \frac{d\Theta}{dt} = 0 \), integration of (7) shows that the magnetic field energy can be shown by a shaded area in fig. 3 and (10) [14]-[15].

\[ W_f = \int_{0}^{\phi} i(\theta, \phi)d\phi \]  (10)

For the fixed angle, \( \Theta \), let the magnetization curve define flux as a function of current, instead of current defined as a function of flux. Addition of field energy and co-energy and then differentiating, we get

\[ dW_c + dW_f = \phi di + id\phi \]  (11)

Solving for the differential field energy of (11) and substituting back into equation (2.8) gives,

\[ T = \frac{id\phi - (\phi di + id\phi - dW_c(\theta,i))}{d\theta} \]  (12)

For simplification, the general torque equation in (12) is usually simplified for constant current. The differential co-energy can be written in terms of its partial derivatives as,

\[ dW_c(\theta,i) = \frac{\partial W_c}{\partial \theta}d\theta + \frac{\partial W_c}{\partial i}di \]  (13)

From (12) and (13), it is fairly easy to show that under constant current,

\[ T = \frac{\partial W_c}{\partial \theta} \]  (14)

Often, SRM analysis proceeds with the assumption that, magnetically, the motor remains unsaturated during operation. When magnetic saturation is neglected, the relationship from flux to current is given by,

\[ \phi = L(\theta)I \]  (15)

And the motor inductance varies only as a function of rotor angle. Substituting (15) into equation for co-energy and evaluating the integral yields,

\[ W_c = \frac{i^2}{2} L(\theta) \]  (16)

And then substituting (16) into (14) gives the familiar simplified relationship for SRM torque,

\[ T = \frac{i^2}{2} \frac{dL}{d\theta} \]  (17)

The reluctance of the flux path between the two diametrically opposite stator poles varies as a pair of rotor poles rotates into and out of alignment. The inductance of a phase winding is the maximum when the rotor is in the aligned position and the minimum when the rotor is in the nonaligned position. Since inductance is inversely proportional to reluctance, a pulse of positive torque is produced if a current flow in a phase winding increases as the inductance of that phase winding is increasing. A negative torque contribution is avoided if the current is reduced to zero before the inductance starts to decrease again. The rotor speed can be varied by changing the frequency of the phase current pulses while retaining synchronism with the rotor position.

III. MATLAB MODELING OF SRM

In this work, linear inductance profile based SRM was simulated using MATLAB. The sequences which are followed in this research is shown in the flow chart below-

![Flow chart of modeling of SRM using MATLAB](image-url)
All the necessary mathematical equations which govern the behavior of SRM are already elaborated in section II. A brief description of each of the aforementioned steps of the flow chart is given below-

Initialization: Value of all the motor parameters such as number of stator and rotor poles, stator arc angle, rotor arc angle, turn on angle, turn off angle, commutation angle, separation of subsequent angle etc are defined. These constant values of the parameters can be changed for different motors or for different data sheets. Data sheet of the motor used for this work is given in the appendix.

Creation of multiphase angular profile: To create different phase angle, MATLAB command rem is used and subsequent separation of angle for different phase is created in the model.

Creation of linear inductance profile: Due to magnetic saturation, inductance profile is generally nonlinear. But if nonlinearity is included the computational burden also increases. So, to just to have a preliminary understanding, the linearized inductance profile of SRM is used.

Creation of multiphase voltage switching profile: For SRM drive, many converter topologies have already been proposed and in this modeling, we assume H-bridge asymmetric converter while simulating the machine model. In fig. 5, H-bridge asymmetric converter is shown.

The conditions for voltage switching are-

i. When 0° < Rotor angle < Turn on angle, then Voltage = 0;

ii. When Turn on angle <= Rotor angle < Turn off angle, then Voltage = +V;

iii. When Turn off angle <= Rotor angle < commutation angle (θα) then Voltage= -V.

The control takes place applying the voltage source to a phase coil at turn-on angle θα until a turn-off angle θoff. After that, the applied voltage is reversed until a certain demagnetizing angle θd, which allows the return of the magnetic flux toward zero. To apply voltage V in one phase, the two IGBTs Q1 and Q2 in fig. 5 must be ON. On the contrary, to apply the -V voltage and assure the current continuity, the two diodes D1 and D2 are used.

Creation of multiphase current and flux linkage profile: Equation (2) is a first order ordinary differential equation (ODE). Many well known methods are already established to solve ODE type problems in MATLAB. In this work, the Euler’s method is used to implement the voltage, current and flux linkage relation.

Creation of the multiphase torque profile: For linearized inductance profile SRM, the torque equation (17) is already derived in the section II. Depending on the varying slope of the inductance for varying angle, torque profile is created.

Creation of total torque profile of the motor: A simple addition operation of all the individual phase torques was done to get the overall torque of the machine.

Output speed profile: Mechanical equations for SRM are

$$\frac{d\omega}{dt} = T - T_l - f \omega$$

(18)

where, ω is speed and $T_l$ is the load torque. Load torque can be varied before running the simulation to see the stability of the speed profile for different load torque. In this work the output characteristic curves are shown only for 3-phase SRM. But this MATLAB model can be assumed as a versatile one, which can be edited a bit to implement model of 4 phase or even more.

IV. SIMULATION RESULT IN MATLAB

The linear inductance profile for the chosen SRM is shown in fig. 6. The simulated plots of voltage, current, Back EMF, torque and speed is shown in figs. 7-10.

The MATLAB code for all the simulation is given in appendix. All the graphs were obtained for turn on angle 30° and turn off angle 60° and for zero load torque. Equation (3) can be rewritten as below-

$$V = RI + L(\theta) \frac{dI}{dt} + I\omega \frac{dL}{d\theta}$$

(19)

In (19), the term $I_0 \omega \frac{dL}{d\theta}$ is the Back EMF induced voltage, which will be high for higher speeds. To increase the current growth and avoid a high Back EMF opposition, the Turn on angle must be chosen in the same way as in Fig. 7-10, which means it should be chosen at the time when both inductance and the Back EMF are the minimum. Using the linear inductance profile the minimum Back EMF value will be zero
since $dt/d\theta = 0$, as shown in fig. 8. However, when the rotor position is in the zone where the inductance increases, the FEM voltage appears.

![Fig. 7. Voltage profile for one phase of SRM](image1)

![Fig. 8. Current profile for one phase of SRM](image2)

![Fig. 9. Back EMF of one phase of SRM](image3)

When the Back EMF surpasses voltage $V$, phase current starts decreasing until the turn off angle is reached, as shown in fig. 9. The sharp switching effects present in the voltage energizing strategy clearly introduce harmonics in the torque signal, by phase current signal, that increase the motor speed ripple. Since this energized strategy is usually applied only when the motor reaches high speed values, the mechanical system will attenuate these harmonics from the motor speed signal.

Impact of providing a disturbance for a small time interval:
If for a very small time interval, an additional load torque as a disturbance is given to the system, then Speed profile and back EMF profile changes. The figures are shown below-
This model is plotting all the characteristic parameters as it should have been and can also incorporate the impact of disturbance. Hence, it can be said that, this is a very useful model for SRM. However, from this multiphase model, any number of phases can be implemented by just some subtle editing in the codes.

V. CONCLUSIONS

Fast response and quick recovery from load disturbances and insensitivity to parameter variations are some of the principal criteria in designing and implementing a high performance variable speed electric motor drive system. Conventional PI controller based motor drive systems need accurate mathematical models to describe the system dynamics. Sophisticated system models incorporating unavoidable conditions such as saturation, disturbances, parameter drifts and temperature variations are often unavailable in the real world. In this paper, a completely MATLAB based model of SRM has been established and the simulation result also proves the exactness of the model. Also the disturbance impact proved its effectiveness.

APPENDIX

MATLAB code for linear inductance based multiphase SRM

```matlab
clc;
clear all;
close all;
% SRM model parameters
NS=6 NR=4 p=3;
V=150; TL=0; W=0.0; ts=0.000065; R=1.30;
J=0.0013; F=0.0183; DELTAI=0.2; DELTAVMIN=0;
DELTAVMAX=150; LMIN=8e-3; LMAX=60e-3;
BETAS=30*(pi/180); BETAR=30*(pi/180);
TETAS=(2*pi)/(1/NS); TETAX=(pi/NR)-((BETAR+BETAS)/2);
TETAY=(pi/NR)-((BETAR-BETAS)/2);
TETAZ=(BETAR-BETAS)/2;
TETAXY=(TETAY+TETAZ+TETAS);
TETAIN=20.1*(pi/180);
TETAON=0.1*(pi/180);
TETAOFF=30*(pi/180);
TETAQ=60*(pi/180);
TETAIN=20.1*(pi/180);
% Program below computes from the giving % minimum and maximum inductance values, % the equations of the linear inductance % profile for the increasing and % decreasing part
G=(inv([TETAX 1;TETAY 1]))*[LMIN;LMAX];
AUP=G(1); BUP=G(2);
H=(inv([(TETAY+TETAZ) 1;TETAXY … 1]))*[LMAX;LMIN];
ADOWN=H(1); BDOWN=H(2); DL=AUP;
% Initializing flux of all phases
flux1=0; flux2=0; flux3=0;
% Initializing voltage and currents of % all phases
Va1=V; Va2=V; Va3=V; I1=0; I2=0; I3=0;
tsim=0.5;
t=zeros(1,tsim/ts);
% starting the euler method
for i=1:tsim/ts th_rem1(i)=rem(theta(i),pi/2);
 th_rem2(i)=rem(theta(i)+pi/6,pi/2);
 th_rem3(i)=rem(theta(i)+pi/3,pi/2);
 if (0<=th_rem1(i)&(th_rem1(i)<=TETAX)) L1(i)=LMIN; end;
 if (TETAX<th_rem1(i)&(th_rem1(i)<=TETAY)) L1(i)=(AUP*th_rem1(i)+BUP); end;
 if ((TETAY<th_rem1(i))&(th_rem1(i)<=TETAXY)) L1(i)=((ADOWN*th_rem1(i))+BDOWN); end;
 if (th_rem1(i)>TETAXY) L1(i)=LMIN; end;
 if (0<=th_rem2(i)&(th_rem2(i)<=TETAX)) L2(i)=LMIN; end;
 if (TETAX<th_rem2(i)&(th_rem2(i)<=TETAY)) L2(i)=(AUP*th_rem2(i)+BUP); end;
 if ((TETAY<th_rem2(i))&(th_rem2(i)<=TETAXY)) L2(i)=(AUP*th_rem2(i)+BUP); end;
 if ((TETAY<th_rem2(i))&(th_rem2(i)<=TETAXY)) L2(i)=LMIN; end;
```
L2(i)=((ADOWN*th_rem2(i))+BDOWN); end;
if (th_rem2(i)>TETAXY) L2(i)=LMIN; end;
if (0<=th_rem3(i)&(th_rem3(i)<=TETAX)) L3(i)=LMIN; end;
if (TETAX<th_rem3(i)&(th_rem3(i)<=TETAY)) L3(i)=(AUP*th_rem3(i)+BUP); end;
if((TETAY<th_rem3(i))&(th_rem3(i)<=TETAXY)) L3(i)=((ADOWN*th_rem3(i))+BDOWN); end;
if (th_rem3(i)>TETAXY) L3(i)=LMIN; end;
if (TETAON<th_rem1(i)&(th_rem1(i)<=TETAOFF)) Va1(i)=V; end;
if ((0<=th_rem1(i))&(th_rem1(i)<TETAON)) Va1(i)=0; end;
if (TETAON<=th_rem1(i)&(th_rem1(i)<TETAOFF)) Va1(i)=V; end;
if(TETAOFF<th_rem1(i)&(th_rem1(i)<TETAQ)) Va1(i)=0; end;
if (th_rem1(i)>TETAQ) Va1(i)=0; end;
if (0<=th_rem1(i))&(th_rem1(i)<TETAON) Va1(i)=0; end;
if(TETAON<=th_rem2(i)&(th_rem2(i)<TETAOFF)) Va2(i)=V; end;
if(TETAOFF<th_rem2(i)&(th_rem2(i)<TETAQ)) Va2(i)=0; end;
if (th_rem2(i)>TETAQ) Va2(i)=0; end;
if (0<=th_rem2(i))&(th_rem2(i)<TETAON) Va2(i)=0; end;
if(TETAON<=th_rem3(i)&(th_rem3(i)<TETAOFF)) Va3(i)=V; end;
if(TETAOFF<th_rem3(i)&(th_rem3(i)<TETAQ)) Va3(i)=0; end;
if (th_rem3(i)>TETAQ) Va3(i)=0; end;
if (0<=th_rem3(i))&(th_rem3(i)<TETAON) Va3(i)=0; end;
if((TETAX<th_rem1(i))&(th_rem1(i)<=TETAX)) I1(i)=flux1(i)/((ADOWN*th_rem1(i))+BDOWN); end;
if (th_rem1(i)>TETAXY) I1(i)=flux1(i)/LMIN; end;
if ((0<=th_rem2(i))&(th_rem2(i)<TETAX)) I2(i)=flux2(i)/LMIN; end;
if((TETAX<th_rem2(i))&(th_rem2(i)<=TETAY)) I2(i)=flux2(i)/((AUP*th_rem2(i))+BUP); end;
if((TETAY<th_rem2(i))&(th_rem2(i)<TETAXY)) I2(i)=flux2(i)/((ADOWN*th_rem2(i))+BDOWN); end;
if (th_rem2(i)>TETAXY) I2(i)=flux2(i)/LMIN; end;
if ((0<=th_rem3(i))&(th_rem3(i)<TETAX)) I3(i)=flux3(i)/LMIN; end;
if((TETAX<th_rem3(i))&(th_rem3(i)<=TETAY)) I3(i)=flux3(i)/((AUP*th_rem3(i))+BUP); end;
if((TETAY<th_rem3(i))&(th_rem3(i)<TETAXY)) I3(i)=flux3(i)/((ADOWN*th_rem3(i))+BDOWN); end;
if (th_rem3(i)>TETAXY) I3(i)=flux3(i)/LMIN; end;

% compute torque
if ((0<=th_rem1(i))&(th_rem1(i)<TETAX)) T1(i)=0; end;
if ((0<=th_rem1(i))&(th_rem1(i)<TETAX)) T1(i)=0.5*(DL)*(I1(i)*I1(i)); end;
if ((TETAX<th_rem1(i))&(th_rem1(i)<TETAXY)) T1(i)=0.5*(DL)*(I1(i)*I1(i)); end;
if (th_rem1(i)>TETAXY) T1(i)=0; end;
while T1(i)<0 T1(i)=0; end;
if ((0<=th_rem2(i))&(th_rem2(i)<TETAX)) T2(i)=0; end;
if ((TETAX<th_rem2(i))&(th_rem2(i)<TETAXY)) T2(i)=0.5*(DL)*(I2(i)*I2(i)); end;
if ((TETAX<th_rem2(i))&(th_rem2(i)<TETAXY)) T2(i)=0.5*(DL)*(I2(i)*I2(i)); end;
if (th_rem2(i)>TETAXY) T2(i)=0; end;
while T2(i)<0 T2(i)=0; end;
if ((0<=th_rem3(i))&(th_rem3(i)<TETAX)) T3(i)=0; end;
if ((TETAX<th_rem3(i))&(th_rem3(i)<TETAXY)) T3(i)=0.5*(DL)*(I3(i)*I3(i)); end;
if ((TETAX<th_rem3(i))&(th_rem3(i)<TETAXY)) T3(i)=0.5*(DL)*(I3(i)*I3(i)); end;
if (th_rem3(i)>TETAXY) T3(i)=0; end;
```matlab
while T3(i)<0 T3(i)=0; end;
flux1(i+1)=flux1(i)+(Val1(i)-(R*I1(i)))*ts;
flux2(i+1)=flux2(i)+(Va2(i)-(R*I2(i)))*ts;
flux3(i+1)=flux3(i)+(Va3(i)-(R*I3(i)))*ts;

while T1(i)<0 T1(i)=0; end;
while T2(i)<0 T2(i)=0; end;
while T3(i)<0 T3(i)=0 end;

% compute FEM
if ((0<=th_rem1(i))&(th_rem1(i)<=TETAX)) DL1(i)=0; end;
if(TETAY<th_rem1(i))&(th_rem1(i)<=TETAXY) DL1(i)=DL1; end;

if((TETAY<th_rem1(i))&(th_rem1(i)<TETAXY)) DL1(i)=DL1; end;
if (th_rem1(i)>TETAX) DL1(i)=0; end;
if ((0<=th_rem2(i))&(th_rem2(i)<=TETAX)) DL2(i)=0; end;
if(TETAY<th_rem2(i))&(th_rem2(i)<TETAXY) DL2(i)=DL2; end;
if((TETAY<th_rem2(i))&(th_rem2(i)<TETAXY)) DL2(i)=DL2; end;
if (th_rem2(i)>TETAX) DL2(i)=0; end;
if ((0<=th_rem3(i))&(th_rem3(i)<=TETAX)) DL3(i)=0; end;
if(TETAY<th_rem3(i))&(th_rem3(i)<TETAXY) DL3(i)=DL3; end;
if((TETAY<th_rem3(i))&(th_rem3(i)<TETAXY)) DL3(i)=DL3; end;

if (th_rem3(i)>TETAXY) DL3(i)=0; end;
FEM1(i)=I1(i)*W(i)*DL1(i); FEM2(i)=I2(i)*W(i)*DL2(i);
FEM3(i)=I3(i)*W(i)*DL3(i);
T(i)=T1(i)+T2(i)+T3(i);
t(i+1)=t(i)+ts;

% disturbance applied
if (t(i+1)>tssim4) & (t(i+1)<tssim/3.9) TL=2; end;
W(i+1)=ts/I*(T(i)-T(i)-F*W(i)+W(i));
theta(i+1)=theta(i)+(pi/314.6);
end;

% plotting figures
figure(1)
plot (t(1:end-1),L1,
(t(1:end-1),L2,
(t(1:end-1),L3)
figure(2)
plot (t(1:end-1),Va1)
figure(3)
```