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Modeling and Control of the Saturation's Transformer

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Abstract

This paper investigates the saturable transformer from modeling and control point of view. After implementing the Simulink model of the three phase transformer simulation of a three phase, two-winding transformer is used to examine the transformer under two operating conditions.

The first is the secondary terminal short circuited and the second is the secondary terminals connected to a non-unity power factor load to verify the results obtained with those predicted from any analysis using the equivalent circuit. The graphical user interface is used for modeling transformer parameters, obtaining the results, check the stability of the control system, the settling time, the Bode plot, Nyquist and Nicols chart finally recording all currents, voltages and phase shift between them in the steady state condition, initial values of states variables for the nonlinear circuit parameters.

Keywords: Transformer, Mutual inductance, Magnetic coupling, Magnetic field, Saturation, Modeling, Control and Simulink.

النمذجة والسيطرة لمحولة في حالة الإشباع

الخلاصة

تفحص هذه الدراسة عمل محولة في حالة تشبع من ناحية النمذجة والسيطرة والتحليل وكذلك كيفية السيطرة على مواصفات هذه ألمحوله واهم عناصر السيطرة في الدائرة حيث انه بعد التمثيل الرياضي للمعادلات التي تمثل ألمحوله ذات الثلاث أطوار بملفين يتم البناء الكتلي باستخدام برنامج السميولنك الذي يستخدم لفحص نقاط عمل ألمحوله تحت شروط معينة هي أولا عندما يكون الطرف الثانوي للمحولة في حالة قصر وثانيا عندما يكون الملف الثانوي مربوط إلى حمل يكون فيه عامل ألنوعيه ذو قيمة لا تساوي واحد واستخلاص النتائج التي تمثل نظام السيطرة المغلق للمحولة واستخراج الأشكال التي توضح حالة المحولة من ناحية ألإستقرارية في العمل ووقت الاستقرار وملائمة المتغيرات على الأداء وكذلك الدائرة المكافئة من ناحية التيار والفولتية والفيض المغناطيسي بالإضافة الى ذلك استخدام مميزات الماتلاب الكبيرة لعرض الأشكال لغرض معرفة عمل عناصر السيطرة وخاصة بالنسبة للمفاتيح او القاطع والتحليل لكل متغيرات الدائرة وفي النهاية تسجيل كافة التيارات والفولتيات وفرق الطور بينهما في حالة الاستقرار والحالات الابتدائية لكل المتغيرات غير الخطية في الدائرة.

الكلمات الدالة:المحولة، الحث المتبادل،الترابط المغناطيسي، الفيض المغناطيسي، الإشباع، النمذجة، التحليل والعرض للمحولة. عناصر السيطرة و السميولنك.

List of Abbreviations

E1	Induced voltage in winding 1.
E2	Induced voltage in winding 2.
I1	Induced current in winding 1.
I2	Induced current in winding 2.
L11	The self inductance of winding 1.
L12	The mutual inductance of w_1 to w_2.
L21	The mutual inductance of w_2 to w_1.

L22	The self inductance of winding 2.
N1	No. of turns of winding 1.
N2	No. of turns of winding 2
Pm	The mutual path of permeance
λ1	Turn times the total flux linked in winding 1
λ2	Turn times the total flux linked in winding 2
Φ1	Total flux linked by each winding for turn
Φ11	The leakage flux component of winding 1
12	The leakage flux component of winding 1 to winding 2
Φm	The mutual flux to both winding

Introduction

Fundamental to any control system is the ability to measure the output of the system, and take the corrective action if its value deviates from some desired value. Different transformer models have been developed for steady state and transient analysis of power systems. Some of these models have nonlinear components to take into account the magnetic core saturation characteristics so that harmonic generation can be simulated[1]. Juan A. Martinez et al.[2] presented a summary of the most important issues related to transformer modeling for simulation of low and mid-frequency transients. Stanley E. Zocholl et al. [3] presented a power transformer model to evaluate differential element performance and they also analyzed transformer energization, over excitation, external fault, and internal fault. A.K.S. Chaudhary et al. [4] listed some of the uses, advantages, disadvantages, and limitations of modeling of protection systems. This report includes some models of instrument transformers and the possible need to model instrument transformers. There are different approaches for transformer modeling and solutions: the matrix models use an impedance or admittance formulation relating terminal voltages and currents; the equivalent circuitry models often use simplified Tee circuit whose elements values are derived from test data; the duality based models account for core topology and the connection between electric and magnetic circuits. Although the latter two model types can also be presented in matrix format, they are easier to understand from a circuit point of view. In electronic circuitry, new methods of circuit design have replaced some of the applications of transformers, but electronic technology has also developed new transformer designs and applications in it's simplest form. It consist of two inductive coils which are electrically separated but magnetically linked through a path of low reluctance[5]. D.V. Otto et al.[6] presented the problem of transformer saturation in the DC-isolated Cuk converter and a novel open-loop damping technique is developed to control transformer saturation. Jiuping Pan et al.[7] proved that the current transformer (CT) saturation leads to inaccurate current measurement and, therefore, may cause malfunction of protective relays and control devices that use currents as input signals. They introduced an efficient compensation algorithm capable of converting from a sampled current waveform that is distorted by CT saturation to a compensated or control current wave form. F. Islam et al. [8] used Artificial Neural Network (ANN) of parallel transformers for controlling secondary voltage in power system in a complex problem.

The two coils possess high mutual inductance. If one coil is connected to a source of alternating voltage, an alternating flux is setup in the laminated core, most of which is linked with the other coil in which it produces mutually, induced e.m.f, (according to *Faraday's Laws* of Electromagnetic $e = MdI/dt$)**[9]**. If the second coil circuit is closed, a current flows in it and so electric energy is transferred (entirely magnetically) from the first coil to the second coil. The first coil, in which electric energy is fed from the ac supply means is called primary winding and the other from which energy is drawn out is called secondary winding**[10,11]**. The main uses of electrical transformers are for changing the magnitude of ac voltage, providing electrical isolation and matching the load impedance to the source they are formed by two or more sets of stationary windings which are magnetically coupled, often but not necessarily with a high permeability core to maximize the coupling by convention. Transformers come in a range of sizes from a thumbnail-sized coupling transformer hidden inside a stage microphone to giga watt units used to interconnect large portions of national power grids, all operating with the same basic principles and with many similarities in their parts**[12,13,14]**.

Model of Two Winding Transformer

Flux Linkage Equations

When leakage fluxes are included, as illustrated in Fig. (1), the total flux linked by each winding may be divided into two components, Φm, that is common to both windings, and a leakage flux component that links only the winding itself. In term of these flux components the total flux linked by each of the windings can be expressed as:

$$\Phi_1 = \Phi_{11} + \Phi_m \quad \text{……………………(1)}$$

$$\Phi_2 = \Phi_{12} + \Phi_m \quad \text{……………………..(2)}$$

As in an ideal transformer, the mutual flux , Φm is established by the resultant mmf of the two windings acting around the same path of the core. Assuming that N_1 turns of winding 1 effectively link both Φm and the leakage flux ,Φ_{11}, the flux linkage of winding 1, defined as the turn times the total flux linked, is:

$$\lambda_1 = N_1\Phi_1 = N_1(\Phi_{11} + \Phi_m) \quad \text{……….(3)}$$

The right side of Eq. (3) can be expressed in terms of the winding currents by replacing the leakage and mutual fluxes by their respective mmfs and permeances. The leakage flux, Φ_{11} is created by the mmf of winding 1, $N_1 i_1$, over an effective path permeance of P_{11}, say . And the mutual flux, Φm, is created by the combined mmf, $N_1 i_1 + N_2 i_2$.

The resulting flux linkage equation for the two magnetically coupled winding , expressed in terms of the winding inductances , are:

$$\lambda_1 = L_{11} i_1 + L_{12} i_2 \quad \text{…………..…………(4)}$$

$$\lambda_2 = L_{21} i_1 + L_{22} i_2 \quad \text{…………………..…..(5)}$$

The induced voltage in each winding is equal to the time rate of change of the winding's flux linkage, expression given in Eq. 4, the induced voltage in winding 1 is given by:

$$e_1 = \frac{d\lambda_1}{dt} = L_{11}\frac{di_1}{dt} + L_{12}\frac{di_2}{dt} \quad \text{………. .(6)}$$

The voltage induced in winding 1 can also be expressed as:

$$e_1 = L_{11}\frac{di_1}{dt} + L_{m1}\frac{d\left(i_1 + (N_2/N_1)i_2\right)}{dt} \quad \text{…..(7)}$$

Whether it is just for convenience of computation or out of necessity, as when the parameters are only measurable from one winding, often quantities of the other winding are referred to the side which has information available directly.

This process of referring is equivalent to sealing the number of turns of one winding to be the same as that of the winding whose variables are to be retained explicitly. For instance, the current $N_2 i_2 / N_1$ is the equivalent value of winding second current that has been referred to a winding of N_1 turns, chosen to be the same as that of winding 1. Denoting the referred value of $i_2 (N_2 / N_1)$ by i_2 , Eq. 7 become:

$$e_1 = L_{11}\frac{di_1}{dt} + L_{m1}\frac{d}{dt}\left(i_1 + i_2\right) \ldots\ldots\ldots.(8)$$

Similarly, the induced voltage of winding 2 may be written as

$$e_2 = L_{22}\frac{di_2}{dt} + L_{m2}\frac{d}{dt}\left(\frac{N_1}{N_2} i_1 + i_2\right) \ldots.(9)$$

The voltage e_2 can also be referred to winding 1, or scaled to a fictitious winding of N_1 turns , using the relation given in Eq.8, Eq. 9 can be rewritten into the form:

$$e_2' = L_{12}'\frac{di_2'}{dt} + L_{m1}\frac{d}{dt}\left(i_1 + i_2'\right) \ldots\ldots.. (10)$$

The terminal voltage of a winding is the sum of the induced voltage and the resistive drop in the winding. The terminal voltage for winding 1 is given by:

$$\upsilon_1 = i_1 r_1 + e_1 = i_1 r_1 + L_{11}\frac{di_1}{dt} + L_{m1}\frac{d}{dt}\left(i_1 + i_2'\right) \ldots\ldots\ldots..(11)$$

Instead of writing a similar equation for the terminal voltage of winding 2, it will written it in terms of quantities referred to winding 1 first side[15-18].

Equivalent Circuit Representation

The form of the voltage Eq. 11 with the common Lm_1 term suggests the equivalent T-circuit shown in Fig. (3) for the two-winding transformer. In Fig.(3), the prime denotes referred quantities of winding 2 to winding 1. For example, i_1 will by the equivalent current flowing in the winding having the same number of turns as winding 1, Equivalent in the sense that it will produce the same mmf, $N_2 i_2$, in the common magnetic circuit shared with winding 1, that is $N_1 i_1$ = $N_2 i_2$. This is apparent from the ideal transformer part of the equivalent circuit. Similarly, the referred voltage, V_2 satisfies the ideal transformer relationship, V_2'/V_2 = N_1 / N_2 in the practical transformer, unlike that in an ideal transformer, the core permeance or the mutual inductance is finite. To establish the mutual flux, a finite magnetizing current $i_1 - i_2$, flows in the equivalent magnetizing inductance on the winding 1 side Lm_1.

The value of circuit parameters of winding 2 referred to winding

$$r_2' = \left(\frac{N_1}{N_2}\right)^2 r_2 \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

$$L_{12}' = \left(\frac{N_1}{N_2}\right)^2 L_{12} \ldots\ldots\ldots\ldots\ldots(13)$$

If it is required to include core losses by approximating them as losses proportional to the square of the flux density in the core, or the square of the internal voltage e_m shown in Fig. 3, an appropriate core loss resistance could be connected across e_m, in parallel with the magnetizing inductance, L_{m1}. The resultant equivalent circuit would be the same as that derived from steady-state considerations in the standard electric machine. An arrangement will be described by which the voltage and flux linkage equations of two winding transformer can be implemented in a computer simulation. There is, of course, more than one way to implement a simulation of the transformer even the same mathematical model is used. For example , when using the simple model described in the earlier section, we could implement a simulation using fluxes or currents as state variables. Note that the equivalent circuit representation of Fig. 3 has a cut set of three inductors. Since their currents obey Kirchhooff´s current law at the common node, all three inductor currents cannot be independent. The magnetizing branch current may be expressed in terms of the winding currents, i_1 and i_2, as shown. In our case, we will pick the total flux linkages of the two windings as the state variables. In terms of these two state variables, the voltage equations can be written as:

$$\upsilon_1 = i_1 r_1 + \frac{1}{\omega_b}\frac{d\Psi_1}{dt} \qquad \text{……………… (14)}$$

$$\upsilon_2 = i_2 r_2 + \frac{1}{\omega_b}\frac{d\Psi_2}{dt} \qquad \text{……………....(15)}$$

Where $\Psi_1 = \omega_b \lambda_1$, $\Psi_2 = \omega_b \lambda_2$, and ω_b is the base frequency at which the reactances are computed[16,17,18].

Incorporating Core Saturation into Simulation

Core saturation mainly affects the value of the mutual inductance and to a much lesser extent, the leakage inductance. Though small, the effects of saturation on the leakage reactances are rather complex and would require construction details of the transformer that are not generally available. In many dynamic simulations, the effect of core saturation may be assumed to be confined to the mutual flux, path. Core saturation behavior can be determined from just the open circuit magnetization curve of the transformer. With core losses ignored, the no load current is just the magnetizing current Further more, with only no load current flowing into winding 1, the voltage drop across the series impedance, $r_1 + j\omega L_{11}$, is usually negligible compared to that across the large magnetizing reactance, p $\chi_{m1} = \omega L_{m1}$. Since the secondary is open-circuited, i_2' will be zero, thus $V_{1rms} \approx I_{mrms}\chi_{m1}$ in the unsaturated region, the ratio of V_{1rms} / I_{mrms} is constant, but as the voltage level rises above the knee of the open circuit curve, that ratio becomes smaller and smaller. Updated in the simulation using the product of the unsaturated value of the magnetizing inductance, $\chi_{m1}{}^{unsat}$, the small voltage drop across the $r_1 + j\chi_{11}$ can be neglected, thus $V_{1rms} \approx E_{mrms}$. When the excitation flux is sinusoidal the value of $\Delta\Psi$ will be positive in the first quadrant. The relation between $\Delta\Psi_m$ and $\Psi_m{}^{unsat}$ or $\Psi_m{}^{sat}$ can be obtained from the open circuit magnetization curve of the transformer.

Instantaneous Value Saturation Curve

The open circuit magnetization curve of the transformer can be obtained from the results of an open circuit test. With $I_2' = 0$, the applied sinusoidal voltage, V_1, to winding $1's$ terminals is gradually raised from zero to slightly above it's rated value Usually, the measured rms value of winding $2's$ output voltage and the measured rms value of winding $1's$ excitation current , that is V_2' vs , I_1, are plotted since all variables in our simulation model are referred to primary winding 1 and are of instantaneous rather than rms value. The correction for saturation, $\Delta\Psi$ should be expressed in term of the instantaneous variables referred to the primary winding. The measured open circuit secondary rms voltage can easily be referred to the primary side using the turn ratio, that is :

$$V^{oc}{}_{rms1} = \frac{N_1}{N_2} V^{oc}{}_{rms2} \ldots\ldots\ldots\ldots\ldots\ldots(16)$$

The relation between the peak value of the primary winding flux linkage and the peak value of its magnetizing current can be obtained by the following the procedure. Beginning with the open circuit curve with rms values referred to the side of the winding that will we use in the simulation and distinguishing the rms values by upper case letters and the instantaneous values by lower case letters, mark on the rms open circuit curve.

Simulation of Two Winding Transformer

The simulation of two winding transformer can be set up using the voltage input, current output model described earlier in this work. Core saturation can be handled using either a piece wise linear analytic approximation of the saturation curve, look up table between Ψ_m^{sat} and $\Delta\Psi$. For example check the decay times of the dc offset in the input current or flux against the values of the time constant for the corresponding terminal condition on the secondary side, with saturation and without saturation. Compare the magnitude of the currents obtained from the simulation when it reaches steady state with those computed from steady state calculations. Energization of one phase of a three-phase 450 MVA, 500/230 kV transformer on a 3000MVA source. The transformer parameters are as in Fig. (5).

In order to comply with the industry practice, you must specify the resistance and inductance of the windings in per unit (p.u.). the values are based on the transformer rated power Pn in VA, nominal frequency fn in Hz, and nominal voltage Vn, in Vrms, of the corresponding winding. For each winding, the per unit resistance and inductance are defined as:

$$R(p.u) = \frac{R(\Omega)}{R_{base}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(17)$$

$$L(p.u)\frac{L(H)}{L_{base}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(18)$$

The base resistance and base inductance used for each winding are:

$$R_{base} = \frac{(v_n)^2}{p_n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(19)$$

$$L_{base} = \frac{R_{base}}{2\pi f_n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(20)$$

For the magnetization resistance Rm, the p.u. values are based on the transformer rated power and on nominal voltage of the winding 1. The saturation characteristic of the saturable transformer block is defined by a piece-wise linear relationship between the flux and the magnetization current as shown in Fig. 2 and the simulation result as shown in Fig. 8. Therefore, if you want to specify a residual flux phi0, the second point of the saturation characteristic should correspond to a zero current as shown on Fig. 2(b). The saturation characteristic is entered as (i, phi) pair values in per unit, starting with pair (0,0). The Power System Block set converts the vector of fluxes Φpu and the vector of currents Ipu into standard units to be used in saturation model of the saturable transformer block [16,17,18, 19,20,21] as shown in Fig. 4 and the complete results are portrayed in Figs[7, 8 and 9].

Concept of the Control System

In control engineering, the way in which the system outputs respond in changes to the system inputs(system response) is very important. The control system design engineer will attempt to evaluate the system response by determining the mathematical model of the system transformer as shown in the above Equations[22].

On-Off Control

One of the most adapted and simplest controllers is undoubtedly the on-off controller, where the control variable can assume just two values, $u_{\max}$ and $u_{\min}$ depending on control error signal. Formally the control law is defined as follows :

$$U=\begin{Bmatrix} u_{\max} & if \quad e\geq 0 \\ u_{\min} & if \quad e\leq 0 \end{Bmatrix} \text{.........................}(21)$$

The control variable is set to its maximum value when the control error is positive and minimum when it is negative. Generally $,u_{\min}=0$ (off) and $u_{\max}=1(on)$. The main advantage of the on off controller is that a persistent oscillation of the process variable (around the set point) occured[23]. Implementing a circuit breaker are very important to control the circuit with non zero internal resistance. The operation of the breaker deals with two mode according to the state of the integrator which is another part of the control circuit of the transformer operation especially against the saturation windup through the controlling the saturation upper limit and the saturation lower limit. Internal initial condition source and external initial condition source. Internal mode with (0.6 p.u) initial condition are used in this work as shown in Fig. 8. The initial value of the flux depends upon the initial condition of the integrator. The overloading protected against is a consequence of the differential between the volt-seconds supplied to the transformer core from one direction as opposed to the other direction, which differential, in turn, causes the flux level to integrate up the B-H loop resulting initially in unbalanced primary winding currents and ultimately in a premature saturation of the transformer core in one direction[24]. A simulink logical signal is used to control breaker operation when the signal becomes zero the breaker opens and gradually closed with the increasing of the signal [25]. The switching circuit generates a control signal to control the switch and regulate the output of the power converter in response to the first signal. Because the pulse width of the flyback voltage is short at light load, the detection circuit is designed to produce a bias signal to help the flyback voltage detection[26]. The control circuit controls the peak value of the pulse current generated in the secondary coil of the high voltage controlling transformer by controlling the primary coil current of the high voltage controlling transformer according to the change of the high voltage output. Then, the control circuit attains the stabilization of the high voltage output by superimposing this pulse having the controlled peak value on the pulse in the primary coil of the flyback transformer so that the high voltage output level is kept constant[27]. Gain are another parameter of controlling the operation of the transformer(1/[230e3/sqrt(3)*sqrt(2)/2/pi/50] was the gain applied to the circuit with sample time of (-1) according to the formula

$$y=k.*u\text{..}(22)$$

Where k are the gain& u are the input.

Conditional Integrator Control and Avoiding the Saturation

The most intuitive way of avoiding the integrator windup is to avoid the saturation of the control variable. This can be done by limiting or smoothing the set-point changes and/or by detuning the controller (by selecting a more sluggish controller). A classical effective methodology is the so-called conditional integration. It consists of switching off the integration (in other words, the error to be integrated is set to zero) when certain condition is verified. For this reason, this method is also called integrator clamping. The following options can be implemented:

- The integral term is limited to a predefined value.
- The integration is stopped when the error is greater than a predefined threshold, namely, when the process variable value is far from the set point value.
- The integration is stopped when the control variable saturates, when (u = u').
- The integration is stopped when the control variable saturates and the control error and the control variable have the same sign (when u*e > 0)[1,28,29].

Stability Checking

In this section we presented different kinds of graphs that were used to represent the frequency response of a system: Nyquist, Bode, and Nichols plots. The critical point for closed loop stability was shown to be the (-1,0) point on the Nyquist plot . The (-1,0) point has a phase angle of (-180) and a magnitude of unity or a log modulus of 0 decibels. The stability limit on Bode and Nichols plots is therefore the (0 dB, - 180) point. At the limit of closed loop stability

L (magnitude) = 0 dB and ϴ = - 180

The system is closed loop stable if:

L < 0 dB ,ϴ(phase) at = - 180

ϴ > -180 at L = 0 dB

Fig. (9) illustrates all the control Figures (step response (normalized)) impulse response (normalized), Bode plot, zero/pole configuration, Nyquist and Nichols plot). Keep in mind that we are talking about closed loop stability and that we are studying it by making frequency response plots of the total open loop system transfer function. These log modulus and phase angle plots are for the open loop system.

Results and Discussion

Simulink/Matlab isused to simulate the operation of three phase transformer. The main difficulty in modeling transformers is the variety of transformer connections and the resultant phase shift effects. The phase shift effects must be simulated because they are an important means of harmonic mitigation. Experience shows that the best approach is to model transformers as coupled windings that have no predetermined connection forms[31]. As in Fig. (2), over voltage drives the peak operation point of the transformer excitation characteristics up to saturation region so that more harmonics are generated also, harmonic amplitudes increase with respect to excitation voltage. In this case, the magnetizing current of over excitation is often symmetrical. Transformers may generate harmonics under rated operation condition (rated voltage, no DC bias). Fig. (8) is a typical excitation currents, voltages and flux wave forms of phase A of a three phase transformer. It can be seen that, except for fundamental component, 3rd and 5th harmonics dominate the current.

A symmetrical variation of the flux produces a symmetrical current variation between Imax and +Imax, resulting in a symmetrical hysteresis loop whose shape and area depend on the value of max flux. The trajectory starts from initial condition of the controller (residue) which must lie on the vertical axis inside the major loop. You can specify this initial flux value phi0, or it is automatically adjusted so that the simulation starts in steady state[30]. As shown in Fig.(7) for the settling time within 2% and rise time from 2% to 90% criteria. Fig. (9) shows that the setting time is 0.071 sec, the poles and zeros configuration of the system lies in the left hand side of the S-plane which means that the system is stable for values of all parameters included. This is quite obvious in step, impulse because the steady state error between the input and the output has small value (≈0).

Conclusions

1. The time of switching (0.04 sec) can be changed by adjusting the phase angle.
2. The initial condition of the integrator play a vital role in adjusting the residual flux hence control the transformer operation.
3. Presence of a dc component by including a dc offset in the sinusoidal input excitation
4. The leakage flux is produced when the m.m.f. due to primary ampere-turns existing between points.
5. At no load and light loads the primary and secondary ampere-turns are small, hence leakage fluxes are negligible.
6. The terminal voltage of a winding is the sum of the induced voltage and the resistive drop in the winding.
7. Determining a control action based on the onset of core saturation; and implementing the control action to control the magnetizing current in the transformer.

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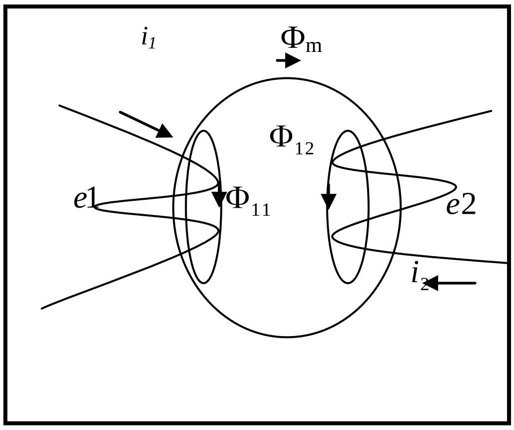


Fig. (1) Magnetic coupling of two winding transformer

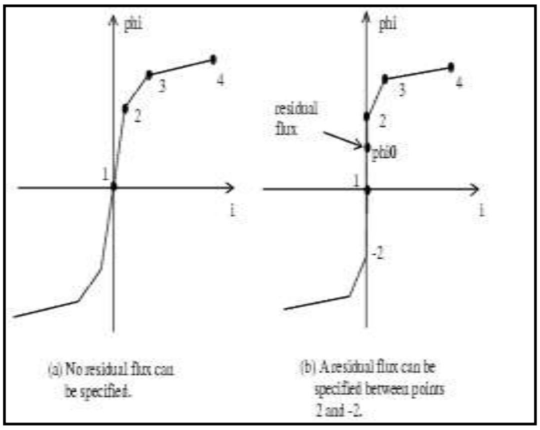


Fig.(2) Piece wise saturation curve

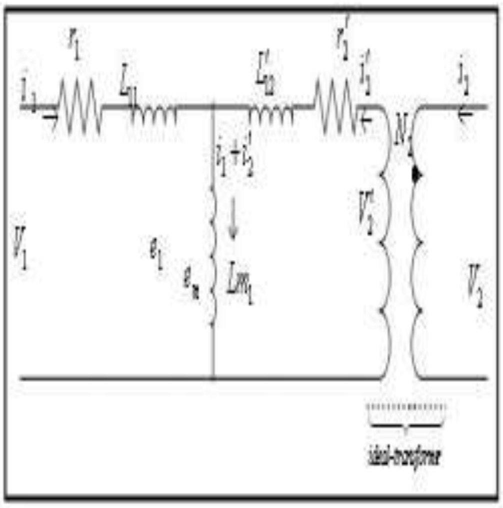


Fig.(3) Equivalent current of two winding transformer

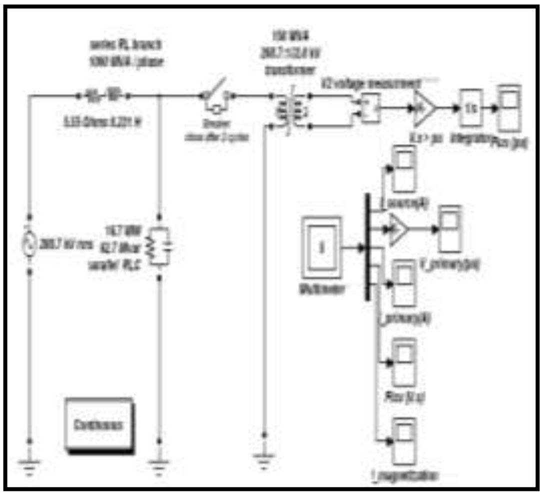


Fig. (4) Simulink block set of the complete work

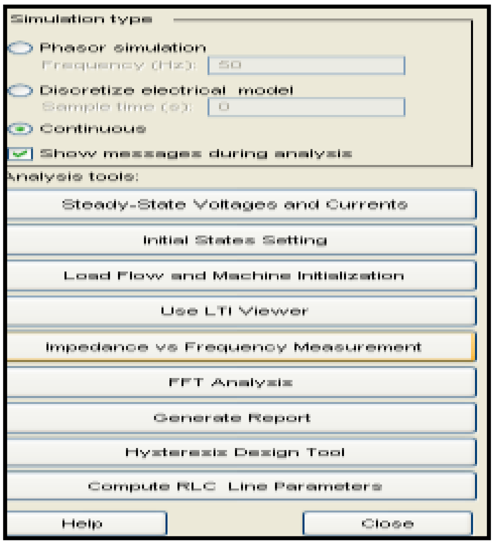
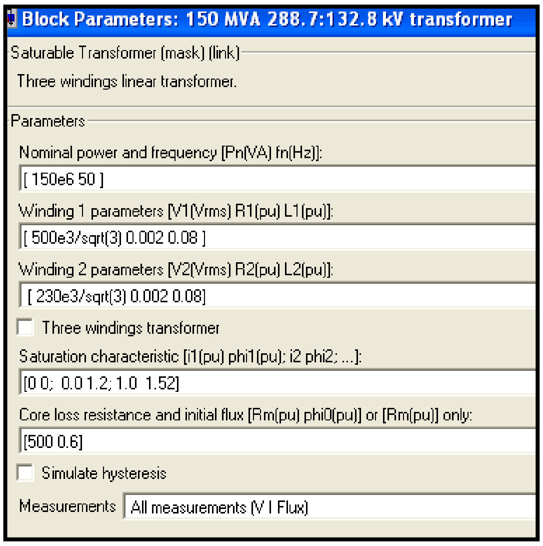


Fig.(5) Parameters values of the Circuit shown in Fig 4


Block Parameters: 150 MVA 288.7:132.8 kV transformer

Saturable Transformer (mask) (link)

Three windings linear transformer.

Parameters

Nominal power and frequency [Pn(VA) fn(Hz)]: [150e6 50]

Winding 1 parameters [V1(Vrms) R1(pu) L1(pu)]: [500e3/sqrt(3) 0.002 0.08]

Winding 2 parameters [V2(Vrms) R2(pu) L2(pu)]: [230e3/sqrt(3) 0.002 0.08]

☐ Three windings transformer

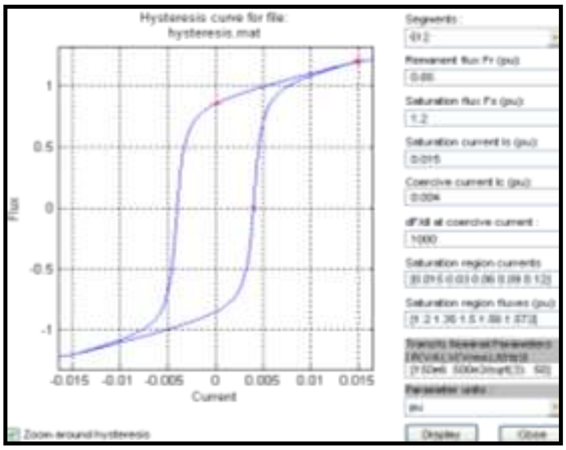
Saturation characteristic [i1(pu) phi1(pu); i2 phi2; ...]: [0 0; 0.0 1.2; 1.0 1.52]

Core loss resistance and initial flux [Rm(pu) phi0(pu)] or [Rm(pu)] only: [500 0.6]

☐ Simulate hysteresis

Measurements: All measurements (V I Flux)

Fig. (6) Analysis tools and simulation type GUI



Segments :

Remanent flux Fr (pu): 0.88

Saturation flux Fs (pu): 1.2

Saturation current Is (pu): 0.015

Coercive current Ic (pu): 0.004

dF/dI at coercive current : 1000

Saturation region currents: [0.015 0.03 0.06 0.09 0.12]

Saturation region fluxes (pu): [1.2 1.35 1.5 1.88 1.87]

Parameter units: pu

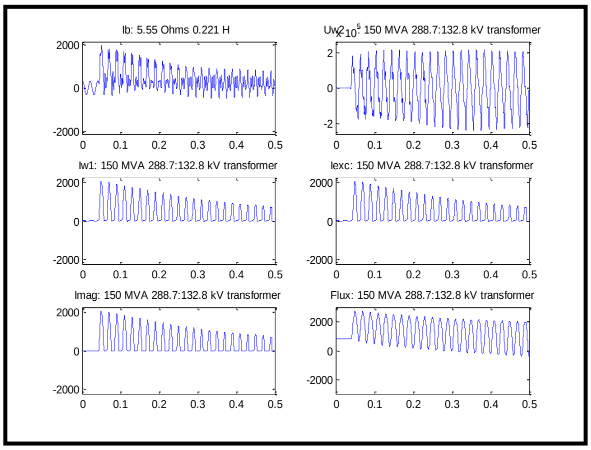


Fig.(7) Hysteresis curve of the magnetization core

Fig. (8) Results of the saturable transformer (Multimeter plots)

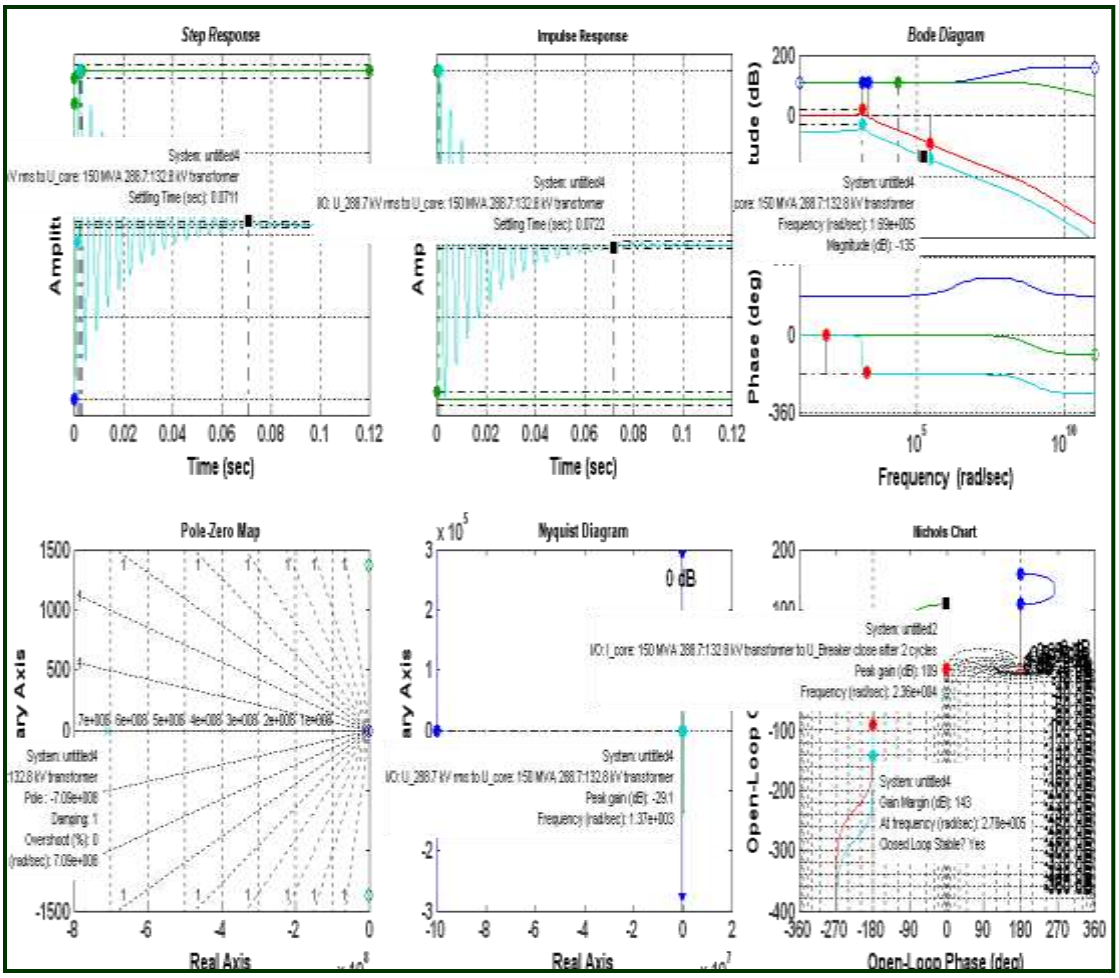


Fig. (9) Control System response for the linear time invariant utility (LTI viewer)