EFFECTS OF NUMERICAL OSCILLATION IN SWITCHING OF POWER TRANSFORMER CONNECTED TO A POWER NETWORK

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CERTIFICATE

This is to certify that the progress report of the thesis entitled, "**Effects of Numerical Oscillation in Switching of Power Transformer Connected to a Power Network.**" submitted by **Shri Keshav Bhatt and Shri Om Prakash Pradhan** in partial fulfillment of the requirements for the award of Bachelor of Technology degree in Electrical Engineering at the National Institute of Technology Rourkela (Deemed University), is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any degree or diploma.

Date: Prof. SHARMILI DAS

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Abstract

This thesis presents a method of modeling nonlinear elements, particularly acceptable in the calculation of low-frequency transformer transients. A program is developed for various variables calculations based on iterations. The development of an accurate transformer model can be very complex due to the large number of core designs and to the fact that several transformer parameters are both nonlinear and frequency dependent. Physical attributes whose behavior may need to be correctly represented are core and coil configurations, self- and mutual inductances between coils, leakage fluxes, skin effect and proximity effect in coils, magnetic core saturation, hysteresis and eddy current losses in core, and capacitive effects The advantages of developing an algorithm which enables study of numerical oscillations in low-frequency transformer transient calculations, are presented. Also, the reasons for the existence of numerical oscillations are identified when the transformer transients are calculated in formulation of equations. The transformer model can be easily interfaced with an electromagnetic transients program. Its main features are: (a) the basic elements for the winding model are the turns, (b) the complete model includes the resistances, inductances, impedances, permittivity and current in the windings, the iron core and the overhead line (c) the solution of the equations is obtained by developing programs and solving the various values and subsequently plotting those values using iterations.

CHAPTER 1

INTRODUCTION

1.1 TRANSIENT PHENOMENA OCCURRING IN TRANSFORMERS

Transient phenomena have probably provided transformer design engineers with their most interesting and stimulating challenge. For many years the very elusiveness of the subject coupled with the difficulties often met with in reproducing in the laboratory or test room the identical conditions to those which occur in practice undoubtedly provided the most significant aspect of that challenge. With the advent of computers quantitative calculations are which were very difficult to calculate; can be computed easily since, under extremely abnormal conditions (for instance, when dealing with voltages at lightning frequencies and with super saturation of magnetic circuits), the qualities of resistance, inductance and capacitance undergo very material temporary apparent changes compared with their values under normal conditions. A considerable amount of connected investigation has been carried out on transient phenomena of different kinds, by many brilliant investigators, and it is largely to these that we owe our present knowledge of transients. A number of individual papers have been presented before technical engineering institutions in the UK, the USA and Europe, and these have formed valuable additions to the literature of the subject. We cannot hope, in a volume of this nature, to cover anything approaching the whole field of the subject, but we have here endeavored to present a brief survey of the chief disturbances to which transformers are particularly liable and to calculate the numerical oscillations occurring in a transformer.

The transients to which transformers are mainly subjected are:

- Impact of high-voltage and high-frequency waves arising from various causes, including switching in
- System switching transients with slower wave fronts than the above.
- Switching inrush currents.
- Short-circuit currents

Voltage transients in power systems are caused by switching actions, lightning and faults in the system. Different phenomena create different types of transients. Oscillatory transients are caused mainly by switching phenomena in the network. The most common switching action is capacitor bank switching. The most severe transients are caused by capacitor energizing while capacitor de-energizing only causes a minor transient .Non synchronized energizing of capacitors is worse than synchronized. Oscillatory transients are characterized by duration, magnitude t. There are subclasses of oscillatory transients depending on the dominant frequency.

Impulsive transients are caused mainly by lightning strikes. The worst impulsive transients are created when the lightning strikes directly on the power line. However the majority of direct strikes lead to a fault, which shows up as a voltage dip at the equipment (monitor or end-user equipment) terminals. Impulsive transients are characterized by rise and decay time. The impulsive transients are divided into subclasses according to their duration. Transients in general are rapidly damped when they propagate due to the resistive part of the system. Therefore transients in general are a local phenomenon.

Exceptions are transients of relatively low frequency that originate in the transmission or sub transmission network, e.g. the switching of a 130-kV capacitor bank. Such a transient spreads in the same way as a voltage dip and may be observable hundreds of kilometers away from its origin.

During the first few cycles following a power system fault, high-speed protective relays are expected to make a correct decision as to the presence and location of the fault in order to preserve system stability and to minimize the extent of equipment damage. The majority of protective relays make their decisions based on 50 and 60 Hz fundamental frequency voltage and current signals. However, it is precisely at this moment that the voltage and current signals are badly corrupted by fault induced transients in the form of an exponentially decaying dc component and with frequencies above and below the fundamental power system frequency. The dynamic performance of high-speed protective relays depends to a large extent on the signals produced by the instrument transformers, and these signals depend on the overall transient response of the instrument transformers and the type of transients generated by the power system. The transient performance of current transformers (ct) is influenced by a number of factors with most notable the exponentially decaying dc component of the primary current. Its presence influences the build-up of core flux, a phenomenon which is likely to cause saturation and subsequently substantial errors in the magnitude and phase angle of the generated signals. The core flux is composed of an alternating and a unidirectional component corresponding to the ac and dc components of the primary fault current. The transient flux swing generated by the dc component of the primary fault current can be quite large compared to the one created by the ac component. The core may also retain an unknown amount of flux, because of the ferromagnetic character and whether or not the transformer has anti-remanence air gaps. This remanent flux will either aid or oppose the build-up of core flux and could contribute to ct saturation, during subsequent faults in the power system such as high-speed auto reclosing into a permanent fault, depending on the relative polarities of the primary dc component and the remanent flux.

Furthermore, after primary fault interruption, the transformer could still produce a unipolar decaying current due to the stored magnetic energy. The transient response of various transformers depends on several distinct phenomena taking place in the primary network such as, sudden decrease of voltage at the transformer terminals due to a fault, or sudden over voltages on the sound phases caused during line to ground faults on the network. Sudden decrease of voltage at the primary terminals could generate internal oscillations in the windings of a transformer which creates a high frequency on the secondary side.

1.2 Impact of High-voltage and High-frequency waves

Transformer windings may be subject to the sudden impact of high-frequency waves arising from switching operations, atmospheric lightning discharges, load rejections, insulator flashovers and short-circuits, and, in fact, from almost any change in the electrostatic and electromagnetic conditions of the circuits involved. An appreciable number of transformer failures occurred in the past, particularly in the earlier days of transformer design, due to the failure of inter- turn insulation, principally of those end coils connected to the line terminals, though similar insulation failures have also occurred at other places within the windings, notably at points at which there is a change in the winding characteristics. The failures which have occurred on the line-end coils have been due chiefly to the concentration of voltage arising on those coils as a result of the relative values and distribution of the inductance and capacitance between the turns of the coils.

1.3 Sources of Oscillating Voltages in Networks

It's found that the existence of oscillating voltages in networks stems from one of three possible sources:

- Lightning
- Faults
- Switching

Oscillations created by lightning need only be considered if this causes a switching operation or triggers a fault. Faults comprise single-phase to earth faults and two- or three-phase short-circuits with or without earth fault involvement. Switching may be initiated by the operator or automatically by the system protection.

It's found out by [4] that in only three of these categories was there a likelihood of oscillations which might coincide with a natural frequency of the transformer.

Which are:

- Polyphase close-up faults on a single line.
- Energisation of a short transformer-terminated line from a strong bus.
- Repetitive re-ignitions during the de-energisation of a transformer loaded with a reactive load.

1.3.1 Close-up faults

These are defined as occurring at a distance of less than 15 km from the transformer, while the line itself is considerably longer. The transformer is likely to be struck by a dangerous oscillatory component only in those cases where one line is connected to the transformer and a two- or three-phase fault occurs at the critical distance *l*, given by:

$$l = \frac{c}{4.fi}$$

(1.1)

where c is the velocity of the travelling wave, which is about 300 km/ms for overhead lines and 150 km/ms for cable

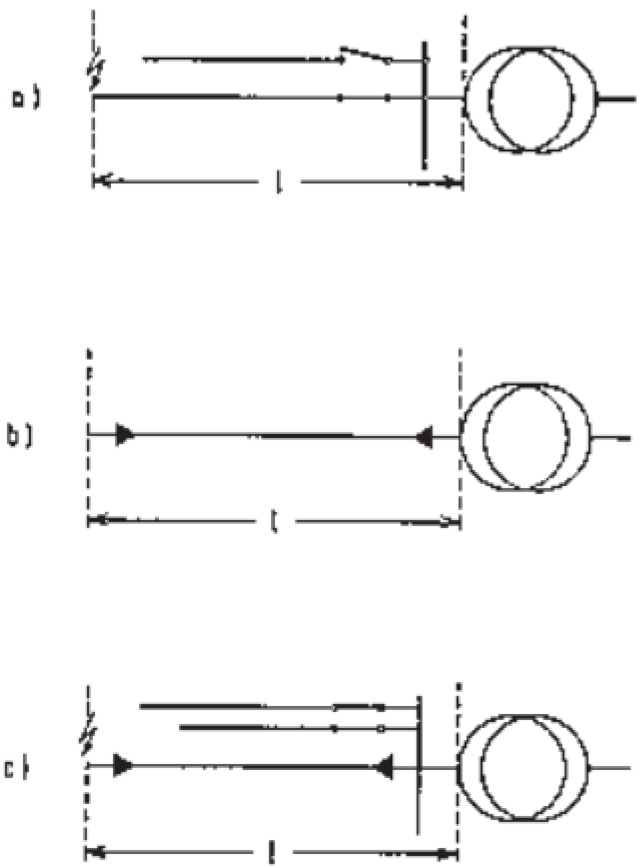


Fig 1.1 (Close-up fault)

1.3.2 Energisation of a transformer-terminated line

Switching in a short line through a circuit breaker fed from a strong busbar (fig. 1.2) creates standing waves which can be within the critical frequency range. Their frequency can be calculated from equation (1.1), where *l* corresponds to the length of the line.

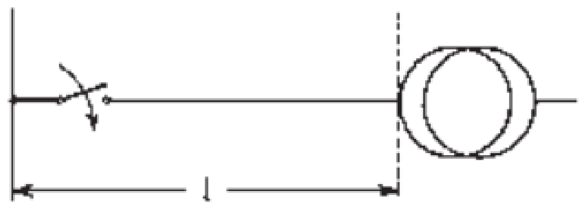


Fig 1.2- Energisation of transformer-terminated line

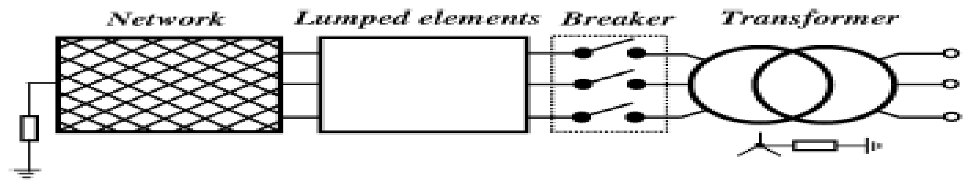
1.3.3 Repetitive re-ignitions

Breaking of small inductive currents (≤ 1 kA), in particular the interruption of magnetising currents of transformers, may cause oscillations, but these are in the kHz range and strongly damped, therefore these do not create a risk of resonance. The interruption of reactive loaded transformer currents can cause repetitive re-ignitions at nearly constant time intervals. If the repetition frequency coincides with one of the lower natural frequencies of the transformer, resonance may result. A typical configuration for which this can happen is the case of an unloaded three-phase transformer with a reactor connected to the tertiary winding.

CHAPTER 2

THE TRANSFORMER MODEL

2.1 Description of the Transformer Model

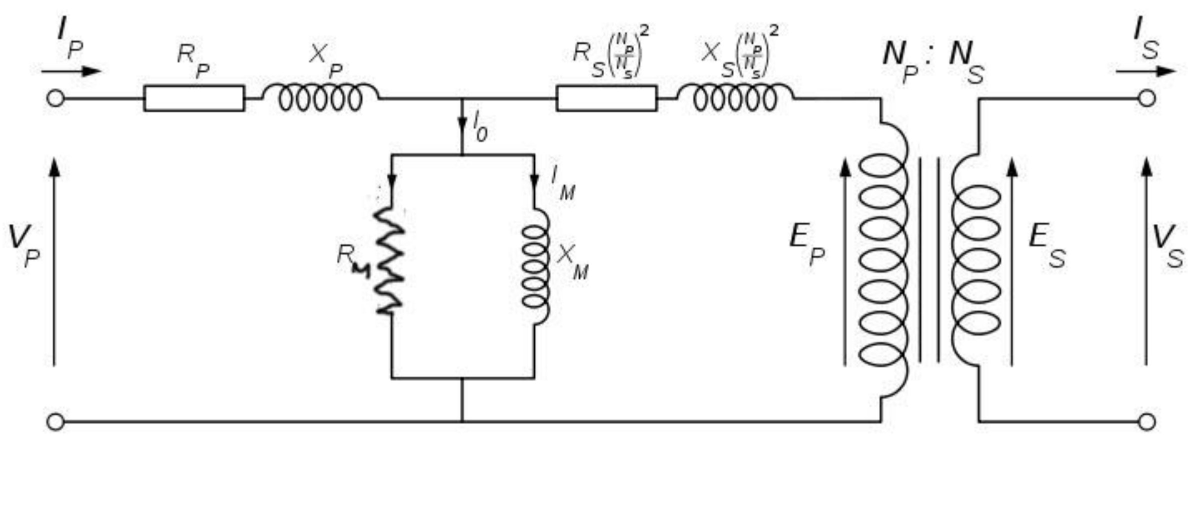


Simplified electrical circuit for transient analysis (Fig 2.1)

2.1.1 Parameters

The windings parameters (inductances and resistances) are calculated starting with the turns as follows:

Leakage inductance between pairs of turns (or sections) and they are the basis of the model for the inductive phenomena in the window of the transformer. The resistance & inductance in the primary and secondary windings are considered.



Simplified circuit with resistances and inductances referred to the primary Fig (2.2)

2.2 TRANSFORMER MODELS

Transformer models for simulation of low-frequency transients can be classified into three groups, whose main characteristics are summarized below.

1) Matrix representation: The transformer equation for transient calculations can be written in the following form $[v]= [R]\,[i]+[L]\,[di / dt]$

where [R] and jω[L] are respectively the real and the imaginary part of the branch impedance matrix. In case of a very low excitation current, the transformer should be described by the following equation $[di/dt]=[L]-1[v]-[L]-1[R][i]$

Both approaches include phase-to-phase couplings and terminal characteristics, but they do not consider differences in core or winding topology; besides these models are linear and theoretically valid only for the frequency at which the nameplate data was obtained, although they are reasonably accurate for frequencies below 1 kHz . For simulation of saturable cores, excitation may be omitted from the matrix description and attached externally at the model terminals in the form of non-linear elements; such core is not always topologically correct, but good enough in many cases.

2) Saturable Transformer Component: A single-phase N winding transformer model can be based on a star-circuit representation, whose equation has the following form

$[L]-1[v]=[L]-1[R][i]+[di/dt]$

Saturation and hysteresis effects can be modeled by adding an extra non-linear inductor at the star point. This model can be extended to three-phase units through the addition of a zero-sequence reluctance parameter. This model is of limited application, even for single-phase units, since magnetizing inductance and the resistance in parallel are connected to the star point, which is not always the correct topological connecting point.

2.3 NONLINEAR AND FREQUENCY-DEPENDENT PARAMETERS

Some transformer parameters are non-linear and/or frequency dependent due to three major effects: saturation, hysteresis and eddy currents. Saturation and hysteresis are included in the representation of the iron core and introduce distortion in waveforms. Excitation losses are caused by hysteresis and eddy current effects, although in modern transformers they are mostly due to eddy current.

A. Modeling of Iron Cores

Iron core behavior is usually represented by a relationship between the magnetic flux density B and the magnetic field intensity H. To characterize the material behavior fully, a model has to be able to plot numerous associated curves (major and minor loops). Hysteresis loops usually have a negligible influence on the magnitude of the magnetizing current, although hysteresis losses and the residual flux can have a major influence on some transients, e.g., inrush currents. Magnetic saturation of an iron core can be represented by the anhysteretic curve, the B–H relationship that would be obtained if there was no hysteresis effect in the material. The saturation characteristic can be modeled by a piecewise linear inductance with two slopes, since increasing the number of slopes does not significantly improve the accuracy.

B. Modeling of Eddy Current Effects

Several physical phenomena, known as eddy current effects, occur simultaneously in a loaded transformer that result in a nonuniform distribution of current in the conductors, and manifest themselves as an increase in the effective resistance and winding losses with respect to those for direct current. A change in the magnetic field induces also eddy currents in the iron. As a consequence of this, the flux density will be lower than that given by the normal magnetization curve. As frequency changes, flux distribution in the iron core lamination changes. For high frequencies the flux is confined to a thin layer close to the lamination surface, whose thickness decreases as the frequency increases. This indicates that inductances representing iron path magnetization and resistances representing eddy current losses are frequency dependent.

Inductive components of these models represent the magnetizing reactances and have to be made non-linear to account for the hysteresis and saturation effects. Since the high frequency components do not contribute appreciably to the flux in the transformer core, it can be assumed that only low frequency components are responsible for driving the core into saturation. It may, therefore, be justifiable to represent as non-linear only the first section of the model, so for low frequency transients a equivalent circuit with order equal or less than 2 may suffice.

CHAPTER 3

CALCULATION OF TRANSIENTS IN A TRANSFORMER

3.1 Equation Representation

The differential equation describing the behavior of the voltages and currents in the transformer model with inductances and resistances referred to the primary is obtained

For the voltage drop V: in the windings of the transformer, we have the following state equations:

$$Vs(t)=\frac{R'_p.I_{new} + (L_p'+L_m)di_{new}}{dt} \qquad (3.1)$$

Where R'_p is the resistance of the transformer referred to the primary (in ohms)

I_{new} is the current after k^{th} iteration (in Amperes)

L_p' is the inductance of the transformer referred to the primary (in Henry)

di_{new} is the differential change in current after k^{th} iteration (in Ampere)

dt is a small time interval (in seconds)

L_m is the Leakage inductance (in Henry)

3.1.1 Iron Core

For the iron core we represent the magnetization inductance as

$$L_m=\frac{N^2\mu_o \mu_r A}{l} \qquad (3.2)$$

Where, N is the number of turns on the primary

μ_o is the absolute permittivity

μ_r is the relative permittivity

A is the core area (in meter-squared)

L is the magnetic flux path length (in meter)

This inductance is defined as the gradient $d\Phi/di_m$ at any point of a nonlinear magnetizing curve: magnetizing current versus magnetic flux Hysteresis, its expected effect is an increase of damping of the transients and, possibly, some remanent magnetization. During transformer transients the inductances are being switched on and off, depending on absolute values of magnetic fluxes $\Phi_1,\Phi_2,\Phi_3,\ldots\ldots\ldots\ldots..\Phi_n$

The differential change in current is found out by

$$di_{k+1}=\frac{V_s(t).dt-R'_pI_k.dt}{(L_p'+L_m)} \qquad (3.3)$$

The incremental change in flux is found out to be :

$$d\Phi=\frac{(L_p'+L_m)di}{N} \qquad (3.4)$$

This gives B (magnetic flux density),

$$B=\frac{d\phi}{A} \qquad (3.5)$$

And H(magnetic field intensity) is found out to be ;

$$H=\frac{\Phi.A}{\mu} \qquad (3.6)$$

The current after k^{th} iteration is found out to be

$$I_{k+1}=I_0+di_k \qquad (3.7)$$

Similarly the new flux is found out to be

$$\mathbf{\Phi_{k+1}= \Phi_0 + d\Phi} \qquad (3.8)$$

Using these values we can plot the B-H curve and $V_s(t)$-dt curve

3.2 Algorithm

Step 1 – Take the values of the various parameters input by the user

R_p: Resistance on primary windings

L_p: Reactance on primary windings

R_s: Resistance on secondary windings

Ls: Reactance on secondary windings

L_m: Magnetizing reactance

R_m: Magnetizing resistance

N: Number of turns of winding on primary side

K: Turns ratio of the primary and secondary

Step 2 – The user inputs a value of a small time interval (Δt) = 1/100 cycle (say)

Step 3 – The user inputs a number of time periods or time cycles = 20 (say)

Step 4- The user inputs the dimension of winding to calculate area (A) and length (l) of the winding

Step 5 – Assume secondary referred to the primary so that

Lp1 = $Lp + \frac{Ls}{K2}$

Rp1 = $Rp + \frac{Rs}{K2}$

Step 6- Calculate the inductance of the core

$$Lm = N^2 \mu_0 \mu_r \frac{A}{L}$$

Step 7- Assume an initial value of current i(0)= $\lim_{t \to 0+} i(t)$ and an initial value of voltage

$v(0) = \lim_{t \to 0+} E(t)$

Step 8 - Initially calculate di (small change in current) by $di(0) = \frac{V(0).d(t)}{Lp'}$

Step 9 – Now, calculate current after first iteration as $i(1) = i(0) + di$

Step 10 – Set initial count as 0

Step 11 – Set number of iterations based on the time period and the number of cycles (e.g. $\frac{20}{1/100} = 2000 = n$)

Step 12 – Differential change in current for k_{th} iteration can be calculated as

$di_k = \frac{i_{k+1} - i_k}{\Delta t}$ (k=1,2,……)

Step 13 – Current after iteration k can be calculated as $i(t)_{k+2} = i(t)_{k+1} + di_{k+1}$

Step 14 - Evaluate rate of change of current i_L *as-* $\frac{di_L}{dt} = \frac{i(t)}{\Delta t}[1 - \frac{X_m}{R_m}]$

Step 15 - Now take the equivalent circuit of the transformer and consider the equation

$$E(t) = Xp' \frac{di}{dt} + Rp'i + Xm \frac{di_L}{dt}$$

Using step 14 , substitute $\frac{di_L}{dt}$ in step 14

Step 16 – Now use iterations to evaluate voltage after iterations

Step 17- Calculate the rate of change of current for various iterations

Step 18- Calculate the voltage $E(t)_k$

Step 19 – Plot various values of voltage along with time after iteration k

Step 20- Plot voltage across current on Y- axis after the iteration

Step 21- Now using another relation for $V_s = R_p i + N\frac{d\phi}{dt}$

Step 22- Comparing $V_s(0) = R_p i + N\frac{d\phi}{dt}$ and $V_s(0) = R_p i + (Lp' + Lm)\frac{di}{dt}$ we obtain the value of $N\frac{d\phi}{dt}$

Step 23 – We obtain the value of $d\Phi = (Lp' + Lm)\frac{di}{dt}$ and comparing it with $d\phi = BXA$ gives the value of B

Step 24 – User inputs Φ(0)

Step 25 – Now $\phi_1 = \phi(0) + d\phi$ where $d\phi = \frac{V_s(0).dt}{N}$ and calculate for the subsequent values of ϕ using multiple iterations

Step 26- Store the various values of $H = \frac{\phi XA}{\mu}$

Step 27 – Now using the various values obtained after iterations plot the B-H curve, V-t curve , I-t curve, V-I curve .

3.3 Program

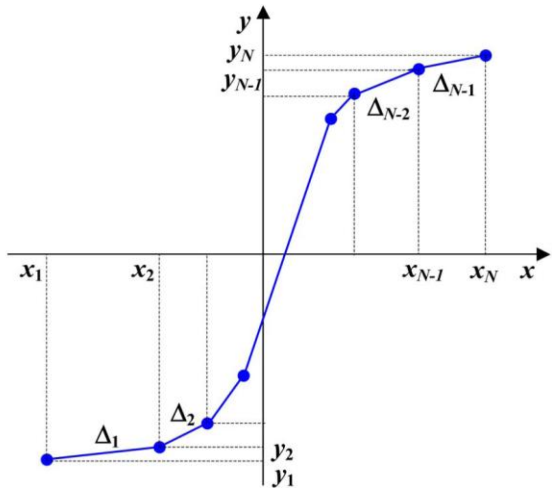
To calculate the transformer transients using the above equations a program is written in C++

```
#include<iostream.h>
#include<dos.h>
#include<ctype.h>
#include<conio.h>

double rp,lp,rs,ls,lm,rm,n,k,delt,t,area,lp1,l,rp1,mu,di,dphi;
double i[],v[],phi[],h[],b[];


void main()
{
cout<<"\n ENTER THE VALUE OF RESISTANCE ON THE PRIMARY WINDING :";
cin>>rp;
cout<<"\n ENTER THE VALUE OF REACTANCE ON THE PRIMARY WINDING :";
cin>>lp;
cout<<"\n ENTER THE VALUE OF RESISTANCE ON THE SECONDARY WINDING
:";
cin>>rs;
cout<<"\n ENTER THE VALUE OF REACTANCE ON THE SECONDARY WINDING
:";
cin>>ls;
cout<<"\n ENTER THE VALUE OF MAGNETISING REACTANCE :";
cin>>lm;
cout<<"\n ENTER THE VALUE OF MAGNETISING RESISTANCE:";
cin>>rm;
cout<<"\n ENTER THE VALUE OF NO. OF TURNS ON PRIMARY WINDING :";
```

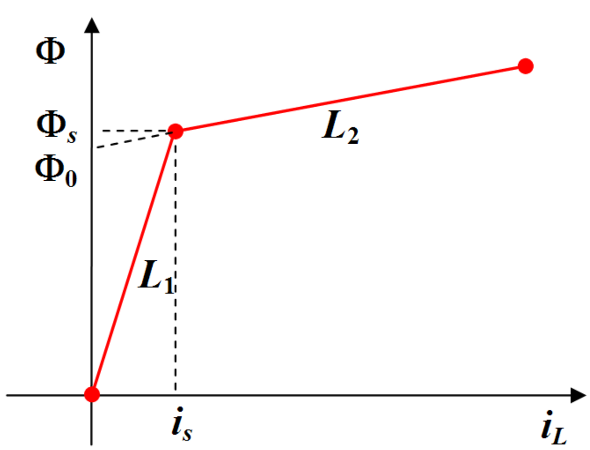
```
cin>>n;
cout<<"\n ENTER THE VALUE OF TURNS RATIO:";
cin>>k;
cout<<"\n ENTER THE VALUE OF SMALL TIME INTERVAL :";
cin>>delt;
cout<<"\n ENTER THE VALUE OF TIME CYCLE :";
cin>>t;
cout<<"\n ENTER THE VALUE OF AREA :";
cin>>area;
cout<<"\n ENTER THE VALUE OF LENGTH :";
cin>>l;
cout<<"\n ENTER THE VALUE OF mu :";
cin>>mu;

double v0,i0;
lp1=lp+ls/(k*k);
rp1=rp+rs/(k*k);
lm=n*n*mu*area/l;
int size=t/delt;
const int size1=2000;
double i[size1];
double v[size1];
double phi[size1];
double b[size1];
double h[size1];

cout<<"\n ENTER THE INITIAL VALUE OF CURRENT :";
cin>>i[0];
cout<<"\n ENTER THE INITIAL VALUE OF VOLTAGE  :";
cin>>v[0];
cout<<"\n ENTER THE INITIAL VALUE OF FLUX  :";
```

```
cin>>phi[0];
di=v*delt/lp1;
i=i+di;
double vnew;
double inc =delt;
int j=1,count=1;
do
{ v[j]=(rp*i)(lp1+lm)*di/delt;
  delt=delt+inc;
  di=((vnew*delt)-(rp*i)*delt)/(lp1+lm);
  i[j]=i[j-1]+di;
  dphi=((lp1+lm)*di)/n;
  b[j]=dphi/area;
  phi[j]=dphi+phi[j-1];
  h[j]=(phi*area)/mu;
  cout<<phi[i]<<"\n"<<v[i];
  cout<<" THE VALUE OF FLUX IN "<<count<<"ITERATION IS :"<<phi[j];
  cout<<" \n Current :"<<i[j];
  cout<<"\n Voltage :"<<v[j];
  cout<<"\n B :"<<b[j];
  cout<<"\n H :"<<h[j];
  j++;
  count++;
  }while(count!=size)


  getch()
```

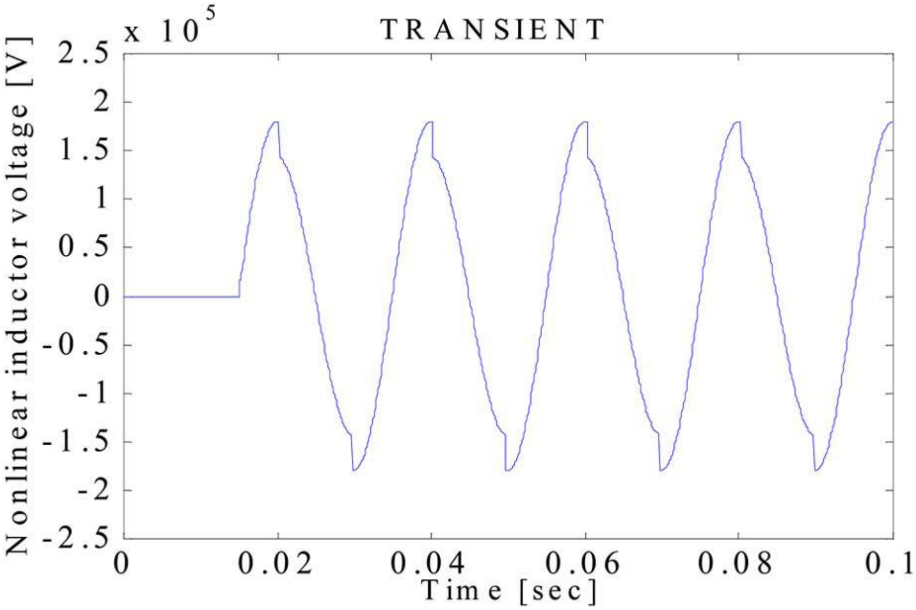
A.Tokic' et al. have found the various characteristics of transformer transients as shown below



Piece-wise linearized nonlinear curve (Fig. 3.1)



Nonlinear magnetizing curve (Fig . 3.2)



Nonlinear inductor voltage $\Delta t = 10^{-4}$ s. [Fig 3.3]

CHAPTER 4

TRANSFORMER CONNECTED TO AN OVERHEAD LINE

4.1 AC POWER LINE TRANSIENTS

Transients on the ac power line range from just above normal voltage to several kV. The rate of occurrence of transients varies widely from one branch of a power distribution system to the next, although low-level transients occur more often than high-level surges. Data from surge counters and other sources is the basis for the curves shown in Figure 4.1. This data was taken from unprotected (no voltage limiting devices) circuits meaning that the transient voltage is limited only by the sparkover distance of the wires in the distribution system.

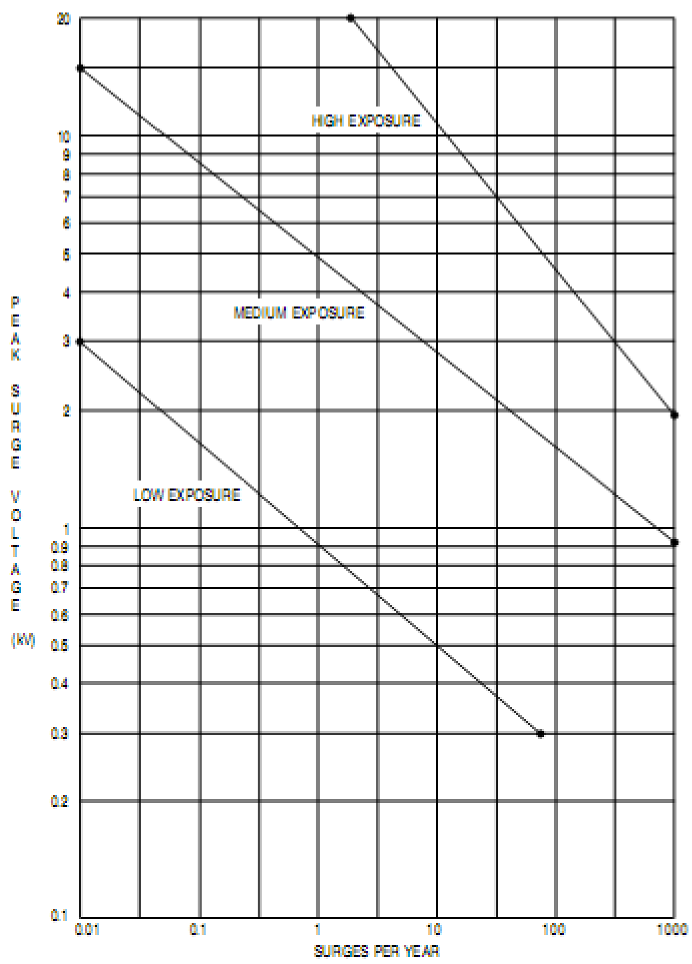


Fig 4.1 Peak surge voltage V/s Surges per year (EIA paper, P587.1/F, May, 1979, Page 10)

The low exposure portion of the set of curves is data collected from systems with little load-switching activity that are located in areas of light lightning activity. Medium exposure systems are in areas of frequent lightning activity with a severe switching transient problem. High exposure systems are rare systems supplied by long overhead lines which supply installations that have high sparkover clearances and may be subject to reflections at power line ends.

When using Figure 4.1 it is helpful to remember that peak transient voltages will be limited to approximately 6 kV in indoor locations due to the spacing between conductors using standard wiring practices.

Overvoltage transients can be caused by switching or lightning strokes or by interference with nearby high voltage lines; such transients are most detrimental to a transformer. For a transformer, the switching overvoltages are of considerable importance .A companion paper by Indulkar et.al describes the transients for the switching operations at the transformer terminals.

But, in a transformer, overvoltages can occur by switching operations in the connected power system also. Energisation of the transformer through an overhead line or cable can cause oscillatory switching surges which can lead to considerable internal overvoltages in the transformer winding. Some work has already been done in this area. Musil et al have developed a simple single- phase lumped parameter model to obtain the transient response of the single-phase line-transformer combination. A series resonant lumped circuit is used for the transformer winding and the line is represented by its surge impedance. Indulkar et.al. [8] have proposed a method of calculating the steady-state voltage distribution in a line-transformer cascade. The method is based on a simple chain matrix eigenvalue technique for the analysis of identical ladder networks representing a single-phase overhead line and a single transformer winding. Methods described in these References [3,7,8] use a detailed distributed parameter model of the transmission line and the transformer winding.

However, both these methods use a simple single-phase representation for the transmission line and the transformer winding. Such a representation is valid only for a system in which the neutral is solidly grounded. Hence, studies need to be conducted on a multiwinding basis for the transformer, and on a multiconductor basis for the transmission line. Transient studies on a multiwinding transformer, and a overhead line or underground cable form the subject matter of this paper.

The complete 3-phase model of the transformer has already been developed in a companion

Paper by Indulkar et. Al [8]. The three- phase models of the overhead line and underground cable are already available and are given in References [9,10]. The purpose of the investigations described in this thesis is to obtain the switching transient oscillations of the line- transformer and cable-transformer cascades for all possible transformer connections.

4.2 <u>The Simulation Model</u>

There are four important steps in formulating the transformer model which are as follows

- Constructing the overall system model
- Obtaining parameters for component models
- Benchmarking the components to confirm proper behaviors
- Benchmarking the overall system model to verify overall behavior

Only after the component models and the overall system model have been verified can one confidently proceed to run meaningful simulations. Even then, if there are some transient event records to compare against, more model benchmarking and adjustment may be required.

Appropriateness of line model depends on the line length and the highest frequency to be simulated. For “short” or “medium” transmission lines, a simple lumped coupled model, or several in series, may suffice For longer lines or higher frequencies, distributed parameter behaviors must be included. Developments of presently used transient transmission line models for this case are based on the “π model” presented in many textbooks [2].

4.3 <u>Calculation of Transmission line parameters</u>

The usual problem in transmission line studies assumes that the line parameters and either the input or output variables are known, and it is desired to calculate the corresponding output or input variables. The inverse problem consists in determining the line parameters when the measured values of the input and output variables are known.

The transmission line parameters from input–output measurements however can be calculated [6]. Where it’s assumed that simultaneous measurements of voltage, current, and power or power factor at the two ends of the transmission line are available and determines the resistance, reactance and susceptance of the equivalent pi network. The method considers the distributed nature of the line parameters, and determines the per-meter line parameters from the equivalent pi network. The case of input–output modelling used consists of the determination of the line model from input and output measurements only. This is often called the black-box approach.

The method determines the line parameters using non-linear equations, and avoids the disadvantage of the methods using linear equations, where the validity of the model is limited. A change in the operating conditions and in the corresponding input and output measurements does not lead to different line parameters when non-linear equations are used. The obtained line parameters will, however, depend on the time of input–output measurements and the corresponding weather conditions. The deterministic method of parameter estimation is applied to a long transmission line .The method assumes that the system has reached a steady-state condition when the voltage and current magnitudes, and power or power factors are measured simultaneously at the two ends of the transmission line. The input–output measurements can be carried out.

4.4 Transmission line model

The long line equations are

$$Vs = cosh\gamma l . Vr + Zo . sinh\gamma l . Ir \quad (4.1)$$

$$Is = \frac{sinh\gamma l}{Zo} . Vr + cosh\gamma l . Ir \quad (4.2)$$

Where the usual variables and parameters are

- Line length, l;
- Propagation constant, c;
- Characteristic impedance, Zo;
- Sending- and receiving-end voltages, Vs and Vr;
- Sending- and receiving-end currents, Is and Ir;

The equivalent pi network of the long line shown in Fig. 4.2 produces

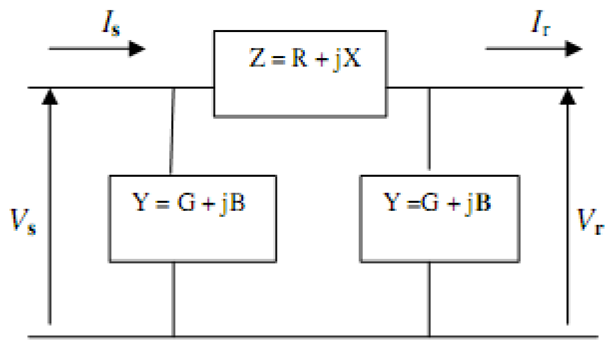


Fig 4.2 Equivalent Pi-network

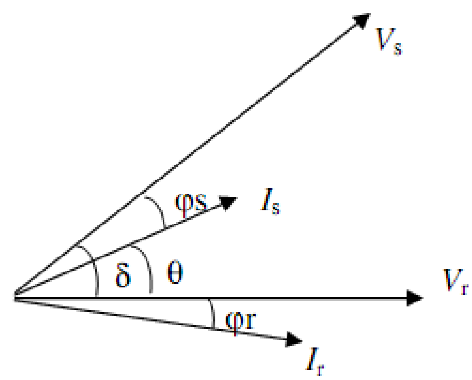


Fig 4.3 Phasor Diagram

$$\boldsymbol{Vs = (1 + ZY).Vr + Z.Ir} \quad (4.3)$$

$$\boldsymbol{Is = (2Y + ZY^2)Vr + (1 + ZY)Ir} \quad (4.4)$$

Where $\boldsymbol{Z = R + jX}$ (4.5)

$$\boldsymbol{Y = G + jB} \quad (4.6)$$

On comparing the values of Z and Y can be calculated and the equations (4.1) and (4.2) can be separated to form four different separate real equations

$$V_s \cos\delta = V_r - BXV_r + RI_r \cos\varphi_r + XI_r \sin\varphi_r,$$
$$\underline{\Delta}\ a,\ \text{say}$$
$$V_s \sin\delta = BRV_r + XI_r \cos\varphi_r - RI_r \sin\varphi_r,$$
$$\underline{\Delta}\ b,\ \text{say}$$
$$I_s(\cos(\delta - \varphi_s)) = -RB^2V_r + I_r \cos\varphi_r - XBI_r \cos\varphi_r$$
$$- RBI_r \sin\varphi_r, \quad \underline{\Delta}\ c,\ \text{say}$$
$$I_s(\sin(\delta - \varphi_s)) = 2BV_r - XB^2V_r - I_r \sin\varphi_r + RBI_r \cos\varphi_r$$
$$+ XBI_r \sin\varphi_r, \quad \underline{\Delta}\ d,\ \text{say}$$

Using these equations Indulkar et.al [6] have calculated the various parameters (such as X,R,G,B etc..)

CHAPTER 5

CALCULATION OF TRANSIENTS IN A TRANSFORMER CONNECTED TO AN OVERHEAD LINE

5.1 The Transformer connected to an Overhead line Model

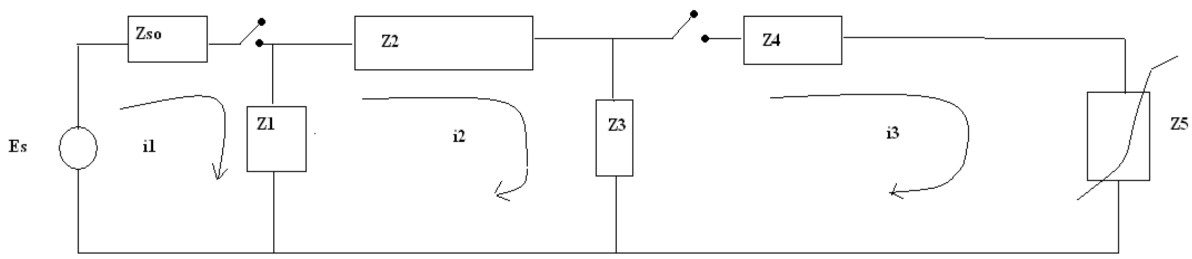


Fig. 5.1 The Transformer connected to an Overhead line.

In this model the transmission line is considered as an equivalent pi-network connected to a transformer. A 220 KV, 300 Km long line is considered and thereafter the various parameters have been calculated [6]. The transformer considered is a 52.6 MVA (45 MW) power transformer.

Transmission line measurements	
Sending-end voltage, V_s (kV) (L-N)	127
Sending-end current, I_s (kA)	0.416
Sending-end real power, P_s (MW) (3-phase)	150
Receiving-end voltage, V_r (kV) (L-N)	102
Receiving-end current, I_r (kA)	0.44
Receiving-end real power, P_r (MW) (3-phase)	135
Load angle, δ (°)	–

Table 5.1 – Transmission Line Parameters

Parameters

	Available parametric data of the 220 kV, 300 km long overhead line
X, ohms	146.4
R, ohms	26.4
B, S	0.000511
G, S	NA
δ, °	30.9
L, H/m	1.33×10^{-6}
R, ohm/m	0.93×10^{-4}
C, F/m	8.86×10^{-12}
g, S/m	NA

Table 5.2 – Estimated transmission line parameters calculated from measurements

5.2 Equation Representation

$$\boldsymbol{Es - I_1 Z_{SO} - (I_1 - I_2) Z_1 = 0} \tag{5.1}$$

$$\boldsymbol{(I_1 - I_2) Z_1 - I_2 Z_2 - (I_2 - I_3) Z_3 = 0} \tag{5.2}$$

$$\boldsymbol{(I_2 - I_3) Z_3 - I_3 Z_4 - I_3 Z_5 = 0} \tag{5.3}$$

These equations are obtained after mesh analysis of the circuit as shown in Fig 5.1
In matrix form

$$\begin{bmatrix} Z_1 + Z_{so} & -Z_1 & 0 \\ -Z_1 & Z_1 + Z_2 + Z_3 & -Z_3 \\ 0 & -Z_3 & Z_3 + Z_4 + Z_5 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} E_S \\ 0 \\ 0 \end{bmatrix} \tag{5.4}$$

Where,

- The first matrix is the Zmatrix ,the second matrix is the Imatrix and the third matrix is the Ematrix
- E_s is Source Voltage
- I_1 is the current in mesh 1
- I_2 is the current in mesh 2
- I_3 is the current in mesh 3
- Z_{so} is Source impedance (431.7 Ω)
- $Z_1=Z_3$= Impedance of the arm of the pi-network
- Z_2 is the impedance of the overhead transmission line represented in the pi-network
- Z_4 is the leakage impedance of the transformer
- Z_5 is the impedance of the core of the transformer

And it's found that

Z_1 = (-1/(13.91*(10^-10)))*j;

Z_{so} = 431.7;

Z_2 = 26.4+(146.4*j);

Z_3 = (-1/(13.91*(10^-10)))*j;

Z_4 = 17.20+(68.82*j);

Z_5 = 43000+(34410*j);

5.3 **Algorithm for calculating the transients for a transformer connected to an overhead line:-**

Step1-Initial values of the various parameters are taken.

Step2-The various static and dynamic variables are declared with their values which are evaluated earlier.

Step3-Z1, Z2, Z3, Z4, Z5, Zso, N, A, l, Rm, B, dt along with their values are hence specified.

Step4-The parameters like B,H,μ are initialized.

Step4-Xm being a variable quantity its initial value is declared.

Step5-A loop is designed to be executed a certain no. of times.(500 cycles here)

Step6-Inside the loop Zmatrix, Imatrix, and Ematrix are specified.

Step7-Using the matrix method of evaluating the current transients are calculated by a set of formulae.

Step8-Now the values of the parameters inside the loop are incremented as per the iterations and for the next cycle successively.

Step9-Values of the variables like B,H and mu are updated by the next iteration.

Step10-The B-H curve and current-time curves are plotted.

5.4 Program

To calculate the transformer transients of the power transformer connected to an overhead line, using the above equations a program is written in Matlab :

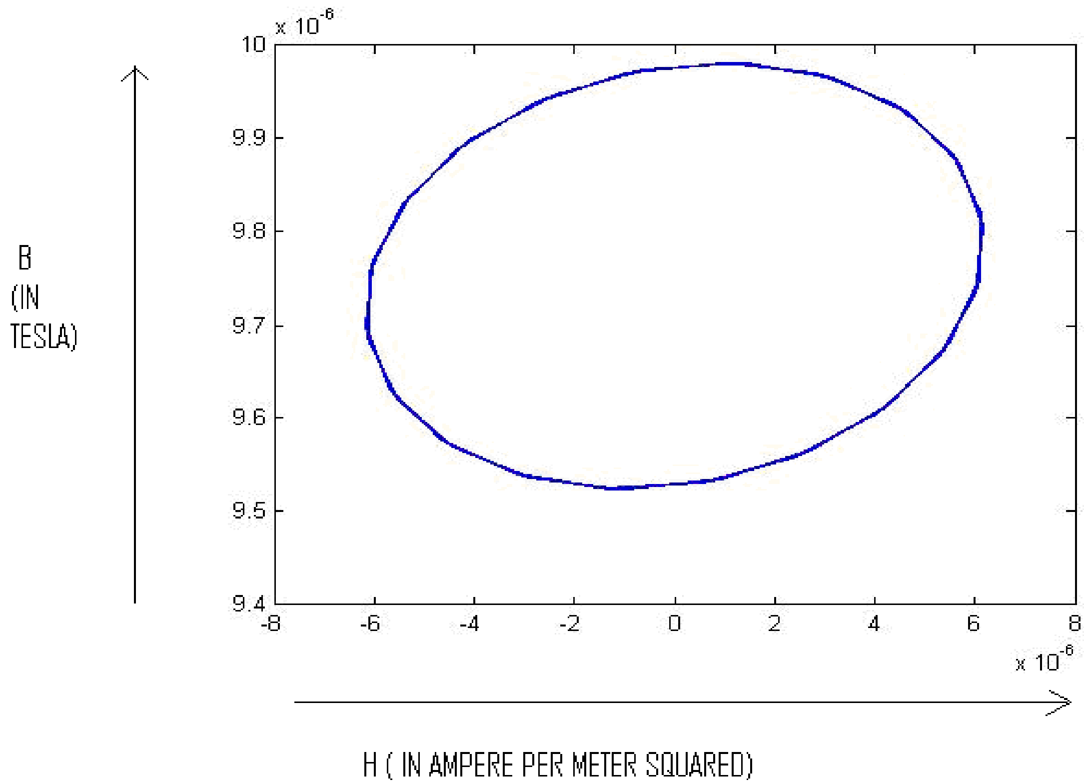
```
z1 = (-1/(13.91*(10^-10)))*j;
zso = 431.7;
z2 = 26.4+(146.4*j);
z3 = (-1/(13.91*(10^-10)))*j;
z4 = 17.20+(68.82*j);
z5 = 43000+(34410*j);
H=[];
Es=[];
T=[];
I1 = [];
I2 = [];
I3 = [];
t = 0;
dt = 0.001;



b(1) = 0;



h(1)=0;
n = 900;
a = 0.9175;
l = 20;
```

```
B=[];
mu0 = 4*3.14*(10^-7);
rm =430000 ;
xm=344100*j

idmat=[1,0,0;0,1,0;0,0,1];

for i=1:500;
   z5 = rm+xm;
   zmat = [z1+zso,-z1,0;z1,z2+z3+z1,-z3;0,-z3,z3+z4+z5];
   es = 220000*sin(100*3.14*t+pi/20);
   emat=[es;0;0];
   y=inv(zmat);
   imat=y*emat;
   i1=(imat(1,:));
   i2=(imat(2,:));
   i3=(imat(3,:));
   db=(i3*z5*dt)/(n*a);
   b = b+db;
   B=[B b];
   h = (n*i3)/l;
   H=[H h];
   mu = b/h;
   t=t+dt;
   xm = ((n^2)*mu*mu0*a)/l;
   mun=mu0*mu;
   Es=[Es es];
   I1=[I1 i1];I2=[I2 i2];I3=[I3 i3];
T=[T t];
  End
```

5.5 **PLOTS**

Various plots are plotted using the Matlab program:

Fig 5.2 B-H curve



- This is in accordance with the B-H curve as shown in F
- ig 5.2.1, the elliptical nature of the curve is due to transients.

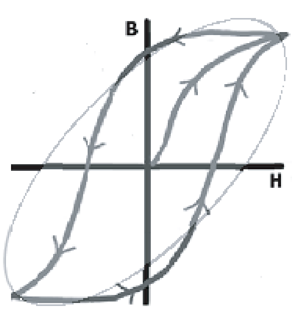


Fig 5.2.1

Fig 5.3 I_1-t curve

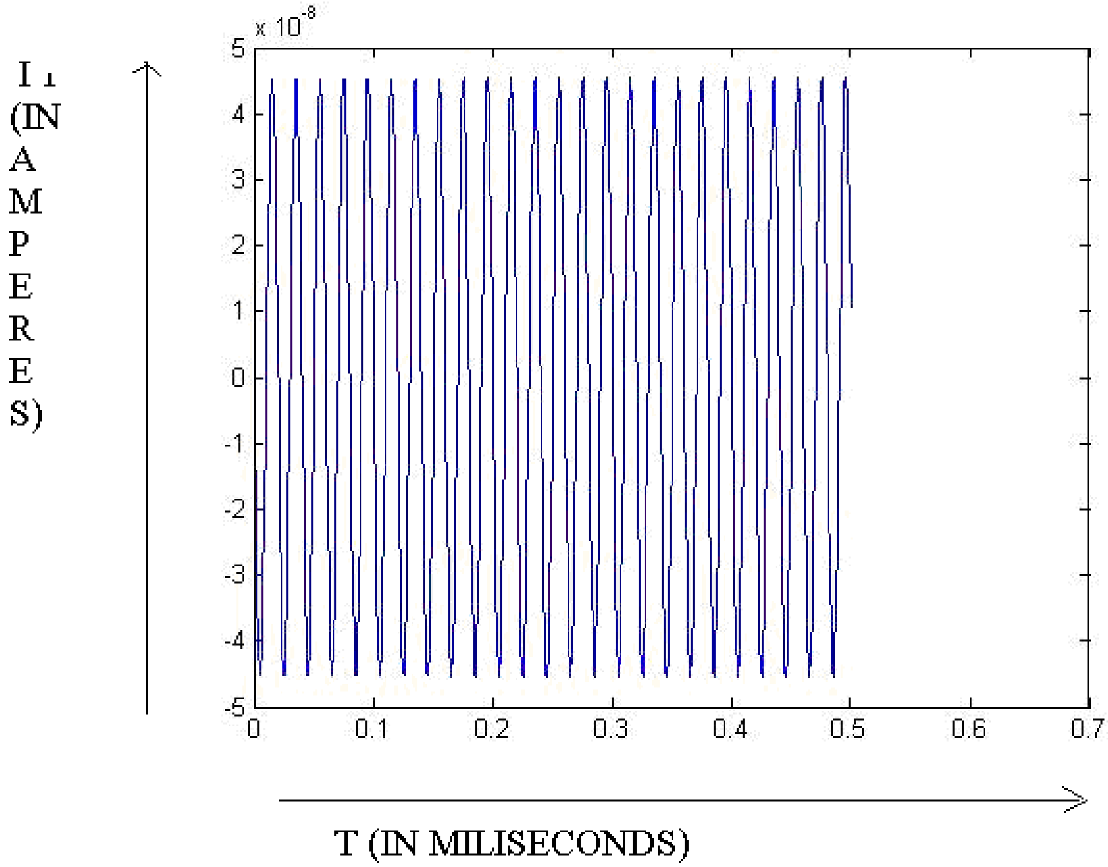


Fig 5.4 I_2-t curve

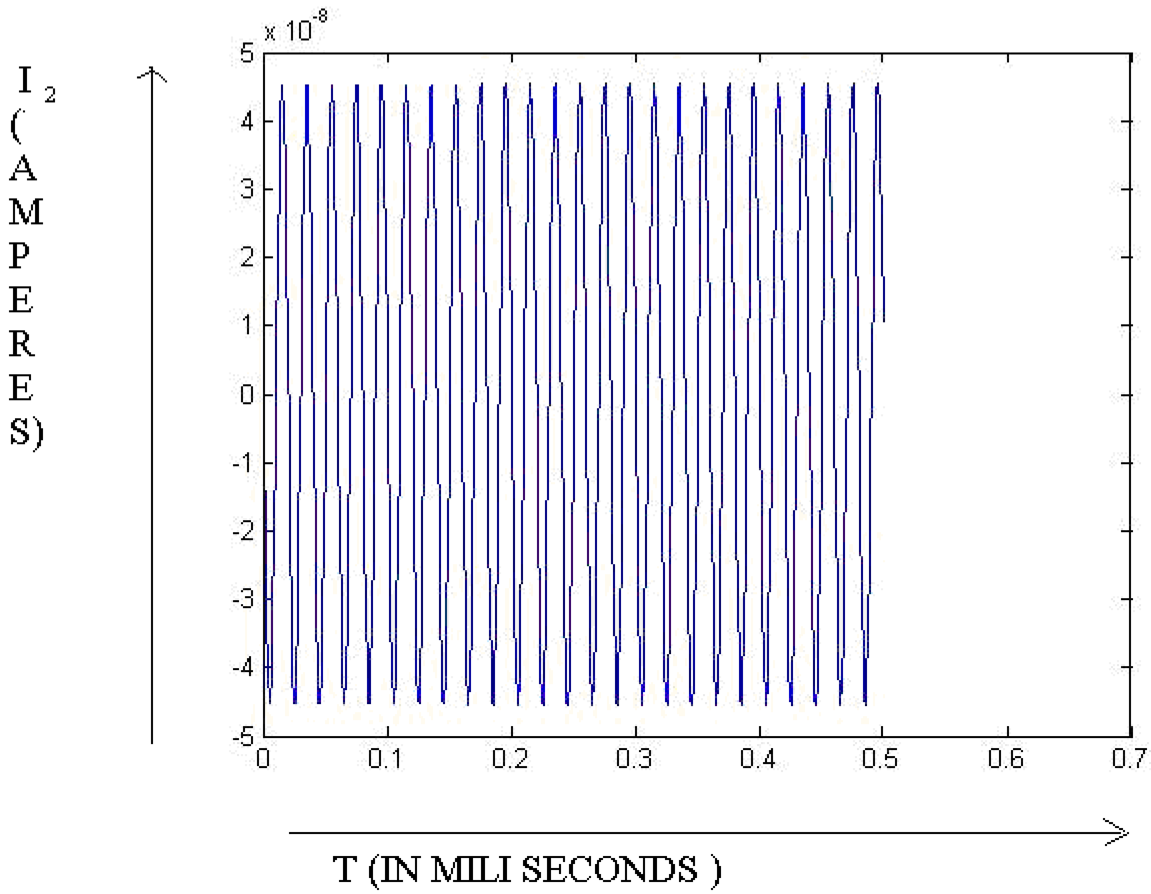
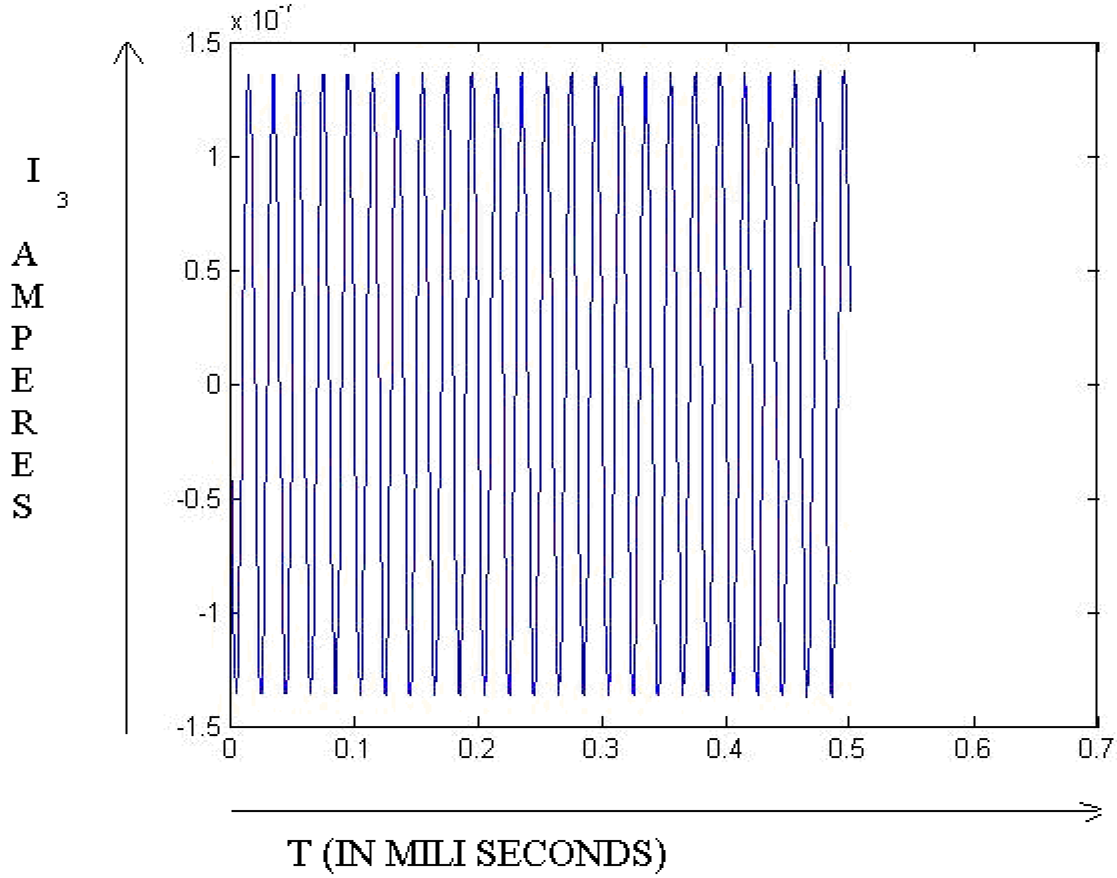


Fig 5.4 I_3-t Curve



CHAPTER 6

CONCLUSION

CONCLUSION

By studying the initial change in voltage and the voltage profile before and after a transient event a characterization of the transient is possible. The number of transients occurring in a transformer is determined by system configuration and the components in it. The components in the transformer and those attached to it are also frequency dependent. The number of transients can vary widely between different parts in the system.
The effects of numerical oscillation in switching of power transformer connected to a power network due to surge voltages in transformer with an overhead line connected to it and a transformer in general have been studied in detail

Measurement errors would affect the values of the estimated parameters. Many factors can reduce the precision of the results like errors in CTs etc. Further work on the sensitivity analysis of the estimated parameters with respect to the measuring errors of voltages, currents and powers at the line ends is suggested. The estimated parameters would be quite sensitive to the order in which measurements are processed. It is necessary to avoid entering bad data right at the beginning of the estimation process. Otherwise, the final solution will be adversely affected.

Hence, processing all measurements simultaneously would tend to eliminate bad data much better.

The importance of the work becomes evident especially with the construction of a new parallel transmission line between two substations due to load growth

The study of the B-H curve and it's deviation from the standard values also proves to be invaluable for the study of transformer transients.

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