

DIGITAL PROTECTION SCHEME FOR DISTANCE RELAYING
OF A SIX-PHASE POWER SYSTEM

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To my beloved father and mother, my sister and brothers and my beloved
wife for their continuous support and encouragement
This work is nothing compares to their scarifies

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ABSTRACT

The objectives of this study are to investigate various algorithms for digital relaying that can be used in six-phase system and to develop a laboratory replica of six-phase system from selected three-phase double-circuit of Tenaga Nasional Berhad (TNB) network. A novel algorithm which is called bounded data uncertainties (BDU) for digital relaying is proposed. The proposed method is an enhanced least-square algorithm, which unlike classical least-square, it allows perturbations in data matrix and measurements or observations. MATLAB programs have been developed to compare the BDU with the Discrete Fourier Transform (DFT) algorithm. The results show the superiority of BDU over DFT method. An existing three-phase double-circuit line between Kuala Krai (KKRI) and Gua Musang (GMSG) substations has been selected as a case study for conversion to six-phase single-circuit system. Using the configuration line data provided by TNB, parameters of six-phase line are calculated. The calculation of parameters of line is also carried out using software package PSCAD/EMTDC. The results from MATLAB and PSCAD programs have revealed that the positive-sequence inductive reactance of six-phase single-circuit is higher than the three-phase double-circuit line. Furthermore, the results of MATLAB show that the maximum fault current occurs for phases *a-b-d-f* fault. Based on the maximum fault current, the necessary components have been obtained to construct the six-phase prototype. The prototype is successfully developed which resembles six-phase line of the KKRI-GMSG. The phase difference of voltages of the six-phase prototype has been successfully validated by LabVIEW software package. The prototype is unique in Malaysia and it is an invaluable tool which can be used by power utilities and graduate students to do research work in six-phase system.

ABSTRAK

Objektif kajian ini adalah untuk mengkaji pelbagai algoritma geganti berdigit yang boleh digunakan dalam sistem enam-fasa dan membangunkan satu replika makmal sistem enam-fasa daripada litar kembar tiga-fasa untuk rangkaian Tenaga Nasional Berhad (TNB) yang dipilih. Satu algoritma baru yang dipanggil ketidakpastian data terhad (BDU) untuk geganti berdigit telah dicadangkan. Kaedah yang dicadangkan adalah satu algoritma kuasa dua-terkecil yang ditingkatkan yang berbeza dari kuasa dua-terkecil klasik, dimana ia membenarkan ubahan dalam data matriks dan pengukuran atau pemerhatian. Program MATLAB telah dibangunkan untuk membandingkan diantara kaedah BDU dengan kaedah Jelmaan Fourier Diskret (DFT). Hasil perbandingan ini memaparkan kelebihan BDU berbanding dengan kaedah-kaedah lain. Bagi tujuan ini, satu talian litar kembar tiga-fasa yang sedia ada, antara pencawang Kuala Krai (KKRI) dan Gua Musang (GMSG) telah dipilih untuk ditukar menjadi litar-tunggal enam-fasa sebagai kes kajian. Menggunakan tatarajah data talian yang disediakan oleh TNB, satu program MATLAB telah dibangunkan untuk mengira parameter talian enam-fasa. Pengiraan parameter talian adalah turut dijalankan menggunakan pakej perisian PSCAD/ EMTDC. Hasil dari perisian MATLAB dan PSCAD telah menunjukkan yang regangan beraruhan jujukan positif litar-tunggal enam-fasa adalah lebih tinggi daripada talian litar kembar tiga-fasa. Keputusan pengiraan dari MATLAB menunjukkan yang arus kerosakan maksimum berlaku untuk kerosakan fasa a-b-d-f. Berdasarkan arus kerosakan maksimum, parameter yang berkaitan adalah diperolehi untuk membina prototaip enam-fasa. Prototaip tersebut telah berjaya dibangunkan yang berupa talian enam-fasa KKRI-GMSG. Beza fasa bagi voltan prototaip enam fasa telah disahkan dengan jayanya menggunakan pakej perisian LabVIEW. Prototaip ini adalah unik di Malaysia dan merupakan alat yang tidak ternilai yang boleh digunakan oleh utiliti kuasa dan pelajar siswazah untuk tujuan penyelidikan dalam sistem enam-fasa.

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LIST OF SYMBOLS

\wedge	-	Taking the square of
\div	-	Division
$\sqrt{\quad}$	-	Taking the square root of
\triangleq	-	Denotes Define
\in	-	belongs to or element of
$\ \cdot\ $	-	Euclidean norm
atan	-	Taking the inverse tangent of
α	-	Six-phase operator $\alpha = e^{j2\pi/6} = e^{j\pi/3} = 0.5 + j0.866$
ϕ	-	Phase angle
ρ	-	Earth resistivity
η	-	Upper bound of the perturbation
ω	-	Angular frequency (rad/sec)
δA	-	Perturbation in data matrix A
δb	-	Perturbation in measurement
$[T_6]$	-	Six-phase transformation matrix
$[A]^\dagger$	-	Left pseudo-inverse of [A]
Δ -Y	-	Delta-Wye connection of transformer winding
C	-	Capacitor
C_k^v	-	Coefficients of k^{th} components in the input voltage
C_k^i	-	Coefficients of k^{th} components in the input voltage
D_{sa}	-	GMR of conductor a
D_{ad}	-	GMD between wire a and d
DY1	-	Vector group of transformer (Delta lag Wye by 30°)
DY11	-	Vector group of transformer (Delta lead Wye by 30°)
$e(t)$	-	Error

$g(\alpha)$	-	Secular equation
$G(z)$	-	Discrete-time transfer function
$i(t)$	-	Instantaneous current
K_0	-	Zero-sequence current compensation factor
L	-	Inductor
Q	-	Quality factor
R	-	Resistor
r_d	-	Earth resistance
R^m	-	m dimension in real number R
T	-	Sampling period
$V_{aa'}$	-	Voltage drops between point a and a'
\bar{V}	-	Voltage phasor
$v(t)$	-	Instantaneous voltage
Y- Δ	-	Wye-Delta connection of transformer winding
$y(k)$	-	k th sample of a signal
$y_{or}(k)$	-	k th sample of orthogonal signal
\bar{Z}	-	Transmission line primitive impedance
\bar{Z}_{aa}	-	Primitive self impedance
\bar{Z}_{ad}	-	Primitive mutual impedance
Z_{m1}	-	Average of adjacent phase mutual impedance
Z_{m2}	-	Average of alternative (group) phase mutual impedance
Z_{m3}	-	Average of opposite (cross) phase mutual impedance
Z_{pq}	-	Impedance between point p and q
Z_s	-	Average of self impedance

LIST OF ABBREVIATIONS

3PDC	-	Three-phase double-circuit
6PSC	-	Six-phase single circuit
AC	-	Alternative Current
A/D	-	Analog-to-Digital
ADC	-	Analog-to-Digital Converter
APS	-	Allegheny Power Service Corporation
BDU	-	Bounded Data Uncertainties
COMTRADE	-	Common Format for Transient Data Exchange
CT	-	Current Transformer
DAS	-	Data Acquisition System
DC	-	Direct Current
DFT	-	Discrete Fourier Transform
DOE	-	Department of Energy
DSP	-	Digital Signal Processor
EHV	-	Extra High Voltage
EMTDC	-	Electromagnetic Transient for Direct Current
ESEERCO	-	Empire State Electric Energy Research Corporation
FACTS	-	Flexible AC Transmission Systems
FIR	-	Finite Impulse Response
GMD	-	Geometric Mean Distance
GMR	-	Geometric Mean Radius
GMSG	-	Gua Musang
HPO	-	High Phase Order
HV	-	High Voltage
IIR	-	Infinite Impulse Response
KF	-	Kalman Filter
KKRI	-	Kuala Krai

LabVIEW	-	Laboratory Virtual Instrumentation Engineering Workbench
LPF	-	Low-Pass Filter
LS	-	Least-square
MATLAB	-	Matrix Laboratory software
MATPOWER	-	MATLAB Power System Package
MOV	-	Metal Oxide Varistor
NYSEG	-	New York State Electric & Gas
NYSERDA	-	New York State Energy and Development Authority
OPF	-	Orthogonal Filter Pairs
PSCAD	-	Power System Computer Aided Design
PT	-	Potential Transformer
PTI	-	Power Technologies Incorporated
ROW	-	Right-of-Way
RTP	-	Real Time Playback
S/H	-	Sample and Hold
SIL	-	Surge Impedance Loading
SVD	-	Singular Value Decomposition
TNB	-	Tenaga National Berhad
UHV	-	Ultra High Voltage
UMEC	-	Unified Magnetic Equivalent Circuit
VAR	-	Volt Ampere Reactive
VT	-	Voltage Transformer

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CHAPTER 1

INTRODUCTION

1.1 Introduction

To date, the major challenging task for an electrical engineer is ensuring a high level of continuity of service to customers even under system disturbance. However, a number of undesirable but unavoidable nature events or human-error incidents may occur and disrupt this condition. The cause of accident includes lightings, wind damage, ice loading, tree falling, bird shorting, aircraft colliding, vehicles hitting, people contacting, digging into underground cable, and so on.

1.2 Power System protection

To avoid damage to the equipment of the utilities, long interruption service to the customers and possible personal hazards, proper protective relays are necessary to take suitable corrective actions during these abnormal conditions. Originally, all protective relays were electromechanical type, which are still being wide used in many systems. Solid state relays were introduced in the 1950's and are commonly used today for their relative accuracy, sensitivity, ease of testing and maintaining. Recently, researchers have been trying to develop a more reliable, secure and fast acting relay with small space and power consumption by using microprocessor technology [1-6].

1.2.1 Zone of Protection

A power system contains generators, transformers, bus-bars, transmission and distribution line, etc. There is separate protective scheme for each piece of equipment or element of the power system, such as generator protection, transformer protection, transmission line protection, bus-bar protection, etc. Thus, a power system is divided into a number of zones for protection. A protective zone covers one or at most two elements of a power system. The protective zones are planned in such a way that entire power system is collectively covered by them, and thus, no part of the system is left unprotected. The various protective zones of a typical power system are shown in Figure 1.1. Adjacent protective zones must overlap each other, failing which a fault on the boundary of the zones may not lie in any of the zones, and hence no circuit breaker would trip [1-6].

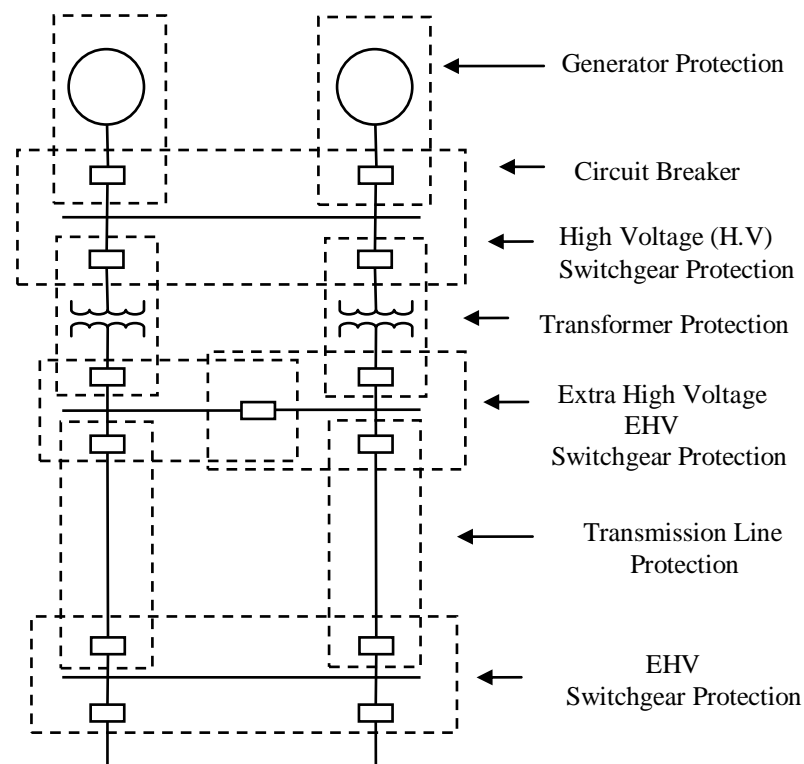


Figure 1.1 Zones of Protection in Power System

1.2.2 Primary and Back-up Protection

It has already explained that a power system is divided into various zones for its protection. There is a suitable protective scheme for each zone. If a fault occurs in a particular zone, it is the duty of the primary relays of that zone to isolate the faulty element. Therefore, the main protection system(s) for a given zone of protection is called the primary protection system. If due to any reason, the primary relay fails to operate and, as a result, fail to clear a fault. It is thus essential that provision be made to clear the fault by some alternative protection system or systems. These alternative protection system(s) are referred to as back-up protection.

More precisely, back-up relaying which provides necessary redundancy in protective systems is defined in the IEEE Standard Dictionary as “protection that operates independently of specified components in the primary protective system and that is intended to operate if the primary protection fails or is temporarily out of service” [6]. Back-up protection includes

- (1) Local back-up; which installed locally, i.e. in the same substation as the primary protection
- (2) Remote back-up; which are completely independent of the relays, transducers and circuit breakers of the protection system they are backing up.
- (3) Breaker failure relaying; Breaker failure is defined as a failure of the breaker to open or interrupt current when a trip signal is received.

Back-up protection for equipment such as generators, buses, and transformers usually duplicates primary protection and is arranged to trip the same breakers. In the event of a breaker failure, some remote line protection would isolate the fault. Back-up relays are generally slower (time delayed) in order to allow the primary protection to work properly, they supposed to operate only if the primary or its duplicate protection fail, and are usually less selective. For example, back-up for a given distribution or transmission line is provided by the primary protection scheme or it's duplicate of the adjacent line.

1.2.3 Main Requirements of Protection Systems

Based on the definition for the function of protective relaying, there are some basic requirements for the performance of protection systems to realize their protective functions. The most important requirements are the correct, adequate and fast operation. These can also be categorized as selectivity, reliability, response speed, simplicity and economics [1-6].

1.2.3.1 Selectivity or Discrimination

At the event of a fault, the protection system must select and trip the proper circuit breakers, in order to disconnect as small portion of the network as possible. For instance, if a fault occurs on a network line, it should be detected by the closest relays (that is, primary relays) which in turn trip their associated circuit breakers to clear the fault. In case either the relays or the circuit breakers fail to operate, then the backup should clear the fault by tripping the breaker of the adjacent lines. Since the backup relays generally disconnect a larger portion of the network, they must always operate slower, to keep the priority for the primary protection equipment. This property of a protection system is referred to as “selectivity” which results in maximum service continuity with minimum system disconnection [4].

1.2.3.2 Reliability

Reliability is generally defined as a measure of certainty that a piece of equipment or a system will perform as intended. A protection system has two alternative ways in which it can be unreliable: it may fail to operate when it is expected to (referred to as fail-to-trip), or it may operate when it is not expected to (referred to as mal-trip). This leads to two categories of reliability as follows [7]:

- a) Dependability, which is the ability of protection schemes to work properly if an internal fault (fault within the protected power system device) occurs, i.e. to remove faults selectively, and

- b) Security, which refers to the ability of protection relay not to send a tripping signal, if there are no internal faults.

1.2.3.3 Availability

Availability is defined as the time a given protection device works properly according to its service time. A high degree of availability is obtained by regular maintenance, the self checking capability devices for the relays, etc.

1.2.3.4 Speed or Fast Operation

Disconnecting of the faulted equipment or lines should be as quickly as possible, so the equipment damages would be minimized and the fault extensions can be avoided. The disconnecting time consists of two parts: the response of the relay, and the operating time of the circuit-breaker. The time period from the fault inception until a protection relay sends a tripping signal to its corresponding circuit breaker is the tripping or fault detecting time, while the period between fault inception and fault clearing (including eventual extinguishing of arcing) is referred as fault clearing time. The fault clearing time includes the tripping time and the time needed for the circuit-breaker to open. Modern circuit-breakers open in approximately two to three periods of the power frequency after receiving a tripping signal and high speed breakers requiring only one and a half cycles of the fundamental power system frequency are available [3-6].

1.2.3.5 Sensitivity

Sensitivity in protective system is defined as the ability of the system to identify an abnormal condition that exceeds a nominal “pickup”. In other words, a protective relay should operate when the magnitude of the current exceeds the pre-set value. This value is called the pick-up current. The relay should not operate when the

current is below its pick-up value. A relay should be sufficiently sensitive to operate when the operating current just exceeds its pick-up value [4, 5].

1.2.3.6 Stability

A protective system should remain stable even a large current is flowing through its protective zone due to an external fault, which does not lie in its zone. The concern circuit breaker is supposed to clear the fault. But the protective system will not wait indefinitely if the protective scheme of the zone in which fault has occurred fails to operate. After a preset delay the relay will operate to trip the circuit breaker [3-6].

1.3 Classification of Protective Relays

Protective relays can be classified into various ways depending on their construction, function, etc [3-6]. In the following the classification of protective relays based on technology, functions and protective schemes are presented in some detail.

1.3.1 Classifications of Protective Relays Based on Technology

- 1) Electromagnetic Relays
- 2) Static Relays
- 3) Microprocessor-Based Relays

Electromagnetic relays contain attracted armature, moving coil, induction disc and induction cup type relays. Static relays contain electronic circuitry which may include transistors, ICs, diodes and other electronic components. Microprocessor-based protective relays are the latest development in this area. The microprocessor-based relays can be programmed for different functionality, they also

cheaper than static relays. These advantages of microprocessor-based relays make them more attractive over static relays for the protection of modern complex power networks. These relays also called digital relay, numerical relay or computer relay [6].

1.3.2 Classification of Protective Relays Based on Their Function

Protective relays can be classified into the following categories, depending on the duty they are required to perform. Some of the important relays in this category are:

- (1) Overcurrent relays
- (2) Undervoltage relays
- (3) Impedance relays
- (4) Underfrequency relays
- (5) Directional relays

Many other relays specifying their duty they perform can be put under this type of classification. The duty which a relay performs is evident from its name. For example, an overcurrent relay operates when the current exceeds a certain limit, an undervoltage relays operate when the system voltage falls below a certain preset value, an Impedance relay measures the line impedance between the relay location and the point of fault and operates if the point of fault lies within the protected section. Directional relays check whether the point of fault lies in the forward or reverse direction. The above relays may be electromagnetic, static or microprocessor- bases relays [3-6].

1.3.3 Classification of Protective Relays Based on Protective Schemes

A protective scheme is used to protect equipment or a section of the line. It includes one or more relays of the same or different types. The following are the most common protective schemes which are usually used for protection of a modern power system [4].

- (1) Overcurrent Protection
- (2) Distance Protection
- (3) Differential Protection
- (4) Pilot Protection

A detail function of these schemes will be given in chapter 3.

1.3.4 Relays as Comparators

Relays may be classified according to the number of input or metered quantities [6]. Relays with one metered quantity designate as simplex relays and those with two or more metered quantities as complex relays. Simplex relays, by definition, use only one metered quantity, which usually a current or a voltage. Most relays used in power system protection are complex relays and utilize two or more input quantities for improved selectivity and speed. As example is the differential protection relay which uses current comparison as a mean of obtaining selectivity. Other complex relays use an impedance, admittance, phase comparison, or other relay computations to improve speed and selectivity in a given abnormal system situation. So this kind of relays practically use comparators for decision making to whether a fault is within a predefined setting zone or not. A comparator is a design element used in relays to compare two phasors either in magnitude or phase. A distance relay will always have a phase comparator or magnitude comparator regardless of the technology used, i.e., electromechanical, solid-state, and microprocessor based relays. For more discussion of comparators one may refer to the Reference [6].

1.4 Microprocessor-Based Relay

The increased growth of power systems both in size and complexity has brought about the need for fast and reliable relays to protect major equipment and to maintain system stability. The conventional protective relays are either of electromagnetic or static type. The electromagnetic relays have several drawbacks

such as high burden on instrument transformers, high operating time, contact problems, etc. Static relays have been increasingly used in recent years because of their inherent advantages of compactness, low burden, less maintenance and high speed. Though successfully used, the static relays suffer from a number of disadvantages, e.g. inflexibility, inadaptability to changing system conditions and complexity.

In the paper [8] published in 1968, Rockefeller outlined the protection of all the equipment in a substation with a digital computer. This comprehensive paper, although speculative in nature and without any supportive experimental data, goes into substantial detail of relaying programs for implementing on computers. This work led to the development and field installation of a system based on process-control digital computer for protecting a transmission line of the Pacific Gas and Electric Company (PG&E) [9, 10]. The computer and its peripherals were large compared to conventional relays, used significantly more station battery power, and the cost about ten times more than the conventional relays. While this uses an experimental installation, it introduced many design approaches that are in use today.

1.4.1 Functional Blocks and Operating Features

A microprocessor-base relay (also called digital relay, numerical relay or computer relay) is a relay that uses microprocessor and software to process the incoming current and voltage signals, quantized signals and implementing protection algorithms to decide whether or not the relay should trip the circuit breaker.

A very simplified block diagram of a typical microprocessor- based relay is shown in Figure 1.2. The relay can be divided into analog input, digital input and digital output subsystem, and a microcomputer [11]. The input to a microprocessor-based relay consists of analog and digital signals derived from the power system. The levels of analog signals, system voltages and currents, are reduced to appropriate levels and are then applied to the analog input subsystem. The outputs from the subsystem are applied to analog interface of microcomputer. The digital input subsystem receives the status of circuit breakers and isolators. Isolation circuitry and

transient protection is used in analog and digital input subsystems for protecting the relay from system transients. The current and voltage signals are next passed through the anti-aliasing filters. The anti-aliasing filter is a low pass filter designed to attenuate frequency components in the input signal which exceed one-half the relay's sampling frequency (f_s). The filter ensures accurate sampling of the input signal to satisfy Nyquist or sampling theorem, more on this is given Chapter 6. The outputs are provided through digital output subsystem.

The microcomputer, in a microprocessor-based relay, consists of a central processing unit, non-volatile memory (ROM), random access memory (RAM), analog interface, and communication hardware and appropriate software. The voltages and currents are sampled and quantized, and are fed into the microcomputer. In the most digital relaying applications, the values of quantized sample complete with time stamps are stored in RAM. These are transferred to permanent memory storage (local or remote) as soon as possible. A non-volatile memory, ROM, is used for storing relay programs and settings. The relay logic is executed in the central processing unit (CPU). Communication link enables the relay to share information with other devices. A self-diagnosis software resides in the relay and checks integrity of the relay at regular intervals. This feature allows the relay to remove itself from service, when a malfunction (component failure) occurs, and to alert the control center. Microprocessor-based relays are usually powered from the station battery which is provided with a battery charger. This ensures that the relays will operate during outages of the station ac supply [11]. A comprehensive discussion of the digital-relay hardware is given in Chapter 6.

1.4.2 Performance and Operational Characteristics of Microprocessor-Based Relay

It has been recognized that many benefits can be gained from the application of digital relays and these can be broadly classified under five main areas [11, 12].

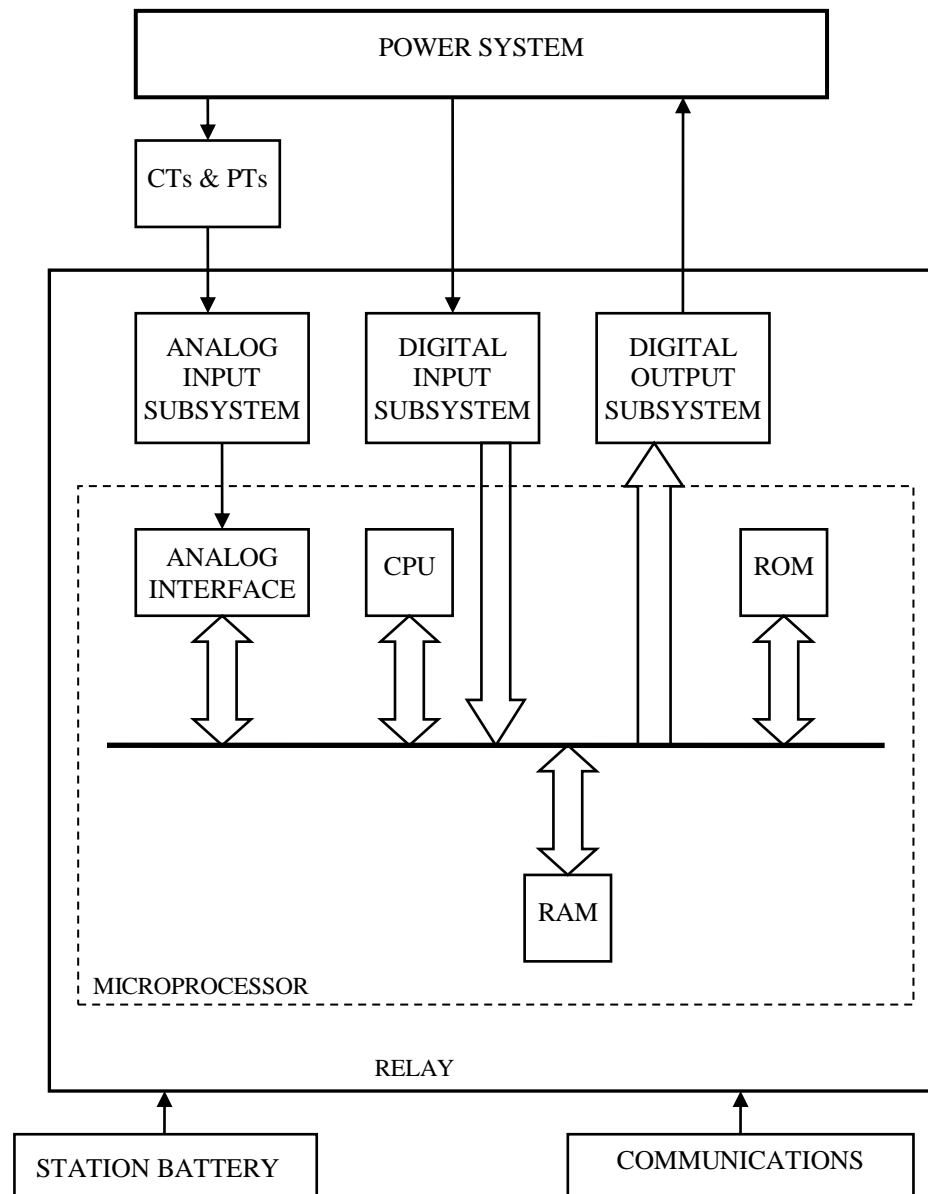


Figure 1.2 A very simplified block diagram of a typical microprocessor-based relay

1.4.2.1 Reliability

Digital relays can be designed to regularly monitor themselves. The process of monitoring involves executing the relay software in conjunction with a pre-

specified data set and comparing the results with those expected from a properly functioning device. If the response turns out to be different from that expected, an error is detected and the relay initiates warning signals to the operator. This feature can be extended by programming the relay to monitor its peripherals. It should be noted that self monitoring does not in itself directly improve reliability, but it does provide a means of signifying the operational state of protection equipment. This in turn has an indirect beneficial effect on overall reliability by ensuring that the number of potential malfunctions is reduced. Reliability can be improved further by building a degree of redundancy into the hardware/software design and using different operating principles within the same relay.

1.4.2.2 Flexibility

Digital relays are generally more flexible than conventional devices. For example, digital relays are programmable, and this in turn makes it possible to use the same hardware for performing a variety of protection and control functions by effecting changes in the software. It is also possible that the same relay can be equipped with multiple characteristics and any revisions or modifications required by changes in the operational conditions of the system can be easily accommodated with virtually no changes in the hardware structure.

1.4.2.3 Operational Performance

Research and field experiments have shown that, in difficult applications in particular, digital relays can be arranged to perform much better than conventional relays. This is particularly so in long distance EHV/UHV transmission lines, series/shunt-compensated lines and multi-ended circuits. It is also recognized that certain features are naturally inherent to digital relays, e.g. memory action and complex shaping of operational characteristics.

1.4.2.4 Cost and Benefit Considerations

The cost of conventional relays has continued to increase during the last two decades and the cost / benefit ratio has consequently generally increased. On the other hand, the advancement in microelectronics technology has led to a substantial reduction in the cost of digital hardware but it must be remembered that, in particular, it is the cost of the software that often dominates the overall cost. Situations exist where the cost of software for commercially developed equipment exceeds that of the hardware by at least an order of magnitude, and in consequence digitally based equipment costs more than conventional equipment.

On the other hand, high-volume digital relays, e.g. overcurrent relays, are relatively cheap because the development costs are spread across many relays and volume production allows the use of special microchip technology. Sales volumes and development costs are also important; these vary significantly according to the degree of functional complexity involved. Overall, it is true to say that substantial improvements in performance made possible by the application of digital technology have resulted in a gradual reduction in the cost / benefit ratio for digital protection equipment.

1.4.2.5 Other Features and Functions

With the introduction of microprocessor-based protective systems, totally new features and facilities, which have no parallel in conventional technology, have been made possible. In particular, digital relays can be programmed to provide post-fault analysis of all observed transient phenomena. This is achieved by reading out sampled data that have otherwise been acquired as part of the fault measurement process. In addition, digital equipment monitoring both voltage and current can be programmed to compute the distance to a fault immediately after the occurrence of the fault.

1.5 Filtering Requirements for Protective Relays

The protective relays must filter their inputs to reject unwanted quantities and retain signal quantities of interest. Filtering requirements depend on the protection principle and the application. In traveling-wave relays, the power-system frequency components are interference, and the transients are the information. In almost all other relays, the system frequency components are the information, and everything else interferes. Among the exceptions are relays using harmonic-restraint, and peak-sensitive voltage relays, which may need to detect off-frequency events. Since distance relays measure impedance, and because impedance is defined at a given frequency, distance relay filters must save only the fundamental frequency [13].

1.5.1 Characteristics of Filter Design

The filter must have certain characteristics, whether it is analog, digital, electromechanical, or some combination. Following are the filter characteristics [13]:

- (1) Bandpass response, about the system frequency, because all other components are of no interest.
- (2) DC and ramp rejection to guarantee decaying-exponentials are filtered out.
- (3) Harmonic attenuation or rejection to limit effects of nonlinearities.
- (4) Reasonable bandwidth for fast response.
- (5) Good transient behavior.
- (6) Simple to design, build and manufacture.

Precisely choosing filtering characteristics, based on the relay requirements, is the best guarantee that the design will be successful in the laboratory and in the field. It would be a serious mistake to simply select a filtering concept, and ‘prove’ it in EMTP and model power system tests. If the requirements and the characteristic of a filter are not studied carefully, then there is much greater likelihood that some day, some system will present the relay with unforeseen conditions, not evaluated and addressed in systems tests [13].

1.6 Modeling of Six-Phase Transmission Line Using EMTDC/PSCAD

PSCAD (Power Systems Computer Aided Design) is a powerful and flexible graphical user interface to the world-renowned, EMTDC solution engine [22]. PSCAD enables the user to schematically construct a circuit, run a simulation, analyze the results, and manage the data in a completely integrated, graphical environment. Online plotting functions, controls and meters are also included, so that the user can alter system parameters during a simulation run, and view the results directly. The six-phase system is constructed by a couple of pairs of identical Delat-Wye (Δ -Y) 3-phase transformation which will be called conversion transformer hereafter. One of each pair of transformers has reverse polarity to obtain the required 60° phase shift. One transformer has vector group of DY1 and another has vector group of DY11 (Figure 1.9). PSCAD has a rich set of components library which user can use them to build their desire model. One such component is Real-Time Playback (RTP for short) recorder which can record a simulation result in three different formats namely RTP, COMTRADE 91 and COMTRADE 99 depend on the user choice. In this study the RTP was set to COMTRADE 91 and therefore the output of the simulation was recorded in this format. The COMTRADE file then use in MATLAB program for post-processing as is depicted in Figure 1.3. For phase-conversion transformer model two pair of the UMEC (Unified Magnetic Equivalent Circuit) transformer (more on this in Chapter 3) is utilized.

1.7 Research Objective

The objectives of research can be outlined as follow:

- (1) To calculate the parameters of a six-phase line which converted from selected existing three-phase double-circuit TNB network.
- (2) To calculate various fault on six-phase line and obtain maximum fault current for getting necessary equipments for the prototype.

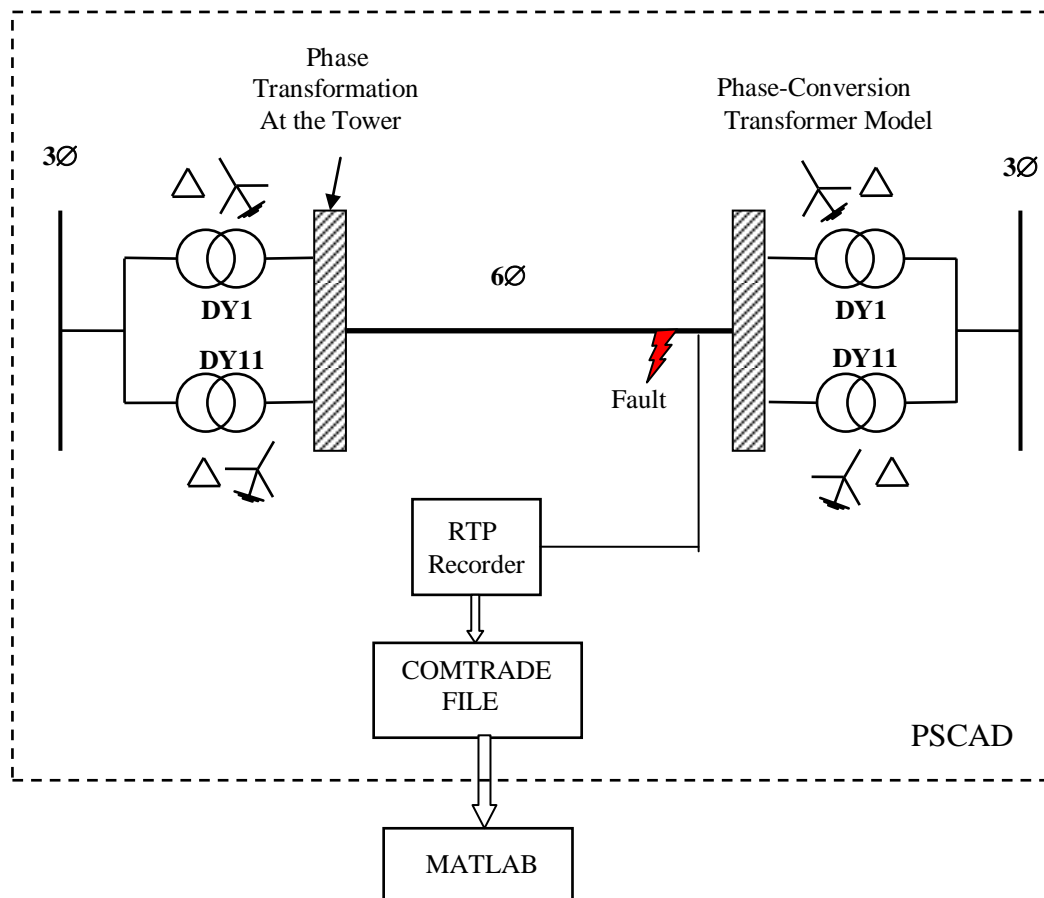


Figure 1.3 PSCAD Simulation of Six-Phase Transmission Line

- (3) To develop an appropriate computer model considering six phase conversion of selected three-phase double circuit line of the TNB transmission system. This model can be made amenable to time-domain power system transient software EMTDC/PSCAD for the analysis of the faulted currents and voltages on six-phase system.
- (4) To develop a laboratory replica (prototype) of the line considered to be converted into a six phase and to develop a digital protection unit scheme for a six-phase transmission line, CTs (current transformer), PTs (potential transformers), transducers, data acquisition cards, a single microprocessor, and interfaces with circuit breakers.

- (5) To identify the most suitable method for the protection of the converted line from among various methods (such as distance, directional comparison, phase comparison and current differential protection, etc.)
- (6) To investigate various algorithm for determining current and voltage fundamental components (such as Discrete Fourier Transform (DFT), least square, Kalman filter, etc.), and to develop a new algorithm for digital relay.

1.8 Problem Statements

In the fast growing countries like Malaysia, the demand for power becomes more important. However, there are many difficulties arise for increasing power transfer such as changing conductors, insulations and more importantly the towers which are very costly. Furthermore increasing power transfer demands more right-of-way which is difficult to obtain. On the other hand continuous supply of electricity to customers is a vital in modern society. If a fault occurs in a network, the protective relays must clear the faulted area as fast as possible to prevent instability in unfaulted area. This requires an accurate and fast algorithm which can be used in digital protection scheme. One solution to increase the power transfer without changing conductors and towers is to use six-phase system. However, that there are several issues in six-phase system that yet have to be explored and investigated more. The problem with six-phase system is that yet there is no six-phase prototype in a “small scale” that could be used to study the various protection schemes in six-phase transmission line. On the other hand algorithms which have been proposed and published so far by other researchers in this field suffered in one or another way of some drawbacks. This issue also needs to be more investigated. These problems will be investigated in this thesis and the solutions to these problems will be given in detail throughout the thesis.

1.9 Methodology

It is obvious that the first step of methodology is to identify and outline the objectives of the research. Then based on the objectives, literature review has to be

conducted to understand the weakness or drawbacks of previous work in this field. The next step is to make appropriate planning for the project. In this project, the planning can be spanned into three parts: (i) to develop a small scale six-phase transmission line prototype which can be used to the study of six-phase in real life (ii) to carefully choose and develop an almost optimal algorithm and (iii) to develop a six-phase model using one of commercially available time-domain software package to investigate and study of fault(s) on six-phase system.

There are two stages for developing a small scale six-phase transmission line prototype. The first stage is regard to electrical part i.e. calculating the R, L and C of a particular line and the second stage is to develop electronic part which is signal conditioning for this project.

The first step of first stage is to select a proper three-phase double-circuit transmission line among the TNB large network which has potential to convert it to six-phase single-circuit. Having selected the specific line, which is three-phase double-circuit Kuala Krai-Gua Musang (KKRI-GMSG) transmission line, the next step is to collect all necessary data for that particular line such as conductors configuration, conductors technical data, transformer data (if exist), and so forth. These data will be used to obtain parameters of the line (i.e. R, L and C). Obtaining parameters of the line, the proper resistors, inductors and capacitors which are available in the market should be bought provided that their technical specification fulfills the calculated parameters.

The second stage of developing prototype is to design a proper signal conditioning circuitry, data acquisition and two interfaces. Signal conditioning design consists of (i) specifying proper current and voltage transducers, (ii) designing offset and gains adjustment circuit, (iii) designing low pass filter with specific cut-off frequency and (iv) designing appropriate interface circuitry between parallel port of PC and outside. Theses step are discussed in detail in Chapter 9. The data acquisition and interface between signal conditioning and data acquisition were bought from National Instruments.

To monitor the experimental results online, LabVIEW software [23] from National Instruments has been used as interfacing software. This makes the modeling process and analysis much easier because LabVIEW has many features and functions that can be used together with data acquisition card from National Instruments.

To obtain an optimal algorithm, is not a readily job. First of all almost most of the available signal processing approaches (which are limited) have been used by researchers in one way or another. Second every protection scheme requires a different algorithm so if suppose one algorithm is suitable for transmission line protection it might be not work for transformer protection and vice versa. Therefore, having a universal algorithm is a tough job. As a consequence, in this research the focus has been in transmission line protection.

To find an appropriate algorithm, one should understand all previous work and to implement their method to verify its correctness. This is because so, some of previously published methods had errors in their results and some have deceived the reader with incorrect published results. As a result in this thesis all the algorithms which are discussed also evaluated, using MATLAB, to ensure the correctness of previous works. The frequency responses of all the discussed algorithms have been derived by aid of programming in MATLAB. MATLAB [24] is high-performance language for technical computing integrates computation, visualization and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. This topic has been covered in Chapter 6 and 7 of the thesis.

For the third part of planning a time-domain power system package which is called EMTDC/PSCAD was chosen as a simulation tool. PSCAD is a powerful and flexible graphical user interface to the EMTDC solution engine. EMTDC is most suitable for simulating the time domain instantaneous responses (also known as electromagnetic transients program) of electrical systems. More on this can be found on Chapter 9. The final stage of methodology is to compare results from simulation in EMTDC/PSCAD with the results derived from the prototype.

1.10 Contributions of the Research

Usually contribution in a research depends on its topic and how much work has been done for that specific topic. For six-phase system work has been started since 1975 and for algorithms which utilize in digital protection scheme research has been started since 1969. It is obvious that there are many researches in these two topics which have been published. As a result finding contribution becomes more difficult in such a situation. However, the contributions of this research are based on not previously published or worked in this area and outlined as follow:

- (1) Developing MATLAB program to calculate parameters of a six-phase line with two ground wires using Carson's line model. This program can be used as commercial software by power utilities such as TNB for calculating parameters of the three-phase double-circuit or six-phase single circuit with ground wire.
- (2) Proposing a novel algorithm based on bounded data uncertainties (BDU) for digital protection scheme which is faster than Discrete Fourier Transform (DFT) algorithm. The relay manufacturer can use the proposed method as an alternative to DFT method for digital distance relaying.
- (3) Developing a six-phase transmission line prototype to be used for research in six-phase system in the laboratory. The prototype is invaluable for power utilities such as TNB as well as research students for investigating various aspects of six-phase system such as loadflow and fault analysis.

1.11 Outline of the Thesis

The thesis starts with this Chapter, introduction. Literature review is presented in Chapter 2. There are several topics are discussed in chapter 3 which includes (i) a detail of six-phase transmission line concept (ii) how to construct the six-phase transmission line, having existing three-phase double circuit line (iii) the calculation of six-phase impedance matrix (iv) fault analysis of six-phase line using previously published methods such as symmetrical components and phase coordinate (v) a detail

of distance relay protection and (vi) a review of different algorithms which utilized in digital protection schemes. The frequency response of various filters and comparison between them is reviewed in chapter 4. Chapter 5 is dedicated to the new propose method for digital relay. This new method have been used in digital signal processing, in general, and image processing, in particular, but to the knowledge of the author it has never been used in digital relay. Modeling of six-phase system is presented in chapter 6. The hardware implementation of protection of six-phase transmission line has been covered in chapter 7. The conclusion and suggestion for future research is given in chapter 8.