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Protection from Internal and External Faults using Differential Protection Scheme for Power Transformer and Validation using Simulation Model

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Abstract- Transformer is an important component in the power system both at transmission and distribution level. Although, transformer faults are less prominent than either line or equipment faults but if unattended can cause major damages to the subsequent interconnected equipment and system. The ratings for distribution level are typically lower than at transmission level. Irrespective of the size of the transformer, the differential protection scheme becomes an ideal choice for engineers. This project mainly identifies the importance of differential protection of transformer by simulating adverse (fault) conditions and operating conditions (inrush) of transformer using ATPDraw modeling. An integrated use of differential relay protection scheme for transformer is simulated using MatLab/Simulink. Several challenges in fault simulation in both ATPDraw and MatLab during initial studies were mainly related to design parameters, and were subsequently addressed by detailed literature review using IEEE researchers. With insights developed in relay protection from classroom notes and textbook, modeling and simulation of fault scenarios namely: internal and external faults, were performed. The goal and scope was further refined to identification of differential currents during the faulty conditions and studying operation of relay designed using basic Boolean logical approach. In the final analysis, results for no fault and fault conditions with relay operation are presented and a need for design of relay sensing the harmonic components is included as part of future scope of this work.

Keywords: Differential Protection, Power System Protection.

I. Introduction

An electric power system has generators, transformers, transmission lines and other equipment that are connected continuously in the process of electrical energy generation, transmission, distribution and consumption. Transformers (Power or Auto) are the most expensive and important elements in the system and are known as technological “hubs” [1]. Therefore, any type of failure or disconnection results in heavy technological damage and economic losses. Hence, to guarantee the continuity of the supply, transformers need to be protected adequately against faults and abnormal operating conditions.

From the electrical point of view, power transformers have two protection schemes: a primary protection scheme based on differential protection (87T) and backup protection, using phase and neutral over-current relays (50/51, 50/51N) [2]. Both protection schemes must provide selectivity, in order to avoid unnecessary disconnection of nearby equipment during faults, such as transmission lines and buses in the substation. In addition, over-current protection must be coordinated with some other protection schemes of nearby electrical equipment. Considering the costs of the power transformer and the energy not supplied during disconnection due to replacement or maintenance, protection engineers must be sure that all protection schemes operate in a reliable way during different load conditions, levels of short circuit currents due to system reconfiguration, fault types, etc. This can be achieved by a proper selection of relay setting parameters, as well as an adequate selection and connection of current transformers in order to avoid saturation. In any case, the protection schemes must be evaluated and tested for different cases of failure in the power system [2].

Recent years have seen extraordinary advances in the technologies for improving the relays and protection scheme. Modern microprocessor relays have replaced the old EM relays emulating all the functions of the latter. Similarly, several new software like PSCAD, MATLAB and ATP have been developed to analyze the power system [3].

Differential protection is one of the foremost transformer protection schemes and is based on Kirchhoff's current Law. This type of protection is based on the balance of the steady magnetic circuit, which can be destroyed during the transient process and can only be rebuilt after the transient process is finished. Therefore, many unfavorable factors need to be taken into account in the implementation of transformer differential protection which will be mentioned in later sections [4].A transformer operates at various conditions namely—magnetizing inrush, over excitation, external and internal fault conditions and normal operating conditions [5]. This project aims at studying the performance of protection systems at varying operating conditions. The time to clear fault and rise in current values and their effects on transformers will be identified. Moreover, a differential protection scheme can have been employed for protection which may be included as part of further analysis.

II. Literature Review

2.1 Transformer operating conditions

S. No.	Operating conditions	Proposed objective
1	Inrush	Ensure no tripping during inrush Analyze the time for inrush
2	Over excitation (during different voltage level operation)	Analyze current and its protection if needed
3	Internal Faults	Currents and protection scheme
4	External faults (bus faults or faults in connected equipment's)	Currents and protection scheme

Several factors need to be taken in account when a scheme is designed to avoid unbalanced currents. These unbalanced currents, existing at the secondary circuit during any external faults, may influence the differential relay's correct operation.There are several reasons due to which these unbalances could occur as enumerated [3]:

- A mismatch of synch between CTs on either side for protection of transformer and Tap changer effects. This means that current flowing to the relay from the two sides of the transformer may not be balanced. The percentage restraint feature solves it.
- Inrush during energization: High magnitudes of current are produced by the magnetizing inrush when the transformer is first energized. This transient phase lasts for a few milliseconds and an intentional time delay for relay can solve such problems. Since it will be read by the supply side CTs, it could be interpreted as an internal fault. Thus it is necessary to prevent an unnecessary fault. The inrush currents could also occur when CBs reclose after clearing a fault or when a transformer, connected in parallel, is energized.
- Over excitation conditions: The transformer core could become saturated during overvoltage and under-frequency conditions. This is because the core flux is directly and inversely proportional to voltage and frequency respectively. The over-excitation poses a serious problem with effects such as noise, vibrations, heating and increased values of exciting currents. So, a V/Hz element is used separately to operate with voltage-frequency ratio.
- CT saturation: Due to saturation in the current transformer, there can be delayed operation of relays and it can cause mal-operation with external fault conditions due to false differential current. Harmonic blocking is used for added restraint and to overcome these effects.
- The inrush current is multiple of rated current and has 2nd harmonic content whereas over-excitation is marked with odd harmonics [2]. So, the second harmonic is used as a blocking element for the relay operation. Fifth harmonic is also used but third is not due to its nullification with delta connections. The relay percentage restraint characteristics will typically solve the first two error sources. Ensuring proper connections of CTs and digital relay can address the problems due to phase-shift.

2.2 Transformer Faults

2.2.1 Internal faults

Faults occurring within the protection zone of the transformer are called internal faults. It not only includes the faults within the transformer enclosure but also the faults that occur inside the current transformer location. The internal faults are classified into incipient faults and active faults. Incipient faults are the ones that develop slowly but can develop into a major fault if not detected and corrected. This could be due to overheating of the transformer, over-fluxing or overpressure and causing gradual deterioration of the insulation [3]. Active faults occur due to insulation breakdown that creates a sudden situation requiring prompt action towards damage control and preventing any further destruction. They happen suddenly and therefore require fast action by the protective relays to open the circuit breakers and isolate the transformer from the system. Active faults can be any type like winding short-circuit, phase-to-phase short-circuit, core faults, tank faults, etc [3] [4].

2.2.2 External faults

External faults are the faults occurring outside the protection zone of the transformer. These faults usually create stresses on the transformer, which may be a cause of concern and could possibly result in shortening of transformers life [5]. External faults could be due any reason like over-loading, overvoltage, under frequency and short-circuit in the external system. Most of the foregoing conditions are often ignored in specifying transformer relay protection, depending on how crucial transformer is and its significance in the system. The exception is protection against over fluxing, which may be provided by devices called ‘volts per hertz’ relays that detect either high voltage or under frequency, or both, and will disconnect the transformer if these quantities exceed a given limit, which is usually per unit [4] [6].

2.3 Differential Protection

Differential relay is the most commonly used primary protection for the protection of transformer especially when the fault clearing speed is very important. By definition, it operates when two or more similar electrical quantities have vector difference more than a predetermined amount [1]. The currents entering and leaving the transformer need to be calculated in order to get the vector difference. It can be said that a circulating current circuit is formed with the current transformers connected at the primary and secondary side of the transformer [2] [7].

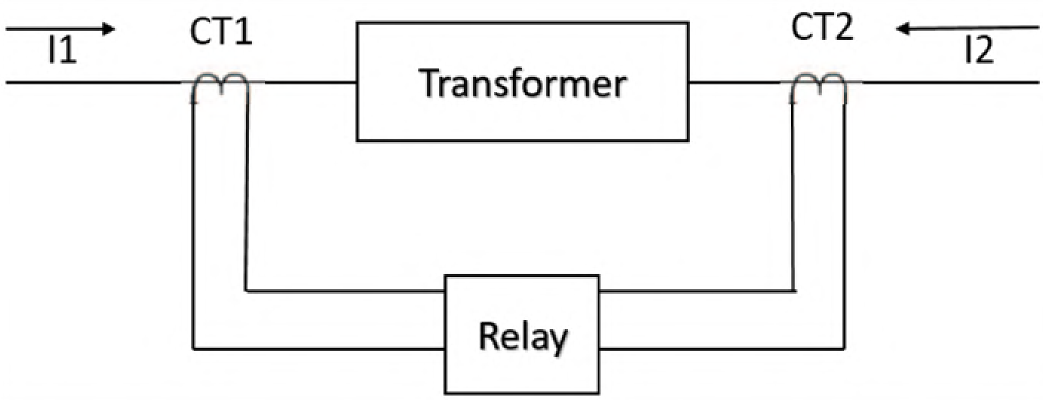

Figure 1: *Differential scheme for transformer protection [1]*

The operating current (Iop) is modulus summation of I1 and I2 as shown in (1) [1]. The operating current is proportional to the restraining current (Irest). The restraining current given by equation (2) [1] [4] [8].

$$I_{op} = |I_1 + I_2| \quad (1)$$
$$I_{rest} = K(|I_1|+|I_2|) \quad (2)$$

Where, k represents the compensation factor (1 or 0.5) [2].
The operation of relay depends upon the value of I_{op} exceeding the slope of the differential characteristics times I_{rest} [2] [9]. The operating region of the relay lies above the slope characteristics and the restraining lies below the slope characteristics. The slope characteristic has a variable percentage feature, making it dual-slope, and can be seen as a dotted lien in the figure below. This feature provides added security for the external faults wit CT saturation [9].

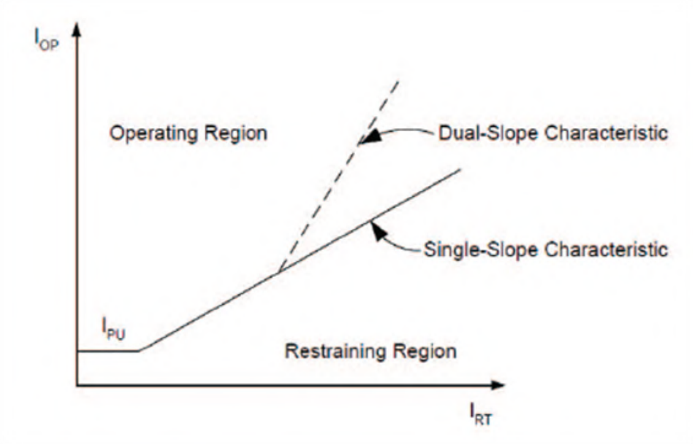

Figure 2: Differential relay characteristics [5]

III. System Modelling

3.1 Fault Analysis using ATP

No fault Condition:

A three phase saturable transformer (150 MVA, 33:132 kV) is connected to a three phase source (33kV) and RLC load (parameters in Appendix A). The RMS value of primary and secondary currents are carried out and their algebraic subtraction i.e. differential current is measured as shown in Fig. 6. Fig. 3 shows the circuit diagram and Fig. 4, 5 are the primary and the secondary measured currents.

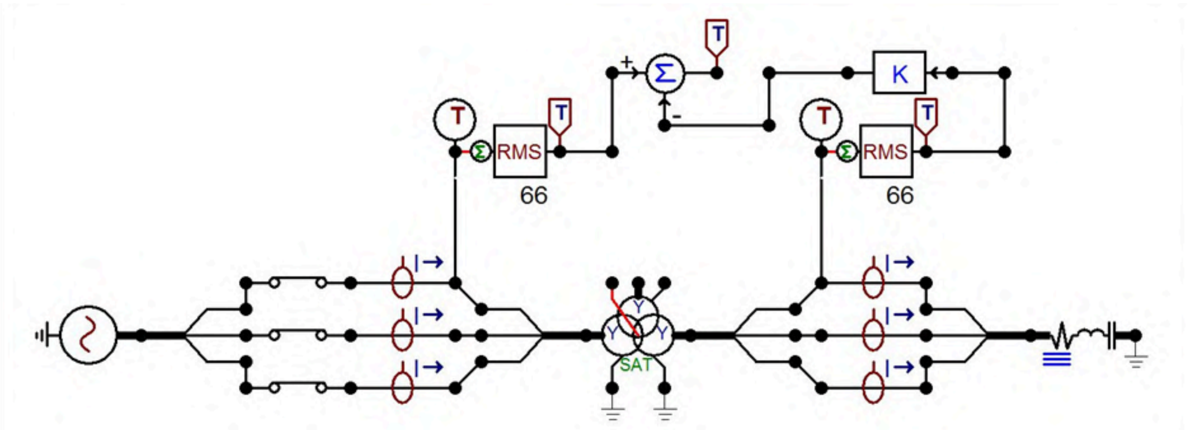

Figure 3: ATP circuit diagram for steady state analysis

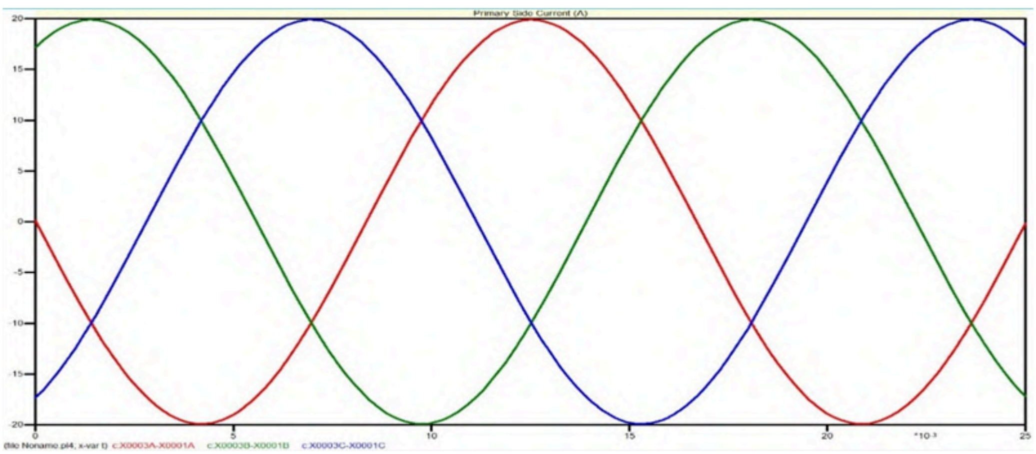

Figure 4 Primary Steady State Current

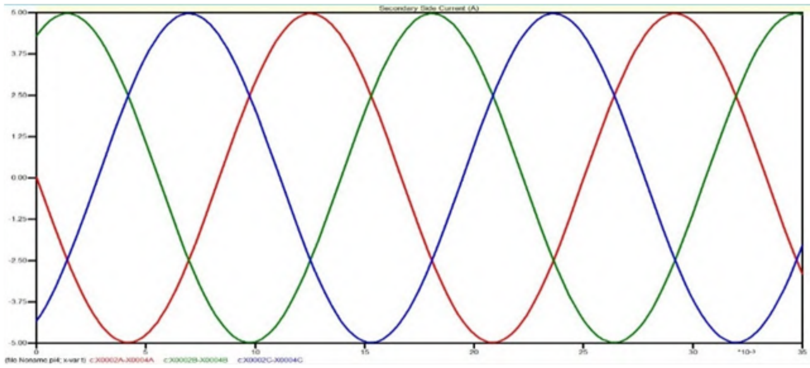

Figure 5 Secondary Steady State Current

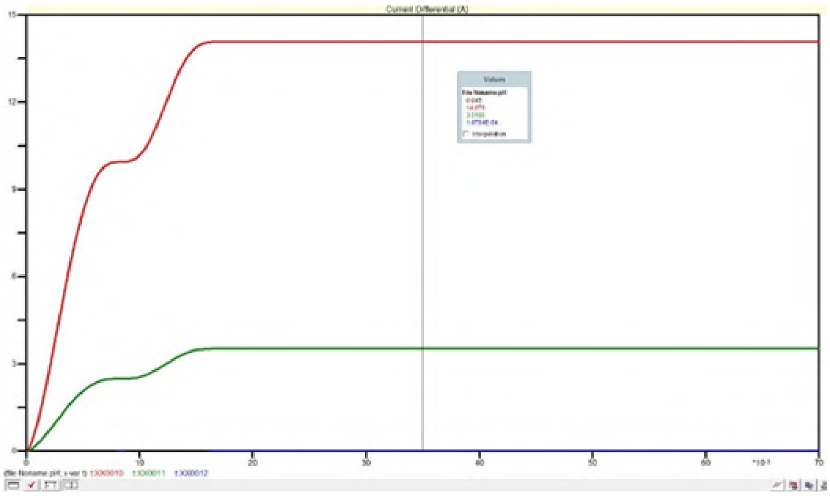

Figure 6 Differential Current during no fault condition

Inrush Conditions:

During the energization of the transformer there is a sudden increase in current which is typically in the range of 10 times the rated current. The primary current during energization with use of switching operation is shown in Fig. 7.

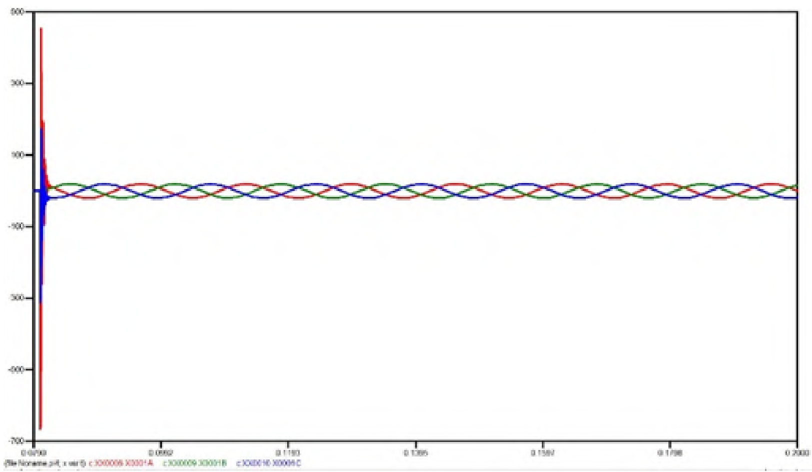

Figure 7 Inrush current

Internal Fault

An internal fault three phase line fault is simulated as shown in Fig. 8. Switching is performed to analyze the effects of faults in differential current as shown in Fig. 9.

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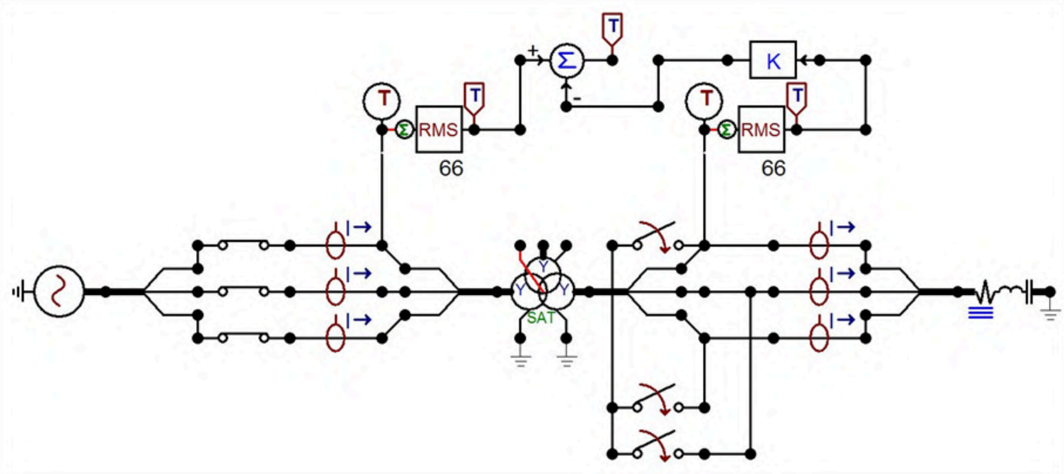

Figure 8 Three phase line internal fault

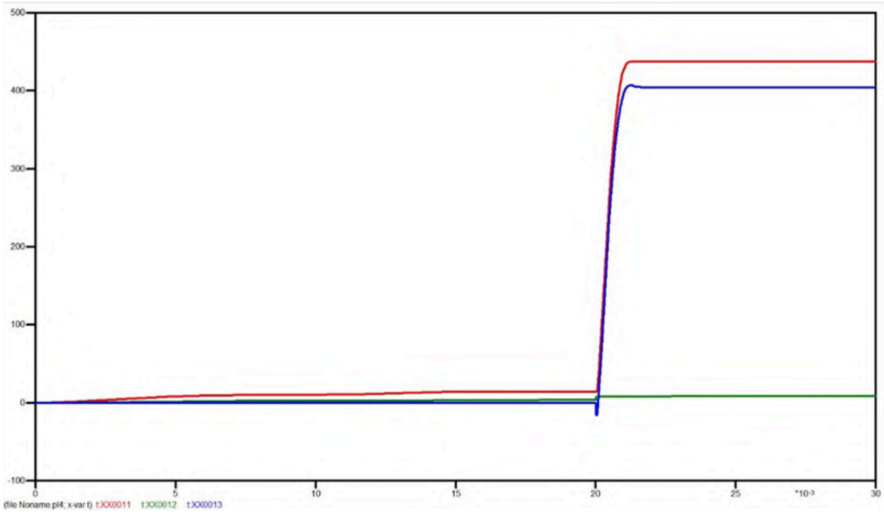

Figure 9 Differential current during three phase line fault

External Fault

For simulation of external fault, an LCC section is introduced as shown in Fig. #. The external fault is simulated near the line section as shown in the Fig. 10. The differential current during this fault condition is shown in Fig.11.

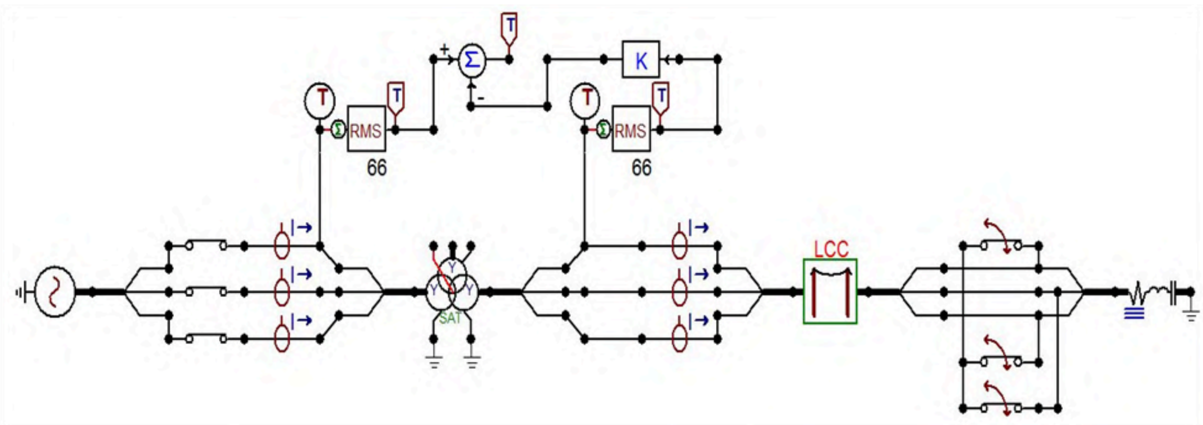

Figure 10 External Fault condition

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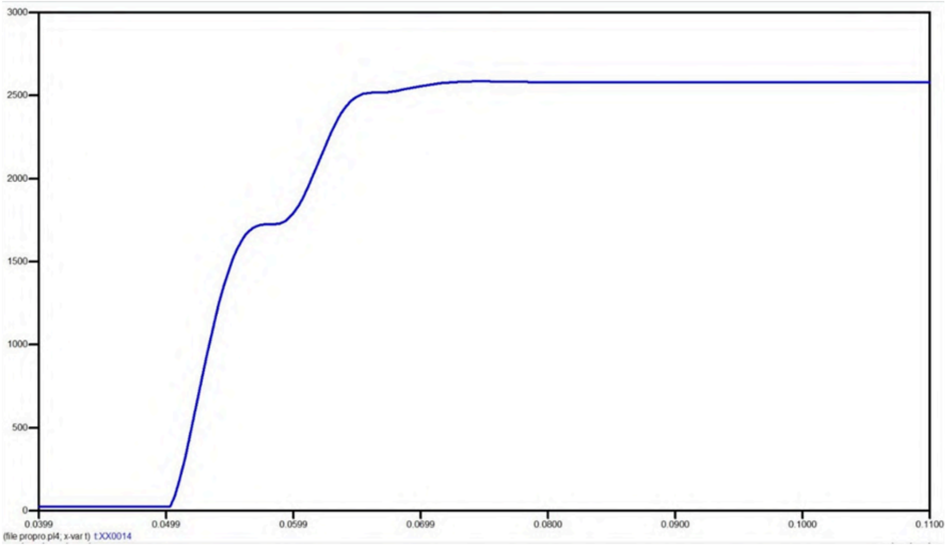

Figure 11 Differential current during external fault

After studying the effects of fault in ATP, an approach in implementing relay protection scheme is performed using Matlab/Simulink and discussed in further sections.

3.2 Power System Model in SIMULINK

Faults are simulated using MatLab Simulink at both near the transformer (internal) and near the line section (external). A 150 MVA, (33/132) kV transformer is used for in this case for studying the differential protection. The transformer serves a system of line section (PI) as shown. Three-phase VI measurement is used to measure the fault currents, inrush currents and differential current for transformer protection. Transformer, line section, source and load blocks are shown in Appendix 1. The system model with faults (internal and external) are shown in Fig. 12,

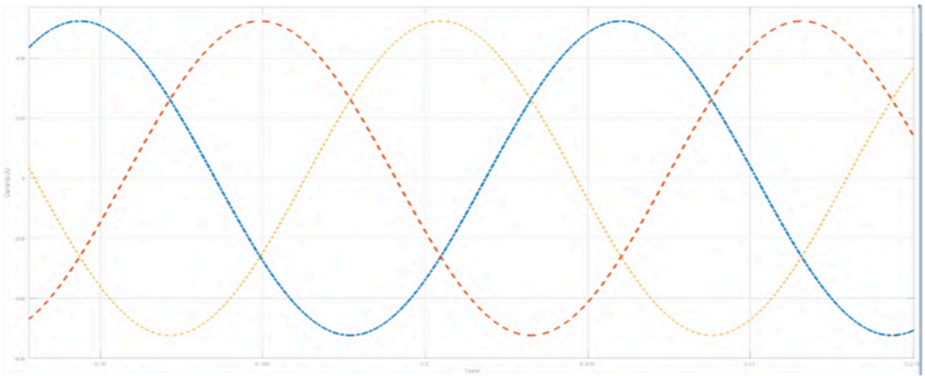

Figure 12 Internal and external fault simulations

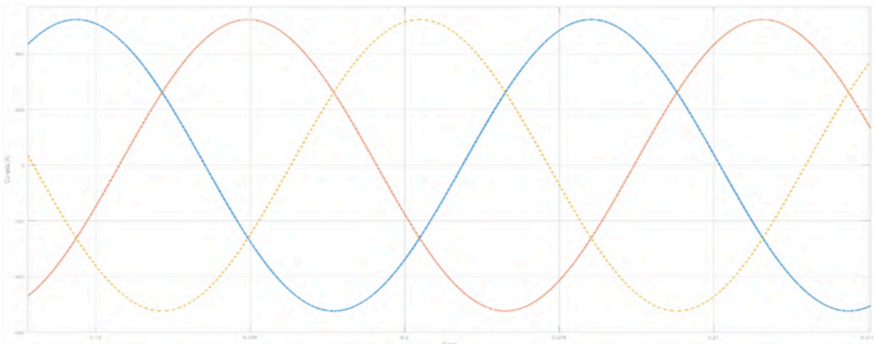

Figure 13 Primary current (no Fault condition)

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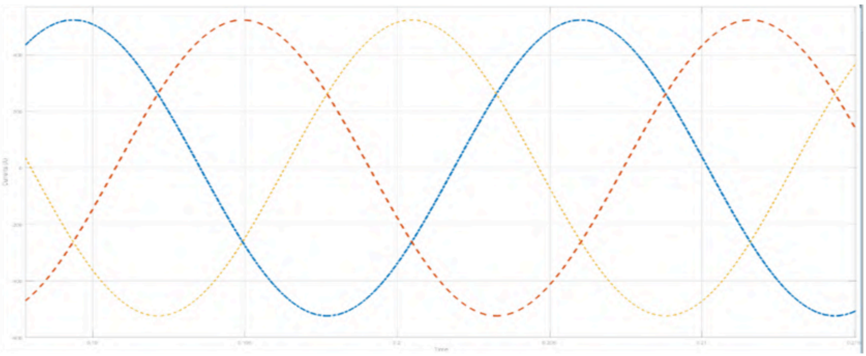

Figure 14 Secondary current (no Fault conditions)

3.3 Differential Relay Subsystem

Moreover, steady state and inrush currents are obtained before the fault conditions. After analyzing the fault currents as shown in Fi. #,#., a relay is used to sense the differential current and operate with a certain pick value of current (1.5 A in particular). The relay first compares the amplitudes from the input primary and secondary current of the transformer. The difference between the two signals is compared with a pre-determined pickup value and signal output is given to the breakers if the difference is more. The relay block diagram designed based on the logical approach shown in [5], is shown in Fig. 15. A detailed diagram showing the entire protection scheme is shown in Fig 16.

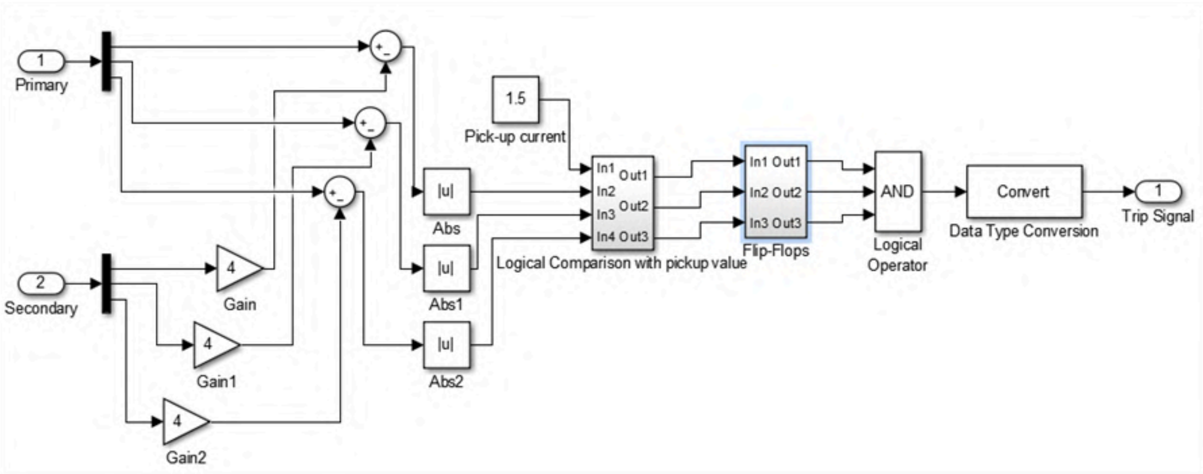

Figure 15 Relay Block

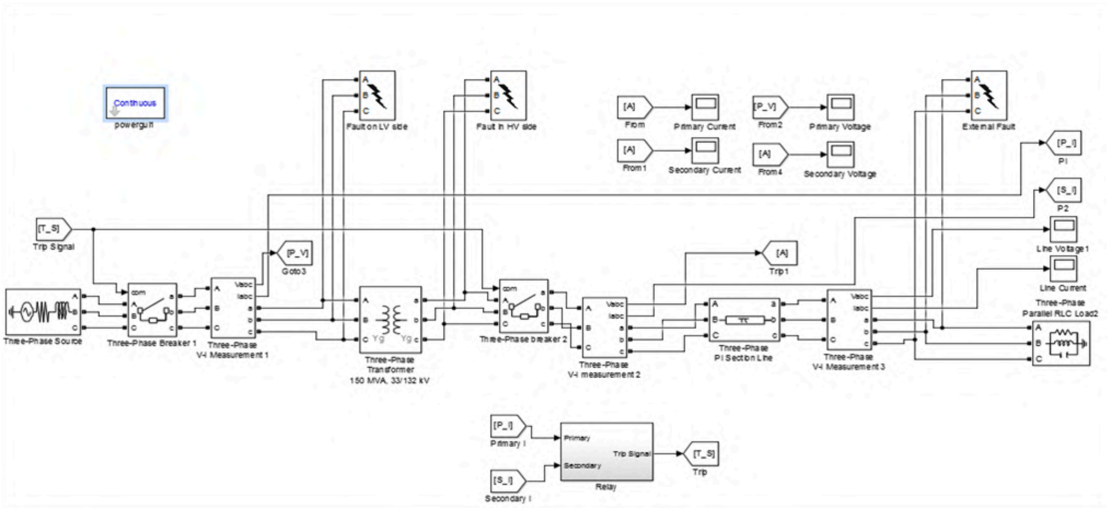

Figure 16 Protection scheme with differential relay

The differential current during no fault condition is almost equivalent to zero as seen in Fig. 17.

Figure 17 Differential current during steady state

IV. Case studies

4.1 Inrush conditions

The inrush current during transformer energization which is typically higher than operating current is shown in Fig. 18.

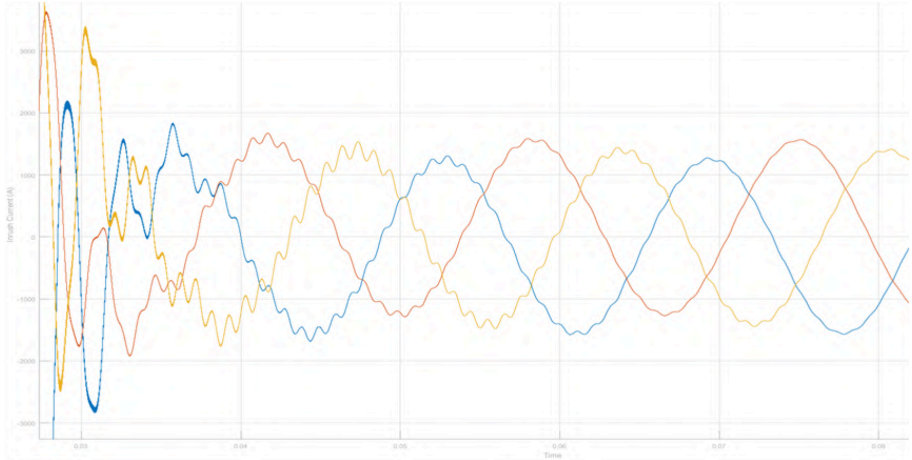

Figure 18 Inrush current during energization

4.2 External faults

The differential current during fault in the line section is shown in Fig.19. Moreover, a state curve near zero shows healthy conditions.

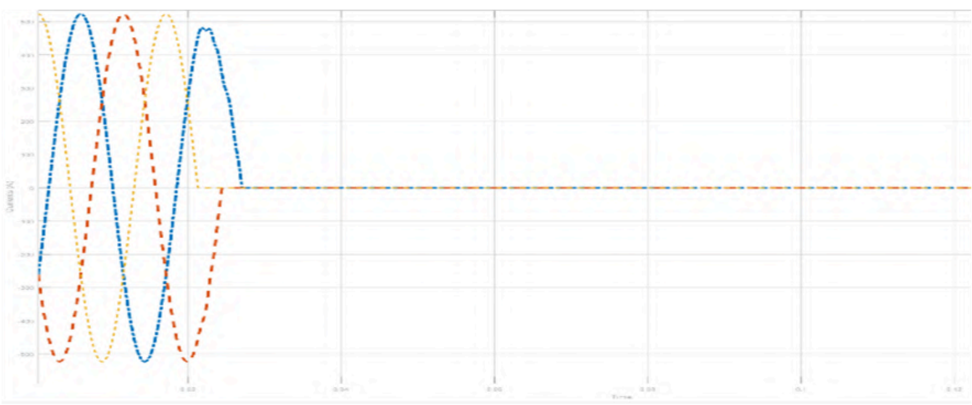

Figure 19 Differential current during external fault in the line section

4.3 Internal faults

The differential current during fault conditions is shown in Fig. 20. Moreover, towards the end a straight line near to zero shows healthy conditions.

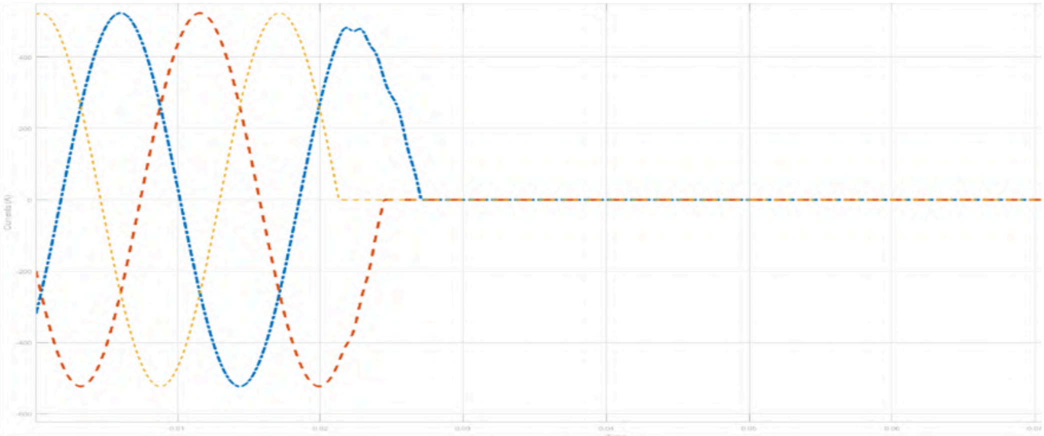

Figure 20 Differential current during internal fault

V. Conclusion

In this work, a model using ATPDraw for performing fault (internal and external) analysis was presented, and transformer operating conditions (inrush) were studied.Hence, after an investigation of these conditions, a relay protection scheme using Matlab/Simulink and its operation during faults is presented. The inrush conditions are not long-lasting; hence, a typical time delay is enough to prevent the malfunction of relays. The presented research modeled the fault conditions in a simplistic manner by using complexities of power system concepts and differential protection schemes.

VI. Future Scope and Recommendations

For sensing the inrush and over-excitation conditions, a relay designed to sense the harmonic component is needed, and hence, the protection scheme studied in this work can incorporate use of such harmonic measuring devices.

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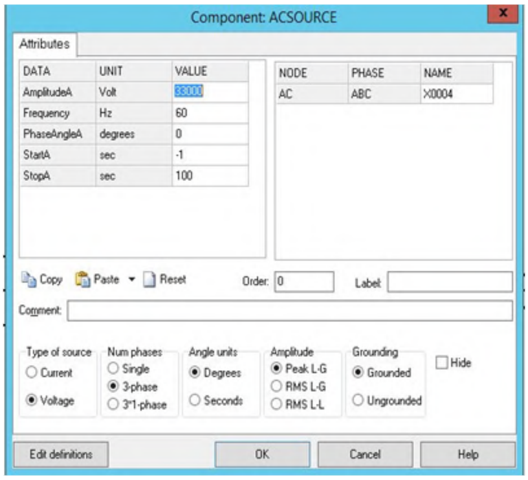
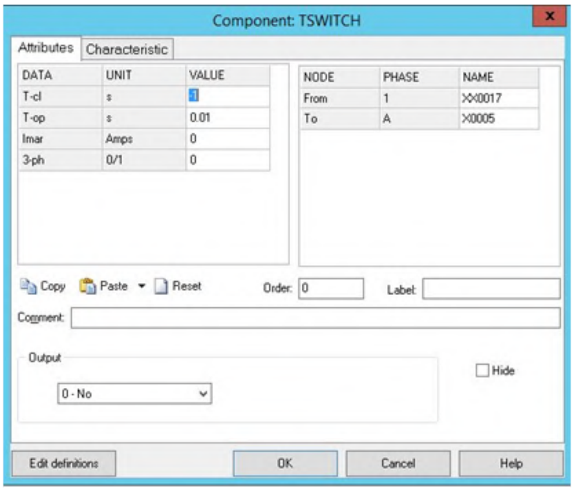
APPENDIX A: ATPDraw parameters

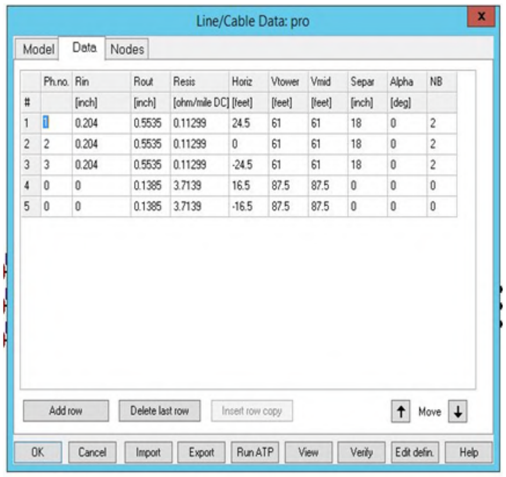
Generator parameters



Switch data

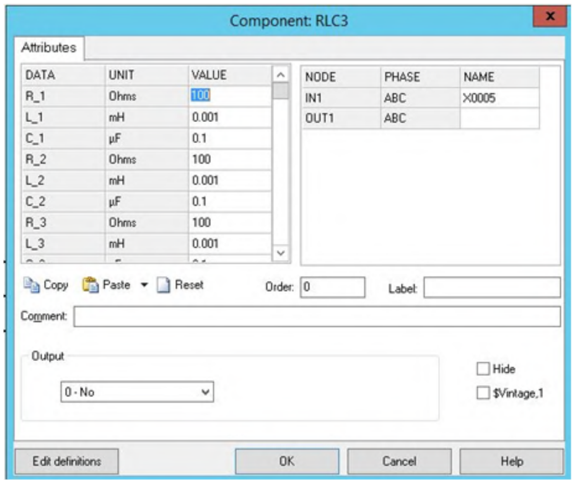


Line section parameters

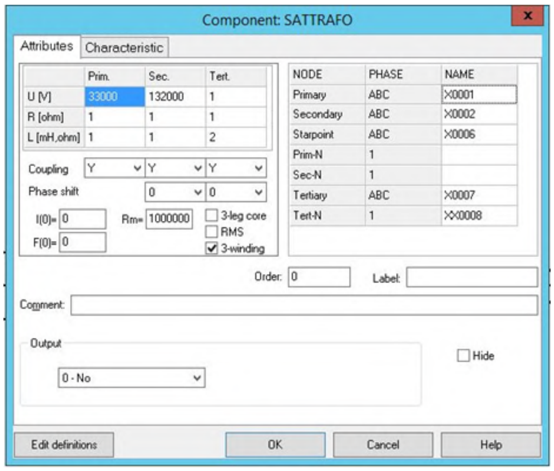


#	Ph.no.	Rin [inch]	Rout [inch]	Resis [ohm/mile DC]	Horiz [feet]	Vtower [feet]	Vmid [feet]	Separ [inch]	Alpha [deg]	NB
1	1	0.204	0.5535	0.11299	24.5	61	61	18	0	2
2	2	0.204	0.5535	0.11299	0	61	61	18	0	2
3	3	0.204	0.5535	0.11299	-24.5	61	61	18	0	2
4	0	0	0.1385	3.7139	16.5	87.5	87.5	0	0	0
5	0	0	0.1385	3.7139	-16.5	87.5	87.5	0	0	0

RLC load parameters

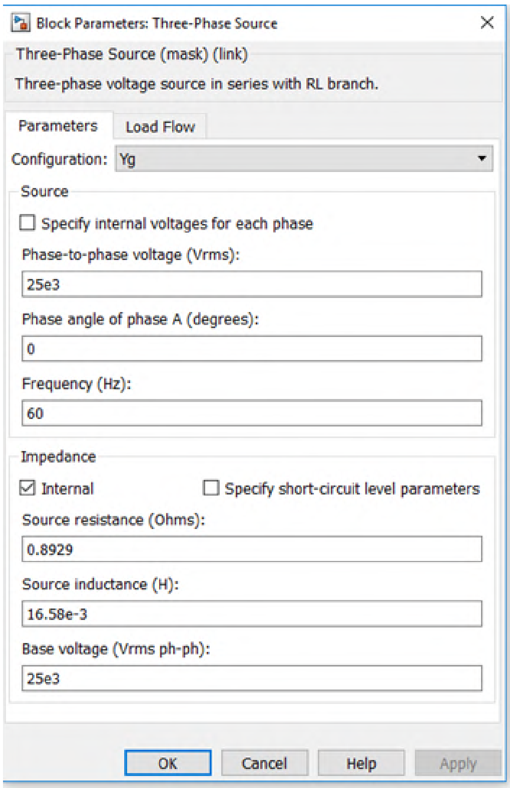


Transformer parameters

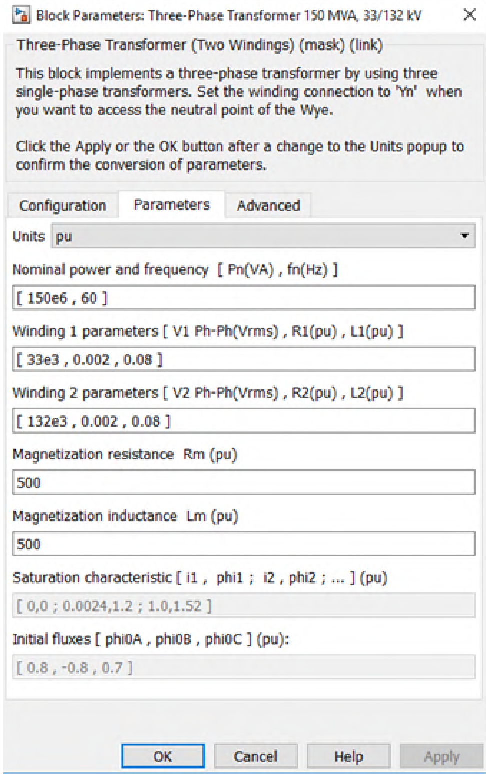


APPENDIX B: Simulink parameters

Generator data

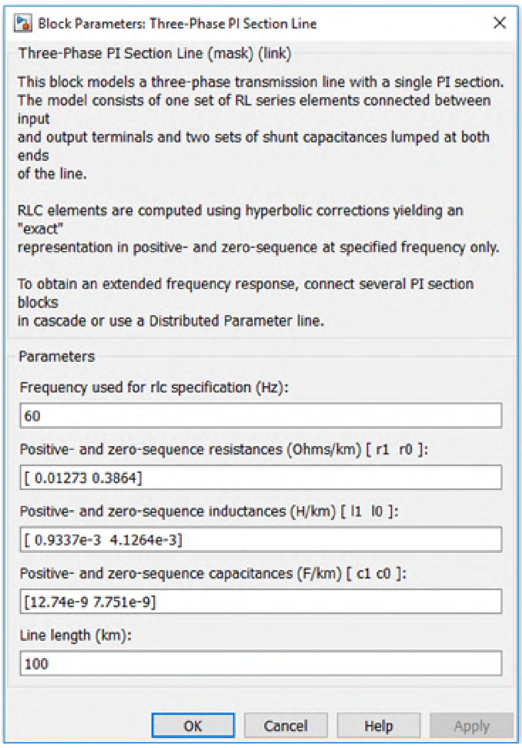


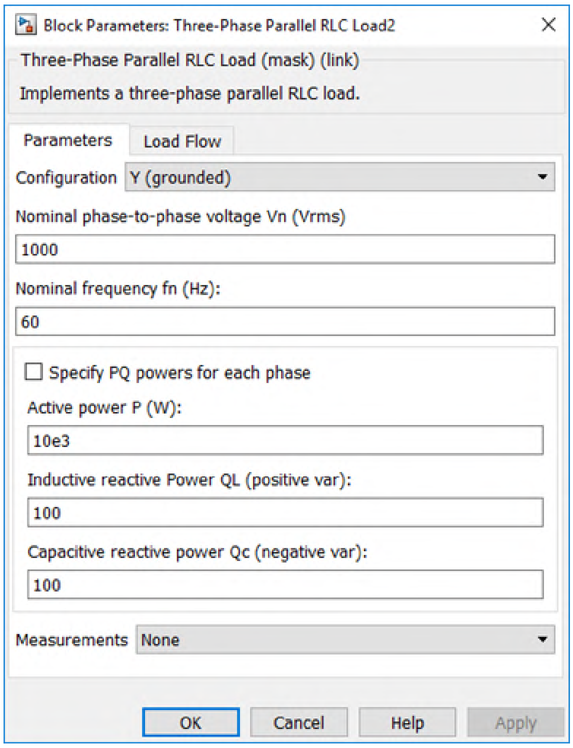
Transformer Data



PI section data

RLC load block data





APPENDIX C: Journal paper review

Title: Optimizing differential protection settings for power transformers
Authors: By S. M. Saad, A. Elhaffar and K. El-Arroudi

Transformer differential protection is important for clearing both internal and external faults. The protection methodology shown in this paper is an improved and optimized differential relay setting to counteract with fault or conditions such as inrush and over excitation. The mal operation of the realy with various operating conditions are studied and the improvements are hence suggested. The authors also converted the simulations in ATP to COMTRADE format and used a numerical differential relay for verification of the settings.

Although, transformer faults are less probable than generator faults due to its non-rotating system but faults unattended can have detrimental effects to itself and the interconnected system. Some of the conditions that transformers are prone to includes short circuit, mechanical and thermal stress during the faults. Thus, a differential protection scheme used for its protection. The currents on both LV and HV sides are compared and with operating current exceeding the restraining values, the relay operates which in turn disconnects the transformer from the system by a circuit breaker.

Although, operating conditions such as inrush and over-excitation, are problems which are not solved using differential protection. In order to combat these two situations an intentional time delay for differential relay is recommended. Moreover, desensitization of relay for a period to by-pass the effects of inrush is also a right choice. Use of harmonics for discrimination faulty conditions has often been used by Kennedy and Hayward, Sharp and Glassburn. With such incorporation of harmonic restraint and blocking methods several modern transformer protection has been designed.
The authors describe a typical transformer differential protection using a simplified diagram as shown in Fig. 1.

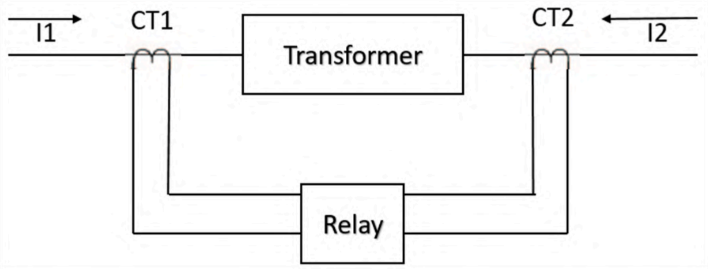


Fig. 1. Differential scheme for transformer protection [1]

The operating current (I_{op}) is modulus summation of I_1 and I_2 as shown in (1). The operating current is proportional to the restraining current (I_{rest}). The restraining current given by equation (2).

$I_{op} = |I_1 + I_2|$ (1)

$I_{rest} = K(|I_1|+|I_2|)$ (2)

Where, k represents the compensation factor (1 or 0.5).

The operation of the relay depends upon the value of I_{op} exceeding the slope of the differential characteristics times I_{rest}.

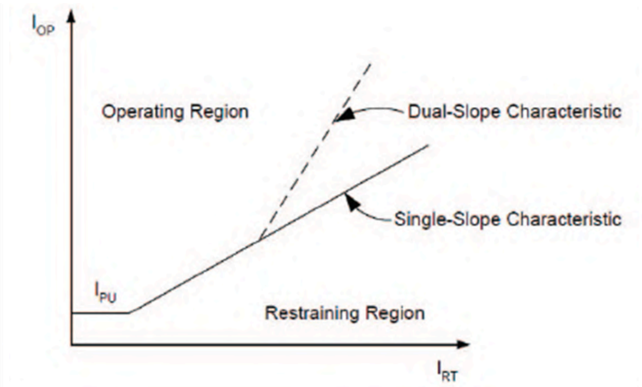


Fig. 2. Differential relay characteristics [1]

The authors discuss the sources of false current differential currents namely:

- A mismatch of synch between CTs on either side for protection of transformer and Tap changer effects: The percentage restraint feature solves it.
- Inrush during energization: This transient phase lasts for a few milliseconds and an intentional time delay for relay can solve such problems.
- Over excitation conditions: The over excitation poses a serious problem with effects such as noise, vibrations and increased values of exciting currents. So, a V/Hz element used to operate with voltage: frequency ratio.
- CT saturation: Due to CT saturation there can be delayed operation of relays and it can also cause mal-operation with external fault conditions. Harmonic blocking used to overcome these effects.

The inrush current is multiple of rated current and has 2nd harmonic content whereas over-excitation is marked with odd harmonics. So, the second harmonic is used as a blocking element for the relay operation. Fifth harmonic is also used but third isn't due to its nullification with delta connections.

The relay logic as proposed by authors includes following equations:

$I_{op} > I_{pu}$ (3)

$I_{op} > (\text{slope}).I_{rest}$ (4)

$K_2 I_2 = I_{op}$

Where, K_2 is constant for the second harmonic. Similarly, fifth harmonic is also used for the logic block by the authors.

The case study discussed by authors includes a system of transformer with 87HB1 as logic element to relay. A 20 MVA transformer with (30:11) kV is used and 18 MW inductive load is connected. The

typical values for all the settings and currents are as per Binina substation in Libya. The authors to record faults used DIGSI software. The external faults as simulated in ATP, the current values converted to COMTRADE files used for relay application. Authors performed a use of DIGSI software to load settings to relay. Three cases simulated by authors are namely: inrush, internal faults due to short-circuit, external fault due to short-circuit.
The authors conclude that a numerical differential protection is a viable solution as it has potential to record the transient conditions and effectively optimize the settings. Use of third and fifth harmonic for blocking purposes is also a recommended option for solving inrush problems. Based on the characteristics of inrush events obtained experimentally the relay settings can be altered.

References:

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