MODELING OF INTERNAL FAULTS IN THREE-PHASE THREE-WINDING TRANSFORMERS FOR DIFFERENTIAL PROTECTION STUDIES

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MSc Graduation Thesis of

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Didik Fauzi Dakhlan

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I. INTRODUCTION

1.1. Power Transformer, Faults, and Transformer Protection System

The power transformer is one of the most important primary piece of equipment of the electric power system. The development of modern power systems has been reflected in the advances in transformer design. This has resulted in a wide range of transformers with sizes ranging from a few kVA to several hundred MVA being available for use in a wide variety of applications.

Different faults can occur inside the transformer and at the electrical system where the transformer is connected. Transformer faults can be divided into two classes: external and internal faults. External faults are those faults that happen outside the transformer: overloads, overvoltage, under frequency, external system short circuits. The internal faults occur within the transformer protection zone such as incipient fault (overheating, overfluxing, overpressure) and active faults (turn-to-earth, turn-to-turn, tank fault, core fault).

The transformer protection is an essential part of overall system protection strategy. Moreover, transformers have a wide variety of features, including tap changers, phase shifters and multiple windings, that require special consideration in the protective system design.

The combination of electrical and non electrical protection system is installed to protect the transformer due to those all possible faults. To reduce the effects of thermal stress and electrodynamic forces, it is advisable to ensure that the protection package used minimises the time for disconnection in the event of a fault occurring within the transformer.

1.2. Problem Definition

A lot of faults can happen at the power transformer. The transformer protection must isolate and clear the fault fast and correctly. One of the main protections of a transformer is differential relay. It works for internal faults of the transformer e.g. turn-to-earth and turn-to-turn fault of the transformer winding.

The internal faults of the transformer can be modeled by modifying the coupled inductance matrix of the transformer. If there is an internal fault of the transformer, the coupled inductance matrix will change due to the fault point. This new matrix is depended on the location of fault and type of faults.
Simulation of the faulty transformer will produce the faulty waveform that can be used to test the correctness and sensitivity of the differential protection.

1.3. Objectives the Present Study

To support the testing of the protection system from transformer internal faults, the above mentioned modeling of internal faults is built and simulation using real system is done to make the fault waveform.

To analyze and verify the model, the no-load test and load/copper losses test result from the transformer can be used. The geometric quantities of the transformer and the impedance test result also can be used to analyze and verify the model.

The calculation of the new transformer parameters due to internal faults has to be used to make the new model of the transformer. Finally, simulations using real system data should be introduced to know the protection system behavior due to the internal faults.

In particular, the following steps have to be taken:

- Collecting the available data of the transformer: geometric quantities of the transformer, factory acceptance test result (no-load losses and copper/load losses test), etc.
- Based on the test result of the transformer : modeling the healthy transformer

- Verification of the model by simulation of test which has been done in factory acceptance test e.g. load losses and no-load losses test.
- Verification of the transformer coupled inductance matrix by using geometric quantities of the transformer.
- Development of new coupled inductance matrix due to internal faults of the transformer.
- Connection the transformer to the model of the real system in the field.
- Simulation of the external and internal faults (turn-to-earth and turn-to-turn winding fault)
- Analyzing the fault waveform which produced by the simulation for protection system studies.

1.4. Thesis Layout

This thesis introduces the reader to the theory of faults in the transformer and the protection due to those faults. In subsequent chapters, the healthy transformer modeling is built using BCTRAN routine and the model is verified by manual calculation and simulation of short and open circuit test during Factory Acceptance Test (FAT) of the transformer. Then, the new models of the faulty transformer due to internal faults are built and simulated with the real data from the network and the transformer protection system behaviors due to these faults are studied.

All of the assumptions and the method of the modeling will be described. A step by step procedure to model and simulate the internal fault and the analysis and evaluation of the transformer protection will be explained. Finally, conclusions are drawn based on the results of the simulation.

II. PROTECTION SYSTEM OF TRANSFORMER

2.1. Introduction

Utilities in some countries are responsible for the generation, transmission, and distribution of electricity to customers. Part of this responsibility is ensuring a safe but yet reliable power supply to customers. For the purpose of safety and protecting transmission and distribution networks from faults, utilities worldwide have sophisticated protective equipment installed on their power system equipment. Collectively, these are known as secondary equipment and include the current transformer (CT), voltage transformer (VT), and protection relays.

The function of protection system is to cause the prompt removal from service of any element of a power system when it suffers a fault; short circuit or when it starts to operate in any abnormal condition that might cause damage or otherwise disturb the operation of the rest of the system. The relaying equipment is aided in this task by circuit breakers that are capable of disconnecting the faulty element when they are called upon to do so by the relaying equipment [21].

Circuit breakers are generally located so that each generator, transformer, bus, transmission line, etc., can be completely disconnected from the rest of the system. These circuit breakers must have sufficient capacity so that they can carry momentarily the maximum short-circuit current that can flow through them, and then interrupt this current; they must also withstand closing in on such a short circuit and then interrupting it according to certain prescribed standards [33]

In the early days of the electricity, electromechanical relays were used. Later, these were replaced by the static relay and then the digital relay. Today, most relays used by the utility are numerical relays. Numerical relays are microprocessor based and have software to perform the necessary calculations, wiring adaptation, and logic functions of the relay.

There are various types of relays, the main types being the over current relay, distance relay, and differential relay. The differential relay plays an important role in the protection of generators, busbars, short lines, and transformers.

2.2. PLN Transformer Protection System Requirements

One of the most important design considerations of protection system is reliability. Protection system reliability is separated into two aspects called dependability and security. Dependability is defined as “the degree of certainties that relay or relay system will operate correctly”. In other words, dependability is a measure of the relay ability to operate when it is supposed to operate. Security is defined as “the degree of certainties that a relay or relay system will not operate incorrectly”. Security is a measure of the relay’s ability to avoid operation for all other conditions for which tripping is not desired. Besides those two aspects, the grid would guarantee to clear off the faults in 150 kV systems not more than 120 ms and in 70 kV system not more than 150 ms [31].

The fault clearing time is the time needed by protection system equipment from the fault occurrence until the fault cleared from the system. The fault clearing time consists of the operating time of the relay and the tripping time of the circuit breaker. So the protection system needs the fast and reliable relay to discriminate the all types of faults.

Table 2.1 Java Bali Grid Code: Transformer Protection System

No	Protection	Ratio and Transformer Rating							
		150/70 kV, 150/20 kV, 70/20 kV						500/150 kV	
		< 10 MVA		10 to 30 MVA		> 30 MVA			
		HV	LV	HV	LV	HV	LV	HV	LV
1	Temperature Relay	√		√		√		√	
2	Buchholz Relay	√		√		√		√	
3	Sudden Pressure Relay	√		√		√		√	
4	Differential Protection Relay					√		√	
5	Over Current Relay	√	√	√	√	√	√	√	√

6	Earth Fault Relay	√	√	√	√	√	√	√	√
7	Restricted Earth Fault Relay					√*	√*	√	√

* : not provided for transformer which grounded in transformer with high impedance grounding

The transformer must be protected against all possible fault condition. The transformer protection system is classified based on MVA rating and the voltage. The revised PLN standard also accommodates and redundancy of differential relay 500/150 kV interbus transformer, the fire protection, and early warning system.

Table 2.2 Faults at the transformer and their protection

No	Type of Fault	Protection		Consequence
		Main	Back Up	
1	Short circuit inside the transformer protection zone	Differential, REF, Buchholz, Sudden Pressure	OCR,GFR	Broken insulation, windings or core
2	Short circuit outside the transformer protection zone	OCR, GFR,SBEF	OCR,GFR	Broken insulation, windings
3	Overload	Temperature	OCR	Broken insulation
4	Cooling system fault	Temperature	-	Broken insulation

The protection system of the transformer could be classified as electrical and non electrical protection. The electrical protection means the working principle of the protection based on the current, voltage, or frequency of that appear on the protected zone.

The non electrical protection will operate based on the physical conditions of the transformer and the insulation media. These physical conditions could be temperature, air (gas) in the insulation media, etc.

2.3. *Non electrical Protection*

The non electrical protection operates independently from current and voltage of the transformer. It operates based on the physical and the chemical condition of the transformer or insulation media of the transformer (oil).

Buchholz relay

This relay is actuated by gas and oil inside the transformer bank. The turn-to-earth fault, turn-to-turn fault or other internal fault inside the transformer will generate gases in sufficient quantities to operate this protection device and actuate the operating of circuit breaker. When a fault occurs inside the oil-filled transformer tank, the fault arc produces gases, which create pressure inside the oil. In the conservator type of tank construction, the pressure created in the oil is detected by a pressure vane in the pipe which connects the transformer tank with the conservator. The movement of the vane is detected by a switch, which can be used to sound an alarm or send the trip contact to the circuit breaker.

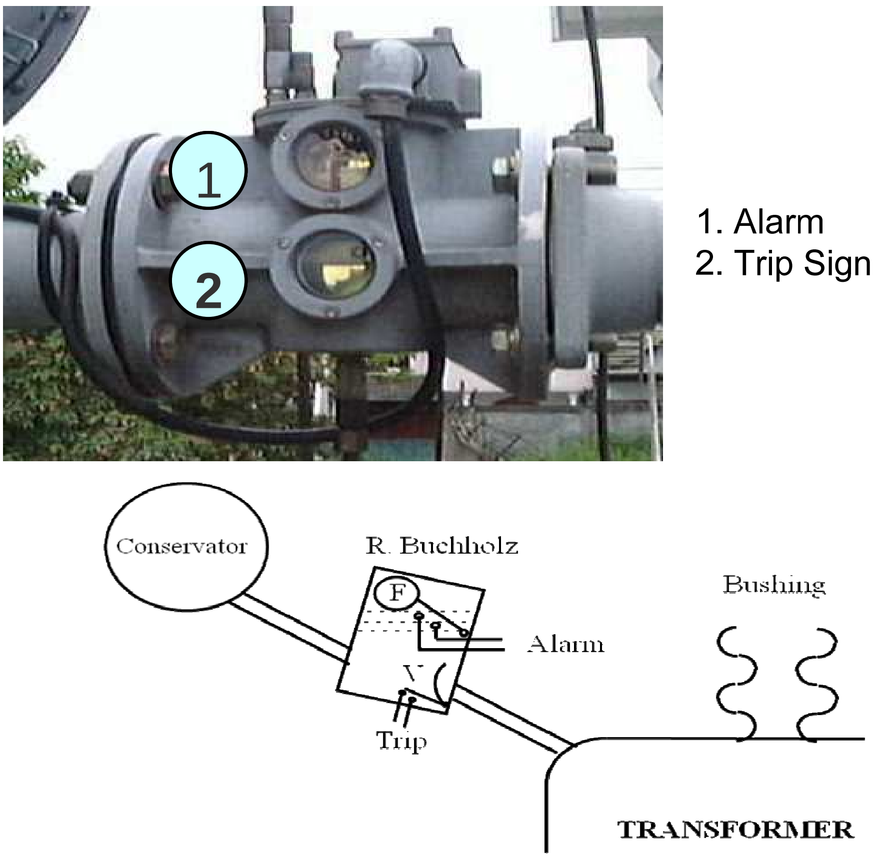


Figure 2.1 Buchholz Relay

Table 2.3 Buchholz Relay on Different Transformer Rating

Transformer rating (MVA)	Pipe diameter (in)	Alarm volume of gas (cm3)	Trip minimum oil velocity (cm/s)
up to 1 MVA	1	110	70 – 130
1-10	2	200	25 – 140
>10	3	250	90 - 160

Transformer conditions can cause an alarm signal:

- hot spots in a core caused by short circuiting in laminations
- breakdown on the insulation
- winding faults causing low currents
- leakage of oil

Buchholz relay has two signals in its operation i.e. alarm signal and trip signal.

Temperature relay

Temperature relay works based on the temperature of the transformer. When the temperature is high, then this relay will give the alarm signal. If the temperature is extremely high, then this relay will send a trip command to the circuit breaker.

The temparature sensors are also commonly used to start and stop the cooling system of the transformer.

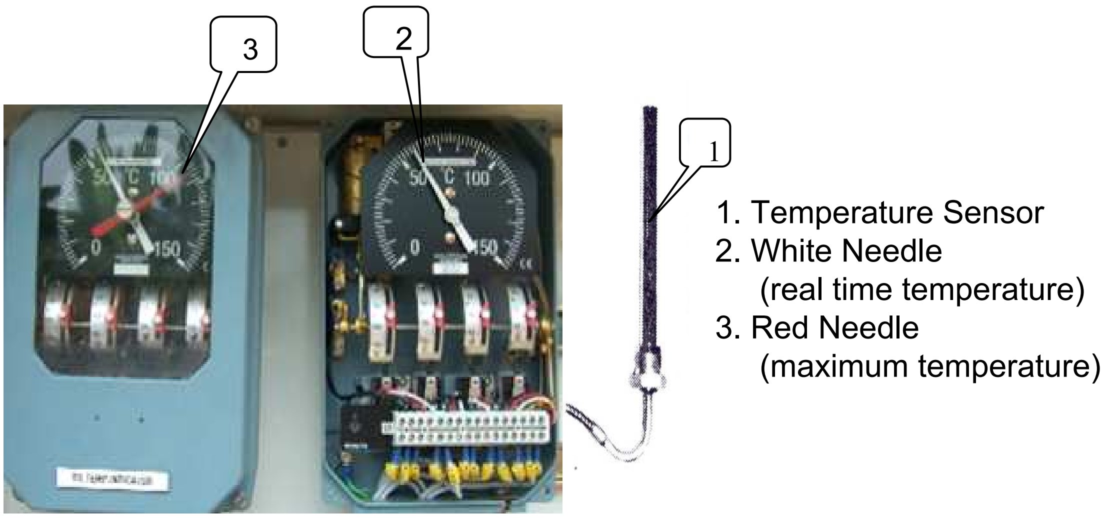


Figure 2.2 Temperature Relay

Sudden Pressure Relay

The sudden pressure relay operates based on the rate of rise of gas in the transformer. It can be applied to any transformer with the sealed air or gas chamber above the oil level. It will not operate on static pressure or pressure changes resulting from normal operation of the transformer. This sudden pressure relay is usually found at the transformer with a gas cushion at the top of the bank. Just the same with Buchholz relay, a pressure wave created by a fault is detected by this relay.

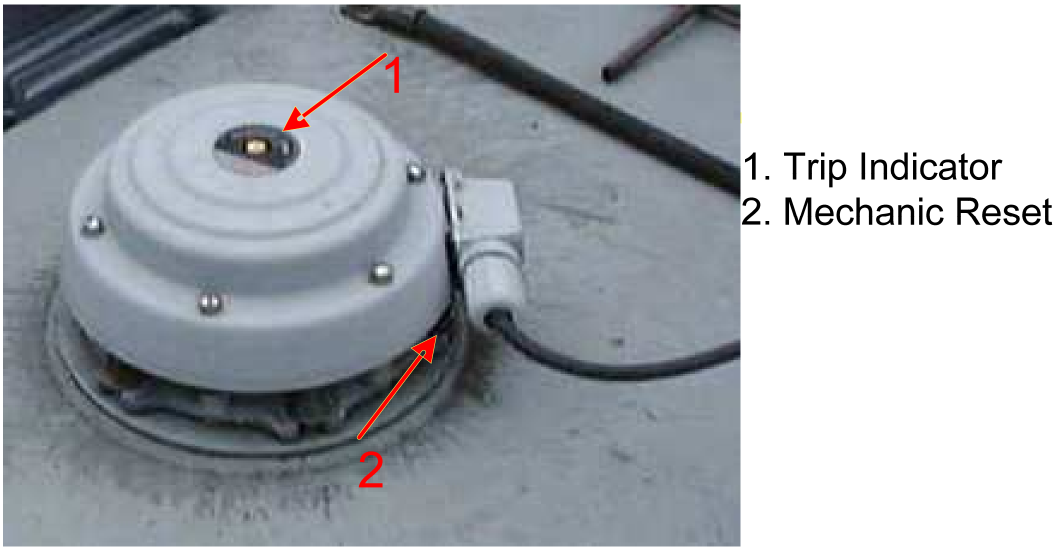


Figure 2.3 Sudden Pressure Relay

There are two types of sudden pressure relay, membrane type and pressure relief valve type. For membrane type, the membrane will break when the pressure is above its design. For pressure relief valve type, the valve will open and remove the pressure with the oil when the pressure inside the transformer exceeds the spring pressure. The valve is pressed by the spring in the normal condition.

Faults on the bushings do not create an arc in the insulating oil and must be protected by other protection system. The combination of the pressure relay (sudden pressure relay and Buchholz relay) and differential relay provides an excellent protection system for a power transformer.

2.4. Electrical Protection

There are many electrical protective relays that are installed to protect the transformer. Figure 2.4 shows all of the electrical protection relays with their protection zone. The transformer is also equipped with some control equipments i.e tap changer control and metering as shown in figure 2.5

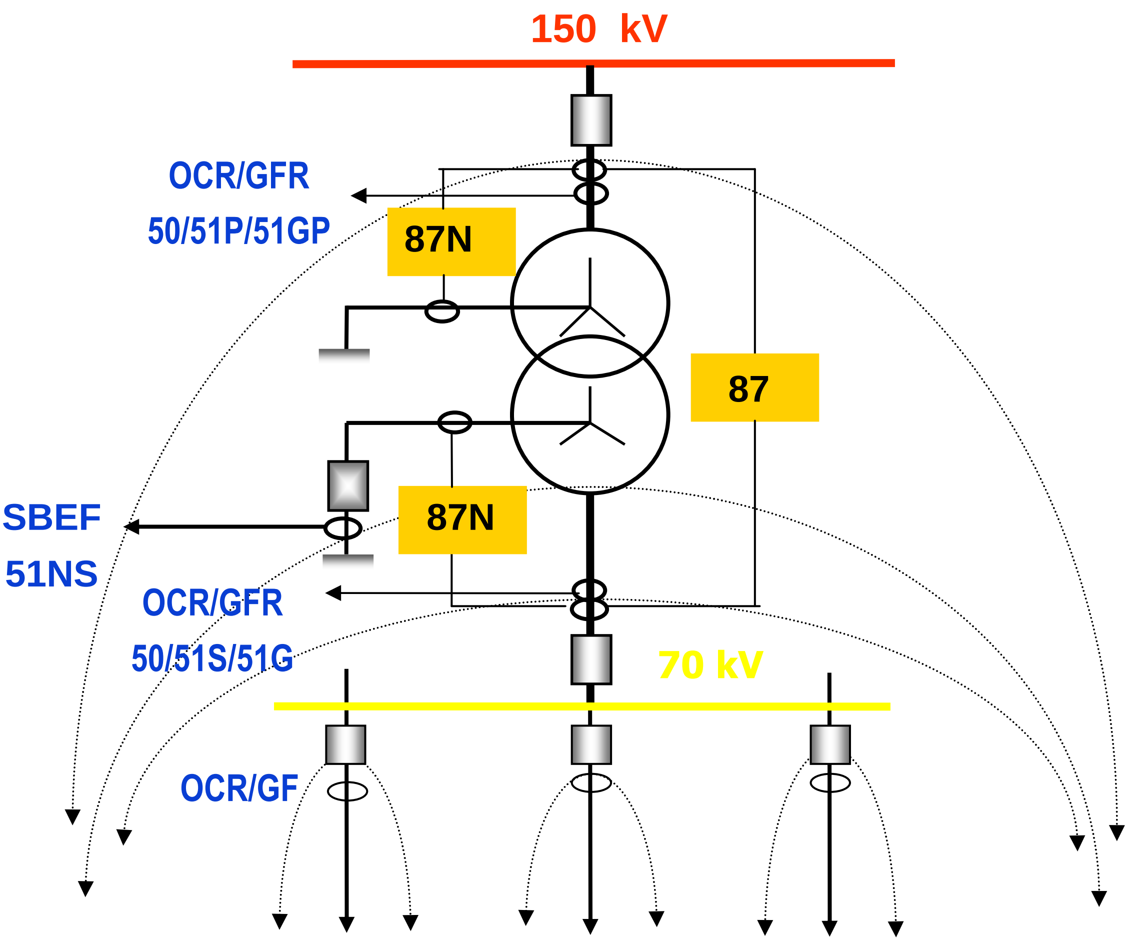


Figure 2.4 Electrical Transformer Protection

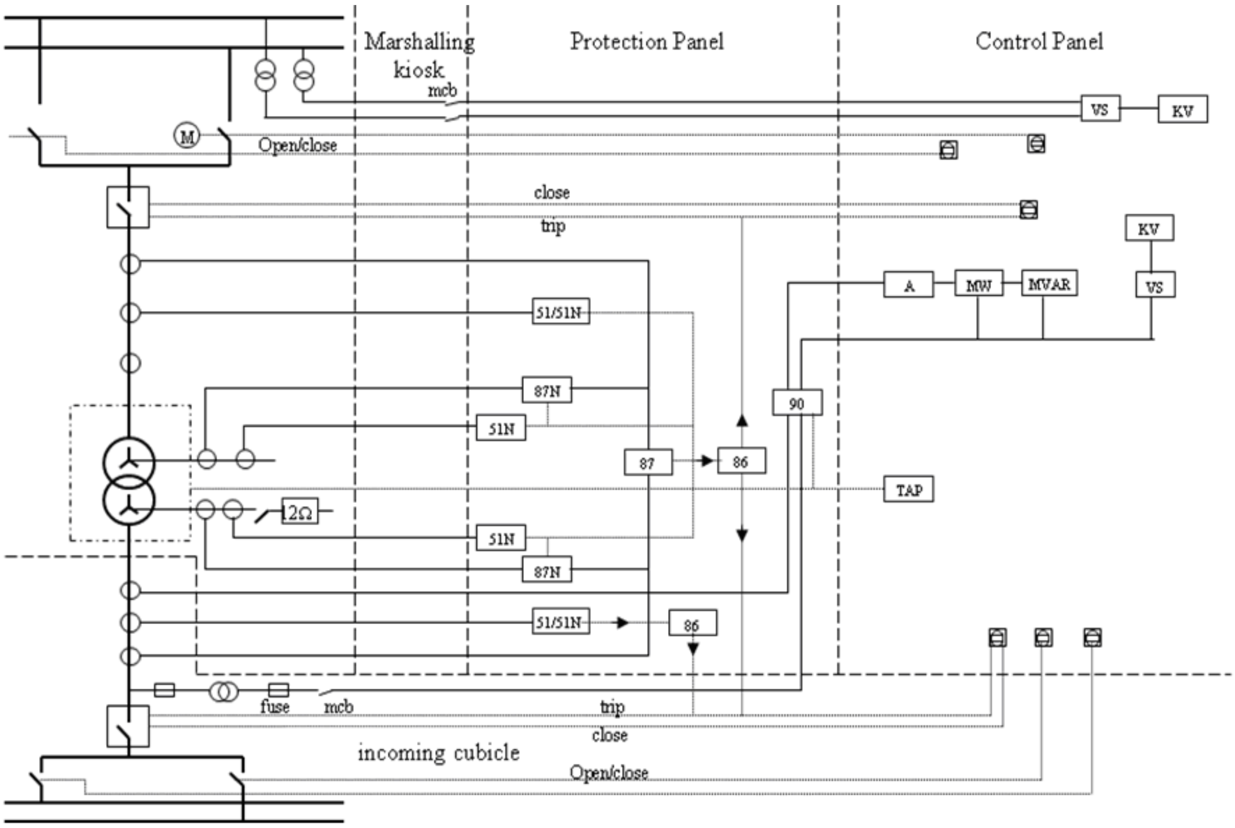


Figure 2.5 Typical Wiring of Electrical Transformer Control and Protection System

Differential relay

Differential protection relies on the Kirchoff's Current Law that states the sum of currents entering a node equals the sum of currents leaving a node. Applied to differential protection, it means that the sum of currents entering a bus (transformer, transmission line, busbar, or generator) equals the sum of those leaving. If the sum of these currents (for a given circuit) is not zero, then it must be due to a short circuit caused either by an earth fault or a phase-to-phase fault.

Differential relays take a variety of forms, depending on the equipment they protect. The definition of such a relay is "one that operates when the vector difference of two or more similar electrical quantities exceeds a predetermined amount" [32].

Differential relay is one of the protective relays of the transformer. It is accurate to detect the internal fault of the transformer even when the primary and secondary currents are not higher than the nominal current. But, it also has limitation when the turn-to-earth fault is near the neutral end of the transformer. The normalized primary and secondary current difference is not big enough to operate the relay. The same condition happen if there is turn-to-turn fault when the faulty (short circuited) turns are small.

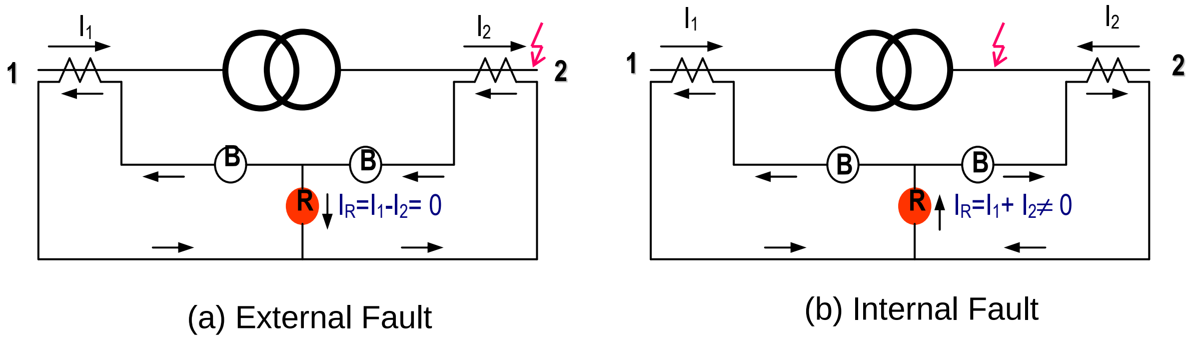


Figure 2.6 Principle of Differential Relay Protection

Figure 2.6 shows an explanatory diagram illustrating the principle of the differential relay protection. Current transformers with similar characteristics and ratio are connected on the both sides of the transformer and a relay is connected between the two current transformers by using pilot wires. Under healthy or external fault conditions, the current distribution as shown in figure 2.6 (a), no current flowing in the relay. When the internal fault occurs as shown in figure 2.6 (b), the conditions of balance are upset and current flows in the relay to cause operation. It can be noted also that the protected zone of this differential relay is between the two current transformers. If the fault had occurred beyond, as shown in figure 2.6 (a), than the operation will not occur as the fault current would then flow through both current transformers thus maintaining the balance.

Transformer differential relay are subject to several factors that can cause maloperation such as : different voltage level, including tap changer, which result in different currents in the connecting circuits, ratio mismatch between current transformers , mismatch that occur on the taps, phase-angle shift introduced by transformer wye(star)-delta connections, and magnetizing inrush currents, which differential relay sees as internal faults.

Those above factors can be accommodated by the design of current transformer and combination of relay with proper connection and applications. The connection of differential relay, current transformers, interposing current transformer, and auxiliary current transformers (ACT) is used to overcome the above factor for the older/electromechanical differential relay protection. For the newer/numerical differential relay, the information of the transformer and current transformer connection must be included correctly to the relay setting without any auxiliary connections.

In general, the current transformers on the wye side must be connected in delta and the current transformers on delta side connected in wye. These arrangements will compensate the phase angle shift introduced by wye delta bank and blocks the zero sequence current from the differential circuit on external ground faults. The zero sequence current will flow in the differential circuit for external ground fault on the grounded wye side; if the current transformer connected in wye, the relay would misoperate. With the current transformers connected in delta, the zero sequence current circulates inside the current transformers, preventing relay maloperation.

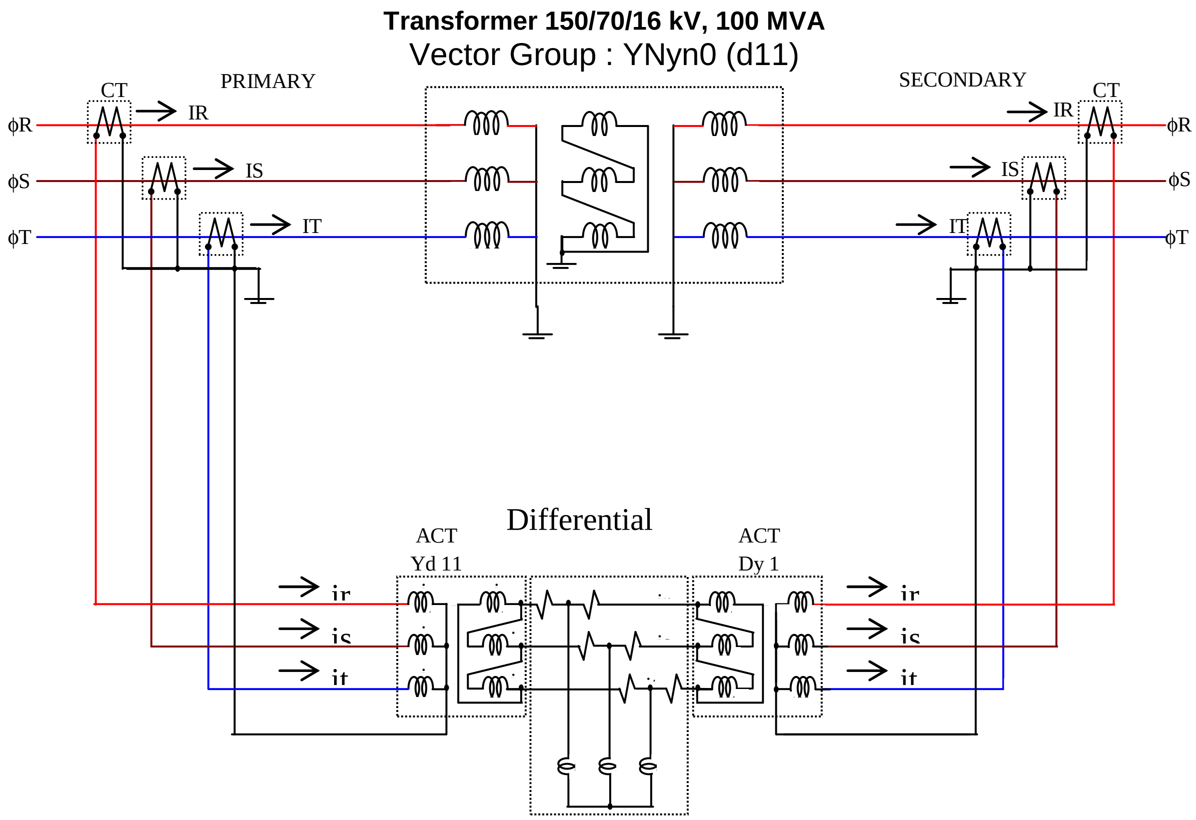


Figure 2.7 The design of current transformer and combination of relay for 150/70/16 kV YYd transformer.

Auxiliary current transformers or relay taps ratios should be as close as possible to the current ratios for a balanced maximum load condition. When there are more than two winding, all combinations must be considered.

After current transformer ratios and auxiliary current transformer taps have been selected, the continuous rating of relay should be checked for the compatibility of transformer load.

If the relay current exceeds its continuous rating, a higher current transformer ratio or auxiliary current transformer may be required.

The percentage of current mismatch should be checked to ensure the auxiliary current transformer selected have adequate safety margin. Percentage mismatch can be determined as:

$$M = \left| \frac{\frac{I_L}{I_H} - \frac{T_L}{T_H}}{S} \right| \times 100\% \qquad (2.1)$$

Where I_L and I_H are the relay input currents for low and voltage side, T_L and T_H are the relay tap setting for low and high voltage side and S is the smaller between those two terms (I_L/I_H) or (T_L/T_H).

The current in the differential relay will not exactly zero at the normal operating condition or when external fault occur. It is normal because the tap of the transformer, the current transformer (CT) error, mismatch, and the excitation current.

The minimum pick current of the differential relay is generally quite safe at 30% of the nominal current. It already accommodated the maximum 10% tap error, 10% CT error, 4 % mismatch, 1% excitation current, and 5% safety margin.

Number of turn Preliminary tap Terminal	Transformer rating			Number of turn Preliminary tap Terminal	Transformer rating		
	5/5 A	5/1 A	1/1 A		5/5 A	5/1 A	1/1 A
1 - 2	1	1	5	X - 7	5	5	25
2 - 3	1	1	5	7 - 8	5	5	25
3 - 4	1	1	5	8 - 9	5	9	25
4 - 5	1	1	5	S_1 - S_2	25	125	125
5 - 6	25	25	125	S_3 - S_4	18	90	90

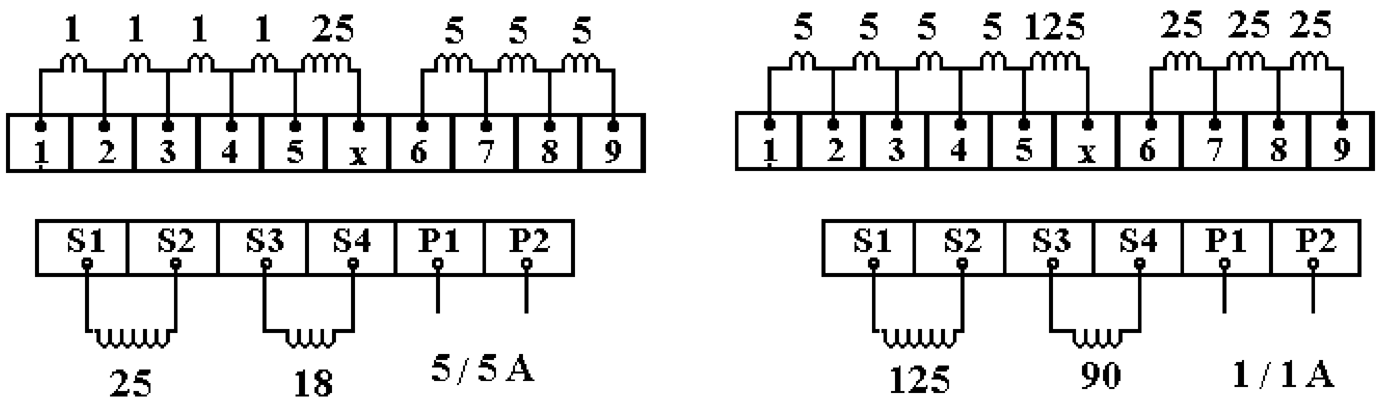


Figure 2.8 Auxiliary Current Transformer

There two types of differential relays, non-bias and bias differential relay protection. The non-bias relay only considers the differential current as a trigger to operate the relay and the bias relay considers not only differential current but also bias current to operate the relay.

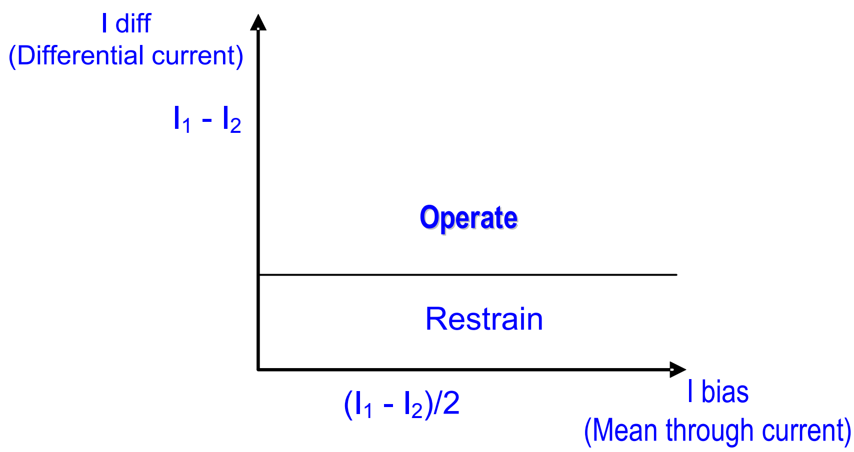


Figure 2.9 Non-Bias Differential Relay

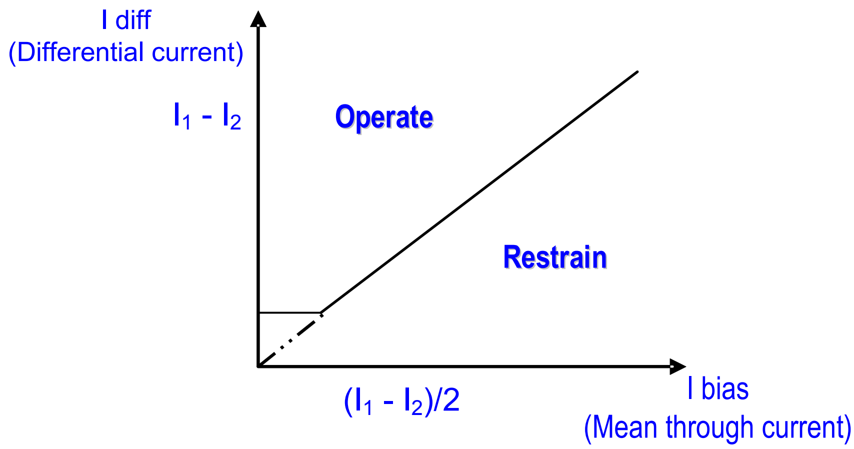


Figure 2.10 Bias Differential Relay

$$\text{Operating current} = \frac{\text{smallest current in operating coil to cause operation}}{\text{rated current of the operating coil}} \times 100\% \quad (2.2)$$

% minimum pick up current = 10 – 30% nominal current

$$\text{Slope} = \frac{\text{current in operating coil to cause operation}}{\text{current in restraining}} \times 100\% \qquad (2.3)$$

$$\%\ \text{slope} = \frac{I_1 - I_2}{(I_1 + I_2)/2} \times 100\%$$

The bias current is a function of the through fault current and stabilizes the relay against heavy through faults.

Under through-fault conditions, when operation is not required, no current should flow on the relay but because of imperfect matching of the current transformers and the effect due to tap changing, some spill current may exceed the minimum pick up current and flow in the relay. This, however, will not cause any operation of the relay unless the ratio of differential current to mean through fault current is exceeded and the restraint or bias which is increases as the through fault current increases, thus enabling sensitive settings to be obtained with high degree of stability.

Over Current Relay (OCR) and Ground Fault Relay (GFR)

Over current relay is classified as back up protection of the transformer because it is not sensitive enough to detect the internal fault. It is installed at the source side and also the load side of the transformer. It will work if the current is over the setting of the relay.

To allow transformer overloading when necessary, the pick up value of the over current relays must be set up above the nominal current. The definite minimum operating time at currents above a certain level or pick up current setting is an essential feature to obtain adequate discriminating time margins. To obtain flexibility, tappings are provided on the main input winding with a current value or percentage being assigned. The pick up current in Java Bali system is set 1.2 times nominal current of the transformer with inverse characteristics.

Fast operation is not possible, since the transformer relays must coordinate with all other relays they overreach. Some times it also has definite time characteristics with instantaneous trip command when the current is around 8-10 times of the nominal current. This setting must be above the inrush current. Often, instantaneous trip units cannot be used because the fault currents are too small.

Table 2.3 Over Current Relay (OCR) Setting

No	Description	Primary (150 kV)	Secondary (70 kV)
1	Relay Type	Non Directional Over Current Relay	Non Directional Over Current Relay
2	Characteristic	Standard Inverse	Standard Inverse
3	Current Setting	1.2 x transformer nominal current	1.2 x transformer nominal current
4	Time Setting	Δt = 0.3-0.5 second from tripping time of the bus 70 kV (recommendation : 0.5 second)	Δt = 0.3-0.5 second from tripping time of the feeder or line (recommendation : 0.5 second)
5	Instantaneous Trip	transformer nominal current x (1/Z(pu))	0.5 x transformer nominal current x (1/Z(pu))

GFR is in the same unit with the OCR but the input comes from the neutral current transformer. The setting of the ground fault relay are :

Table 2.4 Ground Fault Relay Setting

No	Description	Primary (150 kV)	Secondary (70 kV)	Neutral Transformer
1	Relay Type	Non Directional Ground Fault Relay	Non Directional Ground Fault Relay	Stanby Earth Fault Relay

2	Characteristic	Standard Inverse	Definite Time	Definite Time
3	Current Setting	0.2 x transformer nominal current	(0.2 – 0.4) x nominal current of Neutral Grounding Resistor (NGR)	NGR maximum continuous current
4	Time Setting	Δt = 0.3-0.5 second from tripping time of the bus 70 kV (recommendation : 0.5 second)	Δt = 0.3-0.5 second from tripping time of the feeder or line (recommendation : 0.5 second)	0.5 x NGR thermal strength time
5	Instantaneous Trip	Not activated	Not activated	Not activated

Restricted Earth Fault (REF) relay

REF relay use the same mechanism of differential relay. It works when the current flow through the relay is over the setting of the relay. The only difference is that REF relay has inputs from the current transformer of the grounding and neutral. When there's turn to ground fault then the fault current will flow through the grounding and compared to the neutral current and will be detected by this relay.

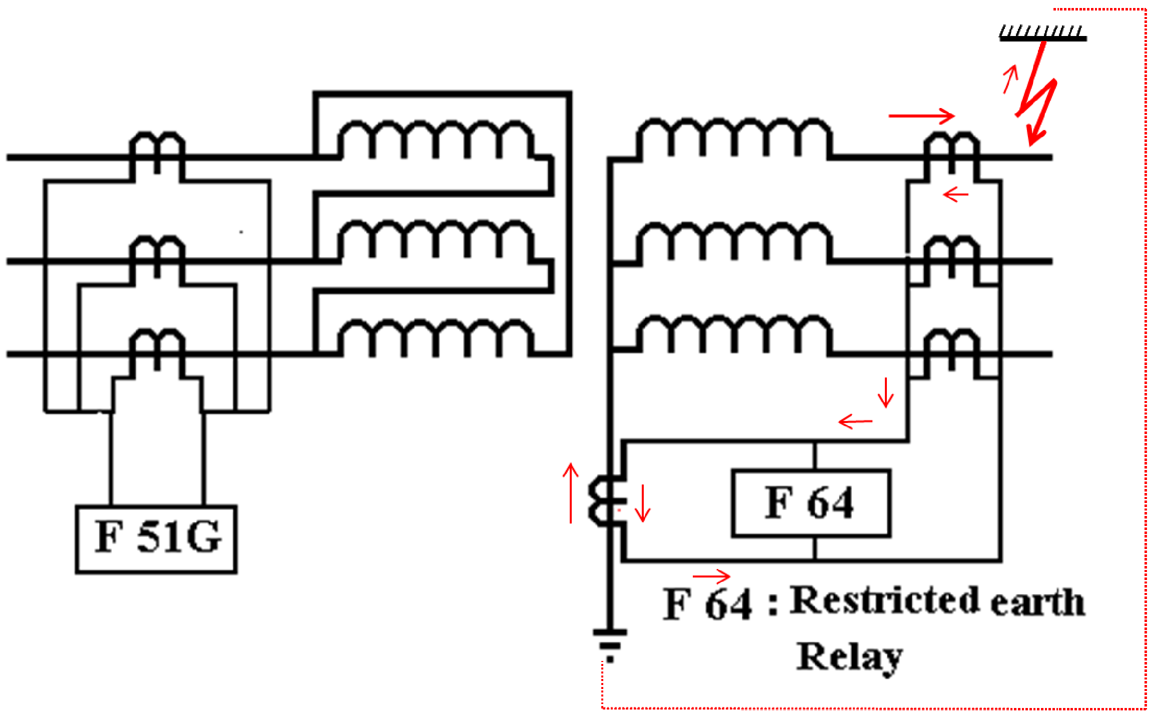


Figure 2.11 External Fault Current Distribution in REF Relay

From figure 2.11 above, it could be seen that there is no current flow at the REF relay when external fault occurs. On the other hand, the REF relay will operate when the earth fault happen in the internal protected zone in figure 2.12.

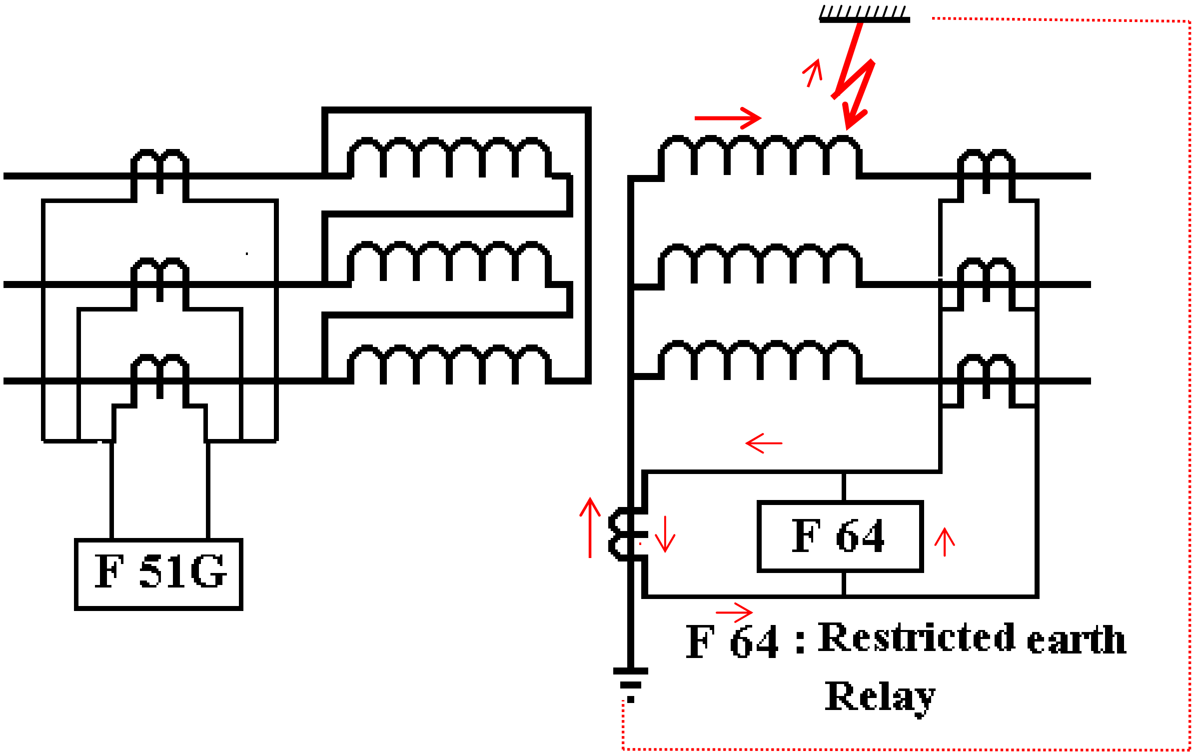


Figure 2.12 Internal Fault Current Distribution in REF Relay

III. TRANSFORMER MODELING ON ATPDraw

3.1. Introduction

The transformer which is modeled in this thesis is 150/70/16 kV three-phase three-winding YYd transformer. The transformer is already installed at Wlingi Substation. It is manufactured by PT Pauwels Trafo Asia, a subsidiary company of Pauwels that produce transformer and other primary equipment in Indonesia. The detail transformer design and factory test result can be shown on the appendix.

3.2. BCTRAN Modeling

The transformer model could be built by using a lot of components, i.e BCTRAN, saturated transformer, coupled inductance, etc. BCTRAN is used in this model because of the available data of the transformer.

The inputs of BCTRAN consist of MVA, voltage, winding connection, grounding, impedance, losses, frequency, short circuit and open circuit test, etc. They can be easily taken from the name plate and the factory test of the transformer. This name plate and factory test of the transformer is prepared by the transformer manufactures when the customer (electrical utility, industry, etc) buy it. So it is easy to get this data because all transformers are accompanied by this data. BCTRAN can make a model of any kind of transformer, two and three winding, single and three phases, wye and delta winding, and autotransformer. BCTRAN generates the impedance matrix (R and L matrix) of the transformer.

Parameters of the transformer are obtained from the transformer name plate. Number of phase, number of winding, frequency, rated power, line to line voltage, winding connection, and phase shift can be included easily without any modification. There's a special case for the type of transformer core.

Under the open circuit tab, the user can specify how the real factory test has been performed and where to connect the excitation branch. In case of a three winding transformer, HV, LV, and the TV winding could be chosen. Normally the lowest voltage is preferred, but stability problems for delta-connected nonlinear inductances could require

the lowest Y-connected winding to be used [2]. Up to 6 points on the magnetizing curve can be specified. The excitation voltage and current must be specified in % and the losses in kW. With reference to the ATP Rule Book[1], the values at 100 % voltage is used directly as IEXPOS=Curr (%) and LEXPOS=Loss (kW). One exception is if External Lm is chosen under positive core magnetization. In this case only, the resistive current is specified resulting in IEXPOS=Loss/(10 * SPOS), where SPOS is the Power (MVA) value specified under Ratings of the winding where the test has been performed. If zero sequence open circuit test data are also available, the user can similarly specify them to the right. The values for other voltages than 100 % can be used to define a nonlinear magnetizing inductance/resistance.
This is set under positive core magnetization:

- Specifying Linear internal will result in a linear core representation based on the 100 % voltage values.
- Specifying External Lm//Rm the magnetizing branch will be omitted in the BCTRAN calculation and the program assumes that the user will add these components as external objects to the model.
- Specifying External Lm will result in calculation of a nonlinear magnetizing inductance first as an Irms-Urms characteristic, then automatically transformed to a current-fluxlinked characteristic (by means of an internal SATURA-like routine). The current in the magnetizing inductance is calculated as

$$I_{RMS}[A] = \sqrt{(10 \cdot Curr[\%] \cdot SPOS[MVA]/3)^2 - (Loss[kW]/3)^2} \,/ V_{ref}[kV] \qquad (3.1)$$

where V_{ref} is actual rated voltage specified under Ratings, divided by 3 for Y- and Auto-connected transformers.

The user can choose to Auto-add nonlinearities under Structure and in this case the magnetizing inductance is automatically added to the final ATP-file as a Type-98 inductance[1]. ATPDraw connects the inductances in Y or D dependent on the selected connection for actual winding for a 3-phase transformer. In this case, the user has no control on the initial state of the inductor(s). If more control is needed (for instance to calculate the fluxlinked or set initial conditions) Auto-add nonlinearities should not be checked. The user is free to create separate nonlinear inductances, however. The Copy+ button at the bottom of the dialog box allows the user to copy the calculated nonlinear characteristic to an external nonlinearity. What to copy is selected under View/Copy. To copy the fluxlinked-current characteristic used in Type-93 and Type-98 inductances Lm-flux should be selected.

Other type is chosen during the build up of BCTRAN for accommodating the type of transformer core. Other type means that the core is three-legged or five-legged core type or shell type. It tells us that there's coupled inductance between windings at different phase. The triplex type means three-single phase transformer in a bank, there's no coupled inductance between windings at different phase.

Open Circuit Test

The positive sequence open circuit parameters can be easily obtained from load/copper test of the transformer. The open circuit test is usually done in the lowest voltage of the transformer [3]. The zero sequence excitation current is set 100%[2]. It means the type of the core is three-legged core type. The leakage flux flows via the transformer bank or air.

The transformer has delta connected windings, so the delta connections should be opened for the zero sequence excitation test. Otherwise, the test really becomes a short circuit test between excited winding and the delta connected winding. On the other hand, if the delta winding is always closed in operation, any reasonable value can be used for the zero sequence exciting current because its influence unlikely to show up with the delta connected winding providing a short circuit path for zero sequence currents.

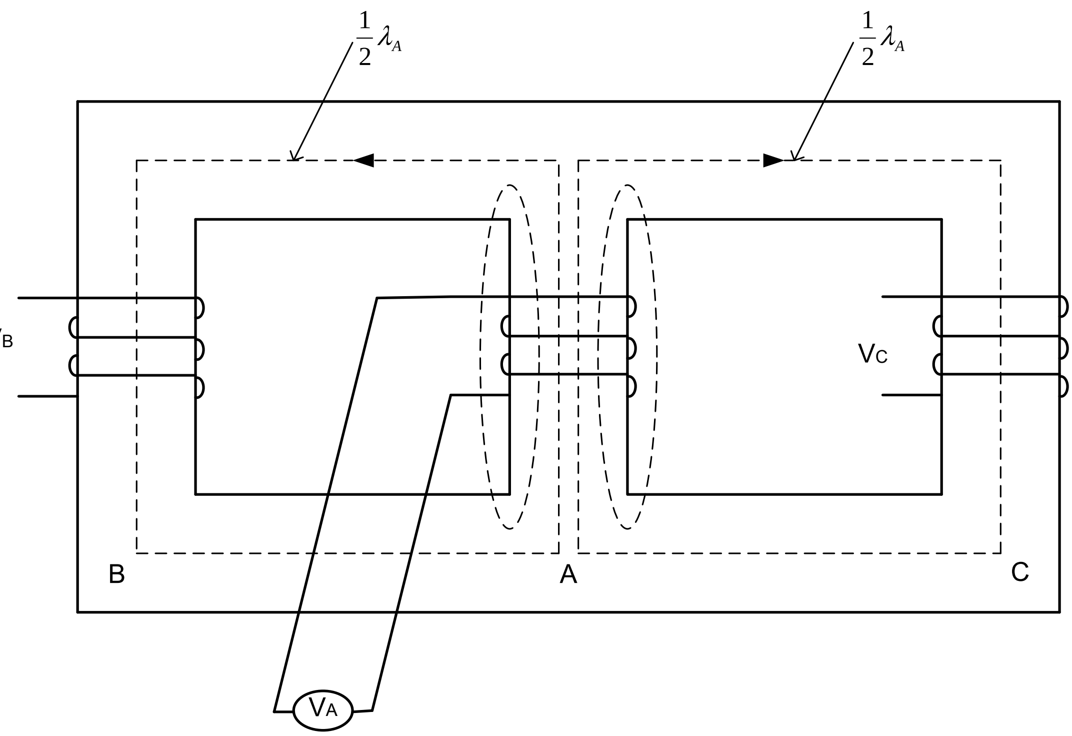


Figure 3.1 Fluxes in Three-legged Core Type Design [2]

In this transformer model, the zero sequence exciting current is not given by the manufacturer, a reasonable value could be found as follows: the one leg of the transformer is excited, then estimate from physical reasoning how much voltage will be induced in the corresponding coils in two other legs. The induced voltage will be different due to the core design of the transformer.

For the three-legged core design, approximately one half of the flux λ_A returns through phase B and C, which means that induced voltages V_B and V_C will be close to 0.5 V_A with reversed polarity. The working formula is :

$$\frac{I_{exc-zero}}{I_{exc-pos}} = \frac{1+k}{1-2k} \tag{3.2}$$

Equation (3.2) above is derived from :

$$V_A = Z_S I_A \tag{3.3}$$

$$V_B = V_C = Z_M I_A \tag{3.4}$$

With Z_S and Z_B are the self and mutual magnetizing impedances of the three excited coils. With

$$V_B = V_C = \frac{Z_M}{Z_S} V_A = \frac{Z_0 - Z_1}{Z_0 + 2Z_1} V_A = -kV_A \tag{3.5}$$

And Z_0 and Z_1 inversely proportional to $I_{exc-zero}$ and $I_{exc-pos}$, equation (3.2) follows. Obviously, k can not be exactly 0.5 because it would lead to an infinite zero sequence exciting current. A reasonable value for to $I_{exc-zero}$ in three-legged core design might be 100%.

The $I_{exc-pos}$ in the modeled transformer is 0.145 %, k would become nearly close to the theoretical value 0.5.

For five legged core type design, the proposed value for Iexc-zero/ Iexc-pos is 4 [2].

Short Circuit Test

The positive and zero sequence short-circuit can be obtained from the no-load test of the transformer. The only modification must be done is the modification of the zero sequence impedance between primary winding and secondary winding of the transformer (Z_{HL})[2]. It must be done because when the manufacture test the zero sequence, the tertiary winding of the transformer is always closed.

The calculation of the zero sequence impedance between primary and secondary winding is:

$$X_{HL}^{closed\Delta} = X_H + \frac{X_L + X_T}{X_{LT}} \tag{3.6}$$

$$X_{HT} = X_H + X_T \quad (3.7)$$

$$X_{LT} = X_L + X_T \quad (3.8)$$

Which can be solved for X_H, X_L, and X_T :

$$X_H = X_{HT} - \sqrt{X_{LT} X_{HT} - X_{HL}^{closed\Delta} X_{LT}} \quad (3.9)$$

$$X_L = X_{LT} - X_{HT} + X_H \quad (3.10)$$

$$X_T = X_{HT} - X_H \quad (3.11)$$

After this modification, the short circuit reactances X_H+X_L, X_H+X_T, and X_L+X_T are used as input data, with tertiary winding no longer being shorted in the test between primary and secondary winding[1].

The BCTRAN supporting objects can generate the R and A (L-1) matrix or R and ωL matrix as representation of coupled inductance which build the transformer.

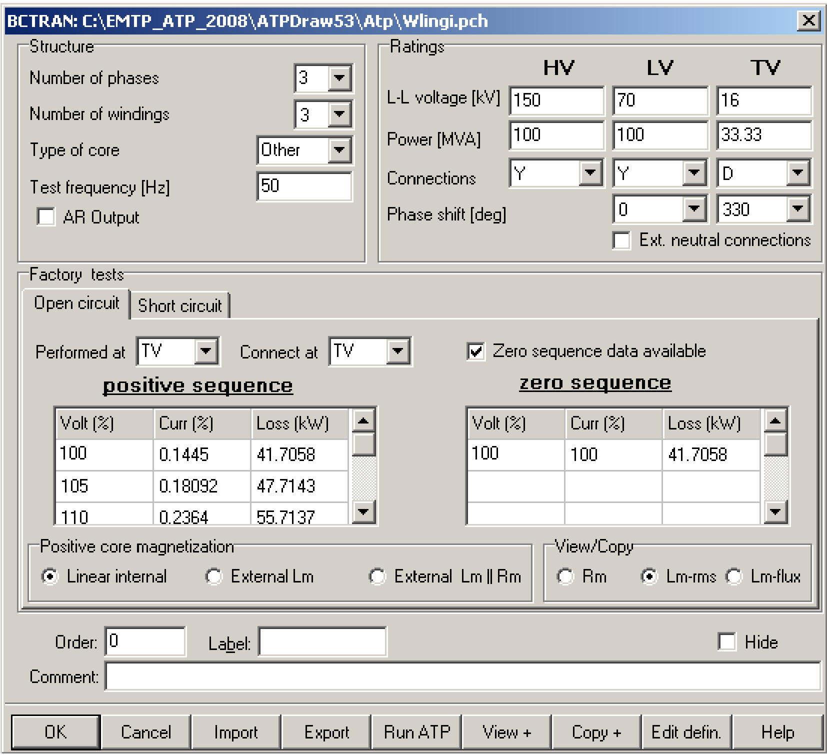


Figure 3.1 Transformer Model in BCTRAN

3.3. *Electrical System Power Component*

The modeled transformer is installed at Wlingi substation. The real condition of the system which the transformer is connected could be obtained from DigSilent program (source impedance of the substation) and Sinaut Spectrum (dynamic load of the transformer).

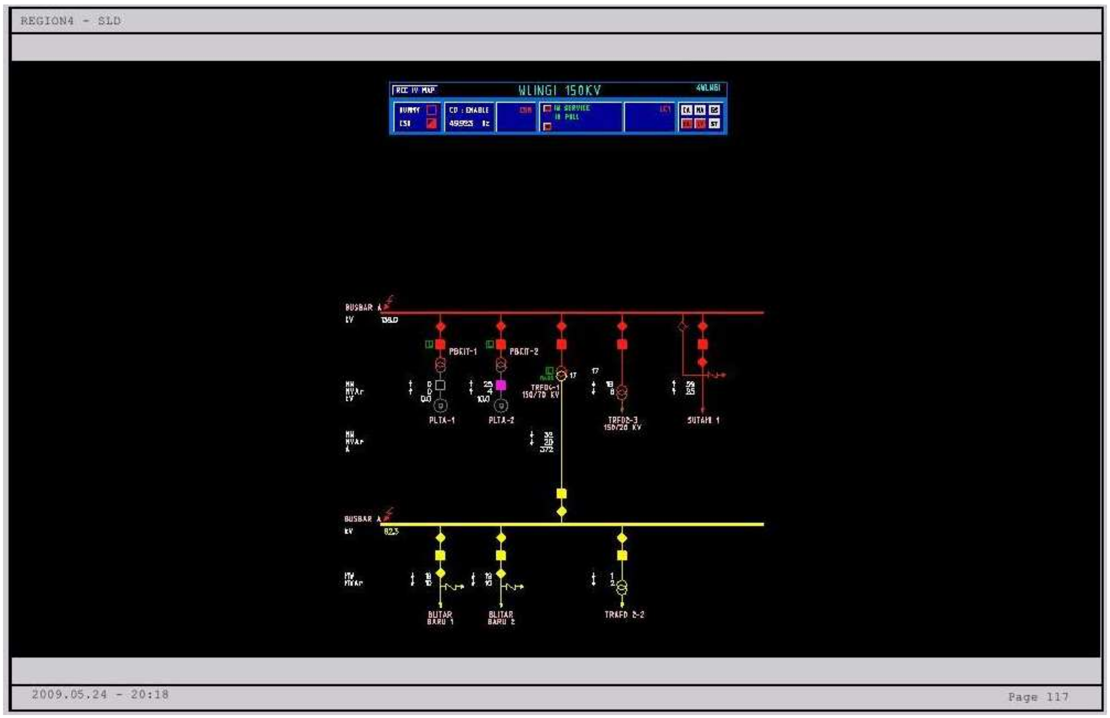


Figure 3.2 Snapshot of Sinaut Spectrum at Java Control Center SCADA system

Source Data

The voltage and source impedance of the primary connection of the transformer in Wlingi substation is provided by DigSilent program. The source impedance model is not provided by the voltage source component in ATPDraw.

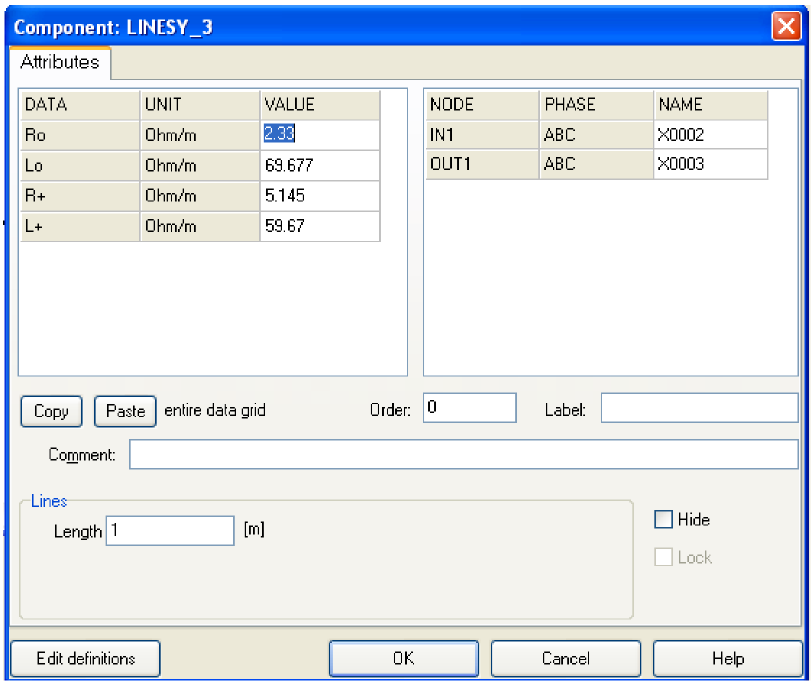


Figure 3.3 Source Impedance Model

However, the user can add the resistance and inductance component (RL component) as representation of the source impedance. The source data and the process of modeling the source is shown in figure 3.3.

Voltage : 150 kV rms line to line
Frequency : 50 Hz
Source Impedance:

Minimum fault level : $Z_{s1} = 0.02888011 + j\,0.01361679$ pu
$Z_{s0} = 0.08565811 + j\,0.1014571$ pu

Maximum fault level : $Z_{s1} = 0.02286682 + j\,0.08327282$ pu
$Z_{s0} = 0.01035353 + j\,0.09723797$ pu

Transformer

Rating : 100 MVA
Frequency : 50 Hz
Connection : Star Star Delta (YNynOd11)
Primary : 150 kV rms line to line
Secondary : 70 kV rms line to line
Tertiary : 16 kV rms line to line

Circuit Breakers

Resistance when open : 1 MΩ
Resistance when closed : 0.005 Ω

Fault Switches

Resistance when open : 1 MΩ
Resistance when closed : 0.01Ω for solid faults

Pre-Fault Dynamic Load

Secondary winding or LV winding will be loaded with variable load. It can be modelled easily by the resistance and inductance component (RL component). The load data is obtained from Sinaut Spectrum of SCADA system at Java Control Center (JCC).

Dynamic Load with

Minimum load : $Z_{Lmi} = 16.65 + j\,8.43$ MVA
Maximum load : $Z_{Lmx} = 36.51 + j\,23.87$ MVA

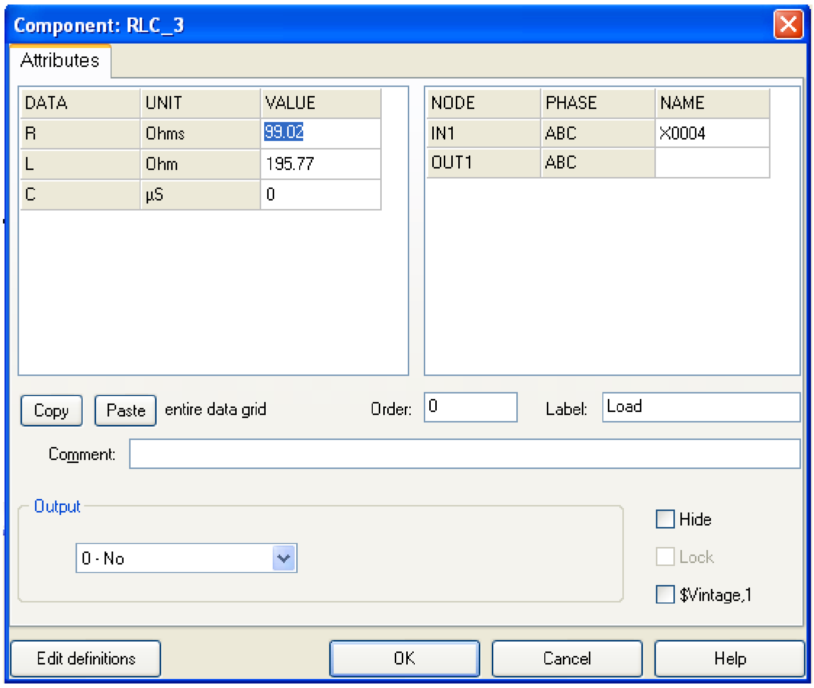


Figure 3.4 Load Model

In the real system, the tertiary winding of the transformer is unloaded. In order to avoid matrix singularity during simulation, the realistic value of capacitance (0.003 μF) is used as the connection from tertiary winding to the earth [1].

Current Transformers (CT)

The current transformers is used for the test cases that involve CT saturation. The current transformer data are as follows:

Knee point voltage (Vknee) : 185 V

Internal secondary winding resistance (Rct) : 2.3 Ω

Internal secondary lead resistance (Rl) : 4.1 Ω

Internal saturated secondary winding resistance (Rctsat) : 50 Ω

Ratio : HV side 400:1

LV side 600:1

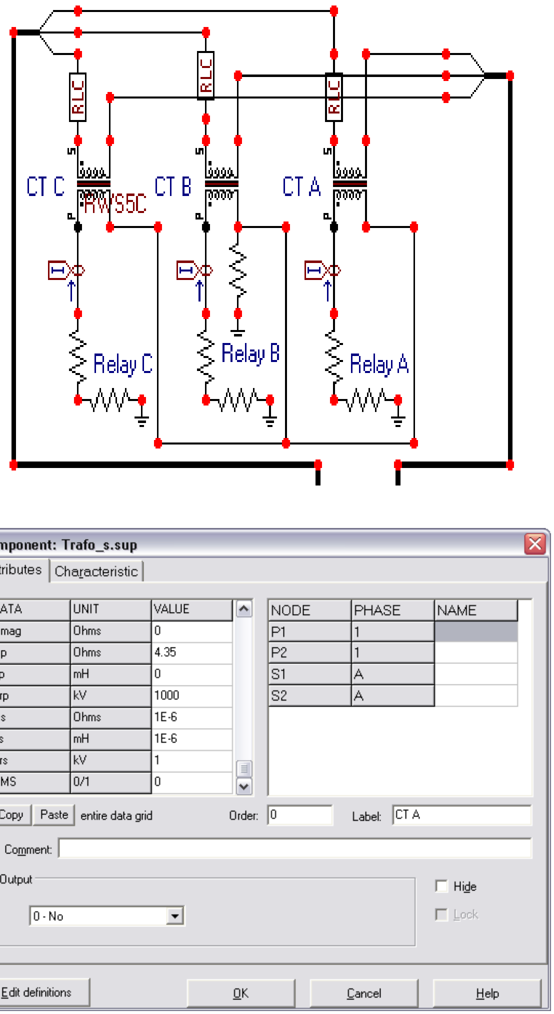


Figure 3.5 Current Transformer Model in ATPDraw

The model in this thesis will not use the CT modeling because the testing of the differential relay will not be done with the real secondary test set. The operation and the characteristics of the differential relay is only plotted manually on Omicron software.

User Specified Object

User specified object with the new library is built to represent transformer when internal fault occurs. The healthy transformer impedance matrix will be generated by the BCTRAN routine. The impedance matrix of this transformer is 9x9 because the modeled transformer is three-phase three-winding transformer. When turn-to-earth fault happen, the impedance matrix will be in 10x10 because it will accommodate the fault point and connected to the earth. Whilst 11x11 impedance matrix will become the representation of turn-to-turn fault that accommodate 2 (two) fault points and connected them each other.

The explanation how to get the new element matrix for internal fault will be described later (chapter 4).

3.4. Verifying the Model

To verify the model, some simulation test of the transformer can be done to compare the result with the open circuit and short circuit test that have been done in the factory. The open circuit simulation test determines the excitation measurement of the transformer. That's why open circuit test is well-known as excitation test. This test is carried out by connecting the lowest voltage winding (tertiary winding) to the voltage source and opening the other winding (primary and secondary winding).

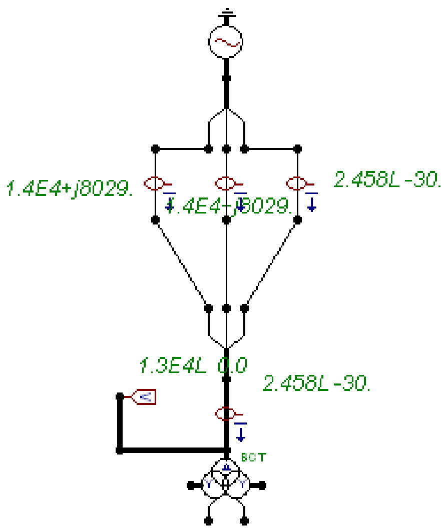


Figure 3.6 Open Circuit Test Simulation

The three-wattmeter method is used for the copper-loss measurement. In real test, the wattmeter current coil is connected to the current in each phase, and the voltage coil is connected across the terminals of that phase and neutral. The sum of the three readings taken each phase successively is the total copper loss of the transformer [27].

In the simulation of this test the total copper loss can be read as the sum of the wattmeter in each phase.

Table 3.1 Open Circuit Test Result

TYPE TEST		Test Data	Simulation	Difference (%)
Excitation Measurement/Open Circuit Test				
Excitation Voltage	kV	71.52	71.52	0
Excitation Current	Amperres	5.1	5.1	0
Excitation Losses	Watts	118.69	118.76	0.0589772

The short circuit simulation test is done three times per transformer. This test is done without connecting the transformer to the load, however it's also called no-load test. This test will provide the information of short circuit current and voltage and transformer losses. The no-load current is given by ammeter reading obtained in each phase. The algebraic sum of the three wattmeter readings will then give the total iron losses.

The test connections and result are shown:

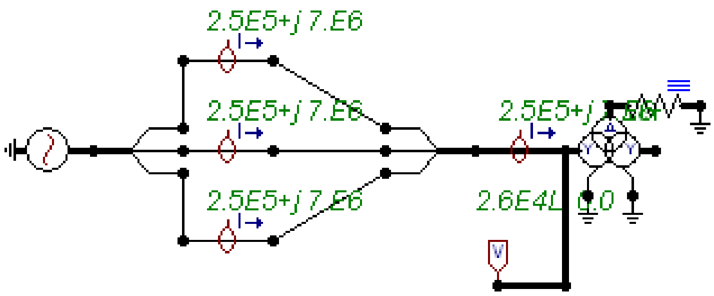


Figure 3. 7 Short Circuit Test

Table 3.2 Short Circuit Test Result

TYPE TEST		Test Data	Simulation	Difference (%)
No-load/Short Circuit Test HV-LV				
SC Voltage	Volts	38093	38093	0
SC Current	Amperres	577	577	0
SC Losses	Watts	369.45	369.50	0.0135336
HV-TV				
SC Voltage	Volts	31225	31225	0
SC Current	Amperres	260	258	0.7692308
SC Losses	Watts	89.19	87.83	1.5248346
LV-TV				
SC Voltage	Volts	3574	3574	0
SC Current	Amperres	773	770	0.3880983
SC Losses	Watts	57.76	57.28	0.8310249

The difference between simulation and the real test is very small, so the model of the transformer can be used and connected to the electrical network (grid) to make further simulation.

After all successful tests have been done to verify the model of the transformer, all of the power system components can be integrated in one system.

IV. TRANSFORMER INTERNAL FAULT MODELING

4.1. Introduction

This chapter is the main part of modeling for internal fault of the transformer. The matrix modification due to the fault will be described. The chosen method and how to calculate the modified impedance matrix element is explained.

4.2. Matrix Representation of Transformers

Matrix representation of power transformer is an important step towards realization of transformer winding fault in the Electromagnetic Transient Program (EMTP/ATP). The BCTRAN routine computes two matrices (R) and (L) representing the transformer based on excitation and short circuit tests for positive and zero sequences. The transformer is three-phase three-winding transformer. In order to explain the concept, a single phase three-winding transformer will be considered first, which can be described by the following steady state phasor equations :

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \tag{4.1}$$

The matrix in equation (4.1) is symmetric. Its elements can be measured in no-load tests: if tertiary winding (coil 3) is energized, then the measured values for I_3 and V_1, V_2, and V_3 produce the column 3 of the [Z] matrix.

$$Z_{ij} = \frac{V_i}{I_j} \tag{4.2}$$

In differential equation for electromagnetic transient analysis, above equation can be written as :

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} + \begin{bmatrix} L_{11} & L_{12} & L_{13} \\ L_{21} & L_{22} & L_{23} \\ L_{31} & L_{32} & L_{33} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \tag{4.3}$$

Where [R] is the resistance (real part of impedance [Z]) and [L] is the inductance (imaginary part of impedance [Z] divided by ω). This model is accommodated by BCTRAN routine in the EMTP.

Extension of the impedance equation to three-phase transformer can be done. Each winding in equation (4.1) for three-phase transformer will consist of three coils for the three phases or core legs. The impedance matrix will become 3x3 matrix as follows :

$$\begin{bmatrix} Z_S & Z_M & Z_M \\ Z_M & Z_S & Z_M \\ Z_M & Z_M & Z_S \end{bmatrix} \tag{4.4}$$

where Z_S is the self impedance of the phase and Z_M is the mutual impedance among the three phases. The self and mutual impedance are related to the positive and zero sequence values Z_1 and Z_0 by:

$$Z_S = \frac{1}{3}(Z_0 + 2Z_1) \tag{4.5}$$

$$Z_M = \frac{1}{3}(Z_0 - Z_1) \tag{4.6}$$

Replacing the element of [Z] in equation (4.1) by the 3x3 sub-matrix of equation (4.4) and relating the diagonal and off-diagonal elements Z_S and Z_M to positive and zero sequence values, the three-phase three-winding transformer matrix will be obtained.

The equivalent matrix can be calculated from the data from factory acceptance test of the transformer that consist of short and open circuit test as long as exciting current is not neglected. If the exciting current is neglected or too small than the impedance matrix can not be obtained because the matrix is singular[2].

First, the imaginary parts of the diagonal element pairs ($X_{S\text{-}ii}$ and $X_{M\text{-}ii}$) from the exciting current of the positive and zero sequence in excitation (no-load) tests as :

$$Z_{ii} = \frac{V_i}{I_i} \tag{4.7}$$

With the positive and zero sequence values $X_{1\text{-}ii}$ and $X_{0\text{-}ii}$ computed by equation (4.7) the pair values are obtained by :

$$X_{S-ii} = \frac{1}{3}(X_{0-ii} + 2X_{1-ii}) \tag{4.8}$$

$$X_{M-ii} = \frac{1}{3}(X_{0-ii} - X_{1-ii}) \tag{4.9}$$

As the sequence excitation tests are only carried out from one-side of the transformer, it is reasonable to assume that per-unit reactance of other windings is quite the same, since these open circuit input impedances are larger than the short circuit input impedances. If the particular winding has very little stray flux (e.g. the tertiary winding of the three winding transformer with cylindrical coil construction), an equivalent circuit where the magnetizing reactance is connected across that winding can be adopted [4].

If the winding resistances are known, they are added to the self impedance $Z_{S\text{-}ii}$ of the diagonal element pairs ($Z_{S\text{-}ii}$ and $Z_{M\text{-}ii}$). If they are not known, but the load losses tests are given, they could be calculated by the load losses. The winding resistances of the transformer model in this thesis are calculated by using the load losses. Calculating winding resistances from the load losses is not exact because the losses also contain stray losses as well, but it is better than simply setting winding resistance to zero [2].

If the excitation losses are known, they must not be included in the calculation of the equation (4.8) and (4.9) because it would be implied as a resistance in series with the magnetization reactance model. Instead, shunt resistances can be externally added across one or more windings in the EMTP network to model the excitation losses. These shunt resistances are additional branches which can not be directly included in the impedance matrix representation of equation (4.1).

With the diagonal element pairs known, the off-diagonal element pairs ($Z_{S\text{-}ij}$ and $Z_{M\text{-}ij}$) are calculated from the short circuit input impedance where:

$$Z_{ij}^{short} = Z_{ii} - \frac{Z_{ij} Z_{ji}}{Z_{jj}} \tag{4.10}$$

Or $$\frac{Z_{ij}^{short}}{Z_{ii}} = 1 - k^2 = \sigma_{ij} \tag{4.11}$$

Where ρ_{ij} is defined as the leakage factor between winding i and j. k is the coupling coefficient which can be calculated as :

$$k = \sqrt{\frac{Z_{ij} Z_{ji}}{Z_{ii} Z_{jj}}} \tag{4.12}$$

In order to calculate the off diagonal elements; from equation (4.10), Z_{ij} is found as :

$$Z_{ij} = Z_{ji} = \sqrt{(Z_{ii} - Z_{ij}^{short}) Z_{jj}} \tag{4.13}$$

Related to equation (4.8) and (4.9), the positive and zero sequences are processed separately in equation (4.13). Then, they are converted into pair values.

Z_{ij}^{short} in equation (4.13) is the complex short circuit impedance and the real part is calculated from load losses and the imaginary part can be calculated by following formula :

$$X_{ij}^{short} = \sqrt{\left|Z_{ij}^{short}\right|^2 - (R_i + R_j)^2} \tag{4.14}$$

Where Z_{ij}^{short} is short circuit impedance (magnitude) and ($R_i + R_j$) is the winding resistances.

The elements must be calculated with high accuracy: otherwise, the short circuit impedance gets lost in the open circuit impedance. The lower the exciting current is, the more equal the impedances between Z_{ii}, Z_{ij}, and Z_{jj} become among themselves in equation (4.10).

4.3. Modeling Principles

The BCTRAN routine of the ATPDraw simulation software provides the model of the healthy transformer. The BCTRAN routine generates impedance matrix of the transformer, this routine can compute the two matrices R (Resistance) and L(inductance) or R and A (L-1) modeling of the transformer.

The impedance matrix of the healthy transformer will be 9x9 because it is three-phase three-winding transformer.

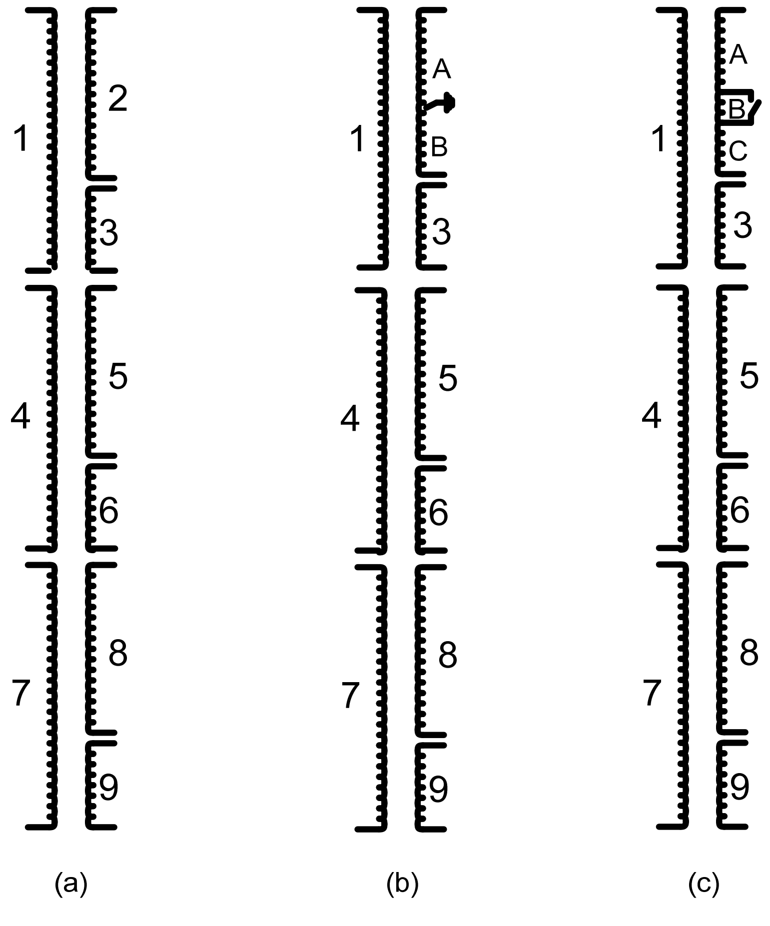


Figure 4.1 (a) Normal Transformer (b) Turn-to-earth Fault (c) Turn-to-turn Fault

Figure 4.1 (b) and (c) are shown the condition of the new matrix impedance when the internal fault occurs.

There are two methods for of calculating the new impedance matrix for representation of the transformer. The first method is by calculating the self and mutual impedance of the transformer directly. This method is proposed by [11], [14], [10], [15]. This model has limitation because it needs the very detail design of the transformer and sometimes it is hard to find this design if the transformer is old or the manufacturer did not give it to the purchaser and will be unstable if there is negative impedance[16].

The second method is by calculating the leakage inductance using leakage factor. This method considers the flux leakage elements and estimation of the flux in different parts of the transformer [4],[5],[6]. This method still needs the geometrical quantities of the transformer but still provide good solution if there is negative impedance on the transformer [16].

$$Z_H = \frac{Z_{HL} + Z_{HT} - Z_{LT}}{2} \tag{4.15}$$

$$Z_L = \frac{Z_{HL} + Z_{LT} - Z_{HT}}{2} \tag{4.16}$$

$$Z_T = \frac{Z_{LT} + Z_{HT} - Z_{HL}}{2} \tag{4.17}$$

The second method is used in this thesis because the secondary winding of the transformer will give the negative impedance value.

4.3.1. Direct Self and Mutual Impedance Calculation Method

Wilcox has proposed the calculation based on modified Maxwell equation that accommodate the finite core[11]. A major assumption of the basic formula is that the core is solid (of resistivity ρ), whereas, in practical core will be laminated to reduce the eddy current. Since the laminations is to restrict the circulation of eddy currents, than the effect of lamination is simulated by continuing treat the core as solid but with the enhanced resistivity of the core. It also becomes the main problem since there’s no exact formula to increase the resistivity value of the core. The proposed method[11] is using the impedance measurement that is almost impossible to get except on the laboratory test.

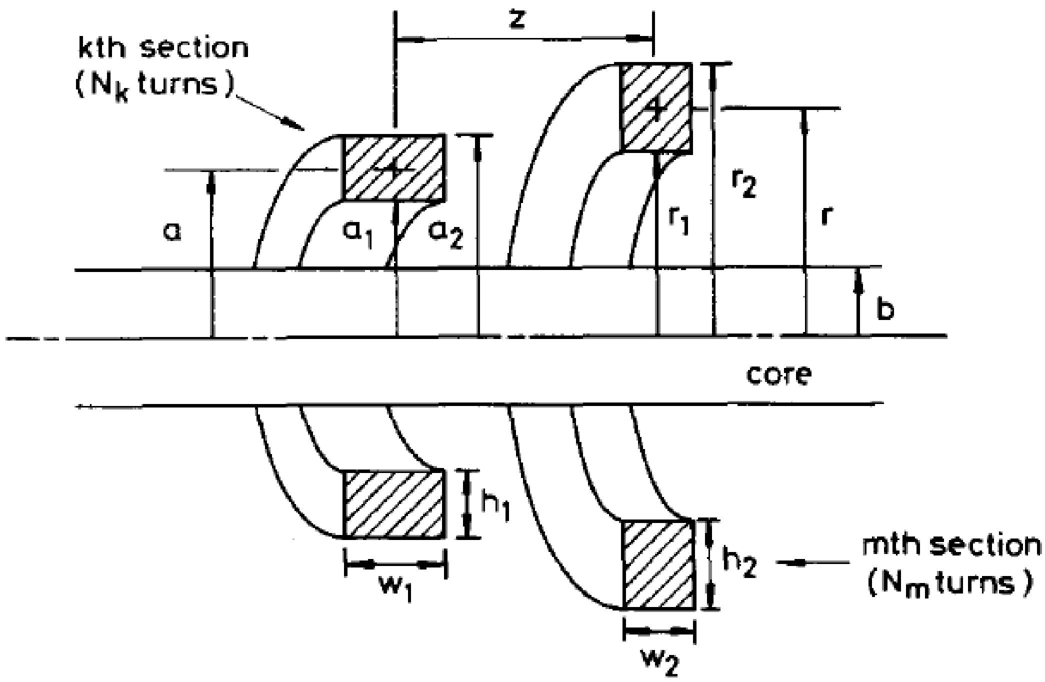


Figure 4.2 Geometric Dimension for Self and Mutual Impedance Calculation [11]

$$Z_{km} = sL_{km} + Z1_{km} + Z2_{km} \tag{4.18}$$

$$Z1_{km} = s \cdot N_k \cdot N_m \frac{\pi b^2}{\lambda} \{ \frac{2 \cdot \mu_z \cdot I_1(mb)}{m \cdot b \cdot I_0(mb)} - \mu_1 \} \tag{4.19}$$

$$Z2_{km} = s \cdot N_k \cdot N_m \frac{\pi}{\lambda} \left\{ \begin{array}{l} \dfrac{4}{h_1 \cdot h_2 \cdot w_1 \cdot w_2} \times \sum_{n=1}^{N} P_1(\beta_n a_1, \beta_n a_2) P_1(\beta_n r_1, \beta_n r_2) \\ \times Q_1(\beta_n w_1, \beta_n w_2) \dfrac{I_1(\beta_n b) F_1(\beta_n b)}{K_1(\beta_n b)} \cos(\beta_n z) \end{array} \right\} \tag{4.20}$$

where

Z_{km} = total mutual impedance between kth and mth sections within a set of transformer windings (function of the Laplace transform parameter s)

L_{km}= component of mutual inductance between kth and mth sections owing to energising field (all iron absent)

$Z1_{km}$=component of mutual impedance between kth and mth sections owing to flux confined to core

$Z2_{km}$= component of mutual impedance between kth and mth sections owing to leakage field (excluding energising field)

ω = angular frequency ($2\pi f$)

$m = \sqrt{(s \cdot \mu_z / \rho)}$ = core skin-effect parameter

s = Laplace transform parameter

ρ = effective resistivity of laminated core when treated as solid

ρ' = modified (frequency-dependent) value of ρ accounting for behavior of core relative to leakage field

μ_z = magnetic permeability of core in axial direction

$\mu_z(rel)$ = relative value of μ_z

μ_r =magnetic permeability of core in radial direction

μ_1 =magnetic permeability of medium outside the core ($\cong 4\pi \times 10^{-7}$)

α =fundamental core parameter, relating to leakage field

λ =actual or apparent length of magnetic circuit

$\beta_n = 2\pi n / \lambda$ = summation parameter (where n is an integer variable)

N_k = number of turns in kth section

N_m = number of turns in mth section

N =number of terms required for convergence

I_0 , I_1 = modified Bessel functions of first kind

K_0 , K_1 = modified Bessel functions of second kind

P_1, Q_1, F_1 = functions, dependent on coil dimensions

b, z = core radius and coil separation

$$L_{km} \cong \mu_0 \cdot N_k \cdot N_m \sqrt{(r \cdot a)} \frac{2}{\kappa}\left[\left(1 - \frac{k^2}{2}\right) K(\kappa) - E(\kappa)\right] \tag{4.21}$$

where $K(\kappa)$ and $E(\kappa)$ are complete elliptic integrals of the first and second kinds respectively, and

$$\kappa = \sqrt{\left[\frac{4 \cdot a \cdot r}{z^2 + (a+r)^2}\right]} \tag{4.22}$$

The other functions are defined by

$$F_1(\beta_n b) = s \cdot \mu_0 \left\{ \frac{f(\beta_n b) - (\mu_0 / \mu_z) f(\Gamma_n b)}{g(\beta_n b) + (\mu_0 / \mu_z) g(\Gamma_n b)} \right\} \tag{4.23}$$

$$P_1(x, y) = \frac{1}{\beta_n^2}\left[p_1(x) - p_1(y)\right] \tag{4.24}$$

$$Q_1(x,y) = \frac{2}{\beta_n^2}\left[\cos\left(\frac{x-y}{2}\right) - \cos\left(\frac{x+y}{2}\right)\right] \tag{4.25}$$

where

$$\Gamma_n = \sqrt{\left\{\frac{\mu_z}{\mu_r}\beta_n^2 + \frac{s\mu_z}{\rho}\right\}} \tag{4.26}$$

The auxiliary functions involved are defined by

$$f(\zeta) = \zeta\frac{I_0(\zeta)}{I_1(\zeta)} \tag{4.27}$$

$$g(\zeta) = \zeta\frac{K_0(\zeta)}{K_1(\zeta)} \tag{4.28}$$

$$p_1(\alpha) = \frac{\pi\alpha}{2}\left[K_1(\alpha)L_0(\alpha) + L_1(\alpha)K_0(\alpha)\right] \tag{4.29}$$

where the modified Struve functions $L_k(\alpha)$ are given by

$$L_k(\alpha) = \sum_{n=0}^{\infty}\frac{(\alpha/2)^{k+2n+1}}{[n+(1/2)]![k+n+(1/2)]!} \tag{4.30}$$

4.3.2. Leakage Impedance Calculation by Using Leakage Factor

Healthy Transformer and External Fault Condition

BCTRAN is one of the routines in ATPDraw that used to model a transformer. The inputs of BCTRAN consist of MVA, voltage, winding connection, grounding, impedance, losses, frequency, short circuit and open circuit test, etc. They can be easily taken from the data of factory acceptance test of the transformer. This test is prepared by the transformer manufactures when the customer (electrical utility, industry, etc) buy it. So it is easy to get this data because all of the transformer will be accompanied by this data. BCTRAN can make a model of any kind of transformer, two and three winding, single and three phases, star (wye) and delta winding, and autotransformer. BCTRAN generates the impedance matrix (R and L matrix) of the transformer.

In the case of three-phase transformer three-winding transformer, the impedance matrices are in order 9, see figure (a). The BCTRAN does not take magnetic asymmetry into account.

$$
R=\begin{pmatrix}
R_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & R_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & R_3 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & R_4 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & R_5 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & R_6 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & R_7 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & R_8 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_9
\end{pmatrix}
$$

$$
L=\begin{pmatrix}
L_{11} & L_{12} & L_{13} & L_{14} & L_{15} & L_{16} & L_{17} & L_{18} & L_{19}\\
L_{21} & L_{22} & L_{23} & L_{24} & L_{25} & L_{26} & L_{27} & L_{28} & L_{29}\\
L_{31} & L_{32} & L_{33} & L_{34} & L_{35} & L_{36} & L_{37} & L_{38} & L_{39}\\
L_{41} & L_{42} & L_{43} & L_{44} & L_{45} & L_{46} & L_{47} & L_{48} & L_{49}\\
L_{51} & L_{52} & L_{53} & L_{54} & L_{55} & L_{56} & L_{57} & L_{58} & L_{59}\\
L_{61} & L_{62} & L_{63} & L_{64} & L_{65} & L_{66} & L_{67} & L_{68} & L_{69}\\
L_{71} & L_{72} & L_{73} & L_{74} & L_{75} & L_{76} & L_{77} & L_{78} & L_{79}\\
L_{81} & L_{82} & L_{83} & L_{84} & L_{85} & L_{86} & L_{87} & L_{88} & L_{89}\\
L_{91} & L_{92} & L_{93} & L_{94} & L_{95} & L_{96} & L_{97} & L_{98} & L_{99}
\end{pmatrix}
$$

To check the R and L matrix generated by BCTRAN, the manual calculation could be done. If the calculation of impedance is almost the same between two methods, the matrix calculation using leakage impedance method could be done to determine the new matrix when internal fault occurs[5].

The leakage reactance between windings can be calculated from the L matrix generated by BCTRAN as shown below:

$$X_{cc} = \omega L_{ii} - \frac{(\omega L_{ij})^2}{\omega L_{jj}} \tag{4.31}$$

where i and j are the windings (primary, secondary, or tertiary) of the transformer. L_{ii}, L_{ij}, and L_{jj} can be found in 9x9 matrix computed by BCTRAN routine.

The second reactance calculation method uses the geometrical data of the transformer. It also calculates the correction factor because one of the windings may not be long enough to cover the height of the core [5],[24].

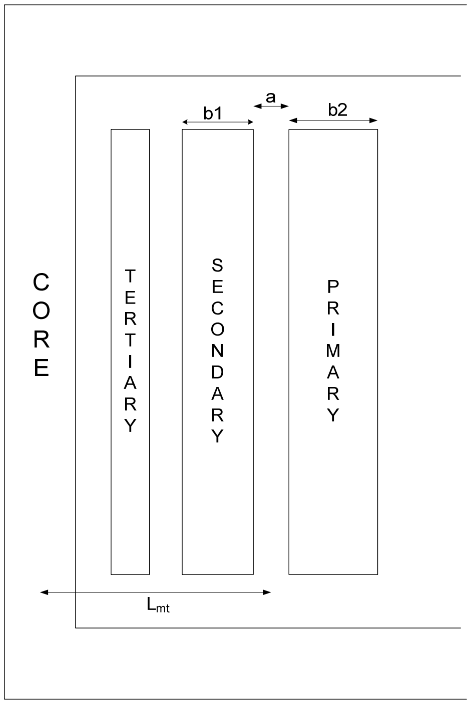


Figure 4.3 Geometrical Arrangement for Two Adjacent Windings

$$X_{cc} = cf \times \mu_0 \times N \times \omega \times \frac{L_{mt}}{L_c} \times (a + \frac{b_i}{3} + \frac{b_j}{3}) \qquad (4.32)$$

Where *cf* is the correction factor, μ_0 is the magnetic permeability, *N* is the number of turns at the winding, ω is the angular frequency ($2\pi f$), L_{mt} is the mean circumferential length of the annular duct between the coils [24],[26],[14], L_c is the height of the core, *b* is the width of the winding, and *a* is the width of the duct between windings.

The formulas which allow calculation of the correction factor have been determined by Maurice Denice-Papin[24] based on many experimental result relating to various transformers.

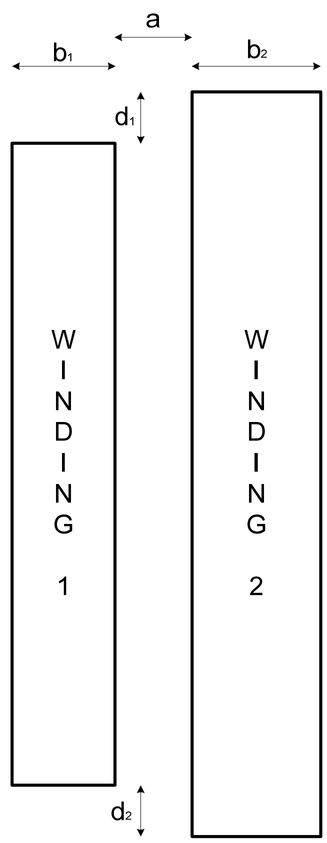


Figure 4.4 Dimension for Correction Factor Calculation

$$cf = \frac{d_1 k_1 + d_2 k_2}{d_1 + d_2} \tag{4.33}$$

The coefficient of k_1 and k_2 are defined as follows:

$$k_i = 1 + 0.1\left(\frac{d_i}{\rho}\right)^{1.6} \quad ;\ i=1;2 \tag{4.34}$$

with

$$\rho = a + \frac{b_1 + b_2}{3} \tag{4.35}$$

Table 4.1 Reactance Calculation Comparison

No	Reactance	BCTRAN (ohm)	Geometric Calculation (ohm)	Difference (%)
1	XHL	6.0755	6.1091	0.5500
2	XHT	1.5646	1.5686	0.2550
3	XLT	0.4198	0.4200	0.0476

The differences of leakage reactance calculation are not so big between those two methods, leakage impedance method can be proposed to calculate the new impedance matrix for internal faults.

The other method to verify that the leakage inductance can be used as comparison correction for the leakage calculation is the transformer impedance test result. In this method, the real part of impedance (resistance) is also included because it based on the real impedance test of the transformer so the value will be higher than two other calculations.

$$Z_{cc} = \frac{V_{LL}(kV)^2}{S(MVA)} \times Z(p.u) \qquad (4.36)$$

Where V_{LL} is the line to line voltage, S is the rating of the transformer, and Z is the impedance of the transformer.

With this calculation, Z_{HL}= 6.1794 ohm, Z_{HT} = 1.6190 ohm, and Z_{LT}= 0.4290 ohm.

Transformer in Internal Fault Condition

Turn-to-earth faults :

The principle used to model a fault between a coil turn-to-earth or between two turns is to divide the faulty coil.

As shown in Fig (b), phase "2" (represent secondary winding of phase R) coil is split into two sub-windings, A and B. Then the updated impedance matrix would become 10x10 as follows:

$$R=\begin{pmatrix} R_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_a & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_b & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & R_6 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_7 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_9 \end{pmatrix}$$

$$
L = \begin{pmatrix}
L_{11} & L_{1a} & L_{1b} & L_{13} & L_{14} & L_{15} & L_{16} & L_{17} & L_{18} & L_{19} \\
L_{a1} & L_{a} & L_{ab} & L_{a3} & L_{a4} & L_{a5} & L_{a6} & L_{a7} & L_{a8} & L_{a9} \\
L_{b1} & L_{ba} & L_{b} & L_{b3} & L_{b4} & L_{b5} & L_{b6} & L_{b7} & L_{b8} & L_{b9} \\
L_{31} & L_{3a} & L_{3b} & L_{33} & L_{34} & L_{35} & L_{36} & L_{37} & L_{38} & L_{39} \\
L_{41} & L_{4a} & L_{4b} & L_{43} & L_{44} & L_{45} & L_{46} & L_{47} & L_{48} & L_{49} \\
L_{51} & L_{5a} & L_{5b} & L_{53} & L_{54} & L_{55} & L_{56} & L_{57} & L_{58} & L_{59} \\
L_{61} & L_{6a} & L_{6b} & L_{63} & L_{64} & L_{65} & L_{66} & L_{67} & L_{68} & L_{69} \\
L_{71} & L_{7a} & L_{7b} & L_{73} & L_{74} & L_{75} & L_{76} & L_{77} & L_{78} & L_{79} \\
L_{81} & L_{8a} & L_{8b} & L_{83} & L_{84} & L_{85} & L_{86} & L_{87} & L_{88} & L_{89} \\
L_{91} & L_{9a} & L_{9b} & L_{93} & L_{94} & L_{95} & L_{96} & L_{97} & L_{98} & L_{99}
\end{pmatrix}
$$

The matrix element in the *italics* is the new element that calculated by the some equation in [6],[5].

The 10x10 matrix R will be determined with the help of the relations:

$$R_a = \frac{n_a}{n_2} R_2 \qquad (4.37)$$

$$R_b = \frac{n_b}{n_2} R_2 \qquad (4.38)$$

To determine the L matrix is more difficult. There are 36 elements must be calculated each case and inserted manually to the new user defined object or library in the EMTP.

$$L_a = \frac{L_{22}}{\frac{1}{k^2} + \frac{2\sqrt{1-\sigma_{ab}}}{k} + 1} \qquad (4.39)$$

$$L_b = \frac{L_{22}}{k^2 + 2k\sqrt{1-\sigma_{ab}} + 1} \qquad (4.40)$$

$$L_{ab} = \frac{L_{22}\sqrt{1-\sigma_{ab}}}{(k + \frac{1}{k}) + 2\sqrt{1-\sigma_{ab}}} \qquad (4.41)$$

If coil i is considered in the same leg as a and b (the faulty coil) and if $n_a > n_b$ then

$$L_{ai} = L_{2i}\,\sqrt{\varepsilon}\,\sqrt{\frac{L_a}{L_{22}}}\,\sqrt{1 + \frac{1-\varepsilon}{\varepsilon}\frac{L_{22}L_{ii}}{L_{2i}^2}} \qquad (4.42)$$

$$L_{bi} = L_{2i} - L_{ai} \qquad (4.43)$$

If coil i is wound on the different leg than a and b then

$$L_{ai} = \frac{k}{1+k} L_{2i} \tag{4.42}$$

$$L_{bi} = \frac{1}{1+k} L_{2i} \tag{4.43}$$

L_{22}, L_{2i}, and L_{ii} are elements of the L matrix computed by BCTRAN.

k = $\frac{n_a}{n_b}$ and $\varepsilon = \frac{\sigma_{ai}}{\sigma_{2i}}$ where σ_{ij} is a leakage factor between i and j windings. Unknown ratio of two leakage factor (ε) is assumed to be 1 as recommended by Kezunovic [8].

The leakage factor σ_{ab} proposed by Darwish [6] is equal to:

$$\sigma_{ab} = \frac{n_a}{n_2} \sigma_{12} \tag{4.46}$$

Where σ_{12} is leakage factor between primary and secondary winding of the healthy transformer and could be calculated by

$$\sigma_{12} = 1 - \frac{L_{12}^2}{L_{11} L_{22}} \tag{4.47}$$

Turn-to-turn faults :

In case of turn-to-turn faults, the phase "2" (represent secondary winding of phase R) is split into three sub-windings, A, B, and C. The updated impedance matrix will be 11x11 :

$$R = \begin{pmatrix} R_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_a & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_b & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_c & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & R_5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_6 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_7 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_9 \end{pmatrix}$$

$$
L = \begin{pmatrix}
L_{11} & L_{1a} & L_{1b} & L_{1c} & L_{13} & L_{14} & L_{15} & L_{16} & L_{17} & L_{18} & L_{19} \\
L_{a1} & L_{a} & L_{ab} & L_{ac} & L_{a3} & L_{a4} & L_{a5} & L_{a6} & L_{a7} & L_{a8} & L_{a9} \\
L_{b1} & L_{ba} & L_{b} & L_{ac} & L_{b3} & L_{b4} & L_{b5} & L_{b6} & L_{b7} & L_{b8} & L_{b9} \\
L_{c1} & L_{ca} & L_{cb} & L_{c} & L_{c3} & L_{c4} & L_{c5} & L_{c6} & L_{c7} & L_{c8} & L_{c9} \\
L_{31} & L_{3a} & L_{3b} & L_{3c} & L_{33} & L_{34} & L_{35} & L_{36} & L_{37} & L_{38} & L_{39} \\
L_{41} & L_{4a} & L_{4b} & L_{4c} & L_{43} & L_{44} & L_{45} & L_{46} & L_{47} & L_{48} & L_{49} \\
L_{51} & L_{5a} & L_{5a} & L_{5c} & L_{53} & L_{54} & L_{55} & L_{56} & L_{57} & L_{58} & L_{59} \\
L_{61} & L_{6a} & L_{5b} & L_{6c} & L_{63} & L_{54} & L_{65} & L_{66} & L_{67} & L_{68} & L_{69} \\
L_{71} & L_{7a} & L_{6b} & L_{7c} & L_{73} & L_{74} & L_{75} & L_{76} & L_{77} & L_{78} & L_{79} \\
L_{81} & L_{8a} & L_{8b} & L_{8c} & L_{83} & L_{34} & L_{85} & L_{36} & L_{87} & L_{88} & L_{89} \\
L_{91} & L_{9a} & L_{9b} & L_{9c} & L_{93} & L_{94} & L_{95} & L_{36} & L_{97} & L_{98} & L_{99}
\end{pmatrix}
$$

$$R_a = \frac{n_a}{n_2} R_2 \qquad (4.48)$$

$$R_b = \frac{n_b}{n_2} R_2 \qquad (4.49)$$

$$R_c = \frac{n_c}{n_2} R_2 \qquad (4.50)$$

There are 57 elements in L matrix must be calculated each case and inserted manually to the new user defined object or library in the EMTP .

Considering that the three leakage factors are known parameters (σ_{ab} , σ_{ac} , σ_{bc}) [6],[5], six equations for six unknowns are formulated (La, Lb, Lc, Lab, Lbc, and Lac) [4]

- Consistency $\quad L_a+L_b+L_c+2(L_{ab}+L_{ac}+L_{bc}) = L_2 \qquad (4.51)$

$$\sigma_{ab} = 1-\frac{L_{ab}^2}{L_a L_b} \qquad (4.52)$$

- Leakage $\quad \sigma_{ab} = 1-\frac{L_{ac}^2}{L_a L_c} \qquad (4.53)$

$$\sigma_{bc} = 1-\frac{L_{bc}^2}{L_b L_c} \qquad (4.54)$$

- Proportion $\quad \frac{L_a}{L_b} = \left(\frac{n_a}{n_b}\right)^2 \qquad (4.55)$

$$\frac{L_a}{L_c} = \left(\frac{n_a}{n_c}\right)^2 \quad (4.56)$$

In case turn-to-turn fault, the proposed values of leakage factors are [6]:

$$\sigma_{ab} = \frac{n_a}{n_2}\ \sigma_{12} \quad (4.57)$$

$$\sigma_{ac} = \frac{n_c}{n_2}\ \sigma_{12} \quad (4.58)$$

$$\sigma_{bc} = \frac{n_b}{n_2}\ \sigma_{12} \quad (4.59)$$

Those six equations with six unknowns above (4.51 – 4.56) are not linear and cannot lead to an explicit expression of the various inductances. In practice, the iteration with a numerical resolution method must therefore be used. The approximate solution to optimize its iterations, the following will be taken[5]:

$$L_a = L_2 \left(\frac{n_a}{n_2}\right)^2 \quad (4.60)$$

Other new elements of the impedance matrix can be calculated :
If coil i is considered in the same leg as a and b (the faulty coil) and if $n_a > n_b$ then

$$L_{ai} = L_{2i} \sqrt{\varepsilon_1} \sqrt{\frac{L_a}{L_{22}}} \sqrt{1+\frac{1-\varepsilon_1}{\varepsilon_1}\frac{L_{22}L_{ii}}{L_{2i}^2}} \quad (4.61)$$

$$L_{ci} = L_{2i} \sqrt{\varepsilon_2} \sqrt{\frac{L_c}{L_{22}}} \sqrt{1+\frac{1-\varepsilon_2}{\varepsilon_2}\frac{L_{22}L_{ii}}{L_{2i}^2}} \quad (4.62)$$

$$L_{bi} = L_{2i} - L_{ai} - L_{ci} \quad (4.63)$$

If coil i is wound on the different leg than a and b then

$$L_{ai} = \frac{L_{2i}}{1+\frac{1}{k1}+\frac{1}{k2}} \tag{4.64}$$

$$L_{bi} = \frac{L_{2i}}{1+k1+\frac{k1}{k2}} \tag{4.65}$$

$$L_{ci} = \frac{L_{2i}}{1+k2+\frac{k2}{k1}} \tag{4.66}$$

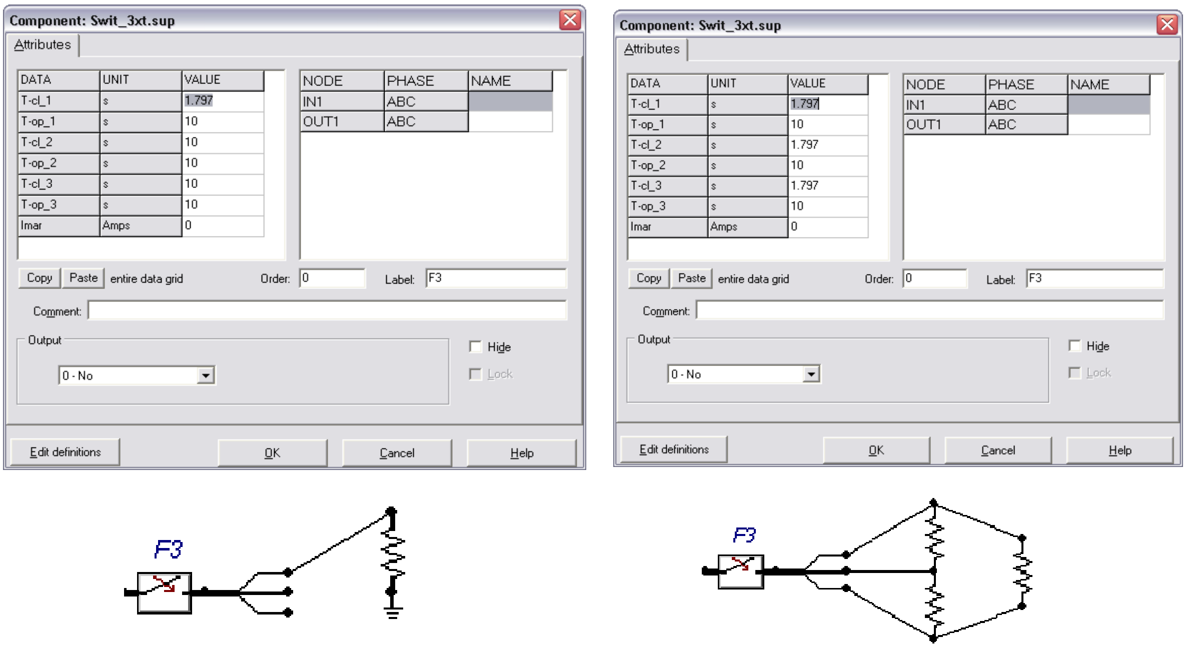
V. SIMULATION AND ANALYSIS

5.1. Introduction

The simulation and analysis of the external fault and internal fault at the transformer will be done in this chapter. The transformer differential protection behavior also studied. From the chapter 2, the differential protection relay must not operate when external fault occur. On the other hand, if the internal fault occur then the differential protection relay must work properly.

5.2. External Fault

After building the whole electrical power components in ATPDraw, simulation of fault can be done. The phase to ground fault, phase to phase, phase to phase to ground, or three phase fault of the load can be simulated. In those faults, the transformer model is in the same model as in the normal/healthy condition. There are no changes in the impedance matrix (R and L matrix) of the transformer.



Phase to Ground Fault

Three Phase Fault

Figure 5.1 External Fault Modeling

The current of the primary, secondary, and tertiary side will change but the differential protection must not work because the fault is outside the protection zone. The differential protection only protects the internal faults of the transformer such as turn-to-earth and turn-to-turn fault. The current waveforms of three winding will change because of the external fault. The current waveforms are shown in the figures below:

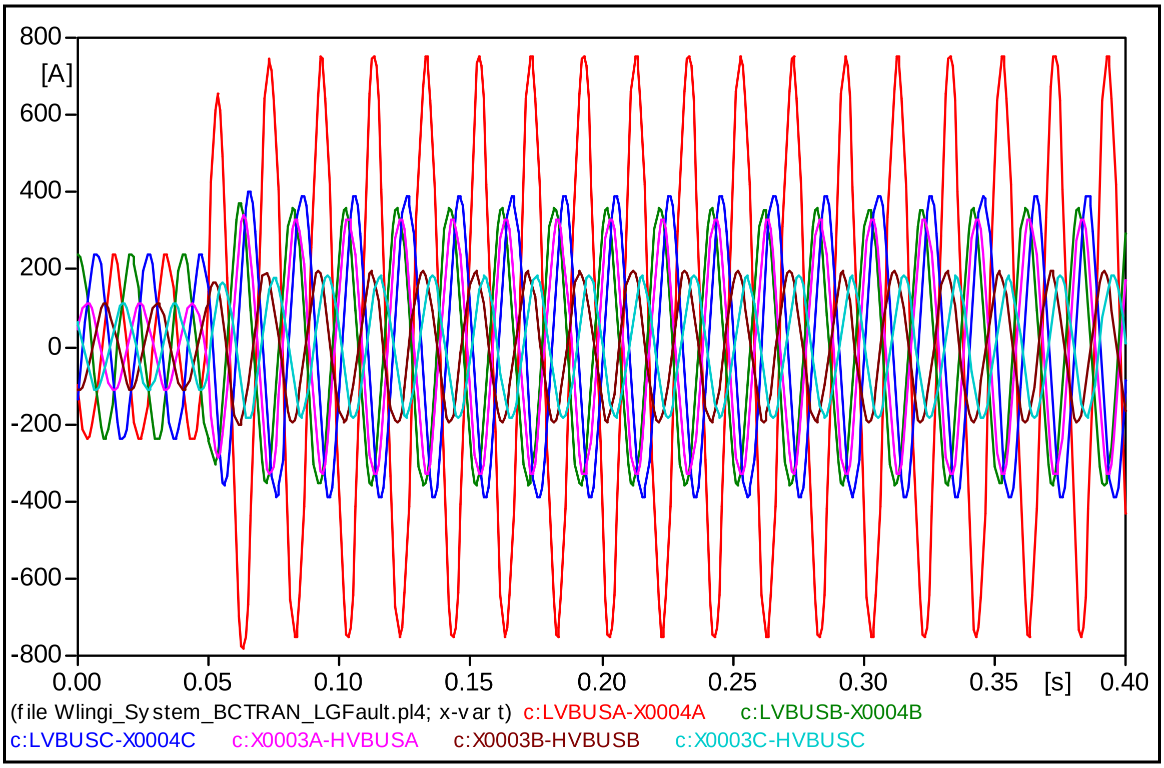


Figure 5.2 External Fault : Phase to Ground Fault near the Bus

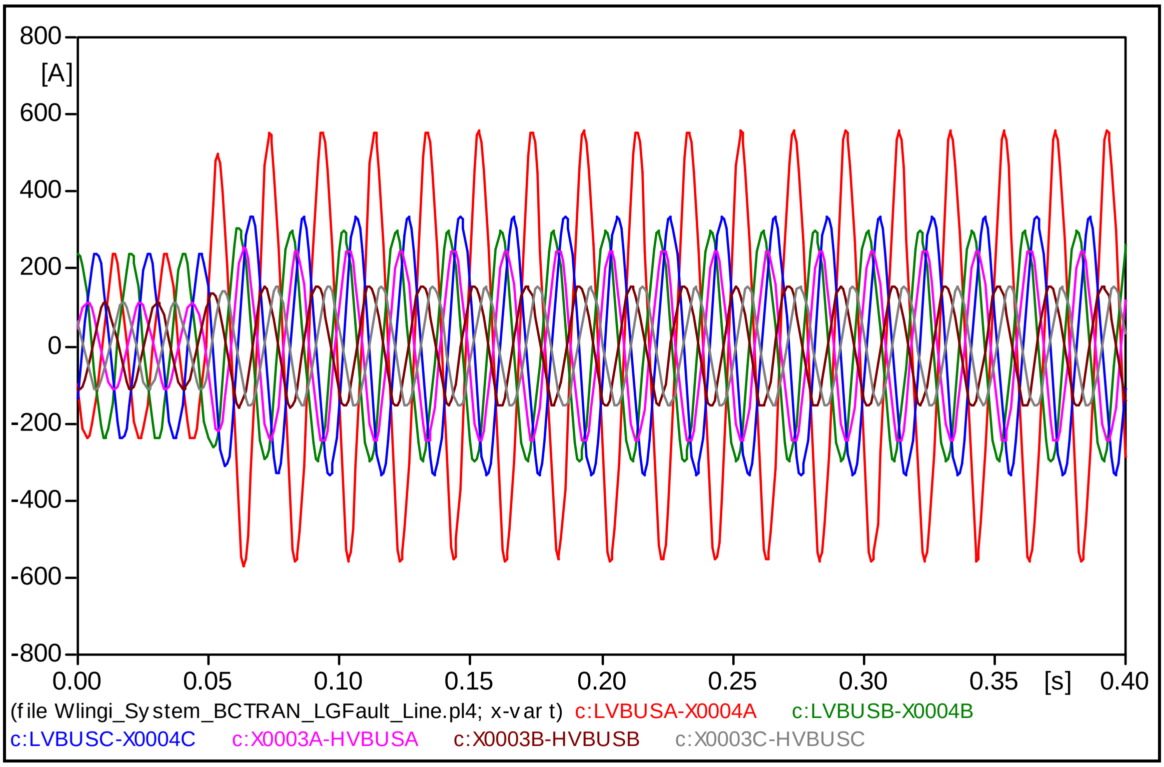


Figure 5.3 External Fault: Phase to Ground Fault in the Feeder

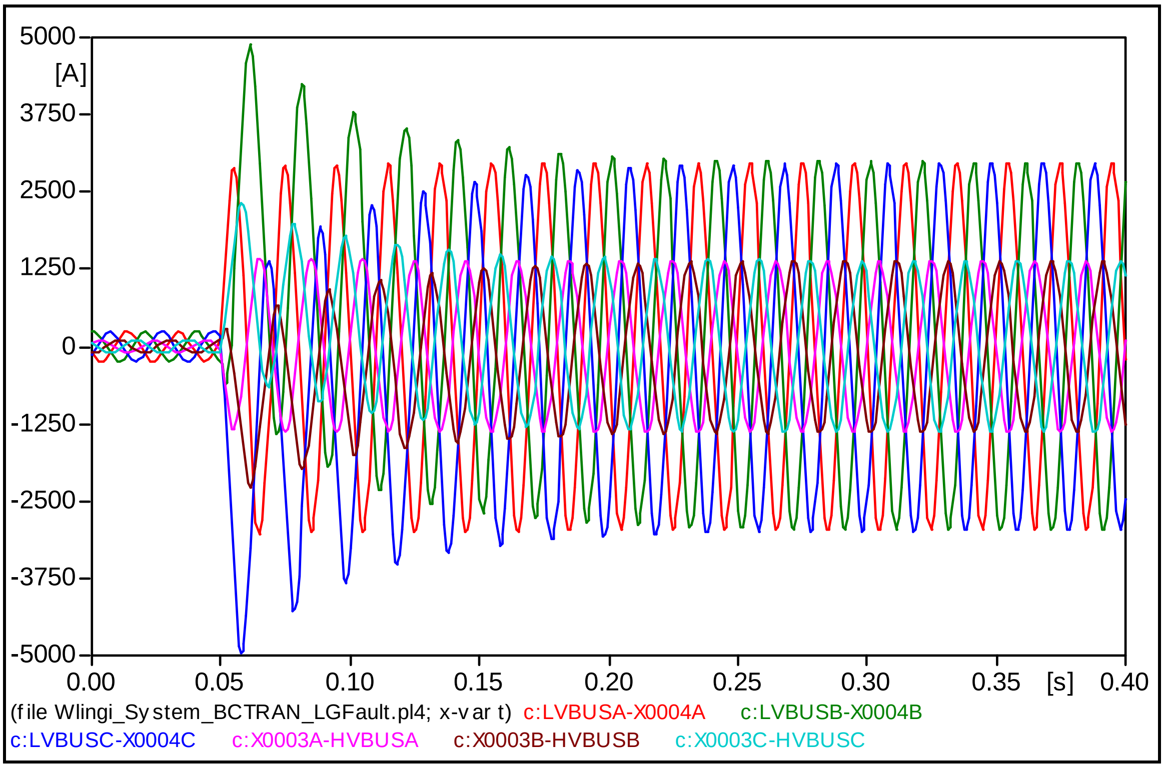


Figure 5.4 External Fault : Three-phase Fault near the Bus

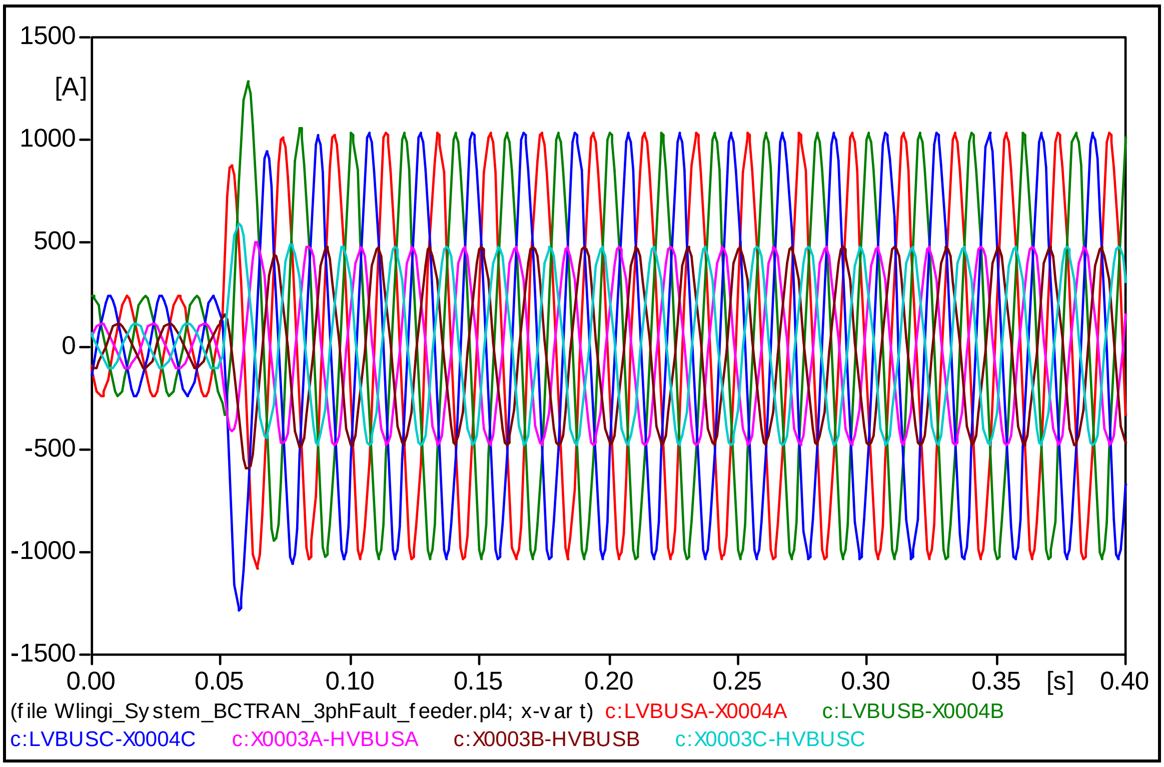


Figure 5.5 External Fault : Three-phase Fault at the Feeder

There are two ways to investigate the operation of the differential relay due to the external and internal fault (turn-to-earth and turn-to-turn fault). The first one is a complete relay testing by injecting the faulty waveform to the secondary test set which is connected to the differential relay. The second way is to calculate manually the differential and bias current of the relay and to plot it into the differential relay characteristics. The second one is chosen because the equipments (secondary equipment test set, circuit breaker (CB) replica, and differential relay protection) for first way are not available.

In this thesis, the manual plotting is done by using Omicron software i.e Omicron Advanced Transplay, Omicron Transview, and Omicron Differential Protection Test View.

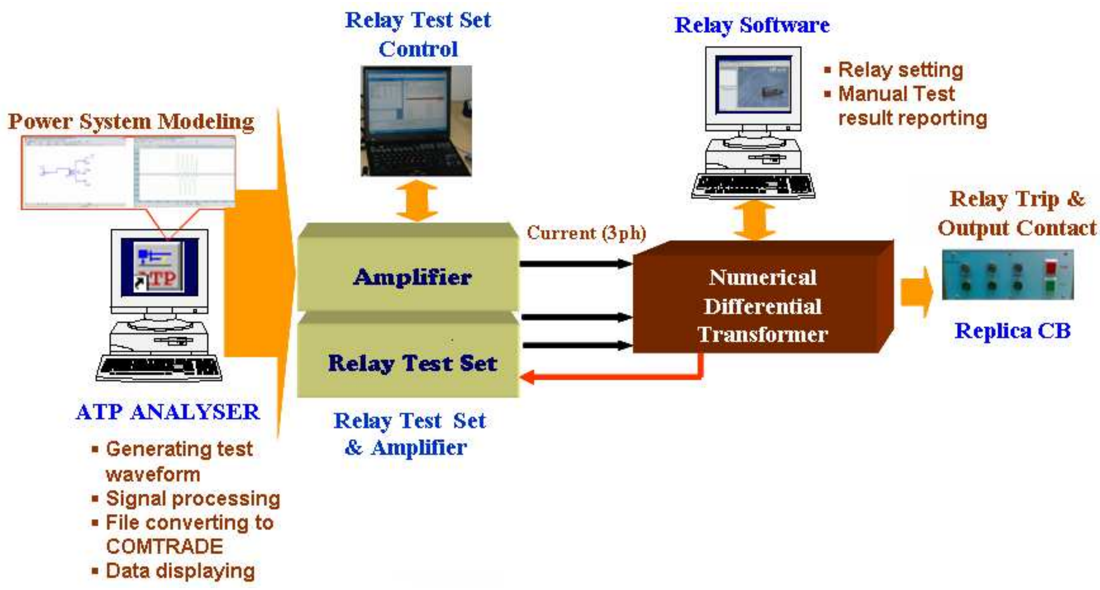


Figure 5.6 Differential Relay Testing Configuration

The first way of differential relay protection testing can be used by the utility as an acceptance test of the relay. It will give the correct and accurate information about the characteristics, operating time, sensitiveness, and selectivity of the differential relay protection. The differential relay protection will operate due to the real condition of the current waveform including harmonics and DC component.

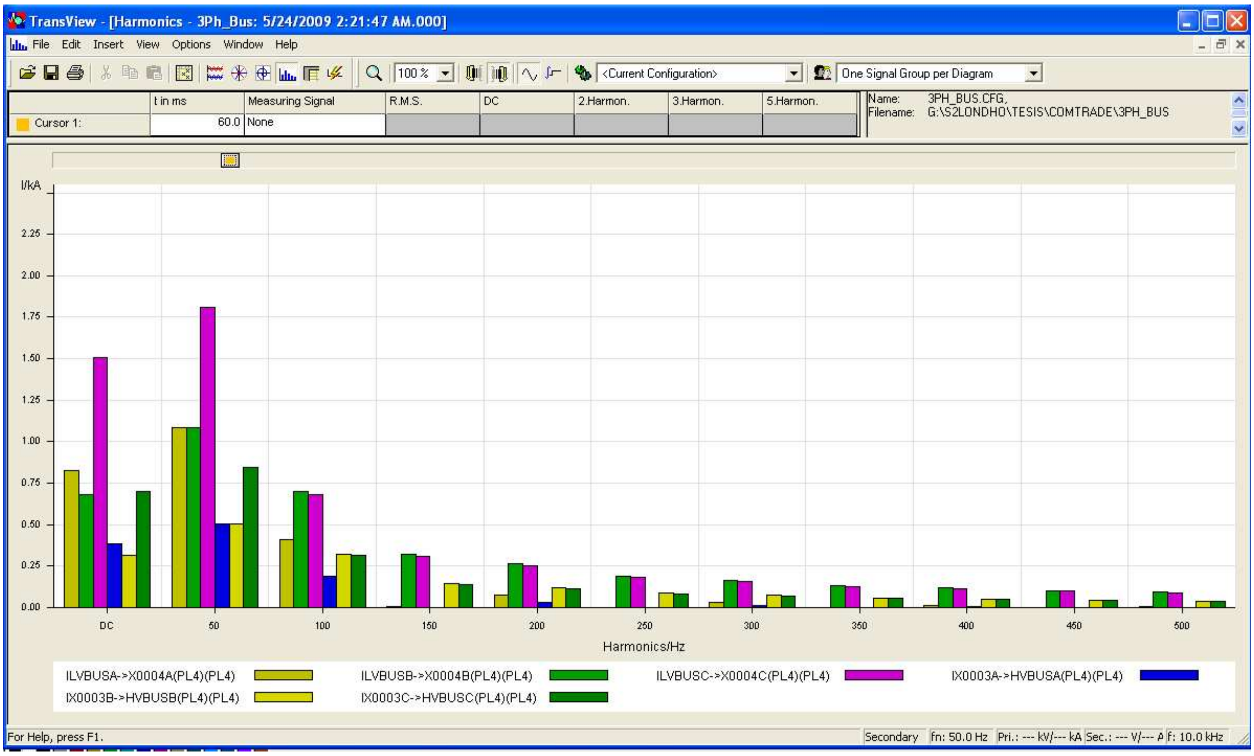
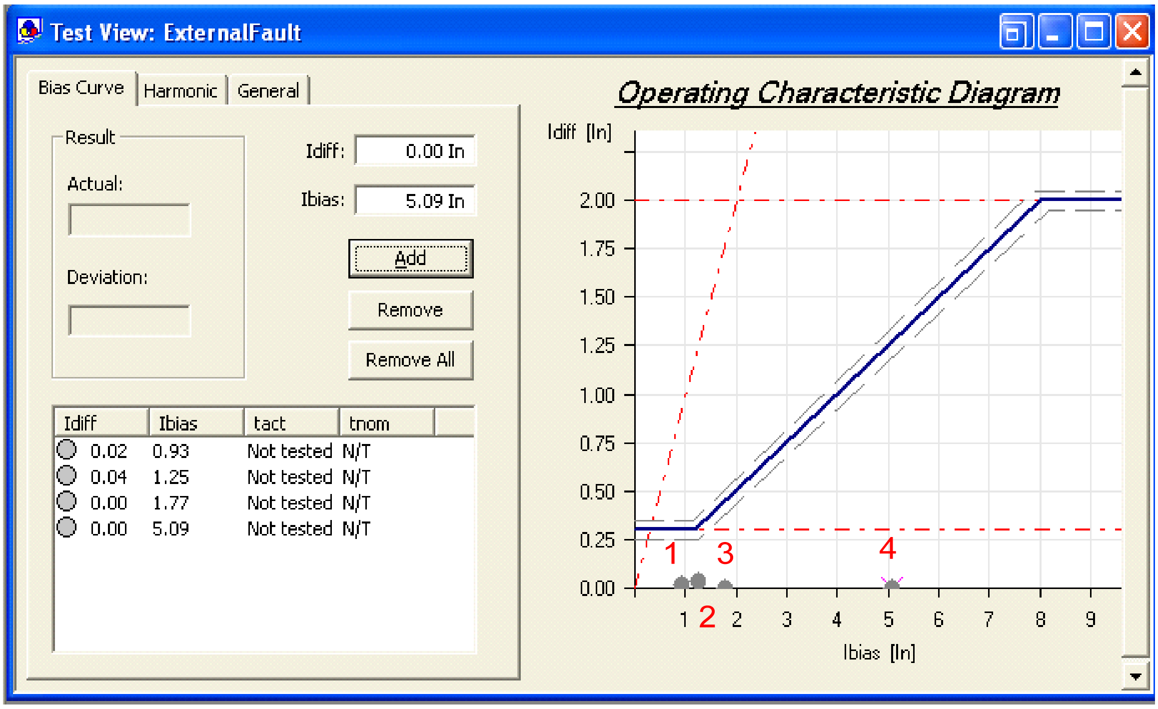


Figure 5.7 Harmonics and DC Component Occur when Fault Occurs

The harmonics and DC component will appear when fault occur inside or outside transformer protection zone. Figure 5.7 shows the harmonics and DC component 1 cycle (20 ms) after the fault happen.

The second way of test only gives the information that the relay will or won't operate due to the changing current at primary and secondary winding. The current value entered to the differential relay plotting is the root mean square (RMS) value of both primary and secondary.



1. Phase to Ground Fault at the Feeder/Line
2. Phase to Ground Fault near the 70 kV Bus
3. Three-phase Fault at the Feeder/Line
4. Three-phase Fault near the 70 kV Bus

Figure 5.8 Differential Relay Characteristics Plotting for External Fault

From the figure above, it can be seen that the differential relay will be stable for the external fault. The differential relay will not operate because the fault is outside the protected zone.

5.3. *Internal Fault*

The electrical system of Wlingi substation with faulty transformer is built in the EMTP network shown by figure 5.9. The modified impedance matrix accommodate the fault point Z. Closing the switch between Z (fault point node) and the ground, the simulation of turn-to-earth fault of transformer winding is elaborated. The new 10x10 impedance matrix of the transformer due to turn-to-earth fault is written as source data in the library. This library will react as BCTRAN routine for the faulty transformer.

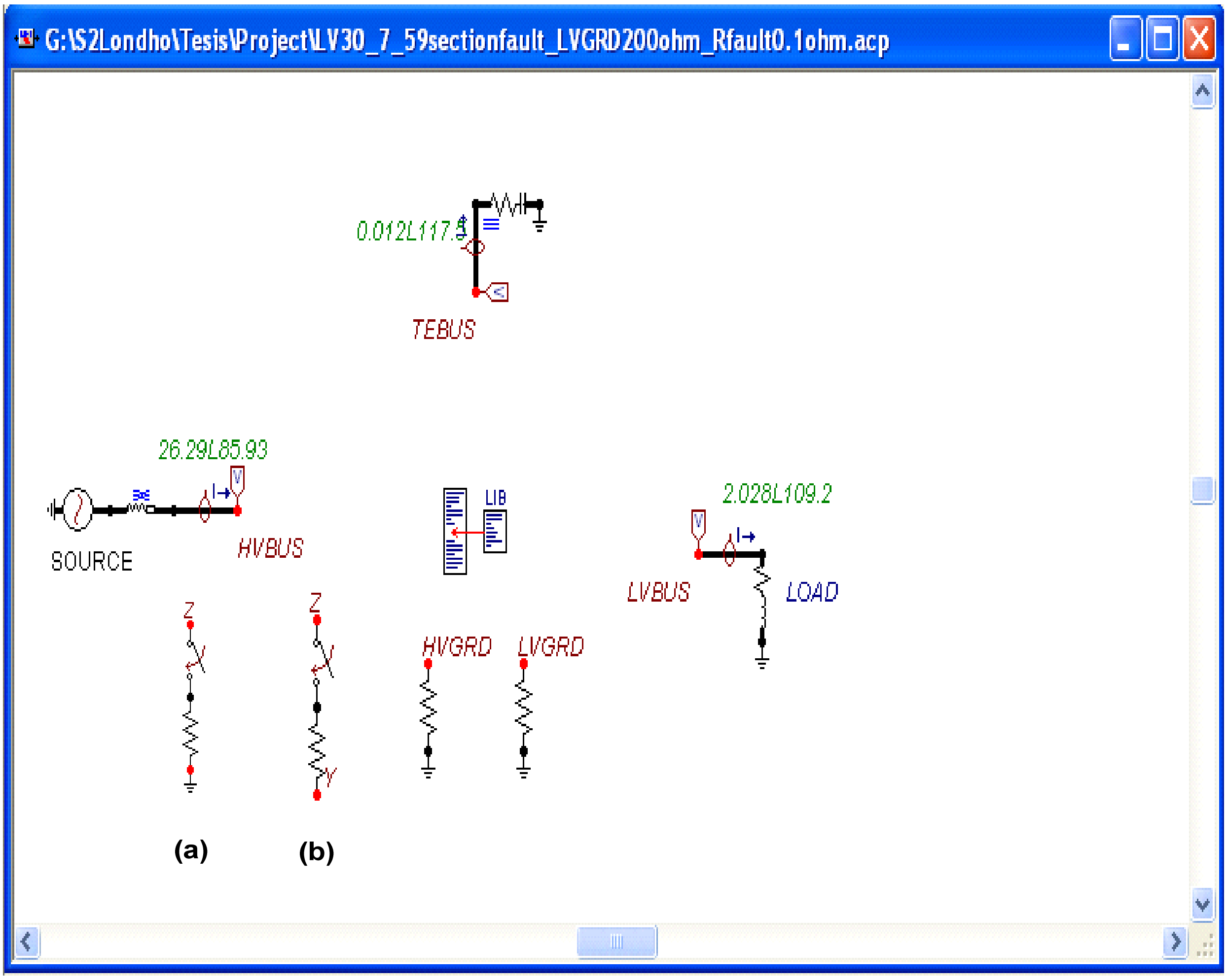
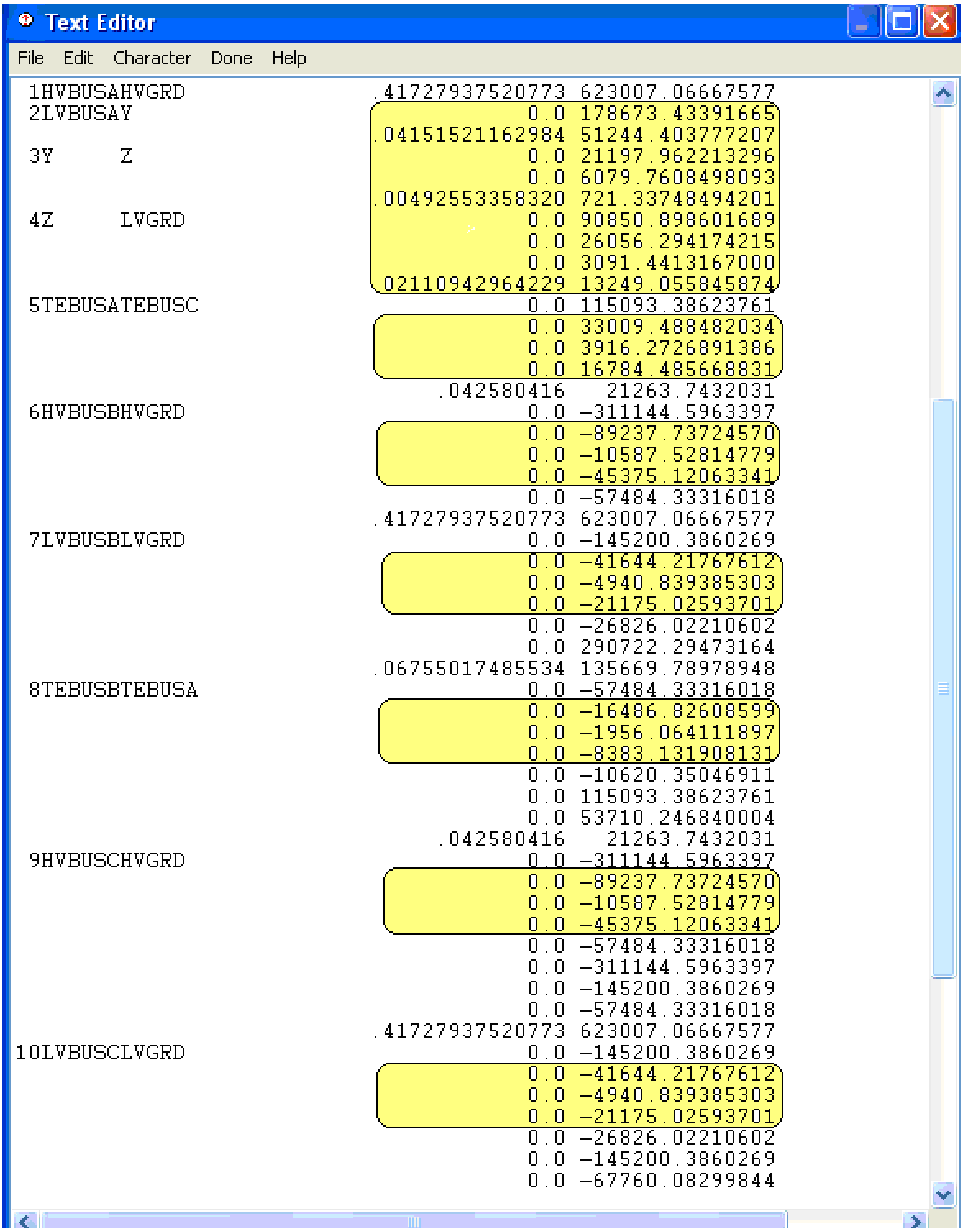


Figure 5.9 Internal Fault Simulation Configuration: (a) Turn-to earth Fault
(b) Turn-to-turn Fault

For the turn-to-turn fault, there are two fault points (Z and Y) and by closing the switch between those fault points, the turn-to-turn fault of the transformer is simulated. The matrix will be 11x11 due to turn-to-turn fault.



```
Text Editor
File  Edit  Character  Done  Help
1HVBUSAHVGRD        .41727937520773 623007.06667577
2LVBUSAY                        0.0 178673.43391665
                    .04151521162984 51244.403777207
3Y      Z                       0.0 21197.962213296
                                0.0 6079.7608498093
                    .00492553358320 721.33748494201
4Z      LVGRD                   0.0 90850.898601689
                                0.0 26056.294174215
                                0.0 3091.4413167000
                     02110942964229 13249.055845874
5TEBUSATEBUSC                   0.0 115093.38623761
                                0.0 33009.488482034
                                0.0 3916.2726891386
                                0.0 16784.485668831
                         .042580416   21263.7432031
6HVBUSBHVGRD                    0.0 -311144.5963397
                                0.0 -89237.73724570
                                0.0 -10587.52814779
                                0.0 -45375.12063341
                                0.0 -57484.33316018
                    .41727937520773 623007.06667577
7LVBUSBLVGRD                    0.0 -145200.3860269
                                0.0 -41644.21767612
                                0.0 -4940.839385303
                                0.0 -21175.02593701
                                0.0 -26826.02210602
                                0.0 290722.29473164
                    .06755017485534 135669.78978948
8TEBUSBTEBUSA                   0.0 -57484.33316018
                                0.0 -16486.82608599
                                0.0 -1956.064111897
                                0.0 -8383.131908131
                                0.0 -10620.35046911
                                0.0 115093.38623761
                                0.0 53710.246840004
                         .042580416   21263.7432031
9HVBUSCHVGRD                    0.0 -311144.5963397
                                0.0 -89237.73724570
                                0.0 -10587.52814779
                                0.0 -45375.12063341
                                0.0 -57484.33316018
                                0.0 -311144.5963397
                                0.0 -145200.3860269
                                0.0 -57484.33316018
                    .41727937520773 623007.06667577
10LVBUSCLVGRD                   0.0 -145200.3860269
                                0.0 -41644.21767612
                                0.0 -4940.839385303
                                0.0 -21175.02593701
                                0.0 -26826.02210602
                                0.0 -145200.3860269
                                0.0 -67760.08299844
```

Figure 5.10 Modified Impedance Matrix for Internal Fault

The element matrix in the yellow box is calculated with high precision based on chapter 4 and entered to the new library. A little error in the calculation or entering the value to the new library will cause the unstable simulation or different waveform on pre-fault condition. This new element will be calculated in each case of the internal fault.

A fault on a transformer winding is controlled in magnitude by the following factors [19]:

- source impedance
- neutral grounding impedance
- transformer leakage reactance
- fault voltage
- winding connection

The 70 kV system in Java-Bali interconnection system has two grounding systems. High resistive grounding (200 ohm) is used in east Java and Bali and low resistive grounding (40-60 ohm) in west and central Java. Wlingi substation is located at east Java, so it has 200 ohm for 70 kV system grounding. This thesis also simulates the effect of different grounding system to the primary winding current if there's internal fault in the transformer.

5.3.1. Primary Winding Fault

Turn-to-earth Fault

The winding turn-to-earth fault current depends on the grounding impedance value and is also proportional to the distance or number of the faulty turns from the neutral point, since the fault voltage will be directly proportional to this distance or number of faulty turns.

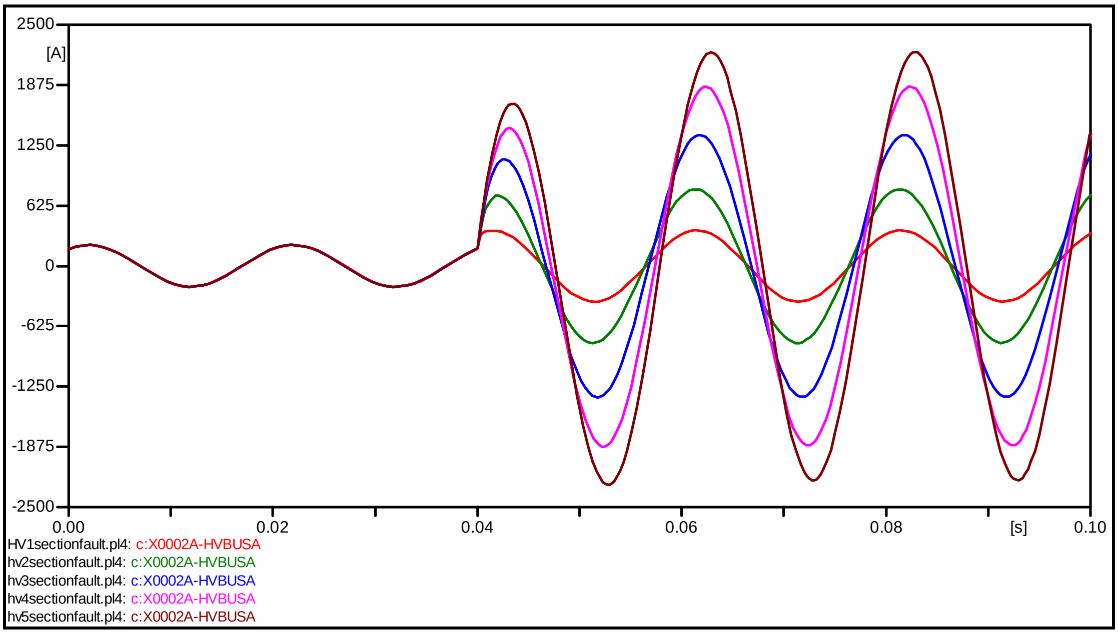


Figure 5.11 Turn-to-earth Fault Primary Windings Current Waveform

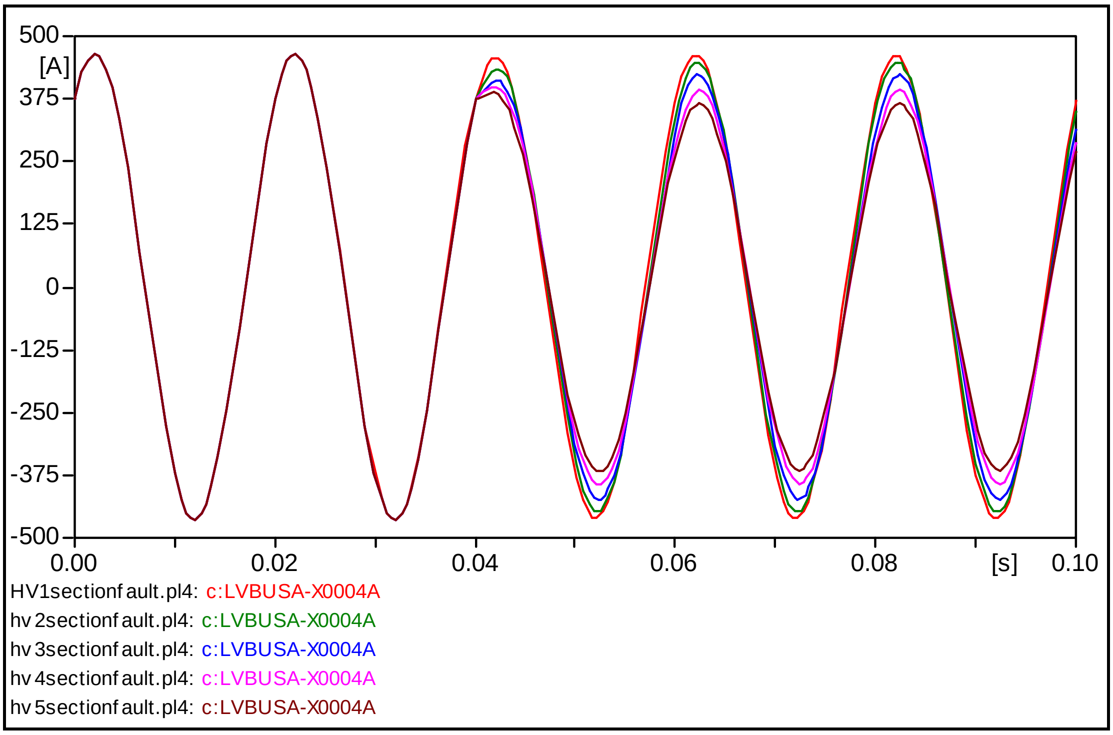


Figure 5.12 Turn-to-earth Fault Secondary Windings Current Waveform

Turn-to-turn Fault

If the faults take place in the primary winding, the faulty turns will act as an autotransformer load on the winding, and the reactance is that between the faulty turns and the whole of the affected phase winding [27].

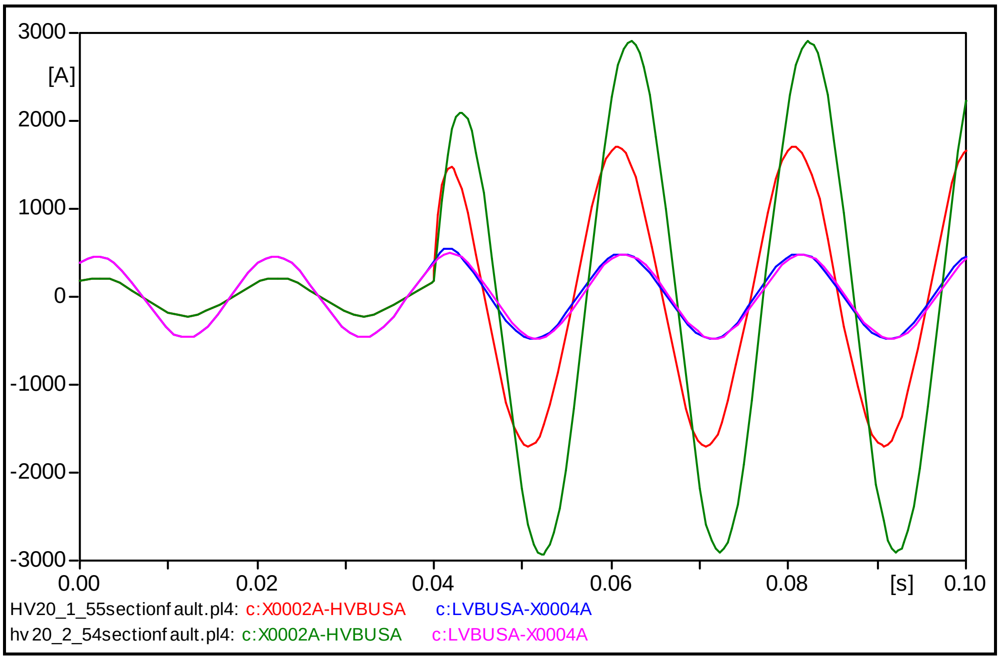


Figure 5.13 Turn-to-turn Fault Current Waveform

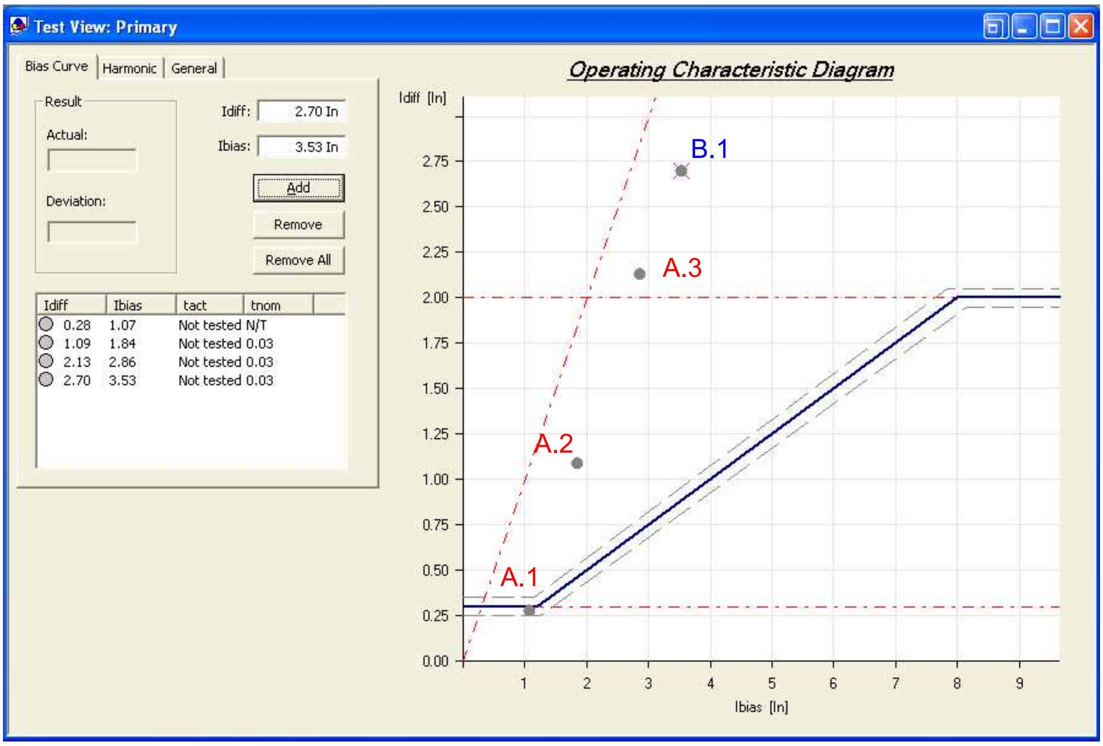


Figure 5.14 Differential Relay Characteristics Plotting for Primary Winding Fault

The differential relay will operate work for all turn-to-turn and turn-to-earth fault at the primary winding except turn-to-earth fault with only one section of 76 sections fault. Primary winding of the transformer consists of 76 sections with 7 turns per section. The over current relay also operate with the same condition but with the delayed operating time due to coordination with the feeder/line protection system.

Table 5.1 Primary Winding Fault Current Distribution

Number of Faulty Sections	Current at High Voltage Side (A)	Current at Low Voltage Side (A)	I diff (x In)	I bias (x In)	I OCR (x 1.2 In)
A. Turn-to-earth Fault					
1	261.14	325.69	0.28	1.07	0.565
2	563.22	310.91	1.09	1.84	1.219
3	960	298.94	2.13	2.86	2.078
4	1310	277.02	3.07	3.74	2.836
5	1570	258.52	3.77	4.39	3.399
B. Turn-to-turn Fault					
1	1200	341.9	2.70	3.53	2.598
2	2050	338.15	4.92	5.74	4.438

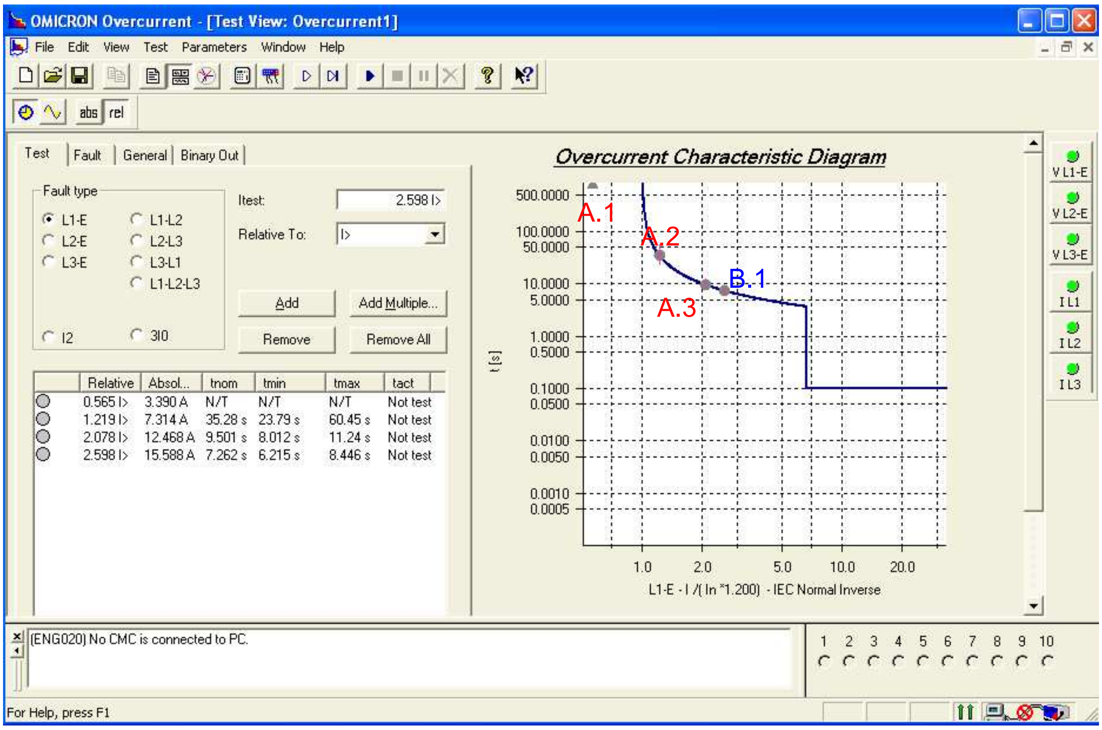


Figure 5.15 Over Current Relay Characteristics Plotting for Primary Winding Fault

5.3.2. Secondary Winding Fault

Turn-to-earth Fault :

The winding turn-to-earth fault current depends on the grounding impedance value and is also proportional to the distance or number of the faulty turns from the neutral point, since the fault voltage will be directly proportional to this distance or number of faulty turns. For a fault on a transformer secondary winding, the corresponding primary current will depend on the transformation ratio between the primary winding and the short-circuited secondary turns. This also varies with the position of the fault, so that the fault current in the transformer primary winding is proportional to the square of the fraction of the winding that is shortcircuited [16].

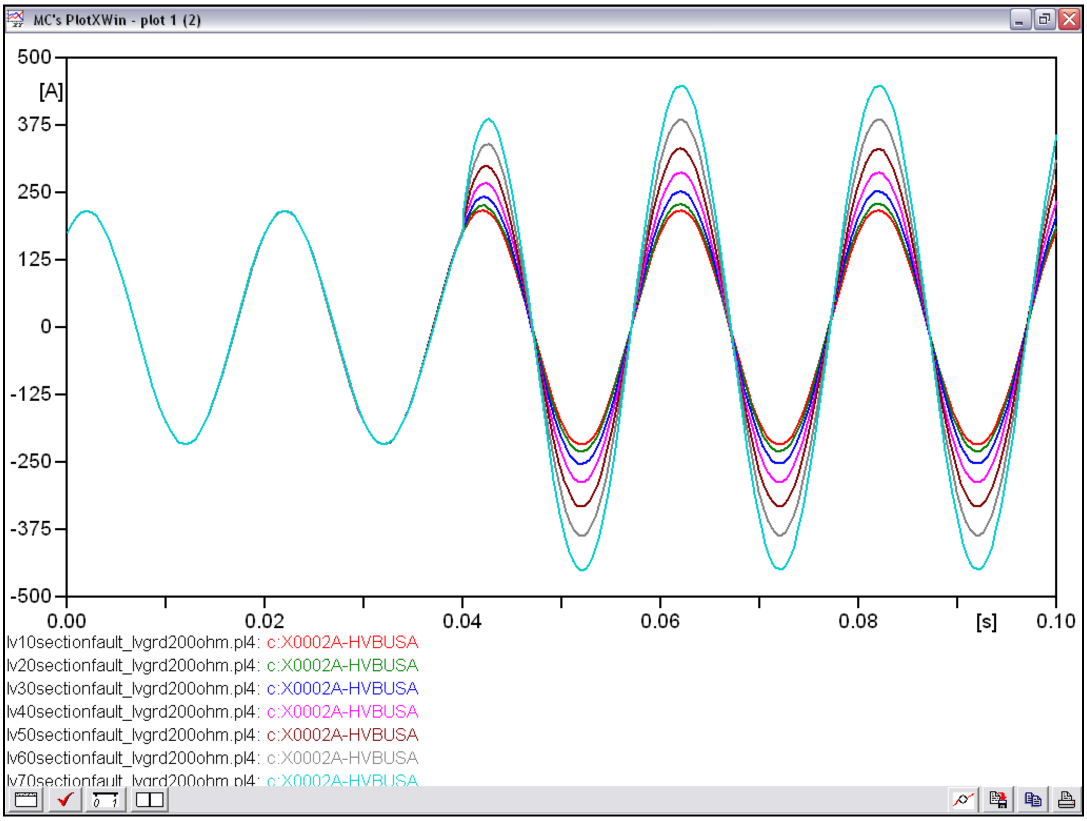


Figure 5.16 Turn-to-earth Fault Primary Windings Current Waveform

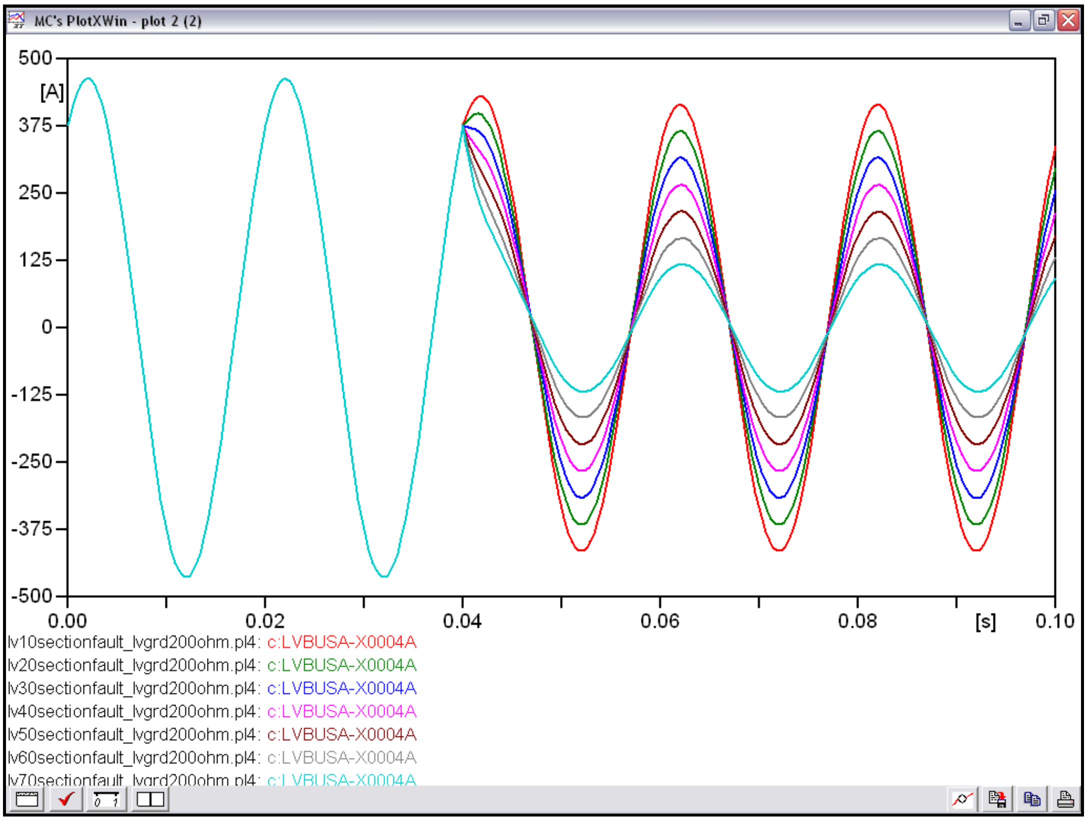


Figure 5.17 Turn-to-earth Fault Secondary Windings Current with 200 ohm Grounding

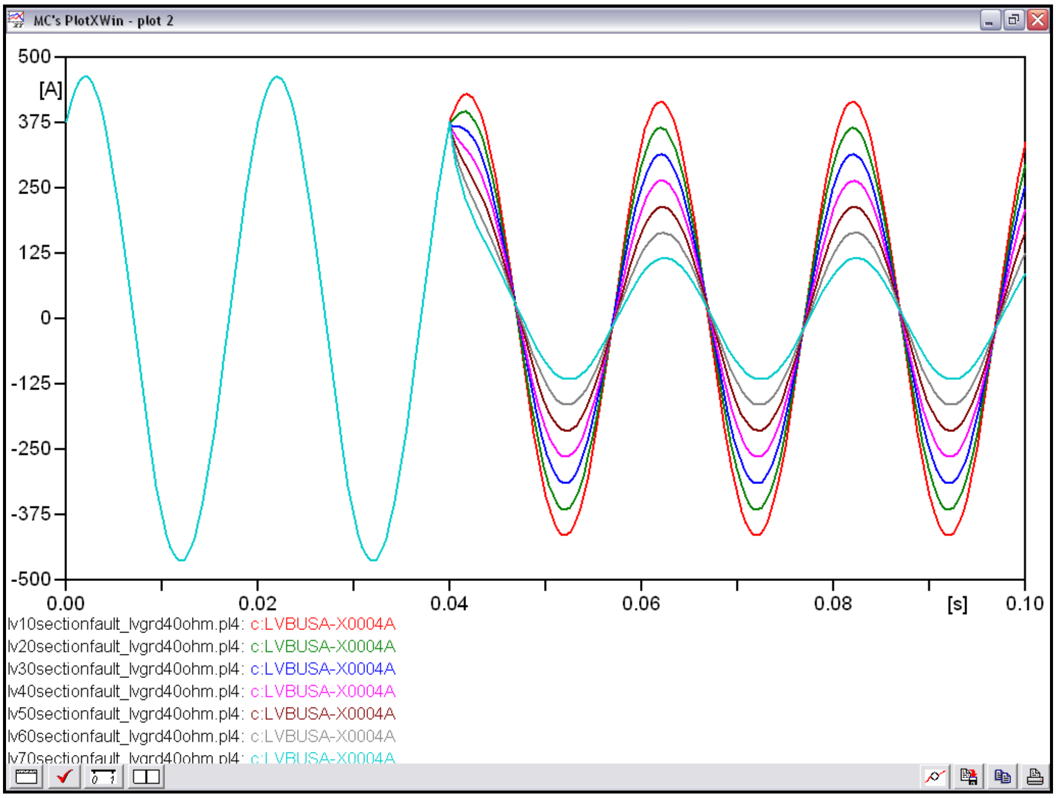


Figure 5.18 Turn-to-earth Fault Secondary Windings Current with 40 ohm Grounding

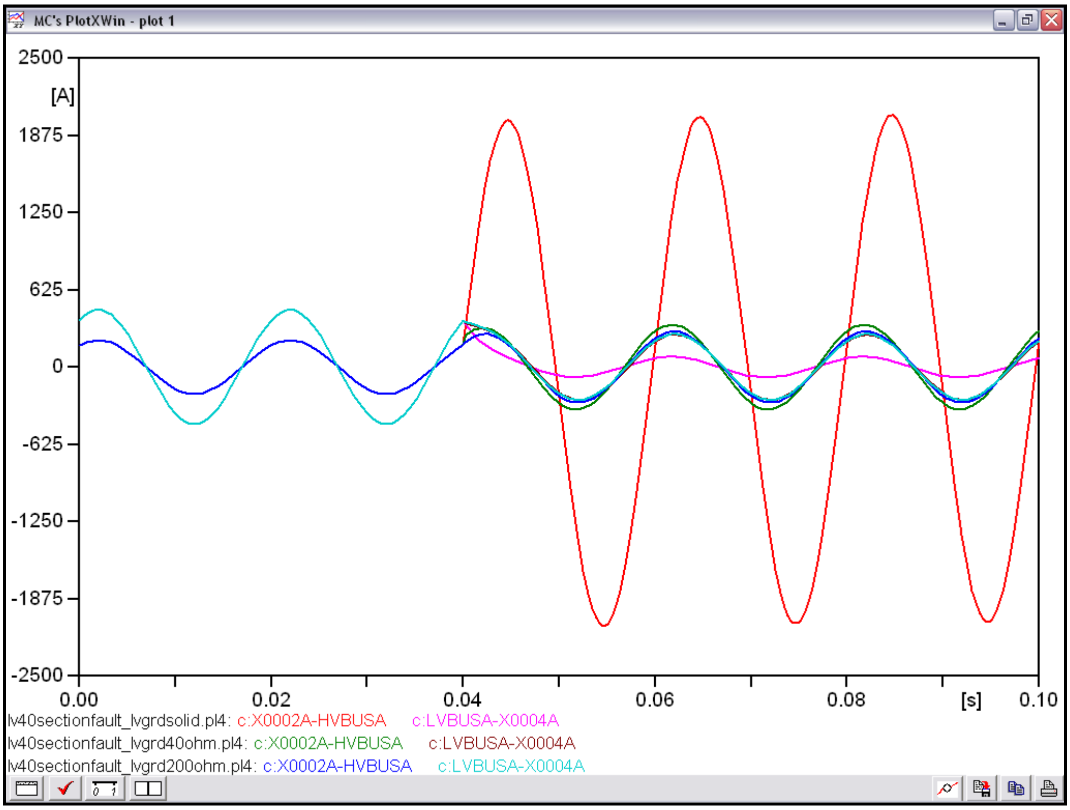


Figure5.19 Turn-to-earth Fault Primary Windings Current with Different Grounding Value (solid, 40 ohm, and 200 ohm)

From figure 5.16 and figure 5.17, it can be seen that the primary current and differential current will increase if the number of turns to the earth increases. The differential current of the differential relay protection is not sufficient to operate the relay if only few of turns to the earth.

Table 5.2 Turn-to-earth Current Distribution

Number of Faulty Sections	Current at High Voltage Side (A)	Current at Low Voltage Side (A)	I diff (x In)	I bias (x In)
0	153.08	327.67		
10	153.73	293.5	0.04	0.76
20	162.41	258.7	0.11	0.74
30	178.95	223.51	0.19	0.74
40	203.32	188.05	0.30	0.76
50	234.57	152.93	0.42	0.79
60	272.85	118.05	0.57	0.85
70	317.4	83.81	0.72	0.93
80	367.47	50.5	0.89	1.02
90	422.08	18.46	1.07	1.12

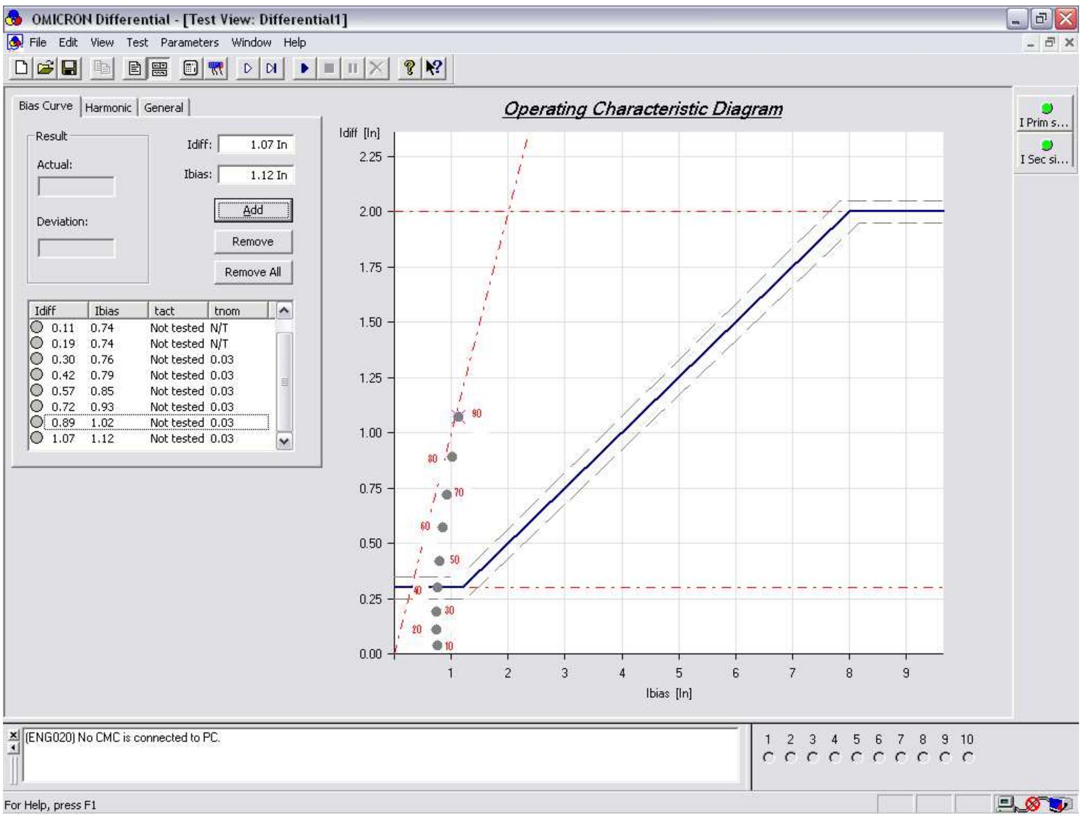


Figure 5.20 Differential Relay Characteristics Plotting for Turn-to-earth Fault

The red number on figure 5.20 represents the faulty sections of the secondary transformer windings. The secondary transformer winding is built with continuous disk configuration with 96 sections. Each section consists of 3 turns.

From figure 5.20 above, it can be seen that if the number of turns to the earth is under 30 % of total turn, the differential relay will not work due to the turn-to-earth fault. The over current relay (OCR) will not react at all if there's turn-to-earth fault in the secondary winding because the primary and secondary winding current are not high enough to operate the OCR, they are still under the OCR pick up current (around 1.2 times the rated current) of the transformer.

Turn-to-turn Fault

The interesting part is the faulty current waveform due to turn-to-turn fault. The normalized primary and secondary current will have big difference even if few turns of the winding are shortcircuited. If the faults occur in the secondary winding the faulty turns act as an ordinary double winding load, the reactance is between the faulty turns and the whole of the corresponding primary phase winding [27].

In low voltage transformers, turn-to-turn insulation breakdown is unlikely to occur unless the mechanical force on the winding due to external short circuits has caused insulation degradation, or insulating oil has became contaminated by moisture. A high voltage transformer connected to an overhead transmission system will be subjected to steep fronted impulse voltages, arising from lightning strikes, faults and switching operations. A line surge, which may be of several times the rated system voltage, will concentrate on the end turns of the winding because of the high equivalent frequency of the surge front. Part-winding resonance, involving voltages up to 20 times rated voltage may occur shortcircuited [16]. The turn-to-turn insulation of the end turns is reinforced, but cannot be increased in proportion to the insulation to earth, which is relatively great. Partial winding flashover is therefore more likely. The subsequent progress of the fault, if not detected in the earliest stage, may well destroy the evidence of the true cause. 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 shortcircuited one section (three turns) of the secondary winding. The differential relay is operated if four section (12 turns of 280 turns) is short-circuited. It also can be seen that the over current relay (OCR) in the primary side (150 kV system) will start reacting if six sections (18 turns) of secondary winding is shorcircuited. The operation of differential relay and over current relay depends on the fault impedance. The current at high voltage side will increase with decreasing fault impedance.

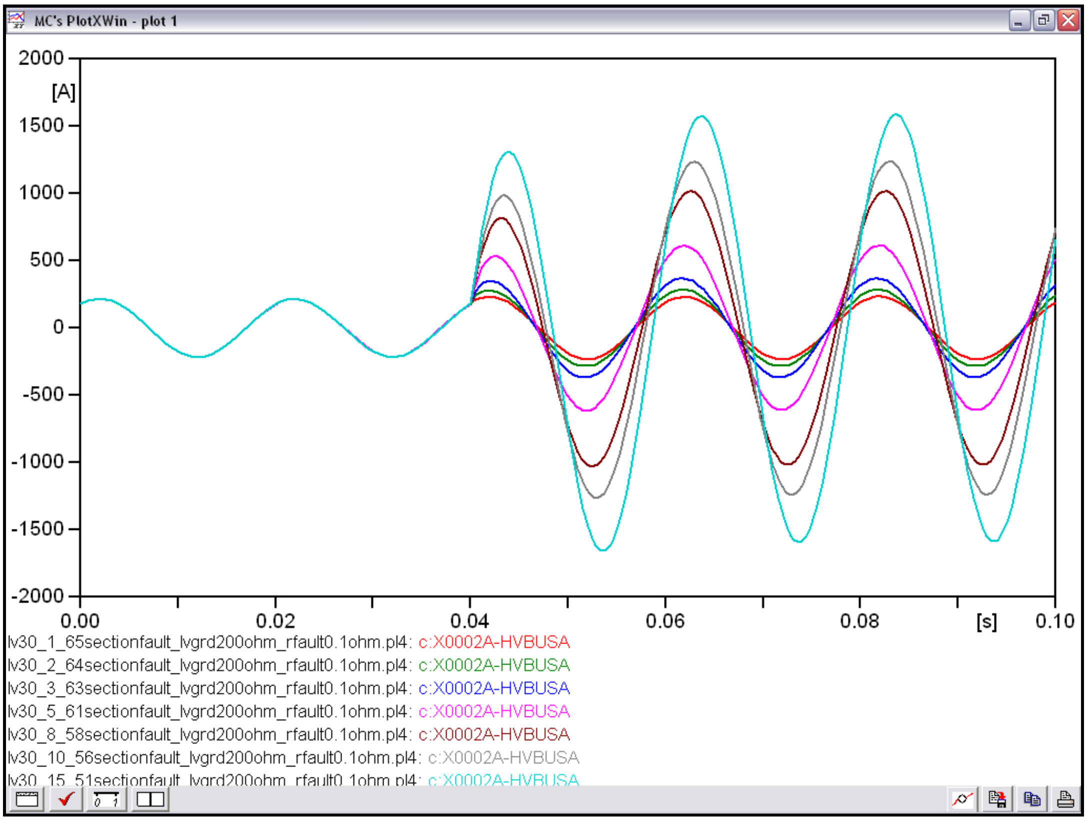


Figure 5.21 Turn-to-turn Fault Primary Windings Current Waveform

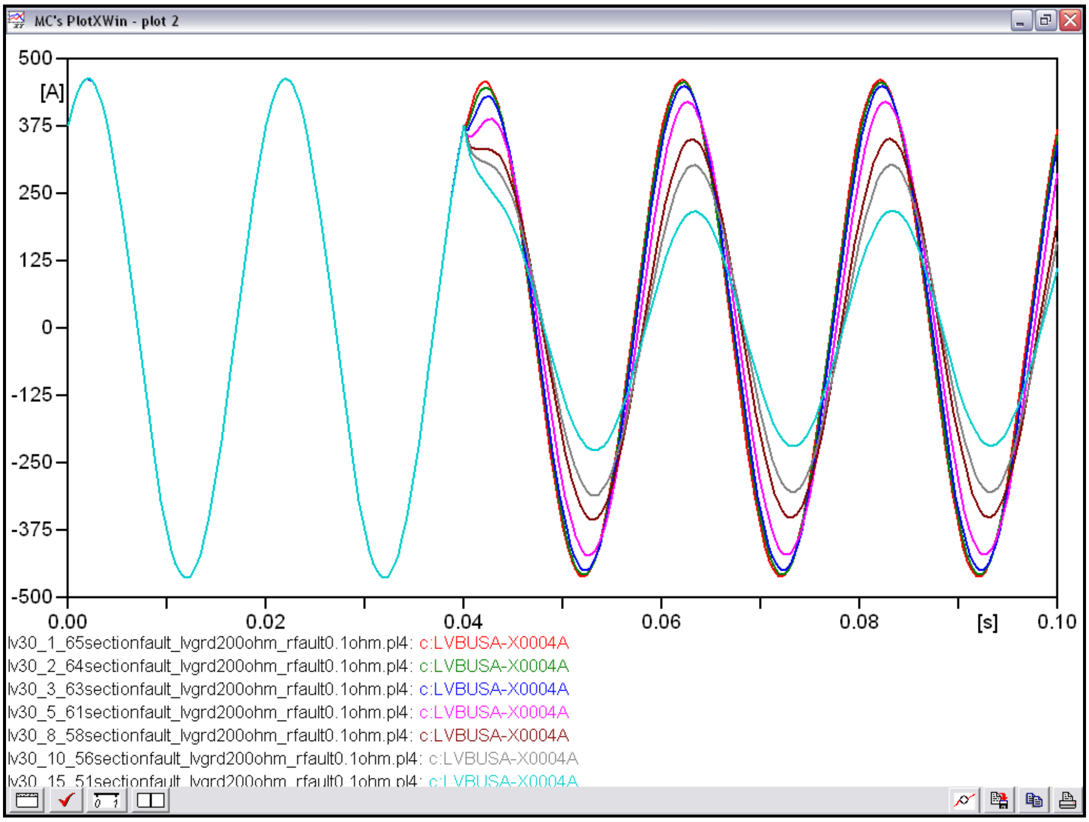


Figure 5.22 Turn-to-turn Fault Secondary Windings Current Waveform

Table 5.3 Turn-to-turn Current Distribution

Number of Faulty Sections	Current at High Voltage Side (A)	Current at Low Voltage Side (A)	I diff (x In)	I bias (x In)	I OCR (x 1.2 In)
0	153.08	327.67			
1	164.44	325.96	0.03	0.82	0.356
2	200.58	323.08	0.13	0.91	0.434
3	260.76	317.6	0.29	1.06	0.565
4	340.85	308.97	0.51	1.26	0.738
5	434.6	297.06	0.77	1.49	0.941
6	532.57	282.35	1.04	1.73	1.153
7	629.8	265.76	1.31	1.96	1.364
8	720.9	248.39	1.57	2.17	1.561
10	880	210	2.03	2.54	1.905
15	1120	150	2.73	3.09	2.425
20	1260	120	3.13	3.42	2.728
25	1350	100	3.39	3.63	2.923

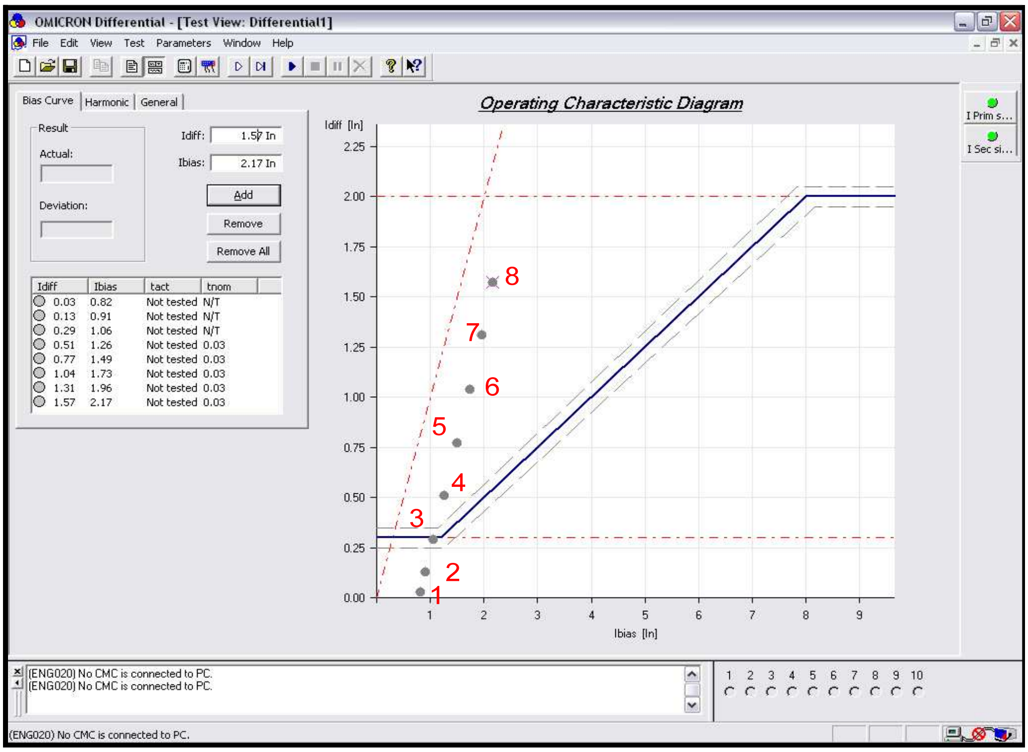


Figure 5.23 Differential Relay Characteristics Plotting for Turn-to-turn Fault

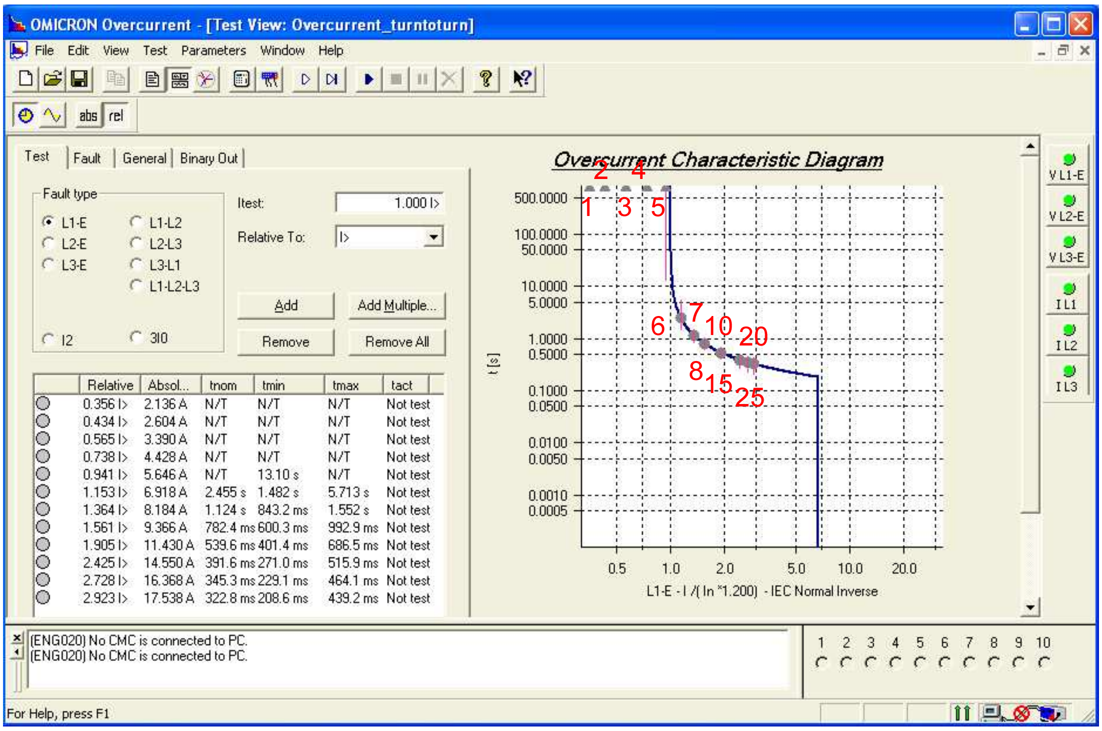


Figure 5.24 Over Current Relay Characteristics Plotting for Turn-to-turn Fault

From the figure 5.24 above, it can be concluded that the back up over current relay will work if 6 (six) of the secondary winding sections are short circuited but the trip time is delayed by the normal inverse characteristics of the transformer over current relay.

The trip time of the over current relay is delayed because the over current relay must be coordinate with the feeder or line protection.

5.3.3. Tertiary Winding Fault

Turn-to-earth Fault

The tertiary winding of the modeled transformer is unloaded. The protective devices must also respond to delta-winding faults. The differential relay is difficult to detect the fault because the primary and secondary winding currents of faulty condition are almost the same with the pre-fault currents. The transformer protection system will probably have to rely on non electrical protection i.e Buchholz relay or sudden pressure relay.

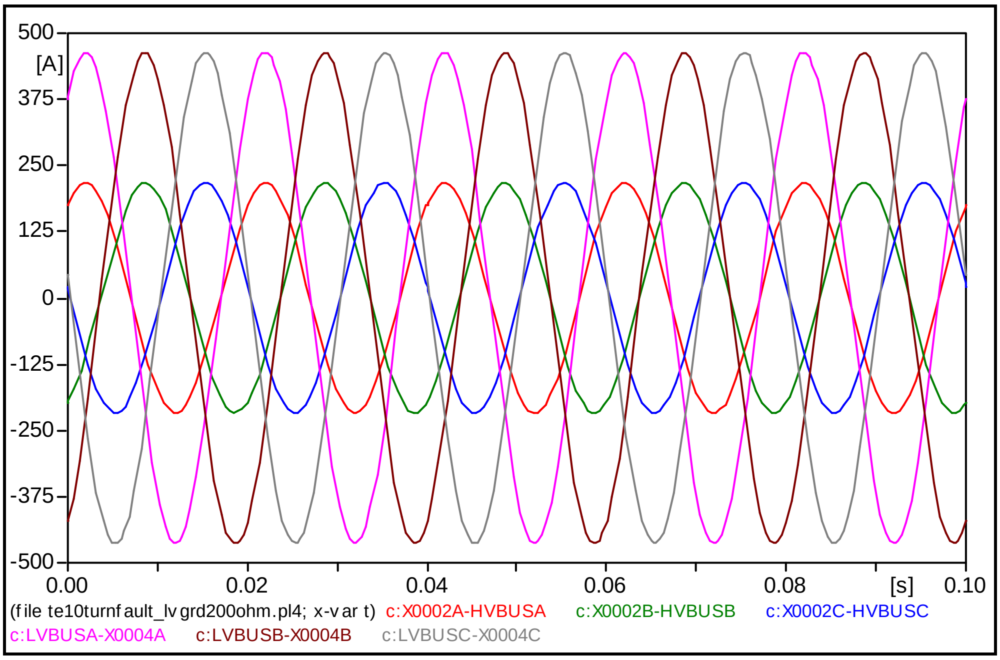


Figure 5. 25 Turn-to-earth Current Waveform

From the figure above, it can be shown that there are no significant current difference between pre-fault and fault condition. The differential or other electrical protection installed to protect the transformer will not react at all due to turn-to-earth fault at unloaded tertiary winding.

The other possibility is by using neutral voltage displacement relay to detect the fault on the tertiary winding because there is are significant change in the voltage of the tertiary winding. But there is no neutral voltage displacement relay at the PLN transformer protection system.

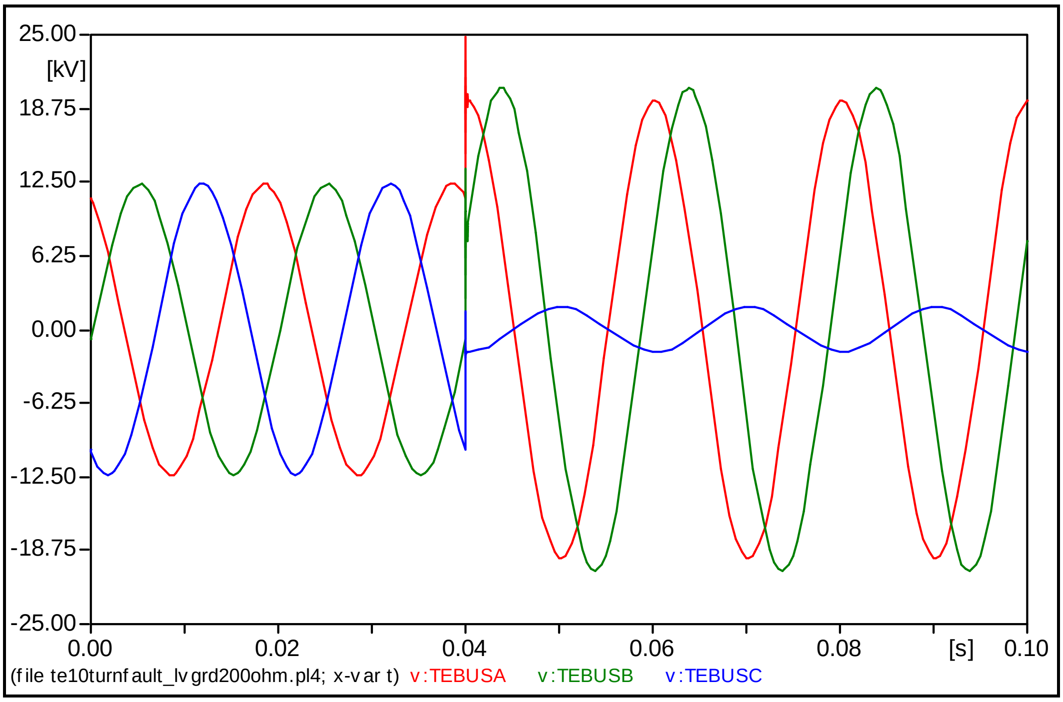


Figure 5.26 Turn-to-earth Voltage Waveform

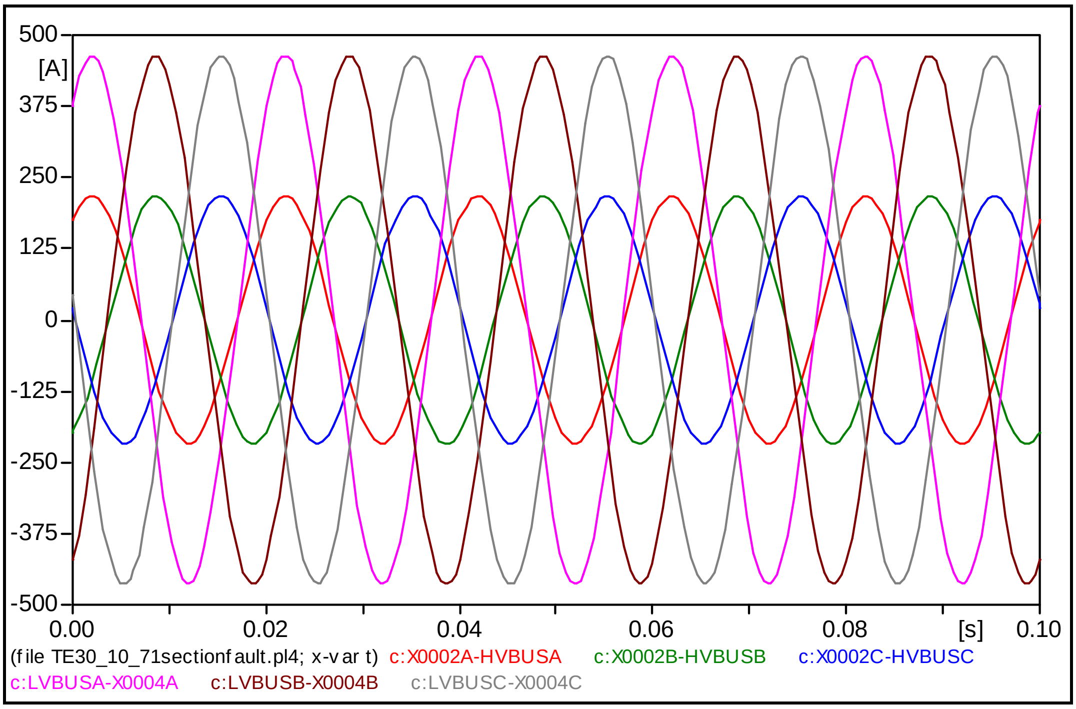


Figure 5. 27 Turn-to-turn Current Waveform

Turn-to-turn Fault

The current waveform due to turn-to-turn fault at the tertiary winding is similar to the current waveform because of turn-to-earth fault. The differential relay and other electrical protection installed at the transformer will not react at all relating to this fault. The protection will rely on the non electrical protection such as Buchholz and sudden pressure relay.

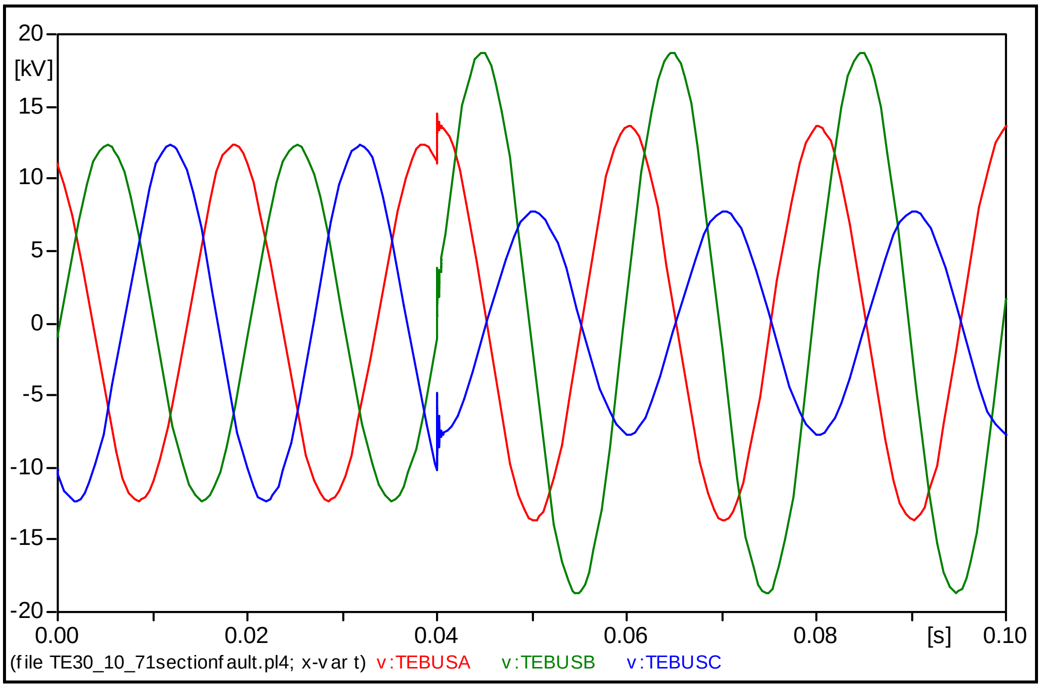


Figure 5.28 Turn-to-turn Voltage Waveform

VI. CONCLUSIONS AND RECOMMENDATIONS

6.1. Introduction

In this chapter the conclusions and recommendations for future study resulting from this thesis report are presented. First the conclusions will be presented and later recommendation will also be presented.

6.2. Conclusions

- The leakage impedance calculation using leakage factor could be done to make a new impedance matrix as the representation of transformer during turn-to-earth and turn-to-turn fault. The verification must be done by comparing the calculation of leakage reactance using geometrical quantities of the transformer and the leakage reactance from the BCTRAN routine.
- The model of the faulty transformer can adequately be used to make the fault waveform that can be used to test the sensitivity and correctness of the protection system.
- The differential relay has a limitation to discriminate the internal fault. The limitation depends on the fault location, type of fault, and system condition (grounding resistance, source impedance, and voltage).

6.3. Recommendation

- The modified impedance matrix calculation is done by introducing the leakage factor estimation based on several papers. To provide more accurate impedance matrix representation of the transformer, the future study could use the finite element method or other accurate and suitable methods.
- The complete transformer fault modeling including inrush current, core fault, and other possible faults could be proposed for future study. The new scheme and algorithm of transformer protection could be studied either.

- To make the real protection relay testing, it would be valuable to complete the laboratory facilities with the secondary test set equipment, circuit breaker replica, and protection relay.

References

1. “Alternative Transient Program (ATP) Rule Book”
2. “Electromagnetic Transient Program (EMTP) Theory Book”
3. Hoidalen H.K., Prikler L., “ATPDraw version 3.5 for Windows 9X/NT/2000/XP User’s Manual”, October 2002
4. Brandwaijn V., Dommel H.W., Dommel I.I., “Matrix Representation of Three-Phase N-Winding Transformers for Steady-State and Transient Studies”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No.6 June 1982, page 1369-1378.
5. Bastard P.,Bertrand P.,Meunier M., “A Transformer Model for Winding Fault Studies”, IEEE Transactions on Power Delivery, Vol. 9, No. 2 April 1994, page 690-699.
6. Darwish H.A.,Taalab A.M.I.,Labana H.E., “Step-by-Step Simulation of Transformer Winding Faults for Electromagnetic Transient Programs”, Transmission and Distribution Conference and Exhibition 2005/2006n IEEE PES, 21-24 May 2006, page 177-182
7. Popov M., “Lecture Notes of Power System Grounding and Protection”, 2008
8. Kezunovic M., Guo Y.,”Modeling and Simulation of the Power Transformer Faults and Related Protective Relay Behavior”, IEEE Transactions on Power Delivery, Vol. 15, No. 1, January 2000.
9. Chen X.S.,Venkata S.S., “A Three-phase Three-winding Core-type Transformer Model for Low-frequency Transient Studies”, IEEE Transactions on Power Delivery, Vol. 12 No. 2, April 1997, page 775-782.
10. Babic S., Akyel C.,”Improvement in Calculation of the Self- and Mutual Inductance of Thin-Wall Solenoids and Disk Coils”, IEEE Transactions on Magnetics, Vol. 36, No. 4, July 2000.
11. Wilcox D.J., Conlon M., Hurley W.G., “Calculation of Self and Mutual Impedances for Coils on Ferromagnetic Cores”, IEE Proceedings, vol. 135, Pt A, No. 7, September 1988.
12. Wilcox D.J., Conlon M., Hurley W.G., “Calculation of Self and Mutual Impedances between Sections of Transformer Windings”, IEE Proceedings, vol. 136, Pt C, No. 5, September 1989.
13. Mork B.A., Gonzalez F., Ischenko D., “Leakage Inductance Model for Autotransformer Transient Simulation”, International Conference on Power Systems Transients (IPST’05) June 2005.
14. Reynders J.,”The Prediction of Fault Currents in a Large Multi-winding Reactor Transformer”, IEEE PowerTech Conference, June 2003.
15. De Leon F., Semlyen A., "Efficient calculation of elementary parameters of transformers" IEEE Trans. on Power Delivery, Vol. 7, No. 1, January 1992, pp. 376-383.
16. Holenarsipur P.S.S, Mohan N., Albertson V.D., Christofersen J., “Avoiding the Use of Negative Inductances and Resistances in Modeling Three-Winding Transformers for Computer Simulations”, IEEE Power Engineering Society, Vol. 2, 1999, pp. 1025-1030

17. Folkers R.,"Determine Current Transformer Suitability using EMTP Models", Schweitzer Engineering Laboratories, Inc.
18. Horowitz S.H., Phadke A.G.,"Power System Relaying", John Wiley and Sons Inc, 1995.
19. Areva T&D, "The Protective Relay Application Guide (PRAG)",
20. Elmore W.A., "Protective Relaying Theory and Applications", ABB Power T&D Company, 1994.
21. C.R. Mason, "The Art & Science of Protective Relaying", General Electric
22. Winders Jr J.J,"Power Transformers Principles and Application", Marcel Dekker, 2002.
23. Gers J.M., Holmes E.J., "Protection of Electricity Distribution Networks", The Institution of Electrical Engineers, IEE Power and Energy Series 28, 1998.
24. Denis-Papin M., "La Pratique Industrielle des Transformateurs", Editions Albin Michel, 1951.
25. Grover F.W., "Inductance Calculations : Working Formulas and Tables", Dover Publications, 1946.
26. Say M.G.,"Alternating Current Machines", 4th Edition, London : Pitman 1976.
27. Heathcote M.J., "J&P Transformer Book", Elsevier, 2007.
28. Areva T&D,"Lecture Notes of Analysis and Protection of Power Systems (APPS) Course", AREVA T&D UK Ltd – Stafford, 2006.
29. Perusahaan Listrik Negara, "Standar Pola Pengaman Sistem Bagian Satu : C. Tranformator 150/66 kV, 150/20 kV, dan 66/20 kV", SPLN No 52-3 1983. (*PLN Transformer Protection System Standard*)
30. PLN P3B Jawa Bali,"Buku Operasi dan Pemeliharaan Sistem Proteksi Gardu Induk", 2005. (*Operation and Maintenance Book of Substation Protection System*)
31. Departemen Energi dan Sumber Daya Mineral, "Aturan Jaringan Sistem Tenaga Listrik Jawa Madura Bali", 2007. (*Java Madura Bali Electrical System Grid Code*)
32. "Relays Associated with Electric Power Apparatus," C37.1-1950, American Standards Assoc., Inc
33. "Standards for Power Circuit Breakers," SG4-1954, National Electrical Manufacturers Association
34. "Omicron User's Manual Book", Omicron

Abbreviation

ACT : Auxiliary Current Transformer

ATP : Alternative Transient Program

CB : Circuit Breaker

CT : Current Transformer

DBM : Data Base Module

DC : Direct Current

EMTP : Electromagnetic Transient Program

FAT : Factory Acceptance Test

GFR : Ground Fault Relay

IBT : Interbus Transformer

JCC : Java Control Center

LG : Line to Ground

LL : Line to Line

OCR : Over Current Relay

PLN : Perusahaan Listrik Negara, state-owned electrical utility company in Indonesia

REF : Restricted Earth Fault

RMS : Root Mean Square

SBEF : Standby Earth Fault

SCADA : Supervisory Control and Data Acquisition

VT : Voltage Transformer

Appendix : Transformer Data