

University of Southern Queensland
Faculty of Health, Engineering & Sciences

Effects of transformer inrush current

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Abstract

Inrush current in transformer is often gets less importance compared to other effects/faults. Though the magnitude of inrush current may be in some cases less than compared to short circuit current, the frequency and duration of inrush current is generally more frequent, hence it will likely have more adverse effect compared to other faults. Inrush current may flow when transformer is energised. The amount of inrush current depends on when in the voltage cycle the transformer is energised and residual flux in the transformer. The other type of inrush current is sympathetic inrush current which flows in already energised transformer when another transformer is energised in parallel connected line.

This report contains basic principle, fundamental theory and relevant laws of the transformer and inrush current. A number of factors affecting inrush current are discussed. The inrush current theory and their equation are derived. The effects of inrush current are described in brief. As a part of this project a number of effects and factor affecting inrush current are considered for simulation. The Matlab Sim-Power system is used for the simulation. The simulation results compared with each other and also data available from actual same size transformer. Finally six solutions to inrush current mitigation techniques with a practical low cost answer are provided.

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Abbreviations

AC:	Alternating Current
AVR:	Automatic Voltage Regulator
CB:	Circuit Breaker
CT:	Current Transformer
CB:	Circuit breaker
DC:	Direct Current
GCB:	Generator Circuit Breaker
IEEE:	The Institute of Electrical and Electronic Engineers
kA:	kiloampere = 1000 amps
MVA:	Mega volt-ampere
A =	Area of coil in m ²
B =	magnetic flux density in tesla or wb-m ² ,
B_m =	maximum value of flux density in the core in weber/meter ²
B_N =	normal rated flux density
B_R =	residual flux density
B_S =	saturation flux density
F =	mmf,
H =	magnetic field strength in oersteds or A/m ² ,
I =	current in amperes
J =	current density
K_w =	constant for 3 phase winding connection
K_s =	constant for short circuit power of network
L =	air core inductance
ℓ =	magnetic path length in meter.
N =	number of turns
P =	permeance.
R =	total dc resistance
R_n =	Neutral earthing resister
R =	reluctance in At/Wb,
t =	time
t_0 =	core saturation point
V_{max} =	Maximum voltage
X_{open} =	open circuit positive sequence reactance of the transformer
Z_t =	total impedance under inrush
μ_0 =	permeability of air in H/m,
μ_r =	permeability of material in H/m,
ϕ =	flux
ϕ_m =	maximum value of flux produced in the core in weber
θ =	Angle between coil and lines of field in degree
τ =	time constant of transformer winding under inrush conditions
φ =	energization angle

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1. Introduction

Transformers transform electric energy. There are varieties of transformer and used for many different purposes. They are nearly inbuilt into every electric/electronic device around us. Power transformers are essential components in power systems. The large power transformers are considered to be important and very expensive asset of electric power systems. The knowledge of their performance is fundamental in determining system reliability and longevity. Potentially disruptive transient condition may occur when an unloaded transformer is connected to the power system. Transient inrush current is often considered less important compared to other effects/faults in the transformers. (Rahman et al 2012) The objective of this report is to understand the factor affecting the inrush current and effects of inrush current.

There are five key parts of this report. The second and third part comprehends the background and relevant literature review. The background contains fundamental principle, basic theory and relevant laws. The construction of transformer including winding configuration, hysteresis effect and circulating current are also described in the background. Literature review is the third part, it mainly contains the theory of inrush current, factor affecting inrush current and their effect. The methodology describes methods of how the key practicals will be performed. The list of key selected simulation scenarios are described here. The technical specification of same sized actual transformer and their data is presented for comparison with simulation results. Sim-power-system of Matlab Simulink was be used for the simulation.

The result and discussion of model building and simulation are listed in section five. Here, the six selected scenarios are described with brief description of key difference of the models and results. Finally in section six the conclusion with a practical low cost solution to inrush current is recommended.

The relevant information was sourced from varieties of resources. Majority of the references are from the relevant research, conference and journals of Institutes of electrical and electronics engineering. Significant parts of citation were derived from professional printed books. A number of figures and photos are sourced from reputed internet sources such as manufactures, professional body, research institutes and universities. The appendix contains project time line chart and relevant project supporting information.

2. Background

Transformers are passive devices for transforming voltage and current. A transformer is a static electrical device. The energy is transferred by means of winding's inductive coupling via core. They are among the most efficient machines, 95 % efficiency being common and 99% being achievable.

Transformer are available and being manufactured in varieties of sizes and configurations. They are found in tiny microphone to large step up/step down power system distribution. They are found in most of electrical/electronic devices around us. Transformers are vital part of electric power system.

The alternating current flowing through a winding produces alternating flux in the core. This alternating flux links with other winding of same transformer and produces electromotive force(emf) or voltage in these windings

It is important to understand the basic principles and common laws in beginning. In this section in beginning common characteristic and their formulas are described. Equivalent circuit, transformer types and their winding configuration, Eddie current and hysteresis effect etc. are briefed in short explanations.

2.1 Flux

Flux is defined as a rate of property per unit area. It is a vector quantity. Fluxes are like lines in space. These flux lines or lines of force, show the direction and intensity of the field at all points. In magnets the field is strongest at the pole, it's direction is from N to S (externally) and flux lines never cross. (Georgolakis 2009)The symbol for magnetic flux is ϕ . The equation of flux can be expressed as,

$$\phi = BA \cos \theta$$

Where ϕ = Flux in weber or Tesla-meter²,

B = Magnetic flux density in Tesla,

A = Area of coil in m², and

θ = Angle between coil and lines of field in degree.

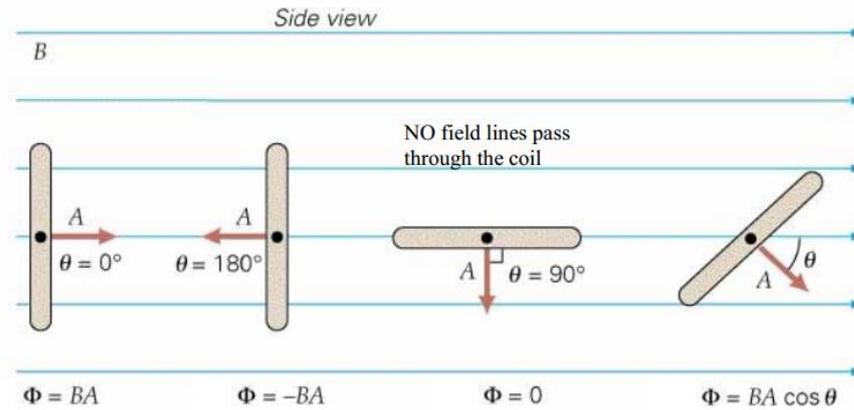


Figure 2.1 :Equitation of flux (Hsu NDT)

2.2 Magnetic field intensity

An object in presence of external magnetic field produces force. As a result it lines up in the direction of field. The magnetic forced produced in the object is called induced magnetisation. The strength of magnetic field is called magnetising field(H)(Flanagan 1992). Magnetic field intensity is also known as magnetising force, is denoted by H and measured in A/m^2 . The equitation of magnetic field intensity is,

$$H = \frac{NI}{\ell} = \frac{mmf}{\ell}$$

Where H = magnetic field strength in oersteds or A/m^2 ,

N = number of turns,

I = current in amperes, and

ℓ = magnetic path length in meter.

2.3 Magnetic flux density

As per name the magnetic flux density is an amount of magnetic flux per area right angle to the flux (Devki Energy Consultancy 2006). It is denoted by B and unit is Tesla or Wb/m^2 . The equitation of magnetic flux density is,

$$B = \mu_0 \mu_r \frac{NI}{\ell}$$

Where B = magnetic flux density in tesla or wb-m2,

μ_0 = permeability of air in H/m,

μ_r = permeability of material in H/m,

N = number of conductor,

I = current in ampere, and

ℓ = length of conductor in meter.

2.4 Reluctances

Reluctance in magnetic circuit is same as resistance in electric circuit. Reluctance varies depending on material of core. Reluctance is opposition force that opposes the flux flow in the magnetic circuit. It is inversely proportional to the permeance (Gardner & Stevenson 2003). In equation form,

$$R = \frac{\ell}{\mu_0 \mu_r A} = \frac{1}{P}$$

Where R= reluctance in At/Wb,

ℓ = length of conductor in meter,

μ_0 = permeability of air H/m,

μ_r = permeability of material in H/m,

A = cross section area in m2, and

P = permeance.

2.5 Magneto motive force (MMF)

Magneto motive force is magnetic potential. It is analogous to electromotive force or voltage. It is a motive force that produces flux. Ampere-turn is a standard unit of magneto motive force. (Georgolakis 2009) The MMF creates a magnetic field in the core having an intensity of H ampere-turns/meter along the length of the magnetic path. Hence,

$$mmf = \int H \partial \ell = Ni$$

Where mmf = Magneto motive force,

$$H = NI / \ell ,$$

ℓ = Length of conductor,

N = Number of coil turns, and

i = Current in the coil.

2.6 Ampere's law

This is Ampere's law which states that the mmf is proportional to the flux ϕ , is proportional to the inductor coil current and to its number of turns. Hence, according to Hopkinson's law, Georgolakis 2009

$$F = R\phi \quad \text{or} \quad F = \phi / P$$

Where F = mmf ,

R = reluctance,

ϕ = flux, and

P = permeance.

Mathematically it can also be proven as below,

$$\phi = BA$$

$$\begin{aligned}
&= \mu H A && (\because B = \mu H) \\
&= \mu \frac{NI}{\ell} A && (\because H = NI / \ell) \\
&= \frac{NI}{\ell / \mu A} \\
&= \frac{mmf}{\ell / \mu A} && (\because mmf = NI) \\
&= \frac{mmf}{R} && (\because R = \ell / \mu A)
\end{aligned}$$

2.7 Faraday's law

Whenever there is change in the flux linking with a coil, electro motive force is induced in the coil. Change in flux linkage can be obtained by two ways, Coil is stationary and there is change in flux. (Gardner & Stevenson 2003) This will produce the statically induced emf.

Flux is constant and the coil rotates. This will produce dynamically induced emf.

The statically induced emf is converts electrical energy to electrical energy only. The first applies to transformer where no moving parts are present however, the continuous change of flux produces the emf. The second applies to generator where coils are stationary and flux remains constant. Note that in AC generator, even though field winding are rotating the actual flux is constant as supply on of the field is DC. The rotation of constant flux which links with stationary stator winding causes emf.

The faraday's law can be expressed by following equation,

$$e = -N \frac{d\phi}{dt}$$

Where, e = emf

N = number of turns

$$\frac{d\phi}{dt} = \text{change in flux with respect to time}$$

The emf produced is proportional to the linkage of coil turns and also rate of change of flux linkage. The statically induced emf is converts electrical energy to electrical energy only.

2.8 Magnetic/electric circuit equitation

Flux density is line right angle flux in given unit area. The SI unit is weber/meter² or tesla. The equation of maximum flux density is,

$$B_m = \frac{\phi_m}{A_i}$$

Where B_m = maximum value of flux density in the core in weber/meter²

ϕ_m = maximum value of flux produced in the core in weber

A_i = area of cross section of core in meter²

The value of flux becomes zero to

$$\phi_m \text{ when time is } \frac{T}{4} = \frac{1}{4f}$$

In terms of transformer the average value of emf induced in a turn of conductor is (Kulkarni & Khaparde 2004)

$$= \frac{\text{change in flux}}{\text{time}}$$

$$= \frac{(\phi_m - 0)}{\left(\frac{1}{4f}\right)}$$

$$= 4\phi_m f$$

$$\text{Now form factor} = \frac{\text{RMS value}}{\text{Average value}} = 1.11$$

$$\therefore \text{RMS emf} = 1.11 \times \text{Average value}$$

$$\therefore \text{RMS emf} = 1.11 \times 4\phi_m f$$

$$\therefore \text{RMS emf} = 4.44\phi_m f$$

For N conductor,

$$\therefore E = 4.44\phi_m fN$$

$$\therefore E = 4.44 B_m A_i fN \quad (\because \phi_m = B_m A_i)$$

Magnetic	Symbol	Unit	Electrical	Symbol	Unit
Magnetic flux	Φ	Wb	Electric current	I	A
Magneto-motive force (mmf)	$F = \int H \cdot dl$	A.t	Electro-Motive force (emf)	$\varepsilon = \int E \cdot dl$	V
Reluctance	R	1/H	Resistance	R	Ω
Hopkinson's law	$F = \Phi \cdot R$		Ohm's law	$\varepsilon = I \cdot R$	
Permeance	$P = 1/R$	H	Conductance	$G = 1/R$	Ω^{-1}
Permeability	μ	H/m	Conductivity	σ	Ω/m
Magnetic field	H	A/m	Electric Field	E	V/m
Flux density	B	H/m	Current density	J	A/m ²
Relation between B&H	$B = \mu \cdot H$	H/m	Microscopic Ohm's law	$J = \sigma \cdot E$	A/m ²

Table 2.1 Comparison between magnetic and electrical circuits (Physical process modelling NDT)

2.9 Equivalent circuit

Transformer has windings called primary and secondary. Primary winding is the one which get the electrical energy input and output is transformed in secondary. There are many different types of transformers however, here we will mainly discuss power transformers. Depending on core design the transformers are identified in manly two categories known as core type or shell type transformers. In core type transformers, winding encloses whole core where, in shell type transformers the core encloses the windings.

Transformer works on the principle of electromagnetic induction. Figure 2.2 shows a single phase transformer with two coils with no load on any of its winding. The winding are wound on core which becomes magnetic with alternating current flowing in the winding. The primary winding is connected to source of which alternating voltage V_1 supplied. In beginning small excitation current flows i_0 flows through this winding. As this current is alternating mutual flux is induced in core (Gardner & Stevenson 2003). The primary and secondary winding contains N_1 and N_2 turns respectively. The instantaneous emf in primary winding caused by mutual flux is,

$$e_1 = N_1 \frac{d\phi}{dt}$$

With assumption of zero resistance of winding,

$$v_1 = e_1$$

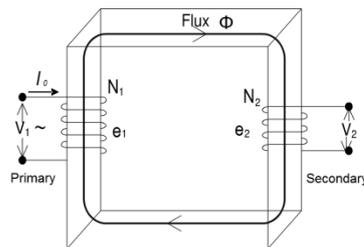


Figure 2.2: Transformer at no-load condition (Kulkarni & Khaparde 2004)

Since the voltage of primary winding v_1 is, $v_m \sin \omega t$, sinusoidal varying, the flux ϕ must also vary with at the rate of ωt .

$$\therefore \phi = \phi_m \sin \omega t$$

Where ϕ = mutual flux

$$\phi_m = \text{pick value of mutual flux}$$

$$\omega = 2\pi f$$

Now substituting value of ϕ in equation of e_1 we get,

$$\begin{aligned}
e_1 &= N_1 \frac{d(\phi_m \sin \omega t)}{dt} \\
&= N_1 \omega (\phi_m \cos \omega t) \\
&= N_1 \omega \phi_m \cos \omega t
\end{aligned}$$

$$\therefore e_{1\max} = N_1 \omega \phi_m$$

$$\begin{aligned}
\therefore e_{1rms} &= \frac{N_1 \omega}{\sqrt{2}} \phi_m \\
&= \frac{2\pi}{\sqrt{2}} f N_1 \phi_m
\end{aligned}$$

$$\therefore e_{1rms} = 4.44 f N_1 \phi_m$$

This equation is known as emf equation of a transformer (Kulkarni & Khaparde 2004). The amount of flux and its density is determined by supplied voltage where number of turn and frequency are considered as constant. Because ϕ_m maximum value of flux is flux density times the area which is constant hence,

$$\phi_m = B_m A_i$$

Where ϕ_m = maximum value of flux produced in the core in weber

B_m = maximum value of flux density in the core in weber/meter²

A_i = area of cross section of core in meter²

Also the voltage induced in the secondary winding due to mutual flux ϕ linkage is,

$$e_2 = N_2 \frac{d\phi}{dt}$$

Similarly the induced voltage in secondary winding is,

$$\therefore e_{2rms} = 4.44 f N_2 \phi_m$$

Therefore the ratio of induced voltages, e_1 and e_2 , is,

$$\frac{e_1}{e_2} = \frac{N_1}{N_2} = \alpha = \text{Turns Ratio}$$

At this instance, no load condition as there is no load on secondary winding, the current in primary winding is i_0 . There are two components of no load primary current i_0 ,

$$1) i_w = i_0 \cos \theta_0$$

This part is called active component. It consists of iron loss (hysteresis & eddy current loss) and primary winding copper loss.

$$2) i_\mu = i_0 \sin \theta_0$$

This part is called the reactive component or the magnetising component. The alternating flux in the core is produced by this component.

$$\text{Here } i_0 = \sqrt{i_w^2 + i_\mu^2}$$

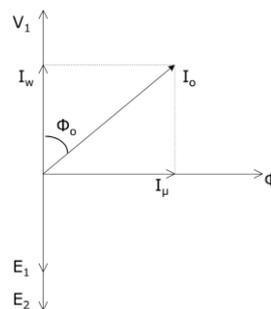


Figure 2.3: Phaser diagram of transformer at no load (Gardner & Stevenson 2003)

When secondary winding of the transformer is connected to the load, secondary current I_2 flows. This current (I_2) lags the secondary voltage V_2 by ϕ_2 . The $\cos \phi_2$ is the power factor of the load. (Gardner & Stevenson 2003) According to Len's law due to this current I_2 , flux ϕ_2 is produced in the core, which opposes the flux ϕ produced by primary winding.

So the net flux in the core tries to reduce. But the primary winding tries to maintain the flux so the primary winding draws more current from the supply and keeps the flux as before. Thus due to the current I_2 flowing in the secondary winding, balancing current I_2' flows through the primary winding. This current I_2' is 180° out of phase by current I_2 . Now, two currents flow through the primary winding- I_2 and

I_0 . The vector sum of both the currents is called the primary current I_1 . This is shown in figure 2.4 and 2.5 as below.

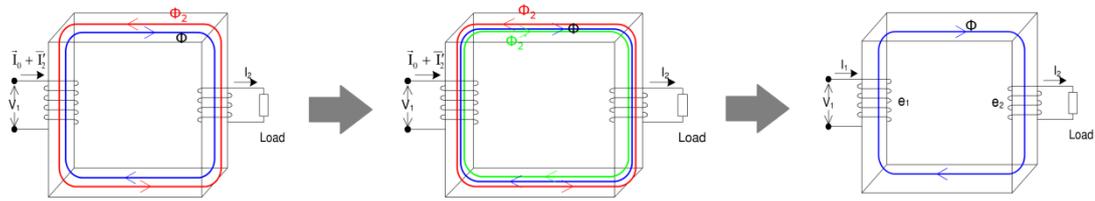


Figure 2.4: Transformer on load

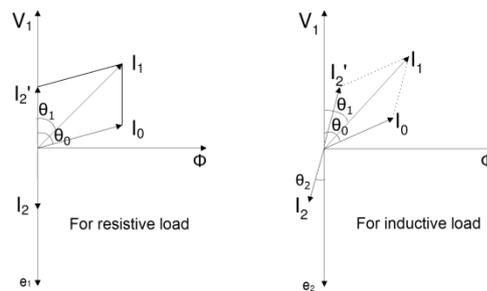


Figure 2.5: Phasor diagram of transformer on load

In actual transformer the primary winding has resistance, which is denoted by R_1 . Similarly, the secondary winding resistance is denoted by R_2 . (Flanagan 1992) Actually, both these resistances are the distributed in nature but for simplicity, these are shown as lumped resistance in following figure.

The total flux produced by the primary winding does not link with the secondary winding but some flux complete its path through air without passing through the core. This is called the primary leakage flux ϕ_{L1} . Due to this leakage flux emf is induced in the primary winding which opposes the primary voltage. To account for this effect, it is assumed that the primary winding has reactance and the voltage drop occurring in this reactance is equal to this emf. (Flanagan 1992) This leakage reactance is denoted by X_{L1} . Similarly, the total flux produced by the secondary winding does not link with the primary winding and some flux completes the path through air. This is secondary leakage flux ϕ_{L2} . Due to this leakage flux electromotive force is induced in the secondary winding. This emf opposes the induced emf due to the main flux. (Gardner & Stevenson 2003) This effect is

structure. Such design improves leakage flux (Farzadfar 1997). Generally the low voltage winding are first wound and high voltage winding are wound on the top of LV winding. This ensures the HV winding away from core as core is earthed. Visually core are surrounded by the coils. Such design has single magnetic/flux paths.

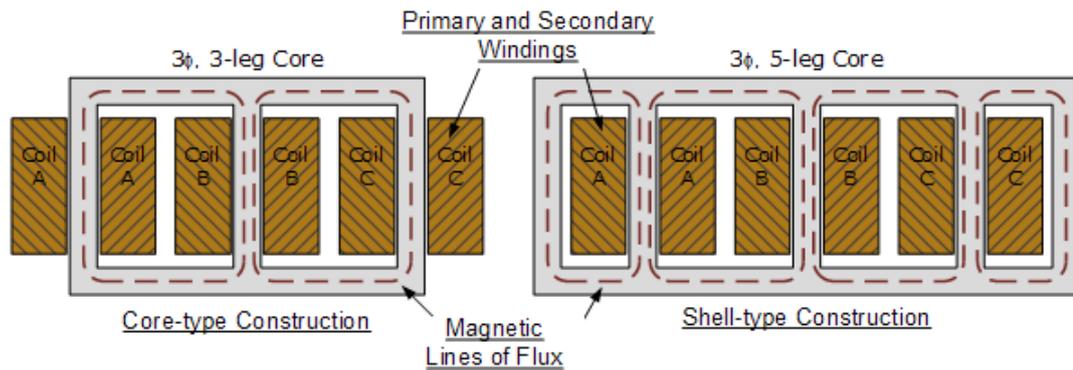


Figure 2.8: Core and shell type transformers winding and core arrangements (Storr 2013)

(ii) Shell-type transformer. The shell type transformer design are as shown in figure 2.8. The winding configuration is same as core type. They contain five limb/legs. The visually coils are surrounded by the cores. In this design there are double magnetic/flux paths and hence it acts as low-reluctance (Li et al 2010).

#	Core type	Shell type
1	The winding encircles the core	The core encircles most part of the winding
2	The cylindrical type of coils are used	Generally, multilayer disc type or sandwich coils are used
3	As windings are distributed, the natural cooling is more effective	As winding are surrounded by the core, the natural cooling does not exist.
4	The coil can be easily removed for maintenance	For removing any winding for the maintenance, large numbers of laminations are required to be removed.
5	The construction is preferred for low voltage transformers	The construction is used for very high voltage transformers
6	It has a single magnetic circuit	It has a double magnetic circuit
7	In a single phase type, the core has two limbs	In a single phase type, the core has three limbs

Table 2.2: Differences between core and shell type transformers (Your electrical home, 2011)

The choice of type (whether core or shell) will not greatly affect the efficiency of the transformer. The core type is generally more suitable for high voltage and small output while the shell-type is generally more suitable for low voltage and high output.

2.11 Three-Phase Transformer

A three phase power transformer are mostly used in transmission and distribution of electric power. The three phase transformer can be built by building a three phase transformer or using bank or three single phase transformers. The primary and secondary winding are connected according to circuit requirement however, generally in $Y - Y$, $\Delta - \Delta$, $Y - \Delta$, or $\Delta - Y$.

2.11.1 BANK OF THREE 1 ϕ TRANSFORMERS

The three single phase transformer if connected in any of the three phase winding configuration works as three phase transformer. The widely used connections are $Y - Y$, $\Delta - \Delta$, $Y - \Delta$, or $\Delta - Y$. The figure 2.9 illustrates on left three single phase transformer and on right a three phase transformer. The primary windings of both of this arrangements are in star and secondary are in delta. This makes then ideal for use in their place.

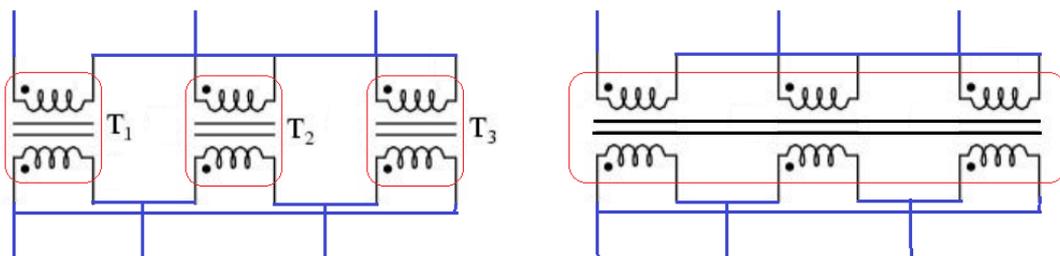


Figure 2.9: Three single phase(left) and three phase transformer (right)

The primary and secondary windings shown parallel to each other belong to the same single-phase transformer (on left). The ratio of secondary phase voltage to primary phase voltage is the phase transformation ratio K . Phase transformation ratio, $K = \text{Primary phase voltage} / \text{Secondary phase voltage}$. As discussed earlier in emf equation the phase transformation ratio is $K (= N_2/N_1)$.

2.11.2 3 ϕ TRANSFORMER

A three phase transformer contains common magnetic circuit. All of its winding are would on core that acts as magnetic circuit. The basic three phase circuit

arrangement is shown in figure 2.9. The figure 2.10 contains a three phase core type transformer. This transformer has windings on each individual limbs but the magnetic circuits end in common magnetic limb. The centre limb completes the return flux path of each phase. The centre limb completes the return flux path of each phase. The primaries as well as secondaries may be connected in star or delta. If the primary is energized from a 3-phase supply, the central limb (i.e., unwound limb) carries the fluxes produced by the 3-phase primary windings (Sainz et al 2004). The instantaneous vector summation in ideal condition is always zero therefore the vector summation of flux should also be zero. Hence no flux exists in the central limb and it may, therefore, be eliminated. This modification gives a three leg core type 3-phase transformer. In this case, any two legs will act as a return path for the flux in the third leg. For example, if flux is Φ in one leg at some instant, then flux is $\Phi/2$ in the opposite direction through the other two legs at the same instant. All the connections of a 3-phase transformer are made inside the case and for delta-connected winding three leads are brought out while for star connected winding four leads are brought out.

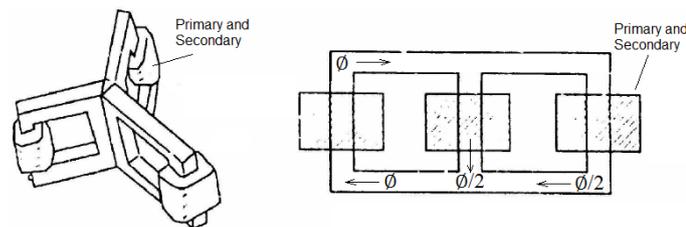


Figure 2.10: Three phase transformer

For the same capacity, a three-phase transformer weighs less, occupies less space and costs about 20% less than a bank of three single-phase transformers. Because of these advantages, 3-phase transformers are in common use, especially for large power transformations. A disadvantage of the three-phase transformer lies in the fact that when one phase becomes defective, the entire three-phase unit must be removed from service. The three phase circuit in which three single phase transformers are used the prime advantage is when a fault occurs in a winding other two phase's circuit can be left in service and defective transformer can be isolated for repair. The only drawback is such arrangements are costly and management in terms of phase load balance can be challenging.

2.12 Three-Phase Transformer Connections

As described in previous two sections, three phase circuit can be built using a single three phase transformer of three single phase transformers. The connection in any case of its primary and secondary will be same for same arrangement. The most widely used connection arrangements are as shown in table 2.3

Transformer Connection (Primary to Secondary)	Primary				Secondary			
	Line		Phase		Line		Phase	
	Volt.	Current	Volt.	Current	Volt.*	Current	Volt.	Current
Δ - Δ	V	I	V	$\frac{I}{\sqrt{3}}$	$\frac{V}{a}$	aI	$\frac{V}{a}$	$\frac{aI}{\sqrt{3}}$
Y-Y	V	I	$\frac{V}{\sqrt{3}}$	I	$\frac{V}{a}$	aI	$\frac{V}{\sqrt{3}a}$	aI
Y- Δ	V	I	$\frac{V}{\sqrt{3}}$	I	$\frac{V}{\sqrt{3}a}$	$\sqrt{3}aI$	$\frac{V}{\sqrt{3}a}$	aI
Δ -Y	V	I	V	$\frac{I}{\sqrt{3}}$	$\frac{\sqrt{3}V}{a}$	$\frac{aI}{\sqrt{3}}$	$\frac{V}{a}$	$\frac{aI}{\sqrt{3}}$

Table 2.3: Voltage and current ratings of common transformer winding configuration

The primary and secondary voltages and currents are also shown. The primary line voltage is V and the primary line current is I. The phase transformation ratio K is given by;

$$K = V_s/V_p = N_s/N_p$$

2.13 Eddy current

The alternating flow of magnetic flux in core generates circulating current (by Faraday's law) in the core. This happens as core material behaves like short circuited single loop of wire. This circulating current is known as Eddy current. (Flanagan 2004) Generally any magnetic core material is made of iron material due to its good permeability. Iron is a good electric conductor and hence large circulating current will be induced.

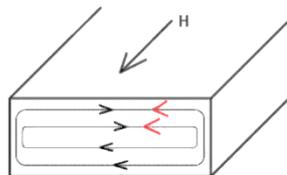


Figure 2.11: Eddy current (black) and current induced by the external magnetic field (red)

The magnetic field generated by circulating current counter acts the main alternating flux. The magnitude of circulating current depends on how strong the alternating magnetic flux is and the conductivity of the core material. Eddie current generates loss and acts as a counter efficient effect. It opposes the induced current which generates loses and causes the resistance in flux path. It generates heats in the core and reduces the efficiency.

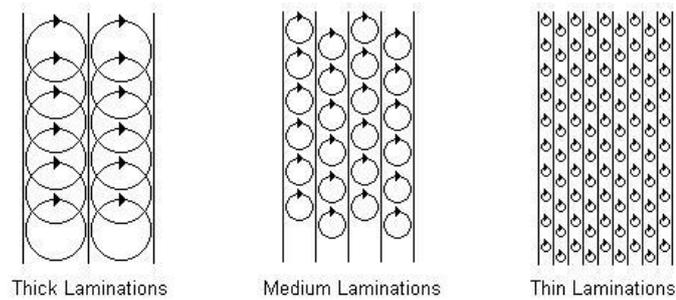


Figure 2.12: Circulating current in thick, medium and thin laminations (Elliott 2012)

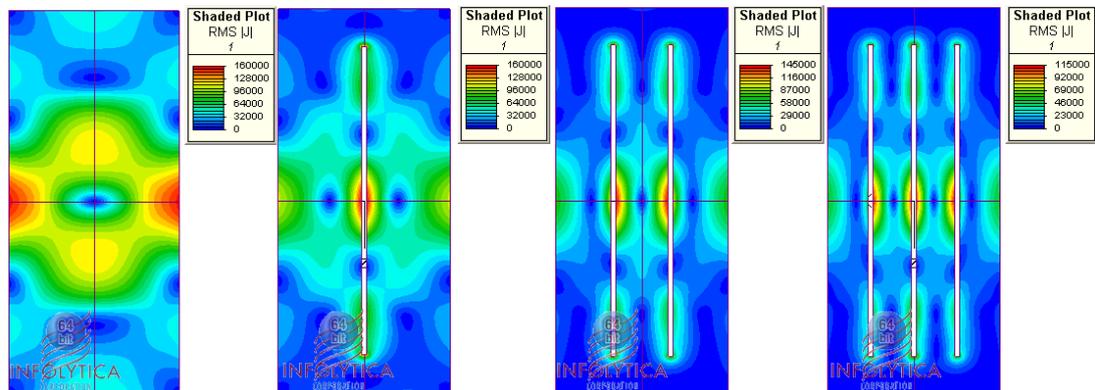


Figure 2.13: Induced Eddie current density of solid to sliced (1,2 &4) (Infolytica NDT)

It is not possible to completely remove the Eddie current in transformer, however, its magnitude can be reduced significantly. The circulating current is proportional to the thickness of the core material (magnetic path) hence if the thickness of the core material is reduced (reduction of magnetic path) then the Eddie current is reduced. Therefore transformer core are made of lamination instead of solid core.

The lamination loss can be predicted using two methods (Brauer et al 2000). One way is to use manufacturer’s datasheets. The information of eddi current loss of specific transformer are generally not available to users. Generally eddi current in normal power frequency is built using standard thin lamination for less loss.

However, for transformer that works on high frequency requires special core design and material to reduce loss considerably (Brauer et al 2000).

2.14 Hysteresis effect

The hysteresis in magnetic material is generated by the resistance of grains against the alternating flux required to magnetise the core. (Flanagan 1992) Heat in the form of I^2R generates due to grain resistance. This heat contributes to energy loss in the magnetic material/ transformer. (Faiz & Saffari 2010) The rate of heat generation depends on the resistance and excessive heat in core is harmful to winding insulation as well as core lamination insulation. The hysteresis effect is inversely proportional to the frequency, meaning decrease in frequency will cause increase in hysteresis losses. The transformer rated 60Hz, if operated at 50Hz will cause higher hysteresis losses and decreases the VA capacity of the transformer.

Hysteresis loop (B-H curve) describes the characteristic of magnetic material. The figure 2.14 presents the B-H curve,

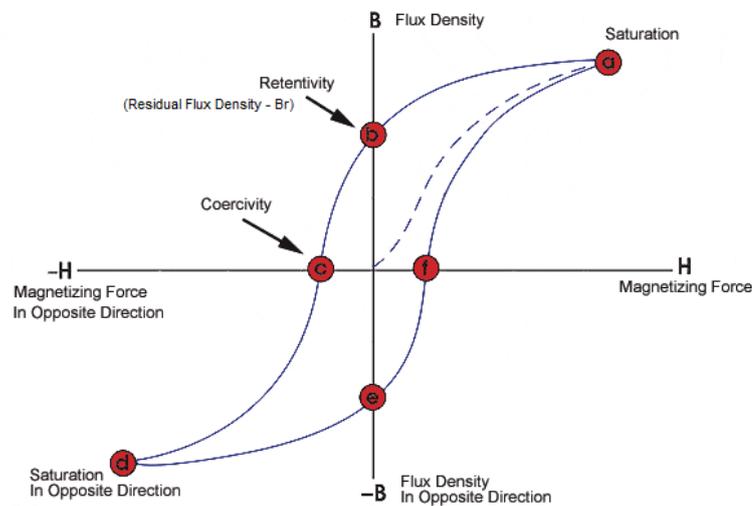


Figure 2.14: Hysteresis loop/ B-H curve (NPTEL, NDT)

This curve loop is developed by measuring flux when mmf(magneto motive force) is alternating at given frequency. It will follow the dotted line when H, magnetic force, is increase for the material which has never been magnetised (no residual flux). The curve shows that higher the magnetic force the greater the magnetic field is. At the sharp tip of max H and B where most of magnetic domains are aligned is called

saturation point. At this point onwards any increase in magnetic force will cause very small amount of increase in flux density. Now if the curve is reduced zero current, it is apparent that the material still retains some magnetism, called residual magnetism. (Bronzeado 1995) On reversing the current, the flux reverses and the bottom part of the curve can be traced. By reversing the current again from bottom saturation point, the curve can be traced back to top saturation point. The result is called a hysteresis loop. (Flanagan 1992) A major source of uncertainty in magnetic circuit behaviour is apparent: Flux density depends not just on current, it also depends on which arm of the curve the sample is magnetized on, i.e., it depends on the circuit's past history. For this reason, B-H curves are the average of the two arms of the hysteresis loop.

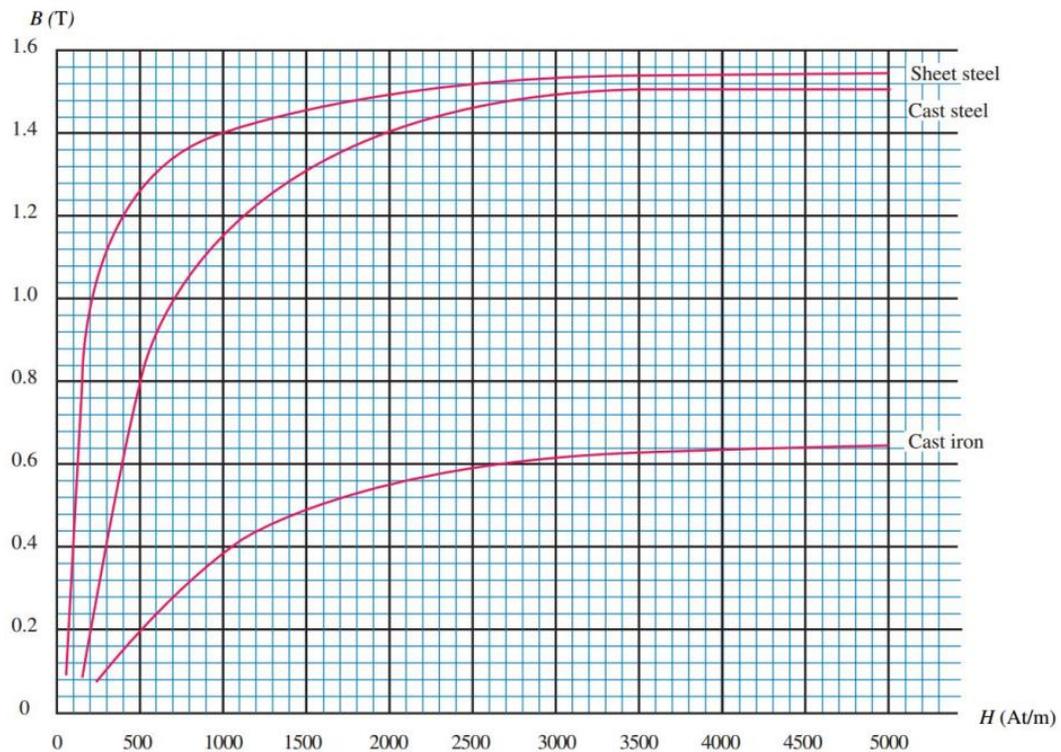


Figure 2.15: B-H curve for selected material

3. Literature Review

This section contains the relevant theory to inrush current, factor contributing to inrush current and finally the effect of inrush current. A number of possible controllable factors are included in the contributing factors. Following is the summary of the factor and effect associated with inrush current.

FACTOR AFFECTING INRUSH CURRENT

- Starting/switching phase angle of Voltage
- Residual flux in core
- Magnitude of Voltage
- Saturation flux
- Core material
- Supply/Source impedance
- Loading on secondary winding
- Size of transformer

EFFECT OF INRUSH CURRENT

- High starting current
- Voltage distortion (harmonics)
- Sympatric inrush
- Vibration/geometric movement of winding
- Life of transformer
- Protection complexity - Actual fault v/s Inrush current

INRUSH CURRENT MITIGATION TECHNIQUES

- Asynchronous switching v/s Inrush Current
- Neutral Earthing Resister v/s Inrush Current
- Comparison of various methods

3.1 Inrush current theory

When a transformer is energised from a standard power source it draws high starting current which can be as high as 10 – 100 times of transformer's rated current. This current will starts to decay at the rate of effective winding resistance and will settle down to steady state condition. The time to decay can be as long as few seconds. This current is known as magnetising inrush current (Naghizadeh et al 2012).

Decay of this transient current is proportional to the series resistance of the transformer winding. If resistance of winding is ignored, the flux offset will never fall back to zero and inrush will continue. (Chiesa et al 2010) In a real transformer, winding resistance will damp out the inrush. The decay time can range from a few cycles up to a minute depending on the transformer size and relevant design parameters.

Inrush current can be divided in to three categories (Vaddebonia et al 2012):

3.1.1 ENERGIZATION INRUSH

Energisation inrush current results from the re-energisation of the transformer. The residual flux in this case can be zero or depending on de-energisation timing.

3.1.2 RECOVERY INRUSH

Recovery inrush current flows when transformer voltage is restored after having been reduced by system disturbance.

3.1.3 SYMPATHETIC INRUSH

Sympathetic inrush current flows when multiple transformers are connected in same line and one of them is energised. Offsets inrush currents can circulate in transformers already energised, which in turn causes a inrush.

It is possible to control or make the incurrent to near zero if it was possible to control the switching time such that the supply voltage angle matches the exact normal flux angle. Since the flux lags the voltage by 90o, switching of voltage should occur at the max value. Generally the flux in the transformer is zero (no remanent flux) and hence switching to voltage when it reach to max value then corresponding flux in

ideal condition should be near zero. This will be like ideal normal condition and hence the normal current will flow in the primary. (Kulkarni & Khaparde 2004)

$$e = E \sin \omega t$$

$$v = V_{max} \cos(\omega t + \alpha) \quad \dots 3.1$$

Where v = Applied voltage at primary

V_{max} = Maximum voltage

t=time

The moment ac voltage is applied to winding, emf is produced in it and it is opposite direction to supply voltage V. (Chen et al 2005)

$$\therefore e \cong -v$$

$$\therefore e = -V_{max} \cos(\omega t + \alpha)$$

Also,

$$\therefore e = -N_1 \frac{d\phi}{dt} \quad \dots 3.2$$

Now, comparing equitation 3.1 and 3.2 we can write,

$$\therefore -N_1 \frac{d\phi}{dt} = -V_{max} \cos(\omega t + \alpha)$$

$$\therefore \frac{d\phi}{dt} = -\frac{V_{max}}{N_1} \cos(\omega t + \alpha)$$

Integrating above equitation we get,

$$\therefore \phi = \frac{V_{max}}{N_1} \int \cos(\omega t + \alpha) dt$$

$$\therefore \phi = \frac{V_{max}}{N_1} \sin(\omega t + \alpha) + C$$

$$\therefore \phi = \phi_{max} \sin(\omega t + \alpha) + C \quad \dots 3.3$$

Where $\phi_{max} = \frac{V_{max}}{N_1}$ and C=asymmetrical component of flux

The core contains some residual magnetic flux in it denoted by $\Phi_{residual}$

The asymmetrical component of flux

$$C = \Phi_{residual} + \Phi_{max} \sin \alpha$$

Now putting value of C in equation 3.3 we get,

$$\therefore \Phi = \Phi_{max} \sin(\omega t + \alpha) + \Phi_{residual} + \Phi_{max} \sin \alpha \quad \dots 3.4$$

Now consider the switching instant when $\alpha=0$ or $= \pi/2$,

($\alpha = \text{phase angle of flux}, \theta = \text{phase angle of voltage} = \alpha + \pi/2$) i.e the voltage is at its peak value. The flux is residual flux in the core at this instant. The operation of transformer is normal at this instant.

$$\therefore \Phi = \Phi_{max} \sin(\omega t + 0) + \Phi_{residual} + \Phi_{max} \sin 0$$

$$\therefore \Phi = \Phi_{max} \sin(\omega t) + \Phi_{residual}$$

$$\therefore \Phi = \Phi_{max} + \Phi_{residual}$$

Now consider the switching instant when $\alpha=-\pi/2$ or $\theta = 0$. In this case equation is,

$$\therefore \Phi = \Phi_{max} \sin(\omega t + \pi/2) + \Phi_{residual} + \Phi_{max} \sin(\pi/2)$$

$$\therefore \Phi = -\Phi_{max} \cos(\omega t) + \Phi_{residual} + \Phi_{max}$$

$$\therefore \Phi = 2\Phi_{max} + \Phi_{residual}$$

Therefore the flux density is almost double. This is often referred as double fluxing, $2 \times \Phi_{max}$. To generate flux more than normal current tends to increase exponentially due to saturation effect.

3.2 Factor affecting inrush current

3.2.1 Starting phase angle of voltage

The starting phase angle of voltage depends on when the transformer was switched. As per the equation of inrush current, $\therefore \phi = \phi_{max} \sin(\omega t + \alpha) + \phi_{residual} + \phi_{max} \sin \alpha$ it is clear that inrush current depends on two variables, the remnant flux and switching angle of voltage. If the residual flux in the transformer is zero and switching angle is $\theta = 90$, then final flux is,

$$\therefore \phi = \phi_{max} \sin(\omega t + 0) + 0 + \phi_{max} \sin 0$$

$$\therefore \phi = \phi_{max} \sin(\omega t)$$

$$\therefore \phi = \phi_{max}$$

This means normal flux will be produced and that mean normal current will be drawn during starting condition (no inrush current). However, if the voltage is switched on when $\theta = 0$ and taking residual flux to zero, the equation of flux is,

$$\therefore \phi = \phi_{max} \sin(\omega t + \pi/2) + 0 + \phi_{max} \sin (\pi/2)$$

$$\therefore \phi = -\phi_{max} \cos(\omega t) + \phi_{max}$$

$$\therefore \phi = 2\phi_{max}$$

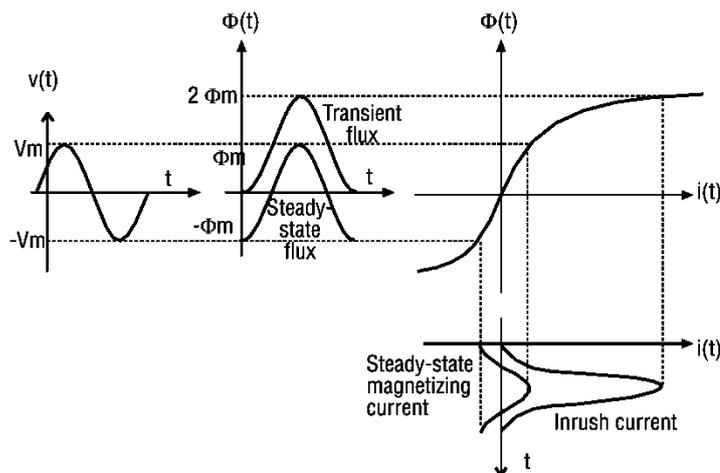


Figure 3.1: Inrush current for twice flux (Gladstone 2004, p.14)

3.2.2 Residual flux in core

In reality transformers are made of ferromagnetic material and hence they have hysteresis effect. This means they always have residual flux present. The figure 3.1 shows the inrush current with respect to twice of the flux and figure 3.2 shows the inrush current for flux with twice and residual flux.

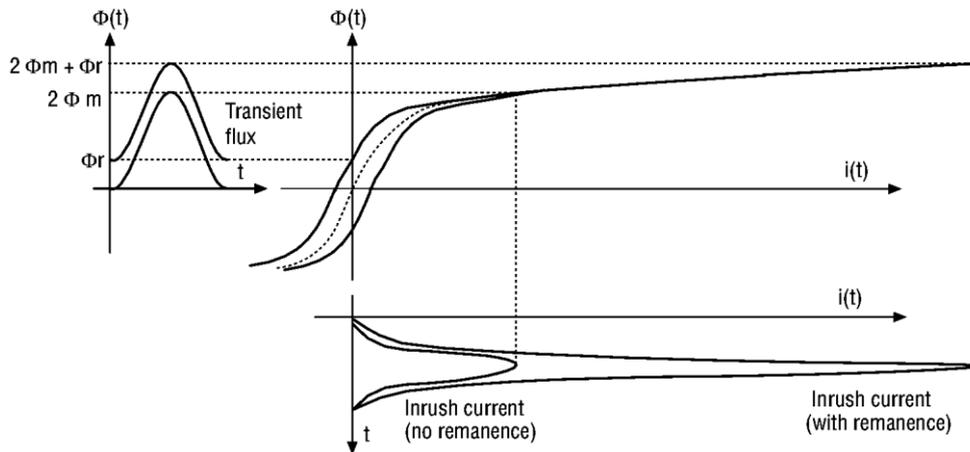


Figure 3.2: Inrush current for twice + residual flux (Gladstone 2004, p.16)

This means the optimum closing time so that no inrush can occur when residual flux is zero is when $\theta = 90$ or 270 . However, optimum switching time with residual flux is when the corresponding voltage angle of flux reaches to the residual flux level in the core. According to (Ebner 2007) the equation of optimum switching time

ignoring CB restrike is,

$$\phi_{residual} < 0: t_{opt} = -\frac{1}{\omega_0} \arccos\left(\frac{\phi_{residual}}{\phi_{max}}\right) \quad \phi_{residual} \geq 0: t_{opt} = \frac{1}{\omega_0} \left[\arccos\left(\frac{\phi_{residual}}{\phi_{max}}\right) + 1 \right].$$

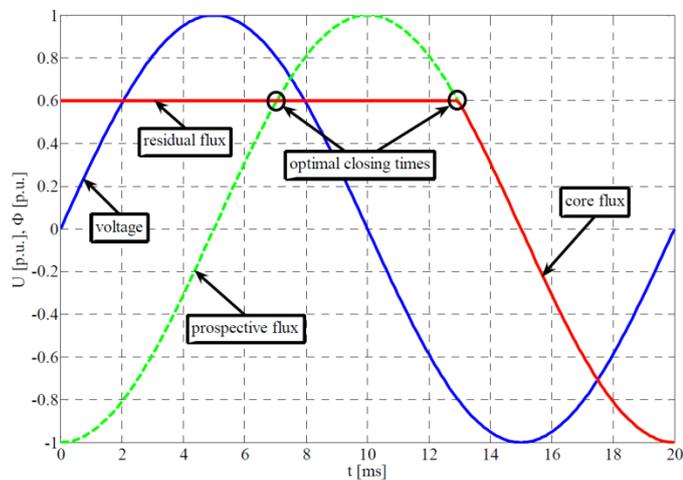


Figure 3.3: The optimum switching time for single phase transformers (Ebner 2007)

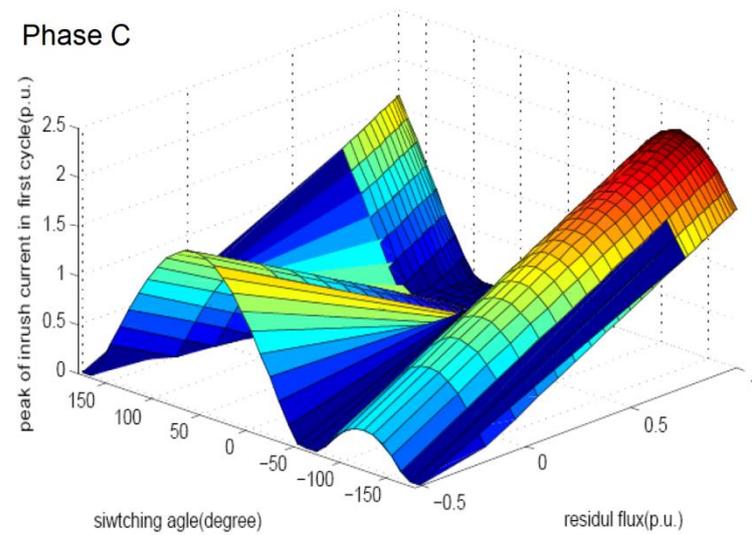
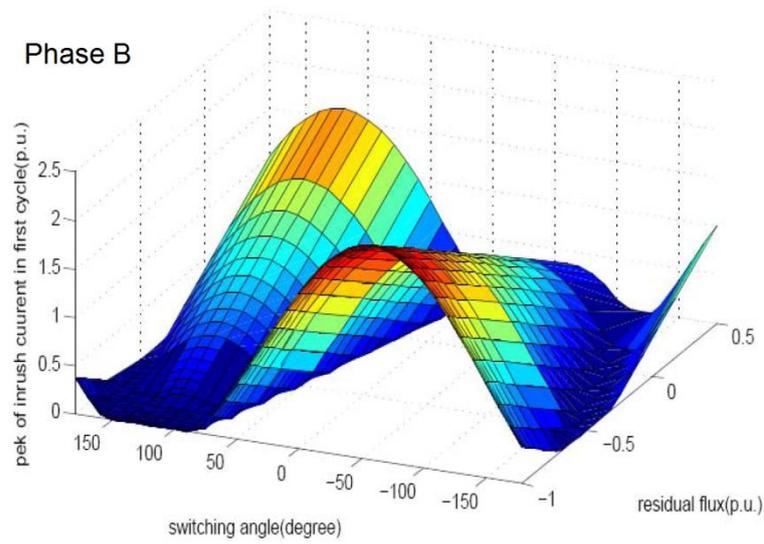
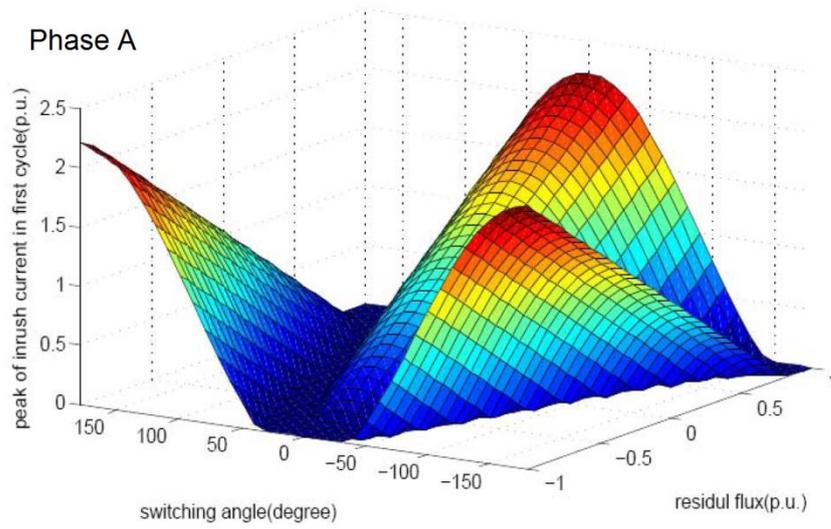


Figure 3.4: Inrush current in first cycle v/s switching angle and residual flux (Ashrami et al 2012)

3.2.4 Saturation Flux

As explained in background that saturation flux plays important part in inrush current magnitude. The B-H curve of the core material and design shows the saturation level. “The base angle of the inrush current is a monotonically decreasing function of the residual flux.” (Wang & Hamilton 2004). Therefore with decrease in saturation flux causes fundamental where increase in saturation flux causes the increase in DC offset and hence increase in second harmonics.

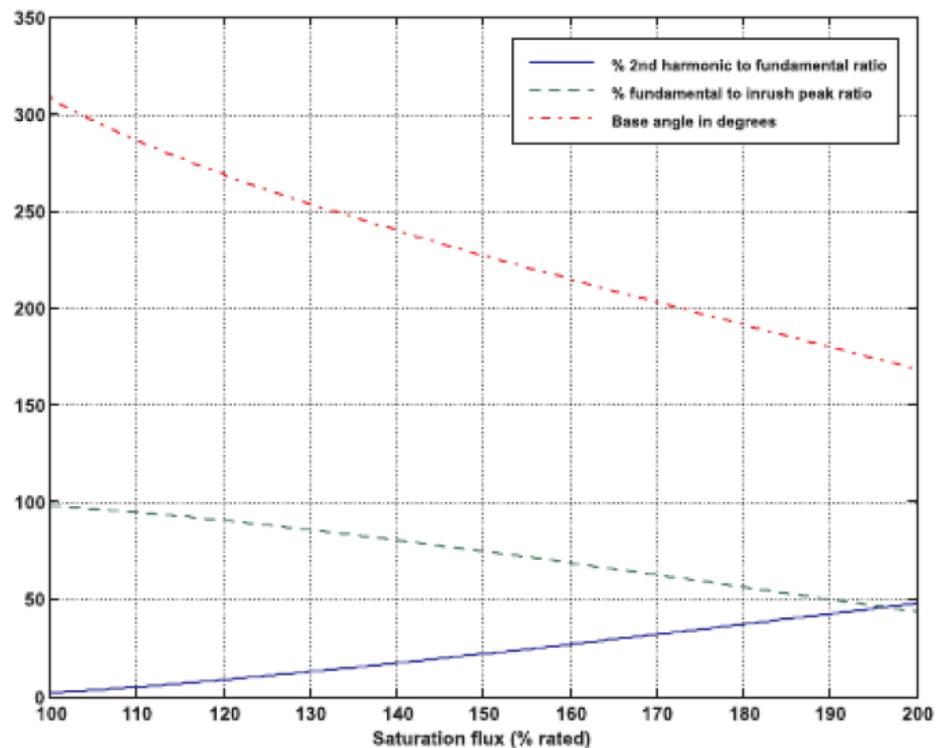


Figure 3.5.1: Saturation flux v/s inrush current (Wang & Hamilton 2004)

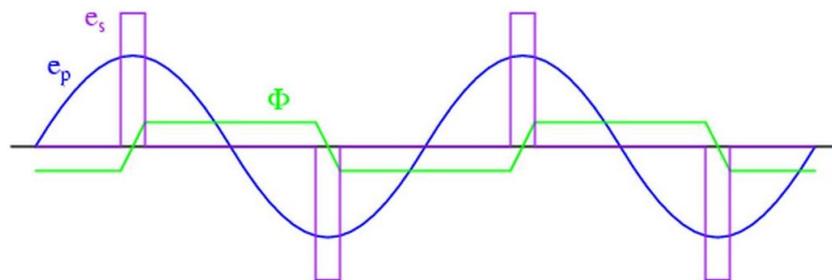


Figure 3.5.2: Effect of core saturation on secondary voltage (ElectronicsTeacher.com)

Al-Khalifah & Saadany (2006) agrees to the same principles. The transformer are generally operates in the range of 1.5 to 1.7 tesla. The inrush current of transformer are lower which operates close to the latter values.

3.2.5 Core material

Magnetic properties are related to atomic structure. Each atom of a substance, for example, produces a tiny atomic-level magnetic field because its moving (i.e., orbiting) electrons constitute an atomic-level current and currents create magnetic fields. For nonmagnetic materials, these fields are randomly oriented and cancel. However, for ferromagnetic materials, the fields in small regions, called domains (as shown below), do not cancel. (Domains are of microscopic size, but are large enough to hold from 10^{17} to 10^{21} atoms.) If the domain fields in a ferromagnetic material line up, the material is magnetized; if they are randomly oriented, the material is not magnetized.

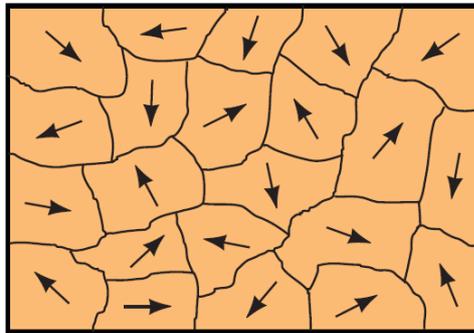


Figure 3.6: Random orientation of microscopic fields in a non magnetized ferromagnetic material

A nonmagnetized specimen can be magnetized by making its domain fields line up. The figure 3.7 shows how this can be done. As current through the coil is increased, the field strength increases and more and more domains align themselves in the direction of the field. If the field is made strong enough, almost all domain fields line up and the material is said to be in saturation (the almost flat portion of the B-H curve). In saturation, the flux density increases slowly as magnetization intensity increases. This means that once the material is in saturation, you cannot magnetize it much further no matter how hard you try. Path 0-a traced from the nonmagnetized state to the saturated state is termed the dc curve or normal magnetization curve.

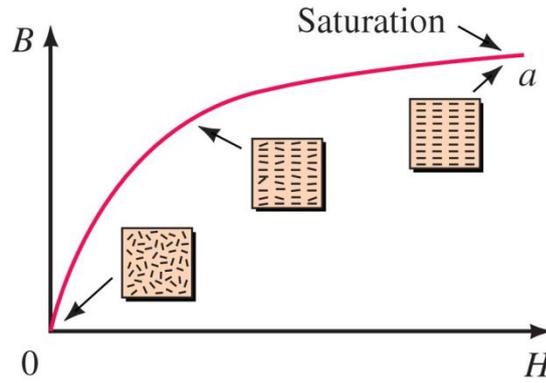


Figure 3.7: Field intensity v/s change in the domain orientations. $H \propto I$

For ferromagnetic materials, μ is not constant but varies with flux density and there is no easy way to compute it. In reality, however, it isn't μ that we are interested in: What we really want to know is, given B, what is H, and vice versa. A set of curves, called B-H or magnetization curves discussed in earlier section, provides this information. (These curves are obtained experimentally and are available in various handbooks. A separate curve is required for each material.) The figure 3.8 shows typical curves for various materials.

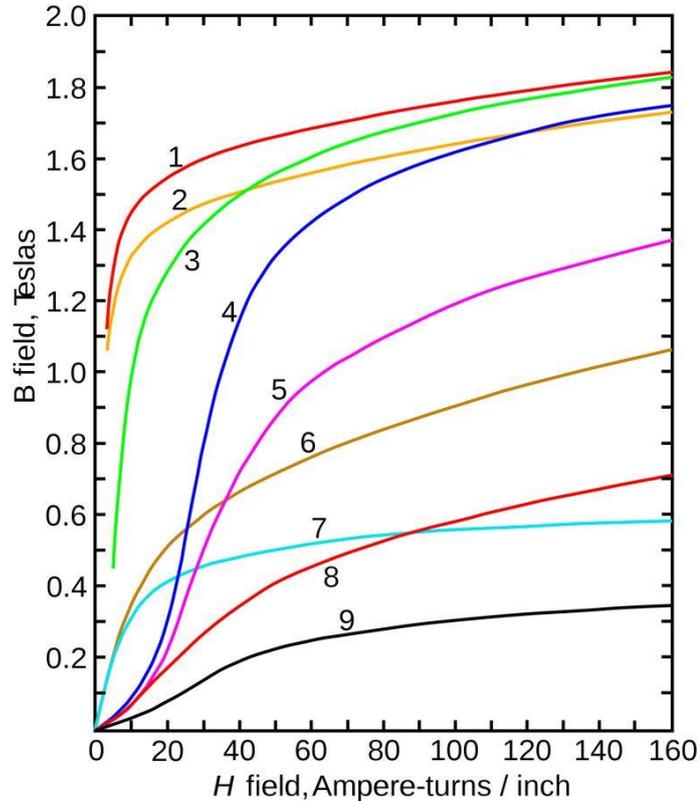


Figure 3.8: B-H curves of various material. 1)Steel steel, 2) Silicon steel, 3) Cast steel, 4) Tungsten steel, 5) Magnet steel, 6) Cast iron, 7) Nickel, 8) Cobalt, 9) Magnetite (Steinmetz 1917, p.84)

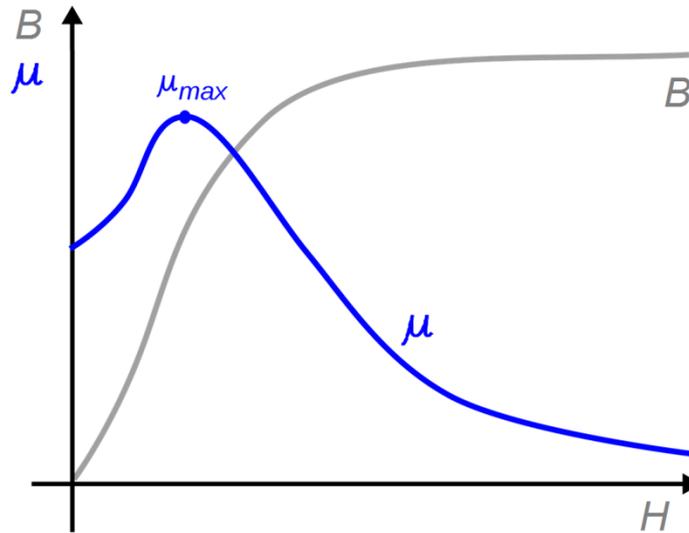


Figure 3.9: Field intensity v/s Permeability and Flux density

In core type transformers the windings are wound around each limb. The general arrangement is as shown in figure 3.10.

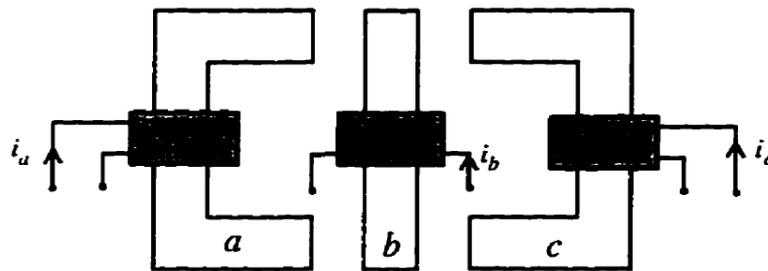


Figure 3.10: Example of core section length

It is clear from the above figure that the limb of centre phase is shorter than remaining two phases. The reluctance of the core is directly proportional to the length of the material. Hence for the given flux density the limb of centre phase will have less reluctance compared to the other two limbs.

3.2.6 Supply/Source impedance

The source impedance in any power supply system is the key parameter that indicates the capacity of maximum current delivery. In terms of inrush current, the maximum current will be transferred if both source and transformer primary impedances are match or source impedance is higher than transformer impedance. However, a small transformer connected to a diesel generator set which often has

smaller impedance than that of transformer causes the inrush current to be limited. This will also cause system voltage drop which is harmful to house/office hold electrical and electronics equipment's. (Seo & Kim 2008) The distance between supply source and transformer is also indication of longer busbars/transmission lines. This indicates additional resistance which contributes to damping of the current. The transformer away from the supply with higher line/busbar resistance has shorter inrush currents in duration compared to the ones which are closer to the generating units (Al-Khalifah & Saadany 2006)

3.2.7 Loading on secondary winding

The load on the transformer secondary side has no effect on the inrush of primary current. There are number of authors who claim that this is not the case. The testing done by [34] shows that the load (resistive or inductive) on secondary winding of the transformer has no influence on the inrush current of primary. "The reason for this feature is that when the transformer is saturated, the current peak mainly depends on the slope in the nonlinear zone of the saturation curve." (Moses et al 2010)

3.2.8 Size of transformer

The size of transformer reflects the internal transformer impedance. The larger the transformer the smaller the impedance it has and the smaller the transformer the higher the impedance it has. As mentioned in the supply/source impedance sections that impedance ratio of power supply system source and transformer internal affects the inrush current in the transformer. If the system has relatively smaller impedance then it will cause voltage drop and increase in inrush current and duration. The smaller transformer generates higher inrush current (i.e 30 times) while duration of inrush currents are generally smaller and decays faster (Al-Khalifah & Saadany 2006) however, larger transformer has comparatively small inrush current but for longer duration. The decay time for smaller transformer (<1000kVA) is in the range of 100 milliseconds while the larger transformer inrush current decay times are in range of seconds.

3.3 Effect of inrush current

3.3.1 High starting current

When a transformer is energised from a standard power source it draws high starting current which can be as high as 10 – 100 times of transformer's rated current. This current will starts to decay at the rate of effective winding resistance and will settle down to steady state condition. The time to decay can be as long as few seconds. This current is known as magnetising inrush current (Naghizadeh et al 2012). This effect is described in section 3.1 and section 3.2.

3.3.2 Voltage distortion (harmonics)

Transformers power quality performance in distribution system is the key performance indicator. Switching due to alteration or load is continuously required and due to this it invites problems like inrush current which is rich of harmonics (Seo & Kim 2008). The figure 3.11 shows a spectrum of harmonics and their magnitude derived by Ashrami and others (2012).

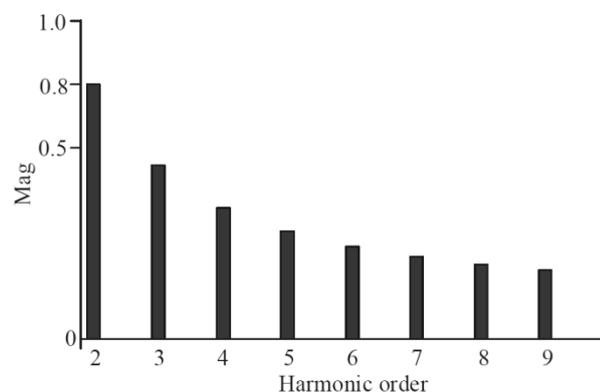


Figure 3.11: Spectrum of harmonics in inrush current (Ashrami et al 2012, p.537)

It is clear that the second harmonics are the dominant in the inrush (Al-Khalifah & Saadany 2006). The main reason here is when inrush current starts it off sets in either positive or negative direction and instead of full wave it will be half wave. This means $50 \times 2 = 100\text{Hz}$. 100Hz is the frequency of second harmonics of which fundamental frequency is 50Hz. The figure 3.12 shows the harmonics distribution of three phases.

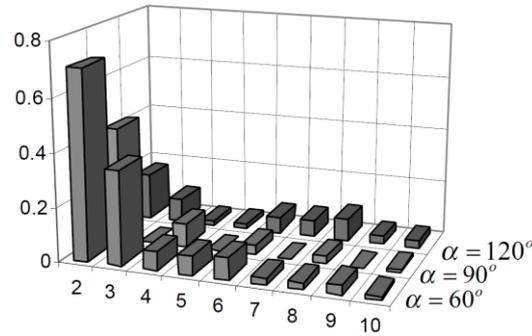


Figure 3.12: Harmonics contents of the idealised inrush current (Kulidjian et al 2001)

When a transformer is energised, due to large inrush current, it also caused the voltage drop especially when transformer impedance is smaller than that of source impedance (Seo & Kim 2008). Such effect can be very sensitive to the some industrial customers and house hole/office electrical equipment. For this reason the calculation of inrush current, voltage drop and harmonics is important. The balanced three phase system the equitation of voltage drop is given by Vaddeboina et al (2012),

$$V_d = \frac{m}{10 S} \%$$

Where Vd =voltage drop

m = change in load in kVA

S = short circuit level in MVA

A desktop study is done by Vaddeboina et al (2012) on transformer (400kv/19kV) with residual flux set so that sum of three phases is zero, the voltage of source is 414kV and source impedance of 8.5GVA. During the simulation they have considered worst case scenarios such as switching at 0 cross over etc. The figure 3.13 shows that voltage shag due to poor impedance matching condition

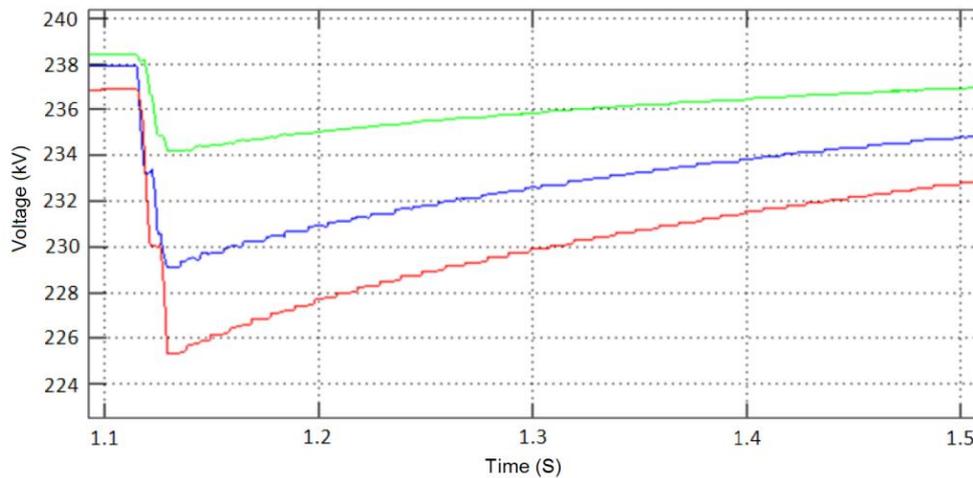


Figure 3.13: Simulated RMS Voltage in kV v/s time in seconds (Vaddeboina et al 2012)

3.3.3 Sympathetic inrush

Sympathetic inrush is a flow of current on already connected transformer due to an inrush current of a transformer just being switched on (Kumbhar & Kulkarni 2007). Due to an inrush of new transformer the already connected transformer goes to saturation mode which is caused by asymmetrical voltage drop throughout the system resistances. This phenomenon makes the already connected transformer contribute to the inrush of the transformer just switched on. This transient interaction known as sympathetic interaction affects the duration and amplitude of the inrush current in already connected transformer and also a transformer just switched on. The key determining factor that causes the sympathetic inrush current is total series resistance of the AC supply system. The study done by (Bronzeado & Yacamini 1995) reveals that the inrush current decays slower when the transformer was connected with a network where other transformers are already energised. The problem of sympathetic inrush gets worse when system impedance is higher that causes resistance to current flow and drop in voltage. The large transformers with small impedance make the effect worst. The long inrush and high magnitude of inrush current generates temporary harmonics and this effect can cause serious problems to power systems. The energy dissipation patterns by the system and saturation level reached by transformer are the two factors that determine the duration and impact of sympathetic inrush current and interaction.

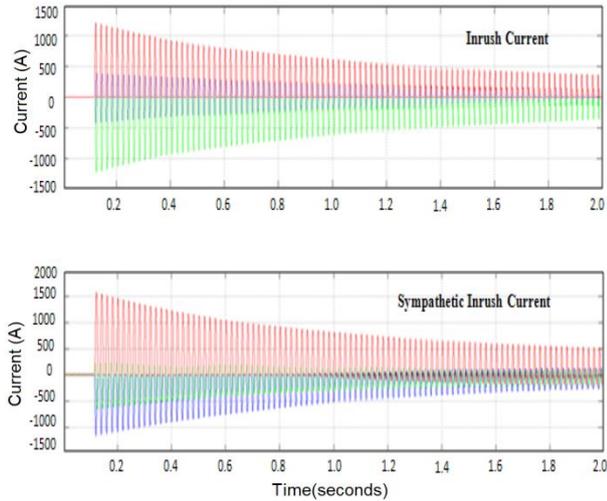


Figure 3.14: Inrush currents v/s sympathetic inrush currents (Vaddeboina et al 2012)

Sympathetic inrush current can be as high as normal inrush. Due to this effect the importance of transformer differential protection and other protection study for nuisance tripping becomes vital. T

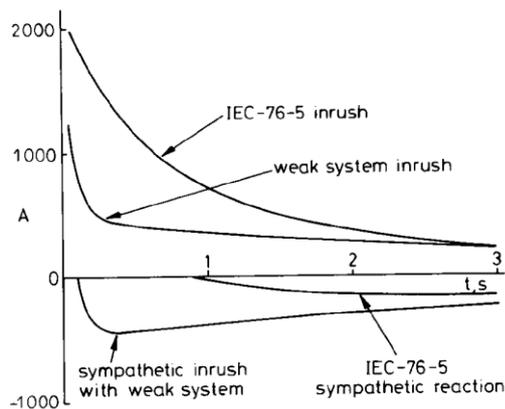


Figure 3.15: System strength v/s sympathetic reaction (Bronzeado & Yacamini 1995)

3.3.5 Vibration/geometric movement of winding

Power transformers are important and valuable assets in any plants. The failure or down time of this equipment costs significantly in terms of money and production time too. For this reason transformers are highly protected compared to other equipment's in the plants. The one of the many reasons of power transformer failure is insulation failure which is caused by vibration and other electromechanical forces during starting, short circuit and normal running conditions. To account these

problems transformer manufacturers accounts for strong structure which holds the winding and core tightly (Steurer & Frohlich 2002).

In a number of discussions it was argued that what (inrush or short circuit) is the worst in terms of electromechanical forces. During the discussion it was pointed that the short circuit last for only few milliseconds as protection system isolates the faulty circuit, where the inrush current last for 10s of seconds. The frequency of occurrences of inrush is far more than short circuit faults too. It was also discussed that the magnitude of current are near similar to each other when transformers are energised at no loads. (Steurer & Frohlich 2002)

Transformer energised during no load exhibits large inrush current which causes unbalanced magneto motive forces and transformer core saturation. (Steurer & Frohlich 2002) This leads to large axial forces on windings. Such forces are much higher in the range of two - ten times compared to the forces generated during short circuit conditions. The key difference between the inrush current and short circuit current however, is the forces on secondary side of the transformer. During inrush condition no or very small amount of current and hence forces being generated, where, in short circuit condition the both sides of the windings are equally(or according to % ratio) loaded and affected due to electro-mechanical forces.

The equitation of the local force density in a coil is given by

$$f = J \times B$$

Where J = current density

B = flux density

During the inrush of current and short circuit of a transformer generates two main types of forces acts on the winding. These forces are square of current.

RADIAL FORCE

Radial force occurs during inrush current. This force tries to strength the winding meaning it will try to make the coil diameter bigger. This only happens to the primary winding or the winding being energised. However, during short-circuit condition the radial force in inner winding compresses

while outer winding, like inrush current, gets stretched. The radial forces during short-circuit are more harmful than that of inrush current. (Neves et al 2011). Please refer to the figure 3.16 for clarification.

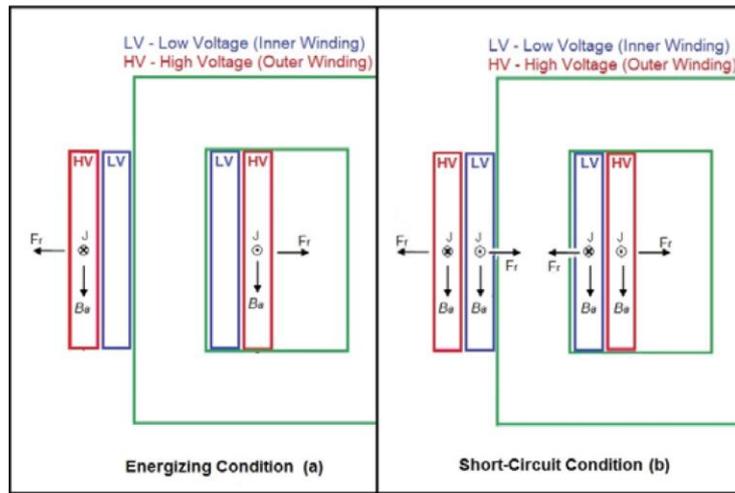


Figure 3.16: Radial forces during inrush and short-circuit conditions (Neves et al 2011)

AXIAL FORCE

The axial force compresses the winding towards the ground means the forces pushes the winding downwards. The force during inrush current is higher than short-circuits as flux during transformer energization is higher. (Neves et al 2011) The inrush current generates axial force only on the winding being energised however the short-circuit, as current flows through both windings, generates axial force on both primary and secondary windings. Please refer to the figure 3.17.

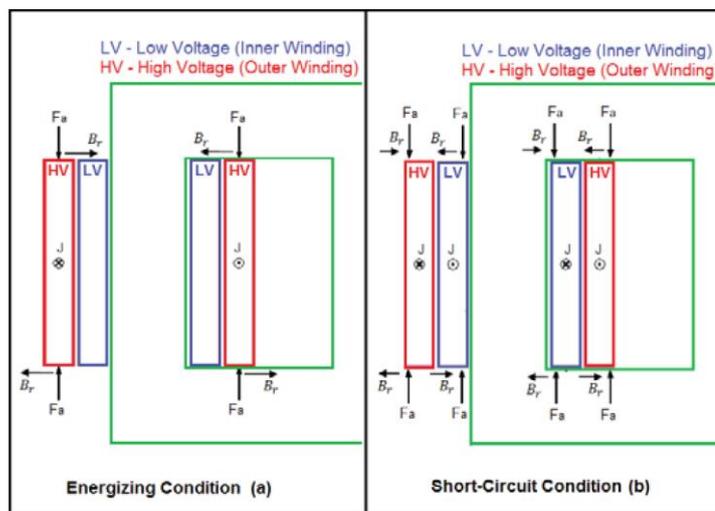


Figure 3.17: Axial forces during inrush and short-circuit conditions (Neves et al 2011)

3.3.6 Protection complexity - Actual fault v/s Inrush current

As discussed in earlier chapter, in B-H curve, to generate any flux higher than knee point a large amount of current is requires as core trends to saturate exponentially.

The general equitation of inrush current that provides amplitudes of current over a function of time is as shown below, .(Apolonio et al 2004)

$$i(t) = \frac{\sqrt{2}V_m}{Z_t} \times K_w \times K_s \times \left(\sin(\omega t - \varphi) - e^{\frac{-(t-t_0)}{\tau}} \sin\alpha \right)$$

Where V_m =maximum applied voltage

Z_t =total impedance under inrush

K_w =constant for 3 phase winding connection

K_s =constant for short circuit power of network

φ =energization angle

t_0 =core saturation point

t =time

τ =time constant of transformer winding under inrush conditions

However, for the purpose of protection system design the most important factor remains the peak magnitude of inrush current.(Apolonio et al 2004) The much simplified version of equitation for peak value calculation is derived as shown below,

$$i_{peak} = \frac{\sqrt{2}V_m}{\sqrt{(\omega L)^2 + R^2}} \left(\frac{2B_N + B_R - B_S}{B_N} \right)$$

Where V_m =maximum applied voltage

L =air core inductance

R=total dc resistance

B_N =normal rated flux density

B_R =residual flux density

B_S =saturation flux density

It is clear from above two equations that the inrush current depends on mainly residual flux and switching angle. (Apolonio et al 2004)

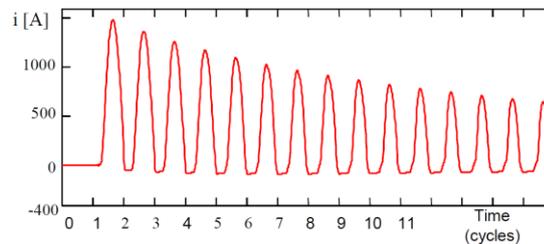


Figure 3.18: Sample inrush current (Kulidjian & Kasztenny 2001)

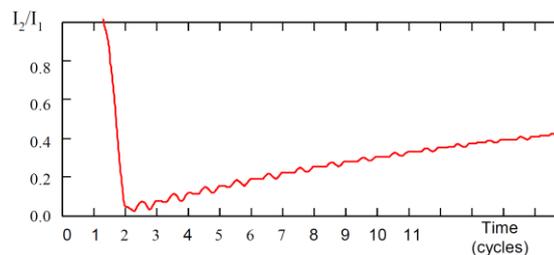


Figure 3.19: Ratio of second harmonics to fundamental (Kulidjian & Kasztenny 2001)

An algorithm developed by Aktaibe and Rahman (2004) based on differential current and harmonics contents in the inrush current. In his logic there are two main parts. The first part compares the differential currents $|Id1-Id2|$. These current is measured from the CTs installed on primary and secondary. If the difference is not zero then it indicates the either internal fault or presence of inrush current. The zero difference shows there is no fault inside the protected boundary. In second parallel part of the logic, the components of harmonics and their amplitudes are calculated. After the calculation the contents of seconds harmonic's percentage amplitude is checked in the range of (0.3 to 0.6) of the components of supply frequency amplitude. If the second harmonic's contents are in the given range then it indicates the presence of inrush current otherwise it is an internal/external fault. Finally if the outputs of both parts are zero than it shows there is presence of inrush current and trip will be prevented. However, if the outputs of both parts are 1 which shows there is an internal fault, the trip signal will be sent to the tripping logic/protection.

The algorithm (figure 3.20) developed by Hooshyar (2012) has same principle however, instead of calculating direct harmonics contents, the waveform correction scheme and odd and even part extraction methods are used to differentiate the inrush current in actual internal fault.

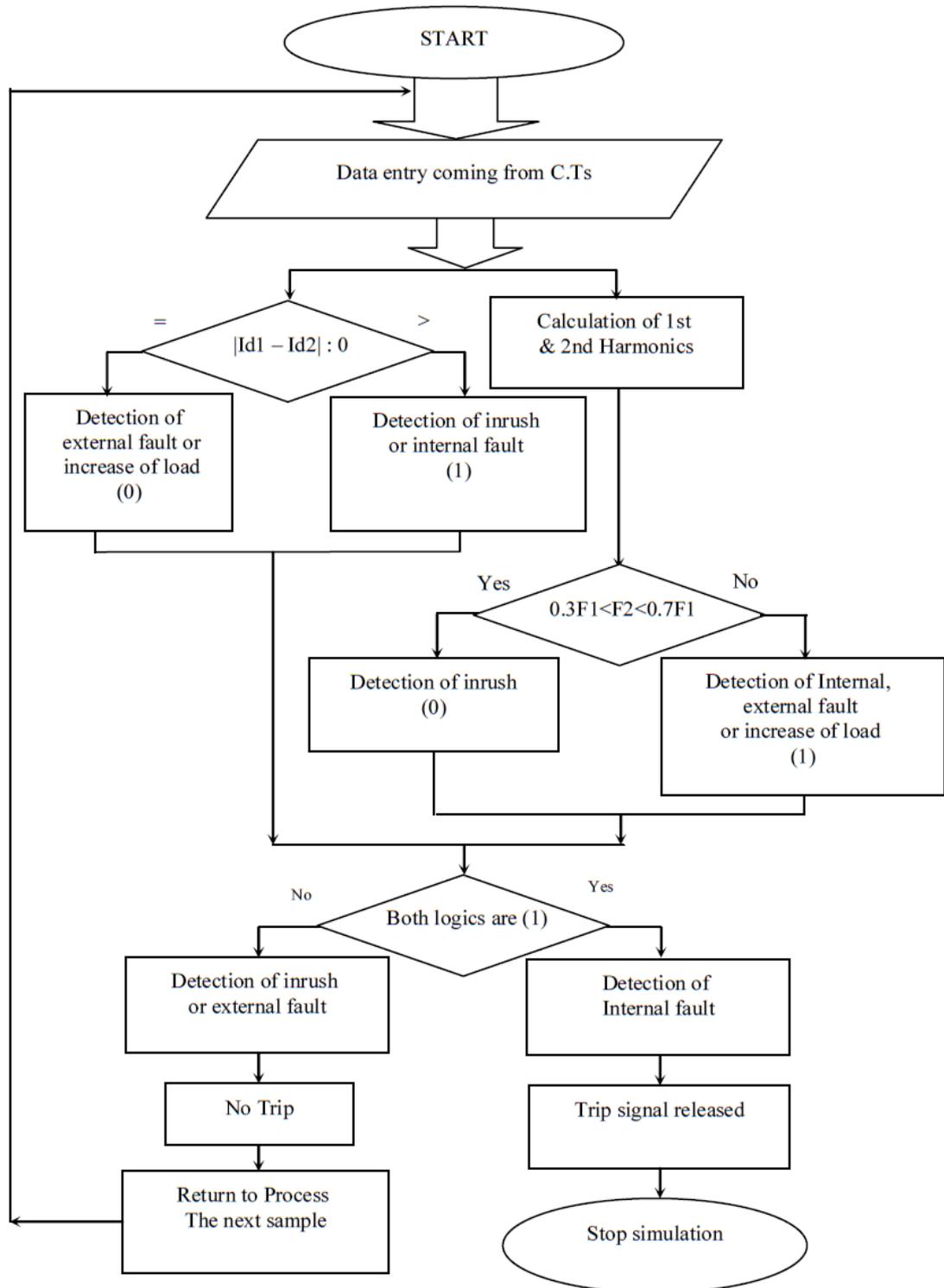


Figure 3.20 : Flow chart to differentiate the inrush current (Aktaibe and Rahman 2004)

The wave form of fault current is full wave but of higher magnitude. This waveform will be close to sine wave. However, the waveform of inrush current is not sine wave. It has DC components and it is half and peaky wave. The difference is as shown in figure 3.21 and figure 3.22. A paper presented by Rehmati and Sanaye-Pasand (2008) shows that transformer fault and inrush can be distinguished by wavelet transform.

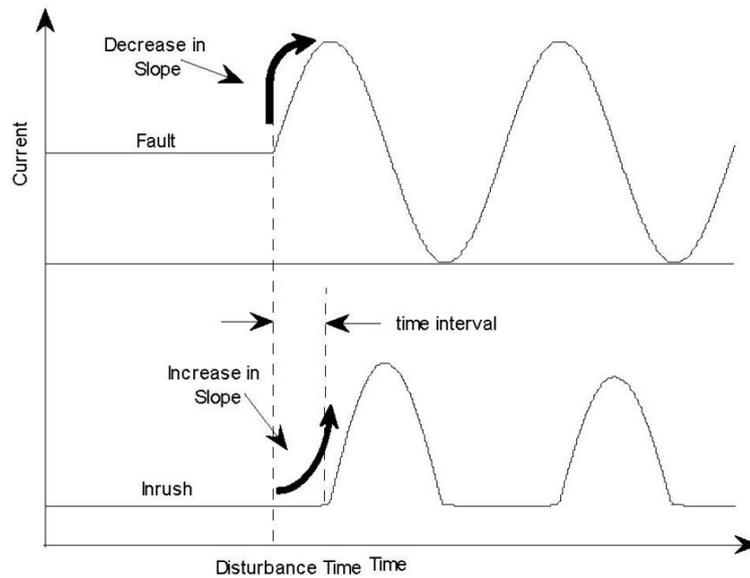


Figure 3.21: The fault current v/s inrush current waveform (Rehmati & Sanaye-Pasand 2008)

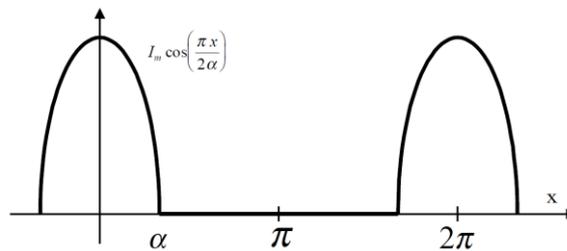


Figure 3.22 : Idealised inrush current (Kulidjian & Kasztenny 2001)

3.4 Inrush current mitigation techniques

3.4.1 Asynchronous switching v/s Inrush Current

A practical done by Rahnavard et al (2010) found that the inrush current can significantly be reduced by asynchronous switching operation. The result based on a Matlab sim-power system simulation shows that the by switching each pole circuit breaker at the interval of 6 milliseconds can reduce current from 5.96/-5.24 pu to 1/-

1pu. However, this exercise can create other problems depending on the connected at downstream of the transformers. It was also noted that the operation can be expensive as exchange of line breakers were necessary.

Asynchronous switching is turning each phase circuit breaker at separate time instead of same time. In start connected primary of transformer, when asynchronous switching takes place, during the first phase switch all current goes from first phase winding to neutral. (Cui 2005) This current is negative sequence current. During second phase switching the neutral current can be even greater than that of second phase as first phase also contributes to the neutral current. However, then third phase is energised the negative sequence current comes to zero instantly.

3.4.2 Neutral Earthing Resister v/s Inrush Current

A practical done by (Cui 2005) on transformer reveals that the optimal neutral resister can be derived from simulation and is as effective as series resistance/voltage divider method and can significantly reduce the inrush current magnitude and duration. The figure 3.23 and 3.24 shows the optimum value of NER is 50ohm based on calculations and analysis done on 225kVA, 2400/600V, 50Hz 3ph, YY transformer.

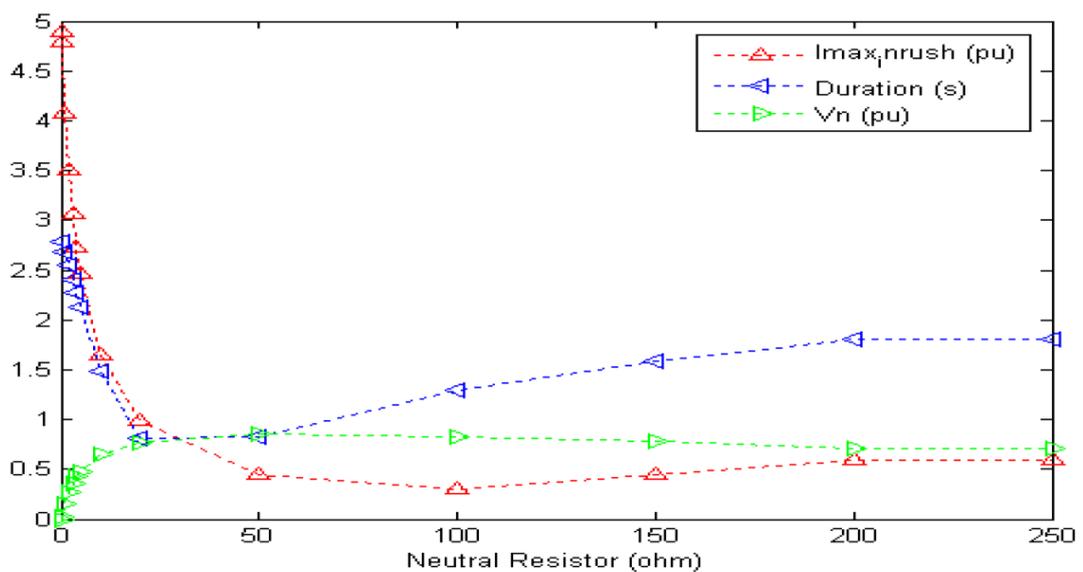


Figure 3.23: Value of NER v/s Inrush current(p.u), duration & neutral voltage(p.u) (Hajivar 2010)

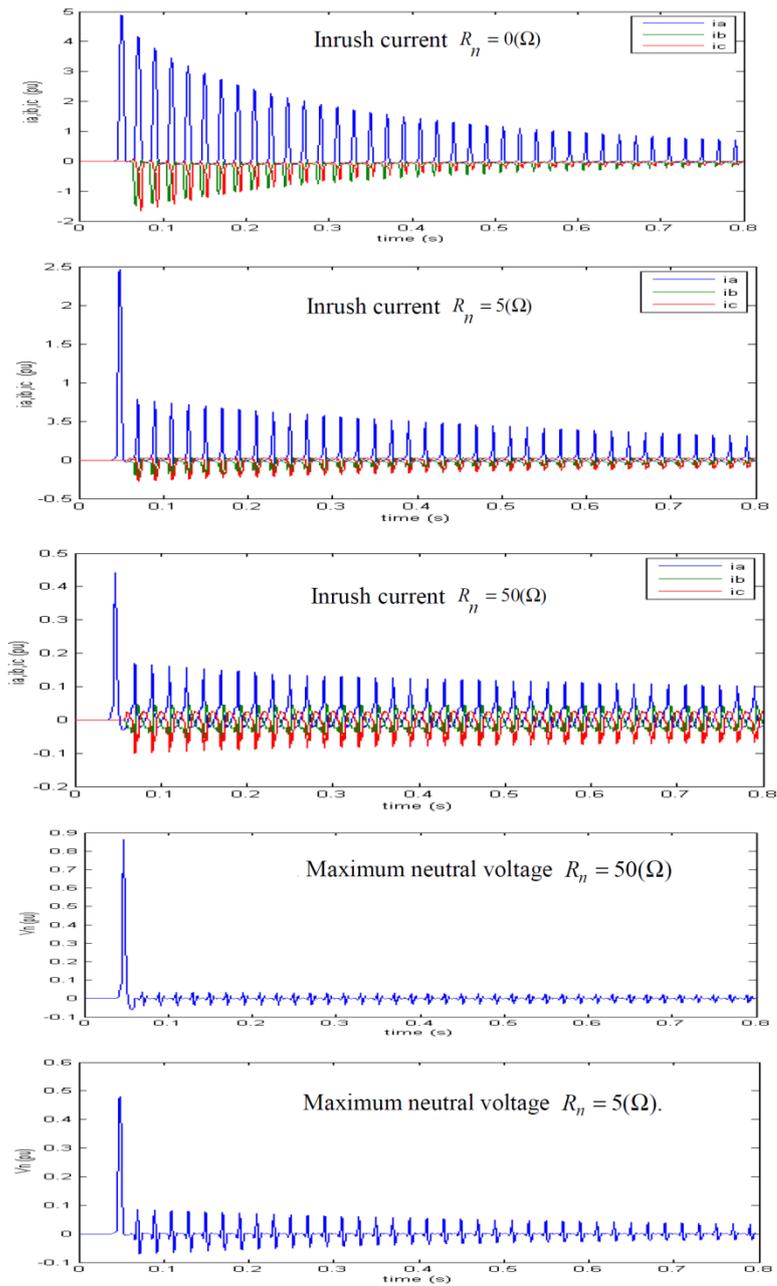


Figure 3.24: Inrush current v/s value of neutral earthing resistors (Hajivar 2010)

The equation derived by Xu et al (2005) for the optimum value of the resistor is,

$$R_n = 0.085X_{open}$$

Where, R_n =Neutral earthing resistor and

X_{open} =open circuit positive sequence reactance of the transformer

(Xu et al 2005) suggests that about 1 quarter of circuit breaker contact voltage and up to 90% reduction of inrush current can be achieved by switching the pole sequence as A, B & then C.

The neutral earthing resister limits the current going to neutral which limits the inrush of current during first and second phase energisation.

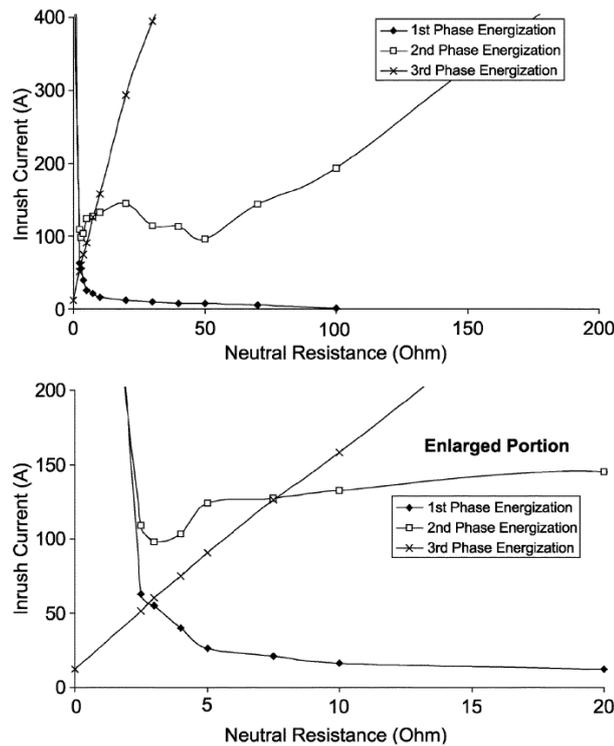


Figure 3.25: The value of neutral earthing resister and effect on inrush current (Cui et al 2005)

3.4.3 Comparison of various methods

Results of studies done by Rahnavad and et al (2010) suggest that best of time switching is as effective as asynchronous switching. In their study they added a circuit breaker and load on secondary side. In primary side of transformer a RLC load and this load's circuit breaker were connected with parallel to main primary circuit breaker. Combinations of various switching patents were done. It was observed that the current can be inrush current can be reduced about five time by switching secondary load first, the RLC load across primary CB second and finally

the main primary circuit breaker. This method is derived from so called reduced initial primary voltage.

Method	Positive max current (pu)	Negative min current (pu)
Normal	5.96	-5.24
A. With pre-resistor	5.05	-4.91
B. With capacitor	4.95	-4.2
C. Capacitor & pre-resistor	4.19	-3.82
D. Auxiliary load	4.78	-2.39
E. Auxiliary load & capacitor	3.2	-2.72
F. Auxiliary load & capacitor & pre-resistor	2.89	-2.48
G. Best time of switching	1.08	-1.01
H. Asynchronous	1	-1

Table 3.1: Comparison of outcome of various methods (Rahnavad et al 2010)

4. Methodology

This chapter contains information about the number of inrush current effects and the construction of the model. It describes the list of simulation scenarios and, the specification of an actual transformer and running data history, modelling software, brief on model, parameter used in model, the sketch of model and finally measurement techniques. The chapter basically presents the methodology of constructed models and simulated scenarios.

When a transformer is energised from a standard power source it draws high starting current which can be as high as 10 – 100 times of transformer's rated current. This current will starts to decay at the rate of effective winding resistance and will settle down to steady state condition. The time to decay can be as long as few seconds. This current is known as magnetising inrush current (Naghizadeh et al 2012). This effect is described in section 3.1 and section 3.2. The inrush current results in nuisance trip of protection system, it generates second harmonics creating power quality issue, and added mechanical stress due to high magnetic forces generated due to such events and due to all of above it negatively affects the life of a transformer.

The listed following simulation effects are based on above principle.

4.1 List of scenarios

- **Inrush current compared to actual transformer**

This model is the base model. This model is later updated for the remaining simulation scenarios listed below. Here the parameters entered in transformer model block resemble the actual transformer. This model resembles the actual remaining system connected with transformer such as transformers connected at input and outputs, the neutral earthing transformer, the circuit breaker pole closing timing accuracy etc. This addition is important as the actual transformer's data will be compared with simulation at results and discussion topic. Transformer also behaves differently when other components are connected with it. This simulation results when compared with actual data will reveal any match/mismatch and will be progressed accordingly.

- **Inrush current in 3 single phase and a 3-phase transformer**

After comparing above model with actual transformer a 3 single phase transformer model will be created that matches all relevant power parameters of 3-phase transformer model. The results of 3-single phase transformer model simulation will be compared with 3 phase transformer model. The discussion and conclusion will be derived according to the findings.

- **Sympathetic inrush current**

This inrush current flows when two or more transformers are connected together in parallel. Sympathetic inrush flows to the transformer which is already energised when another new transformer on same parallel line is energised. Due to inrush on new transformer the remaining connected transformer will feed the necessary current (as impedance goes down). This effect will be simulated by connecting a number of transformers in the system and switching a new transformer on the system. The magnitude and duration will be a key focus in this simulation result.

- **Sequential phase energisation (with/without NER)**

As listed in literature review the inrush current depends on two key parameters, the pole switching time and residual flux. In large transformer it is difficult to control/remove residual flow in the core. Hence the only low cost practical controllable option is the pole switching time. The switching time can be easily adjusted in many circuit breakers. This simulation which reduces the inrush current will be carried out by phase of supplying source voltage at several instant. Here optimum switching time will also be recommended from the derived results.

4.2 Modelling package

SimPowerSystem is specially designed Simulink block library that has all necessary power system components. This system was developed by Hydro-Quebec of Montreal. “SimPowerSystem models are assembled as a physical system. Models are connected by physical connections that represent ideal conduction paths. This method of modelling being physical and schematic it is easier to understand while at backend the system automatically constructs the differential algebraic equations (DAEs) that characterize the behaviour of the system and integrates with the rest of the model”. (Mathworks NDT)

4.3 Measurement techniques

The three phase voltage and current is measured using a VI meter as modelled below. The Fast Fourier Transformation reveals the harmonics contents and magnitude. The time of inrush current decay is also noted.

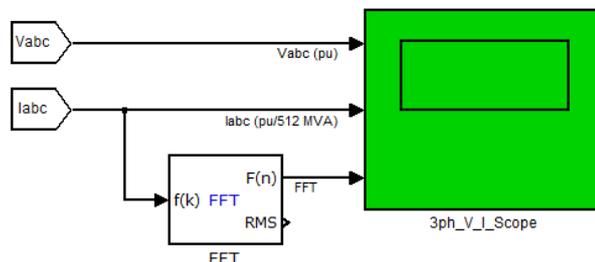


Figure 4.1 : Three phase V, I and I_{FFT} scope

4.4 Existing arrangement

The existing power system arrangement is as described in figure 4.3. A 592MVA, 2 pole, 50Hz synchronous machine rated 20kV p-p terminal output connected to a 600MVA transformer known as generator transformer through a GCB. The HV side of Generator transformer is connected in star and directly grounded. This transformer steps up the generator voltage to 500kV. The power station load is supplied via a 11kV, 70MVA unit transformer which is connected between generator circuit breaker and generator transformer. Generator gets its field power from stator

terminal via an AVR and three single phase $\frac{20}{\sqrt{3}}/900V$ transformer rated 2.2MVA. Generator is star connected and neutral is grounded via a neutral earthing transformer and 5.6Ohm resistor.

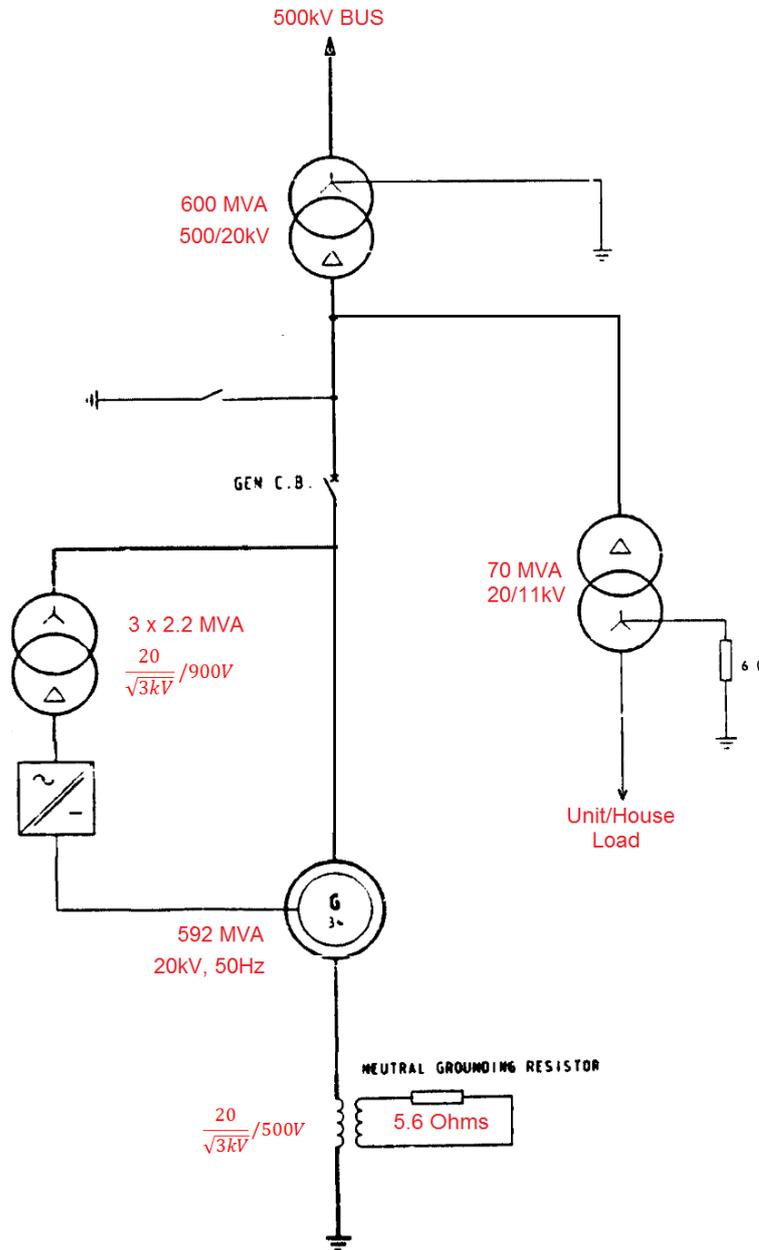


Figure 4.2 : Simplified one diagram of actual system arrangement

4.5 Actual data sourcing

High speed data is be sourced from the IDM-Hathaway unit. The device has already captured varieties of different data from various system disturbances to new start and shutdown event etc. This data from the date file will be converted to appropriate file format to import in to Matlab simulation program.

IDM (HATHAWAY)

IDM-Hathaway is electrical fault recorder. It is a well-known brand in large electric power stations. This recorder in the event of any system disturbances captures the high speed data triggered according to user defined settings. “The product, when coupled with the Qualitrol Hathaway Replayplus software package, provides a powerful platform for the acquisition, analysis and reporting of data from power systems.” (Hathaway, NDT)

SAMPLE DURATION AND RATE

The existing IDM unit is set to capture 128 samples per cycle for fast data capture. This high speed recorder captures the data for 6 seconds. The settings are done so that it starts recording 1 second pre event and 5 second post event. The second inbuilt recording function is slow speed type. This recorder captures the data at 10 samples per cycle. This data is continuously being recorded however, due to memory issues the data after 3 months gets over written.

4.6 Model subsystems & parameters

Following is base model built during this semester to get general concept of what are the possible obstacles and issues. The data in table 4.10 three phase power transformer block is actual data of the 600MVA transformer as discussed in section 4.4. The key parameter is hysteresis data. This data of the existing transformer is not available. However, about 5 year back the same capacity spare transformer from different manufacture has been bought. Some hysteresis data were available however they were incomplete. Enquiry was done to the manufacturer for the actual hysteresis

curve however the curves were unavailable due to confidentiality issue. Therefore instead of using user defined curves, here a standard more widely referred in Matlab's curve is used by selecting the transformer as saturable transformer.

The following are the key components of the models that can be used in a subsystem however, for simplification they are left on the main system.

Circuit Breaker Timer

The circuit breaker timer was created to simulate the circuit breaker turning on times. The low voltage side of the transformer was switched on at half second interval and the high voltage side of the circuit breaker was switched on at two seconds interval.

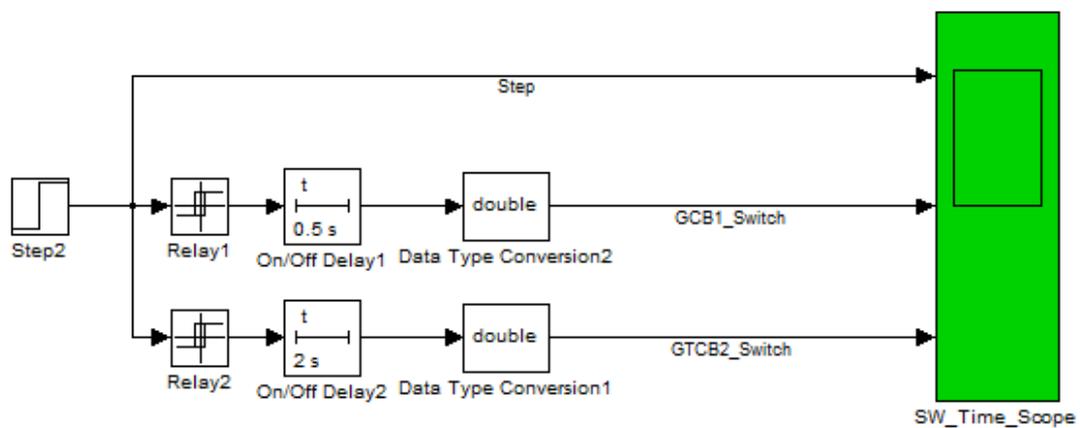


Figure 4.3 : Circuit breaker timing circuit

The circuit breaker timer system as shown in figure 4.3 was used in model. This system runs with the main model and when running it generates step up input from 0 to 1 by Step2 block. This sends the trigger signals to Relay1 and Relay2. The relay 1 has 0.5 seconds on delay timer in series and Relay2 has two seconds on delay timer in series. Both of this relays at definite time send on trigger signals to dedicated circuit breaker via data type conversation block. The data conversion block required to match the data signals between the timer and circuit breaker. The GCB1_Switch sends trigger signal to the circuit breaker which is located at the input (low voltage side) of the transformer and the GTCB2_Switch triggers the circuit breaker located the output (high voltage side) of the transformer.

Transformer Input model

The input model described in figure 4.4 provides the energy to low voltage side of the transformer. This model consists of a three phase generator, V/I sensor, excitation transformer, three phase isolated circuit breaker and a unit transformer.

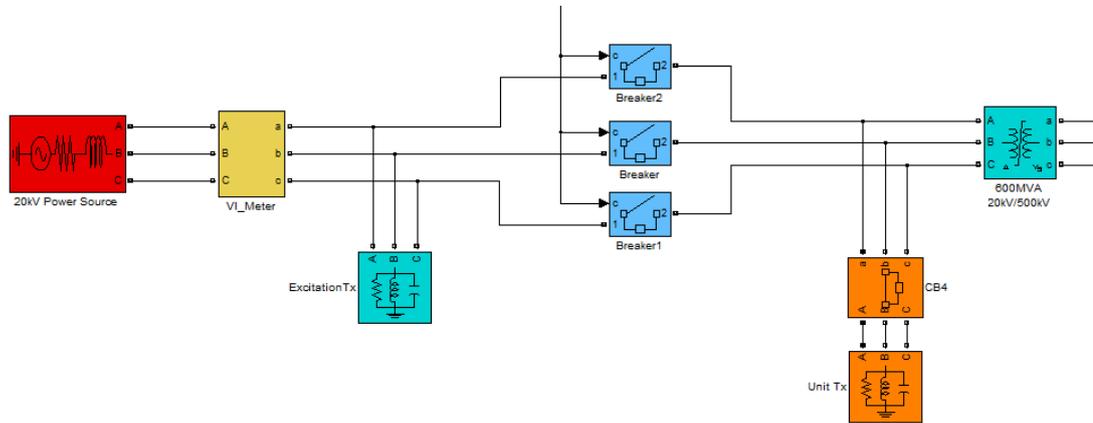


Figure 4.4: Transformer output system

The three phase synchronous generator generates 20kV voltage and is connected to three phase isolated circuit breaker via a V/I_Meter block. The isolated circuit breaker resembles the actual plants isolated air circuit breaker. They all get the relay signal at the same time however, since they are physically/mechanically isolated from each other the actual contact time varies in order of up to 10 milliseconds in its healthy state.

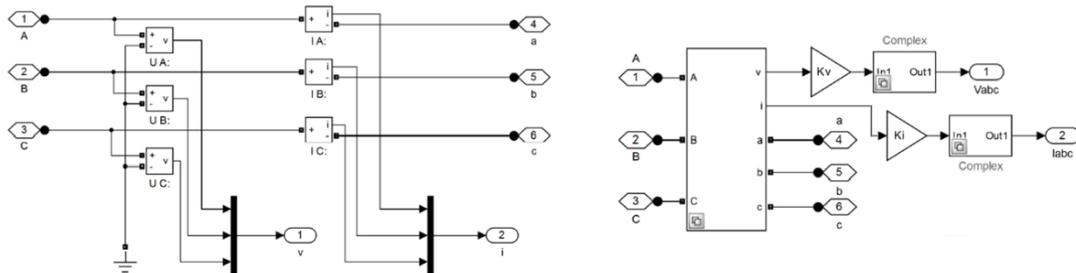


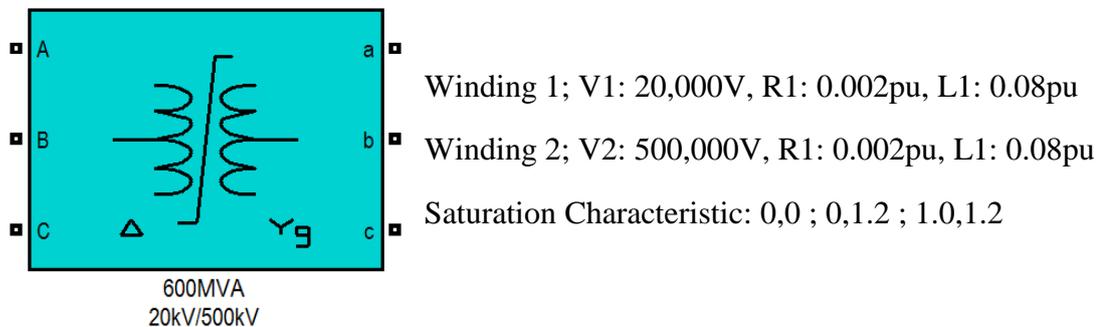
Figure 4.5: VI_Meter subsystem

The VI_meter block senses each phase voltage and current signals and stores in variable which are connected to scope for analysis. For simplification, the excitation transformer here is represented as RLC circuit with active power 6MW, inductive reactive power 1MVAR and capacitive reactive power of 0.5MVAR. The excitation transformer also acts as initial starting load before the generator circuit breaker turns on. The actual rating of unit transformer is 70MVA however in actual plant the

transformer is only partially loaded. The unit transformer provides the energy to station's local load. For actual simulation here the unit transformer is represented as RLC load with active power of 30MW, the inductive reactive power of 6MVARs and capacitive power of 2MVARs.

Main Transformer model

The main transformer is 600MVA, 20kV to 500kV step up transformer. It gets power from synchronous generator, steps up the voltage to 500kV and sends full output to transmission line. The transformer is delta-star grounded with saturable core. All units are described in per unit quantity.



The details of inrush current model that matlab sim-power system has used is as shown below. The model consist of mainly a s function, couple of lookup tables and switches.

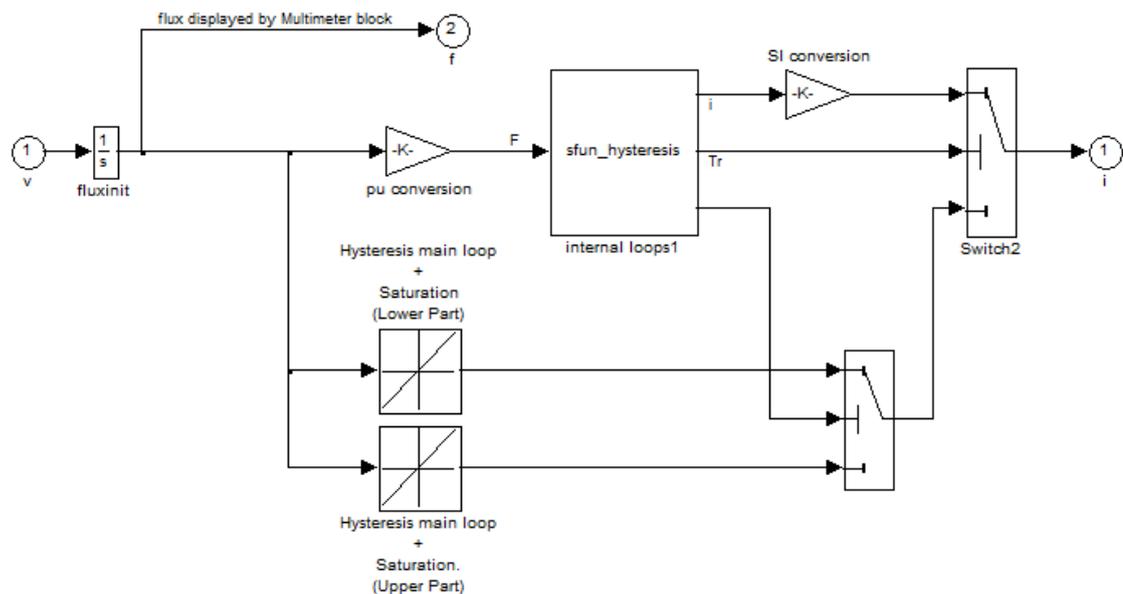


Figure 4.6: Transformer hysteresis model

Transformer output model

The output model described in figure 4.7 provides the energy to load from high voltage side of the generator transformer. This part of model consist of a HV circuit breaker and load that is represented by a similar size step down transformer and load as RLC load at both LV and HV side of the transformer.

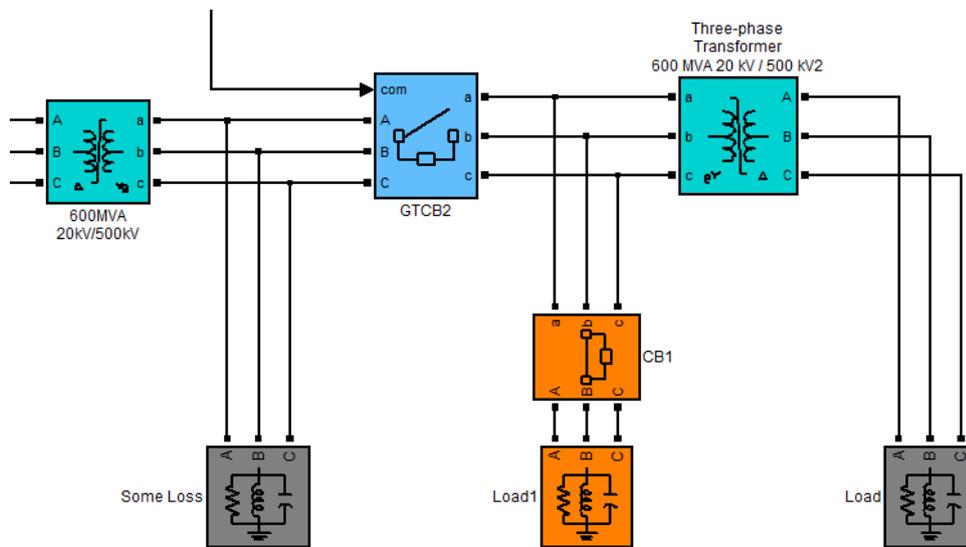


Figure 4.7: Transformer output system

In this model, the three phase power at 500kV phase – phase voltage is transferred to same size transformer however in this case stepping down the input voltage from 500kV to 20kV representing the distribution transformer of the grid. Between these two transformers the 500kV circuit breaker is placed to switch the load instantaneously to simulate the large load switching. A small line loss (10MW, 0.3MVAR L & 0.1MVAR C) representing the transmission line loss as a RLC load is placed between the generator transformer and 500kV CB. A decent size RLC load representing large transmission line loss is represented as 60MW active power, 3MVAR inductive and 1MVAR capacitive load. At the end of distribution transformer 60MW load with some inductive and capacitive load is connected. The reason for not connecting full load is when a generator is synchronised to grid the loading on it is controlled carefully and hence load is increased gradually in steps not instantaneously.

5. Result & Discussion

This chapter contains details about each model, the results and discussion. As described in methodology here mainly five models are built and simulated for analysis of inrush current effect. The conclusion and outcome will be listed in the next chapter.

The computer used here has 64bit i7-2620 CPU with 2.70GHz speed and 8GB RAM that runs on Windows 7 operating system. The Matlab version 7.10 (R2010a) with Simulink 7.5 and SimPowerSystem 5.2.1 is used. The model takes significant amount of processing power and time to simulate each scenario.

The first model described in section 5.1 is a base model. It basically consist of a three phase generator, three phase isolated circuit breaker, the 600MVA generator transformer, a load breaker at output side and grid consist of another transformer and load. The model is simulated at 50Hz and the three phase voltage, current and harmonics are measured and presented on scope. The harmonics content of current for each second is also presented on a separate live figure. This figure automatically runs and updates when model is run.

There are three stages of the switching in each model described in section 5.1 to 5.6. In the beginning of simulation for first 500mS only excitation transformer is in circuit. This transformer is represented by RLC load and hence only small steady state current is seen in the results. At the 500mS interval the generator 3 phase isolated circuit breaker is energised. Here all phases are switched at same time and considered no lag in stitching time. Switching this circuit breaker energises the generator transformer and also unit transformer. Unit transformer is represented as RLC load and hence it has only a small steady state component in power sharing. The output of generator transformer is connected to 500kV load breaker and it is also connected to some line loss represented as RLC load. Hence except small RLC load there is no significant load on the circuit.

However, as seen in the plot on scope the large amount of three phase inrush current flows. This current slowly decays towards the steady state current. The magnitude of current depends on the hysteresis characteristic of core material and switching angle of applied voltage. The rate of inrush current decay is proportional to circuit

resistance of core material. This large amount of inrush current will always be present in all three phases of the circuit as each phase is 120 degree apart from each other. Even if it is considered to have no residual magnetism in core and one phases switches at 90deg to contribute zero inrush current for that phase, the other two phases will 120 deg apart and contribute to out of sync(v/f). This means there will always be an inrush of current in any given condition in three phase circuits.

The inrush current decays exponentially with increase in time. As time reaches to 2000 mS, the load circuit breaker located on 500kV line is energised. This results in energisation of distribution transformer and supply to distribution load. This results in inrush current in main transformer. This current is called sympathetic inrush current as transformer is already energised and inrush of another transformer causes the inrush to the already connected and energised transformers. The magnitude of peak inrush current again depends on voltage switching angle, residual flux in core and also load connected to on secondary.

In section 5.2 instead of one, three phase generator transformer, three single phase transformers are used. This is simulated to understand the effect of separate tank transformers on inrush current. The rating of these three single phase transformer is estimated to be equivalent to one three phase transformer. The inrush current results of this simulation seem to be almost identical to a three phase transformer. However, when transformer is de-energised the residual flux in each single phase transformer will be proportional to the switching off angle of voltage. Hence, each three transformer will contain different level of residual flux. The level of residual flux will also be proportional to phase angle, 120 degree. This means if the transformer is energised in proportional to remaining residual flux in core, the existing flux in core will match 120 degree phase angle of each voltage angle. This will result in minimum or zero inrush current which is not possible in one three phase transformer.

The HV size of generator transformer which is star connected is grounded via a 150mH reactor in section 5.3. The result simulation did not reveal any different results. It was expected to see reduced inrush current with addition of NER.

The last three sections contain 90° lag voltage phase lock switching system. Here first phase was energised when phase one voltage reaches to 90°. The second and third phases were energised 120° and 240° respectively. This results in zero inrush

current. The following six sub section of this section contains matlab sim-power system model, three phase instantaneous current plot and fast furrier transformed plot of the three phase current.

5.1 Model 1 – Three phase transformer

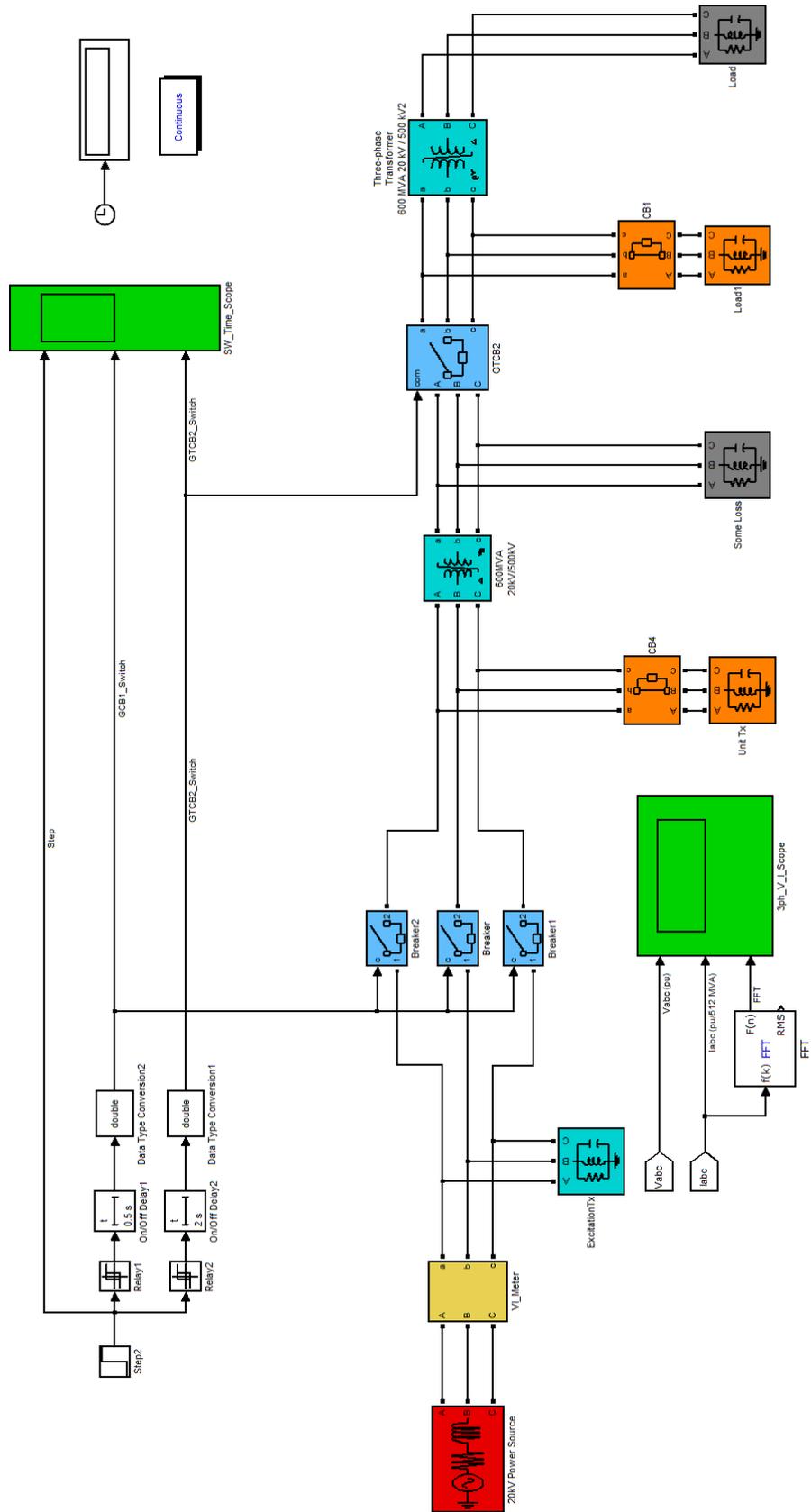


Figure 5.1: Three phase transformer model

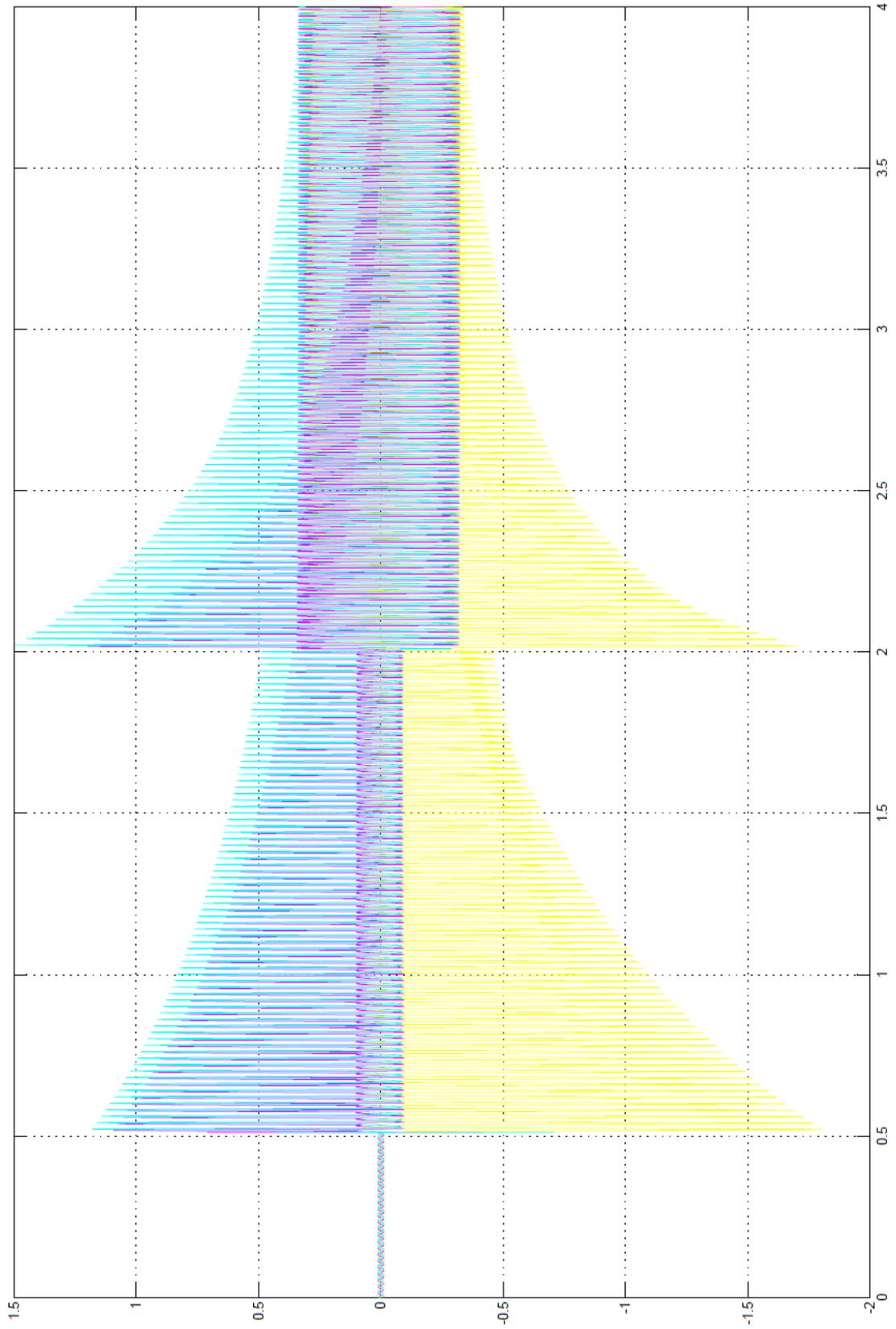


Figure 5.2: Three phase transformer model I_{abc}

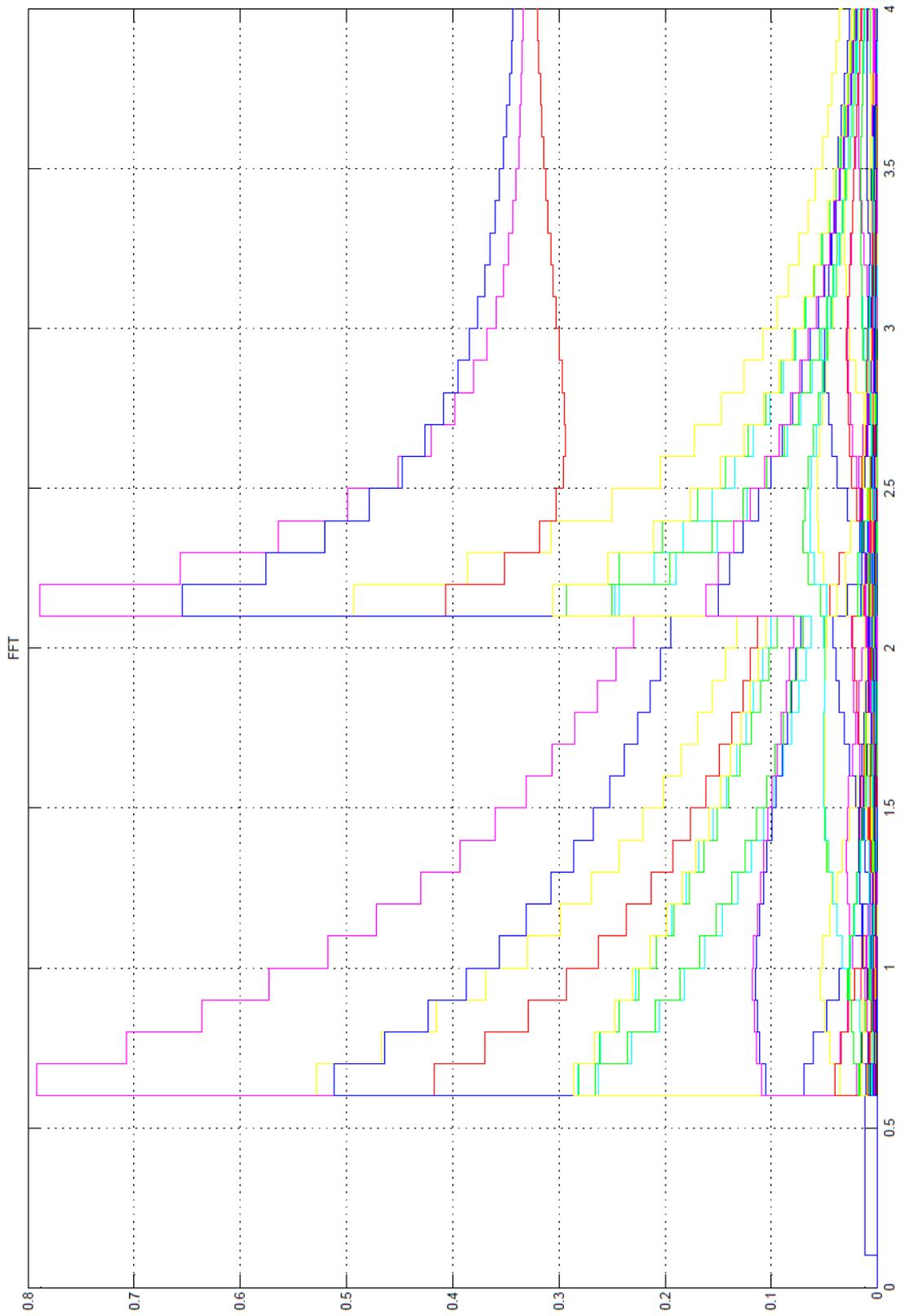


Figure 5.3: Three phase transformer model FFT of I_{abc}

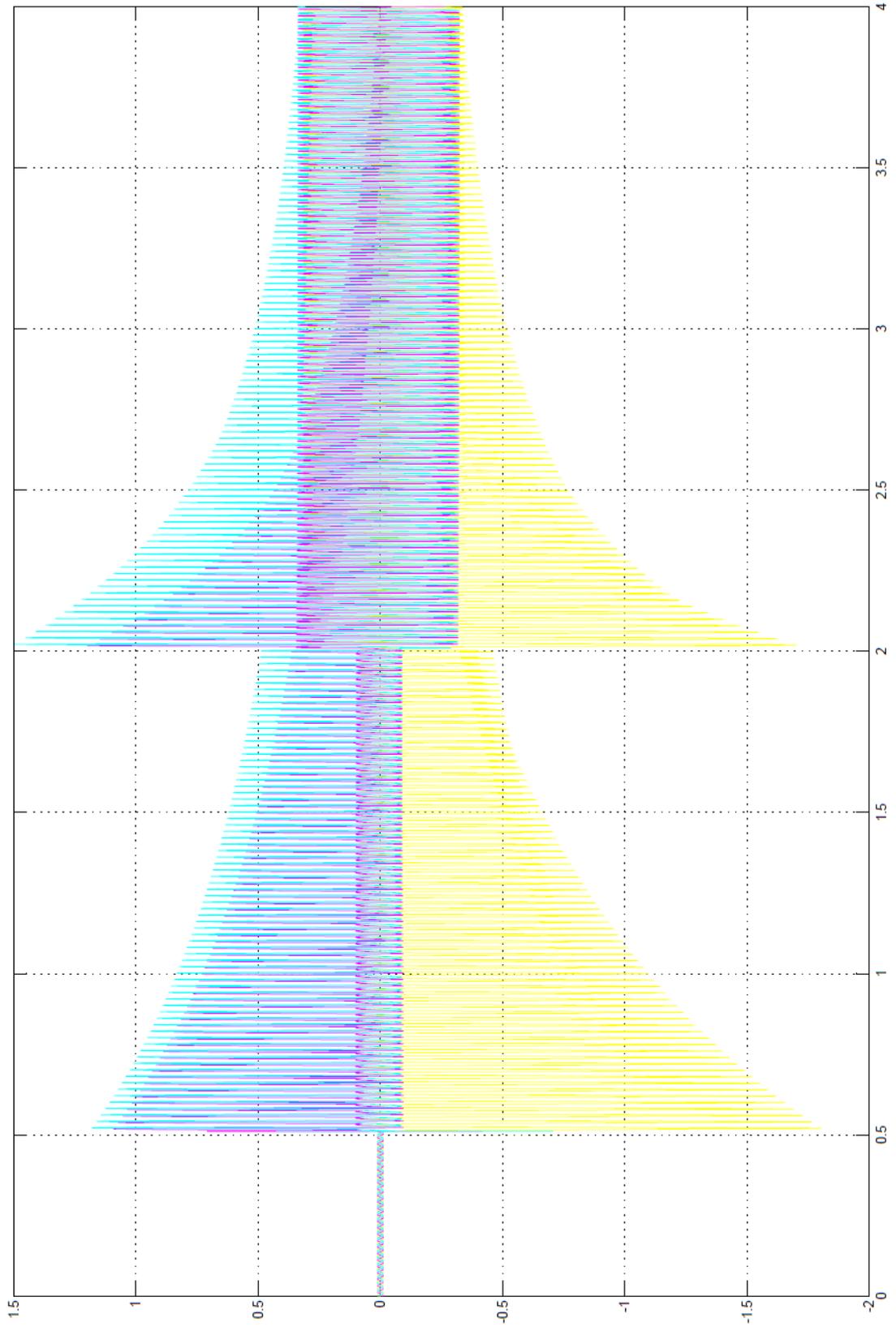


Figure 5.5: Three single phase transformers model Iabc

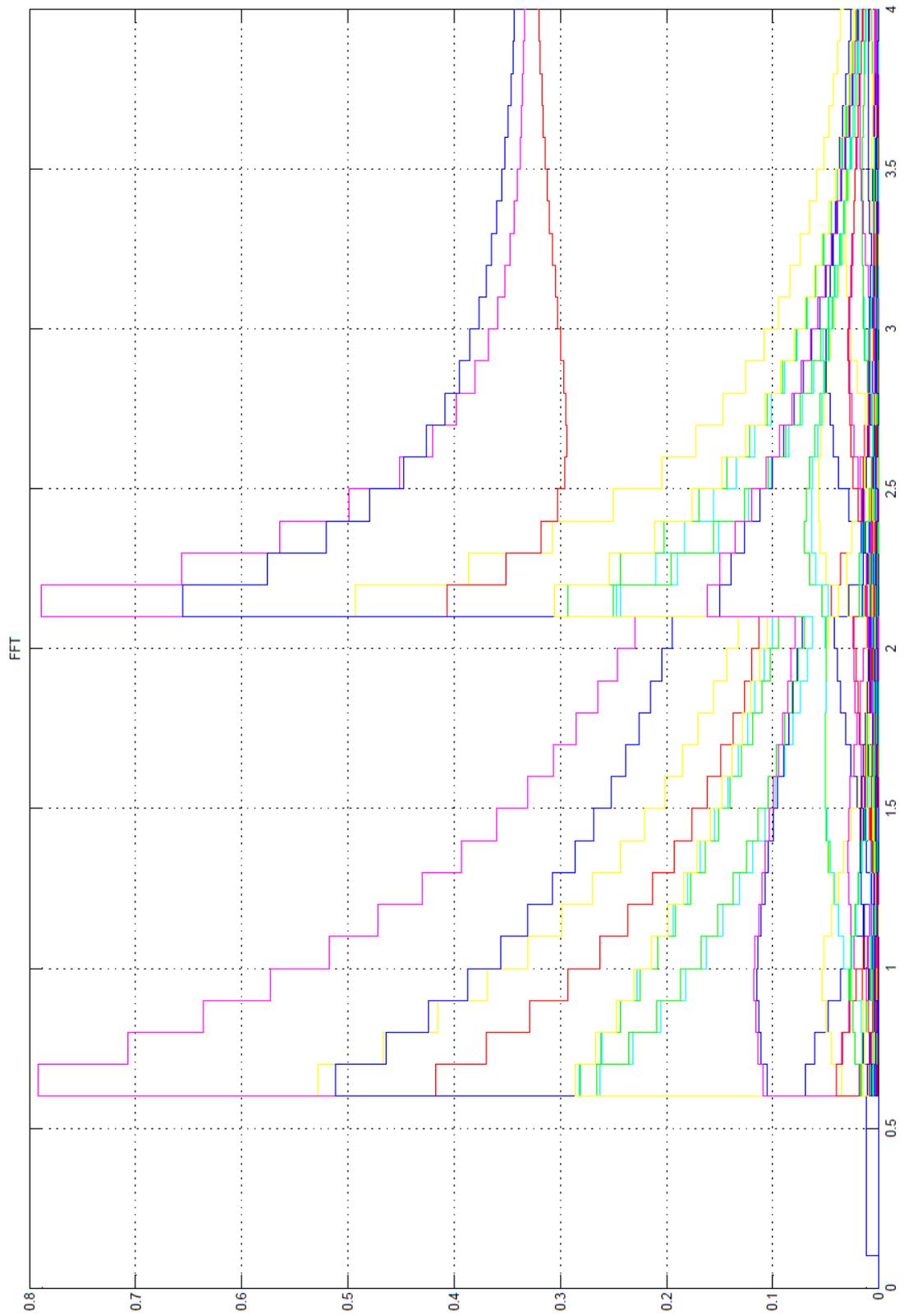


Figure 5.6: Three single phase transformers model FFT of I_{abc}

5.3 Model 3 – Three single phase transformers with NER at HV

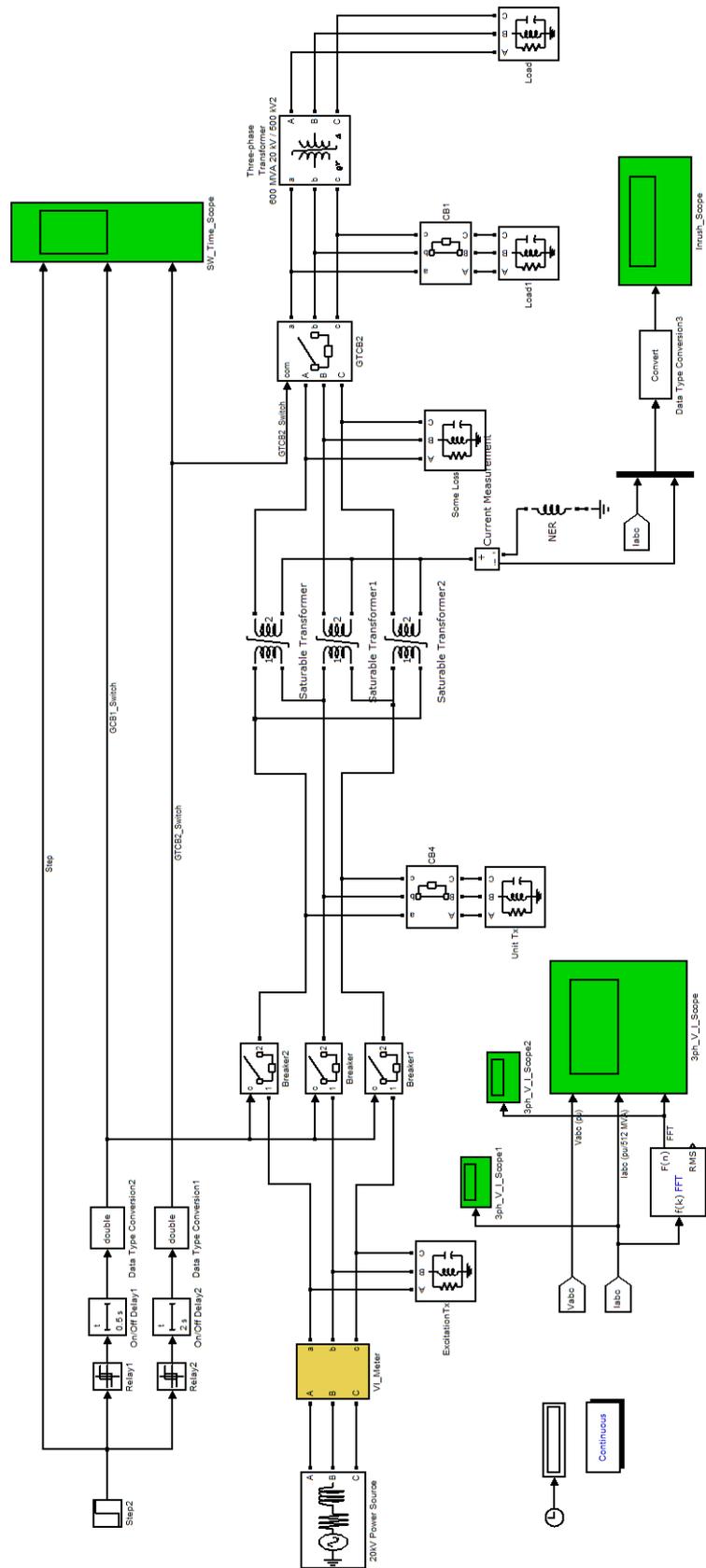


Figure 5.7: Three single phase transformers with NER model

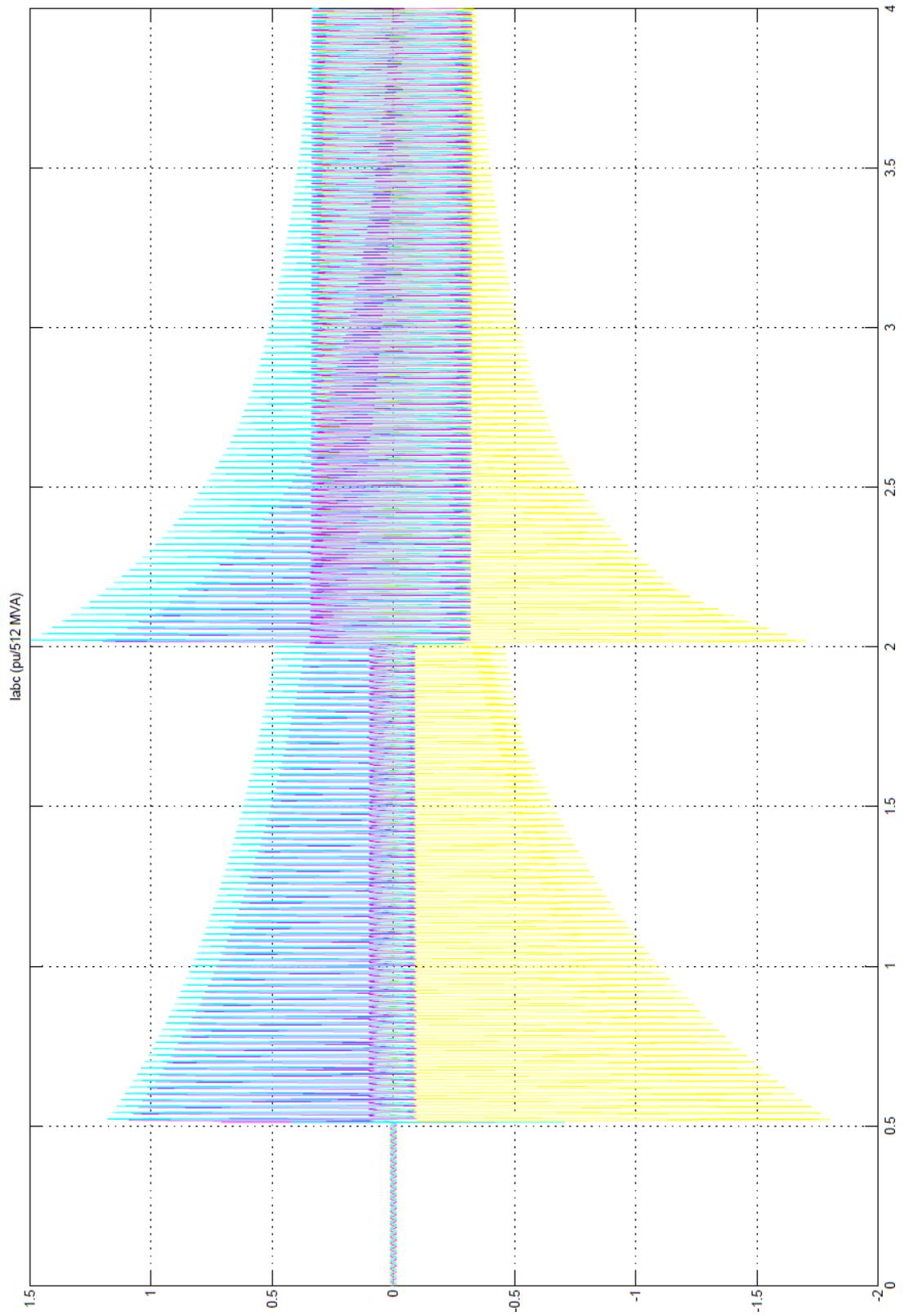


Figure 5.8: Three single phase transformers with NER model iabc

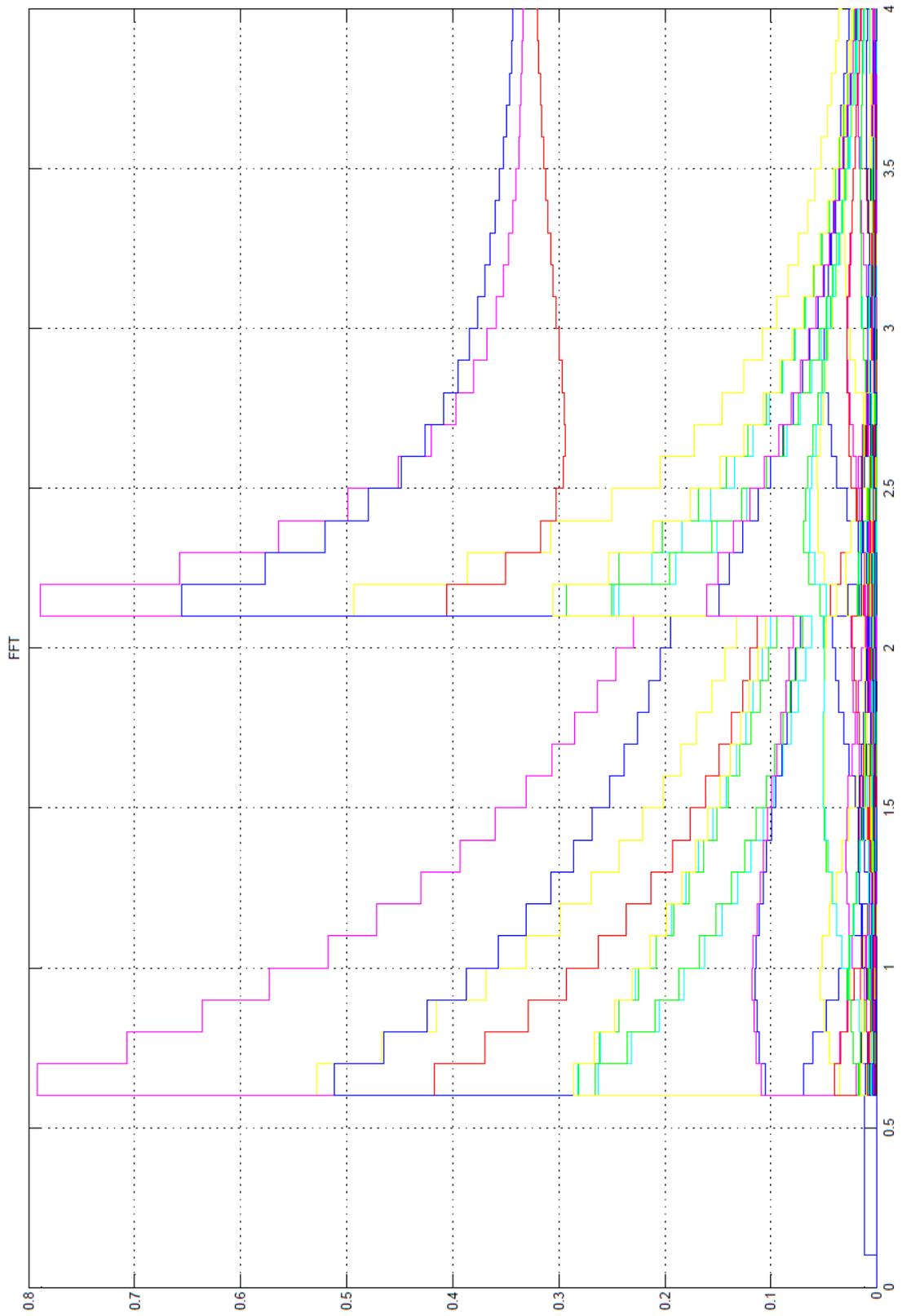


Figure 5.9: Three single phase transformers with NER model FFT of Iabc

5.4 Model 4 – Three single phase transformer with sequential switch

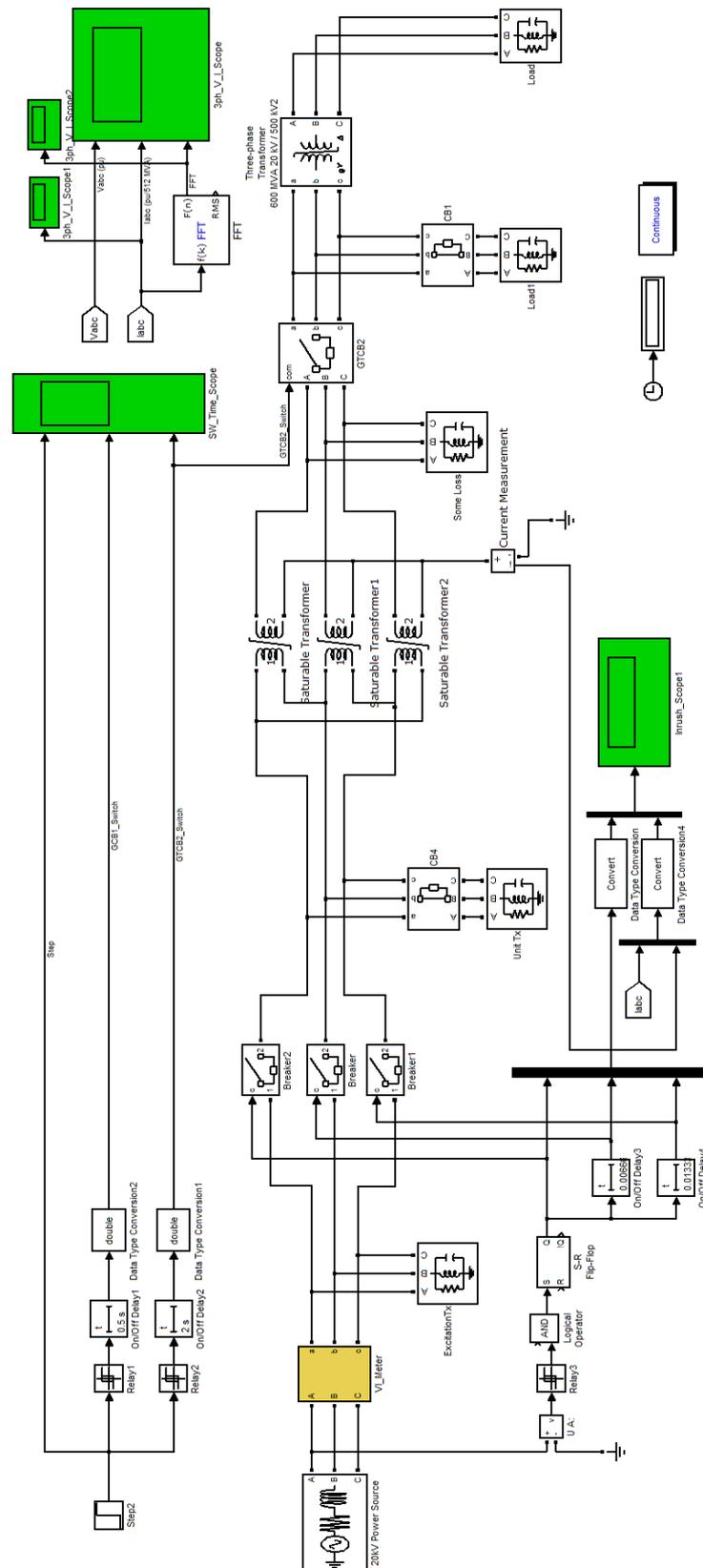


Figure 5.10: Three single phase transformers with sequential switch

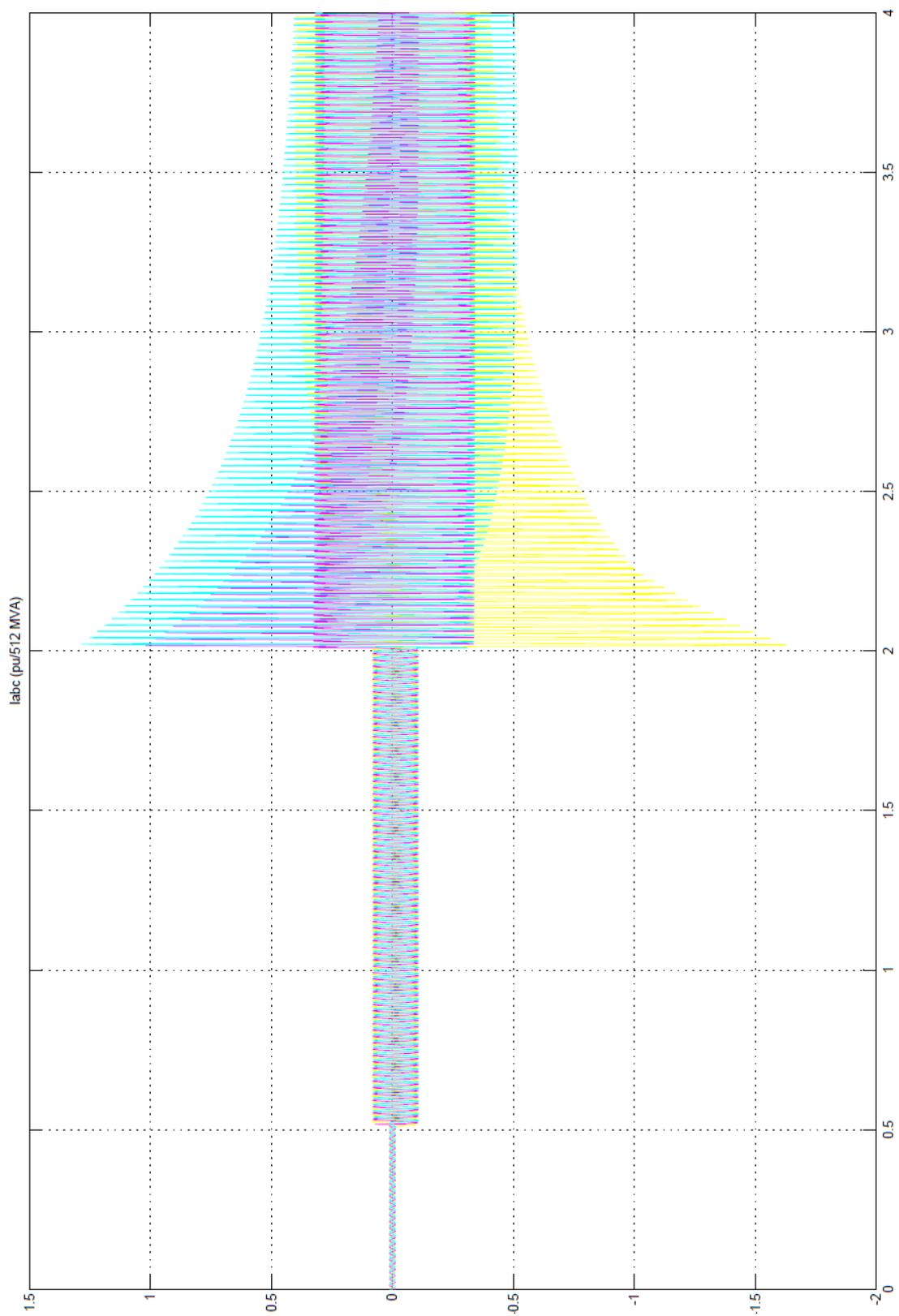


Figure 5.11: Three single phase transformers with sequential switch i_{abc}

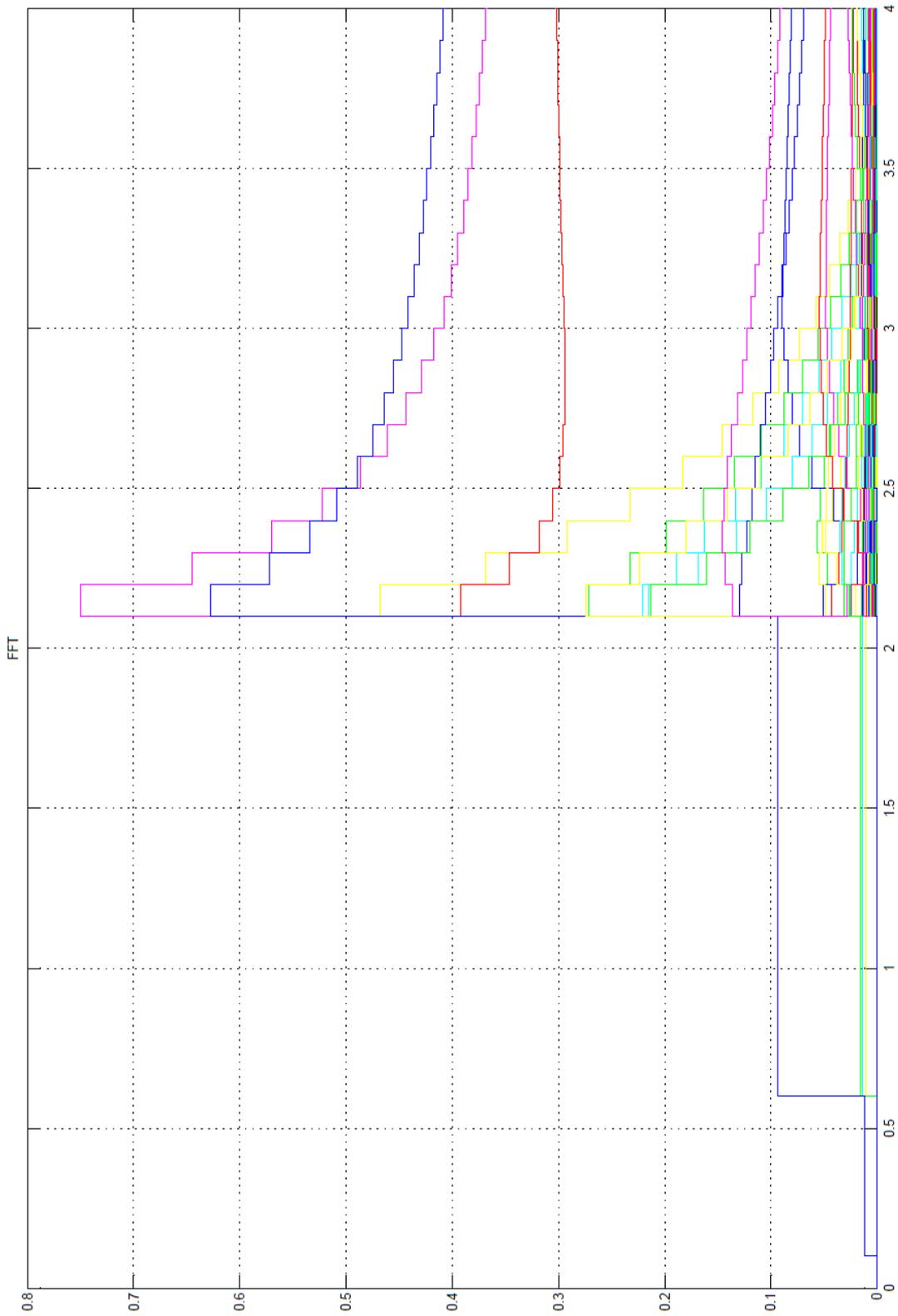


Figure 5.12: Three single phase transformers with sequential switch FFT of *labc*

5.5 Model 5 – Three phase transformer with sequential switch

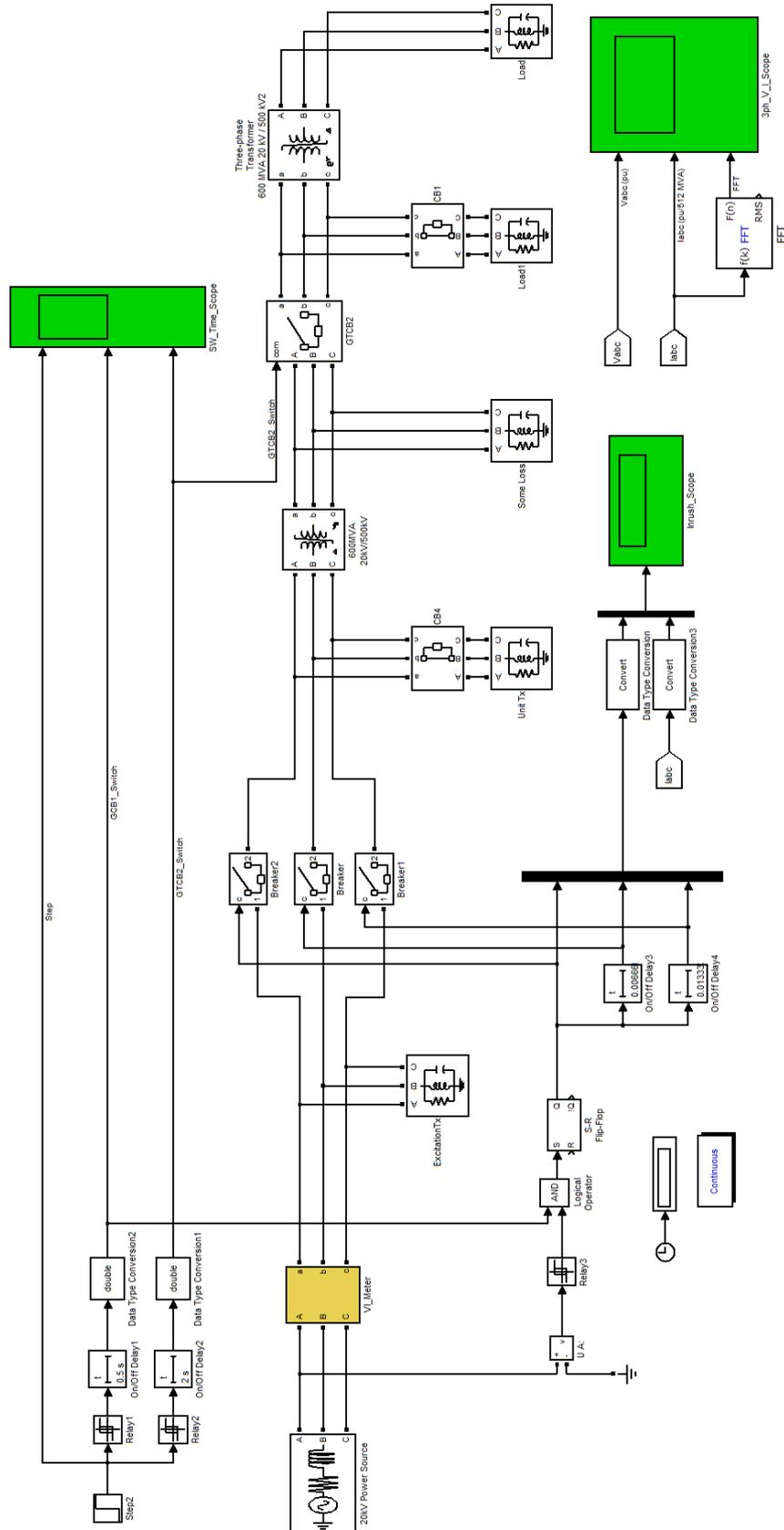


Figure 5.13: Three phase transformer with sequential switch

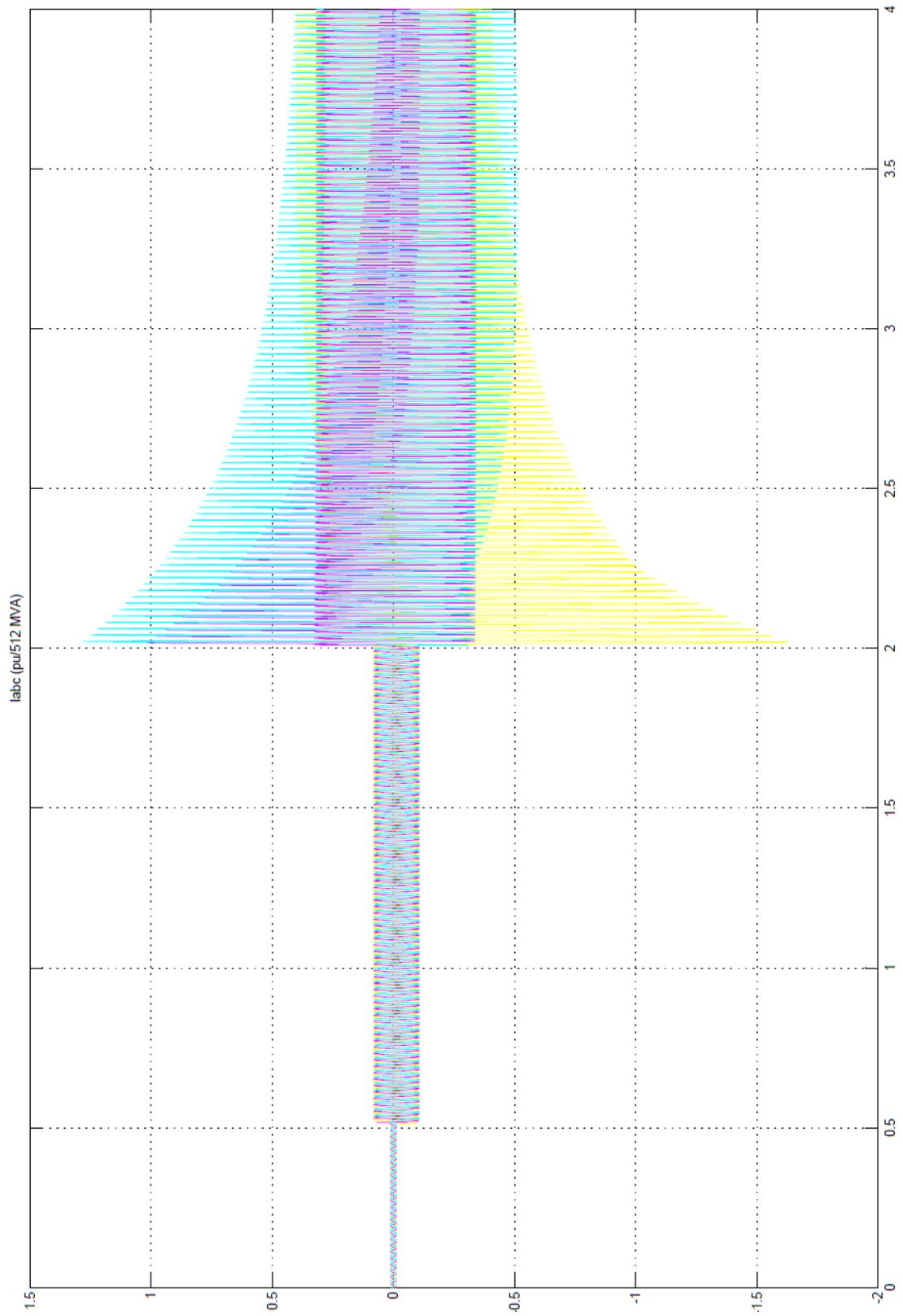


Figure 5.14: Three phase transformer with sequential switch Iabc

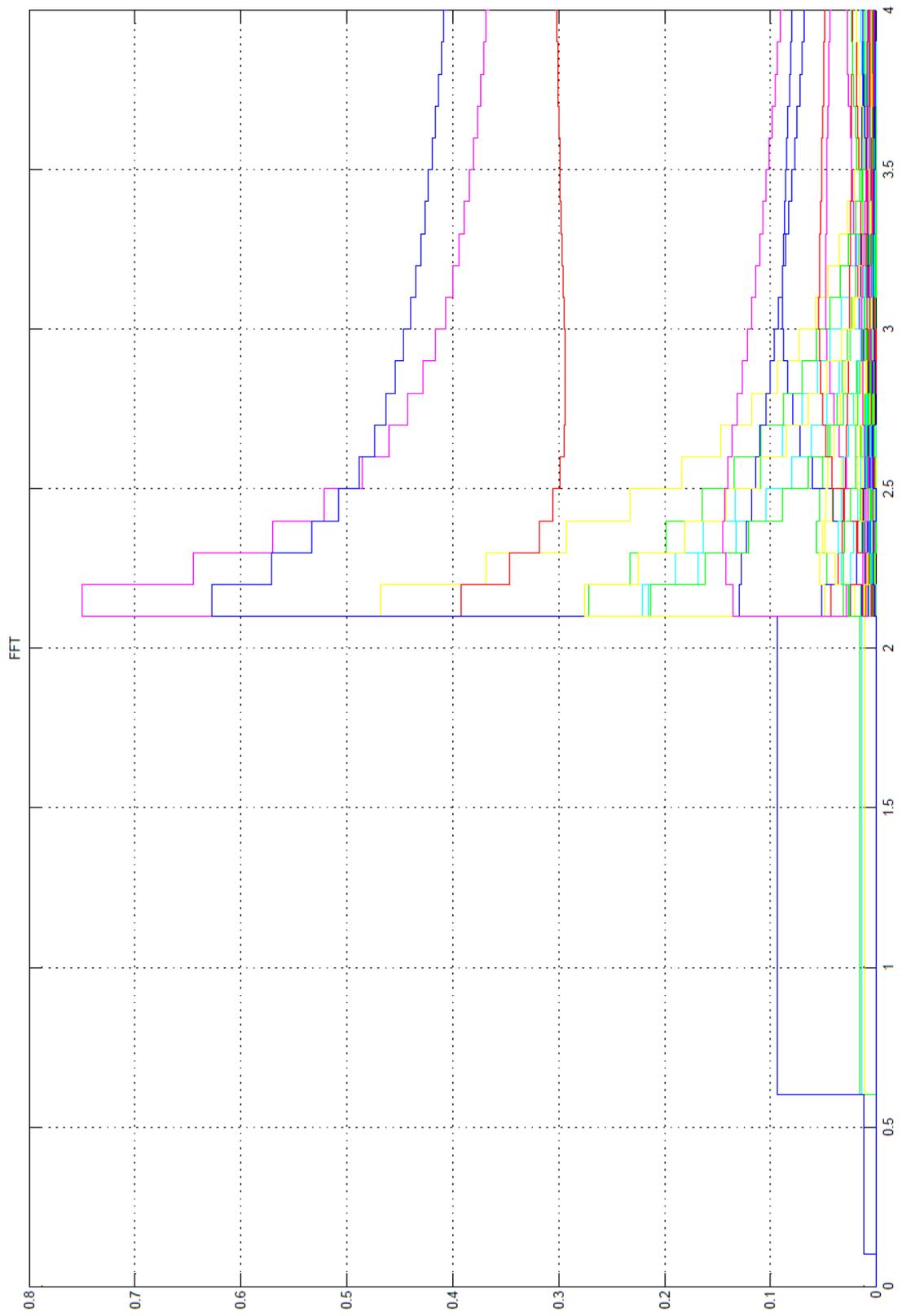


Figure 5.15: Three phase transformer with sequential switch FFT of Iabc

5.6 Model 6 – Three single phase transformers with NER at HV and sequential switch

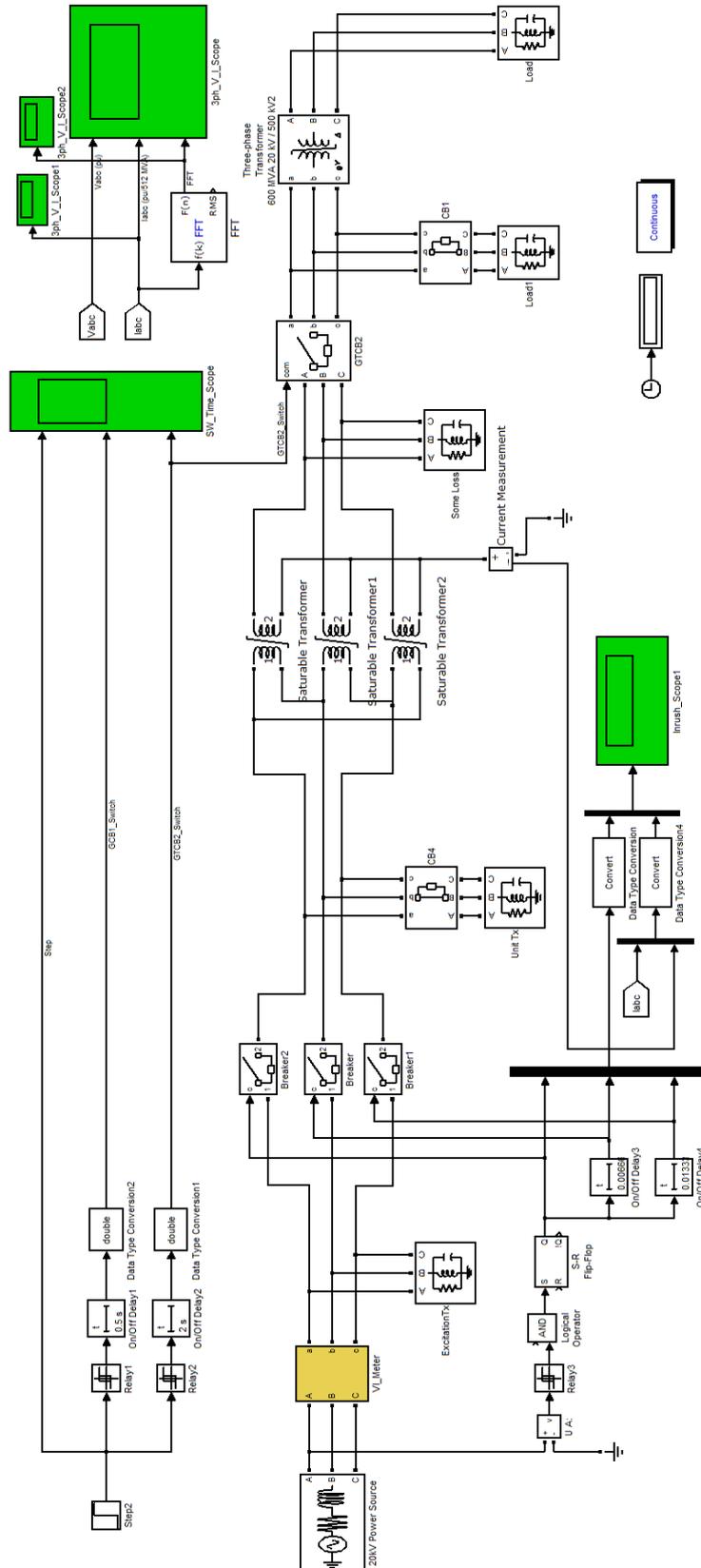


Figure 5.16: Three single phase transformers with NER at HV and sequential switch

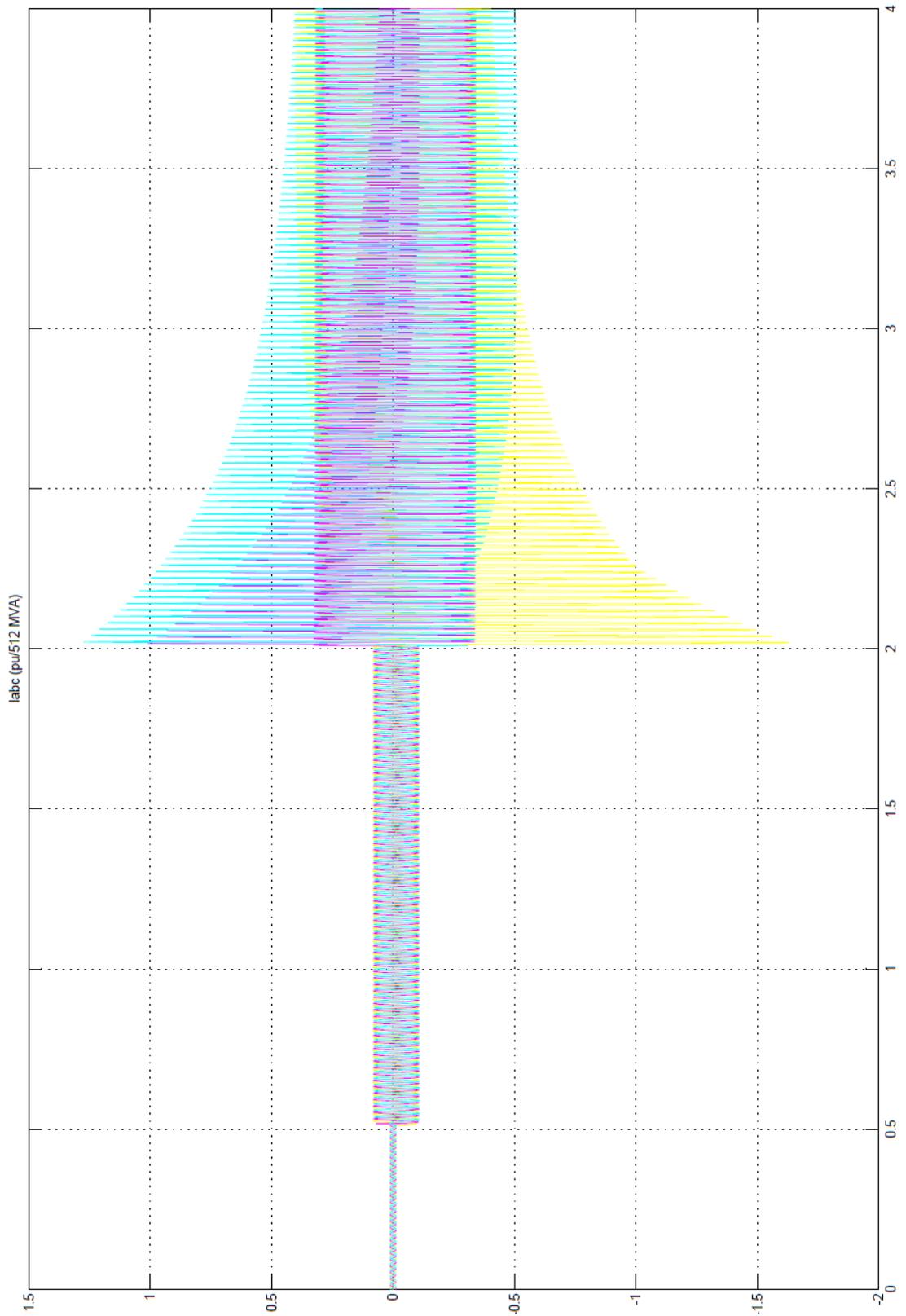


Figure 5.17: Three single phase transformers with NER at HV and sequential switch iabc

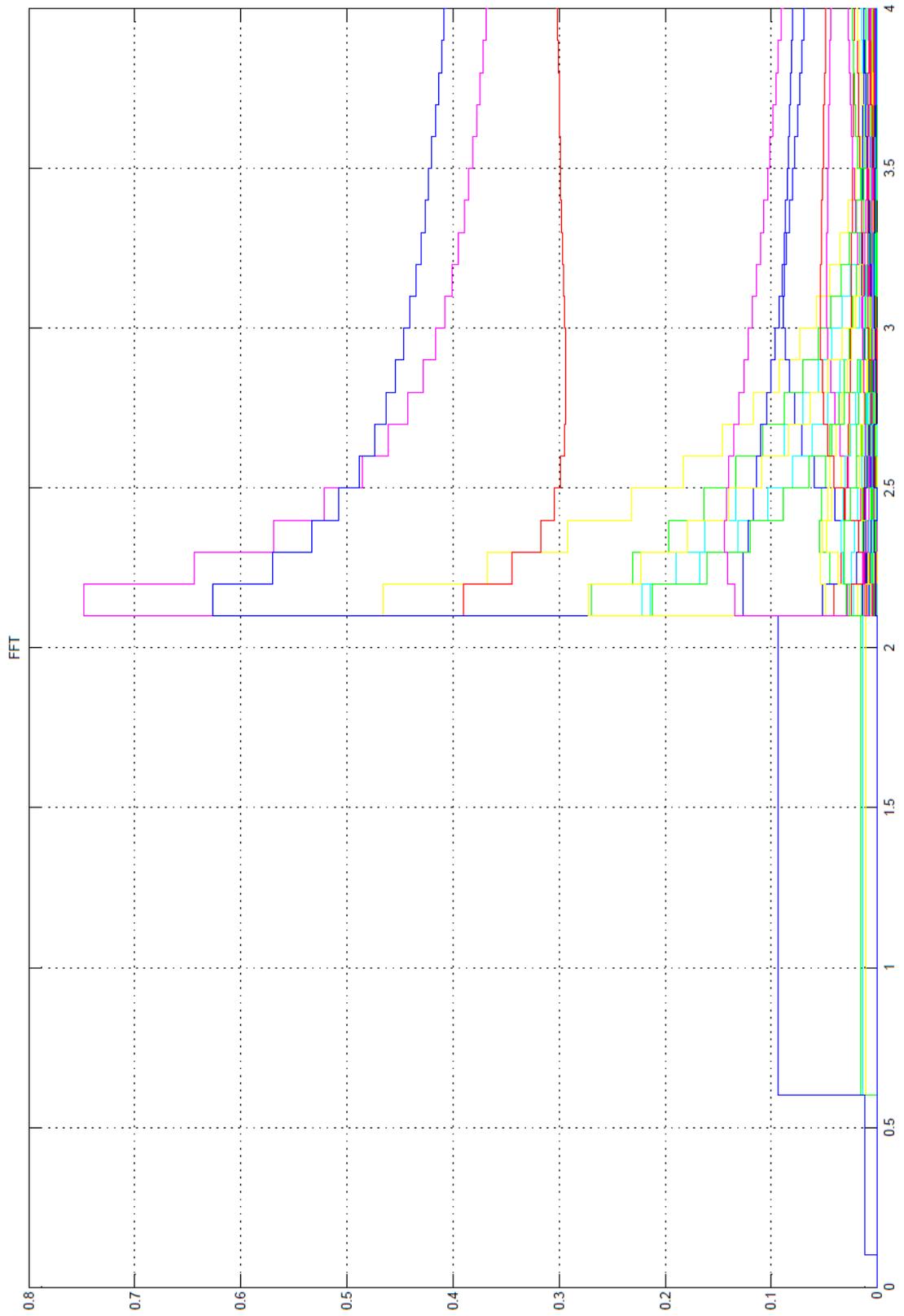


Figure 5.18: Three single phase transformers with NER at HV and sequential switch FFT of Iabc

6. Conclusion

The contribution of transformer inrush current is affected mainly by starting phase angle of switching voltage and residual flux in the core. It also depends on magnitude of voltage, core material's hysteresis characteristic, supply/source impedance and also loading on secondary side of transformer.

The effect of inrush current are high starting current, voltage distortion/harmonics, sympathetic inrush current, vibration of transformer/winding, protection system nuisance operation. Due to all of these effects the life of transformer is reduced.

In three phase circuit where a three phase transformer is used zero inrush current is not practical even if a phase is switched when phase is at its peak. This is not achievable due to fact that each phase is 120° apart hence only one phase's inrush can be made to near zero. The remaining two phases will be 120° out of phase and hence will contribute to inrush current.

The three single phase transformers with separate cores used in three phase circuit can achieve near zero inrush current if switched when voltage is at its peak. This is practical as each core will contain, when transformers are switched off, residual flux proportionate to 120° difference of corresponding phase.

The inrush current in already established transformer or systems can be effectively controlled by sequential switching. This is most convenient when circuit breakers are isolated because 120° pole switching is achievable with small modification and does not require replacing the expensive circuit breaker. The residual flux in this system can be detected by detecting the switching off angle by monitoring the system voltage and current. The starting time of first pole is then decided based on residual flux in core. The second and third poles are switched at 120° and 240° respectively. As the method does not require purchasing expensive new equipment or large modification in system, it is the most economical solution of transformer inrush current mitigation.

FUTURE WORK

Modelling based on the system described in above paragraph (residual flux calculation from de-energisation time) can be considered.

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8. Appendices

8.1 Appendix A Project Specification

8.2 Appendix B Extended Abstract

8.3 Appendix C Project Timeline

8.4 Appendix D Project Presentation

8.1 Appendix A Project Specification

University of Southern Queensland
FACULTY OF HEALTH ENGINEERING & SCIENCES

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR: **KUNAL PATEL**

TOPIC: EFFECTS OF TRANSFORMER INRUSH CURRENT

SUPERVISOR: Dr. Nolan Caliao

ENROLMENT: ENG 4111 – S1, EX, 2013
ENG 4112 – S2, EX, 2013

PROJECT AIM: To build a transformer inrush current model using Sim Power System (MatLab) and simulate the effects.

SPONSORSHIP: Ergon Energy

PROGRAMME: Issue B, 9/05/2013

- 1) Research the background information for the effects of transformer inrush current from,
 - Literature review
 - Data analysis from actual large 3ph HV transformers
- 2) Prepare the list of effects of transformer inrush current and their relations with design, construction and operation
- 3) Construct a model using SimPowerSystems (MatLab)for,
 - three phase transformer model
 - three single phase transformers
 - three single phase transformers with NER (neutral Earthing resistor) at HV
 - three single phase transformers with sequential switching
 - three phase transformer with sequential switching
 - three single phase transformers with NER at HV side and also sequential switching
- 4) Set the relevant parameters and simulate the model
- 5) Analyse and compare the results simulated effects

AGREED:

_____ (STUDENT) _____
(SUPERVISOR)

____/____/_____

____/____/_____

8.2 Appendix B Extended Abstract

Effect of Transformer Inrush Current

Sponsor – Ergon Energy & School of Mechanical and Electrical Engineering, USQ



Kunal Patel

DEE, PDCA, B.Tech (Robotics),
B. Eng (Power System)

Supervisors: Dr Nolan Calio, USQ

Keywords: Transformer Inrush Current.

1. Introduction

The transformers are nearly inbuilt into every electric/electronic device around us. Power transformers are essential components in power systems. The knowledge of their performance is fundamental in determining system reliability and longevity. Potentially disruptive transient condition (due to inrush current) may occur when an unloaded transformer is connected to the power system.

This report contains information about effect of inrush current in power transformers. The analysis is done through system modelling and a practical solution is provided.

2. Background

Inrush current in transformer is often gets less importance compared to other effects/faults. Though the magnitude of inrush current may be less in some cases compared to short circuit current, the frequency and duration of inrush current is generally more frequent, hence it will cause more adverse effect compared to other faults. High magnitude inrush current may flow when transformer is energised.

3. Methodology

A design data of a large step up transformer is used to model it in Sim-Power System of Matlab. A number of models are created and simulated to resemble the actual system. The simulation results are compared with actual results of the transformer. The inrush current effects between three single phase and a three phase transformers are compared. Sequential phase energisation model is created and combined with transformer inrush current model to simulate the desired outcome.

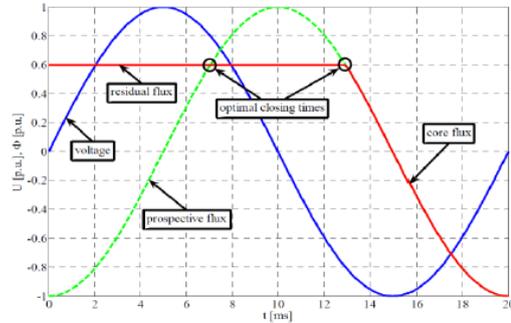


Figure 1 – Optimum switch time for minimum inrush current

4. Key Outcomes

The results show that inrush current is affected/contributed by a number of factors such as switching phase angle and residual flux in core. The key inrush current effects are high starting current with second harmonics, voltage distortion, sympathetic inrush current, vibration, false protection trip and reduction of transformer life.

5. Further Work

For low cost practical implementation of phase energisation technique, further modelling is required to memorise de-energisation time. This time will then be used to re-energise to counter-act residual magnetism.

6. Conclusions

The inrush currents are harmful for life of the power transformer and system stability. They are mainly contributed and controlled by residual flux in transformer and switching instance of voltage cycle.

Acknowledgements

I would like to thank Dr Nolan Calio for supervising this project and his much appreciated continuous guidance. I have also very much appreciated assistance from Dr Chris Snook and Dr Tony Ahfcock.

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8.3 Appendix C Project Timeline

ENG4111 / ENG4112 PROJECT TIMELINE (S1/S2 2013)

Week	Days Left	W1	W2	W3	W4	W5	W6	W7
Month	Date	25	26	27	28	29	30	31
		M	a	r	c	h	A	p
		01	02	03	04	05	06	07
		08	09	10	11	12	13	14
		15	16	17	18	19	20	21
		22	23	24	25	26	27	28
		29	30	31	01	02	03	04
		05	06	07	08	09	10	11
1 IDENTIFY PROJECT								
1.1 Search project topics (USQ & External)								
1.2 Find project supervisor & agreement								
1.3 Fill & submit project proposal form								
1.4 Get approval								
2 SET PROJECT SPECIFICATION								
2.1 Quick search for the background								
2.2 Understand the scope & requirements								
2.3 Prepare a list of the key stakeholders								
2.4 Get pre-agreement on the specification								
2.5 Fill project proposal form								
2.6 Get approval								
3 CREATE PROJECT PLAN								
3.1 Create a list of key/main tasks								
3.2 Create a list of sub-tasks								
3.3 Create grant chart								
4 DO LITERATURE REVIEW								
4.1 Google search								
4.2 Library database search								
4.3 IEEE database search								
4.4 IET database search								
4.5 Books, magazines & journals search								
5 PREPARE REPORT								
5.1 Create report format								
5.1 Title page								
5.1 Abstract								
5.1 Disclaimer								
5.1 Certificate								
5.2 Acknowledgements								
5.2 Table of Contents								
5.2 Risk Assessment								
5.2 Reference List & Citation								
5.2 Appendices								
5.2 Glossary of terms								
5.3 Introduction								
5.4 Literature Review								
5.5 Methodology								
6 Build a base model								
6.1 Create a measurement system								
6.2 Understand matlab's inrush current model								
7 SUBMIT THE REPORT								
8 FEEDBACK & CORRECTION ON S1-2013 PROGRESS AND REPORT								
8 BUILD TRANSFORMER INRUSH MODEL (MATLAB)								
8.1 Inrush current compared to actual transformer								
8.2 Inrush current in 3 single phase and a 3-phase transformer								
8.3 Symphathetic inrush current								
8.4 Sequential phase energisation (with/without NER)								
9 SIMULATE EFFECT								
9.1 Wave switching								
9.2 Optimise the output								
10 RESULT & DISCUSSION								
11 CONCLUSION								
12 REPORT WRITING								

ENG4111 / ENG4112 PROJECT TIMELINE (S1/S2 2013)

Days Left	J u l y							A u g u s t							S e p t e m b e r																											
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Week	V16							V17							V18							V19																				
Month	J u l y							A u g u s t							S e p t e m b e r																											
1	IDENTIFY PROJECT																																									
1.1	Search project topics (USQ & External)																																									
1.2	Find project supervisor & agreement																																									
1.3	Fill & submit project proposal form																																									
1.4	Get approval																																									
2	SET PROJECT SPECIFICATION																																									
2.1	Quick search for the background																																									
2.2	Understand the scope & requirements																																									
2.3	Prepare a list of the key tasks																																									
2.4	Get pre-agreement on the specification																																									
2.5	Fill project proposal form																																									
2.6	Get approval																																									
3	CREATE PROJECT PLAN																																									
3.1	Create a list of key/main tasks																																									
3.2	Create a list of sub-tasks																																									
3.3	Create grant chart																																									
4	DO LITERATURE REVIEW																																									
4.1	Google search																																									
4.2	Library database search																																									
4.3	IEEE database search																																									
4.4	IET database search																																									
4.5	Books, magazines & journals search																																									
5	PREPARE REPORT																																									
5.1	Create report format																																									
5.1	Title page																																									
5.1	Abstract																																									
5.1	Disclaimer																																									
5.1	Certificate																																									
5.2	Acknowledgements																																									
5.2	Table of Contents																																									
5.2	Risk Assessment																																									
5.2	Reference List & Citation																																									
5.2	Appendices																																									
5.2	Glossary of terms																																									
5.3	Introduction																																									
5.4	Literature Review																																									
5.5	Methodology																																									
6	Build a base model																																									
6.1	Create a measurement system																																									
6.2	Understand matlab's inrush current model																																									
7	SUBMIT THE REPORT																																									
8	FEEDBACK & CORRECTION ON S1-2013 PROGRESS AND BUILD TRANSFORMER INRUSH MODEL (MATLAB)																																									
8.1	Inrush current compared to actual transformer																																									
8.2	Inrush current in 3 single phase and a 3-phase transformer																																									
8.3	Symptomatic inrush current																																									
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9.2	Optimize the output																																									
10	RESULT & DISCUSSION																																									
11	CONCLUSION																																									
12	REPORT WRITING																																									

8.4 Appendix C Project Presentation

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EFFECT OF TRANSFORMER INRUSH CURRENT

By - Kunal Patel

Engineering and Built Environment Conference 2013

UNIVERSITY OF SOUTHERN QUEENSLAND



CONTENTS

- Background theory
- Factor affecting transformer inrush current
- Effects of transformer inrush current
- Models overview
- Results & Conclusion
- Future work
- References
- Q&A

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VIDEO



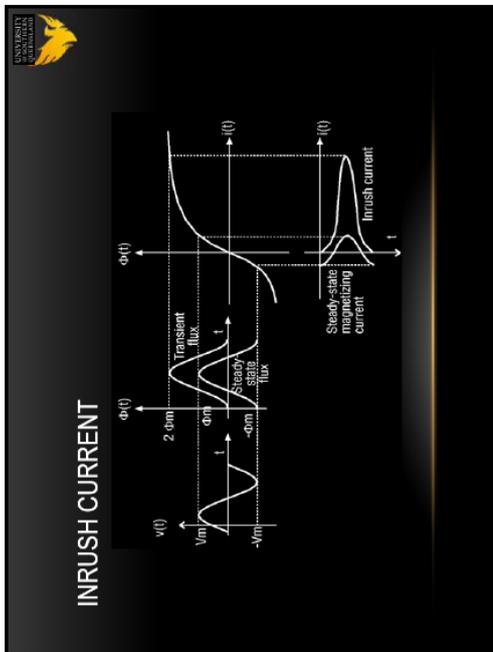
Energizing a 138,000 / 24,900V 28MVA transformer

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BACKGROUND

	Symbol	Unit	Electrical	Symbol	Unit
Magnetic flux	Φ	Wb	Electric current	I	A
Magneto-motive force (mmf)	$F = \int H \cdot dl$	A \cdot m	Electro-Motive force (emf)	$\varepsilon = \int E \cdot dl$	V
Reluctance	R	1/H	Resistance	R	Ω
Hopkinson's law	$P = \Phi \cdot R$	H	Ohm's law	$\varepsilon = I \cdot R$	Ω^{-1}
Permeance	$P = 1/R$	H	Conductance	$G = 1/R$	Ω^{-1}
Permeability	μ	H/m	Conductivity	σ	Ω/m
Magnetic field	H	A/m	Electric Field	E	V/m
Flux density	B	Wb/m ²	Current density	J	A/m ²
Relation between B&H	$B = \mu \cdot H$	H/m	Microscopic Ohm's law	$J = \sigma \cdot E$	A/m ²



INRUSH CURRENT

THEORY

- $v = V_{max} \cos(\omega t + \alpha)$
- $e = -N_1 \frac{d\phi}{dt} = -V_{max} \cos(\omega t + \alpha)$
- $-N_1 \frac{d\phi}{dt} = -V_{max} \cos(\omega t + \alpha)$
- $\frac{d\phi}{dt} = -\frac{V_{max}}{N_1} \cos(\omega t + \alpha)$
- $d\phi = -\frac{V_{max}}{N_1} \cos(\omega t + \alpha) dt$

THEORY

- $\phi = \frac{V_{max}}{N_1} \int \cos(\omega t + \alpha) dt$
- $\phi = \frac{V_{max}}{N_1} \sin(\omega t + \alpha) + C$
- $\phi = \phi_{max} \sin(\omega t + \alpha) + C$
- $C = \phi_{residual} + \phi_{max} \sin \alpha$
- $\phi = \phi_{max} \sin(\omega t + \alpha) + \phi_{residual} + \phi_{max} \sin \alpha$

THEORY

- $\alpha = \text{phase angle of flux.}$
- $\theta = \text{phase angle of voltage} = \alpha + \pi/2$
- $\alpha = 0 \text{ or } \theta = \pi/2$
- $\phi = \phi_{max} \sin(\omega t + 0) + \phi_{residual} + \phi_{max} \sin 0$
- $\phi = \phi_{max} \sin(\omega t) + \phi_{residual}$
- $\phi = \phi_{max} + \phi_{residual}$



THEORY

- $\theta = \text{phase angle of voltage} = \alpha + \pi/2$
- $\alpha = -\pi/2$ or $\theta = 0$
- $\phi = \phi_{\text{max}} \sin(\omega t + \alpha) + \phi_{\text{residual}} + \phi_{\text{max}} \sin \alpha$
- $\phi = -\phi_{\text{max}} \cos(\omega t) + \phi_{\text{residual}} + \phi_{\text{max}}$
- $\phi = 2\phi_{\text{max}} + \phi_{\text{residual}}$



TYPES OF INRUSH CURRENTS

- Energization inrush
- Recovery inrush
- Sympathetic inrush



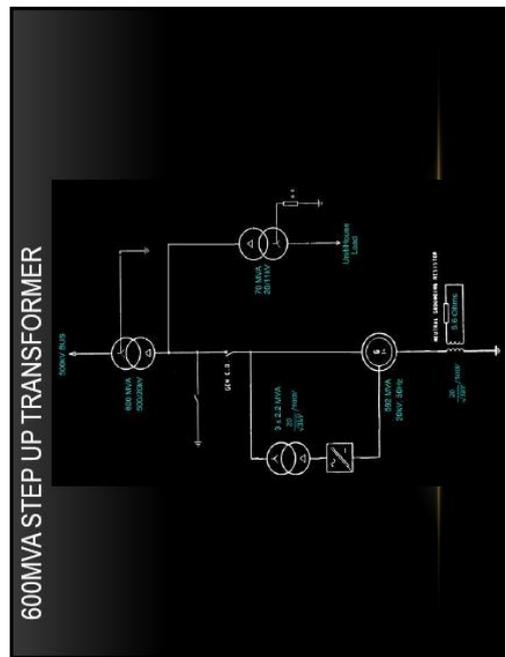
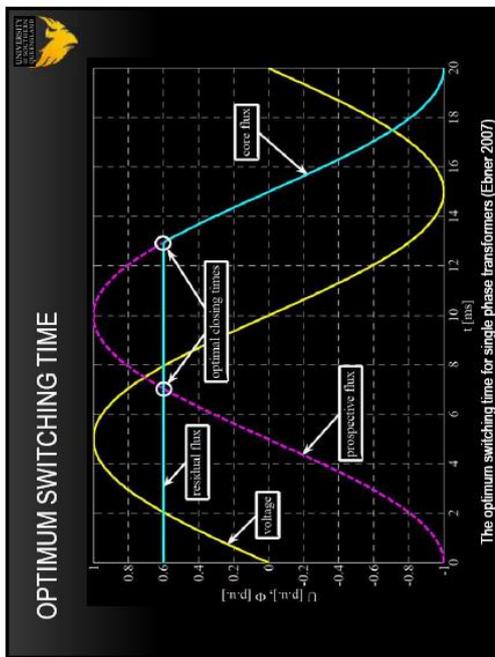
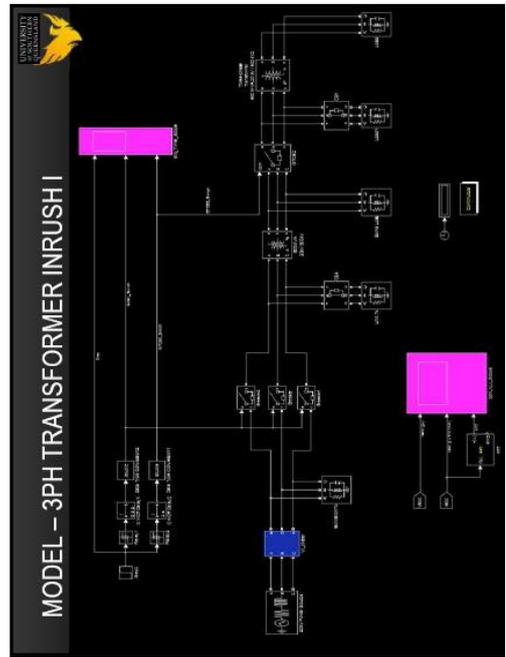
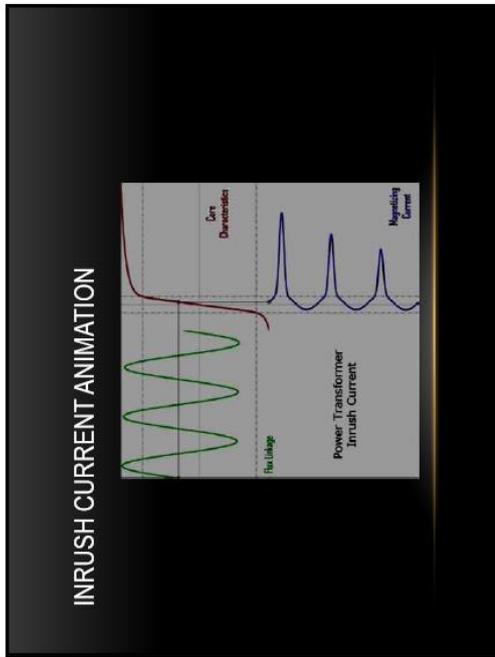
FACTOR AFFECTING INRUSH CURRENT

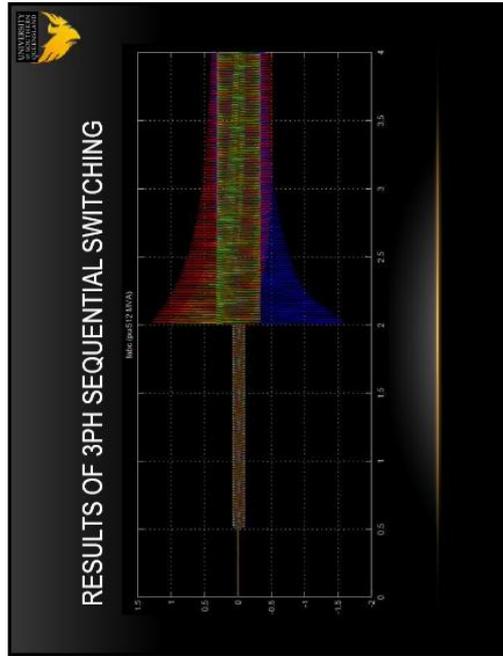
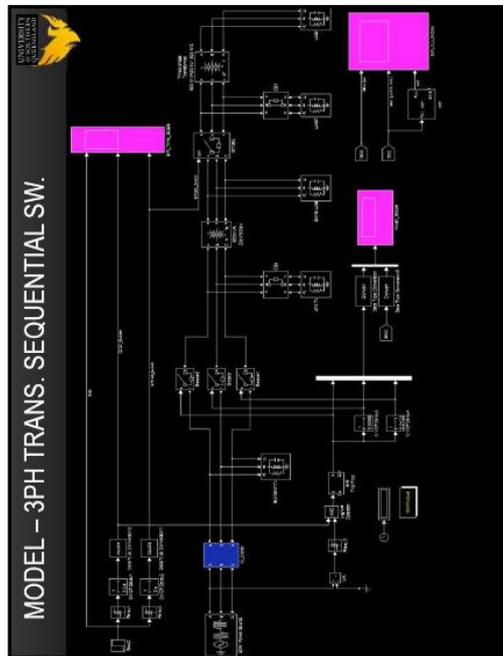
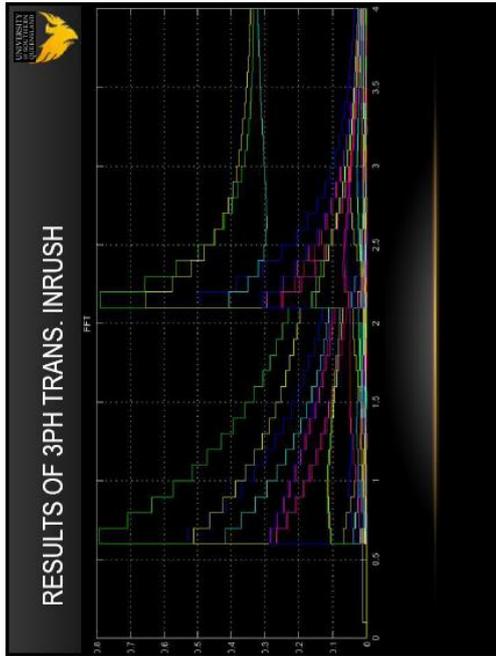
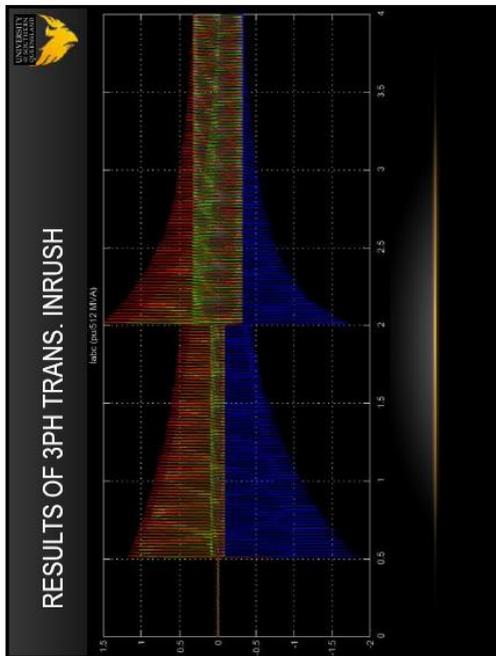
- Starting/switching phase angle of Voltage
- Residual flux in core
- Magnitude of Voltage
- Saturation flux
- Core material
- Supply/Source impedance
- Loading on secondary winding
- Size of transformer

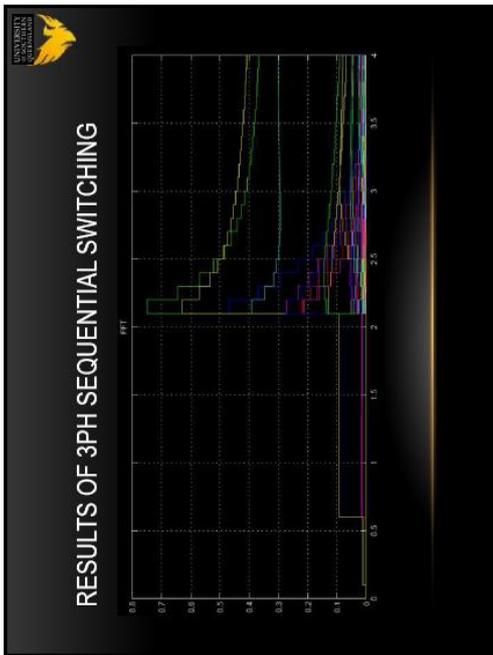


EFFECTS OF INRUSH CURRENT

- High starting current
- Voltage distortion (harmonics)
- Sympatric inrush
- Vibration/geometric movement of winding
- Life of transformer
- Protection complexity - Actual fault vs Inrush current



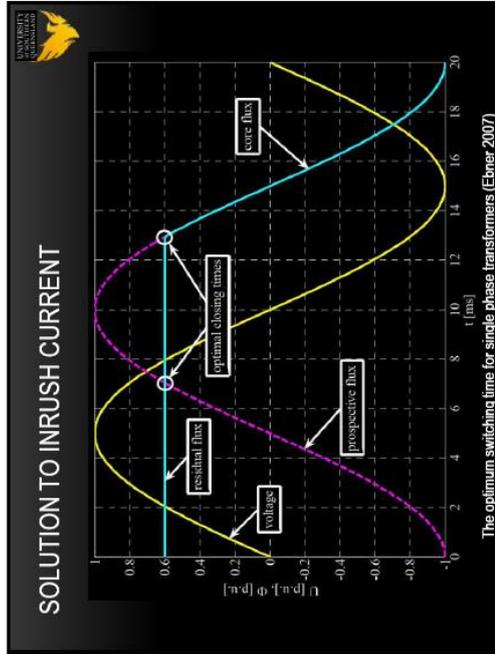




RESULTS OF 3PH SEQUENTIAL SWITCHING

- ### CONCLUSION
- High starting current
 - Voltage distortion (harmonics)
 - Sympatric inrush
 - Vibration/geometric movement of winding
 - Life of transformer
 - Protection complexity - Actual fault v/s Inrush current
 - However, there is a potential and cost effective solution to this problem

- ### FUTURE WORK & CHALLENGES
- Time switching
 - Based on constant switch time
 - Based on calculating residual magnetism
 - Complications in 3 phase isolated CB timing
 - Complication in constant switching time



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