Line outage detection using phasor angle measurement

ENG470 Engineering Honours Thesis

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Abstract

A continuous power supply is a pre-requisite to maintenance of successful economic activities and modern lifestyles. Supply interruptions lead to adverse commercial and social effects which worsen as the duration of the power outage increases. A system that can monitor the location of the outage will greatly help in the response time needed to restore power. The current project suggests such a solution. The primary aim of the project was to develop an algorithm that could detect where and when line outage exists based on “phasor angle measurement” technique. From a central position, the system is able to detect the location of a fault and show the lines affected by outage. The information will then be sent to a team on the ground to respond immediately to restore the power.

The literature review conducted describes similar existing systems focusing on their operation and limitations. The project then suggests a solution to counter shortcomings of previous systems. A detailed description of the design and operation of the proposed system is provided. The report concludes that the proposed design is low cost, more reliable and more user-friendly than pre-existing systems.
Dedication

This project report is dedicated to my parents and siblings for their financial support towards the efforts related to project and my course-mates for their moral support and positive criticism. Your efforts have been very much appreciated. Thank you.
Acknowledgements

I would like to express my gratitude to my supervisors and lecturers for their unwavering support and task insight without which the project would not have been possible. Not forgetting the support of my parents and the classmates who made magnificent contribution towards the success of the project.

My gratitude also goes towards the School as whole for their support in one way or the other.

Thank You.
**Declaration**

The following report is presented for the partial fulfillment of the bachelor’s degree in Industrial Computer Systems Engineering. All works presented here are my own efforts and this report has never been presented before, in this institution or any other, for the purpose of assessment by any panel. All secondary sources of information have been duly cited and acknowledged and any omissions are not intentional and are regretted. Any corrections regarding this are accepted and are highly welcomed.

Signature: ……………………………… Date: 13/10/2015
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Chapter One

1. Introduction

1.1 Introduction

This chapter outlines the power flow analysis and the phasor measurement units (PMUs) used to determine the power line outage detection. The chapter also discusses the significance of the problem and set out the objectives to be achieved. Power line outage detection works by detecting signals relating to faults and performs sampling by converting the acquired signals to digital signals for processing. The proposed design only measures the synchronized voltage and current phasors in a power system. With the introduction of the phasor measurement unit in a power system, it has been possible to improve the possibilities for monitoring and analysing power system dynamics. An improved monitoring method permits rapid remedial action before the fault spreads to other parts of the power system, and avoiding damage to power equipment.

1.2 Background information

Electrical power is not necessarily generated at its site of consumption. There are transmission lines used to transfer power. Power flow refers to the flow of electrical power from its source to loads [1]. A power flow analysis is an analysis conducted to determine the quality of power components. Power flow analysis is a fundamental component of power system evaluation playing a significant role in planning of additional lines or expansion of transmission and generation facilities.
Power system analysis is not only essential for planning future enlargement of transmission networks, but also in defining best performance of pre-existing networks. Power generated can be transmitted at high voltage as an alternating current (ac) or direct current (dc) [2].

A fault occurs when the power flow is interrupted during transmission or distribution. Transient waveforms resulting from the fault, measurement of the line impedance and the values that the phasor units determine, namely PMU are some of the various parameters used to detect faults [3][4].

Phasor measurement unit refers to a device which measures the electrical waves with respect to a common time source [1]. A phasor provides both the voltage magnitude and phase angle of the electrical sine wave. They are sampled from a widely dispersed location in the power system network and are synchronized by a global positioning system (GPS) radio clock. Due to the advent of the phase measurement unit technique, it is now possible to carry out measurement and perform analysis of the performance of any power system on a much higher scale which was not previously possible. It works by performing sampling on signals derived from the GPS, and high accuracy analogue to digital converters [3]. This generates the magnitude and phase angle of the input signal for each sample from the line. Phasors can therefore be combined to generate a positive sequence phasor for a given set of three phase inputs. Using these positive sequence data, voltage and current phase and magnitude, real and reactive power can be determined. The parameters (positive sequence) are normally acquired at the same time. As a result, the state of the system at the measured voltage nodes can be referred to as the sample time.

An example of PMU used is the phasor angle which can be used to detect both a single line outage and a double line outage. Changes in phasor angle can be matched with an event on
the line in order to detect a single line outage on a power grid [5]. A PMU can be used to measure voltage, phasor angle, or current of waveforms with frequency 50 / 60 Hz at a high rate, about 48 samples per cycle. This translates to 48*60=2880 samples per second for a 60Hz system [7].
1.3 Motivation

Global power consumption is substantial. The majority of modern day tasks rely on electrical power supply. Power outages lead to inconvenience and loss. Lengthier outages result in more serious economic and social consequences [7]. Thus, whenever there is a fault on the line causing the power outage, a quick means of detecting the exact location is needed to facilitate a quick response to restore the power back to the users. It is with this background in mind that this project idea has been conceived and will be developed. The project aims at coming up with a system of line outage detection for a transmission and distribution network that can be monitored remotely from a central point. The project will employ the phasor angle measurements method using a single line.

1.4 Aim and objectives

The primary aim of the project is to design and produce a system for fault detection in transmission lines. The following specific objectives were formulated;

1. To investigate line outage detection using phasor angle measurement
2. To build an algorithm to determine fault in transmission lines
3. To enhance and test performance of the algorithm.
1.5 Project significance

The proposed system will help in reducing response time for power companies in finding the fault locations and restoring power to consumers. In a greater extent, the losses incurred due to prolonged power outages will be reduced. A data bank on areas of frequent fault as will be recorded by the system can be used in decision-making. From the system, one can analyze the power consumption patterns of a specific supply line and decisions made on this. The proposed system using two software applications will aim at increasing the efficiency and reliability of fault detection methods at a reduced cost without compromising on the accuracy.

1.6 Report organization

The report is organized into seven chapters, Chapters 1 to 6. In order to help readers understand the nature of the project, the contents of the report are divided as follows:

**Chapter 1** - In this chapter of the report, the project is introduced by highlighting background information, project motivation and its significance. It also provides the objectives that need to be achieved by the end of the project.

**Chapter 2** - This chapter is a literature review providing detailed information on the background data, phasor measurement unit as a tool for detecting power fault and offering quick advisory steps to be taken to quickly eliminate the fault. The chapter explores DC power flow and how it is relevant to the current project. The chapter also describes both the single and double line outage detections using phasor methods.
Chapter 3 - The following are addressed in this chapter: General description of the way/method that is designed to solve the problem; a comprehensive description of the problem or project; Powerfactory software and MATLAB programming software.

Chapter 4 - This chapter describes the construction of the physical components of the project. Building blocks, system and simulation description, circuits, diagrams and explanation, proposed method and a comparison provided.

Chapter 5 - Results of the project testing are provided and interpreted in light of similar studies.

Chapter 6 - An evaluation and conclusion to the work completed is provided. The chapter focuses on problems encountered, and lessons learnt, areas of future work, and a self-appraisal of successful attainment of the objectives of the project.
Chapter Two

2. Literature review

2.1 Introduction

Several online power system monitoring tools/applications are available. A problem with such tools is that they are often designed offline based on the transmission network parameters and historical power generation as well as the forecasted power generation and/or demand [8]. The analyses conducted are based on repeated computations of power-flow solutions using linearized and non-linearized models. Knowledge of transmission lines is critical and should be updated regularly given that new connections are made daily. An efficient and robust technique for conducting such analyses is using phasor measurement units (PMU). The technique has the advantage of giving a timely identification of transmission line outages and real time notification of changes on the network. Phase difference between two sets of PMU voltage measurements is considered and forms the basis for calculations in existing approaches employed to detect line outage [3]. It is assumed that the line outage instance is known and occurs once, as opposed to being persistent. Such approaches then work towards isolating the line outage.

2.2 Background

Globally electric power grids continue to expand. It is a trend necessitated by an ever-growing demand for electrical power and the need for greater spatial connection. The trend has led to a situation where network complexity is high. Such complex networks are becoming increasingly difficult to model accurately. With such systems in place, the cascading effects of an outage in one section is of concern to power companies since such a big geographical area makes it difficult to pin point accurately the source of the outage.
Most existing systems estimate the state of the power system from the measurement of power flowing through the power grid. The parameters used are the positive sequence voltage and the phase angle at each network node. This offers the challenge of affecting the real-time system control given that the power system rarely operates at the nominal frequency which is what is used to calculate the phase angle. At the time of measurement, the system is supposed to take into account the actual frequency of the system at that time of measurement. For instance, given that for a 60Hz, the operating range of frequency can be given as ±0.5Hz, thus on the lower side, we will have the nominal frequency of 59.5Hz. This represents a difference of 0.167% [7]. While this might seem as a small difference, the effect it has in PMU measurement is significant.

2.3 Modelling a power system

Only linearized power systems will be considered in the project for the purposes of simplicity. Statistical models describing PMU measurements obtained just before and after line outage will be used.

2.3.1 Linearization of the power flow model

To linearize power flow equations [9] assume a power system network is represented using a graph and having N number of buses and L number of lines, and is denoted as $N = \{1, \ldots, N\}$ with each corresponding to a bus and $L = \{1, 2, \ldots, L\}$ each corresponding to a line [10]. Sets of edges denoted by $\mathcal{E}$ are on the graph. The edges represent grid transmission lines on a power system. The focus thus turns out to be detecting a line outage. A line outage would be taken to mean an event those results in the loss of a subset of lines in $L$ [10]. The implication is that the total possible number of outage events is $2L - 1$. But this subset will be made smaller for easy understanding and simplicity in use based on the following arguments [10].
• A single line outage normally results in overloading and subsequent overheating of a connected line. The overheated line will take some time (several minutes) before it trips from the time the line outage occurs. It would not be possible to detect many line outages happening at the same time given their probabilistic independence [10].

• The different outages have different impact and effect on the grid. Based on the interconnections, there are cases of line outrages not causing overheating of other lines as may be assumed. The lines which cause heating of other lines have a greater impact and cause a cascading effect on the grid.

• The limitations of computational power limits the number of outage events that can be considered. This is because we would want a real time representation of the performance of the systems and a long computation will take a longer time.

2.4 Phasor angle measurement units

2.4.1 Introduction

A phasor measurement unit (PMU) is a measurement and monitoring device used as a wide area monitoring system (WAMS). PMU has found a great application in electricity transmission networks and they have been found to have values which are provable in a wide variety of power system applications [11]. Examples of such values include oscillation detection and control, state estimation, voltage stability analysis and the more common line outage detection [11]. The current project will focus on line outage detection. GPS can be leveraged and incorporated into the system for a more accurate detection and advancement of the communication capabilities in order to give a more accurate, real-time detection.

PMU is used to measure phasor quantities such as the bus voltage magnitude and the angles tagged with their measurement time. Each PMU will utilize a common time source to enable
synchronization of several PMUs in a transmission network. As a result of this synchronization, the phasors measures by the PMU are referred to as synchrophasors (or synchronized phasors).

2.4.2 Origin and development of PMU

The first application of phasor measurements can be traced back to early 1970s when the Symmetrical Component Distance Relay (SCDR) was developed [2]. The technology was later developed into Symmetrical Component Discrete Fourier Transform (SCDFT) which made it possible to calculate the positive sequence voltages and currents much faster than the predecessor SCDR. The initial intent of SCDR and SCDFT was line protection in the transmission networks. Research showed that such could be extended to measurement of the phasor units and the start of phasor measurement technique. The extension was made possible by the precision of SCDFT. The only problem then was the inability to have a common time source which made synchronization a bit impossible [2]. This meant that the two measurements could not be compared given that any time difference, however small, could have been interpreted as having been taken at two entirely different operating conditions.

Synchronization was made possible with the advent of GPS in 1978 [2]. A common time reference was made possible and this enabled comparison of two phasor measurements. The measurements were, and continue to be, taken relative to GPS clock. The measurements could then be aggregated at the phasor data concentrator, a common location with the absolute time reference coincident for all measurements. The following figure shows how a GPS time source provides an absolute time reference.
Synchrophasors found a big application in state estimation (SE). The need to estimate the state of power was and is necessary for the sake of predicting the trend in power demand and growth. This information is important to any government or local authority for economic reasons as well as security reasons as it helps in planning. Initially, in the early 1960s [2], estimation of the bus voltage magnitudes and angles was done using active and reactive line flows. This had the limitation of a slow time convergence which meant that for a big system (network), the result of the SE would be obsolete by the time the estimate converged. But by using a value of accurate bus voltage magnitude and phase and angle measurements, it has been shown that there will be a remarkable increase in the SE performance [3]. These helped to eliminate the need to measure quite a number of line flows needed by the traditional methods of state estimation. Few measurements meant a faster convergence, and in cases
where the data for all the buses are given (magnitude and angle measurement), the convergence would be achieved at the first iteration. Originally, PMUs were designed to be standalone devices but with advancement in technology, the current existing synchrophasors are an added feature found in microprocessor based relays. PMUs are known to measure phasors at a higher frequency, up to thirty times in one second, then the synchrophasor measurements can be used to measure waveforms with a much greater resolution unlike SCADA systems. They help to cover measurements for a wide area.

2.4.3 Wide area monitoring systems

Wide area measurement systems (WAMS) [12] are used to provide a more comprehensive knowledge of the power system in general [3]. WAMS cannot be used on their own and are generally used to complement SCADA systems in understanding and managing large, complex power systems. They do so by providing real time data for increased situational awareness and event analysis [11]. There is one use of WAMS that has been developed after many years of use, although it was not an initial intention of WAMS. This is the dynamic modelling of the power system and its validation. This means, a simulation of the system can be done and on the event that the actual measurement is taken, the two can be compared to determine the validity of the model.

WAM, however, has been greatly developed to monitor and provide better situational awareness, such as event detection. The system itself is efficient but once the human factor is considered, then the efficiency depreciates. For instance, an operator may not detect quickly the changes in phasor measurements and his reaction time will also play a role in the effectiveness of the system. The event detection process can be summarized as being made up of three stages [11]. These are:
• Actual detection of the event
• Extracting information about the event
• Classifying the event to determine the appropriate solution

2.5 Application of PMU in line outage detection

Phasor measurement units’ applications [17]

1. It monitors disturbances in the line i.e. transient and steady state responses.
2. Behaviour of power system can be monitored globally
3. Bus power transmission can be easily calculated by collecting the phase directly

Power system parameters are represented by complex variables. A phasor contains magnitude and angles of any sinusoidal signal represented by a cosine function with a magnitude \( A \), frequency \( \omega \), and phase \( \phi \). The figure below illustrates the sinusoidal function together with the phasor representation.

![Figure 2: phasor representation of a sinusoidal waveform](image)

PMU measures angles and magnitudes of phasors at higher rates of 10 - 60 samples per second with an accurate time lag [3], [4]. Phase measurement unit refers to a phasor that is
time stamped to an accurately and extremely exact time reference. It provides real time power measurement in a power system by using the voltage/current magnitudes and angles. The sampled phasors’ resultant time can be transferred at the rate of 60 samples per second to a receiver remotely or locally. It uninterruptedly collects phasors of voltages and currents and transmits the time stamped signals to the receiver. Figure 3 shows the connection of the phase measurement unit.

![Figure 3: Performing measurement using PMU [24]](image)

From the diagram it can be seen that instrumentation cable is connected to the PMU via anti-aliasing filter which aids in removing noise associated with the collected voltage and current signals. The measured signals are transmitted via GPS radio link to the receiver for analysis.

In order to effectively assess the dynamic performance of a power system, a wide area of information will be required and from correctly spread PMUs. The sensor also needs to be placed at the appropriate distance to capture the signals correctly and to maximize the
information content. A numerical analysis will then need to be carried out in order to understand the data collected from the sensors. There are several methods of numerical analysis that can be used to achieve this goal. These methods are designed to maximize the overall response of the sensor but at the same time minimize the correlation between the sensor outputs. This helps to reduce any redundant information resulting from the multiple sensors being used at the same time. The parameters that are of interest during measurement are three: the magnitude of the bus voltage, the frequency coherency index and the angle coherency index [7]. The last two are estimated using statistical sampling using a transient stability program.

![Figure 4 : PMU using ADC for data acquisition](image)

2.6 PMU location selection

In case of PMU location selection [13] ideally all the buses are supposed to have PMU measurements in order to give a synchronized and timely updates of the phase angle vector. Each then has to constantly communicate to the control center on the status of the bus. Practically, this task is costly and would not be economical. Thus, the choice of the buses
from which the PMU measurements can be done will be made based on the following two factors:

- The cost of installation – PMU measurement for high voltage networks is expensive. To reduce the cost, only a few buses will be used.
- Having PMU installed in all the buses leads to information redundancy. If all the buses were fitted with measuring devices and they all send information to the same control center, then some of the data sent will be repetitive especially for buses which are identical or related in the network. To avoid this, only a few selected buses will be installed with PMU measurement devices.

**2.7 Implementation of PMU**

This report proposes use and installation of PMU for phasor measurement to be installed at each of the substations in a power grid network. The oscillators used will be synchronized internally by the PMU once their signals are received by the GPS. The output Coordinated Universal Time (UTC) information is given out in the form of an Inter-Range Instrumentation Group-B (IRIG-B) time code format. In order to compare the phasor of the power, there are voltage input terminal and current input terminal. There is an internally stored reference signal which is synchronized with the GPS. This signal will be used to compare the system phase frequency (normally set as 50 Hz conventionally although there are some countries that use 60 Hz). This will then allow for assessment of the performance of the PMU by comparing it with the IRIG-B code (an output signal that will be generated by the internal reference signal earlier mentioned).
2.8 Performance measurement with PMUs

Based on [14] the method shown in figure 5, the phase difference between the 1 Pulse-per-second (PPS) output of atomic clock and the reference output of PMU was measured using a time interval counter (TIC) in a laboratory where constant temperature and humidity were maintained. PMU1133a does not output second pulses, and thus an optimal trigger level was found by performing an experiment that establishes the trigger level to get an optimal point for Inter-Range Instrumentation Group-B (IRIG-B) output (5V) in advance. IRIG-B output is general digital code data, rather than a pulse type that has an abrupt rising edge for timing. Finding a stable trigger point is important for precise measurement. For this purpose, comparisons were made at 2V, 3V, and 3.5V, which are middle levels with relatively small noise and signal distortion. In the case of the 2V setting, outliers occurred, but the most stable data could be obtained. As shown in the measurement results, outliers occurred intermittently, but the signal level was less than 100 ns. The average of the measured data was 3.7 ns, and the standard deviation was 11.9 ns, which showed substantially outstanding performance. The stability and the maximum time interval error (MTIE) are given by the
method. As shown in the figures above, for the 10-second average interval, the frequency stability was about \(10^{-10}\) Hz and for the entire measurement period, the MTIE value was less than 200 ns. It is thought that this performance is sufficient for a power measurement system.

2.9 Design of remote outage line measurement with PMU

The remote measurement system of reference phase of power grid is a system for the remote evaluation of the synchronization signal of a power grid of GPS based PMU system. In this study, a PMU reference phase remote measurement monitoring system that can monitor normal operation by measuring the status of 1 PPS by the GPS signal reference IRIG-B signal outputted from PMU was designed. In an actual substation, the levels of voltage and current of a power system for measurement are changed to the input range of PMU by lowering the voltage using a potential transformer or by lowering the current using a current transformer, and are then inputted to the installed PMU. PMU measures the phases of the voltage and the current of a power system based on the 1 PPS signal provided by GPS (an accuracy of less than hundreds of ns), and transmits them to a data collector of phasor. In this regard, for the same measurement, an accurate synchronizing signal based on reference time needs to be used; and in most cases, PMU measures the phase angles of voltage and current by applying a synchronizing signal that provides a reference signal (e.g., GPS). The IEEE 37.118 standard states that the phase angle of power needs to be measured and calculated using 1 PPS of UTC as the synchronizing signal [7]. For synchronization with UTC using GPS time information, PMU based on the synchronizing signal using GPS needs to be used at each measurement point. When PMU is used as mentioned above, the phase differences of voltage and current at the measurement location of a transmission line can be measured through the measurement of the transmission line. Based on the real-time measurement of
these measurement values, the effects of system load and the change in the power phase of the entire substation line can be monitored.

Figure 6 shows the remote power phase measurement.

![Remote power phase measurement](image)

*Figure 6: Remote power phase measurement [21]*

The components of the phase measurement unit include:

1- Phase data concentrator (PDC)

2- Anti-aliasing filter

3- GPS time tagging

4- Phase locked oscillator
Phase data concentrator (PDC):

It is a software application which runs on a normal personal computer and collects data from the phase measurement units. It receives several data from the PMUs and analyse depending on the application requirement.

It aligns data by time the received PMU data from several measuring devices and sends out the combined synchronized messages set as a single data stream[15]. It also archives information and process it. It helps in exchanging information records with PDCs at other stations. Figure 7 shows phase data concentrators.

![Figure 7: PDC [23]](image-url)
The automated system makes it necessary for the PDC to collect, measure, and analyze energy usage and transfer information to a central location for quick action to be taken. The PDCs are networked to several meters which enable it to freely communicate with the network servers. Data concentrators provide information that is used by the utility companies to avail data to their servers. Data concentrators use microcontrollers or programmable logic controllers for data processing. Phase measurement unit are connected to the PDC and there can be as many PMUs connected to the PDC as the number of connected buses [16]. The following are the features of the PDC that makes it usable on power system analysis:

1. It has multiple inputs and outputs communication data protocols
2. It is capable of PMU monitoring
3. It can be managed remotely

**Anti-aliasing filter**

This filter limits the bandwidth of signal to fulfill sampling theorem

**GPS time tagging**

It offers a signal’s time stamp

**Phase locked oscillator**

It keeps frequency of the reference and measured signal equal

Figure 8 [17] illustrates components of phase measurement unit.
PMUs measures the following [17]:

- local frequency
- local rate of change of frequency
- circuit breaker and switch status
- Positive sequence phase voltages and currents.

2.10 Review of power flow

Power flow [18] is the movement of power from a generation point through transmission and distribution lines up to a point of consumption. A simple understanding of instantaneous power can be given by a mathematical expression as being the product of voltage and current, i.e. [9]

\[ p \text{ (Watts)} = i \text{ (amperes)} \times v \text{ (volts)} \]

There are two types of power based on the type of current being transferred, i.e., alternating current (ac) and direct current (dc). The two are different from each other and as one goes deeper into the particular current type, other factors affecting the power flow begin to appear
and play a considerable role. For example, in ac systems, power factor (PF) becomes vital given the type of load being supplied so that $P = I \times V \times PF$. Also of concern is the active and reactive power as a result of the power factor, although this is absent in dc systems. Thus power flow in ac systems is carried out to determine the degree of flow of the active and reactive power.

In both ac and dc, power flow is governed by basic electric circuit theory. The equations governing the power flow in general are derived as follows [3] [11]:

$$P_i = \sum_{n=1}^{N} |Y_{in}| |V_i||V_n| \cos(\delta_{in} + \theta_n - \theta_i)$$  \hspace{1cm} (1)

$$Q_i = \sum_{n=1}^{N} |Y_{in}| |V_i||V_n| \sin(\delta_{in} + \theta_n - \theta_i)$$  \hspace{1cm} (2)

Where $P$ and $Q$ are active and reactive power respectively. From the equations, $N$ refers to the number of buses; $I$ refer to the bus at which the real power and reactive power ($P_i$ and $Q_i$) are injected. Each branch element has an admittance represented by

$$|Y|_{in} < \delta_{in}$$  \hspace{1cm} (3)

At the point of injection, the magnitude of the bus voltage and the angle at this bus is represented by

$$|V_i| < \theta_i$$  \hspace{1cm} (4)

Given these parameters, the task of solving the power flow is defined as solving these equations by making the active power generated equal to the active power losses and the real power of the loads. Also, the sum of the reactive powers of the loads should be equated to the reactive power generated.

It is important to note that the problem of power flow in not linear and the solutions are obtained by iterations. However, if we can determine the stable operating point of the system
(done using the Newton Raphson method) [19], then the problem can be linearized. For this reason, the DC power flow is used. The method is discussed in the following section. The system, though, provides a slightly less accurate solution but at a faster time. The DC power flow is a representation of an entirely linear set of equations and these equations do not need iteration to be solved.

2.11 DC power flow

The DC power flow gives estimations of the line power flow by considering only the active part of the AC power. The method is non-iterative and convergent but less accurate as compared to the AC power flow analysis system. In order to carry out dc power flow analysis, the following assumptions must be taken into account [9], [20]:

1. Line resistances are assumed negligible
2. Voltage and current phasor angle are assumed negligible
3. Bus voltage magnitude are set to 1.0 p. u
4. Tap settings are ignored
5. Total number of buses is N and that of branches is M
6. Bus number 1 used as the reference bus

In order to determine the solutions for DC power flow equations, it is assumed that there are many large systems which have branch impedances.

- The real part of these impedances is considered to be quite insignificant when compared to the imaginary part [1]. That is,

$$z = r + jx \quad \text{where} \quad r \ll x \quad \Rightarrow z \approx jx$$

(5)
• The impedance of the buses can be taken to be equal to the reactance thus the imaginary part \( j \) can be neglected.

• When the angles are measured in radians, then the sine of the angle is approximately equal to the angle, i.e. \( \sin \theta \approx \theta \)

• Since the p.u (per unit) system will be used, it is assumed that the voltage at each bus will be approximated to 1 p.u.

2.11.1 Importance of DC model

Generally, power flow in a power system is characterized by voltage and current in a power line and is given by basic electric circuit theory. A power flow system is designed and evaluated to determine where and to what degree the active and reactive powers flow in the power line. In DC power flow reactive powers are ignored and small changes of the angles are considered.

The main reason of using DC power flow in this project is its ability to ease and speed up the calculation of the system. In case of fault presence, in a four bus system, performing hand calculation would not take long time. However, in a system with a large number of buses, the need of DC power flow method is essential in order to ease and accelerate the calculation required. Also, there are other advantages as listed below [1]:

a. Results are consistent distinct and not redundant.

b. It has simplicity when used in coding.

c. Easy to get its network data.

d. The approximated values of power are close enough to the exact values.
2.11.2 DC power flow equations

To implement DC power flow method there are few assumption needed to be made on a selected transmission network [20], [9].

Given the following non-linear equations:

\[
P_k^I - \sum_{i=1}^{N} V_k V_i \left[ G_{ki} \cos(\theta_k - \theta_i) + (B_{ki} \sin(\theta_k - \theta_i)) \right] = 0 \quad (6)
\]

\[
Q_k^I - \sum_{i=1}^{N} V_k V_i \left[ G_{ki} \sin(\theta_k - \theta_i) + (B_{ki} \cos(\theta_k - \theta_i)) \right] = 0 \quad (7)
\]

1- Neglect reactive power:

\[
P_k^I - \sum_{i=1}^{N} V_k V_i \left[ G_{ki} \cos(\theta_k - \theta_i) + (B_{ki} \sin(\theta_k - \theta_i)) \right] = 0 \quad (8)
\]

2- Neglect resistance of the branches:

\[
P_k^I - \sum_{i=1}^{N} V_k V_i \sin(\theta_k - \theta_i) = 0 \quad (9)
\]

3- Assuming all voltage magnitudes are 1.0 p.u:

\[
P_k^I - \sum_{i=1}^{N} B_{ki} \sin(\theta_k - \theta_i) = 0 \quad (10)
\]

4- Assume all angles are small:

\[
P_k^I - \sum_{i=1}^{N} B_{ki} \sin(\theta_k - \theta_i) = 0 \quad \text{or} \quad p_k^I - \sum_{i=1}^{N} \frac{(\theta_k - \theta_i)}{x_{ki}} = 0 \quad (11)
\]

\[
P_{ki} = \frac{(\theta_k - \theta_i)}{x_{ki}} \quad (12)
\]

In the derived equation above, phasor angle, reactance, and power are treated as voltage, current, and resistance from ohm’s law.

\[
\Delta \theta = B^{-1} \Delta P \quad (13)
\]
B is Y-bus / admittance matrix.

2.12 Review of line outage detection

Line outages in a power system can be detected if the line flow measurements and a small number of synchrophasor bus angle measurements are given [18]. There are two steps that can be used in the general process of line outage detection. The first step involves modelling the system and analyzing it offline and simulating it to determine the possible effects of an outage on one line. Later, this can be used to compare the actual results in the event of an actual outage. The second step involves monitoring the synchrophasor measurements on-line to detect any abrupt changes. The quantities that are measured and analyzed offline are referred to as power transfer distribution factors (PTDFs). These quantities are derived from the assumptions of the dc power flow. PTDF is used to relate the power transferred between two buses \((i \ and \ j)\) following the removal of a line \(l\). This power that will be injected into the system is given by the equation [18]:

\[
\bar{P}_l = \frac{-P_{ij}}{1 + PTDF_{ij}}
\]  

This power when injected into the system will definitely affect the magnitude and the phases of the voltage on the other buses in the network but only a subset of the buses will be observed by the PMUs. The buses to be examined can be selected in the following manner;

\[
\left( min \left\| \Delta \theta_{observed} - \Delta \theta_{calc,l} \bar{P}_l \right\| \right)
\]  

The minimization expression above is used to determine the shortest distance between the observed angle changes and relating them to all the possible angle changes.
2.12.1 Line outage detection methods

There are several methods [3] that have since been applied to detect faults in a line namely: PMU method, call-in reporting via modem, SCADA based method and many others. These methods serve the purpose of fault detection and relaying the information about the fault to the operator remotely. In call-in reporting method, once a fault is detected in a power system, it relays the information about the fault to the operator by dialing the operator number to alert about the fault. It is suitably placed at the transformers and generator set stations.

The main PMU uses the PMUs to remotely collect data relating to the system fault and relays the information using GPS to the operator to alert concerning the system fault. The Supervisory Data Acquisition and Control method collects data remotely using sensors and relays the system fault information via internet network or modem for operator to take the necessary steps to mitigate the faults before spreading to other power equipment on the line. In some applications both SCADA are used together with the PMUs for system fault identification and eradication.

2.12.2 Single line outage detection

Single line outage detection [3] is a method that is used to detect a system fault on a single line characterized by voltages and currents. This method uses phase angle to perform power system measurement using PMU data, transmission line and transformer parameter data. In so doing there exists assumptions made which includes; well damped fast system dynamics and that it also must be steady in a quasi-stable state after the presence of the line outage and that after the fault occurrence power flow solution will almost resemble system values obtained after the damped oscillations have been filtered out. However, there could be the
possibility that the signals may be poorly damped due to the electromechanical oscillations resulting from the low pass filter used.

In case of the system fault, the difference in the phase angle between the observable buses with respect to the pre-fault values can be determined. This is done by first noting the changes in the angles at each bus and formulating an optimization equation shown below;

\[
E^* = \arg \min_{E \in \varepsilon} \| \Delta \theta_{\text{observed}} - f(E) \|
\]  

(17)

In the above equation, \( \varepsilon \) represents the occurrence of the fault events and \( f(E) \) defines the function which forms the relationship between fault event and the changes in the angles caused by the event.

**Event detection and angle extraction**

In order to determine the probability that an event has occurred in the power system, it will require first to determine steady state changes in the phasor angles. Considering a bus \((i)\) system, the phasor angle will be given by the expression below.

\[
\theta_i[n]
\]

(18)

In this case, \( n \) is the nth sample of the phase angle. It is worth noting that the fast oscillations i.e. high frequency oscillations are filtered out hence only the quasi-steady state angles are considered. The sampled signal or the measured signal may also contain high frequency noise which is also cancelled out by the filter. This implies that the original angle measurements are filtered with a low pass filter tuned at a cut-off frequency of 0.2Hz hence giving the phasor angle at bus \((i)\) as \( \theta_{i,\text{LPF}}[n] \). Figure 9 shows the detected phase angle change.
Once the noise has been cancelled out by the filter, a candidate angle is generated which is given by the equation below.

$$\theta_{i,\text{candidate}}[n] = \theta_{i, \text{LPF}}[n] - \theta_{i, \text{LPF}}[n - N_{\text{trans}}]$$  \hspace{1cm} (19)

A fault event is therefore detected by use of edge detection method in which case each of the candidate signals are continuously compared with the reference angle signal $\tau$.

**Single line outage detection algorithm**

The method employed here [3] is the use of quasi-steady state angle changes. Considering that $\xi$ is specified for a given number single line outages on the power system, line outage equation can be obtained as shown below.

$$\text{line outage } l^* = \arg \min_{E \in \{1, 2, 3 \ldots L\}} \left( \min_{P_l} \| \Delta \theta_{\text{observed}} - \Delta \text{Angles } l(P_l) \| \right)$$  \hspace{1cm} (20)

Whereby L is the line operating normally before an event fault is detected and $\Delta \text{Angles } l(P_l)$ is the calculated change in the angles that would occur if power flow in the line l. When the above equation is solved, a relationship between pre-outage power flow on a
line and the observed angle changes can be determined. In case of dc power flow, the equation is reduced to the one given below:

\[ \Delta \theta = B^{-1} \Delta P \]  

(21)

Whereby \( \Delta \theta \) is the small change in the angle of the buses of the power system due to change of the power injections of \( \Delta P \). B matrix has been used to represent the transmission lines’ impedances.

These procedure as listed below allow to detect the occurrence of a line outage and locate the outaged line in the network. Also, show the pre-outage flow on a line.

1. By filtering the phasor angles find out a presence of the outage and check if a change in the angles is greater or equal to \( \tau \). If the result of comparison is true, then proceed to the next step

2. Determine the change in the observed angle vector

3. For each line calculate the following:
   - Set of changes of the observable angle vector \( \Delta \theta_{calc,l} \).
   - Power flow in the line \( P^*_l \).
   - Normalized angle difference.

4. Determine which of the line \( l \) was outaged by obtained the solution to the equation

\[ \text{line } l^* = \arg \min_l NADVals_l \]

5. Find the pre-outage flow on the line that matches the observed angle.

**2.12.3 Double line outage detection**

This method [4] is built on the single line outage detection procedures. It can be measured by considering a combination of both pre-outage topology and real-time phase angle
measurement unit. In so doing, equivalent outages must be identified and event search space reduced.

**Event detection**

Event detection can be carried out using phasor angle in case the observed phasor angle is compared with the referenced threshold phasor angle. The fault can be demonstrated as a set of power injections in order to determine the effect of a double line outage on the angles in a network, and not impedance matrix. With two powers injected in a double line power system P1 and P2 on lines L1 and L2, the flow from the rest of the system is assumed zero.

Using the formula for $\Delta \theta_{dbl}(l_1, l_2, f_1, f_2)$, the optimization equation can be written as given below.

$$ (l_1^*, l_2^*) = \arg \min_{(l_1, l_2) \in L \times L, (f_1, f_2) \in \mathbb{R} \times \mathbb{R}} \left\| \Delta \theta_{obs} - (f_1 \Delta \theta_{dbp, l_1} + f_2 \Delta \theta_{dbp, l_2}) \right\| $$

(22)

For a given line selection, the power flow values can be calculated from the equation above.

It is important to consider DC power equation as compared to ac power flow equations since the dc power flow requires uses single matrix inversion and therefore easier to work with.

**Determination of expected angle changes**

In order to determine a double line outage [4] of a power system, the function $\Delta \theta_{dblp}(l_1, l_2, f_1, f_2)$ is used to give the expected angle change. Using the power injection vectors $f_1$ and $f_2$, the angle changes can be obtained, which then allows a substantial decrease in the search space.

The following procedure is adopted in calculating the double fault:
1. In each line $l_1 \in L , l_2 \in L / l_1$

2. Determine $\Delta \theta_{d b , l_1}$ and $\Delta \theta_{d b , l_2}$

3. Determine $\tilde{f}_1^*$ and $\tilde{f}_2^*$

4. Determine error value given by the equation

$$Error \ Value \ (l_1^*, l_2^*) = \left\| \frac{\Delta \theta_{obs} - (\tilde{f}_1^* \Delta \theta_{d b , l_1} + \tilde{f}_2^* \Delta \theta_{d b , l_2})}{\tilde{f}_1^* + \tilde{f}_2^*} \right\|$$

By solving the error equation above, the optimal value of the double line outage can be determined. In a case of parallel line, the Error Value entries do not change for several outages since the terminal buses are the same. Additionally, the parallel line can be treated as a single line by obtaining a single line equivalent and modelling line outage using single transfer.

It is worth noting that the method employed for single line outage detection can be extended for use in double line outage detection. While performing this detection, the following reduction has to be implemented search space and handling of island outages. Besides, fitting in extra data from frequency devices will help detect the double outaged lines on the system by utilizing the information obtained from geographical locations and information and sending to the operator for quick action.
Chapter Three

3. Project approach

3.1 Problem statement

Power outages are serious. For electricity generation and distribution companies, management of outages is a core function. Power outages pose serious threats to power equipment such as generators, sub-station transformers, switch gears and many of the consumer equipment. Its occurrence has been manifested as power line short circuit faults leading to deaths in developing and developed countries. By some estimations, congested cities have recorded a good number of serious threats imposed by the power line faults, which is not limited to burning buildings and in some areas plantation. The big questions therefore emerge as how can we get clean power free from faults and damages. The answer to this questions lies on the methods that have been adopted to overcome the power fault scenario.

Several methods have been proposed in order to combat this which includes: incorporating switch gears, switches, fuses on the power line sub-stations to clear the fault and hence preventing wide spread damages. But these methods have not been relaying fault information to the operators thereby making it hard to find whether the fault really occurred and so that whoever is in charge can do service to the equipment.

Some of the methods which have been implemented with a means of relaying fault information to the operators remotely includes: PMU, Supervisory data acquisition and control (SCADA) and call-in point modem which alerts the operator by dialing the operator’s number. The project in mention utilizes the principles of phase angle measurement unit
(PMU) to collect data and relay to the operator of the GPS network. The approach has been seen to be more efficient and cost effective as it covers wide area region.

3.2 Project approach

An outaged line in a transmission line leads to a change in the power flow thereby developing variations in the voltages and currents phase's angles. The most affected bus is always the bus near the outage section of the line. It is therefore imperative to take wide or large scale measurement of the connected buses. The PMUs are connected at some stations for complete observability after which a mathematical model applied to calculate the phase angles.

The proposed approach uses Matlab algorithm which depends on the successive samples to determine the phasor voltage magnitude and angle. This project has also been proposed to use two software applications together for line outage detection. The proposed software includes PowerFactory and Matlab. PowerFactory acts as the real world system and Matlab acts as an approximated system using DC power flow method. The algorithm for this system and the project will be written in Matlab. The variable for this scenario will be the phasor angle measurements. The system will assume an ideal situation, that is, there will be no reactive power in the line, no resistance and assume all the voltages in all the bus to be 1.0 per unit (PU). In essence, the project will be seeking to compare the changes in phase – squared.

Matlab tool will be used in this system to simulate the dc power analysis by giving a graphical and analytical approach to implement the object. For most of the complex mathematical analysis Matlab provides the best method to perform calculations. Matlab has been used following the procedure given: Identify system inputs function, formulate and
determine Y-bus matrix generator, formulate and determine phasor matrix calculator, design an array compare function and formulate, locator function. Matlab code will also calculate and record the sum of each phasor angle change at each bus squared for all the possible single line outage. When a value of the sum of phasor angle change at each bus squared is inserted into Matlab the array “Compare Function” will compare it with all the recorded values and then the “Locator Function” will locate the outage line.

Power factory tool has been extensively used to determine line outage and possibilities of remedying the situation. It is a leading power system analysis tool for applications in power generation and transmission. It is easy to use fully compatible with MS Windows and combines reliable and flexible system modelling techniques with state of the art algorithms. The following are the steps involved in implementing the project with PowerFactory:

1. Identify the number of the system bus
2. Define input and output variables
3. Implement the system and in this project 4-bus and 6-bus system were implemented
4. Locate the place of the fault in one of the buses
5. Generate contingency report to view the detail of the power redistribution due to the fault occurrence
Chapter Four

4. Methodology

4.1 Circuits diagrams

The diagram below shows a 4-bus system that was modelled in the PowerFactory and Matlab. Bus one had a voltage given by 1.01 per unit value. The buses were connected by per unit values of the impedance network.

![Diagram of a 4-bus system](image)

*Figure 10: 4-bus system*
The circuit was constructed in the Matlab by following the procedure below:

The Matlab code was written to calculate voltage phase angle of the 4-bus system.

- An approximated version of the system has been built via DC Power flow derivation method.
- Matlab code is mainly consisted of:
  1. System inputs function.
     This function asks the operator to insert the system parameters.
  2. Y-bus matrix generator.
     This part collect impedances and create the admittance matrix.
  3. Phasor matrix calculator.
     This will multiply the inverse of admittance matrix by power matrix
  4. Array compare function.
     This function waits for an operator to insert a value then compare it with all the possible values that Matlab has already created for every possible fault in the system.
  5. Locator function.
     This function locate the outaged line in the network.
The MATLAB procedure code is as given below.

4-bus system was implemented using PowerFactory by following the procedure below:

1. Identify the input and output of the system
2. Drag the buses into the work area
3. Connect the power sources to the buses 1, 2, 3 and 4
4. Note that the bus 1 is the slack bus with powers assumed as zero
5. Define the Y network by specifying the given parameters
6. Go to contingency report to view the details of the buses and the phase angle values

Newton Raphson method was used with Matlab to compute the phasor angles. This method provided an iterative means of solving the power flow equations.

4.2 Possible outage detection

As previously mentioned, the detection algorithm is considered to be made up of two parts – the first part being the detection part and the second part being the identification of the event. The PMU measurements are constantly under monitor to find out any abrupt changes in the bus voltage angle. This is a bit tasking and in some cases this may go unnoticed is if the operator is not keen enough. This is made more complex by the noise in the communication line and surges caused by capacitor switching [3].

There is need to filter the phasor measurement unit angles before any processing can be done. This is specially done to remove erroneous high frequency content. To achieve this, a low pass frequency filter is usually employed with the phasor measurement unit. This helps to get rid of momentary lapses occurring in the communication signal which otherwise would give a false indication. Removing the high frequency content would not be advisable given that the extent of the fault’s effects varies. Thus it is only the lower frequencies that we can be sure of as causing a false alarm. Also, the line outage detection requires a change in angular value. When monitoring, the abrupt changes can be seen as edges of a cliff. An edge detection system is constructed by examining the first derivative of the intensity values of pixels, similar to what is done in image processing. The result of the derivative is interpreted such that small values are taken to mean no sharp edge thus no much changes to the phase angle while large numbers would be taken to mean a sharp edge thus a big change in phasor
angle. The values will have to be defined as the terms small and big are relative and ambiguous. This would depend on the bus voltages and frequency.

4.3 Comparison

In PowerFactory, buses were dragged in the work area together with other components of the power system whereas in MATLAB the buses were modelled mathematically and components analysed. A contingency report giving details of the fault location and power redistribution in the system were tabled in PowerFactory. Results of simulations in Matlab were tabulated in the Matlab command window.
Chapter Five

5. Results and Discussion

5.1 The 4-bus system

5.1.1 Test MATLAB code for 4-bus system

MATLAB code was used to calculate and record the sum of each phasor angle change at each bus squared for all the possible single line outage. When a value of the sum of phasor angle change at each bus squared is inserted into Matlab the array compare function will compare it with all the recorded values and then the locator function will locate the outage line. So far, Matlab code has been tested for a 4-bus system and the results met the desired values. Table 1 shows all calculated \( \sum \Delta \theta_i^2 \) values from Matlab and collected \( \sum \Delta \theta_i^2 \) values from PowerFactory and the response of Matlab code.

Table 1: Results of 4-bus simulation

<table>
<thead>
<tr>
<th>Fault</th>
<th>From bus</th>
<th>To bus</th>
<th>MATLAB</th>
<th>POWER FACTORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td></td>
<td>0.00731</td>
<td>0.0069</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td></td>
<td>0.00054</td>
<td>0.0006</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td></td>
<td>0.01067</td>
<td>0.0106</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td></td>
<td>0.00004</td>
<td>0.0001</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td></td>
<td>0.00087</td>
<td>0.0009</td>
</tr>
</tbody>
</table>

The results obtained using both the power factory and MATLAB for a 4-bus system were tabulated as shown in Table 1. The square of the phasor angle was observed to be nearly similar with small deviations of
for a fault from bus 1 to bus 2

5.1.2 PMU location selection

Phasor measurement units location selection [12] could be implemented for application such as line outage detection. It helps to lower the cost especially for wide area transmission network.

Tables 2, 3, and 4 illustrate the results when some of the phasor measurement units are eliminated from some selected buses. Tables 2, 3, and 4 show the effect of removing phasor measurement units from buses 2, 3, and 4 respectively. Also, these tables show that the results are still reliable after removing phasor measurement units from selected buses of the network.

<table>
<thead>
<tr>
<th>Fault</th>
<th>From Bus</th>
<th>To Bus</th>
<th>MATLAB</th>
<th>POWER FACTORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>0.00224</td>
<td>0.0020</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>0.00039</td>
<td>0.0005</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>0.00989</td>
<td>0.0097</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.00002</td>
<td>0.0000</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>0.00065</td>
<td>0.0005</td>
<td></td>
</tr>
</tbody>
</table>
### Table 3 PMU at bus 3 eliminated

<table>
<thead>
<tr>
<th>Fault</th>
<th>From Bus</th>
<th>To Bus</th>
<th>MATLAB</th>
<th>POWER FACTORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>0.00529</td>
<td>0.0053</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>0.00019</td>
<td>0.0002</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>0.00893</td>
<td>0.0090</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.00003</td>
<td>0.0001</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>0.00038</td>
<td>0.0005</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4 PMU at bus 4 eliminated

<table>
<thead>
<tr>
<th>Fault</th>
<th>From Bus</th>
<th>To Bus</th>
<th>MATLAB</th>
<th>POWER FACTORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>0.00709</td>
<td>0.0065</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>0.00051</td>
<td>0.0005</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>0.00251</td>
<td>0.0025</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.00004</td>
<td>0.0001</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>0.00007</td>
<td>0.0008</td>
<td></td>
</tr>
</tbody>
</table>
5.2 6-bus system

This 6-bus system was used as a start to make sure that Matlab code performs as desired.

Consider a 6-bus system as shown if Figure 6. The line parameters are chosen as:

- \( Z_{12} = j0.2 \text{ p.u} \)
- \( Z_{23} = j0.1 \text{ p.u} \)
- \( Z_{34} = j0.2 \text{ p.u} \)
- \( Z_{45} = j0.2 \text{ p.u} \)
- \( Z_{56} = j0.1 \text{ p.u} \)
- \( Z_{16} = j0.3 \text{ p.u} \)

Power values were given as:

- \( P_2 \) and \( V_2 \) as 2.0 p.u and 1.05 p.u respectively,
- \( V_1 = 1.0 \) p.u,
- \( \text{Ang1} = 0 \) p.u,
- \( P_3 \) and \( Q_3 \) as 0.5 p.u and 0.2 p.u respectively,
- \( P_4 \) and \( Q_4 \) as 0.4 p.u and 0.1 p.u respectively
- \( P_5 \) and \( Q_5 \) as 0.2 p.u and 0.0 p.u respectively
- \( P_6 \) and \( Q_6 \) as 0.25 p.u and 0.1 p.u respectively

Running the simulation with a base KV of 30 and base MVA 100, the result was as obtained in Table 5.
The results obtained from MATLAB illustrating phase angle difference after the fault was tabulated in Table 5.

Table 5: MATLAB phase angle results

<table>
<thead>
<tr>
<th>from bus</th>
<th>to bus</th>
<th>phasor angle difference between buses</th>
<th>MATLAB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td></td>
<td>0.0855</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td></td>
<td>0.0232</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td></td>
<td>0.103</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td></td>
<td>0.00632</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td></td>
<td>0.0295</td>
</tr>
</tbody>
</table>
Chapter Six

6. Conclusion and Future Research

6.1 Conclusion

Given the increased complexity of the modern power systems, the need to improve the monitoring capabilities is greatly emphasized. This is in order to improve the performance and quickly carry out corrections on the system in the event of a fault. This has been made possible by the constant nature of the electrical power, that is, its characteristics do not change greatly with time. This nature has also made it possible to operate the systems with a minimal closed loop control. But given the nature and complexity of the networks, a constant check needs to be carried out using a closed loop control system to avoid major catastrophes such as national blackouts. The systems are automated to improve the monitoring capabilities.

6.2 Review of the project’s objectives

The main objective of the project was achieved as it was able to detect fault using PMU and provided a comprehensive analysis of the power system. The analysis was done using PowerFactory and Matlab software. The result obtained from both software tools was similar with small or negligible deviations. These deviations could have been caused by the parametric model of the buses and the impedances in the PowerFactory software. The specific objectives were as well achieved as each step involved in the construction of the project model was achieved. The result of this project obtained from Matlab were analyzed and discussed with some information borrowed from background information which also provided a backdrop on which this project is based has been discussed. The project timeline represented by the Gantt chart gave direction towards achieving success of the project and
was useful as well in breaking each activity and allocating a specific time to project segment. This implemented project is open to suggestions and recommendations on areas for future improvement.

6.3 Areas of future development

Complete automation of power system has not been fully achieved and may take a while to achieve given the increasing complexity of the power system networks. This may also not be fully supported given that the control would be subjected to interference from noise and the control system may end up causing the disaster instead of a line outage. The human factor will still need to be considered when making some of the decision and not left entirely to a machine. A large-scale black out would have big repercussions, mostly economical and the monitoring systems being put in place are specifically to prevent such from happening. A single line outage can have a cascading effect and lead to a wide area blackout. In order to handle this, research on how to increase the number of PMUs in a network without creating redundancy in some of the buses is ongoing. Also, as mentioned in chapter two, an increased number of PMUs in a network causes delayed time in computation. A look into how to carry out faster computations and iterations is being carried out. Given the high speed microprocessors being developed, fast computations will be possible and the number of PMUs will be increased in the power systems and consequently, this will increase the efficiency of the monitoring capabilities.
Bibliography


This article highlights a well detailed background, basics, and issues of DC power flow. Also, it describes in depth DC power flow derivation method. Moreover, this article lists 6 advantages of the DC model. Furthermore, this article includes a section which discusses the accuracy of DC power flow model.


This book discusses DC power flow method in detail. Also, it lists the required steps to linearize an AC power flow equations which creates an approximated version of the system.


This reference highlights a brief description of the following aspects: power flow analysis, approximate solutions of power problem, DC Power Flow model. This book gives hints on finding an algorithm to detect and locate a fault in a network. However, this project does not rely on this reference because it does not discuss the mentioned aspects in depth.
J. E. Tate, and T. J. Over by. “Line outage detection using phasor angle measurements,” 


These two articles illustrate alternative methods to solve line outage using phasor angle measurements. Besides, the articles help to ease the understanding of the problem, and enrich the reader with several valid sources and related to the topic.
6.4 References


[16] M. Variants, “SYNC 4000 SERIES PHASOR DATA CONCENTRATOR.”


[24] Dinesh K. and Karthik R. Phasor Measurement Unit or Synchrophasors University at Buffalo
## 7. Appendix

### 7.1 Timeline

**Table 6: Timeline**

<table>
<thead>
<tr>
<th>ACTIVITY</th>
<th>STARTING WEEK</th>
<th>DURATION IN WEEKS</th>
<th>WEEK NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16</td>
</tr>
<tr>
<td>Project Identification</td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Aims &amp; Objectives formulation</td>
<td>2</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Project Research &amp; Analysis</td>
<td>4</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Weekly Meeting &amp; Reading</td>
<td>1</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Proposal Submission</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Project Building (MATLAB coding)</td>
<td>6</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Project Testing</td>
<td>8</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Project Presentation</td>
<td>14</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Writing Project Report</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Report Submission</td>
<td>16</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
7.2 MATLAB code for 4-bus system

clc
clear all
% defining system inputs
% operator should insert the system parameters here
y(1)=5;
y(2)=2.5;
y(3)=10;
y(4)=10;
y(5)=5;
r(1)=0.2;
r(2)=0.4;
r(3)=0.1;
r(4)=0.1;
r(5)=0.2;
FB(1)=1;
FB(2)=1;
FB(3)=1;
FB(4)=2;
FB(5)=4;
TB(1)=2;
TB(2)=3;
TB(3)=4;
TB(4)=3;
TB(5)=3;
P=[1.1;-0.5;-0.4;-0.2];

nLine=5;
for i=1:nLine
r_inf(i)=r(i);
y_inf(i)=y(i);
end
for i=1:nLine
if i >= 2
    r_inf(i-1)=r(i-1);
end
r_inf(i)=inf;
for j=1:5
    y_inf(j)=1./r_inf(j);
end
Y_fault(i,1:nLine)=y_inf;
r_fault(i,:)=r_inf;
end
Y_fault=Y_fault';
r_fault=r_fault';
% this section creates the admittance matrix (Y bus)
nbus = max(max(FB),max(TB)); % number of buses
Y = zeros(nbus,nbus); % Initialise YBus
X = Y;
YY= Y;
A_fault =zeros(nbus,nbus);
for k=1:nLine
    Y(FB(k),TB(k)) = Y(FB(k),TB(k)) - y(k);
    Y(TB(k),FB(k)) = Y(FB(k),TB(k));
    for i=1:nLine
        A_fault(FB(i),TB(i)) = A_fault(FB(i),TB(i)) - Y_fault(i,k);
    end
    if k==1
        a=A_fault;
    elseif k==2
        b=A_fault;
    elseif k==3
c=A_fault;
elseif k==4
    d=A_fault;
elseif k==5
    e=A_fault;
end
A_fault =zeros(nbus,nbus);
end
% Diagonal Elements
for k=1:nLine
    if k==1
        X=a;
    elseif k==2
        X=b;
    elseif k==3
        X=c;
    elseif k==4
        X=d;
    elseif k==5
        X=e;
    end
    for m =1:nbus
        for n =1:nLine
            if FB(n) == m
                X(m,m) = X(m,m) + Y_fault(n,k) ;
            if k == 1
                Y(m,m) = Y(m,m) + y(n) ;
            end
            elseif TB(n) == m
                X(m,m) = X(m,m) + Y_fault(n,k) ;
            if k == 1
                Y(m,m) = Y(m,m) + y(n) ;
            end
        end
    end
end

end
end
end
end
end
if k==1
    a=X;
elseif k==2
    b=X;
elseif k==3
    c=X;
elseif k==4
    d=X;
elseif k==5
    e=X;
end
X=YY;
end
Y_new=Y([2:1:nLine-1],[2:1:nLine-1]);
P_new=P([2:1:nLine-1],1);
a_new=a([2:1:nLine-1],[2:1:nLine-1]);
b_new=b([2:1:nLine-1],[2:1:nLine-1]);
c_new=c([2:1:nLine-1],[2:1:nLine-1]);
d_new=d([2:1:nLine-1],[2:1:nLine-1]);
e_new=e([2:1:nLine-1],[2:1:nLine-1]);
phase_norm_op=inv(Y_new)*P_new*57.29577;
phase_a=inv(a_new)*P_new*57.29577;
phase_b=inv(b_new)*P_new*57.29577;
phase_c=inv(c_new)*P_new*57.29577;
phase_d=inv(d_new)*P_new*57.29577;
phase_e=inv(e_new)*P_new*57.29577;
a_delta=phase_a-phase_norm_op;
b_delta=phase_b-phase_norm_op;
c_delta=phase_c-phase_norm_op;
d_delta=phase_d-phase_norm_op;
e_delta=phase_e-phase_norm_op;
a_delta_squared=a_delta.^2;
b_delta_squared=b_delta.^2;
c_delta_squared=c_delta.^2;
d_delta_squared=d_delta.^2;
e_delta_squared=e_delta.^2;
a_sum = sum(a_delta_squared)*(10^-4);
b_sum = sum(b_delta_squared)*(10^-4);
c_sum = sum(c_delta_squared)*(10^-4);
d_sum = sum(d_delta_squared)*(10^-4);
e_sum = sum(e_delta_squared)*(10^-4);

% This function waits for an operator to insert a value then
% compare it with all the possible values that MATLAB has
% already created for every possible fault in the system.

Array=[a_sum; b_sum; c_sum; d_sum; e_sum];
numinput = input('n INSERT the value of the sum of phasor
angle n difference squared at each bus from POWER FACTORY n
');
[m, n] = size(Array);
Error = zeros(m,n);
MinimumErrors = [];
MinimumLocation = [];
for ii = 1:n
    for jj = 1:m
        Error(jj,ii) = abs(numinput - Array(jj,ii));
    end
end
for ii = 1:n
position = find(Error(:,ii) == min(Error(:,ii)));  
MinimumErrors = [MinimumErrors; Error(position,ii)];  
MinimumLocation = [MinimumLocation; position, ii];  
end  
finalposition = find(MinimumErrors == min(MinimumErrors));  
position = MinimumLocation(finalposition,1);  
y = MinimumLocation(finalposition,2);  
selection = Array(position, y);  
fprintf('

The the fault occurs at line from bus %d to bus %d',FB(position),TB(position));
7.3 MATLAB code for 6-bus system

\[
\begin{align*}
zdata &= \begin{bmatrix} 1 & 2 & 0 & 0.2; \\
2 & 3 & 0 & 0.1; \\
3 & 4 & 0 & 0.2; \\
4 & 5 & 0 & 0.2; \\
5 & 6 & 0 & 0.1; \\
1 & 6 & 0 & 0.3; \end{bmatrix}; \\
\end{align*}
\]

\[
\begin{align*}
j &= \sqrt{-1}; \\
\nl &= \text{zdata(:,1)}; \quad \text{% starting bus of the element} \\
\nr &= \text{zdata(:,2)}; \quad \text{% end of bus} \\
R &= \text{zdata(:,3)}; \quad \text{% resistance of the network} \\
X &= \text{zdata(:,4)}; \quad \text{% reactance of the network} \\
nbr &= \text{length(zdata(:,1))}; \quad \text{% length of vector} \\
nbus &= \text{max(max(nl),max(nr))}; \quad \text{% largest element in array} \\
Z &= R + j \times X; \quad \text{% branch impedance column vector} \\
y &= \text{ones(nbr,1)}/Z; \quad \text{% branch admittance vector} \\
Y &= \text{zeros(nbus,nbus)}; \quad \text{% initialize Y to zeros} \\
\text{for} k = 1:\text{nbr}; \quad \text{% formation of the diagonal matrix} \\
\text{if} nl(k) > 0 \quad \text{and} \quad nr(k) > 0 \\
Y(nl(k),nr(k)) &= Y(nl(k),nr(k)) - y(k); \\
Y(nr(k),nl(k)) &= Y(nl(k),nr(k)); \quad \text{% Y-bus Matrix is symmetrical} \\
\end{align*}
\]
for n=1:nbus %formation of the diagonal matrix
for k=1:nbr
    if nl(k)==n || nr(k)==n
        Y(n,n)=Y(n,n)+y(k);
    else
    end
end
end

kv=input('Enter the base KV: '); %prompt the user to enter base KV
mva=input('Enter the base MVA: '); %prompt the user to enter the base MVA
bc=(mva*1000)/(sqrt(3)*kv); %calculate base current of the power system network
Zbus=inv(Y); %obtaining the impedance matrix
disp('Bus impedance matrix: ');
disp(Zbus);

fbn=input('Enter the fault bus number: ') %prompt the user to enter the fault bus number
Zf=input('Enter the fault impedance Z=R+j*R: ') %prompt user to enter the fault impedance
V0=ones(nbus,1)+j*zeros(nbus,1);
If=V0(fbn)/(Zf+Zbus(fbn,fbn));
Ifmag=angle(If)*180/pi;
fprintf('Phasor angle =%8.4f per unit 
\n', Ifmag) %printing phasor angle
for n=1:nbus
    if n==fbn;
        Vf(fbn)=V0(fbn)*Zf/(Zf+Zbus(fbn,fbn));
        Vfm=abs(Vf(fbn));
        angv=angle(Vf(fbn))*180/pi;
    else
        Vf(n)=V0(n)-V0(n)*Zbus(n,fbn)/(Zf+Zbus(fbn,fbn));
        Vfm=abs(Vf(n));
        angv=angle(Vf(n))*180/pi;
    end
    fprintf('   %4g', n), fprintf('%13.4f
', Vfm),
    fprintf('%13.4f\n', angv)
end