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FUNCTION BASED OPTIMIZED PROTECTION SCHEMES FOR DISTRIBUTION SUBSTATION

M. AFIFI, A. M. ABDIN, W. HELMY & S. EL DEBEIKY
Department of Electrical Power and Machines, Faculty of Engineering, Ain Shams University, Cairo, Egypt

ABSTRACT

Protection engineers face difficulties to choose the suitable protection scheme in the practical life. They can find, in some cases, the need to choose inordinate protection schemes. In this paper, by using MATLAB SIMULINK some of the most common protection functions are simulated. The model introduced in this paper has subjected to different types of faults and the results are monitored to ensure the reliability of the model. This simulation of the protection relay enables to have full control to choose and also to modify any protection scheme and to monitor its results so it can save cost and time to make an optimum selection of the protection schemes.

KEYWORDS: Multifunction Relays, MATLAB SIMULINK, Micro Processor Based Relay, Protection, Differential Protection, Voltage, Restrained over Current Protection, over Frequency Protection, Under Frequency Protection

INTRODUCTION

A power system is vulnerable to faults, either due to natural disasters or by misoperation of the system due to operators' negligence. This can result in permanent damage to power system components leading to considerable costs for their replacement and in longer disconnections of power supply to customers, which is highly undesirable. This sets a requirement for a power system to sustain faults, while protection systems should minimize the damage in important components and the effect of faults as much as possible. This is achieved by using power system protection techniques and methodologies [1]. Microprocessor-based relays have their own algorithms for monitoring the power system through current and voltage inputs from CTs and VTs respectively. Protection relays are thoroughly tested using relay test sets to confirm their reliability and safe operation before commissioning them in a substation. With the advent of Real-Time Simulators and compact reconfigurable I/O controllers, large power systems can be simulated and their behavior can be analyzed in both steady state and faulted conditions [2].

The purpose of protection relays is to detect a fault and give a trip order to the switching device that is closest to the fault location. Figure 1 shows typical microprocessor multifunction relay [3].

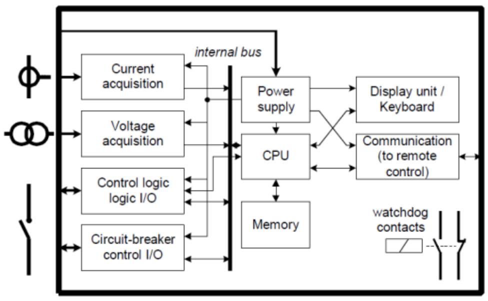

Figure 1: Typical Microprocessor Multifunctions Relay [3]

The use of microprocessor based multifunction relays is on the increase due to the advantages they offer such as communications, measurements, simplified wiring, and reduced space requirements. One of the most difficulties that face the protection engineers is to select the optimum protection scheme. This paper discusses models for the most common protection functions by using MATLAB SIMULINK and monitoring the power system before, during and after the fault. This model will save costs for selecting the suitable protection scheme because it will help the protection engineer to adjust many variables to get the optimum protection scheme.

THE MICRO PROCESSOR BASED RELAY

- **Benefits & Shortcomings of Microprocessor-Based Relay**

In late 1960's when researchers ventured into the use of computers for power system protection. Their attempts and the advances in the Very Large Scale Integrated (VLSI) technology and software techniques in the 1970's led to the development of Microprocessor-based relays that were first offered as commercial devices in 1979 [4].

Benefits of the microprocessor-based relays:

- They provide many functions that were not available in electromechanical or solid-state designs.
- The cost per function of microprocessor-based relays is lower compared to the cost of their electromechanical and solid-state counterparts.
- They allow users to develop their own logic schemes, including dynamic changes in that logic.
- They require significantly less panel space than the space required by electromechanical and solid-state systems that provide similar functions.
- They place significantly less burden on instrument transformers than the burden placed by the relays of the previous technologies.
- They have reporting features, including sequence of events recording and oscillography.
- They have the ability to perform self-monitoring and self-testing functions.

Shortcomings of Microprocessor-based Relays:

- They have short life cycles. While each generation of microprocessor-based systems increases the functionality compared with the previous generation, the pace of change makes the equipment obsolete in shorter times.
- They are more susceptible to transients because of the nature of the technology compared to the systems built with the electromechanical technology.
- They have a significant number of settings. The increased number of settings may pose problems in managing the settings and in conducting functional tests [4] [1].

- **Major Functional Blocks of a Typical Microprocessor Relay**

The block diagram of a typical microprocessor-based relay is shown in Figure 2. The Microprocessor Relay samples voltages and currents, which, at the power system level, are in the range of hundreds of kilo volts and kilo amperes respectively. The levels of these signals are reduced by voltage and current transformers. The outputs of instrument transformers are applied to the analog input subsystem of the relay. This subsystem electrically isolates the relay from the power system, reduces the level of the input voltages, converts currents to equivalent voltages and removes high frequency components from the signals using analog filters. The outputs of the analog input subsystem are applied to the analog interface, which includes amplifiers, multiplexers and analog-to-digital (A/D) converters. These components sample the reduced level signals and convert their analog levels to equivalent numbers that are stored in memory [4].

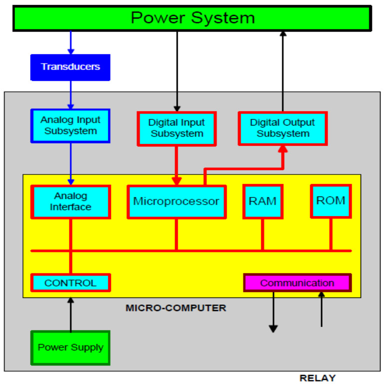

Figure 2: Block Diagram of a Typical Microprocessor-Based Relay [4]

The status of isolators and circuit breakers in the power system is provided to the relay via the digital input subsystem and are read into the microcomputer memory. A relaying algorithm, which is a part of the software, processes the acquired information. The algorithm uses signal-processing techniques to estimate the magnitudes and angles of voltage and current phasors. In some cases, the frequency of the system is also measured. The computed quantities are compared with pre-specified thresholds (settings) to decide whether the power system is experiencing a fault/abnormal operating condition or not. If it is, the relay sends a command to open one or more circuit breakers for isolating the faulted zone of the power system. The trip output is transmitted to the power system through the digital output subsystem. The relay settings and other vital information are stored in non-volatile memory of the relay. Random-access memory (RAM) is used for storing data temporarily. The power supply to a relaying microcomputer must be available even when the system supply is interrupted. Arrangements are, therefore, made to provide energy to the relay during normal and abnormal operating conditions of the power system [4].

The signal and data flows in these relays are shown in Figure 3. The relay is isolated from the power system by using auxiliary transformers which receive analog signals and reduce their levels to make them suitable for use in the relays. Since the A/D converters can handle voltages only, the currents are passed through precision resistors to convert them to voltages proportional to the currents [4] [6].

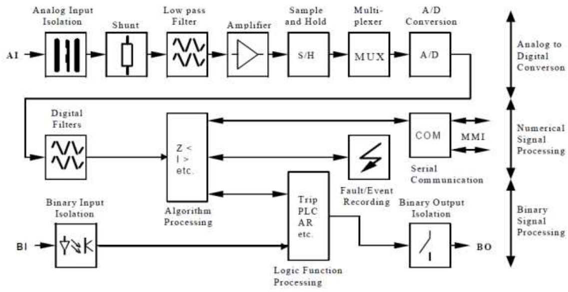

Figure 3: Signal Flow Diagram of a Numerical Relay [4]

During digital processing, high frequency components can appear to belong to the fundamental frequency class. This phenomenon is referred to as aliasing. To prevent aliasing from affecting the relaying functions, anti-aliasing filters (which are low pass filters) are used along with the analog input isolation block. After being quantized by the A/D converter, analog electrical signals are described by discrete values of the samples taken at specified instants of time. These discrete numbers are processed by using numerical methods. The digital signals, also called binary or contact inputs, are applied to the relay via optic isolators that insure physical disconnection of the relay from the power system [4] [6].

THE NETWORK ARCHITECTURE

Substation Understudy

In this paper the model is applied on 66/11KV substation (ALKOBA substation). The substation consists of three incomings connected to double bus bar system. There is a bus coupler and bus riser dividing the incomings into two and one. There are three 25MVA 66/11KV transformers; the first transformer is connected to six outgoings and 100KVA 11/0.415KV auxiliary transformer, the second transformer is connected to six outgoings, and the third transformer is connected to three outgoings and 100KVA 11/0.415KV auxiliary transformer. First, by modeling three phase power sources, power transformers, current transformers, voltage transformers, power cables, circuit breakers, bus-bar system, and protection relays, then applying different types of faults to the system by using MATLAB SIMULINK. Figure 4 shows the system understudy and the fault location.

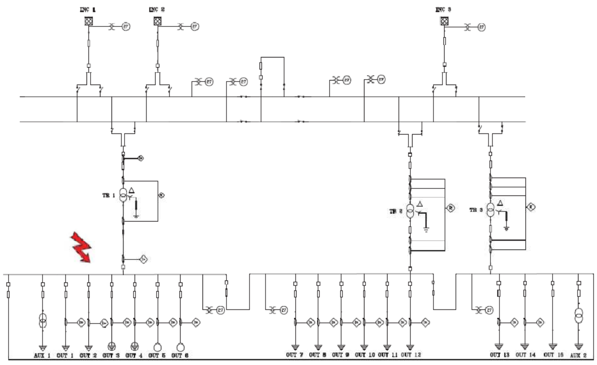

Figure 4: 66/11KV ALKOBA Substation Single Line Diagram

MODELED PROTECTION FUNCTIONS

In this paper, some of micro processor based relay functions will be simulated then tested by applying different faults to it and monitor its responses. The micro processor based relay can be simulated generally as shown in figure 5.

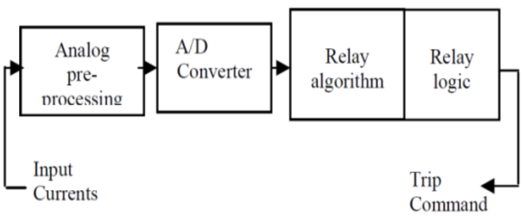

Figure 5: Block Diagram of a Microprocessor-Based Relay [6]

The relay model will be connected on the 11KV bus-bar then applying different faults.

The following functions will be modeled:

- **Differential Protection (87)**

Differential protection is a unit-type protection for a specified zone or piece of equipment. It is based on the fact that it is only in the case of faults internal to the zone that the differential current (difference between input and output currents) will be high. However, the differential current can sometimes be substantial even without an internal fault. This is due to certain characteristics of current transformers (different saturation levels, nonlinearities) measuring the input and output currents [6]. Figure 6 shows the block diagram of the differential relay. The differential relay model receive analog signal from the current transformers that are connected before and after the protected equipment then this signals are converted into digital signal by using A/D converter then the relay calculate the rms value of the primary and secondary currents then calculate the average of the primary and secondary currents.

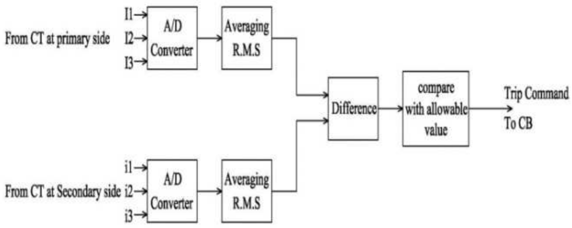

Figure 6: Block Diagram of the Differential Relay

In the healthy case there won't be difference between primary and secondary currents, but the relay allow a small variation between primary and secondary currents because of different saturation levels and nonlinearities of current transformers. In case of internal fault the relay will detect the difference between the primary and secondary currents so it will send command to trip the CB.

Figure 7 shows the percentage-based curve. The percentage-based curve comprises a number of segments, which are defined as follows:

- A low set point (Ids)
- 2 straight lines crossing zero and with adjustable slopes (Id/It and Id/It2)
- The slope change point.

The curve must be set so that it can protect itself against current-sensor measurement errors and transformation errors, which can be attributed to the tap changer. Furthermore, the protection function must be made immune to power shunts on auxiliary windings.

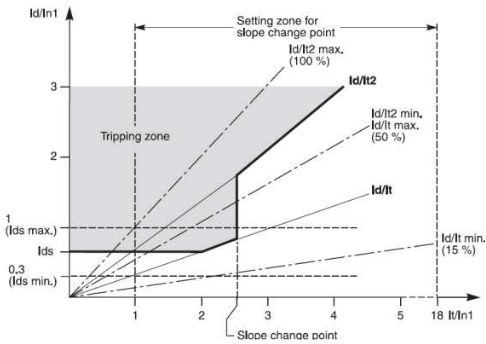

Figure 7: The Tripping Curve of Differential Relay

Figure 8 shows the connections of the current transformers in the system; it will be connected before and after the 11KV bus bar. In this model we use 5P10 current transformers. 1000/1A current transformer is connected before the bus bar and 200/1A current transformers are connected at each outgoing.

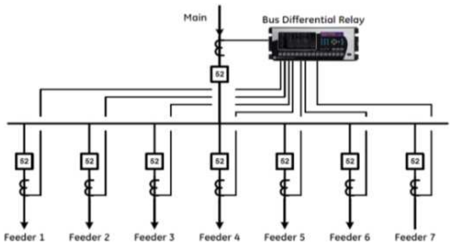

Figure 8: Current Transformers Connections [8]

To test this model, it will be subjected to fault inside the protection zone, 11KV bus bar, and another fault outside the protection zone.

Case (1) Internal Fault

The current for phase A, faulty phase, will jump from 920A in the healthy case into 15344A during the fault. This high current value is necessary to be instantaneously tripped because it can produce a severe destructive energy. Figure 9 shows the current and voltage waves during internal differential fault. Both voltages for phase A and phase C will drop by 40% while voltage for phase B will increase by 10% during the fault. After clearing the fault by disconnecting the faulty area, the voltage returns to its healthy value.

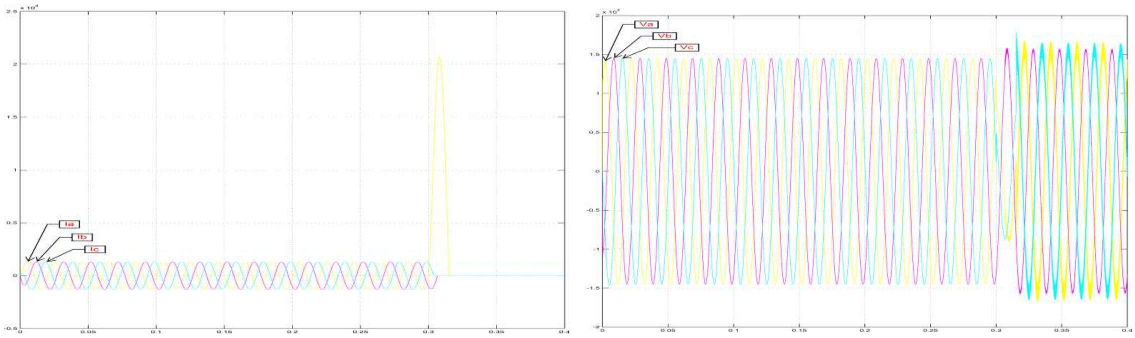

Figure 9: The Current and Voltage Waves during Internal Differential Fault

Case (2) External Fault

CTs perform reasonably in most operating scenarios, faithfully reproducing primary current as a secondary current, with little distortion or error. C37.110, the IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes [9] allows that a ANSI C-class CT connected to a standard burden should have no more than 10% error at 20 times rated voltage. In practice, modern C-class CTs have an error of 1% to 2%, and keep this high level of accuracy over their operating life.

Table 1 shows that when the RMS values of the current at the downstream, the value of the difference current as a percentage from the current passing through both CTs, and the current transformer statuses. As shown the differential relay model wont trip as the Id % didn't reach to 40%. Figure 12 shows the current and voltage waves during external fault. The model doesn't trip.

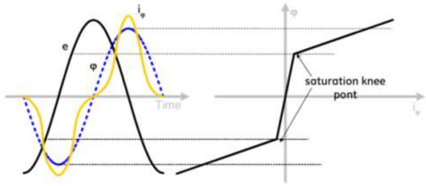

Figure 10: Flux and Exciting Current Hysteresis during Core Saturation [8]

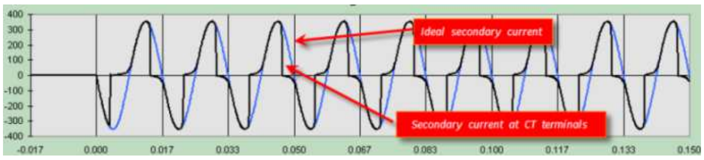

Figure 11: Measured CT Secondary Current during Saturation [8]

Table 1: The Voltage Wave during Internal Differential Fault

I2rms (A)	Id (%)	CTs Status	Differential Model Status
5000	10	Both CTs in linear region.	Doesn't Trip
8000	16	Both CTs in linear region.	Doesn't Trip
9950	14.95	CT2 saturated. CT1 in Linear region	Doesn't Trip
12000	20	Both CTs in saturation region.	Doesn't Trip
13000	20	Both CTs in saturation region.	Doesn't Trip

I_{2rms} = the rms value of the current at the secondary side
$I_d\% = ((I_1 - I_2)/ I_2)$ = the rms of the difference between currents at the primary side (I_1) and the secondary side (I_2) then divide by the secondary current (I_2)
CT_1 = current transformer at the primary side
CT_2 = current transformer at the secondary side

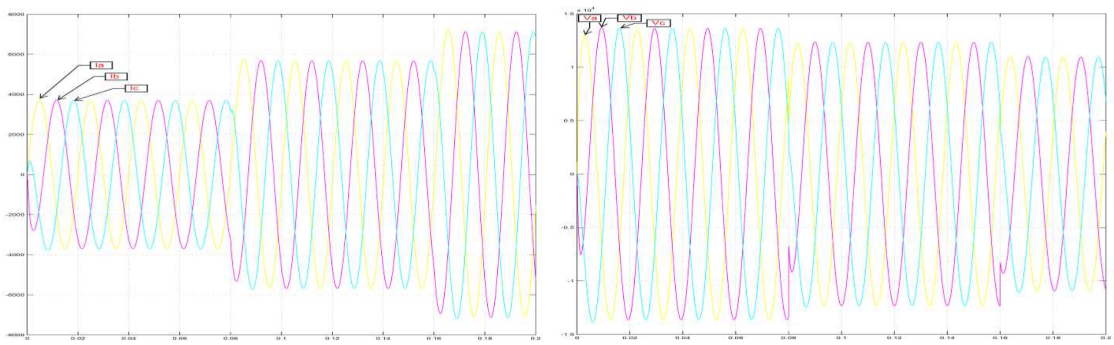

Figure 12: The Current and Voltage Waves during External Fault

- **Voltage-Restrained over Current Protection (50/51V)**

Correct over current relay application requires knowledge of the fault current that can flow in each part of the network. The relay settings are first determined to give the shortest operating times at maximum fault levels and then checked to see if operation will also be satisfactory at the minimum fault current expected. Among the various possible methods used to achieve correct relay co-ordination are those using either time or over current, or a combination of both. The common aim of all three methods is to give correct discrimination [1]. Figure 13 shows the block diagram of the over current relay. The over current relay model receive analog signal from the current transformers that are connected before the protected equipment then this signals are converted into digital signal by using A/D converter then the relay calculate the rms value of the three phase currents then calculate their average.

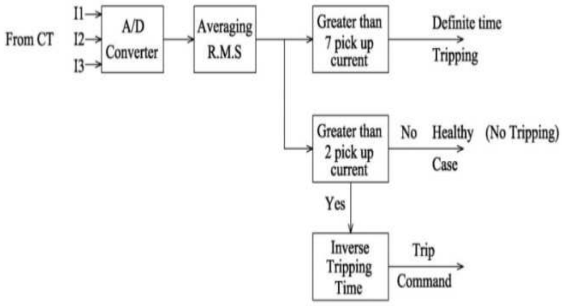

Figure 13: Block Diagram of the over Current Relay

There are three cases:

- **Healthy Case:** if the current is less than the twice (adjustable) the pickup current.
- **Inverse Case:** if the current is greater than twice (adjustable) the rated current but less than seven times (adjustable) the pickup current. The model enables the protection engineer to choose any inverse characteristics.
- **Definite Time:** if the current is greater than seven times (adjustable) the pickup current. The model enables the protection engineer to choose the multiples of the pickup current for definite time tripping.

Figure 14 shows the North American IDMT relay characteristics. In our relay model we will use USco8.

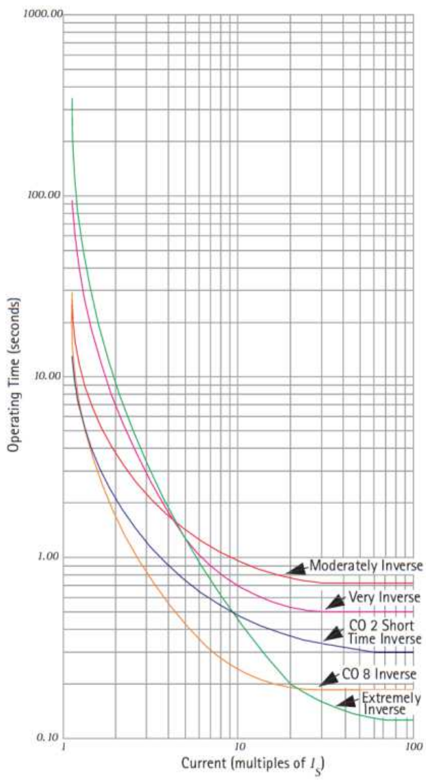

Figure 14: North American IDMT Relay Characteristics [11]

Figure 15 shows the tripping curve of voltage-restrained over current protection. To ensure correct tripping command the voltage restrained function can be employed that if the voltage drops less than 80% of its rated value, the pickup current will be adjusted to new value according to the voltage level according to eq.1

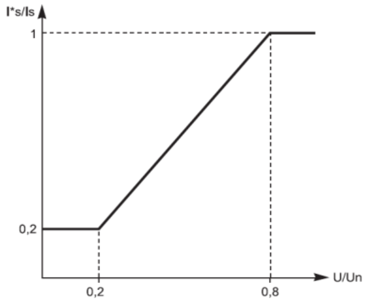

Figure 15: The Tripping Curve of Voltage-Restrained over Current Protection

$$I_S^* = \frac{I_s}{3} \times \left(4\frac{U}{U_n} - 0.2\right)$$

Equation 1: Voltage-Restrained Current Setting

To test this model, fault will be projected at two locations at the beginning, and at the end of the outgoing cable. Figure 16 shows the fault locations.

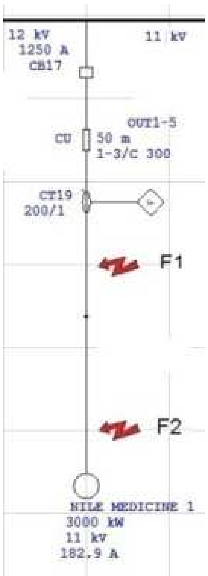

Figure 16: Fault Locations

He model will be adjusted to US CO8 Inverse characteristics with TD = 0.5 and 400A pickup current. Equation 2 shows the US CO8 Inverse.

$$t = \frac{TD}{7}\left\{\left(\frac{5.95}{I_r^2 - 1}\right) + 0.18\right\}$$

Ir = (I/Is), where Is = relay setting current
TD = Time Dial setting

Equation 2: US CO8 Inverse [11]

Case (1) Fault Location at F1

By using 50/51V protection; the fault occurs at 0.04sec. It will draw 900A and the voltage will drop to 5.6KV during the fault. Then it will be restored to 11KV after clearing the fault after 0.0437sec. as shown in figure 17.

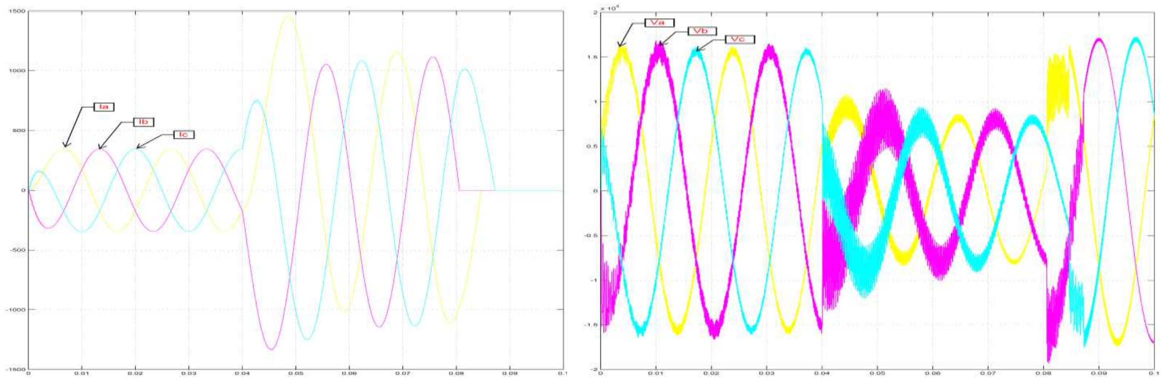

Figure 17: The Current and Voltage Waves at F1 during over Current Fault under 50/51V Protection

By using 50/51N protection; the fault occurs at 0.04sec. It will draw 900A and the voltage will drop to 5.6KV during the fault as shown in figure 18. Then it will be restored to 11KV after clearing the fault after 0.045sec.

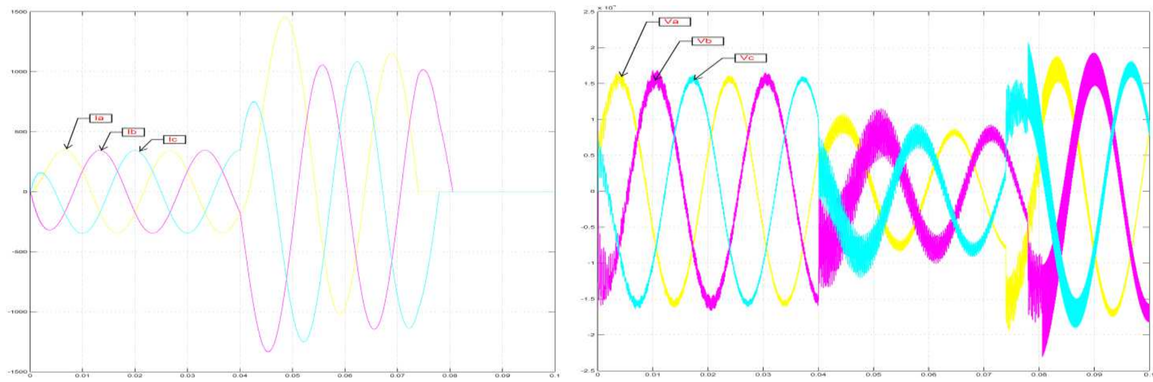

Figure 18: The Current and Voltage Waves at F1 during over Current Fault under 50/51N Protection

Case (2) Fault Location at F2

By using 50/51V protection; the fault occurs at 0.04sec. It will draw 378A and the voltage will drop to 5.1KV during the fault as shown in figure 19. Then it will be restored to 11KV after clearing the fault after 0.0474sec.

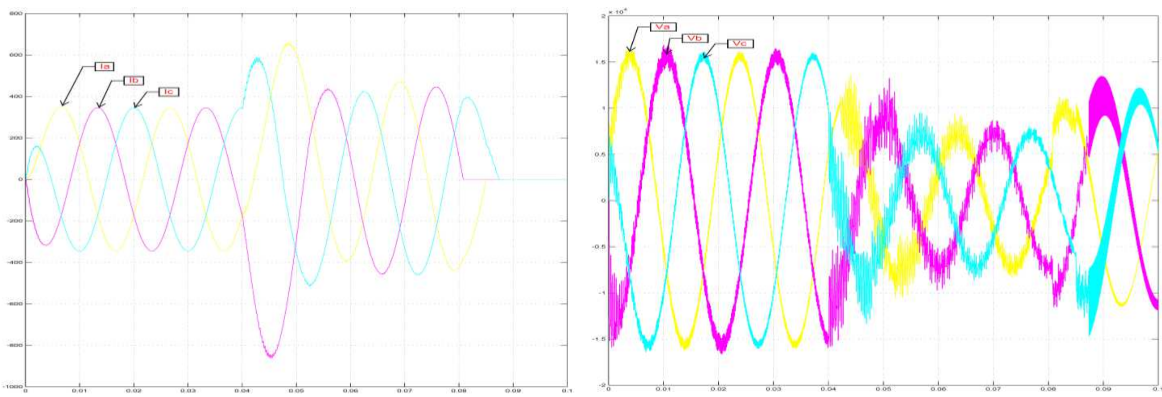

Figure 19: The Current and Voltage Waves at F2 during over Current Fault under 50/51V Protection

By using 50/51N protection; the fault occurs at 0.04sec. It will draw 378A and the voltage will drop to 5.1KV during the fault as shown in figure 20. But the voltage will not restore to 11KV because it don’t detect the fault as the current value is less than the pickup current. So the fault continues without clearing it.

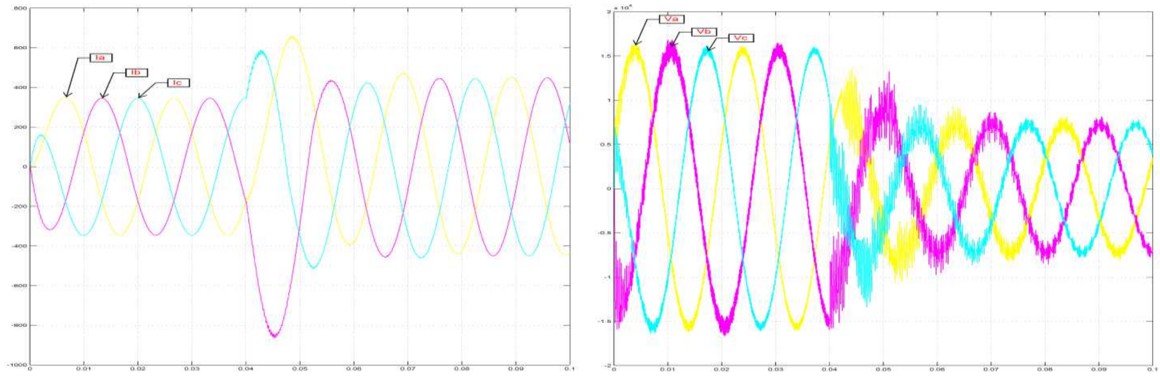

Figure 20: The Current and Voltage Waves at F2 during over Current Fault under 50/51N Protection

Over and under Frequency Protection (81H/81L)

The deviation of the frequency from the rated system frequency indicates unbalance between the generated power and the load demand. If the available generation is large compared to the consumption by the load connected to the power system, then the system frequency is above the rated value. The over-frequency protection function is usually applied to decrease generation to control the system frequency. Another possible application is the detection of unintended island operation of distributed generation and some consumers. In the island, there is low probability that the power generated is the same as consumption; accordingly, the detection of high frequency can be an indication of island operation. Accurate frequency measurement is also the criterion for the synchro-check and switch functions [1].

The over frequency relay model receive analog signal from the voltage transformers that are connected after the protected equipment then this signals are converted into digital signal by using A/D converter then the relay model calculates the frequency of the voltage signal then averages it, then the model compares it with the required system frequency. In the healthy case there won't be difference between them, but if the frequency measured is higher so the model will send command to trip the CB instantaneously to disconnect the unnecessary loads then it compares the frequency again if the frequency still high the model send signal to trip the generator. Figure 21 shows the block diagram of the over/under frequency relay.

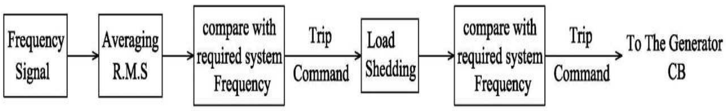

Figure 21: Block Diagram of the over/under Frequency Relay

To test this model, the model is connected on the 11KV bus-bar then increase the frequency to be 60HZ at 0sec.

Under frequency occurs due to the excess overload. During an overload, generation capability of the generator increases and reduction in frequency occurs. The power system survives only if we drop the load so that the generator output becomes equal or greater than the connected load. If the load increases the generation, then frequency will drop and load need to shed down to create the balance between the generator and the connected load. The rate at which frequency drops depends on the time, amount of overload and also on the load and generator variations as the frequency changes. Frequency decay occurs within the seconds so we cannot correct it manually. Therefore automatic load shedding facility needs to be applied [1].

The under frequency relay model receive analog signal from the voltage transformers that are connected after the protected equipment then this signals are converted into digital signal by using A/D converter then the relay model calculates the frequency of the voltage signal then averages it, then the model compare it with the required system frequency. In the healthy case there won't be difference between them, but if the frequency measured is lower so the model will send command to trip the CB instantaneously to disconnect the unnecessary loads then it compares the frequency again if the frequency still high the model send signal to trip the generator. Figure 12 shows the block diagram of the differential relay.

To test this model, the model is connected on the 11KV bus-bar then power source with 40HZ will be connected at 0sec. The system will be subjected to under frequency after 0.04sec. The under frequency relay model detect the under frequency then it sends the tripping signal to the CB to trip the loads after 0.04sec. Figure 22 shows the system frequency.

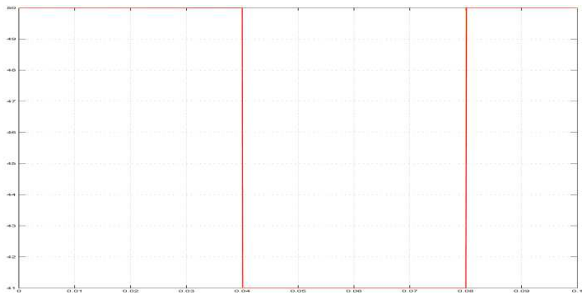

Figure 22: The System Frequency

The current falls down to zero after 0.03sec after load shedding. Figure 23 shows the current and voltage waves under under-frequency fault. After disconnecting the loads the voltage signal doesn't restored to healthy case, this means that the power source is the source of under frequency so the relay model send signal to the relay that protect the power source to trip.

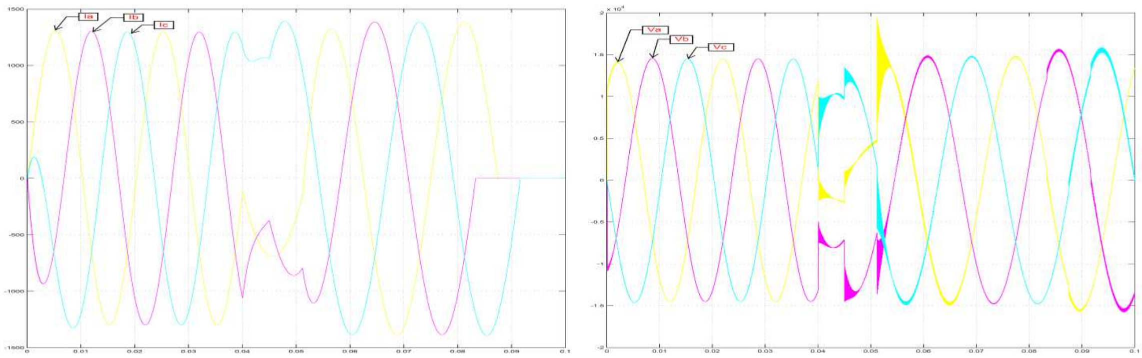

Figure 23: The Current and Voltage Waves during under Frequency Fault

CONCLUSIONS

This paper models differential protection function (87), voltage-restrained over current protection function (50/51V), and over and under frequency protection function (81H/81L) by using MATLAB SIMULINK. The proposed model was tested under various faults.

Results indicate that the model successfully detects the faults and protect the system. So this model can be used by protection engineers as a guide to facilitate choosing the suitable protection scheme.

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