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Phasor Measurement based Out-Of-Step Detection

Master of Science Thesis in the Master Degree Program, Electrical Engineering

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Abstract

This thesis deals with Out-Of-Step conditions in a network, how to detect the events and how to make improvements on the protection devices that are being used today.

Power systems and stability analysis are studied in general and Out-Of-Step conditions are reviewed in detail. Experiments with a one machine against an infinite bus are performed to connect theory with reality. The laboratory model is exposed to transient faults in the range 100 ms to 800 ms. A PMU is used to measure voltages and currents at the generator bus and at the infinite bus.
The thesis includes the development of an algorithm that can detect power swings. The algorithm is programmed in MATLAB. This algorithm detects faults in the system and predicts loss of synchronism. The data collected with the PMU from the laboratory measurements are run in the program to be able to determine the capability of the algorithm.

The thesis also includes design and assembly of two voltage transformers. The voltage transformers are needed to be able to connect the PMU to the laboratory model. The voltage transformers are rated 400:110 V, 45 VA.

Sammanfattning

Detta examensarbete behandlar urfasfall i kraftnät. Samt hur urfasfall bäst kan förutses och detekteras. Dessutom diskuteras förbättringar som kan göras på reläskyddssystem som används i dagsläget.

På grund av den ökade efterfrågan på elektricitet, har kraftöverföringen kommit närmare överföringsgränserna. Om ett fel eller ett avbrott inträffar finns det stor risk för att systemet kan förlora sin synkronism. Eftersom överföringen har ökat ställs det högre krav på detekteringen av effektpendling och skydd för urfasfall.
Fram tills idag har det huvudsakliga skyddet för effektpendling varit distansreläer. Med hjälp av forskning och utveckling har nya skyddsanordningar tagits fram för att detektera urfasfall däribland fasmätenheter, PMUer. Detta examensarbete kommer att lägga fokus på funktionsduglighet hos PMUer.

I detta examensarbete studeras kraftsystem generellt och ett system med en synkronmaskin mot ett starkt nät studeras mer ingående med hjälp av en laborationsmodell. Avbrott från 100 ms upp till 800 ms genereras på modellen och en PMU är kopplad till laborationsmodellen där den mäter ström och spänning. Mätdata läses in till en algoritm som är programmerad i MATLAB. Algoritmen kan detektera fel i systemet och dessutom förutse om felen kommer leda till förlorad synkronism.

Examensarbetet omfattar även design och montering av två spänningstransformatorer. Transformatorerna behövs för att kunna koppla ihop PMU:n med laborationsuppsättningen. Transformatorerna har omsättningen 400:110 V och märkeffekten 45 VA.

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List of Main Abbreviations

DC	Direct Current
HVDC	High Voltage Direct Current
PMU	Phasor Measurement Unit
GPS	Global Positioning System
CT	Current transformer
VT	Voltage transformer
PSS/E	Power System Simulator for Engineering

1 Introduction

In the 18th century great scientists like Benjamin Franklin, Michael Faraday, André-Marie Ampère among others provided the basis for modern electrical technology. Since the 18th century and until today the demand for electricity has increased very much. The power systems of today are transmitting power up to their limits, and have become more sensitive to disturbances.

1.1 Definition of the Problem

If and when a disturbance occurs in a network it is important to discover the changes as fast as possible and to take accurate actions against it. Modern power systems use distance relays with power swing detection to detect Out-Of-Step conditions. Pre-set tripping relays island different parts of the network to get rid of the oscillations and to keep important sources running without disturbances.

Instead of using distance relays to detect Out-Of-Step events new measurement systems are available where it is possible to measure phase angles in the whole power system with the same time and angle reference. The main device in such a system is called a phasor measurement unit, PMU. Studies have been done with the PMU to measure voltages and currents in power systems. This master thesis work goes one step further in the direction of making the PMU a usable device in the power system network to detect power swing oscillations and prevent Out-Of-Step conditions.

1.1 Aim of the Thesis

The aim of this thesis is to study power oscillations with a laboratory model comprising a strong network, a transmission line, and a generator. With the results from the laboratory measurements an algorithm that can detect power swings is developed.

1.2 Main Contribution of the Thesis

The main contribution of this thesis is an algorithm that works and easily can be developed further in future works. The results of this thesis work are also a good basis for further research in the subject.

1.3 Thesis Layout

Chapter 2 describes the fundamentals of the power systems. The chapter starts with describing the power system and then moves on to a stability analysis. Further on is a description of how to protect the system against power swings.

Chapter 3 is the main chapter of the thesis, the laboratory measurement of the model is presented, and the theoretical calculations of critical fault clearing time of the model and the Out-Of-Step algorithm are described.

Chapter 4 contains a discussion of the results in this thesis work.

Chapter 5 contains the conclusions drawn from the results of this thesis work.

Chapter 6 exemplifies possible future work on the subject of PMUs and Out-Of-Step detection.

2 Power System Fundamentals

The transmission networks that exist today are very complex. There are many different components; generators, transformers, transmission lines, substations, circuit-breakers that together build transmission systems that can supply a house, a factory, the city of Göteborg, a country, a whole continent with electricity. With today's technology, we can even transmit power overseas with HVDC cables.

2.1 Transmission and Distribution Systems

To be able to transmit energy, there must be sources that generate electric energy. There is a variety of electric power generators; nuclear power plants, coal-fired power plants, gas turbine stations, hydroelectric stations, etc. Sources generate electric energy at low voltage levels. To be able to transmit the power without a great deal of losses, a transformer transforms the generated power to a higher voltage level to reduce the current level. The power is transmitted in overhead lines or cables throughout the whole country at a voltage level of 400-800 kV, the power arrive at substations, transformers decrease the voltage level again and then power can be distributed to customers at a desired level and amount.

2.2 Faults

If a fault occurs in the transmission or distribution network it can cause severe problems for the customers, patients at a hospital may not survive without electrical equipment and industry can lose a lot of money when the electricity is down.

The transmission system is a dynamic system i.e. there are always load variations that are controlled by generation adjustments. A sudden large load variation is an abnormal event in the dynamic system. The large load variations and faults arise from: lightning and overloading, loss of a line or generating unit, or failure in a piece of equipment.[1] The faults can be divided into four different categories; three-phase fault, fault between two phases with or without ground included and the most common fault is a flashover from one phase to ground[2].

2.3 Power System Stability

In a stable power system, if a generator is lost the rest of the generators must be capable of meeting the load demand or if a transmission line is lost, the rest of the transmission lines must be able to carry that extra power from the lost line in a meshed system. During a fault period, growing oscillations over the transmission lines or loss of synchronism can

[1] Power system control and stability
[2] Nordel Statistics

occur. These events must be taken care of to prevent large failures. Figure 2-1 shows a schematic classification of power system stability[3].

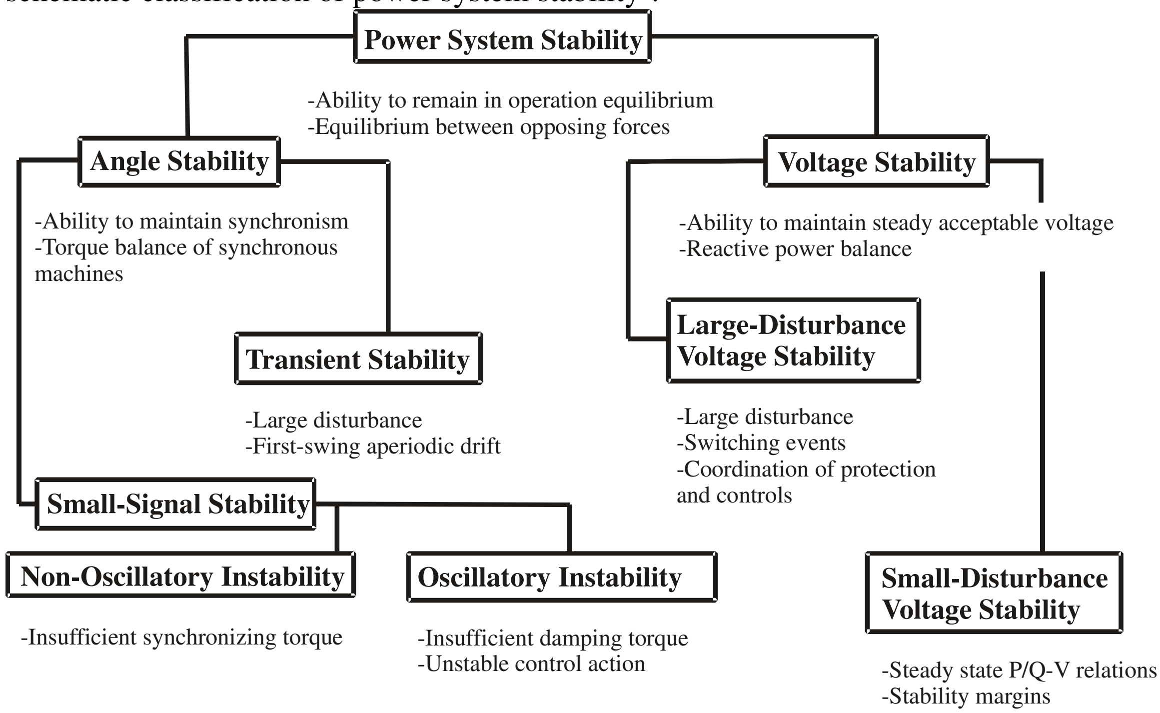


Figure 2-1: Schematic classification of power system stability

2.3.1 Out-Of-Step Condition

An Out-Of-Step condition in a network occurs when a generator or a group of generators lose synchronism with the rest of the network.
The event forces generators to shut down and sometimes large parts of the network are forced out of service. Before losing synchronism the network normally experiences power oscillations between neighboring generator groups. The oscillations cause voltage and current variations throughout the power system and there will be a variation in power flow between two areas, this phenomenon is called a power swing[4].
The simplest network to study power oscillations is a one machine against an infinite bus, shown in Figure 2-2.

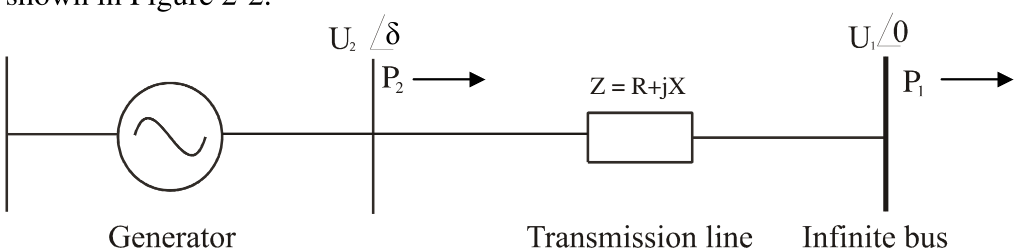


Figure 2-2: One machine against infinite bus diagram

[3] Power system stability and control
[4] Out of Step Relaying Using Phasor Measurement Unit and Equal Area Criterion

The infinite bus symbolizes a strong network. A change in the impedance between the two buses will affect the rotor angle, speed and acceleration of the generator. This will be explained in detail in the following sections.

2.3.2 Visualization of an Oscillation in a Power System

The generator in Figure 2-2 is in stable operation at a phase angle of δ compared to the infinite bus, i.e. the voltage at the generator bus U_2 is leading the voltage at the infinite bus U_1 by an angle δ. The mechanical power input, P_m, and the electrical power output, P_e, drawn in Figure 2-3 describe the power balance of the generator. The curves intersect at two points, the stable equilibrium point and the unstable equilibrium point.

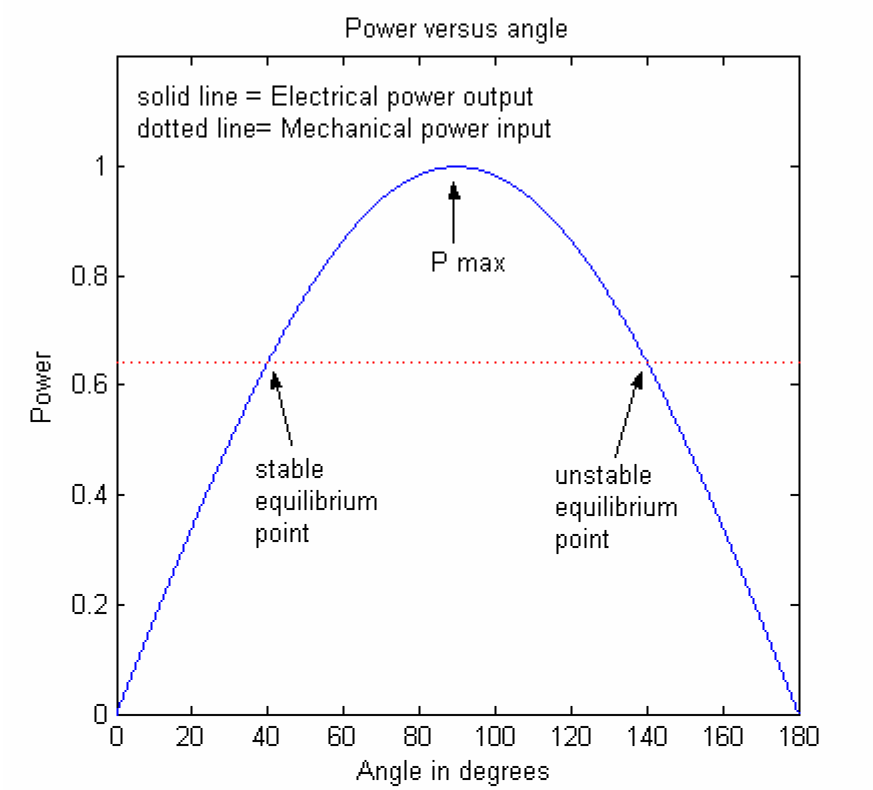


Figure 2-3: Input (dashed) and output (solid) power of a turbine-generator

The stable equilibrium point is the only operation point for a steady-state condition. The angle for the stable point is referred to as δ_0. The angle δ_0 also describes the rotor angle of the generator. If δ_0 increases to 90˚, the maximum input and output power is reached. Beyond this point, moving to the right in Figure 2-3, an unstable system close to lose synchronism is achieved. In a secure system it is good to have a margin between the stable equilibrium operation point and the maximum electrical power output.

In Figure 2-4 the changes of angle and power transfer between the generator and the infinite bus, before, during and after a fault, are plotted.

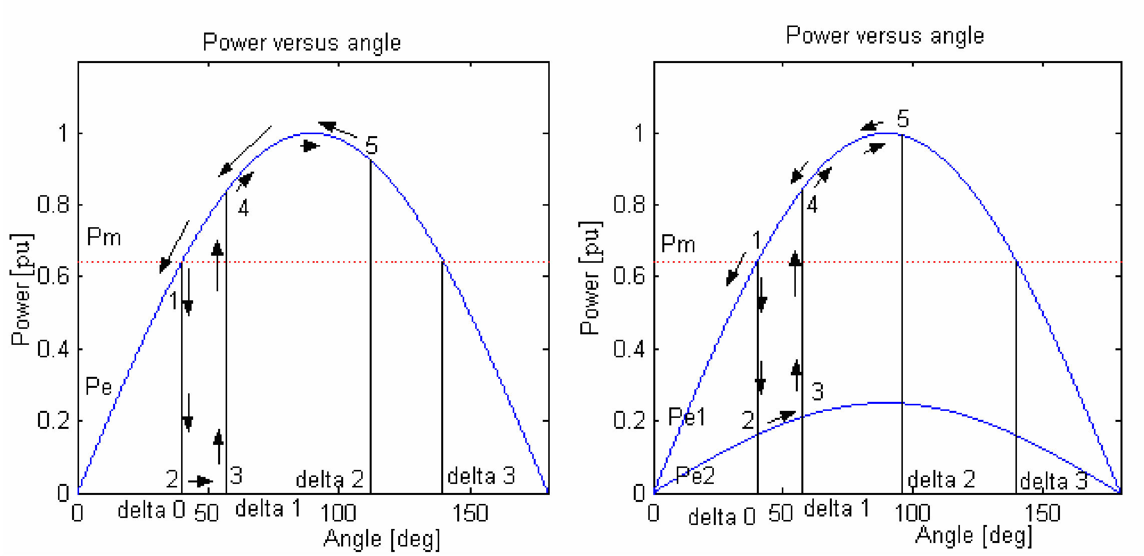


Figure 2-4: Power transfer before, during and after a fault close to the turbine-generator
Left diagram: Electric power output decrease to zero during fault.
Right diagram: Electric power output decrease to P_{e2} during fault.

A step-by-step analysis of a fault on the one machine against infinite bus in Figure 2-2 is described below[5].

1. Before the fault, at steady-state condition, the system operates at the stable equilibrium point at angle δ_0 in Figure 2-4.
2. When a fault occurs, the electrical power output gets an instantaneous decrease and becomes much smaller than the mechanical power due to the change in the impedance of the system. The mechanical part of a turbine-generator does not instantaneously experience that a fault occurred. Depending on what type of fault and the design of the system, the electrical power will become zero or decrease to a different electrical power output curve, compare left and right curves in Figure 2-4.
3. During the fault the angle δ will increase from δ_0 to δ_1. The rotor angle is gaining velocity and starts to accelerate in the right direction during the fault. When the fault is cleared, at point 3, the impedance between the machine and infinite bus will change again. The change leads to an increased level of the electrical power output.
4. If it is assumed that the system goes back to its pre-fault conditions the electrical output power will jump from point 3 to point 4. The angle δ_1 will remain the same. During the time when the electrical power output was lower than the mechanical power input the generator gained energy.
5. The energy gained has to be transferred into the system, before a stable equilibrium point can be reached again. Therefore the rotor angle is still increasing, but it has started to decelerate. Point 5 is reached when all the power gained during the fault is transferred into the system, the turbine-generator will

[5] Voltage Control and Short Circuits in Power Systems

now move to the left in Figure 2-4 with the goal to find a new stable equilibrium point.

The critical point in this scheme is how much the angle increases during the fault, i.e. how long the fault clearing time is. If point 5 is beyond the unstable equilibrium point at angle δ_3 the generator will continue to accelerate and lose synchronism and the phenomenon of Out-Of-Step condition is reached.

2.4 Stability Analysis

To be able to understand and build proper protection devices to prevent this type of events in the network, a number of equations are needed.

2.4.1 Power Transfer Equation

In Figure 2-2 the voltage U_2 leads the voltage U_1 by an angle δ. The voltage at the infinite bus is the reference voltage. The voltages are represented in complex form:

$$\overline{U}_1 = U_1 \tag{2-1}$$

$$\overline{U}_2 = U_2 \cos\delta + jU_2 \sin\delta \tag{2-2}$$

The real part of the apparent power is the active power transported over the line.
In a real network there are always losses due to; heat, corona, etc. The following equations describe the active power flow over the line. The derivation of equation 2-3 and 2-4 are explained in Appendix A.

$$P_1 = -\frac{|U_1|^2}{|Z|} * \sin(\varepsilon) + \frac{|U_1||U_2|}{|Z|}\sin(\delta+\varepsilon) \tag{2-3}$$

$$P_2 = \frac{|U_2|^2}{|Z|} * \sin(\varepsilon) + \frac{|U_1||U_2|}{|Z|}\sin(\delta-\varepsilon) \tag{2-4}$$

P_1= Active power flowing into the infinite bus
P_2= Active power flowing into the transmission line from the generator

The angle ε is the loss angle, in mathematical terms it is expressed as:

$$\varepsilon = \frac{\pi}{2} - \arctan\frac{X}{R} \tag{2-5}$$

X = Imaginary part of the line impedance, the reactance [Ω]
R = Real part of the line impedance, the resistance [Ω]

It is possible to simplify the calculations by considering a lossless line, the loss angle is then equal to zero and Equation 2-3 and 2-4 becomes identical:

$$P = \frac{|U_1||U_2|\sin\delta}{X} \qquad \textbf{2-6}$$

The impedance in Equation 2-6 is reduced to the reactance of the line because the resistance is often small and gives little contribution to the solution.
The maximum amount of power that can be transferred over the line, P_{max}, is achieved when sin δ = 1, i.e. δ = 90°.

2.4.2 Power Swing Equation

If an unbalance between the mechanical and electrical power exists, there will be a change in rotational energy, a relationship between the rotor angle and the acceleration power is expressed as:

$$J\omega_m \frac{d\omega_m}{dt} = P_m - P_e \qquad \textbf{2-7}$$

J = Moment of inertia of the turbine-generator [kgm²]
ω_m = Angular velocity of the rotor, mechanical [rad/s]

Since $\omega_m \approx \omega_{0m}$ during the power swing Equation 2-7 is often replaced with:

$$J\omega_{0m} \frac{d\omega_m}{dt} = P_m - P_e \qquad \textbf{2-8}$$

ω_{0m} = Nominal angular velocity of rotor, mechanical [rad/s]

The combined moment of inertia can be normalized with the inertia constant, H, expressed in per unit values as:

$$H = \frac{\frac{1}{2} J\omega_{0m}^2}{S_b} \qquad \textbf{2-9}$$

S_b = Generator apparent power [VA]
H = Inertia constant [s]

If the moment of inertia in Equation 2-8 is replaced with the inertia constant H Equation 2-10 is achieved:

$$\frac{2HS_b\omega_{om}}{\omega_{0m}^2}\frac{d\omega_m}{dt} = P_m - P_e \Leftrightarrow 2H\frac{d}{dt}\left(\frac{\omega_m}{\omega_{0m}}\right) = \frac{(P_m - P_e)}{S_b} \qquad \textbf{2-10}$$

It is more useful, when doing theoretical calculation, to express the rotor angle in electrical degrees instead of mechanical degrees. The power swing equation should therefore be expressed using δ as the rotor angle in electrical degrees.

Equation 2-11 and 2-12 defines the relationship between electrical and mechanical degrees and the relationship between angle and angle velocity.

$$\begin{aligned} \omega_m * p &= \omega_e \\ \omega_{0m} * p &= \omega_{0e} \end{aligned} \qquad \textbf{2-11}$$

p = Number of pole pairs in the generator
ω_e = Angular velocity of the rotor, electrical [rad/s]
ω_{0e} = Nominal angular velocity of the rotor, electrical [rad/s]

The angular velocity of the rotor, in electrical rad/s is the derivative of the rotor angle over time:

$$\omega_e = \frac{d\delta}{dt} \qquad \textbf{2-12}$$

A rearrangement of Equation 2-10 with electrical degrees results in:

$$\begin{aligned} &2H\frac{d}{dt}\left(\frac{\omega_m}{\omega_{0m}}\right) = \frac{(P_m - P_e)}{S_b} \Leftrightarrow \\ &2H\frac{d}{dt}\left(\frac{\omega_m * p}{\omega_{0m} * p}\right) = 2H\frac{d}{dt}\frac{\omega_e}{\omega_{0e}} = \frac{2H}{\omega_{0e}}\frac{d^2\delta}{dt^2} = \frac{(P_m - P_e)}{S_b} \end{aligned} \qquad \textbf{2-13}$$

The final expression for the power swing equation is normally expressed in per unit value:

$$P_{p.u.} = \frac{P}{S_b} \qquad \textbf{2-14}$$

P = Power [W]
$P_{p.u.}$= Per unit power [pu]

A rearrangement of Equation 2-13 with power expressed in per unit and rotor angle expressed in electrical radians:

$$\frac{2H}{\omega_{0e}}\frac{d^2\delta}{dt^2} = P_m - P_{\max}\sin\delta \qquad \textbf{2-15}$$

P_{max}= The maximum electric power output [pu]

Equation 2-15 is then multiplied with 2dδ/dt:

$$2\frac{d\delta}{dt} * \frac{2H}{\omega_{0e}}\frac{d^2\delta}{dt^2} = 2\frac{d\delta}{dt} * \left(P_m - P_{\max}\sin\delta\right) \qquad \textbf{2-16}$$

If Equation 2-16 is integrated once the final power swing equation that is useful for calculating equal area, rotor angle velocity and rotor angle is given by:

$$\left[\frac{d\delta}{dt}\right]^2 = \int \frac{\omega_{0e}\left(P_m - P_{\max}\sin\delta\right)}{H} d\delta \qquad \textbf{2-17}$$

Equation 2-17 is used to solve for the equal area criterion discussed in the following section.

2.4.3 The Equal-Area Criterion

The equal-area criterion can be used to calculate the maximum fault clearing time before the generator loses synchronism. The equal-area criterion integrates the energy gained when the turbine-generator is accelerating, during the fault (area A, in Figure 2-5) and compares that area with the decelerating area, (area B, in Figure 2-5) when the generator exports the energy stored during the fault.

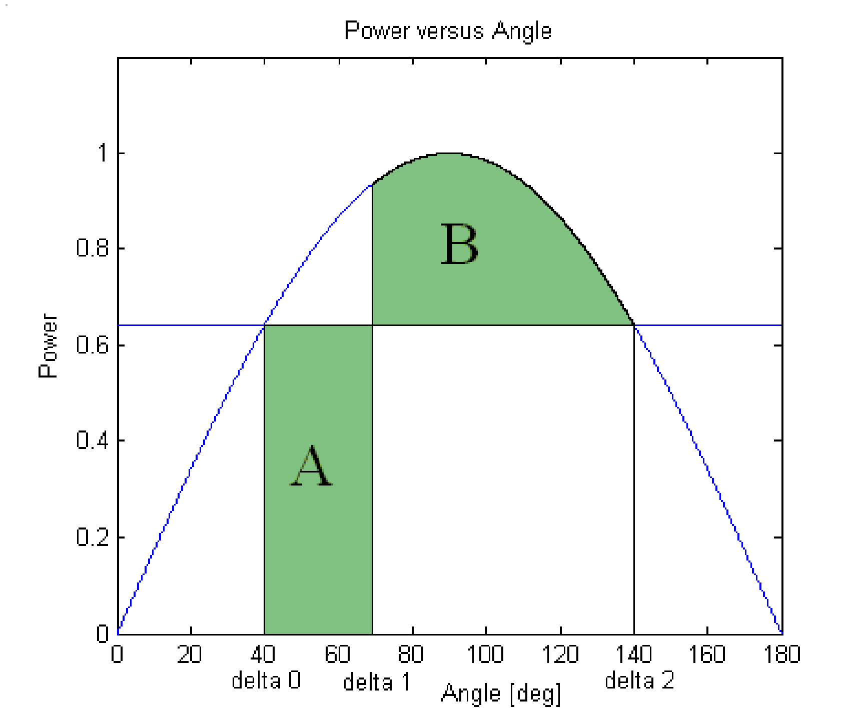


Figure 2-5: Equal-area criterion with an acceleration area A and a decelerating area B

The accelerating and decelerating area at the different generator conditions are calculated by integration of the power swing equation between the boundary angles. In Figure 2-5 the simplest condition is shown, i.e. immediately at the occurrence of a fault the electric power output drops to zero and as soon as the fault is cleared the electric power output returns to its initial curve. Equation 2-18 and 2-19 describes area A and area B.

$$A = \int_{\delta_0}^{\delta_1} \left(P_m - P_{e,fault} \sin\delta\right) d\delta = P_m\left(\delta_1 - \delta_0\right) - P_{e,fault}\left(-\cos\delta_1 + \cos\delta_0\right) \qquad \textbf{2-18}$$

$$\begin{aligned} B &= \int_{\delta_1}^{\delta_2} \left(P_{e,\max} \sin\delta - P_m\right) d\delta = P_{e,\max}\left(-\cos\delta_2 + \cos\delta_1\right) - P_m\left(\delta_2 - \delta_1\right) \\ &= \left\{\delta_2 = \pi - \delta_0\right\} = P_{e,\max}\left(\cos\delta_1 + \cos\delta_0\right) - P_m\left(\pi - \delta_0 - \delta_1\right) \end{aligned} \qquad \textbf{2-19}$$

$P_{e,fault}$ = Electrical power output during the fault period
δ_0 = Angle before fault
$\delta_2 = \pi - \delta_0$ = Maximum angle before losing synchronism

Area A represents the total kinetic energy gained during the acceleration period. As soon as the fault is cleared, at angle δ_1, the angle will continue to increase and the kinetic energy gained during the fault period will expand into the power system. When area B is equal to area A angle δ has reached its maximum value.
Because electric power output is still greater than mechanical power input the generator will continue its retardation but the rotor angle δ will decrease.
The rotor angle oscillates around the stable equilibrium point, the amplitude and the duration of the oscillation depend on how large the rotor angle became before it started to decrease. It is possible to have damping equipment on generators to create faster damping.

Area A and B can be set equal to solve for angle δ_1, shown in Equation 2-20:

$$\begin{aligned}&A = B \Leftrightarrow \\ &\left(P_m(\delta_1 - \delta_0) - P_{e,fault}(\cos\delta_0 - \cos\delta_1)\right) = \\ &\left(P_{e,\max}(\cos\delta_1 + \cos\delta_0) - P_m(\pi - \delta_0 - \delta_1)\right)\end{aligned} \qquad \textbf{2-20}$$

Solving for δ_1 gives:

$$\delta_1 = \arccos\left\{\left(\frac{P_{e,fault} + P_{e,\max}}{P_{e,fault} - P_{e,\max}}\right)\cos(\delta_0) - \left(\frac{P_m}{P_{e,fault} - P_{e,\max}}\right)(\pi - 2\delta_0)\right\} \qquad \textbf{2-21}$$

The maximum time before the fault needs to be cleared at the angle δ_1 is solved with Equation 2-15. The first derivative of δ gives the speed of the rotation and the second derivative gives the acceleration of the rotation. An iterative integration method, like Runge-Kutta or Euler can be used to calculate the clearing time. The theoretical calculation of the fault clearing time in the lab model in Chapter 3 is calculated with Runge-Kutta iteration method; see Appendix B for mathematical formulas.

2.5 Fault Protection

Power system protection is complicated because of the topology of the power system itself. Figure 2-6 shows a small meshed system with relays and circuit breakers.

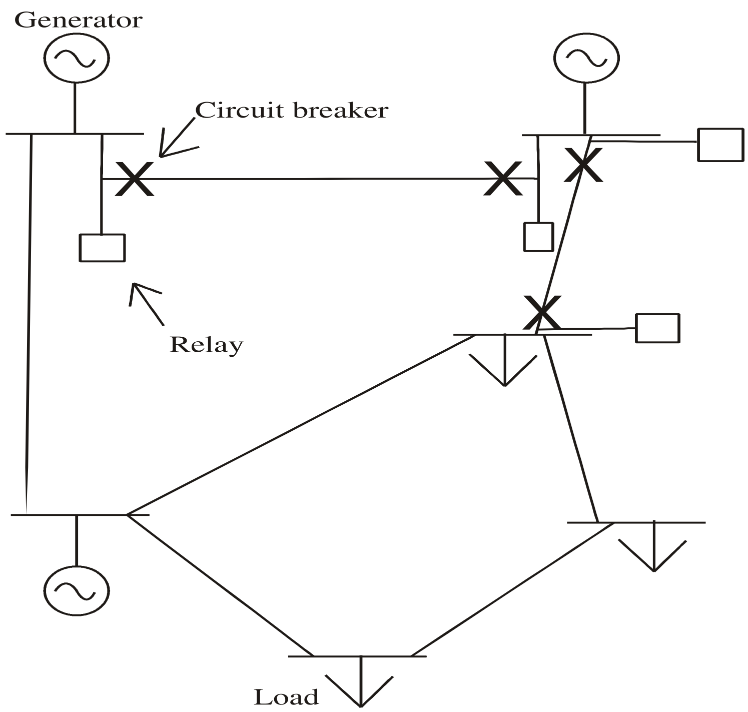


Figure 2-6: Meshed power system

The current can follow many different paths in a meshed system. This complexity of the network leads to very high requirements on the protection devices. The power systems today use different types of Out-Of-Step relays to protect the system from Out-Of-Step events. Different tests with PMUs as a protection device for Out-Of-Step events have been done[6].

2.5.1 Relays

In a meshed transmission network the most common protection device is a distance relay. The distance relay measures voltage and current at one location see Figure 2-6 and the relay is connected to a circuit breaker that will interrupt the current if a fault occurs. The relay has a pre-set threshold value around 80-90 % of the line impedance. When a fault occurs the voltage and current ratios measured by the relay estimates the impedance between the relay and the fault, a trip signal is generated to the circuit breaker when the estimated impedance is less than the threshold impedance.

[6] Adaptive Out-Of-Step relay with phasor measurement

As simple as it may seem there exist complications with relays. The relays today are required to distinguish between normal conditions, short circuits, swings with large amplitudes and Out-Of-Step operation. To be able to clear these events in the right way, different operations, explained in Section 2.6, of the relays are required.

2.5.2 Phasor Measurement Units

A phasor measurement unit, PMU, is a device that can measure voltage and current phasors, i.e. as complex quantities, with a common time reference for all the PMUs in the system. Line parameters such as; resistance, inductance and capacitance can be calculated, even corona and zero sequence parameters can be determined with the PMU.

2.5.2.1 Technical Data

In this thesis work a RES 521*1.0[7] phasor measurement terminal is used. It provides phasors of the AC voltages and currents. The reference for the phase angle is the NavStar Global Positioning System, GPS. The PMU provides a timing accuracy of one micro second between the synchronizing pulses. For a 50 Hz system this corresponds to a phase angle of 0.018 degrees[8].
The PMU can handle four three phase currents and two three phase voltages at the same time. The analog phase to phase voltage input is 110 V and the analog current input is 1 or 5 A.

2.5.2.2 Phasor Measurement Units in Transmission Systems

Studies have been made with implementing PMUs in the transmission network. In Iceland two PMUs have been installed to find out if voltage phase-angles are suitable inputs for damping equipment when islanding different parts of the network[9]. In Sweden (Luleå, Göteborg and Lund) three PMUs are connected to the national grid. The PMUs in Sweden measures phase voltage. During a failure in a transformer outside a nuclear power reactor at Ringhals in Göteborg the voltage curves in Figure 2-7 were recorded.

[7] Technical reference manual
[8] Out-Of-Step protection fundamentals and advancements
[9] Phasor measurements recording in Iceland

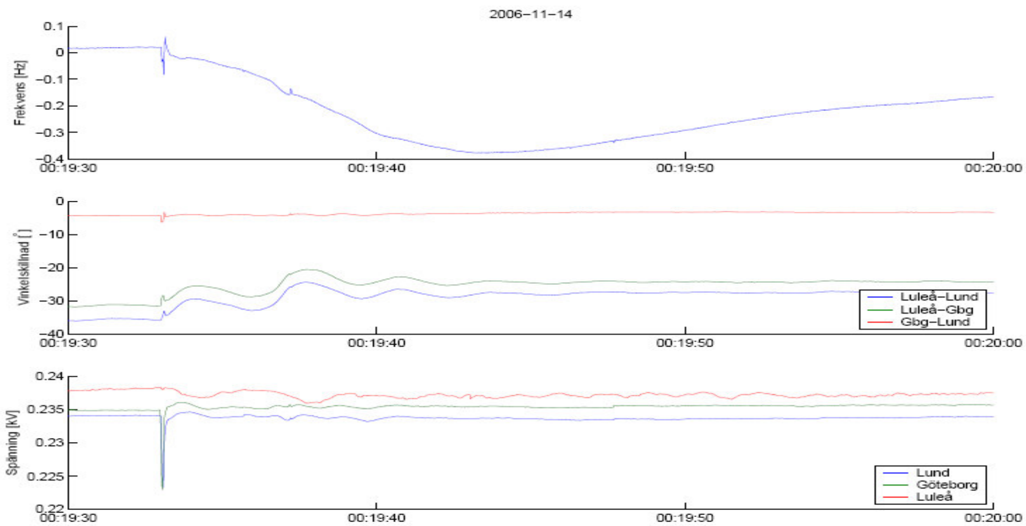


Figure 2-7: Voltage, voltage phase difference and frequency recordings 14th of November 2006

In the recordings above, the PMUs in Lund and Göteborg sensed an inverted voltage impulse when the fault occurred in the transformer. The national grid had a fast recovery and no larger failure happened due to a quick fault clearance.
A larger implementation with six PMUs has been done in USA, in the power system connecting the states of Florida, Georgia and Tennessee. The results have been good, dependable accurate phasor measurements on the power system were obtained and the GPS system was reliable and precise enough for applications in power system engineering[10].

2.6 Out-Of-Step Detection Methods

As mentioned in the beginning of Chapter 2, it is very important to detect any unstable oscillation in a system and to disconnect the unstable machines or generators from the system. In this section existing methods to detect and predict power swings are discussed.

2.6.1 Relay Protection Schemes

A distance relay can be set to protect different zones of a transmission line either in forward direction (mho characteristic) or in both forward and backward direction (Offset mho characteristic). See Figure 2-8 (A) for relay characteristics of a mho and Figure 2-8 (B) for offset mho characteristics.

[10] Synchronized phasor measurements of a power system event

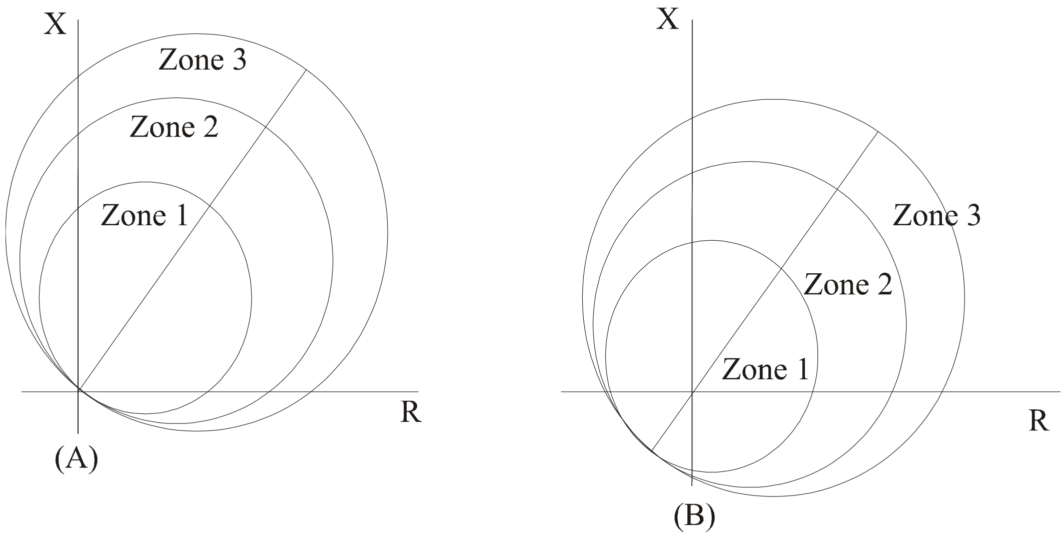


Figure 2-8: Mho and offset mho characteristics

The zone 1 protection for a mho relay should never fall outside of the line to be protected. Normally it is protecting up to 80-90 % of the line. Therefore the remote transmission line end is not protected by zone 1. Zone 2 protects the entire transmission line. Zone 3 is normally a backup protection for an adjacent transmission line that already has a zone 1 protection. The reaches of the zones in a small meshed system can be viewed in Figure 2-9.

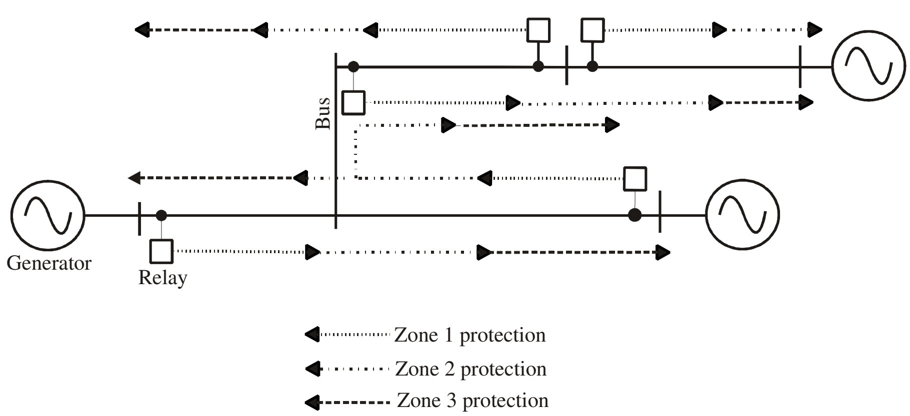


Figure 2-9: Protection zones of a transmission line

Faults are very fast, almost instantaneous, compared to power swings that are more gradual events. This fact is used in the distance relay to distinguish between short circuit faults and stable/unstable power swings.

In Figure 2-10 (A), (B) and (C) traditional impedance-based characteristics to detect power swings are shown, they are called Out-Of-Step blocking and Out-Of-Step tripping schemes[8]. The longitude line crossing over X-axis with R = 0 indicates the total reactance between two generators.

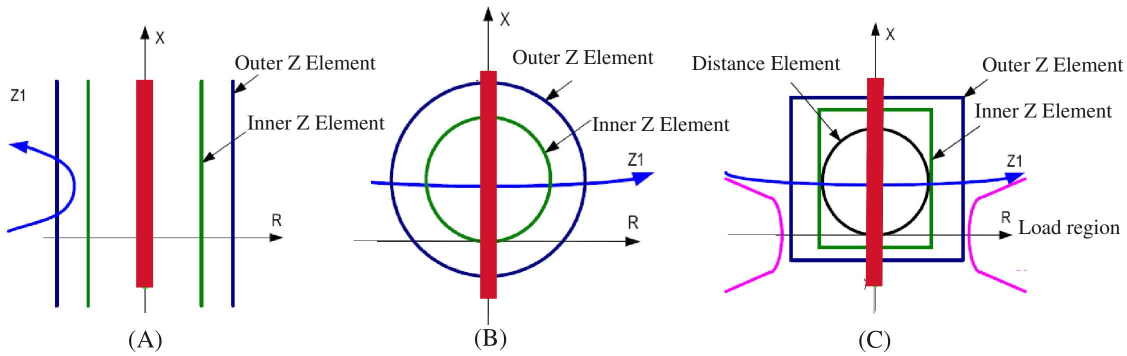


Figure 2-10: Different power swing protection schemes

2-10 (A) : Double blinder, power swing detection characteristic
2-10 (B) : Offset mho, power swing detection characteristic
2-10 (C) : Quadrilateral, power swing detection characteristic

When an apparent impedance change occurs in a system a timer will start as soon as the impedance value enters the outer Z element in Figure 2-10. If the impedance crosses the inner Z element before a pre-set time delay the relay will detect a fault and do necessary operations to clear the fault.
To detect a stable or unstable power swing the distance between the outer and inner Z element and a timer is used. In Figure 2-10 (A) a power swing blocking scheme is drawn. If the impedance does not cross the inner Z element and moves back outside the outer Z element during a certain time a stable power swing is detected. If the impedance stays within the elements for to long time or the impedance decreases further than the inner Z element an unstable power swing is detected.
Figure 2-10 (B) and (C) show the power swing tripping scheme. It is an extension of the power system blocking scheme. The timer measures different time delays and decides on the basis of numerous stability studies if tripping should be done when the impedance is on the way in or on the way out in the characteristic scheme[11].
It is important that the power swing detection is placed outside the fault detection scheme so that the power swing detector will block the fault detector and prevent tripping for a period of time if a power swing is detected.
If an unstable power swing is detected, fast actions need to be taken in the network by islanding parts of the network.

2.6.2 Stability Analysis for Relay Settings

The inner and outer Z element in Figure 2-10 is determined after numerous transient stability studies. The power system are exposed to different operation conditions and stressed to its limits. An analysis of the results will reveal weak nodes and possible locations to implement Out-Of-Step tripping and blocking relays.

[11] Application Guidelines for Power Swing Detection on Transmission Systems

The electric center in a power system is the location or area where the voltage appears to be closest to zero. The best location for detection of Out-Of-Step condition is near the electric center[12].

Studies are needed to be done to get correct nodes to island different parts of the power system in case of a power swing. Therefore the amount of generation available and the load demand within each pre-selected island is studied. It is important that new power swings do not occur in the islands after a system separation.

After these nodes are identified, a study of the impedance locus starts. The R-X impedance plane is analyzed to determine forward reach and reverse reach settings of the relay. The timer settings are determined by studying maximum rate of slip between systems.

[12] Out-Of-Step protection enhancements

3 Laboratory Measurements

At the Division of Electric Power Engineering at Chalmers there is a model of a part of the Swedish transmission network. The model describes a hydro power plant at Harsprånget with a transformer and a high voltage transmission line with the length of 900 km divided into six identical π-sections each of length 150 km. One end of the transmission line can be connected to the rest of the Swedish network. The model in the lab can be described as one machine against an infinite bus.
The model is scaled down; the scaled rate of voltage is 1:1000 and scaled rate of the power is 1:18000. Nominal voltage is 400 V and nominal current is 100 A.

3.1 Laboratory Measurement Setup

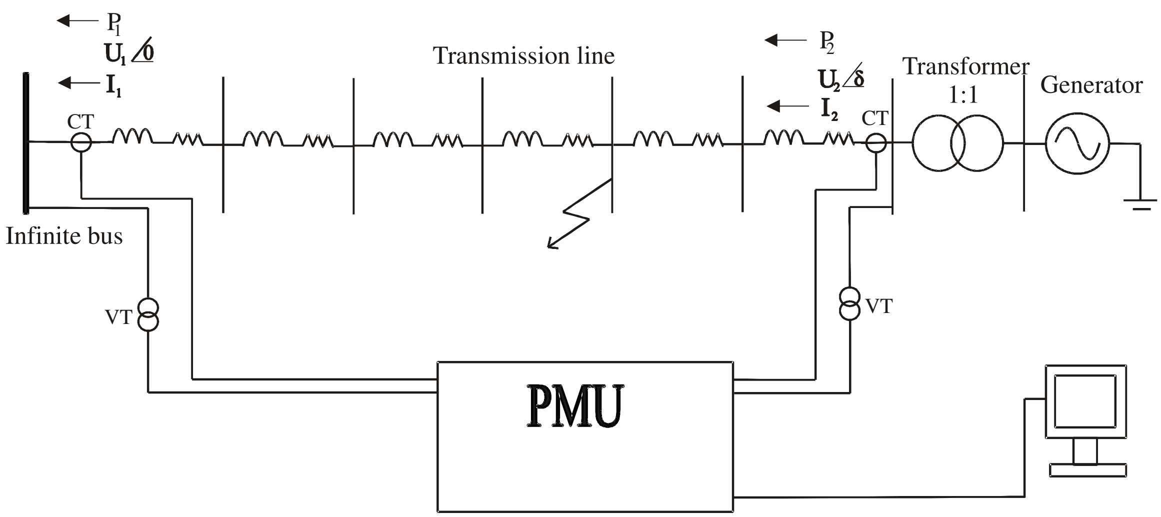


Figure 3-1: The power system model of the laboratory setup

Figure 3-1 shows the laboratory measurement setup of the power system model. The data of the different parts of the network model in the lab are described in Section 3.2. To be able to connect the PMU to the model, both current and voltage instrument transformers are needed; the instrument transformers are described in Section 3.3. The PMU is connected to the network model and to a computer. The software to the PMU supplies measured values of the voltages and currents in complex form, the frequency and the derivative of the frequency at every power system cycle of the fundamental frequency; in this measurement setup it will be 50 Hz or every 20 ms. The values will be saved in a Microsoft Excel sheet. The Excel sheet is then read into a MATLAB program that will run the Out-Of-Step detection algorithm explained in Section 3.5 to test for Out-Of-Step conditions on the network model.
The arrow shown in Figure 3-1 indicates a fault. It is possible to create all four types of fault (three phase fault, phase to phase fault, phase to phase to ground fault and phase to ground fault). The fault can be set to any of the busses in the network, but a fault at a bus near the infinite bus will cause very high fault currents and will not be possible to measure, therefore faults will be applied at busses closer to the generator bus.

3.2 Data of Laboratory Model

The data of each part of the laboratory model can be found in data sheets and on the equipment in the lab. When performing the theoretical calculations the steady-state data values are used and then compared to the measured results.

3.2.1 DC Motor

The hydro turbine of Harsprånget power plant is modeled with a DC motor. A one-quadrant converter supplies the 85 kW DC motor, it can be controlled either by speed or armature current.

Parameters:
Power = 85 kW
Nominal speed = 1000 rpm
Moment of inertia = 7.3 kgm²
Armature voltage = 220 V
Armature current = 420 A
Armature resistance = 0.0118 Ω
Armature inductance = 182 mH
Field voltage = 220 V

3.2.2 Flywheel

There is a flywheel in between the DC motor and the synchronous generator. The flywheel in the lab model is used to model the moment of inertia of the real power plant.

Parameters:
Diameter of wheel = 900 mm
Moment of inertia = 50 kgm²
Maximum allowable speed = 1100 rpm

3.2.3 Generator

The synchronous generator is equipped with a voltage regulator. The regulator can control the terminal voltage, field current, reactive power and power factor.

Parameters:
Frequency = 50 Hz
Number of pole pairs = 3
Apparent power = 75 kVA
Voltage = 400 V
Synchronous reactance = 2.93 Ω
Transient reactance = 0.437 Ω
Sub-transient reactance = 0.332 Ω
Stator resistance = 0.081 Ω/phase

Field voltage = 110 V
Field current = 4.7 A
Moment of inertia = 18.8 kgm²

3.2.4 Power Transformer

The transformers nominal voltage is 400 V on the generator side, the nominal current is 100 A and the lines are fed at a voltage level of 400 V. The three phase power transformer in the lab is thereby of ratio 1:1 the reason to have a transformer is to create the same losses that exist in the real network.

Parameters: Frequency = 50 Hz
Ratio = 1:1
Primary/Secondary voltage level = 400 V
Apparent power = 75 kVA
Winding connection = YΔ11
Transformer impedance = 0.075 + j0.06 Ω/phase

3.2.5 Transmission Line

The transmission line is built-up by six identical π-sections; each corresponds to 150 km of the 400 kV line. The sections can be connected arbitrarily in series or parallel. Each π-section is characterized by four parameters: R, the series resistance due to the conductor resistivity, C_j, shunt capacitance due to leakage currents between the phases and ground, L, series inductance due to magnetic field surrounding the conductors and C_f, shunt capacitance due to the electric field between the conductors. The shunt capacitors in the lab can either be connected or disconnected. See Figure 3-2 for visualization of the parameters[13].

Parameters: Resistance = 0.052 Ω/phase
Inductance = 0.953 Ω/phase
Shunt capacitance, C_f = 3.49 μF/phase
Shunt capacitance, C_j = 35.4 μF/phase
Total impedance of one π-section = 0.052 + j0.644 Ω/phase
without shunt capacitors connected

[13] ElSystem LAB 1

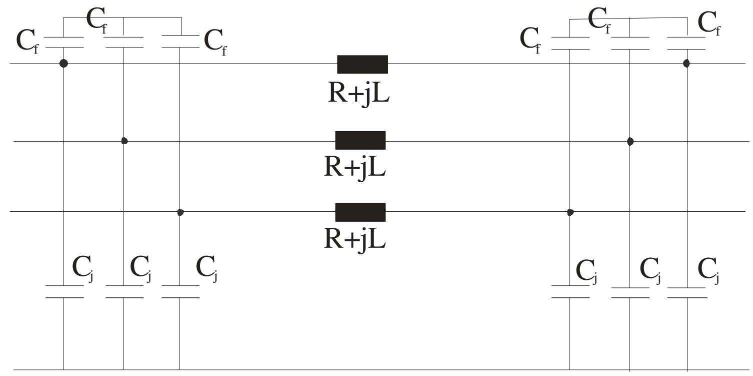


Figure 3-2: Resistance, inductance and capacitance of one π-section

3.2.6 Loads

In the lab it is possible to connect additional load to the generator and transmission line. But in this thesis work the generation in the lab will be connected through the transmission line directly to the infinite bus (Swedish power system network), without additional load.

3.3 Instrument Transformers

An instrument transformer or a measurement transformer is a device that transforms voltage or current, from the power system level to the level required by the measuring unit.

3.3.1 Voltage Transformer

A voltage transformer is used for metering and protection in high-voltage circuits. It is designed so that the supply being measured does not get an additional load, i.e. the load of the transformer should be negligible. The voltage transformer should have a precise voltage ratio to accurately step down voltage because of the high requirements of the measuring unit.
Voltage transformers are of different types, toroidal and laminated EI type. A toroidal transformer is built around a ring-shaped core. The closed ring shape eliminates air gaps.
The primary and secondary coils are wound concentrically around the core, when doing the windings it is better to cover the surface entirely. If the surface of the core is totally covered screening of the electromagnetic interference generated by the magnetic field in the core is automatically done and the length of winding wire is decreased.

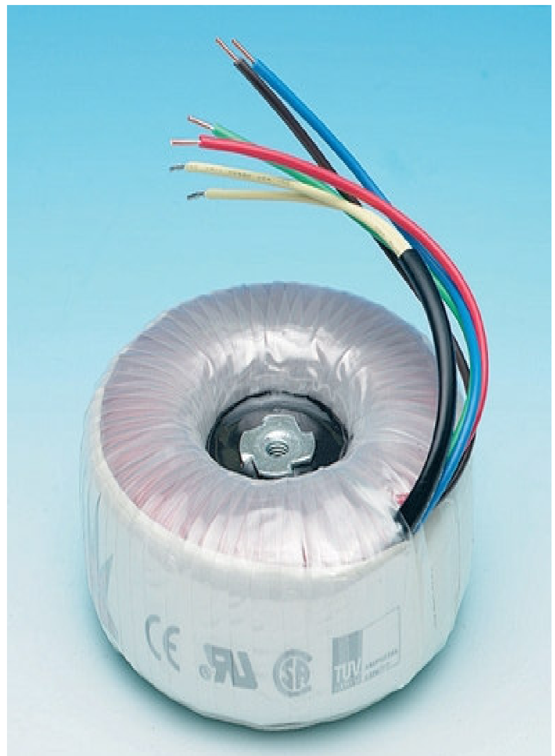


Figure 3-3: Toroidal transformer

3.3.2 Current Transformer

A current transformer is a device that is designed to make the current in the secondary winding accurately proportional to the current flowing in the primary winding. The configuration of the current transformer is a single turn on the primary side (either an insulated cable or an uninsulated bus bar) through a well-insulated toroidal core wrapped with many turns of wire.

3.3.3 Voltage Transformer Design and assembly

When measuring with the PMU in the lab both voltage and current transformers are needed to meet the requirements of the PMU. Current transformers already exist in the lab but voltage transformers of ratio 400:110 volt are needed. Two transformers where built, see Appendix C for details.

3.4 Theoretical Calculations

In the theoretical calculations an estimation of the power transferred in the laboratory model is made. The parameter values are at a steady state condition. The critical fault clearing time is also estimated. See Figure 3-4 for a single phase model of the laboratory model. In single phase calculation the phase to ground voltage is $400/\sqrt{3} = 230\,\text{V}$.

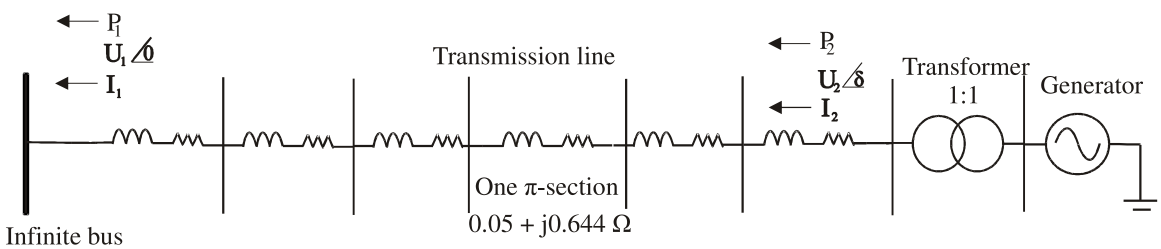


Figure 3-4: Single phase diagram

3.4.1 Power Transfer

In the theoretical equations a system base of 75 kVA and a voltage base of 400 V are used.

The total line impedance is:

$$\begin{aligned} Z_{Tot} &= Z_G + Z_T + Z_\pi * 6 = \\ &= j0.437 + 0.075 + j0.06 + (0.05 + j0.644) * 6 = 0.375 + j4.391\Omega \end{aligned} \qquad \textbf{3-1}$$

$$Z_{Tot,pu} = Z_{Tot} * \left(\frac{S_b}{V_b^2}\right) = (0.375 + j4.391) * \left(\frac{75000}{400^2}\right) = 0.1758 + j2.058\,pu \qquad \textbf{3-2}$$

In Equation 3-2 the resistance is less than 10 % of the reactance and thereby the resistance can without any major difference be excluded from the rest of the theoretical calculations.
In the theoretical calculations it is assumed that the voltage at the generator bus and the voltage at the infinite bus are 230 V phase to ground. As mentioned before, Equation 2-6 has its maximum when sin δ = 1.

Maximum electric output power:

$$P_{e,\max} = \left(\frac{400 * 400}{|j4.391|} * \sin 90 \right) = 36.4\,kW \qquad \textbf{3-3}$$

If a stability margin of 50 % of the maximum output power is selected, the mechanical input power is:

$$P_m = 0.5 * P_{e,\max} = 0.5 * 36.4 = 18.2\,kW \qquad \textbf{3-4}$$

In Figure 3-5 the electrical output power and the mechanical input power are plotted.

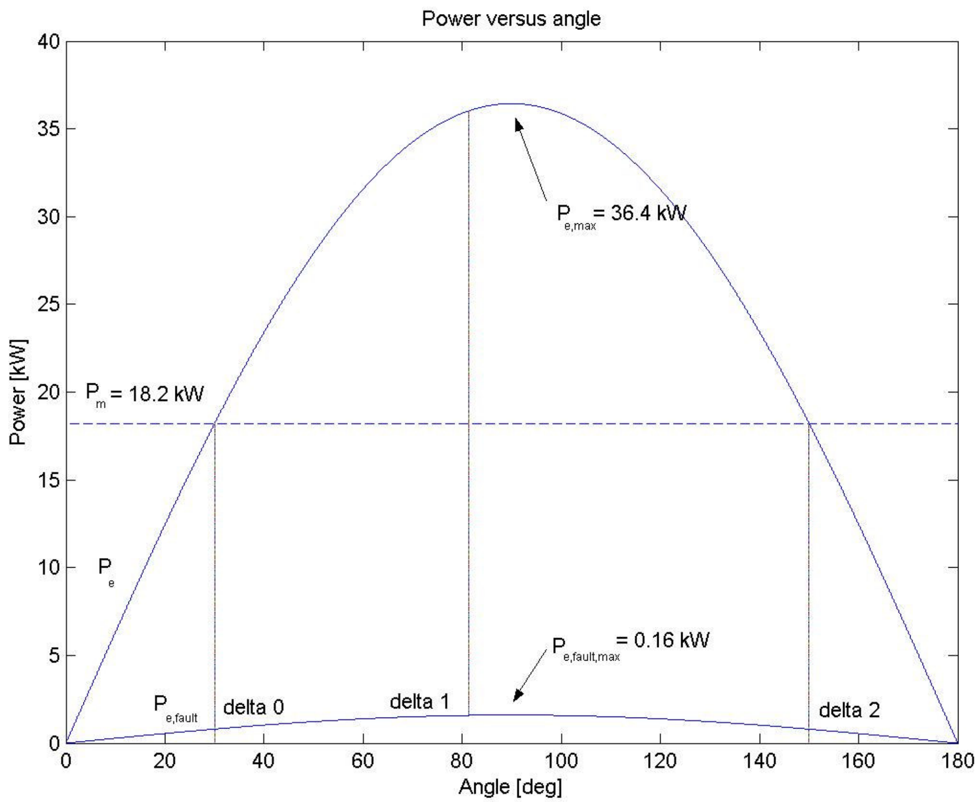


Figure 3-5: Input (dashed) and output (solid) power

3.4.2 Critical Fault Clearing Angle and Time

In the theoretical calculations it is assumed that a fault occurs at time t_0 at a stable operation point. The electric output power during the fault is decreased to $P_{e,fault}$. In reality this value is not known. For a metallic three-phase fault the impedance between the infinite bus and the generator is infinite during the fault and the active power transferred over the line is zero. In the theoretical calculations, it is assumed that during the fault the reactance between the infinite bus and the generator is 100 Ω instead of 4.291 Ω. The voltage at the generator and at the infinite bus remains at 400 V during the fault. In the theoretical calculations, it is assumed that the electrical output power returns to its initial, pre-fault, curve as soon as the fault is cleared.

The angle of the stable equilibrium point is:

$$\delta_0 = \arcsin\left(\frac{P_m * |jX_{Tot}|}{V_G * V_{IB}}\right) = \arcsin\left(\frac{18.2 * 4.391}{400 * 400}\right) = 30° \qquad \textbf{3-5}$$

The maximum angle before losing synchronism is:

$$\delta_2 = \delta_3 = 180 - \delta_0 = 180 - 30 = 150° \qquad \textbf{3-6}$$

Setting the areas equal as explained in Equation 2-20 and solving for maximum fault clearing angle with Equation 2-21 yields:

$$\delta_1 = \arccos\left\{\left(\frac{P_{e,new} + P_{e,\max}}{P_{e,new} - P_{e,\max}}\right)\cos(\delta_0) - \left(\frac{P_m}{P_{e,new} - P_{e,old}}\right) * (\pi - 2 * \delta_0)\right\}$$
$$\delta_1 = \arccos\left\{-1.09 * \cos(30) + 0.523 * \left(\pi - 2 * 30 * \left(\frac{\pi}{180}\right)\right)\right\} = 81.3° \qquad \textbf{3-7}$$

To solve for critical fault clearing time, Runge-Kuttas iteration method in Appendix B is used. Some constants of the machine are needed before the iterations can start.
Total moment of inertia of motor, flywheel and generator:

$$J_{Tot} = J_{DCmotor} + J_{Flywheel} + J_{Generator} = 7.3 + 50 + 18.8 = 76.1 \text{ kgm}^2 \qquad \textbf{3-8}$$

The nominal speed is:

$$\omega_{0m} = 2\pi \frac{f}{polpairs} = 2\pi \frac{50}{3} = 104.7 \text{ mechanical rad/s} \qquad \textbf{3-9}$$

The inertia constant is:

$$H = \frac{\frac{1}{2} J_{Tot}\omega_{0m}^2}{S_b} = \frac{0.5 * 76.1 * 104.7^2}{75000} = 5.56\ s \qquad \textbf{3-10}$$

The first objective function is the first integration of Equation 2-15. The power in this equation is expressed in per unit values. Note that the nominal speed, ω_{0e}, in Equation 2-15 is multiplied in the second integration in Runge-Kuttas formula.

$$f(\Delta\delta, t) = \frac{d^2\delta}{dt^2} = \frac{1}{2H}\left(P_m - P_{e,\max}\sin\delta\right) \qquad \textbf{3-11}$$

The second objective function is the second integration of Equation 2-15 which will solve for the angle at different time steps:

$$f(\delta, t) = \frac{d\delta}{dt} = \omega_{0e}\Delta\delta \qquad \textbf{3-12}$$

The constants see Appendix B, of Runge-Kutta can then be written as:

$$\begin{aligned} k_1^{'} &= \frac{1}{2H}\left(P_m - P_{e,fault,\max}\sin(\delta)_n\right) * \Delta t \\ k_1^{''} &= (\omega_{0e}) * (\Delta\delta)_n * \Delta t \\ k_2^{'} &= \frac{1}{2H}\left[P_m - P_{e,fault,\max}\sin\left((\delta)_n + k_1^{'}\right)\right] * \Delta t \\ k_2^{''} &= (\omega_{0e}) * \left[(\Delta\delta)_n + k_1^{''}\right] * \Delta t \end{aligned} \qquad \textbf{3-13}$$

The iterative velocity of angle and angle is:

$$\begin{aligned} (\Delta\delta)_{n+1} &= (\Delta\delta)_n + \frac{k_1^{'} + k_2^{'}}{2} \\ (\delta)_{n+1} &= (\delta)_n + \frac{k_1^{''} + k_2^{''}}{2} \end{aligned} \qquad \textbf{3-14}$$

The time span, Δt, is the same as the sample interval for the PMU, 0.02 seconds.

In Figure 3-6 the angle and the angle velocity are plotted for the theoretical calculations above.

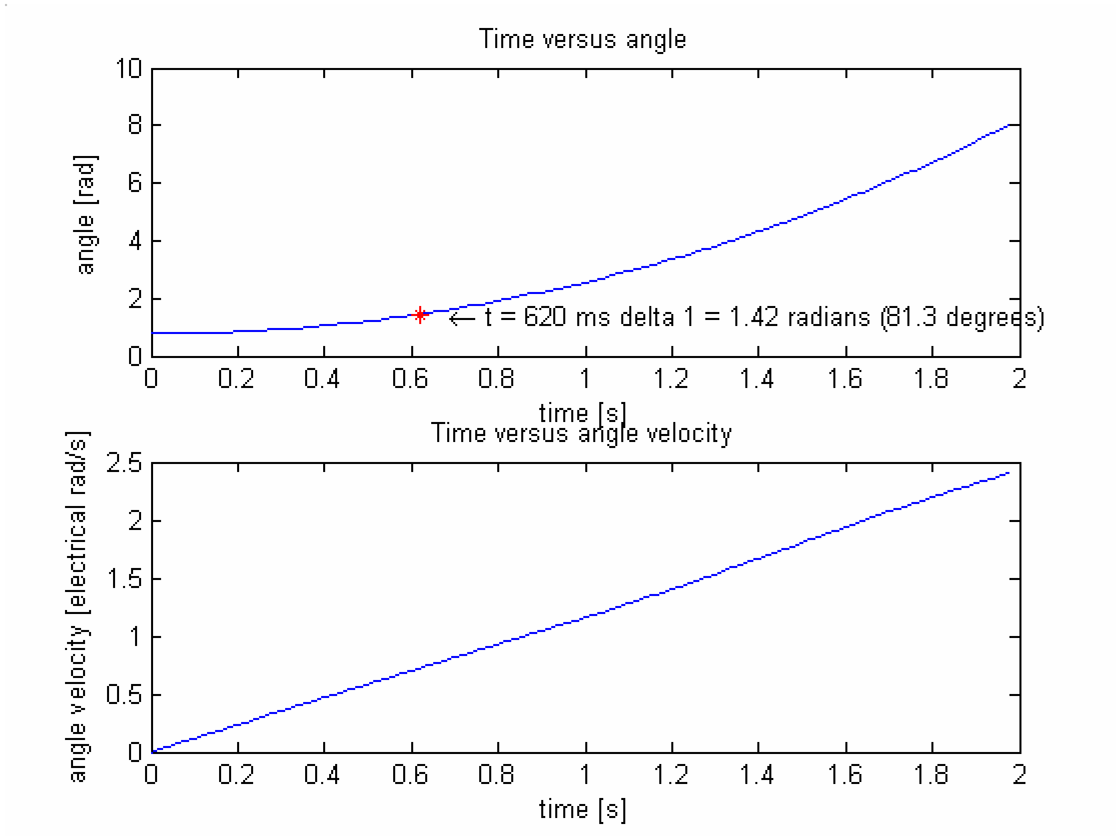


Figure 3-6: Angle and angle velocity over time

Figure 3-6 visualizes that the angle velocity increases linearly and the angle has a quadratic increase. The swing equation is a differential equation of second order, so the results are as expected.

If the electric power output had decreased to zero during the fault a shorter fault clearing time and a decreased fault clearing angle would be necessary for the system not to lose synchronism, the opposite yields if the electric power output would not decrease as much as assumed in the example above.
The MATLAB program for the theoretical calculations can be found in Appendix D.

3.5 Out-Of-Step Detection Algorithm

The PMU software outcomes are two phase-currents and two phase-voltages expressed in complex form. These values are received every 20 ms. With these measurements an algorithm is created to detect Out-Of-Step conditions.

3.5.1 Flowchart

The algorithm is built up from the following flowchart:

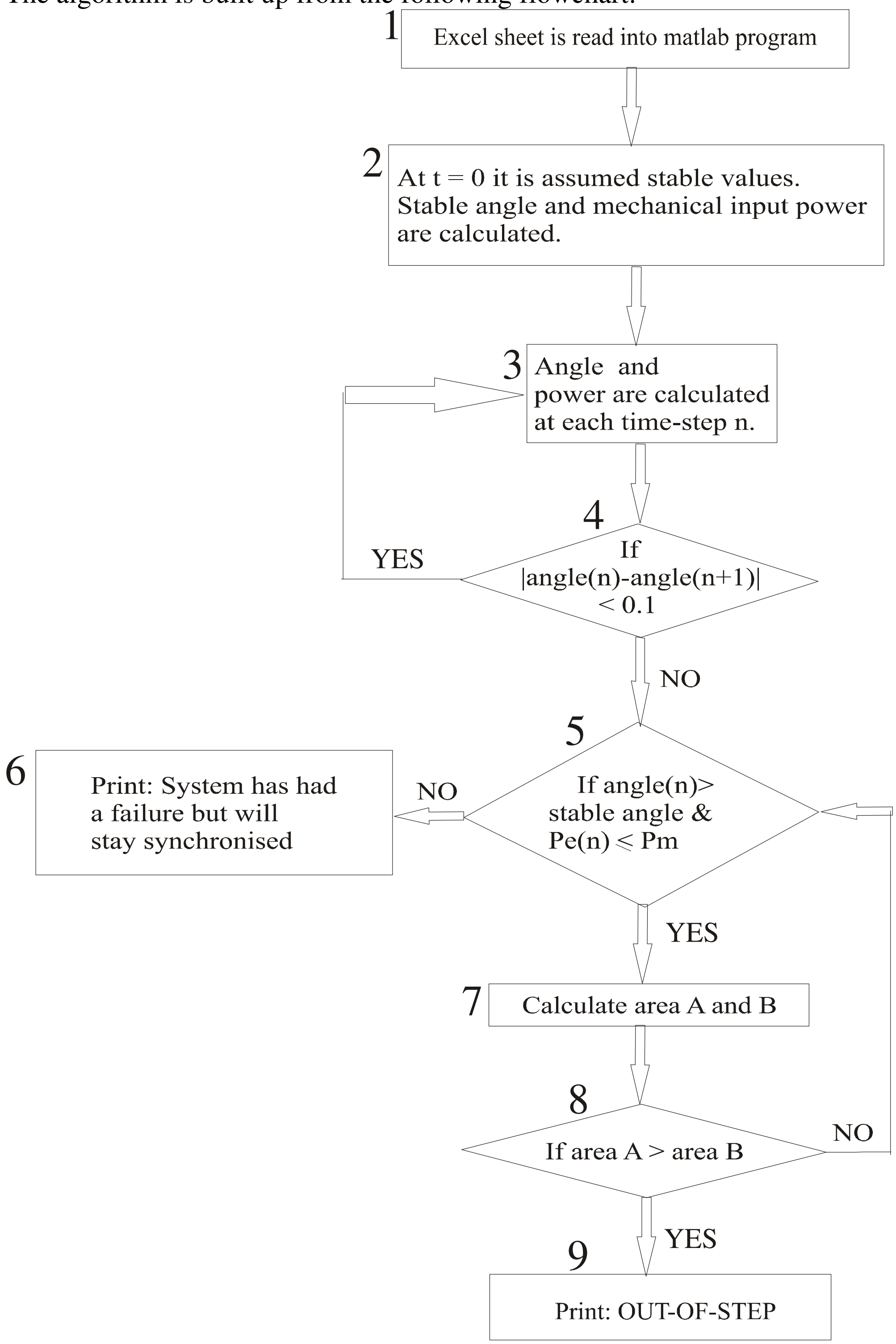
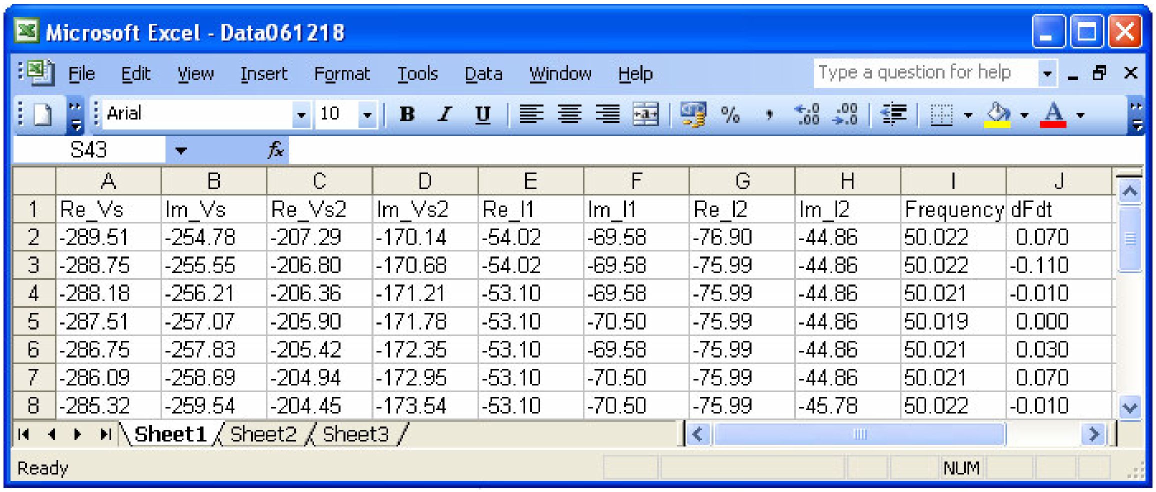


Figure 3-7: Flowchart of algorithm

The flowchart is explained in detail in the following text.

1. Excel sheet is read into matlab program.



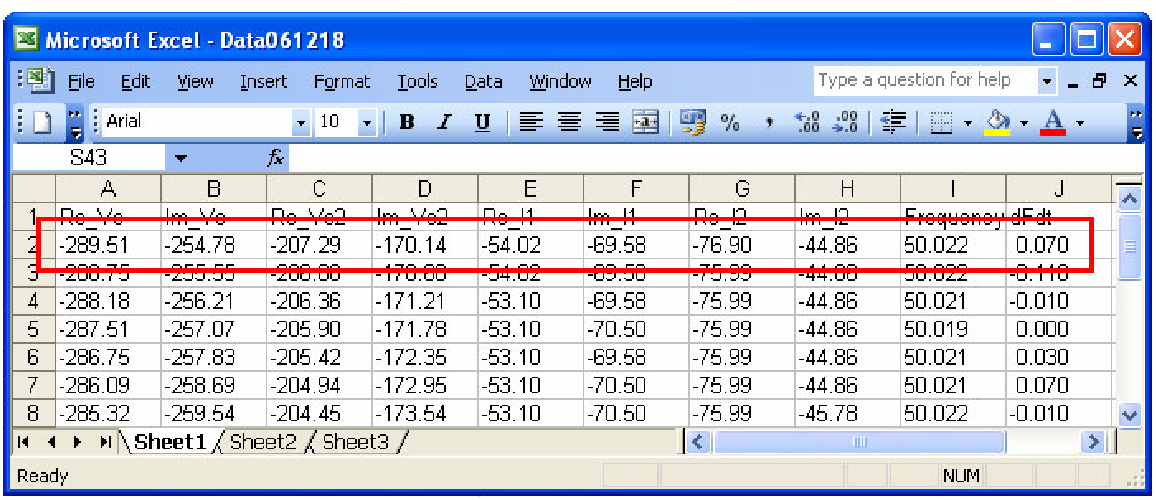
Microsoft Excel - Data061218

	A	B	C	D	E	F	G	H	I	J
1	Re_Vs	Im_Vs	Re_Vs2	Im_Vs2	Re_I1	Im_I1	Re_I2	Im_I2	Frequency	dFdt
2	-289.51	-254.78	-207.29	-170.14	-54.02	-69.58	-76.90	-44.86	50.022	0.070
3	-288.75	-255.55	-206.80	-170.68	-54.02	-69.58	-75.99	-44.86	50.022	-0.110
4	-288.18	-256.21	-206.36	-171.21	-53.10	-69.58	-75.99	-44.86	50.021	-0.010
5	-287.51	-257.07	-205.90	-171.78	-53.10	-70.50	-75.99	-44.86	50.019	0.000
6	-286.75	-257.83	-205.42	-172.35	-53.10	-69.58	-75.99	-44.86	50.021	0.030
7	-286.09	-258.69	-204.94	-172.95	-53.10	-70.50	-75.99	-44.86	50.021	0.070
8	-285.32	-259.54	-204.45	-173.54	-53.10	-70.50	-75.99	-45.78	50.022	-0.010

Figure 3-8: Excel sheet with measured data

The software of the PMU saves the data in Excel sheets, a maximum of 10 minutes can be saved in one Excel sheet corresponding to 30 000 lines with data measurements, i.e. 30000 time steps, $\Delta t = 0.02$s.
The algorithm explained in this thesis does not get a data set every 20 ms it gets the whole 10 minutes period. If the algorithm should work in reality it needs to receive the value from the PMUs continuously.

2. First line, at t =0, is assumed to give stable values. Stable angle and mechanical input power are calculated.



Microsoft Excel - Data061218

	A	B	C	D	E	F	G	H	I	J
1	Re_Vs	Im_Vs	Re_Vs2	Im_Vs2	Re_I1	Im_I1	Re_I2	Im_I2	Frequency	dFdt
2	-289.51	-254.78	-207.29	-170.14	-54.02	-69.58	-76.90	-44.86	50.022	0.070
3	-288.75	-255.55	-206.80	-170.68	-54.02	-69.58	-75.99	-44.86	50.022	-0.110
4	-288.18	-256.21	-206.36	-171.21	-53.10	-69.58	-75.99	-44.86	50.021	-0.010
5	-287.51	-257.07	-205.90	-171.78	-53.10	-70.50	-75.99	-44.86	50.019	0.000
6	-286.75	-257.83	-205.42	-172.35	-53.10	-69.58	-75.99	-44.86	50.021	0.030
7	-286.09	-258.69	-204.94	-172.95	-53.10	-70.50	-75.99	-44.86	50.021	0.070
8	-285.32	-259.54	-204.45	-173.54	-53.10	-70.50	-75.99	-45.78	50.022	-0.010

Figure 3-9: Values at line n=1 is assumed to be in a stable system

It is assumed that the first line with data measurements in the Excel sheet is measured when the system is in a stable condition. The algorithm uses these values as reference values for some of the IF statements to be able to determine changes in the network.

3. Angle and power are calculated at each time step.

The algorithm creates vectors for complex current, voltage and impedance. From these vectors it calculates new vectors with phase angle and power for all time steps.

4. IF statement for change in angle.

An IF statement compares values with each other or with a threshold value, the outcome can be either Yes or No.
The IF statement in this section compares the difference of two values next to each other in the phase angel vector, if the values differ too much the part of the algorithm that detect power swings will start.

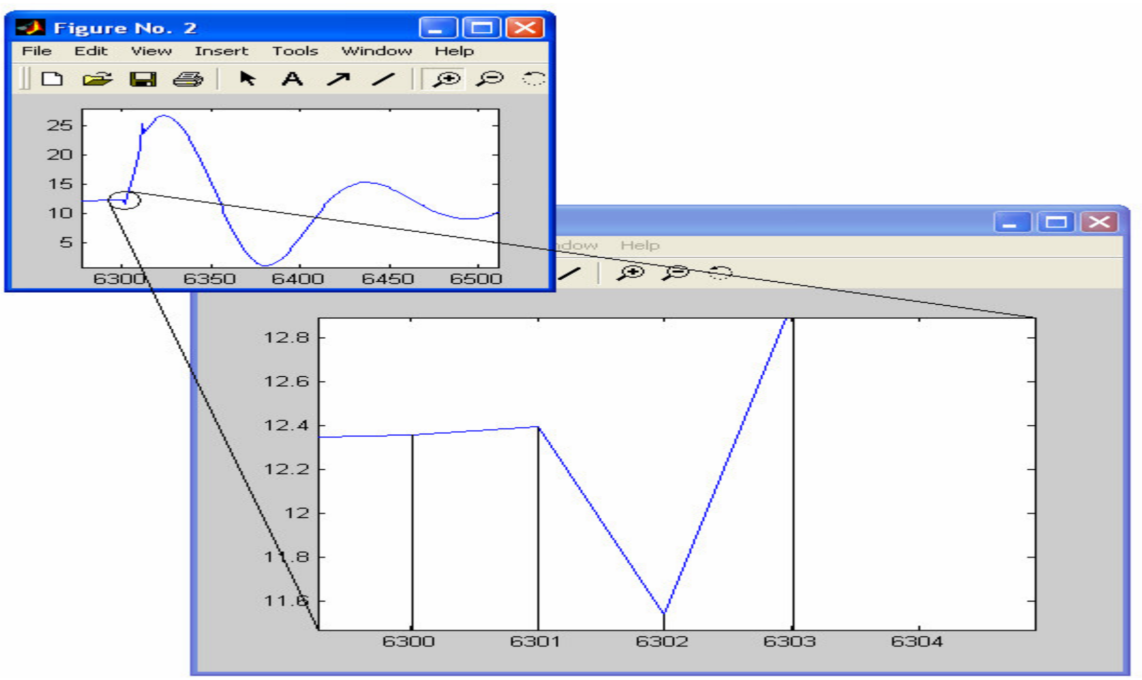


Figure 3-10: Phase angle calculated for each time step

A difference larger than 0.1 degrees will alert the algorithm. The threshold value is taken from studying the graphs of the change of phase angle.

5. IF statement for change in angle and value of electric power output.

This IF statement is the most important part of the algorithm. If the angle has changed too much and the electric power output has decreased to a level below the mechanical power input, it is for sure that the system will experience a power swing. If the IF statement receives Yes when doing the comparison, the algorithm starts to calculate area A and area

B and if the IF statement receives No the algorithm tells the user that there has been a disruption but the system will stay synchronized.

6. Message box: WARNING!

Figure 3-11: Warning message when system has had a failure

7. Calculate area A and area B.

If the answer was Yes in the IF statement at number 5 this part of the algorithm is alerted. Area A is calculated with Riemann integration. This integration is built up from calculating areas of bars and adding them. One bar has in x-direction the change of the angle between two time step and in y-direction the difference between the mechanical power input and the electric power output. Figure 3-12 visualizes the summation of the bars. The growing area A and the decreasing area B.

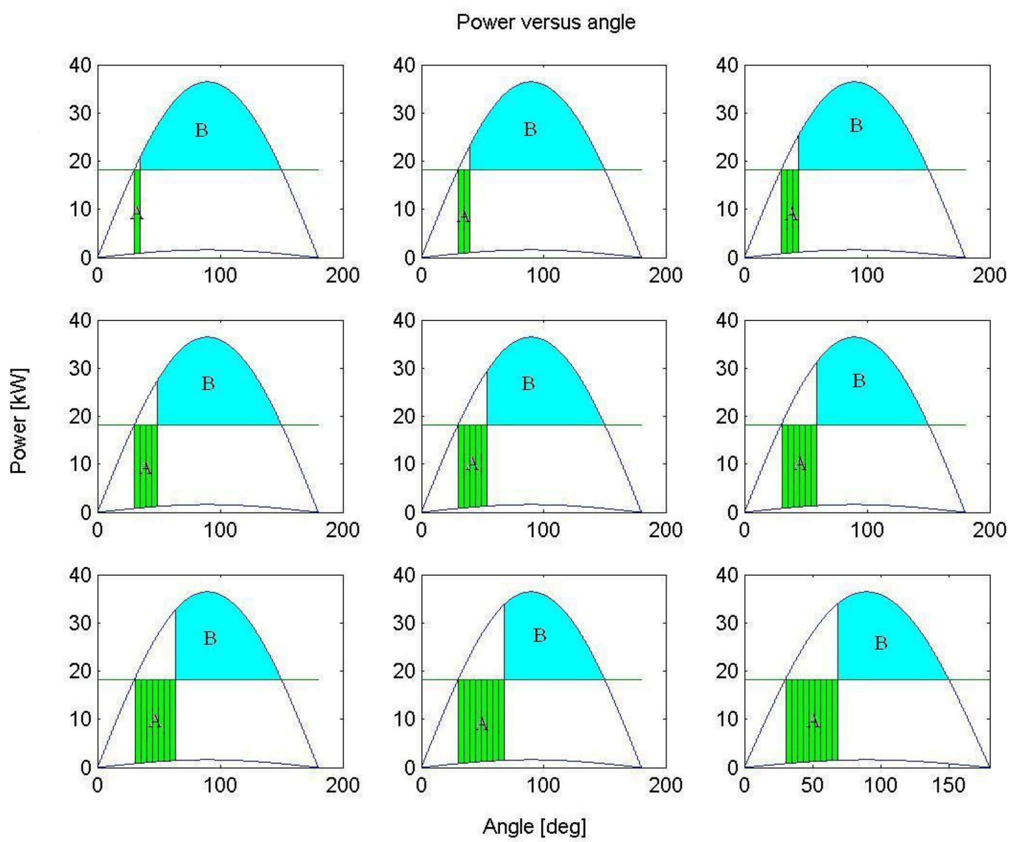


Figure 3-12: Riemann integration for equal-area criterion

8. IF statement to compare area A and area B.

This IF statement compares the areas, as long as area A is smaller than area B the IF statement will receive NO and the algorithm continues but if the angle grows too large and area A is larger than area B the IF statement receive a YES and the algorithm stops. The algorithm sends out a warning about Out-Of-Step conditions. In reality islanding of different parts of the network should start at this point.

9. Message box: ERROR!

Figure 3-13: Warning message when system is about to lose synchronism

3.6 Recordings

A three-phase fault was applied at three different nodes in the network, see Figure 3-14.

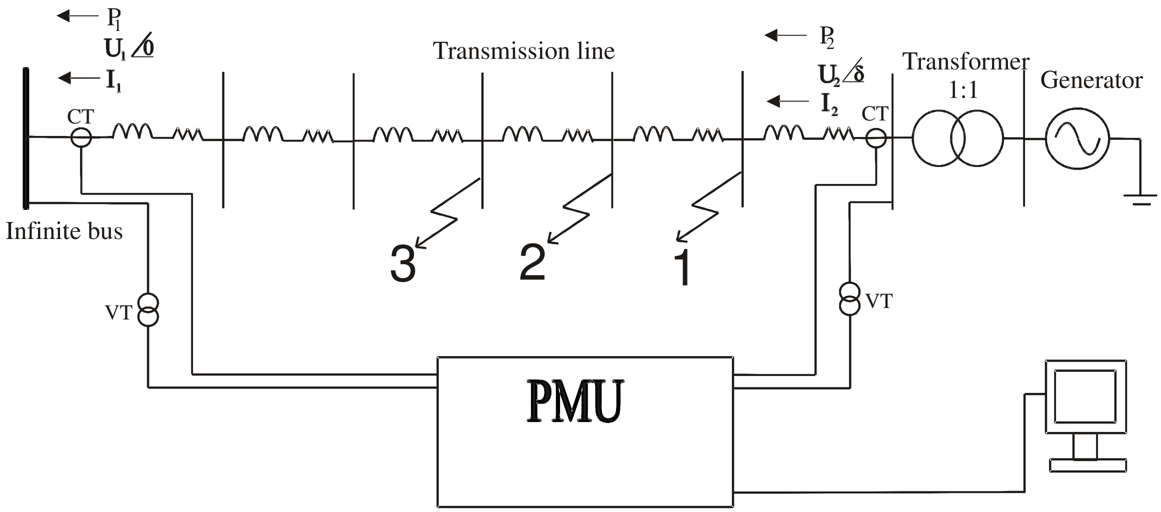


Figure 3-14: Lab setup with fault at three different locations

The duration of a fault was in the range of 0.1-0.8 seconds. There were no faults simulated when the generator actually lost synchronism because of the danger of that condition. Even though no Out-Of-Step conditions occurred, power swings were recorded. The following plots visualize the power flow variations from the generator to the infinite bus.

The first graph, Figure 3-15, shows the value of the generator output power for the three different fault positions.

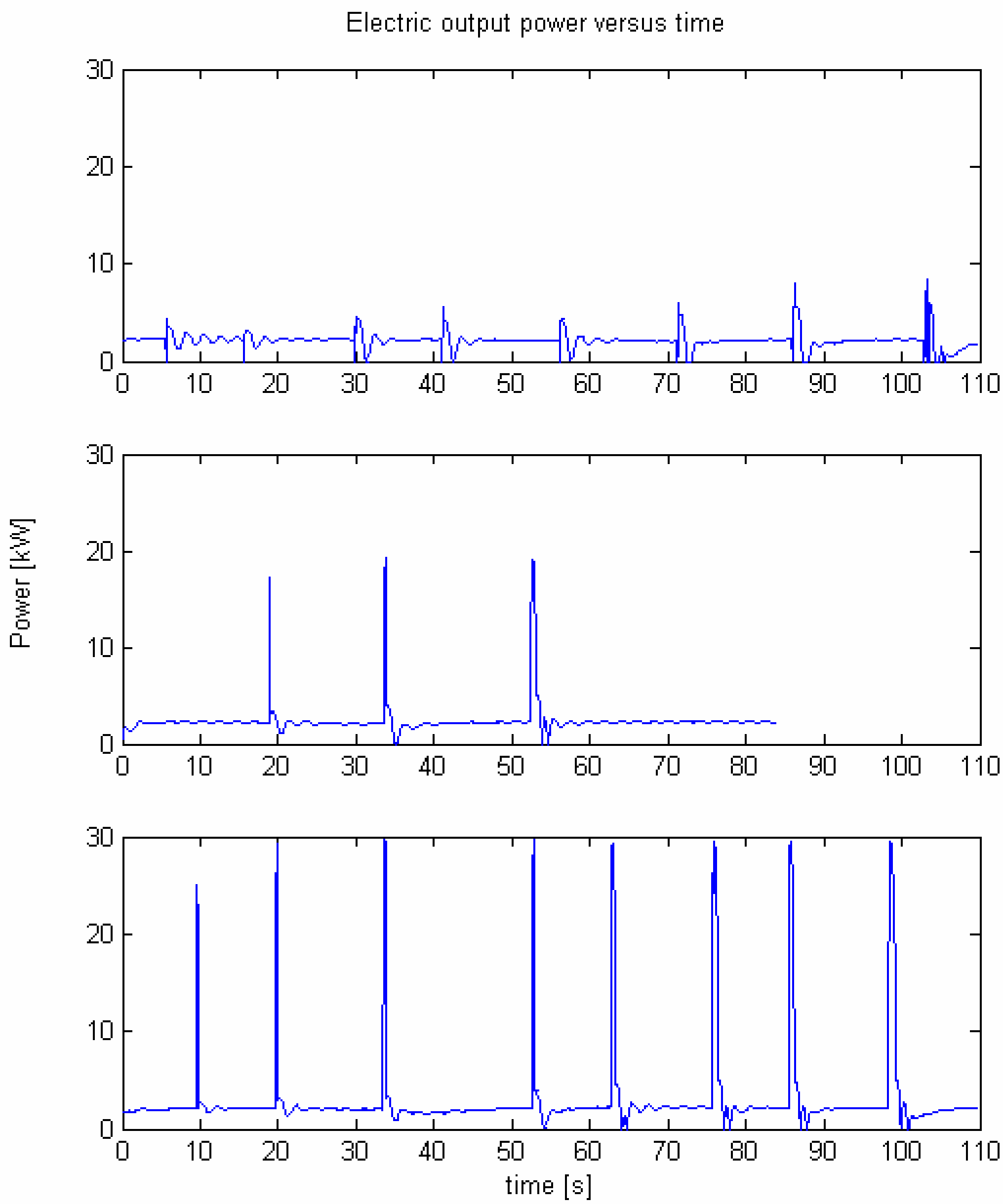


Figure 3-15: Electric power output at every 20 millisecond

In Figure 3-15 the spikes are at the initial time of the fault and as soon as the fault is cleared, the power oscillates before the system has recovered totally from the fault. When a fault is generated at fault position 1 the top window plot clearly shows that the spike increases with increasing fault time i.e. larger power swings in the system when faults of longer duration are applied.

In reality there is normally only one fault in the system and not so many as shown in one window in Figure 3-15. Therefore when the laboratory data is analyzed with the algorithm only one fault is selected. In this particular case the fault at time 56 second at fault position 1 is examined in more detail. In Figure 3-16 this fault is zoomed.

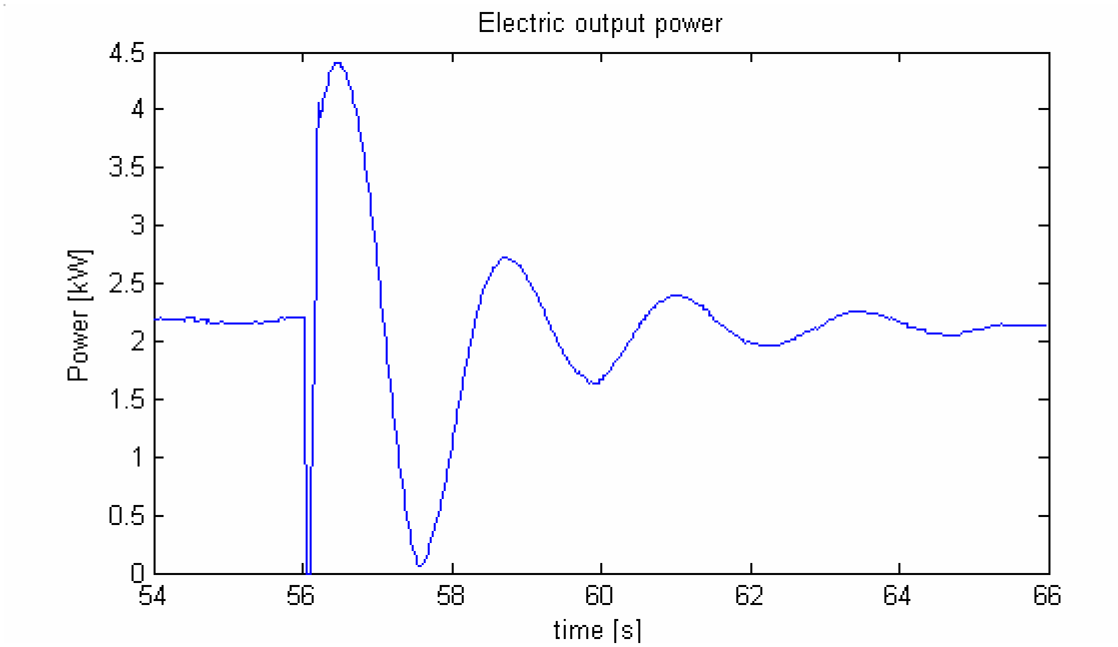


Figure 3-16: Electric output power at the selected fault position t = 56 s

The duration of the fault drawn in Figure 3-16 was 500 ms.

Figure 3-17 shows the power at the stable point and the change of power around the time of the fault instant.

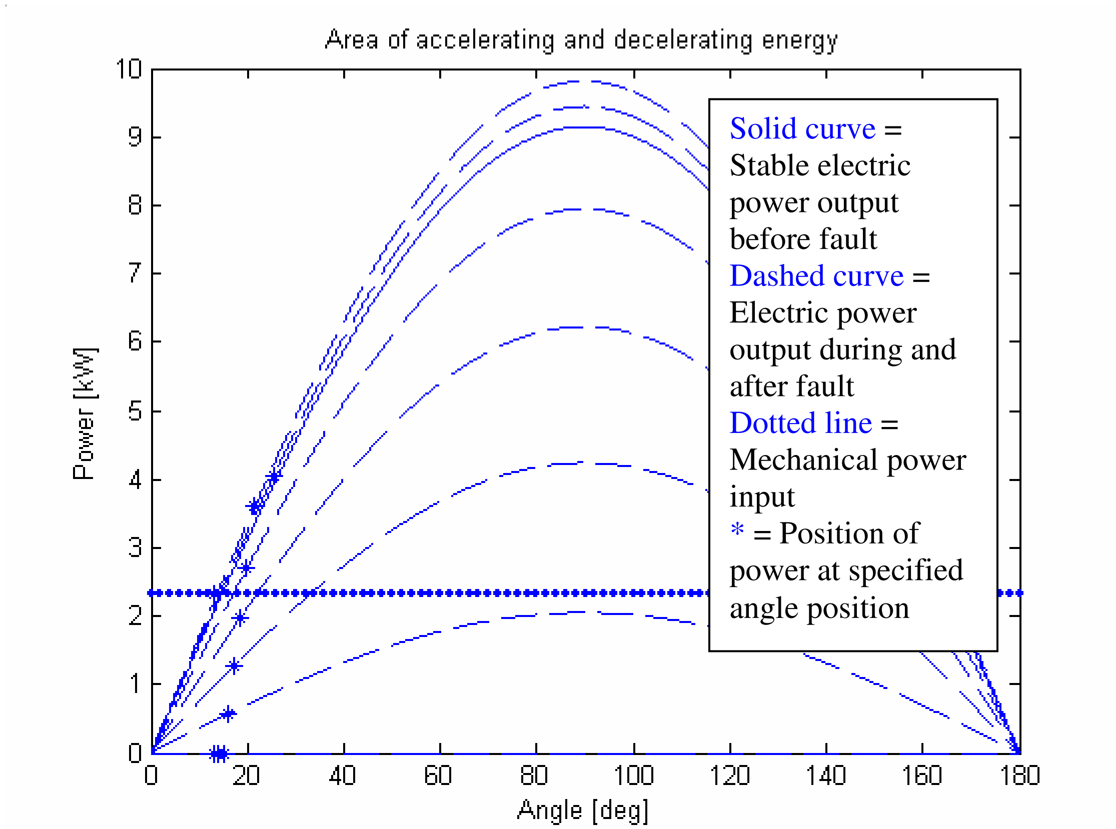


Figure 3-17: Power and angle variations during and after a fault.

In Figure 3-17 it is clearly visualized that during a three-phase fault there is no power flow from the generator to the infinite bus and as soon as the fault is cleared the electric power output increases. Figure 3-18 shows a zoomed graph of the stars in Figure 3-17.

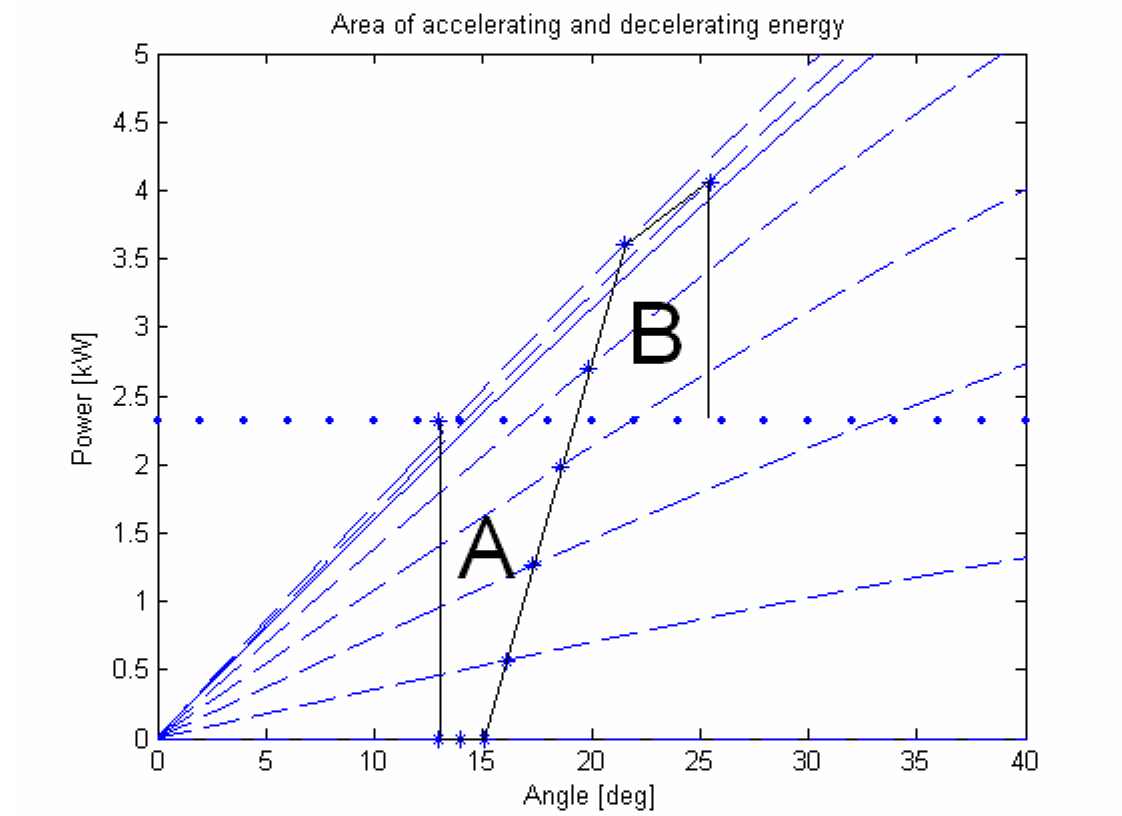


Figure 3-18: Equal area criterion

In Figure 3-18 it can be seen without any proofs with mathematical formulas that area A is of same size that area B. In this thesis the equal area criterion has been reviewed both with mathematical and theoretical statements and with the laboratory experiments the equal area criterion has been verified!
In this particular case the generator was far from losing synchronism. In theory the power will oscillate back to its stable equilibrium point, in Figure 3-19 this oscillation is drawn.

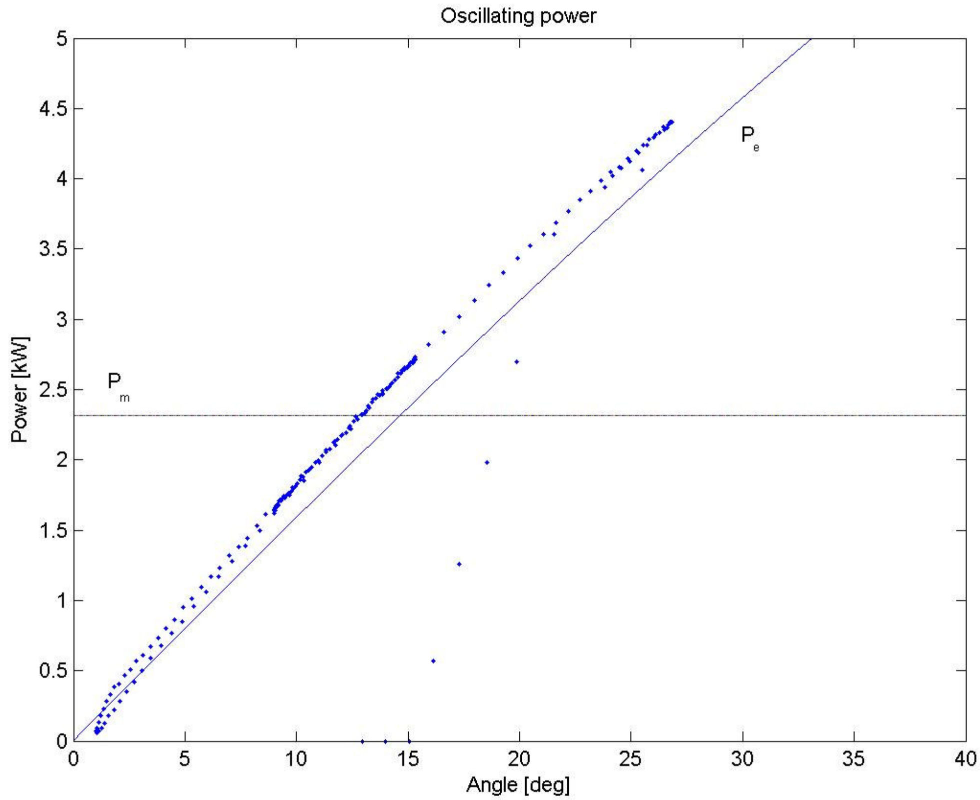


Figure 3-19: Power oscillation when recovering from fault

The dots in Figure 3-19 describe the electrical power output flow when the generator is going back to a stable operating point. The reason the dots does not follow right on the P_e-curve is that the original P_e-curve is calculated at an assumed stable point t = 0 and therefore it is possible that they vary a little. The maximum rotor angle is 26.8 degrees compared to the stable equilibrium point that is at an angle of 12.3 degrees.

When this measurement was run in the algorithm, the algorithm responded with an alarm that there had been a fault but the system would remain stable, which was correct. But it had not yet been verified that the algorithm could predict Out-Of-Step conditions.

It is of high interest to confirm that an Out-Of-Step condition can be detected with the algorithm. With Runge-Kuttas iterative formulas it is possible to create different vectors with electric power output and rotor angle values. The vectors were constructed in MATLAB and run in the algorithm to confirm the capability of the algorithm.

In Figure 3-20 and Figure 3-21 power versus angle for two different cases with simulated values of the power and the rotor angle are shown.

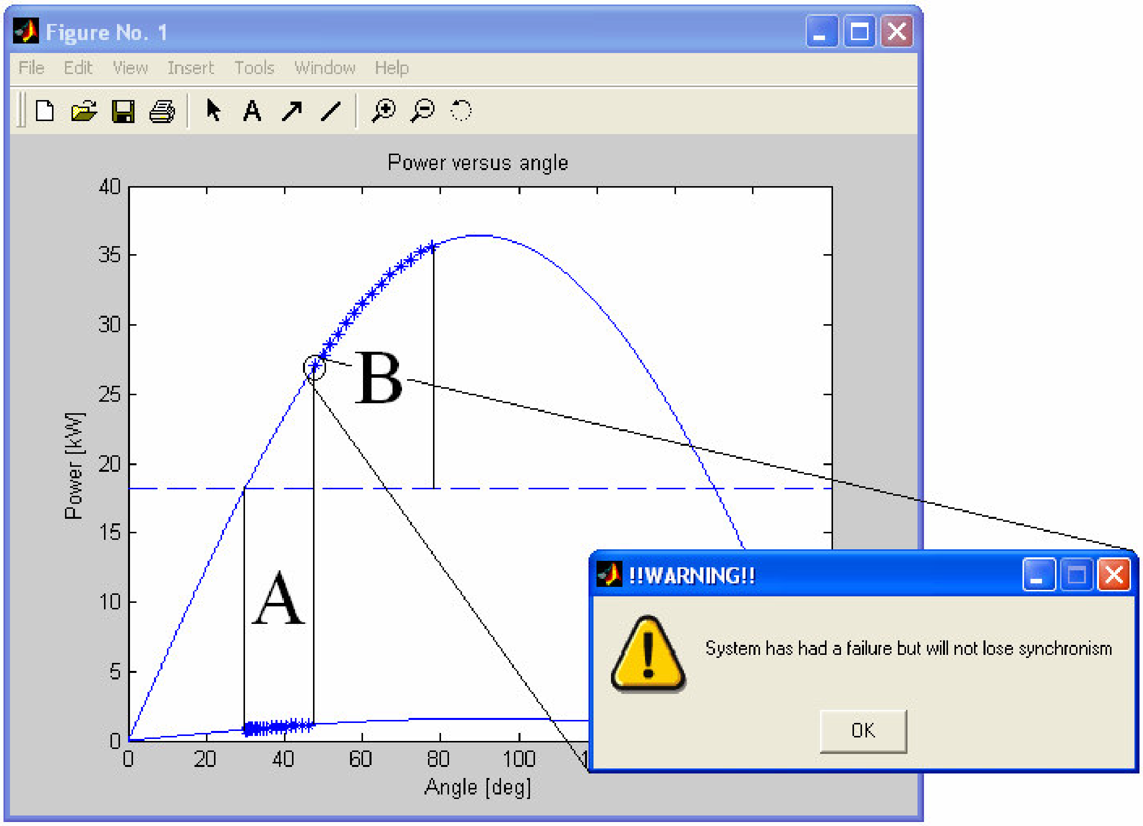


Figure 3-20: Fault is cleared before the critical fault clearing time

In Figure 3-20 a simulated fault is tested. The fault is cleared before the critical fault clearing time and the algorithm returns the message:
“System has had a failure but will not lose synchronism”

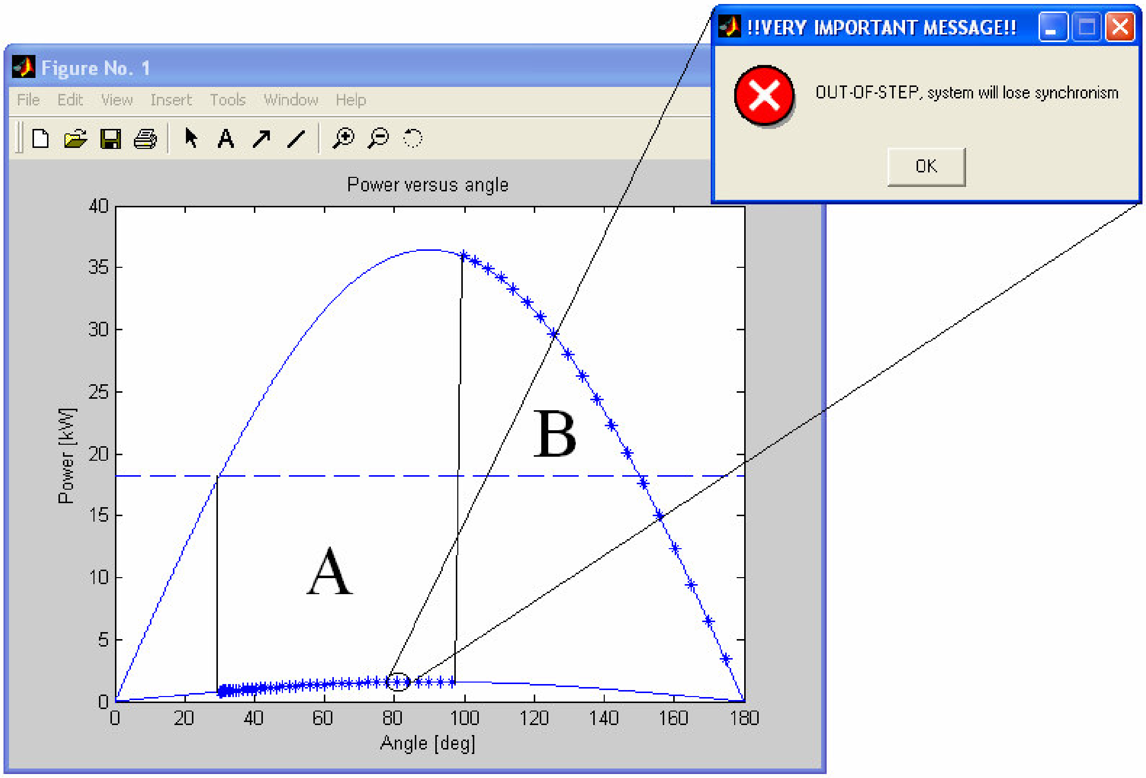


Figure 3-21: Fault is cleared after the critical fault clearing time

In Figure 3-21 another simulated fault is tested. The fault is cleared after the critical fault clearing time and the algorithm returns the message:
"OUT-OF-STEP, system will lose synchronism"
This message is displayed as soon as area A is larger than area B. In Figure 3-21 the message is displayed when the angle is 80.7 degrees.

The response from the algorithm is in both cases correct and it can therefore be assumed that the algorithm works correctly.

3.7 Electric Power Output after Fault

In the algorithm above it is assumed that the electric power output returns to its original curve as soon as the fault is cleared. This is a special case that only holds for rather specific faults. In a meshed system like the one in Figure 2-6 the power will probably not increase to the pre-fault curve as fault might be cleared on different lines at different times. In this section a scenario where the pre-fault and post-fault curve does not agree is discussed.

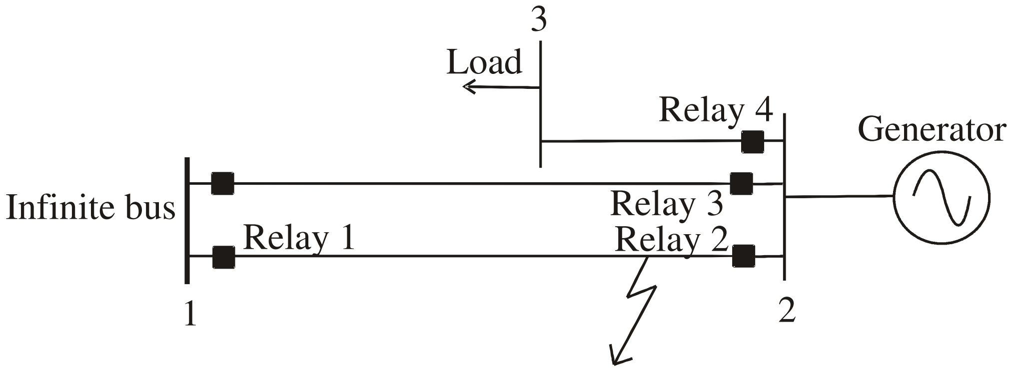


Figure 3-22: Fault in a larger network

In Figure 3-22 a larger network than the one described by the laboratory model is drawn. If a fault occurs between relay 1 and relay 2 and it is assumed that the circuit-breakers connected to relay 1 and 2 will open. After 100 ms circuit breaker to relay 2 opens, zone 1, after 500 ms circuit breaker to relay 1 opens, zone 2. The impedance between bus 1 and bus 2 changes as the relays are tripped. In Figure 3-23 the scenario above is drawn. At the instant of fault the electric power output goes from the stable equilibrium point to P_{e1}. After 100 ms relay 2 trips, the electric power output increases to P_{e2}. After another 500 ms relay 1 trips and the electric power output increases to P_{e3}. If the line later is successfully reconnected the output power moves up to curve P_{e4} depending on weather the faulted line will remain disconnected or will be reconnected.

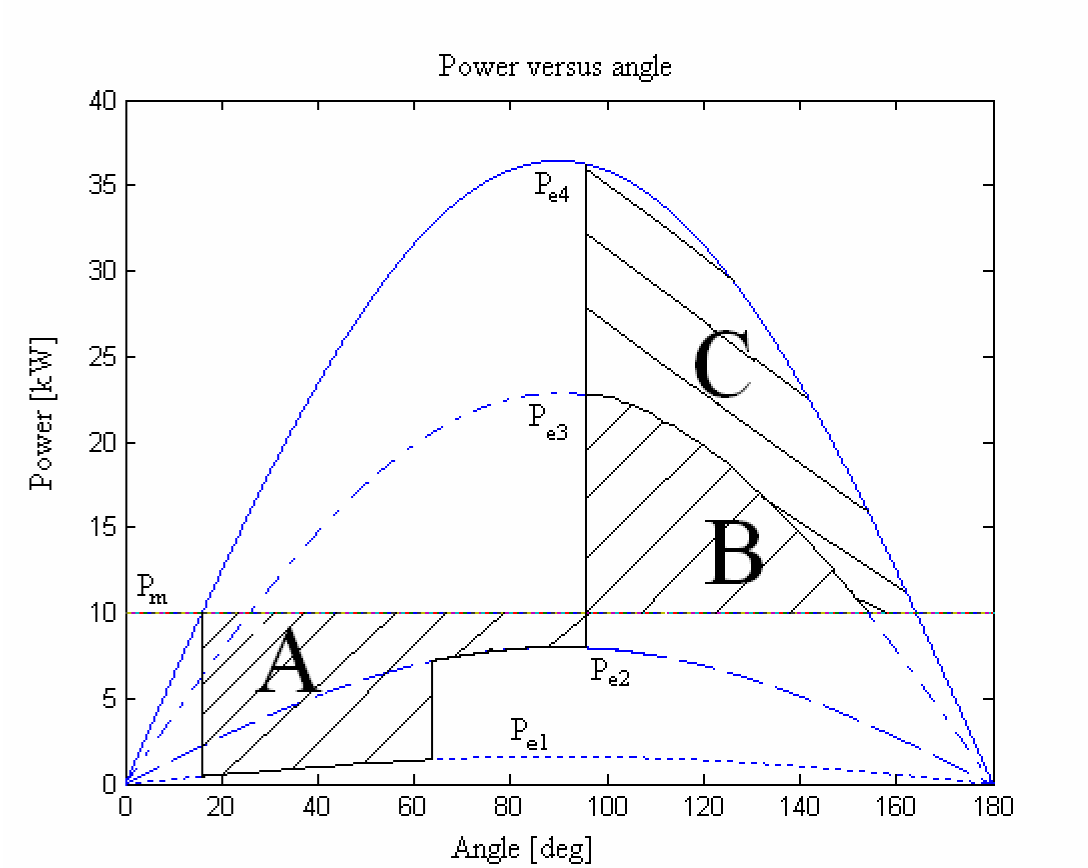


Figure 3-23: Electric power output, before fault, during fault and after fault is cleared

If the line remains disconnected the electric power output stays at P_{e3}, the remaining area is area B which is smaller than area A and the system will lose synchronism. The algorithm explained in Section 3.5 had in this case only detected a fault and not an Out-Of-Step condition because area A is smaller than area B plus area C. The total area of area B plus area C is only possible if the line is reconnected after 500 ms.

3.8 Results

The results of the measurement and the workability of the algorithm are good. From Figure 3-18 it is clear that the equal area criterion works for power swings. Therefore it is possible to use this criterion in an algorithm to determine Out-Of-Step conditions.
The algorithm responded correctly both with data from the laboratory measurements and values that were constructed iteratively. This shows the capability of the program.
When executing the theoretical calculation a mechanical power output of 50 % was used. In the measurements the mechanical power output was much lower, 25.3 %. Therefore the fault clearing time can be much longer than 620 ms before the critical fault needs to be cleared.

3.9 Conclusions

The results of the measurements and the algorithm are good. The measured data from the PMU was accurate and easy to read into a Matlab program. Even though the algorithm received a 10 minute interval with data sets it could easily handle the data and calculate the voltage phase angles and the power flow at each time step. The data, as seen in the figures, could easily be viewed in graphs with Matlab. From the results the conclusion that it is possible to detect power swings and predict Out-Of-Step condition with the PMU can be drawn.

4 Discussion

This thesis presents an alternative way to detect power swings and oscillations. By using a Phasor Measurement Unit instead of a distance relay it is possible to get more details of the parameters in the power system network. The parameters given by the PMU are very useful to detect power oscillations and to predict Out-Of-Step conditions.
Since the PMU is a rather new development and only tests have been done with the device in a real network, this thesis has tried to, by laboratory experiment, come a little bit further in the development by making an algorithm that can detect and predict Out-Of-Step conditions.
The results of the measurements show that the equal-area criterion is a useful method to predict loss of synchronism in a network. The equal-area criterion is therefore a reliable device in the mathematical algorithm to predict the dangerous condition.

5 Conclusions

In this thesis stability and fault analysis have been studied. Out-Of-Step conditions and power swings in the power system has been the principle focus. Existing protection for these conditions and new ways to protect the power systems from these events have been reviewed.

The conclusion is that the PMU has great potential to be a useful measurement unit to detect Out-Of-Step conditions in the complex power system networks that are used today. The data from the PMUs are reliable and very useful to calculate the parameters needed to determine Out-Of-Step conditions with the equal-area criterion. In this thesis it is verified that it is possible to create an algorithm that can detect power swings on a one machine against infinite bus from the data given by the PMU.

6 Future Work

There are many ways to improve the development of implementing PMUs in a power system. Examples for future work both with the PMU and the algorithm are listed below.

The experiments in this thesis included one machine against infinite bus and one PMU measuring at two busses on a transmission line. It would be interesting to make experiments or simulations on larger networks that include more generators and machines and to find possible nodes to implement PMUs.
The PMU is today measuring at every cycle of the fundamental frequency 50/60 Hz, every 20/16.67 ms, future work could be to increase the rate of measurement to get more than one measure every cycle. This increased measuring rate could improve the algorithm for detecting and predicting power swings.

Another path is to develop the algorithm. The algorithm has not been run side by side with an ongoing laboratory experiment. As mentioned in the thesis the algorithm should get values every 20 ms and be able to work together with the PMU and not with a data sheet afterwards.
The algorithm needs to be developed further to be able to handle data from several PMUs.
The algorithm also needs further development to be able to handle different electric power output levels after the fault clearance.

The algorithm in this thesis was based on the equal-area criterion an extension of the algorithm is to also make decisions dependent on the velocity and the acceleration of the rotor angle. To be able to work with these parameters iterative methods like Runge-Kuttas iterative method, used in this thesis, are good mathematical working tools.

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[14] Petersson J., *Matematisk analys del 2*[*]

Appendix A: Derivation of Power Transfer over a Transmission Line

To calculate active and reactive power flows in simple networks with few nodes the two-port equations are used.

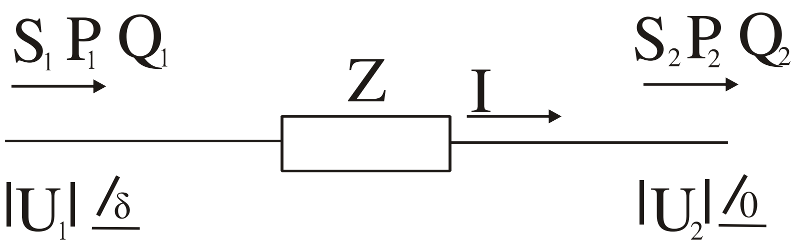

Figure A-1: 2-node network

S_1 = Apparent power at node 1 [VA]
P_1 = Active power at node 1 [W]
Q_1 = Reactive power at node 1 [VAr]
$|U_1|$ = Absolute value of voltage at node 1 [V]
S_2 = Apparent power at node 2 [VA]
P_2 = Active power at node 2 [W]
Q_2 = Reactive power at node 2 [VAr]
$|U_2|$ = Absolute value of voltage at node 2 [V]
I = Current flowing from node 1 to node 2 [A]
Z = Impedance over transmission line between node 1 and node 2 [Ω]
δ = transmission angel [deg]

The impedance, Z, contains one real part, resistance R and one imaginary part, reactance X, i.e. Z = R + jX.

ε' is the impedance angle, it is defined as:

$$\varepsilon' = \arctan\left(\frac{X}{R}\right) \qquad \textbf{A-1}$$

The loss angle ε is defined:

$$\varepsilon = \frac{\pi}{2} - \varepsilon' \qquad \textbf{A-2}$$

See figure A-2 for impedance angle and loss angle.

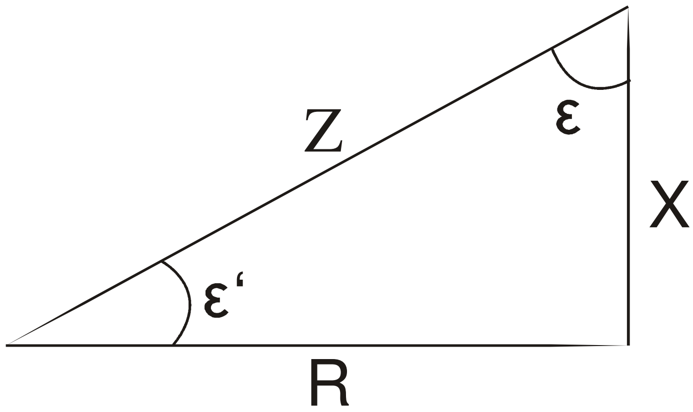

Figure A-2: Impedance angle and loss angel

The apparent power can be expressed as:

$$S_1 = P_1 + jQ_1 = U_1 I^* \qquad \textbf{A-3}$$
$$S_2 = P_2 + jQ_2 = U_2 I^* \qquad \textbf{A-4}$$

I^* = Complex conjugate of the current [A]

Equation A-3 can be rewritten using absolute values of voltage and impedance seen in Figure A-1.

$$\begin{aligned} S_1 &= U_1 I^* = U_1 * \left(\frac{U_1^* - U_2^*}{Z^*} \right) = \\ &= |U_1| e^{j\delta} * \frac{|U_1| e^{-j\delta} - |U_2| e^{j0}}{|Z| e^{-j\varepsilon'}} = \\ &= \frac{|U_1|^2 e^{j\varepsilon'} - |U_1||U_2| e^{j\delta} e^{j\varepsilon'}}{|Z|} = \left\{ \varepsilon' = \frac{\pi}{2} - \varepsilon \right\} = \frac{|U_1|^2 e^{j(\frac{\pi}{2} - \varepsilon)}}{|Z|} - \frac{|U_1||U_2| e^{j(\delta + \frac{\pi}{2} - \varepsilon)}}{|Z|} \end{aligned} \qquad \textbf{A-5}$$

S_2 is calculated in a similar way.

Equation A-5 can be rewritten in a real, active power transfer, and an imaginary, reactive power transfer, using trigonometric functions. Equations A-6 and A-7 describe the rewriting of the trigonometric functions and A-8 and A-9 the active and reactive power flows at node 1.

$$e^{j\left(\frac{\pi}{2}-\varepsilon\right)} = \left(\cos\left(\frac{\pi}{2}-\varepsilon\right) + j\sin\left(\frac{\pi}{2}-\varepsilon\right)\right) = (\sin\varepsilon + j\cos\varepsilon) \qquad \textbf{A-6}$$

$$\begin{aligned} e^{j\left(\delta+\left(\frac{\pi}{2}-\varepsilon\right)\right)} &= \left(\cos\left(\delta+\left(\frac{\pi}{2}-\varepsilon\right)\right) + j\sin\left(\delta+\left(\frac{\pi}{2}-\varepsilon\right)\right)\right) = \\ &= \cos\delta\sin\varepsilon - \sin\delta\cos\varepsilon + j\sin\delta\sin\varepsilon + j\cos\delta\cos\varepsilon = \\ &= \sin(\varepsilon-\delta) + j\cos(\varepsilon-\delta) = -\sin(\delta-\varepsilon) + j\cos(\delta-\varepsilon) \end{aligned} \qquad \textbf{A-7}$$

$$P_1 = \frac{|U_1|^2 \sin(\varepsilon)}{|Z|} + \frac{|U_1||U_2|\sin(\delta-\varepsilon)}{|Z|} \qquad \textbf{A-8}$$

$$Q_1 = \frac{|U_1|^2 \cos(\varepsilon)}{|Z|} - \frac{|U_1||U_2|\cos(\delta-\varepsilon)}{|Z|} \qquad \textbf{A-9}$$

Appendix B: Runge-Kuttas Iteration Formula

Runge-Kuttas iteration method[14]:

First order differential Equation:

$$\frac{dx}{dt} = f(x,t) \qquad \textbf{B - 1}$$

To determine next value x_1 at a time Δt, the starting time at t_0 and starting value x_0 must be known.

$$x_1 = x_0 + \Delta x = x_0 + \frac{k_1 + k_2}{2} \qquad \textbf{B - 2}$$

The constants k_1 and k_2 are defined as:

$$\begin{aligned} k_1 &= f(x_0, t_0)\Delta t \\ k_2 &= f(x_0 + k_1, t_0 + \Delta t)\Delta t \end{aligned} \qquad \textbf{B - 3}$$

The general formula gives:

$$x_{n+1} = x_n + \frac{k_1 + k_2}{2} \qquad \textbf{B - 4}$$

[14] Matematisk analys

Appendix C: Voltage Transformer Design and Assembly

When building an instrument voltage transformer important features are how low the losses can be kept and how exact the voltage transformation can be made. To reduce the losses a high apparent power (high VA-value) requirement can be set on the transformer. The accuracy of the voltage transformation can vary with different transformer types. In this transformer construction a toroidal type is used. Another feature is the financial part of this project. The VA-value of the transformer is proportional to the cost, to keep the expenses low a lower VA-value was chosen.

Material List

Table C-1: Material list

Quantity	**Type**
1	Connection box
3	Toroidal single phase transformers
12	Terminal blocks
1	Mounting rail
1	Mounting plate
3	Rubber insulation plates
10	Cable spouts
10	Cable lugs
3	4 A, slow fuses
6	0.25 A, fast fuses
8	Screws
5 meters	1.5 mm² Cable

Connection Diagram

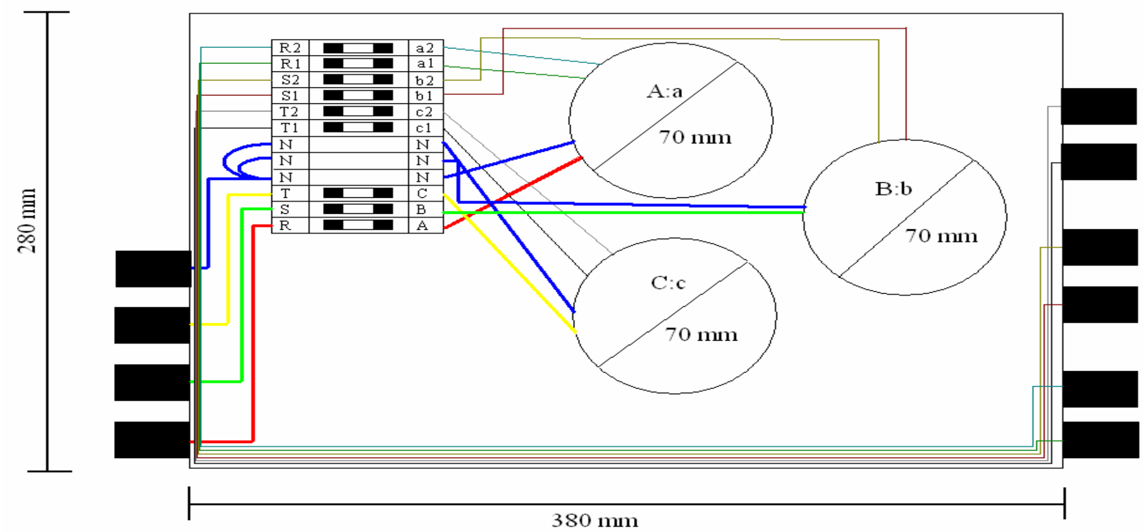

Figure C-1: Connection diagram of a three phase instrument transformer

In Figure C-1 the connection diagram of an instrument transformer is shown. The primary side of the transformer is a Y connection through a slow 4 A fuse. The size of the fuse is dependent on the load current and energizing current of the transformer. The secondary side of the instrument transformer is connected to the PMU. The inputs of the PMU are high impedances and thereby carry a low current. A fast 0.25 A fuse will be enough to protect the measurement device. The PMU measures each phase voltage separately, the cables from each toroidal transformer is prolonged through the fuse.

Figure C-2: Voltage instrument transformer

The two voltage transformers that were built for this master thesis worked as they were supposed to in the circuit. Worth mentioning is that the voltage on the secondary side was a little higher that expected, 66 V instead of 63 V phase to ground, the PMU has a calibration factor and therefore it is possible to correct this mismatch.

Appendix D: MATLAB program, theoretical calculation

```
clc
clear all
close all

V1 = 400;
V2 = 400;
X = 4.391;
X1 = 100;
H = 5.56;
Sb = 75000;
delta = [0:0.01:180];
delta1 = [0:2:180];
N=length(delta);
Pe = (V1*V2/X).*sin(delta*(pi/180));
Penew = (V1*V2/X1).*sin(delta*(pi/180));
Pemax= (V1*V2/X)*sin(90*(pi/180));
Penewmax = (V1*V2/X1)*sin(90*(pi/180));

for t = 1:N
   Pm(t) = 0.5*Pemax;
end

figure(1)
plot(delta,Pe/1000)
hold on
plot(delta,Pm/1000,'--')
hold on
plot(delta,Penew/1000)
hold on
delta0=asin((Pm(1)*X)/(400*400));
delta2=pi-delta0;
delta1=acos(((Penewmax+Pemax)/(Penewmax-Pemax))*cos(delta0)-(Pm(1)/(Penewmax-
Pemax))*(pi-2*delta0));
plot(delta1*(180/pi),(Penewmax*sin(delta1):Pemax*sin(delta1))./1000)
hold on
plot(delta0*(180/pi),(0:Pm(1))./1000)
hold on
plot(delta2*(180/pi),(0:Pm(1))./1000)
axis([0 180 0 40])
title('Power versus angle')
xlabel('Angle [deg]')
ylabel('Power [kW]')
```

```
%Runge-Kutta
k1 = zeros(1,1000);
k11 = zeros(1,1000);
k2 = zeros(1,1000);
k22 = zeros(1,1000);
tid = zeros(1,1000);
tid(1)=0;
vinkelhastighet = zeros(1,1000);
vinkel = zeros(1,1000);
k1(1) = (1/(2*H))*((Pm(1)/Sb)-(Penewmax/Sb)*(sin(44.2*(pi/180))))*0.02;
k11(1) = (2*pi*0)*0.02;
k2(1) = (1/(2*H))*((Pm(1)/Sb)-(Penewmax/Sb)*(sin((44.2*(pi/180))+k1(1))))*0.02;
k22(1) = (2*pi*50)*(0+k11(1))*0.02;
vinkel(1)=(44.2*(pi/180));
vinkelhastighet(1)=0;

for n = 2:1000
   vinkel(n)=vinkel(n-1)+(k11(n-1)+k22(n-1))/2;
   vinkelhastighet(n)=vinkelhastighet(n-1)+(k1(n-1)+k2(n-1))/2;
   k1(n) = (1/(2*H))*((Pm(1)/Sb)-(Penewmax/Sb)*(sin(vinkel(n))))*0.02;
   k11(n) = (2*pi*vinkelhastighet(n))*0.02;
   k2(n) = (1/(2*H))*((Pm(1)/Sb)-(Penewmax/Sb)*(sin(vinkel(n))+k1(n)))*0.02;
   k22(n) = (2*pi*50)*(vinkelhastighet(n)+k11(n))*0.02;
   tid(n)=tid(n-1)+0.02;
   if vinkel(n-1)<=delta1 && delta1<=vinkel(n)
      n
   end
end

figure(2)
subplot(2,1,1);
plot(tid(1:100),vinkel(1:100).*(180/pi))
hold on
plot(tid(32),vinkel(32)*(180/pi),'*r')
text(tid(32)+0.05,vinkel(32)*(180/pi),' \leftarrow t = 620 ms delta 1 = 81.3
degrees','FontSize',10)
title('Time versus angle')
xlabel('time [s]')
ylabel('angle [degrees]')
subplot(2,1,2);
plot(tid(1:100),vinkelhastighet(1:100).*(180/pi))
title('Time versus angle velocity')
xlabel('time [s]')
ylabel('angle velocity [electrical rad/s]')
```

Appendix E: Out-Of-Step Detection Algorithm

```
clc
clear all
close all

% Reed excel sheet to MATLAB
x=xlsread('Meassure3');

%(Re_Vs1,Im_Vs1,Re_Vs2,Im_Vs2,Re_I1,Im_I1,Re_I2,Im_I2,Frequency,dFdt)
Re_Vs1=[x(:,1)'];
Im_Vs1=[x(:,2)'];
Re_Vs2=[x(:,3)'];
Im_Vs2=[x(:,4)'];
Re_I1=[x(:,5)'];
Im_I1=[x(:,6)'];
Re_I2=[x(:,7)'];
Im_I2=[x(:,8)'];

% Create vectors of correct length containing zeros
N = length(Re_Vs1);
time = zeros(1,N);
psi = zeros(1,N);
delta = zeros(1,N);
Varians = 100;
tspan = 0.02;
Area1 = zeros(1,N);
Area2 = zeros(1,N);
vinkel = [0:0.001:180];
vink = [0:2:180];
P1exaktnew= zeros(1,N);
P1exaktnew1 = zeros(1,N);
psi1 = zeros(1,N);
Constant = zeros(1,N);
Pm=zeros(1,N);
teta = zeros(1,N);

%Time vector
for n = 0:N-1
   time(n+1)=0.020*n;
end

%Complex voltage and current
V1 = complex(Re_Vs1,Im_Vs1)./sqrt(3);
V2 = complex(Re_Vs2,Im_Vs2)./sqrt(3);
```

```
I1 = complex(Re_I1,Im_I1)./8.8;
I2 = complex(Re_I2,Im_I2)./8.8;

% Put psi-angle in 1st quadrant always
for n = 1:N
   if imag(V1(n))>= 0 && imag(V2(n))>= 0
      psi(n) = angle(V1(n)) - angle(V2(n));
      if psi(n)<=0 || psi(n)>(50*pi/180)
         psi(n)=psi(n+1);
      end
   elseif real(V1(n))<= 0&&imag(V1(n))<= 0&&real(V2(n))<= 0 && imag(V2(n))>= 0
      psi(n) = (2*pi + angle(V1(n)))-angle(V2(n));
      if psi(n)<=0 || psi(n)>(50*pi/180)
         psi(n)=psi(n+1);
      end
   elseif imag(V1(n))<= 0 && imag(V2(n))<= 0
      psi(n) = (2*pi+angle(V1(n)))-(2*pi+angle(V2(n)));
      if psi(n)<=0 || psi(n)>(50*pi/180)
         psi(n)=psi(n+1);
      end
   elseif real(V1(n))>= 0&&imag(V1(n))>= 0 && real(V2(n))>= 0 && imag(V2(n))<= 0
      psi(n) = angle(V1(n))-angle(V2(n));
      if psi(n)<=0 || psi(n)>(50*pi/180)
         psi(n)=psi(n+1);
      end
   end
end

%Correct invalid current values
for n = 1:N
   if I1(n) == 0
      I1(n) = I1(n-2);
   end
end

%Calculate impedance
Impedance = (abs(V1).*exp(i*psi)-abs(V2))./(abs(I1));

%Calculate delta-angle, angle between real and imaginary impedance
for n = 1:N
   if imag(Impedance(n)) == 0
      delta(n) = pi/2;
   else
      delta(n) = atan(real(Impedance(n))/imag(Impedance(n)));
   end
end
```

```
%Calculate the power in sending and receiving end
P1exakt =
(((((abs(V2)).^2)./(abs(Impedance))).*sin(delta))+((((abs(V1)).*(abs(V2))./(abs(Impedan
ce)))).*sin(psi-delta)));
P2exakt = (-
(((abs(V1)).^2)./(abs(Impedance)).*sin(delta))+(((abs(V1)).*(abs(V2))./(abs(Impedance))
).*sin(psi+delta)));
P1gen =
(((((abs(V2(1)))^2)/(abs(Impedance(1))))*sin(delta(1)))+((((abs(V1(1)))*(abs(V2(1)))/(a
bs(Impedance(1)))))*sin((pi/2)-delta(1))));

for n = 1:N
        Pm(n)=(((((abs(V2(1)))^2)/(abs(Impedance(1))))*sin(delta(1)))+((((abs(V1(1)))*(
        abs(V2(1)))/(abs(Impedance(1)))))*sin(psi(1)-delta(1))));
end

psistabil = psi(n);

for n=1:N
   if P1exakt(n) < 0
      P1exakt(n) = 0;
   end
end


for n = 6200:N-1
   if abs(psi(n)-psi(n+1))<0.0017
   else
      start = n+1;
      break
   end
end

figure(1)
plot(1:N,psi*(180/pi))

for m = start:N
   if P1exakt(m) < Pm(m) && psi(m) > psistabil
      Constant(m)=P1exakt(m)/sin(psi(m));
      P1exaktnew(m) = Constant(m)*sin(pi/2);
      Area1(m)=Area1(m-1)+Pm(m)*(psi(m)-psi(m-1))+P1exaktnew(m)*(cos(psi(m))-
cos(psi(m-1)));
      Area2(m)=P1gen*(cos(psi(m))-cos(pi-psistabil))-Pm(m)*(pi-psistabil-psi(m));
      mellan = m;
      if Area1(m) > Area2(m)
```

```
        msgbox('OUT-OF-STEP, system will lose synchronism','!!VERY IMPORTANT
MESSAGE!!','error') %Dialog box
        break
      end
   elseif P1exakt(m)>Pm(m) && psi(m) > psistabil
      if psi(m)>psi(m-1)
        Constant(m)=P1exakt(m)/sin(psi(m));
        P1exaktnew(m) = Constant(m)*sin(pi/2);
        Area1(m)=Area1(m-1);
        Area2(m)=P1exaktnew(m)*(cos(psi(m))-cos(psi(m-1)))-Pm(m)*((psi(m)-psi(m-
1)));
      else
        stop=m-1;
        maxangle = psi(m-1);
        figure(start)
        plot(vinkel,P1gen*sin(vinkel*(pi/180))./1000)
        hold on
        plot(vinkel,Pm(1)./1000)
        hold on
        for s = start+1:stop
          teta(s)=psi(s)*(180/pi);
          plot(teta(s),P1exakt(s)/1000,'*')
          hold on
        end
        for s = start+1:start+200
          teta(s)=psi(s)*(180/pi);
          plot(teta(s),P1exakt(s)/1000,'b.')
          hold on
        end
        for s = start+1:stop
          plot(vinkel,P1exaktnew(s)*sin(vinkel*(pi/180))./1000,'--')
          hold on
        end
        plot(psi(start+1)*(180/pi),Pm(1)/1000,'*')
        axis([0 40 0 5])
        title('Oscillating power')
        xlabel('Angle [deg]')
        ylabel('Power [kW]')
        msgbox('System has had a failure but will not lose
synchronism','!!WARNING!!','warn')
        break
      end
   end
end
```