Research on the Use of Matlab in the Modeling of 3-phase Power Systems

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***Abstract* -This paper describes the modeling and simulation library for power systems si[1]mulation under SIMULINK environment. The different features of MATLAB Toolboxes used in the analysis of power systems are described. Software introduces SIMULINK environment of MATLAB for implementing user friendly and future expansion. To illustrate the capabilities of SIMULINK simulation tool, a case study based on a test system is presented.**

Key words: modelling, simulation, MATLAB, simulink, three phase, power systems

I INTRODUCTION

MATLAB software is a 4th level technical computing language that allows matrix manipulations, plotting data and functions, implementing algorithms, creation of interfaces as well as interfering with programs written in other languages that include JAVA, C++ or Python (Santosh, Kulkarai, & Chile, 2013). In mechanical engineering, MATLAB is used mainly in the modeling and simulation of objects in real time so as to appreciate their functionality, arrangement in space and mathematical models before they are actually manufactured (Moura & Izzat, 2010). As a result MATLAB and other technical computing languages have received full appreciation in the mechanical engineering fields, as well as other engineering fields especially electrical engineering.

This project focuses on the use of MATLAB in the modeling of three-phase power systems, which include but not limited to transformers, motors and generators. In such power systems, MATLAB can manipulate and invert large matrices and can be used in the numerical applications involved (Alvarado, 2000). MATLAB's capabilities can be extended with addition called SIMULINK, a program which is normally used in the analysis and synthesis of such modern systems (Santosh, Kulkarai, & Chile, 2013). SIMULINK, now incorporated into MATLAB, can also be used to analyze and design of power systems.

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A Problem statement

There are inconveniences in the cumbersome process of calculations and trial and error set ups that are experienced in the setting up of three phase circuits.

B Aim

The aim of the project is to research on the use of MATLAB in the modeling of 3-phase power systems (filtering method).

C Objectives

The project objectives are;

- To review the basics of three-phase electric circuits, three-phase AC power applications and advantages over other power sources, such as DC and single phase AC power.
- To investigate how MATLAB can be used in the modeling of three-phase AC systems, and the necessary tools used
- To give an example of the use of MATLAB in a typical modeling problem of three-phase AC circuits

D Justification

The use of modern software in the applications has received widespread use especially in this technologically advanced world, where most machines and equipment are either automatic or semi-automatic in their operation. As a result, there is need to use such computer software in industry. By modeling and simulation, it is possible to het the appreciation of an object, circuit (as in this project) or tool behavior in real time before it is actually used, made or assembled. As a result, there is no possibility of correcting, amending or otherwise discarding an already made product, thus reducing the wasting material and time.

MATLAB is used in the modeling of electrical circuits, thus providing a brief layout of the circuits, and goes on a step further to give values of the parameters that are common to circuits, voltage, current and power (Alvarado, 2000). In addition, there is need to simulate these solutions before visualize the actual behavior of circuits.

E Methodology

The research will be conducted based on published journals on MATLAB and specifically power modeling and simulation. Text books on three-phase AC power and related written material will be used to substantiate to the data. Also, text on MATLAB will be used to give a general understanding and appreciation of the MATLAB software and how it is used in programing, modeling and simulation as is mentioned in the project objectives.

II LITERATURE REVIEW

A Three phase power systems

Power systems in real applications are in the form of three-phase ac circuits. A three-phase ac power system consists of three-phase generators, transmission lines and loads. AC

power systems have a great advantage over dc power systems in that:

1. AC power systems have a more power per kilogram of metal ratio, thus transmitting more power for the same material of single phase AC power supply
2. The power delivered by three-phase power systems is constant at all times rather than pulse setting as in single phase system, that is unlike single phase supplies whose currents alternate in each cycle, the three phase phases themselves alternate but supplying a constant power supply (Dhote, Asutkar P, & Dutt, 2013)
3. Voltage level can be changed by using transformers, thus economical way transmission and distribution unlike in DC power supplies where the voltage is delivered as it were at the source
4. Three-phase power systems make induction motors easier by allowing them to start without special auxiliary starting windings.

B Generation of three-phase voltages

A three-phase generator consists of three single-phase generators, with voltages equal in magnitude but differing in phase angle from the others by 120°. The three generators could be connected to one of three identical loads by a pair of wires and the resulting power system would be as shown below in Figure 1.

The resulting waveform of the circuit shown is shown in the following diagram, figure 2.

It is important to note that the peak voltage is the same for each phase. And thus a constant supply is maintained (Santosh, Kulkarai, & Chile, 2013). This in turn results in the pre-mentioned fact that the three phase system will provide a constant power in each cycle, as the currents are all equal in magnitude and alternating at equal phase angle relative to each other.
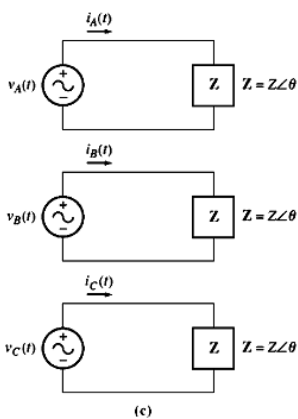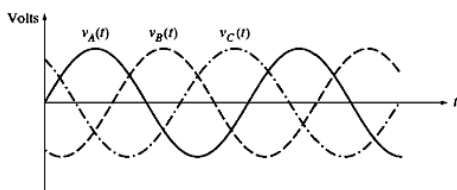

Fig 1: Three connected generators

Fig.2: Waveform circuit of three generators

It is possible to connect the negative terminals of each of the voltage supplies, to get an overall system shown in figure 3. below. In the connection, each negative terminal on the three sources power supply is connected to the negative of the other source. The result is a common point on each terminal, which can then be used as a local connection on the three connections. In the system below, the loads, Z are all equal, thus the currents in each line are equal and the connection is called a balanced connection. If the values of impedances Z are different, such that the current values differ, then the circuit is termed unbalanced.
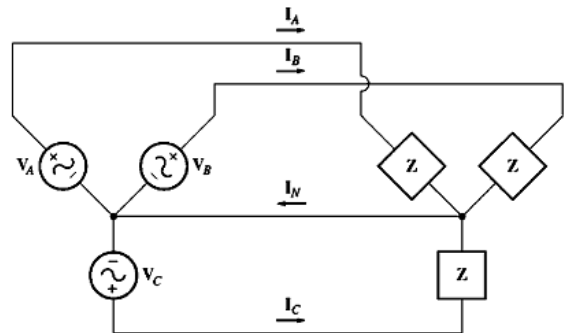

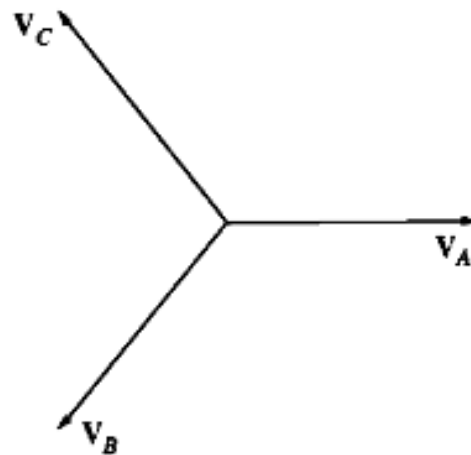Fig 3: Negative terminals of each of the voltage supplies

Fig.4: Star operation

A common return line is connected across each of these supplies and loads, carrying a current denoted by I_N. It can be shown that for a balanced system, as shown in the diagram above, this value of neutral return line current is equal to the sum of the individual currents. For a balance system, this value is equal to zero. If a three phase system contains equal values of supply voltage and equal load resistance is called a balanced three-phase circuit. The phasor diagram of the system for an ABC phase-sequence can be as shown below;

The connections in three- phase systems can be either;

1. Wye (Y) connections
2. Delta (Δ) connections

Each of the connection has a different orientation and thus the expressions for instantaneous voltages and currents differ.
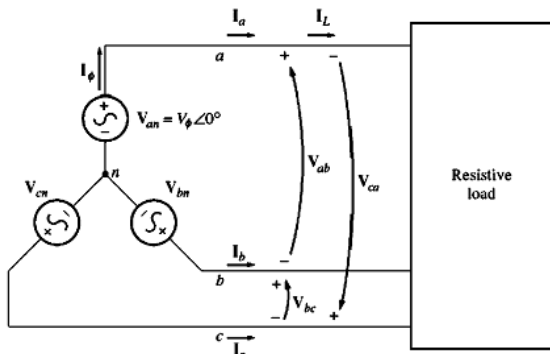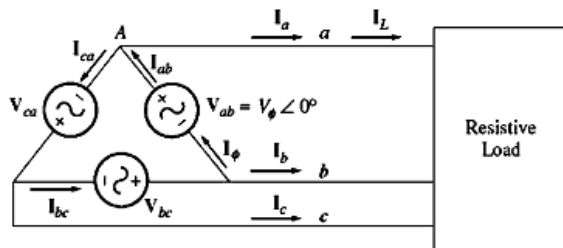
Fig.5 Wye (Y) Connection

Fig.6 Delta (Δ) connection

It is important however to note that the power in each arrangement is always constant, as shown in the equations of real power (P), reactive power (Q) and apparent power (S) below.

Table 1: A summary of the voltages, currents and output power is given and from these combinations, expressions for power (P, Q and Q) can be derived.

	Y connection	Δ connection
Voltage magnitudes	$V_{LL} = \sqrt{3}\, V_\phi$	$V_{LL} = V_\phi$
Current magnitudes	$I_L = I_\phi$	$I_L = \sqrt{3}\, I_\phi$
abc phase sequence	V_{ab} leads V_a by 30°	I_a lags I_{ab} by 30°
acb phase sequence	V_{ab} lags V_a by 30°	I_a leads I_{ab} by 30°

$$P = 3V_\phi I_\phi \cos\theta$$

$$Q = 3V_\phi I_\phi \sin\theta$$

$$S = 3V_\phi I_\phi$$

The angle theta is the angle between the voltage and the current in any phase of the load. From this angle, the value of the power factor can be defined as the cosine of the angle θ.

C Unbalanced loads

Three phase systems deliver power in enormous amounts to single phase loads such as lamps, heaters, air conditioners, and small motors (Alvarado, 2000). It is the responsibility of the power systems engineer to distribute these loads equally among the three phases to maintain the demand for power fairly balanced at all times. While good balance can be achieved on large power systems, individual loads on smaller systems are generally unbalanced and must be analyzed as unbalanced three phase systems.

III MATLAB STANDARDS

During last four decades' simulation of power systems have gained more importance. A published IEEE paper discussing different approaches to modeling protective relays and related power system events indicates a variety of possible software tools that may be used for this purpose (McLaren *et al.* 2001). The following items summarize their most important features in protection systems simulation:

1. MATLAB/SIMULINK can be used to simulate power system faults and protective relay algorithm at the same time
2. MATLAB/SIMULINK offers more possibilities in power electronics, signal processing and control
3. Users can easily create new relay model with MATLAB/SIMULINK
4. MATLAB/SIMULINK encompasses better graphic function tools

Therefore, for ideal use and modeling, MATLAB has received widespread use as modeling and simulation software.

A Matlab toolbox features

The features of the MATLAB toolboxes used in the analysis of power systems are facilitating future revision and expansion of software. This is very important for researches that are interested in the developing and testing of new power system applications as it provide opportunities to easily prepare input data files in commonly accepted formats for networks that are created. The results produced by one application can be easily used either fully or partially by any other application supported by the package (Cartina G. Grigoras G. Bobrick E-C, 2007).

The MATLAB/SIMULINK toolbox consists of:

- **MatPower Toolbox**
  It is a package for solving power flow and optimal power flow problems. This package is designed to give the best performance possible while keeping the code simple to understand and modify
- **Power System Analysis Toolbox**
  It is for electric power system analysis and control. It includes power flow, continuous power flow, optimal power flow and small signal stability analysis and time domain simulation
- **Voltage Stability Toolbox**
  It is used to analyzes voltage stability problems and provides information for power system planning, operation and control

The Power System Blockset (PSB) is a graphic tool that allows building schematics and simulation of power systems in the SIMULINK environment. A Blockset then uses the SIMULINK environment to represent common components and devices found in electrical power networks. It consists of a block library that includes electrical models such as RLC branches and loads, transformers, lines, surge arrester, electric machines, power electronics devices, etc. Diagrams can be assembled simply by using click and drag procedures into SIMULINK windows. The Power System Blockset uses the same drawing and interactive dialogue boxes to enter parameters as in standard SIMULINK block. (Hahn & Valentine, 2000)

Simulation results can be visualized with SIMULINK scopes connected to outputs of measurement blocks available in the PSB library. These measurement blocks acts as an interface between the electrical blocks and the SIMULINK blocks. The voltage and current measurement blocks can be used at selected points in the circuit to convert electrical signals into SIMULINK signals. Nonlinear elements requiring control, such as power electronic devices, have a SIMULINK inputs that allow control from a SIMULINK system.

IV CASE STUDIES

A. Case one-matlab applied in power system block set (PBS). The following example illustrates applications of PSB.

1: Circuit description:

A three-phase generator rated 200 MVA, 13.8 kV, 112.5 rpm is connected to a 230 kV, 10,000 MVA network through a Delta-Wye 210 MVA transformer. At t = 0.1 s, a three-phase to ground fault occurs on the 230 kV bus. The fault is cleared after 6 cycles (t = 0.2 s). The system will initialize in order to start in steady-state with the generator supplying 150 MW of active power and the dynamic response of the machine and of its voltage and speed regulators are observed. It is observed that the terminal voltage VA (Figure. 10) is 1.0 p.u. at the beginning of the simulation. It falls to about 0.4p.u. during the fault and returns to nominal quickly after the fault is cleared. This quick response in terminal voltage is due to the fact that the Excitation System output Vf (Figure. 11) can go as high as 11.5 p.u. which it undergoes during the fault. The speed (Figure.6) of the machine increases to 1.01p.u. During the fault then it oscillates around 1 p.u. as the governor system regulates it. The speed takes much longer than the terminal voltage to stabilize mainly because the rate of valve opening/closing in the governor system is limited to 0.1 p.u./s.

2: Procedure of modeling and simulation of the circuit described above by matlab, using the Simulink extension.

The power system Blockset system library that is useful in modeling the above circuit is as shown below in Figure 7 below. Figure 8 shows the load flow to initialize the synchronous machine, in this case the generator in the circuit.
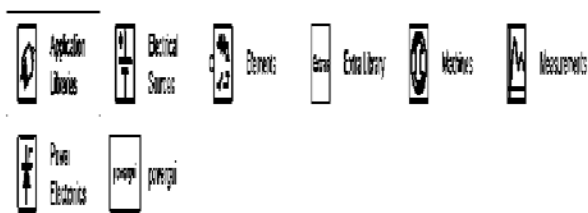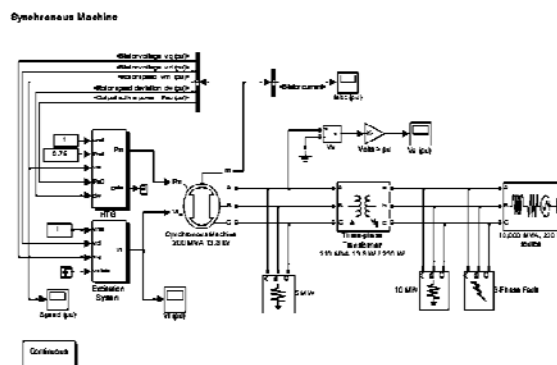

Fig.7 The power system Blockset system library

Fig.8 Load Flow to Initialize Synchronous Machine Currents

The currents in the generator stator are as show below. The voltage is constant in the initialization stage, the first 6 cycle up to 01 sec where there is a noticeable change in peak voltage as in the diagram below.
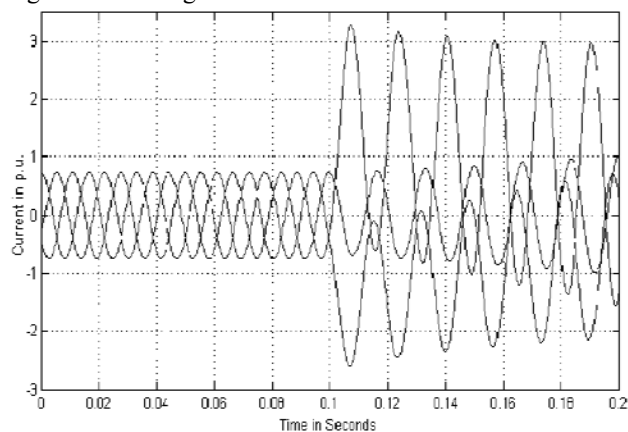

Fig.9 Stator Currents of Synchronous Machine

In the diagram below, the transmission voltage is also at peak in the first 6 cycles as shown as the system initialize. The voltage then falls to 0.4p.u. during the fault and then return to its normal after the fault is over.
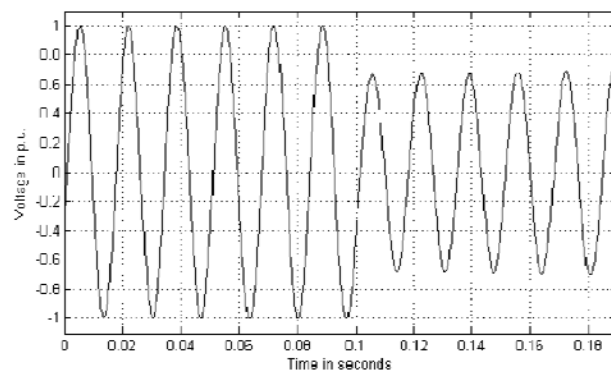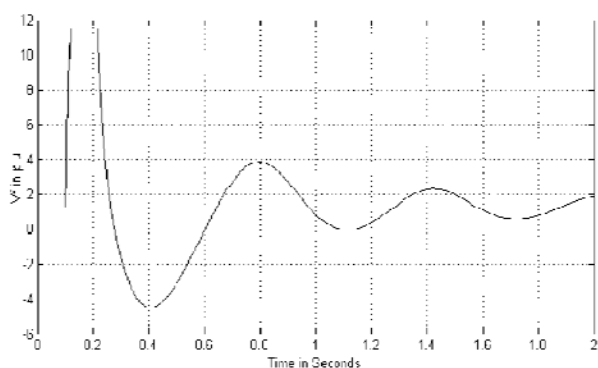

Fig.10 Terminal Voltage VA (p.u.)

Fig.11 Excitation System output Vf

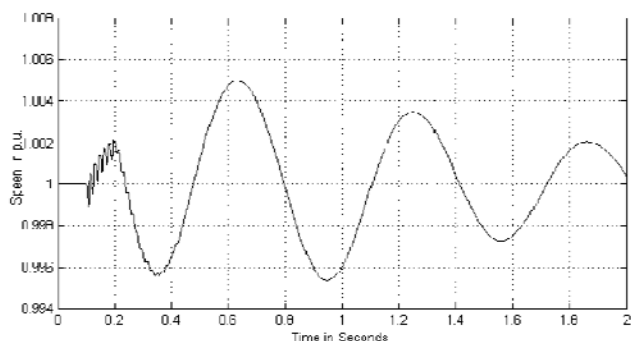Again, the speed is disturbed but takes longer to settle to a constant value, as shown below.

Fig.12 Speed of Synchronous Machine

D. CASE TWO- MODELING AND SIMULATION OF A THREE-PHASE TRANSFORMER

A transformer experienced two main types of faults;

- External faults-those that occur outside of the transformer: overloads, overvoltage, over -fluxing, under frequency, and external system short circuits.
- Internal faults-those that occur inside of the transformer: winding phase-to-phase, phase-to-ground, winding inter-turn and over-fluxing.

A very large number of transformers are used in the electric power systems. These costly and critical devices provide the necessary voltage conversions to transfer power through the system. Internal faults in transformers can cause huge damages in a very short time, and in some cases the damages are repairable, and also about 70%-80% of transformer failures are caused by internal faults. So fault locating is a necessary work for repairing the faulted transformers, which can be repaired and turned back in service again. Internal faults especially turn-to-turn faults are common in transformer failures. There are many different techniques available for detecting and/or locating these kinds of faults such as: high frequency analysis, Frequency Response Analysis (FRA) , Artificial Neural Networks (ANNs) and winding transfer functions, finite element analysis, online diagnostics of transformer winding insulation failures by Park's vector approach, combination of discrete wavelet transforms and back-propagation neural networks experimental studies, double Fourier series [12], numerical technique based on

symmetrical components ,Genetic Algorithm (GA),and etc. Also transformer model's equivalent circuit is different in each method. In this example, the physical model of a 440V/440V transformer is simulated in MATLAB/SIMULINK. This transformer model's equivalent circuit considers each of the winding turns separately, so simulating and testing the faults in each one of the winding turns or sections is possible. In this equivalent circuit just three turns of each of the primary and secondary windings are Modeled, which is a simplified model of windings with n turns, and this simplification decreases the process time. Some of the equivalent circuit's elements values are measured from and others are experimental values. All of the mentioned faults are applied in this model one by one in different step times and analyzed. The first step after applying faults on the model is calculating the Fourier transform of the signals. In further analyzes the harmonics and frequency components of all of the faults are extracted from the Fourier transform's plots and are saved as indexes. And the last step is pattern recognition which the fault signals of a real transformer can compared with the saved indexes in the database and the type and location of the fault can be measured, as illustrated in the following example modeling.
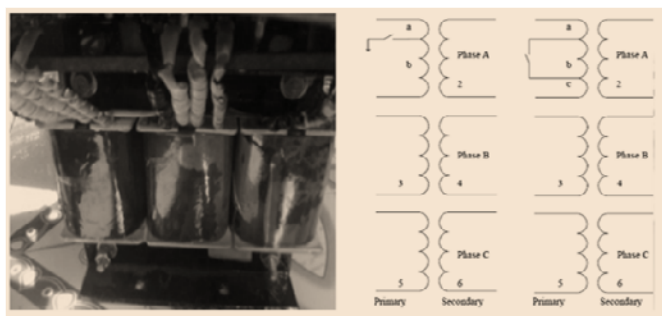

Fig 13: Three phase transformer tapings and Equivalent Transformer Circuit Diagram

In this equivalent circuit just three turns of each of the primary and secondary windings are modeled, which is a simplified model of windings with n turns, and this simplification decreases the process time. Some of the equivalent circuit's elements values are measured from and others are experimental values. All of the mentioned faults are applied in this model one by one in different step times and analyzed

1. Experimental set-up

The three phase laboratory core-type transformer in open geometry design; there is a possibility to connect both primary and secondary windings either in star (wye) or in delta connection. The investigated transformer is with wye-wye connections; the rated data for this case are: Burden Total 900VA; Per Phase 300VA; Current 1.18Amps. The equal limb 2½″ stack, 440/440V, 3 coils –254 Volts each with tapings are 50%, 86.6% and 100%. The physical model of a transformer is simulated in MATLAB/Simulink. This transformer model's equivalent circuit considers each of the winding turns separately, so simulating and testing the faults in each one of the winding turns or sections is possible. The used transformer model as mentioned before has only three

turns in each of the windings. So simulating all of the possible short circuit faults in each of the turns and all of the possible turn-to-turn faults are achievable. Primary winding to secondary winding faults are simulated several times too, because each time different primary winding turns are short circuited into different secondary winding turns. Different cases of inter turn short circuit are staged, considering the effect of number of turns shorted on primary and secondary and load condition.

2. Linear model validation

For the model validation a three-phase, three-leg transformer, of 0.9 kVA, 440/440 V, was used. The transformer has three-windings per phase on the primary and on the secondary side, having, one of each, been modified by addition of a number of tapings connected to the coils, for each of the three phases, allowing for the introduction of different percentages of shorted turns at several locations in the winding, for subsequent studies of inter-turn short-circuits occurrence. The direct and homo-polar short-circuit and excitation tests were performed with the transformer having a star-star winding connection, without neutral wire, in order to obtain the matrices elements. The transformer digital model, with Y/Y connections, was initially tested under no-load conditions. With the secondary side open-circuited, a symmetrical three-phase voltage system, with transformer nominal values, was applied to the primary side. The primary side energized by a symmetrical three-phase voltage system, with transformer nominal values. In this simulation all of the data is generated by the current and voltage signals of input and output terminals of the transformer model's equivalent circuit, one time in no load mode and another time in with-load mode. No-load mode's scopes obtain three parameters: input voltage, input current, and output voltage. With-load mode's scopes obtain four parameters: input voltage, input current, output voltage, and output current. Each of these scopes' time domain data is saved in a separate table. Both of the no-load and with-load tests are applied once without fault and several times with different types of short circuit faults that mentioned earlier. When a fault happens, a ripple is generated in the scope's output. These ripples have a very lower frequency band than the waveform, and a variable domain, and it happens in a very short time. After the ripples, the sinusoidal waveform continues, but the waveform's domain is changed: usually voltage domains are decreased and current domains are increased, depends on the number of short circuited turns and location of faults. And also the measured terminal: output or input. All of the faults are applied in several step times so the fault can occur in different locations of the scopes sinusoidal output waveform. This is so important to have the faults' data in different step times because the ripples' domains vary in each point of the waveform. And the worst situations are those that the fault happens in y=0 or when it happens in each of the peaks of waveform. In these situations the ripple's domain has the biggest size and usually the ripple's domain is several times bigger than the waveform's domain itself. And the more it is bigger; the more it is dangerous for the transformer. In the firstly simulations (no-load and with-load without applying any of the faults), two step times for each signal is measured (in y=0 and in the peak) to apply the faults in these times.

There is also important to apply the fault in the simulation after several sinusoidal cycles when the transformer is stable, not running it with a fault at first, because having the ripples values is important for our next analysis. After simulating all of the faults in both no-load and with load mode, and running each of the faulted circuit models in MATLAB/Simulink one by one in several step times, each of the waveform output values is saved in a separate table, then there are ready for the next process; The Fourier transform. Fast Fourier Transform (FFT) of each of the voltage and current waveforms is calculated. Then by plotting the absolute value of each of the waveforms' FFT result, faults are diagnosable in the plotted figures

Power system harmonics are sinusoidal components of Periodic waveforms that have frequencies that are multiples of the fundamental frequency of the waveform. For example if the system frequency (fundamental frequency) is 50 Hz, typical harmonics are odd harmonics such as the third harmonic (150 Hz), the fifth harmonic (250 Hz), the seventh harmonic (350 Hz), and so on. And also the third harmonic is one of the most important harmonics in harmonic analysis of a power system (Harahara & Chids).

3. Simulation test results

The used transformer model as mentioned before has only three turns in each of the windings. So simulating all of the possible short circuit faults in each of the turns and all of the possible turn-to-turn faults are achievable. Each of the single turn short circuit faults is simulated and all of the possible turn-to-turn faults are simulated too. Other kinds of faults such as turn-to-core, turn-to-transformer body, turn-to-earth, and primary winding to secondary winding are simulated. Primary winding to secondary winding faults are simulated several times too, because each time different primary winding turns are short circuited into different secondary winding turns. Some of the plotted figures of voltage and current signals' FFTs are represented as samples in below, and list of the simulated faults are showed

4. Turn to turn fault on primary

If the faults take place in the primary winding, the faulty turns will act as a three phase transformer load on the winding, and the reactance is that between the faulty turns and the whole of the affected phase winding.
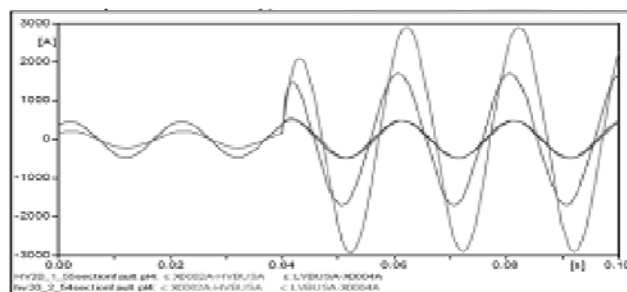

Fig 14: Faults in the winding

4.2.5. TURN-TO-TURN FAULT ON SECONDARY SIDE

A short circuit of a few turns of the winding will give rise to a heavy fault current in the short-circuited loop, but the terminal currents will be very small, because of the high ratio of transformation between the whole winding and the short-

circuited turns. The simulation of turn-to-turn fault is started by short-circuited one section (three turns) of the secondary winding.
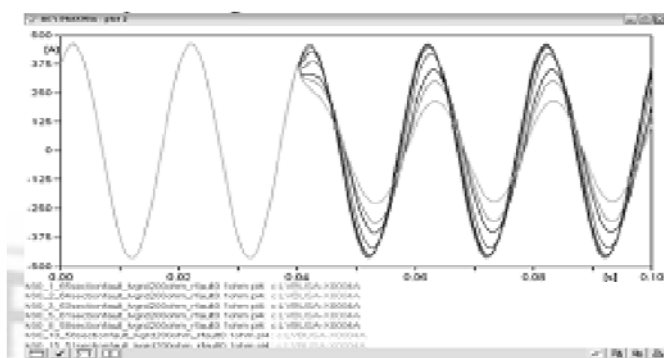

Fig 15: Short circuit of few turns

V. CONCLUSIONS AND RECOMMENDATIONS

This research presents user friendly features of simulation under SIMULINK environment and various. Simulink model and MATLAB Figure windows include a "Copy" function in the "Edit" menu. This is useful for reporting results: you can simply copy and paste your models or graphical results into a Word or PowerPoint document. One can also explore other options in the MATLAB Figure window. For example, find out how add a grid, change the line type, thickness or color, change the x-axis or y-axis scales, etc. MATLAB toolboxes which can be used in power system analysis. The user friendly features are facilitated with the use of a simple drag-and-drop and cut-and-paste approach to building the exercises with pre-defined library elements. This is very important for researches who are interested in developing and testing new for various power system applications. Application example for power systems with simulation results obtained with SIMULINK has been presented to illustrate the capabilities of the PSB.

In this project, it is also achieved to show a simplified model of a power transformer simulated and different kinds of faults applied on it. The frequency components and the harmonics of the FFT signals of all of the simulated faults are extracted and saved as special indexes. The indexes are saved in the database and could be compared with any kind of similar transformer for finding the short circuit fault's location. This method can also be used for other kinds of internal winding faults too.

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