CONDITION BASED MONITORING FOR PROTECTION SYSTEM

by

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Dissertation submitted in partial fulfilment of
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CERTIFICATION OF APPROVAL

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DECEMBER 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

AHMAD ALIFF IRWAN BIN ZAKARIA

ABSTRACT

The objective of this project is to implement Condition Based Monitoring into Power System Protection. This project is focusing on the distribution level protection system with 11kV voltage rating. Our aim is to improve the method of detecting the fault that happens in the protection system, by applying CBM. With this, we suppose to be able to identify the malfunction within the system and prevent it from happening. This is important because when the malfunction happens it can disable the protection system and cause the whole system unprotected. Other instrument may be damaged which later require maintenance or even replacement and this means waste of production time and money. To capture the objective of this project, we first need to have the understanding about what is protection system and CBM. Then, using the knowledge and the understanding on the topic, we need to list the potential sources that can cause malfunction to happen or any potential cause that can disable/damage the protection system. This data need to be origined from the actual maintenance data such as statistic on the type of failure, root cause and the frequency of the failure. By analyzing these data, we can determine the suitable method that can be implemented to prevent these failures.

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In the name of Allah, the Most Graceful and Most Merciful

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LIST OF ABBREVIATIONS

CB	Circuit Breaker
V	Voltage
I	Current
R	Resistance
CM	Corrective Maintenance
PM	Preventive Maintenance
CBM	Condition Based Monitoring
AC	Alternative Current
DC	Direct Current
VCB	Vacuum Circuit Breaker
MTBF	Mean Time between Failures
LIRA	Line Resonance Analysis

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Power system protection is deal with the protection of electrical equipment in electrical power system from faults by isolating the faulted part from the healthy parts of electrical network. If the fault is not isolated, it will affect other equipments and damaged them before disabling the whole power system network. [01]

The objective of a protection system is to keep the power system remains in stable condition by isolating the faulted equipment in shortest time as possible. By doing this, we can keep the network in service and the status of the equipment will be ensured to be saved from further damage. The second objective of a protection system is to minimize interruptions. To minimize the interruption the protective device must be selective, to be able to decide and to isolate only the faulted equipment and not the healthy equipments. This is because the objective in protection system is to keep the system in good condition as possible and still be running even when fault happen.

There are two basic components in protection system which are:

- Sensing device
- Relay

In this project, I am conducting a study that involves the application of condition based monitoring via online onto the protection system. The concept of condition based monitoring is evaluating the equipment using real time data that obtained via online then use it to evaluate the condition of the equipment without have to take out the equipment. The normal practice is, you have to take the equipment from service to check its condition. This practice will cause the network to be halted in the period of the maintenance.

Currently electrical equipment such as relay is still not readily assessable using this online monitoring technique. These electrical equipments are part of protection system, so if the online condition based monitoring can be applied it can help us to monitor the whole protection system process and condition of the whole system. This then will allows us to avoid a fault from happening and ensure the safeguard of the equipments rather than isolating it when it already occurred.

1.2 Problem Statement

The normal practice in maintaining the protection system nowadays require maintenance interval which is the schedule of the maintenance based on time interval that is decided by the previous condition of the equipment recorded. We can only check the equipment condition when we perform the routine maintenance, but in between that, we do not know what is happening. We may do a maintenance check up routine today but a fault may happen just after we finished our maintenance and causing damage to the equipment.

Also, the more frequent the maintenances are done, the higher the cost will be. When performing maintenance, we have to consider the cost of man power, the cost of maintaining the equipments and the cost when we halted the network. Why do we need to halt the network? It is due to the maintenance procedure of the normal routine maintenance check. We have take the equipment off the network to avoid any damage to happen to the whole system or even damage to the maintenance personal that is conducting the check. This means that during maintenance interval it is non-productive period.

One of the solutions is by using online condition based monitoring. But as for the protective electrical equipments such as relay, it is not as readily assessable using this technique.

1.3 Objective and Scope of Study

The objective of this project is to apply the online condition based monitoring onto protection system devices. This will allow us to obtain and gather the real time data and use them to do the analysis to determine the condition of the protection equipment. This will help us to get rid the concept of maintenance interval, save the costs of the whole process and remain the system to be in operation without having to remove the equipment while we gathering the data.

My work scopes is include the study on the protection system equipments, the condition based monitoring process, performing and creating the procedure to apply this system onto protection equipments and to do several related analysis.

CHAPTER 2
LITERATURE REVIEW

2.1 Protection System

The purpose of a protection system is to isolate faulted electrical component from affecting other healthy parts within the shortest time as possible. This is to ensure the safeguard of the equipment while keeping as much network as possible to still be in operation. [02] An unprotected system also can affect human life and its surrounding. When a fault happens, the possibilities of arching, flashover or equipment to explode are high. This will result in damage not only to the equipment itself but also to human, animals and other things around it.

There are two basic components in protection system which are:

- Sensing device
- Relay

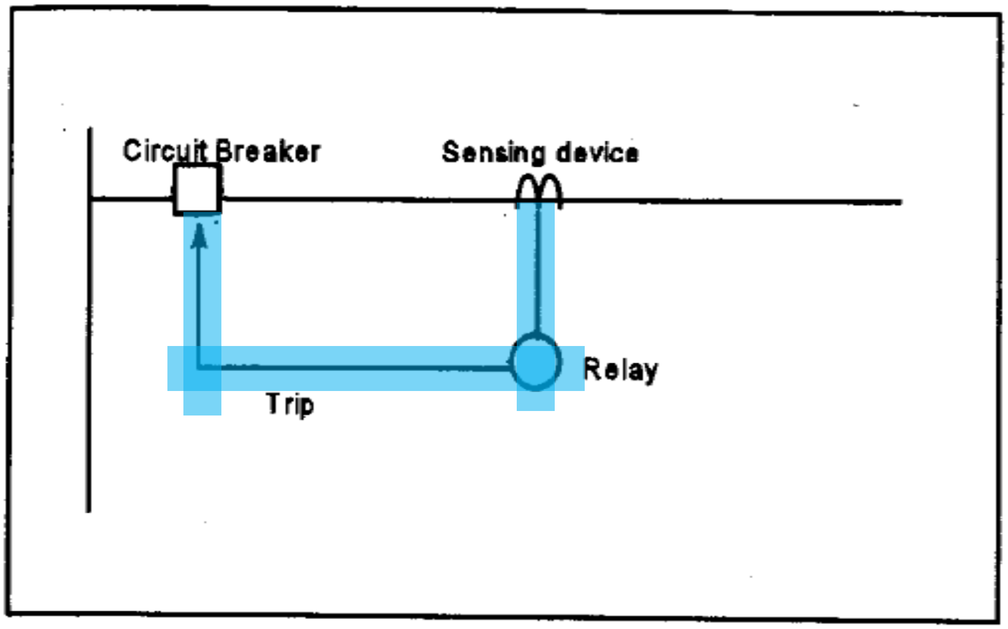


Figure 1: Components in Protection System

The scope of protection system covers from the output part of the current transformer, relay and tripping circuit. Sensing device (current transformer) and circuit breaker are excluded from protection system because it falls under primary equipment category.

So in this project, I will only focus on those parts and excluding the current transformer and circuit breaker. As you can see in the figure 1 (highlighted parts), those are the section which covers by protection system. Later on, I will explain more about the components that included at those areas.

So, how does a circuit breaker trip? What cause it to operate? To gains the understanding about the system, we can follow the operation flows in the diagram below.

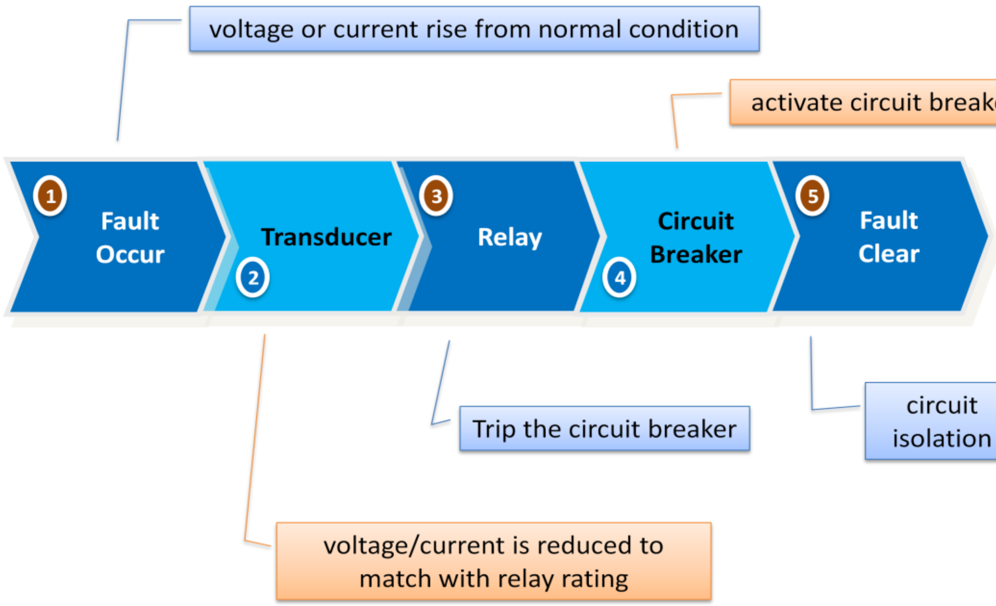


Figure 2: Operation Flow of Circuit Breaker Tripping

First, when a fault happens, it will cause the voltage or current level to rise (spike) from the normal condition. This can be explained based on the Ohm's law: **V= I/R.** Fault are the result of short circuit, and short circuit means resistance is small. So, when R is minimum, current, I will increase. This increment can be detected/sense by the sensing devices. Transducer works by lowering the voltage/current value to the level where it matches the relay rating. As for the current, the normal relay rating values are from 1- 5 amp.

When the relay is operated, it will initiate the tripping circuit to activate the circuit breaker which will break the circuit. This is to isolate the fault from spreading to other parts of the equipment. The shorter time taken to isolate the fault, the better the system is.

2.2 Types of Maintenance

RCM or Reliability Centered Maintenance is a scheduled maintenance program to optimize system reliability. As for inexpensive and non-critical equipments, the CM method will be applied. While the expensive and critical equipments, they will use either PM or CBM. [5]

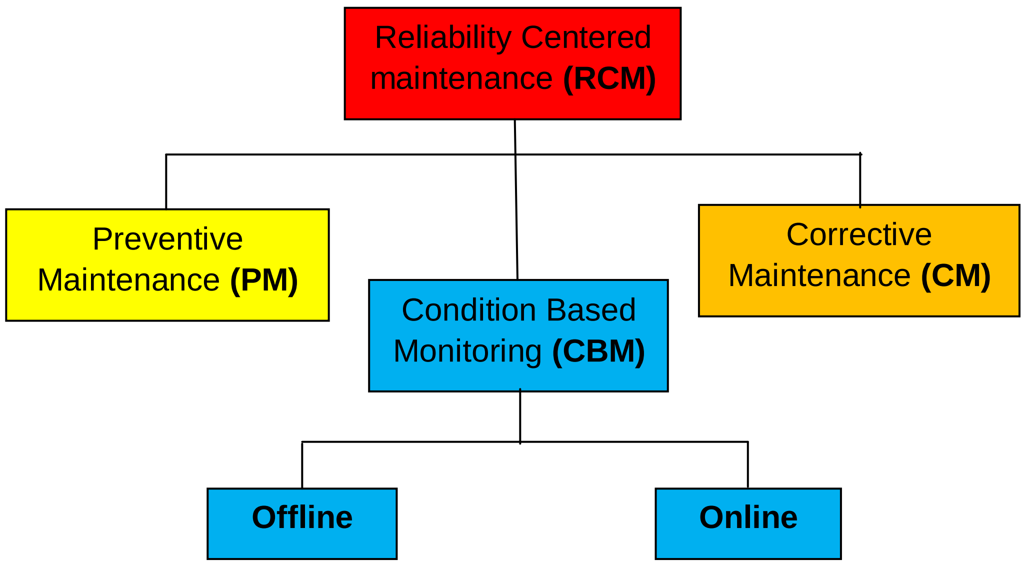


Figure 3: Simplified Block Diagram of RCM

Corrective Maintenance (CM) is the most commonly used type of maintenance. This type of maintenance is applied only when the equipment already faulty. The purpose of this maintenance is to repair and to correct the problem of the equipment, usually results in replacing the components. Example of the equipment that used this type of maintenance is light bulb and small exhaust fans.

Another type of maintenance is the Preventive Maintenance (PM) which is a calendar-based maintenance that means that the equipment is tested on periodic basis, for example – annually. The main concerns about the preventive maintenance are time and cost. This type of maintenance is balanced based on these two points. For example in case of lubricating oil for a car, it needs to be change for every 3000 miles or every 6 months whichever come first. We can change it earlier but it will increase the maintenance cost. Here we can observe that preventive maintenance does not focus of the condition of the lubricating oil itself but just on the time interval and cost. [6]

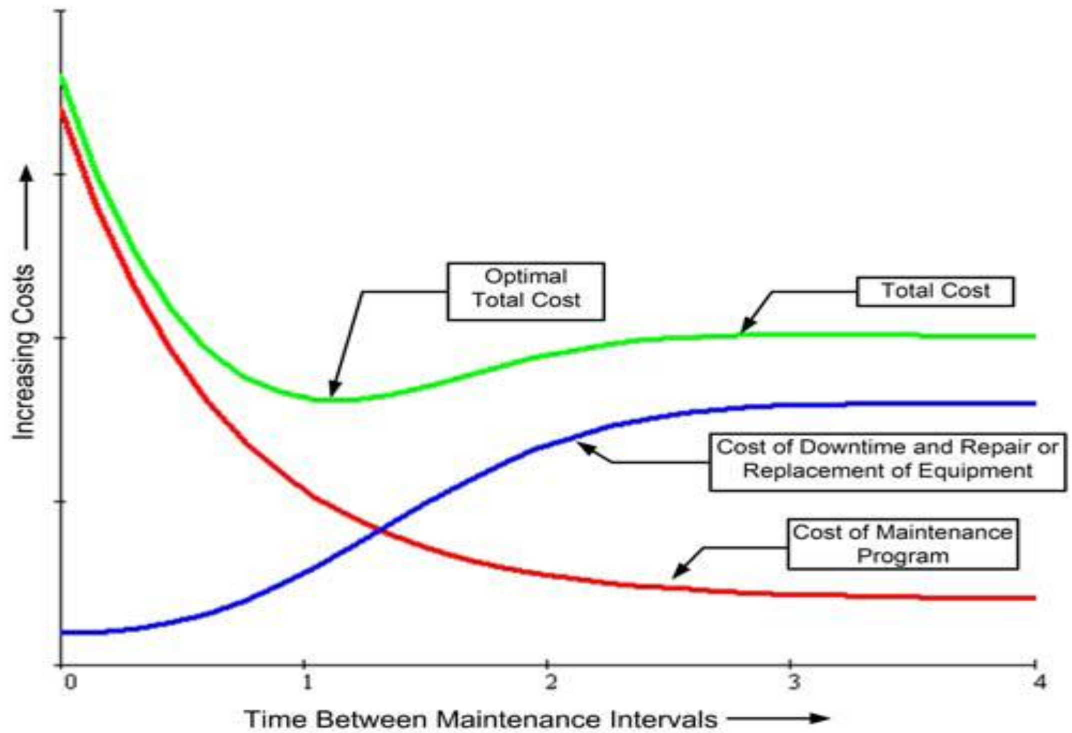


Figure 4: Cost versus Maintenance Intervals

2.2.1 Condition Based Monitoring, CBM

CBM is the process of gathering and monitoring the information available from the desired components. These components generate monitoring information during normal operation (without need to shutdown the operation), and the information can be assessed at a convenient location remote from the substation. The information can came from:

- Diagnostic and performance data
- Maintenance history
- Operator/event logs
- Design data

All this data are required to make timely decisions about maintenance requirements of major/critical equipment. This methodology is often regarded as having existed for many years, it is in fact a recently developed methodology that has evolved over the past three decades from precursor maintenance methods.[7]

CBM is using the assumption that all equipment will worsen and that partial or complete loss of function will occur. CBM monitor the condition or performance of equipment through the data that gathered, analyzed, trended and used to predict equipment failures. When the failure is predicted, the action to prevent or delay it from happening can be taken. That is why CBM is said to be able to increase the reliability of the equipments.

The main goal of CBM is to optimize the reliability level of the equipments. To obtain that, we need to determine the need for maintenance activities based on equipment's condition. CBM assumes that equipment has indicators that can be monitored and analyzed to determine the need for condition directed maintenance activities. CBM allows the lowest cost and most effective maintenance programme by determining the correct activity at the correct time. The advantages of CBM are including these:

- Non-invasive Maintenance:

  Experience has shown that keeping human hands away from equipment known to be working correctly enhances reliability of the system. By using CBM, the system is kept in its normal operating state, without human intervention for checking. Therefore, it will reduce the risk of damage, or risk of leaving the system in an inoperable state after a manual test.

- Virtually Continuous Monitoring:

  CBM can report component failure problems within seconds or minutes of when they happen. This will reduce the percentage of problems that are discovered through incorrect relaying performance. By contrast, a component failure discovered by normal maintenance (CM or PM) may have been there for much of the time interval between tests. The frequent or continuous nature of CBM makes the effective verification interval far shorter than any required CM maximum interval.

To further explaining the concept of CBM, we can refer the example about the lubricating oil earlier, if we can do a test to evaluate the condition of the lubricating oil, we may able to extend its usage for another 1000 miles which definitely save cost by increasing its time period.

CBM is still in the introduction stage, many developments and researches are done regarding this type of maintenance. The goal of this project is to be able to apply CBM into protection system.

CHAPTER 3

METHODOLOGY

3.1 Procedure Identification

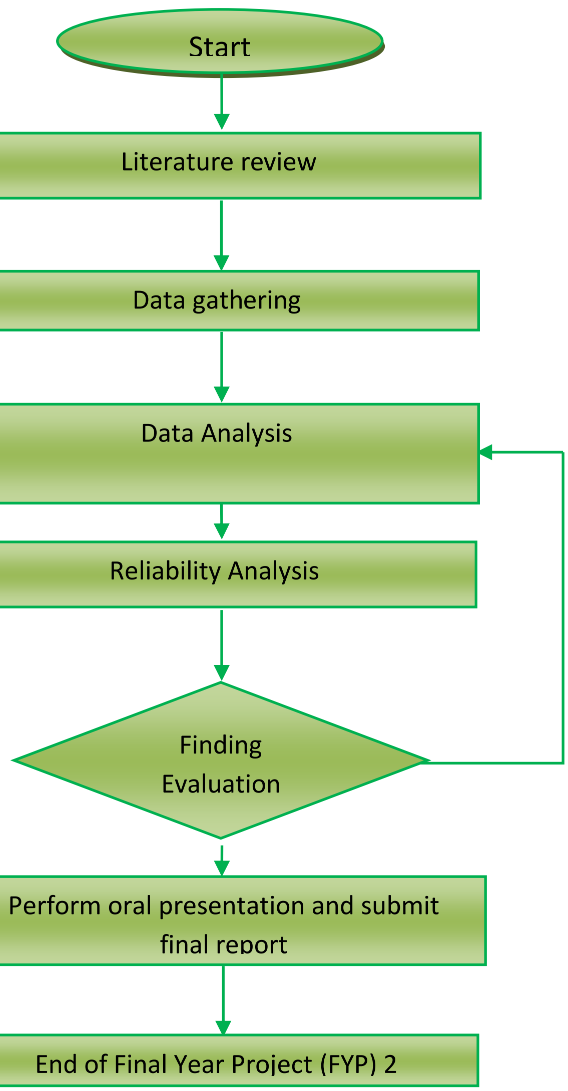


Figure 4: Project Flow Chart

In the first phase of this project, I have focused on doing studies about the elements that will be used in this project to gained better understanding of the topic. Most of the elements in this topic are new to me although I have studied some of them before but it not in details.

I have focused on studying:

i. Protection system
    - Overview of protection system
    - The components in protection system
    - The suitable devices to be apply with online CBM and its output

ii. Maintenance
    - The general overview of maintenance
    - Types of maintenance
    - Choosing suitable maintenance method

iii. Online Condition Based Monitoring
    - Online VS offline CBM
    - CBM flow
    - Data gathering
    - Data analysis
    - Risk assessment
    - Economic/cost analysis

After finished with literature review, I continue with the data gathering. First, I start with listing the problems and faults that possibly to happen in the protection system based on my reading. This is just to have the better understanding of the topic. The data that will be used in the analysis will be requested from the utilities companies. We need to use the real maintenance data in this project to make sure the finding is reliable. As for this stage, I have already sent several requests for the data statistic on type of failure, root cause and their frequency.

Later, when the data and information are obtained, the project is continued with the data analysis and conducting the risk analysis assessment techniques. From here I will determine the most crucial element of the problems in the protection system. By forming the Quadrant Analysis, we can see the separation of 4 different categories.

The analysis will focus on the most crucial section of the Quadrant Analysis (we will go through all 4 sections if possible but the main focus is the main quadrant). We will determine the solution/method that can be used to detect and prevent the problems/faults from happen.

To complete the analysis, we also need to find out the implement cost. We need to present the suitable cost for the solutions. Cost can be the major factor of the implementation of the system in the real design. If the finding is not reasonable, we need to redo the analysis to find the better solution.

The final part of the project is the paper presentation, oral presentation and the final report presentation.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Problem in VCB 11kV Switchgear

In section 2.1 (literature review about protection system), I had mentioned about the areas covered by protection system. These areas cover from the output of the current transformer to the circuit breaker. Using the example of VCB 11kV switchgear, I had conducted some analysis about the types of faults/problems happened within the system. The diagram of actual equipment can be referred in the appendices.

The components inside VCB 11kV switchgear can be divided into two categories, AC and DC components. As for the AC, the components are connected with AC source from the incoming feeder. But as described before, the scope of protection system only cover from the output of current transformer to the circuit breaker only.

Current transformers are connected to the incoming feeder. The current transformer will step down the current value in its secondary circuit. These current will be used for the metering and the monitoring of the system's condition. If there is a fault in the system, the current value will rise from the normal value. This can be detected by the relay, and the relay will act by activating the tripping circuit which then causing the tripping coil inside circuit breaker to energize and tripping/ breaking the circuit. This action will make sure that the fault is not spreading to the whole network, just isolated in the affected area.

Here I have listed the problems that can happen inside the protection system. (AC and DC components)

4.1.1 AC components

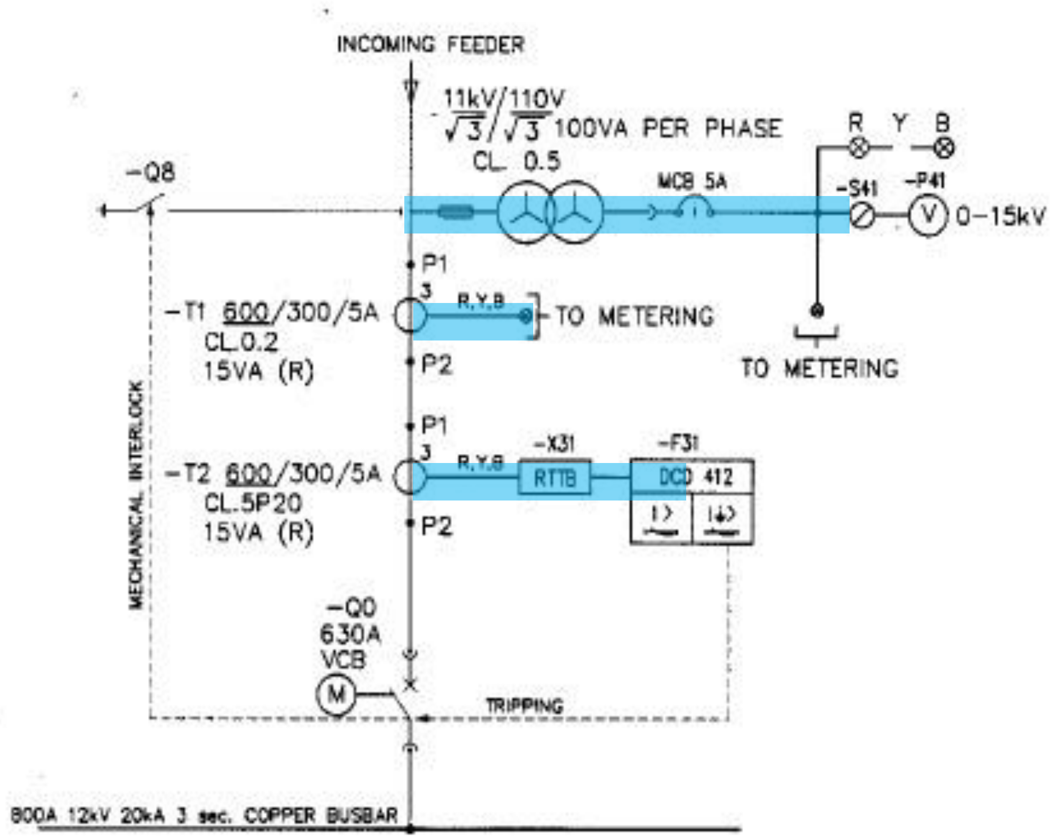


Figure 5: Single Line Diagram of protection system (highlighted: AC components)

The area highlighted in single line diagram (figure 7) is the components that are included in the protection system for AC components. I first, identified the components involved and listed the problem that may occurred according to the component using tree diagram as in figure 8.

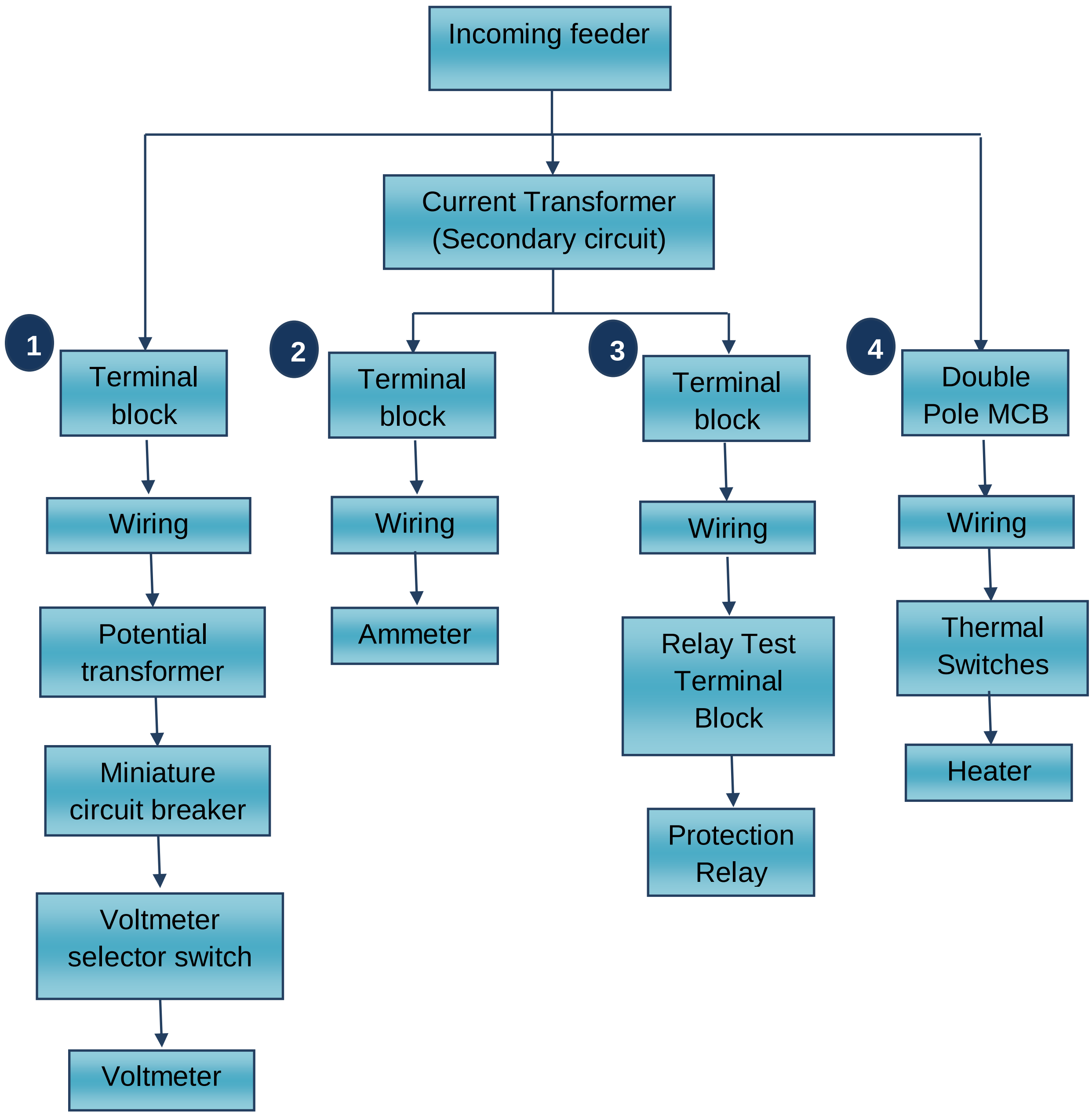


Figure 6: Tree Diagram for AC Components

Table 1: Terminal Transformer

		Sub-component		Potential Malfunction
Voltage Transformer	1	Terminal Block	A	damaged terminal (rusty)
			B	melted terminal due to high current
	2	Wiring	A	wire bitten by animal (rat)
			B	wire melted due to high current
			C	poor insulation/coating
			D	loose termination
	3	Potential Transformer	A	winding insulation failure
			B	winding shorted
	4	Miniature Circuit Breaker	A	lever stuck in 'ON' position
			B	magnetic trip inside MCB failed
	5	Voltmeter Selector Switch	A	faulty selector switch
	6	Voltmeter	A	faulty meter

Table 2: Metering Current Transformer

		Sub-component		Potential Malfunction
Metering Current Transformer	1	Terminal Block	A	damaged terminal (rusty)
			B	melted terminal due to high current
	2	Wiring	A	wire bitten by animal (rat)
			B	wire melted due to high current
			C	poor insulation/coating
			D	loose termination
	3	Current Transformer	A	winding insulation failure
			B	winding shorted
	4	Ammeter	A	faulty meter

Table 3: Protection Current Transformer

		Sub-component		Potential Malfunction
Protection Current Transformer	1	Terminal Block	A	damaged terminal (rusty)
			B	melted terminal due to high current
	2	Wiring	A	wire bitten by animal (rat)
			B	wire melted due to high current
			C	poor insulation/coating
			D	loose termination
	3	Current Transformer	A	winding insulation failure
			B	winding shorted
	4	Relay Test Terminal Block (RTTB)	A	RTTB stuck in 'disconnect' position
			B	RTTB slot not working
	5	Protection Relay	A	damaged input coil

Table 4: Heater

		Sub-component		Potential Malfunction
Heater	1	Double Pole MCB	A	leaver stuck in 'ON' position
			B	magnetic trip inside MCB failed
	2	Wiring	A	wire bitten by animal (rat)
			B	wire melted due to high current
			C	poor insulation/coating
			D	loose termination
	3	Thermal Switch	A	switch stuck
			B	switch disconnected
	4	Heater	A	heating element rusty
			B	heating element doesn’t warm up
			C	overheated

4.1.2 DC components

As for DC components, it consist of tripping and closing circuit. Referring to the single line diagram below, we can observe that the highlighted area which is the tripping circuit consists of DC components. These components are powered up by 30V DC voltage and used to control the closing and tripping circuit.

Why we must use DC voltage for the closing and tripping circuit? This is because DC power with built in battery system is more reliable than AC.

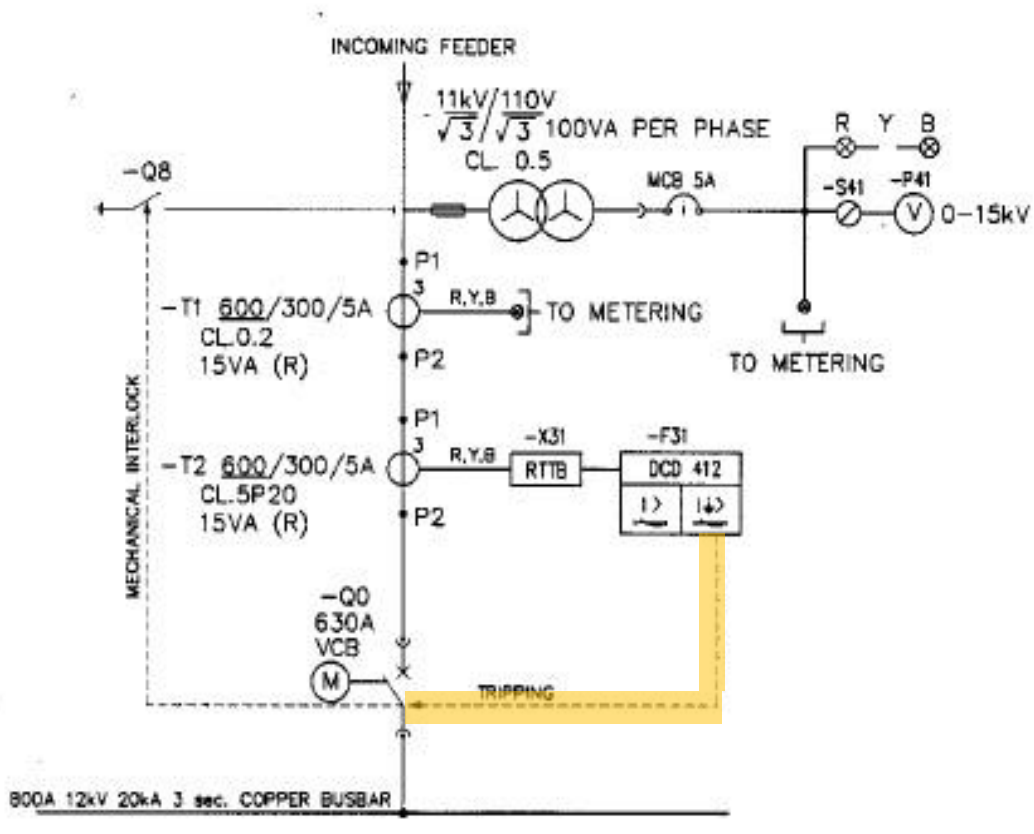


Figure 7: Single Line Diagram of protection system (highlighted: DC components)

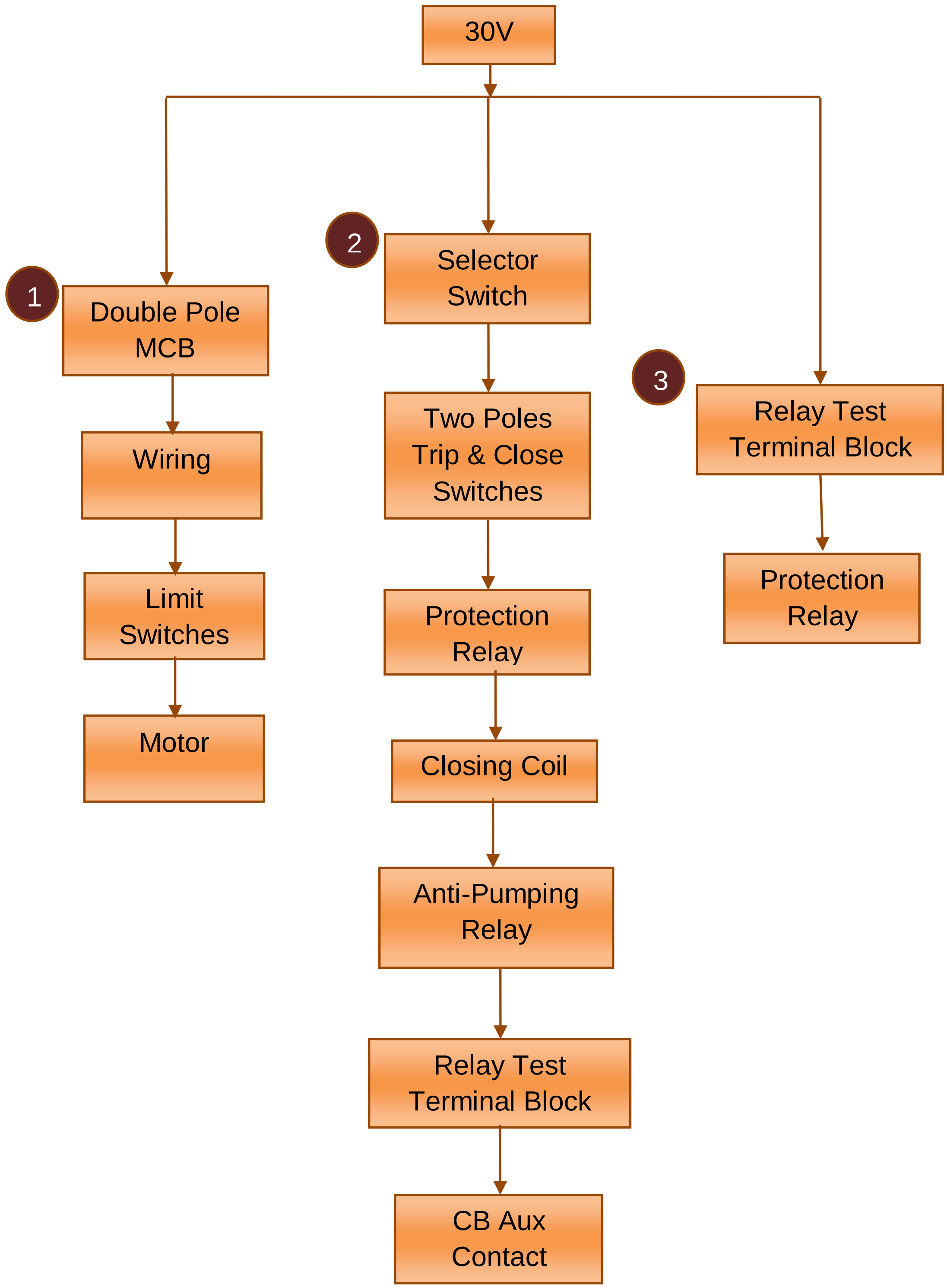


Figure 8: Tree Diagram for Closing and Tripping Circuit

Table 5: Spring Charge Motor

		Sub-component		Potential Malfunction
Spring Charging Motor	1	Double Pole MCB	a	leaver stuck in 'ON' position
			b	magnetic trip inside MCB failed
	2	Wiring	a	wire bitten by animal (rat)
			b	wire melted due to high current
			c	poor insulation/coating
			d	loose termination
	3	Limit Switches	a	faulty limit switch
	4	Motor	a	faulty motor

Table 6: CB Closing & Tripping Circuit

		Sub-component		Potential Malfunction
Circuit Breaker Closing and Tripping Circuit	1	Selector Switch	a	faulty switch
	2	Two Poles Trip & Close Switch	a	faulty switch
			b	
	3	Protection Relay	a	internal relay fault
			b	faulty relay output contact
			c	relay miscoordination
	4	Closing Coil	a	faulty closing coil
	5	Anti-pumping Relay	a	faulty anti-pumping relay
	6	Relay Test Terminal Block	a	RTTB stuck in disconnect position
			b	RTTB slot not working
	7	CB Aux Contact	a	faulty aux contact

Table 7: Power Supply Protection

		Sub-component		Potential Malfunction
Power Supply To Protection Relay	1	Relay Test Terminal Block	a	RTTB stuck in 'disconnect' position
			b	RTTB slot not working
	2	Protection Relay	a	faulty power supply module

4.2 Analysis of Relay Fault Data

The scope of this project is to analyze each of the components within protection system from AC to DC and then choose the most critical and suitable parts to be apply with Condition Based Monitoring. The data is suppose to be collected from the utility companies based on their actual record and as for that, I have contacted quite a number of utility companies ranging from local to international companies. Most of them replied that they do not keep record on the information or the information was confidential. I also have taken other approaches including searched for the information from library, books, internet and journal.

The only related information that I acquire was from a paper written by Roy Moxley with the title of "Analyze Relay Fault Data to Improve Service Reliability" [11]. In this paper, the author has analyzed the data taken from an anonymous utility company using 18 months of data (January 1996-August 1997).

As for brief introduction, protective relay is one of the parts in the protection system and come with many varieties and mainly can be divided into three categories which are electromechanical relay, solid state relays and microprocessor relay. The operation of a protective relay can be measured by its security against false operation, the dependability to operate for faults in its zone of protection, speed of operation and its impact on control of the overall power system.

In this section, I am applying a reliability analysis using the fault tree method in finding the total unavailability caused by the failures of the relay. Based on the data from [11], there are a total of 1425 events, which 1346 of them are correct operations (94.5%), 66 incorrect operations (4.6%) and 13 failures to operate (0.91%).

First, we will look into the overall incorrect operation and the failures to operate by breaking them using IEEE Power System Relay Committee Working Group 117 Report, Transmission Relay System Performance Comparison [12] which is shown in table 8. This is just to give the better overview of the failures listed in the data.

Table 8: IEEE Working Group I17 Incorrect Operation Reporting

			% INCORRECT OPERATIONS (DUE TO RELAYS) YEARS 1996/7							
Total Events	**K-Factor**	**Relay Misoperations**	**Voltage**	**Failure to Trip**	**Failure to Interrupt**	**Slow Trip**	**Unnecessary Trip During Fault**	**Unnecessary Trip Other Than Fault**	**Failure to Reclose**	**Total Misoperations**
20	Not Calculated	See Right	Above 400	0%	0%	Not Determined	30%	5%		35%
7			301-400	0%	0%		14%	0%		14%
49			201-300	2%	4%		4%	12%		22%
13			101-200	0%	0%		15%	31%		46%
5			51-100	0%	0%		0%	0%		0%
705			4.8-51*	1%	0.6%		2.5%	2.1%	0.14%	6.4%
* Not reported voltage in Working Group I17 Report										

Then, from the total of incorrect operation and the failures to operate listed in appendix 4 and 5, we can break down the types of the failure into few broad categories (the details of the failures can be refer in appendix 4 and 5).

Table 9: False Operation and Failure to Operate of Protective Relay

	False Operations	Failure to Operate
Setting or coordination failure	18 (27 %)	1 (7.7%)
Accessory component failure	12 (18%)	10 (76.9%)
Human Caused	12 (18%)	0
Relay design hole	9 (13.5%)	0
Induced Signal/Noise	5 (7.6%)	1 (7.7%)
Force majeure	5 (7.6%)	1 (7.7%)
Relay component failure	3 (4.5%)	0
Others	2 (3%)	0

From these data, we can observe that the rate of the failure to happen for protective relay is relatively low (79 failures out of 1425 events). Logically this shows that the system can be consider as good, but as described before protection relay is a crucial and need to be 100% operational without any failure.

The failure caused by false operation shows 5 times more frequent compared to the failure to operate. From the data in appendix 4 and 5, we can observe that most of the failures to trip are caused by either connected wires or circuit breaker problem. To overcome this, we must make sure that every activity that involves the protection system must be done thoroughly. All the setting, connection and the placement of the devices must be correct.

To estimate the failure rate of the system, we can apply reliability analysis to get the estimation of the failure to happen. This can helps us to evaluate the system, determine the weak link and improve it. One of the easiest yet effective reliability analyses is fault tree analysis.

4.2.1 Reliability Analysis Using Fault Tree Method

This is the method that will be used to find the total unavailability cause by protective relay based on the data from the previous anonymous utility company. Reliability is important because it is one of the most important key elements in the protection system and is defined as the ability of equipment not to fail in the events of the faults in the protected zone. The use of backup protection can help to cover any failure happen in primary protection system [01]. We use the fault tree method to evaluate the part of the system which influences the probability of a particular failure. The failure of interest is called the Top Event.

For the better understanding of the method, I have included an example as in the figure below, which modeled a protection system consist of circuit breaker, current transformer, relay, DC supply and associated control wiring.(this is the original/planned design that suppose to be use if not because of the insufficient of data).

Failure of any one component would render the whole protection system in-operate, therefore the reliability of each component must be ensure. This analysis will allow us to calculate the possibility of protection system not clear a fault [13].

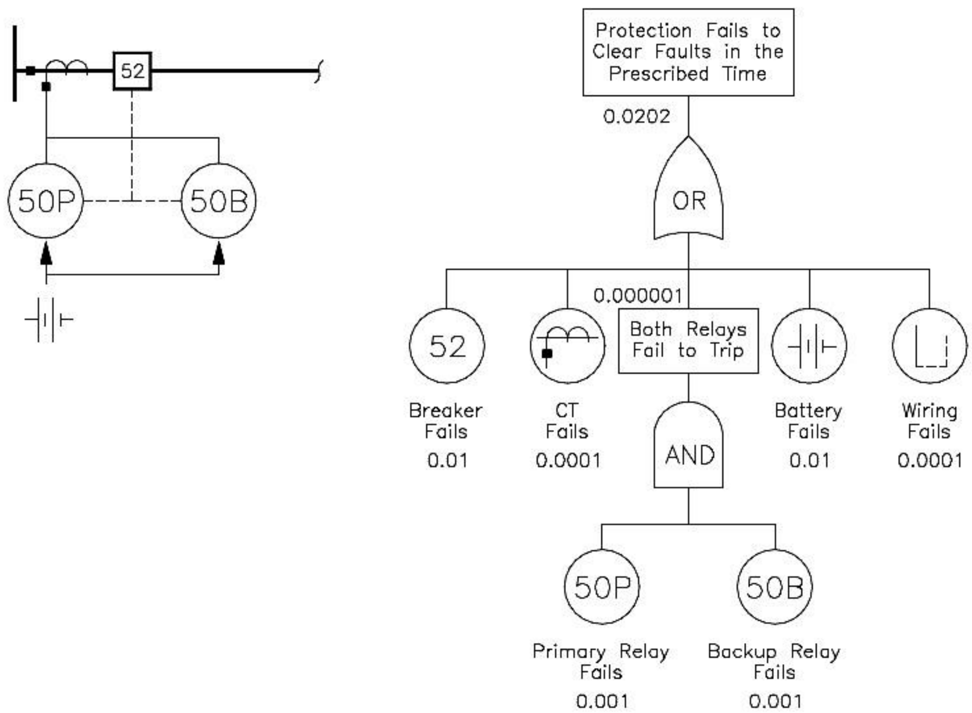


Figure 9: Fault Tree for Radial Line Protection with Redundant Relays

The top event is usually described in terms of the event that occurred which in this case is protection fails to clear faults in the prescribed time. It is assumed the power system is faulted and it intended to detect/isolate the fault in a very short time. [13]

OR gate	Any of the failures can cause the protection system to fails. The probability is calculated using summation. For example: breaker fails (**0.01**)+CT fails (**0.001**)+both relays fails to trip(**0.000001**)+DC power fails(**0.01**)+wiring fails(**0.0001**)=**0.0202**
AND gate	Both failures must happen at the same time. AND gate is the expression of the redundant system. By adding redundant system, we can improve the system's reliability by decreasing the failure rate. Relay to fails=0.001. two relays to fails at the same time $(0.001)^2$=0.000001

The values in this example are only based on the assumption. From this analysis also, it is observed that when we use redundant system, we can increase the system reliability and decrease its probability to fail (this should be able to be proved if we have sufficient data for each component).

Referring to the figure 11, using the same assumed value of the failure rates but instead of using redundant relay system, we are using single relay. So we do not use AND gate anymore, the calculation only include OR gate which is:

*breaker fails (**0.01**)+CT fails (**0.001**)+relay fails to trip(**0.001**)+DC power fails(**0.01**)+wiring fails(**0.0001**)=**0.0212***

It is proved that when we use the redundant protection system, we can increase the reliability of the protection system, in this case by 0.001. This example only shows a basic protection system, we can include other components and change the failure rate using the data that we have.

4.2.2 Device Failure Rates and Unavailability

Back to our analysis, because of the limited data, we will only focus on protective relay. In this analysis, we will find the device failure rate and the value of unavailability of the protective relay used. A device failure rate gives us the number of failures we can expect per unit time. During the useful lifetime of a device, we frequently assume a constant failure rate. Failure rates can come from theoretical calculations, such as MIL-HDBK- 17F [12] parts-count procedures, or from field experience.

For example, suppose there is an in-service population of 10,000 devices, and we observe 10 failures of devices in one year. An estimate of the failure rate from these field data is10/10,000 = 0.001 failures per year. The reciprocal gives an estimated MTBF (Mean Time between Failures) of 1000 years. This does not imply that a device is likely to last 1000 years. Instead it is a reliability figure valid during the useful lifetime of the device.

Failure rates are very useful in predicting maintenance costs, but do not tell the whole story about whether a device will be available when called upon to perform. Thus we need to consider unavailability. Unavailability is the fraction of time a device cannot perform. It is unit-less. Based on [6] we can calculate unavailability from a failure rate and the time it takes to detect and repair a failure.

$$\boxed{\mathbf{q} = \frac{\mathbf{T}}{\mathbf{MTBF}}}$$

q - Unavailability

T - Average down-time per failure

MTBF - Mean Time between Failures.

Each failure causes downtime T. Therefore the system is unavailable for time T out of total time MTBF. The fraction of time the system is not available is therefore q= T/MTBF. Assuming that self-tests function of the relay detects problems within seconds, but it will take around two days to repair the failure once it is detected. If the alarm contact of the relay is monitored, then the relay can be backed in service in two days but if the alarm contact is NOT monitored and suppose we test relay every one year, the T will become 356 days which is 182.5 times worse. This show how important is CBM.

In our case, it is recorded that there are 1425 operations in 18 months that involve electromechanical, solid–state and digital relays. So to calculate our MTBF, we will divide all the failures for each category based on 1425 operations per 18 months. Because we are focusing only to protective relay and we earlier assumed that the average down-time per failure **T**=2days, we will use this value through out all the calculation for unavailability. The example for the calculation of MTBF and q are per below:

(Based on the setting/coordinate failure for false operation)

$$\frac{1425 \text{ Operations}}{18 \text{ Months}} = 79.1667 \ \frac{\text{Operations}}{\text{Month}}$$

So, to calculate in year,

$$79.1667 \ \frac{\text{Operations}}{\text{Month}} \text{ X } 12 \ \frac{\text{Month}}{\text{Year}}$$

$$= 950 \ \frac{\text{Operations}}{\text{Year}}$$

If we take setting/coordination failure for false operation (18 failures)

18/950 = 0.0189

The **MTBF** for this will be

1/0.0189 = **52.78 years**

As for the unavailability, **q**

q= 2days/52.78 years

$$= \mathbf{0.0379} \ \frac{\text{Days}}{\text{Year}}$$

From the data in appendix 4 and 5, we can majorly divide the failures into two categories, false operation and failure to operate. From the main branches, we can further narrows down the failure into 8 sub-branches and calculate the MTBF and unavailability for each branches.

4.2.3 False Operation

a) ***4.2.3.1 Setting/Coordination Failure***

- Line differential relays with fuses taps on line **- 5**
- System conditions not considered when applying setting **- 4**
- Over-current/circulating current when lines is parallel **- 3**
- System delayed/repeated tripping of adjacent lines **- 2**
- Frequency relays operated for transient conditions **- 2**
- Incorrect echo signals **- 1**
- Setting not changed for new breaker **- 1**

MTBF = 52.78

Unavailability = 0.0378

The prime cause of the false operations in this category is caused by tapped loads on differentially protected lines and conditions do not modeled. Tapped load coordination is using the sum of both line end currents provides shorter coordinating margins than with a single end time over-current relay supervising the differential relay. By using multiple settings groups we can use external inputs to change to a setting that accounts for paralleling sources or other changed system conditions.

Comparing the single and multiple setting groups, we found that the settings/coordination-caused false trips can be reduced by over 50%

(redundant system, proved in the section 4.2.1 when we compare the usage of OR with AND gate). This solution can be found available using modern relay.

b) Accessory Component Failure

- Copper pilot wires being shorted
    - Long term failures **- 3**
    - Fault on nearby lines **- 3**
- Bad wiring **- 5**
    - Ground return wire not installed
    - Control wiring problem
    - CT wired backward
    - One phase of CT wired incorrect
    - Switches wrongly connected/labeled
- Electromechanical auxiliary relay continually keying permissive causing transmitter to stay keyed on **-1**

MTBF = 79.17
Unavailability = 0.0252

As for false trips that caused by copper pilot wires being shorted (6 failures), this then has eventually causing a false trip on an external fault and can be handled using long-term monitoring of communication channels and high-speed supervision of trips with a loss of channel signal.

Then, for the other cause which is bad wiring, the use of relay with the capability to display phase rotation and steady state operating quantities can provides a means of checking secondary CT and VT wiring, that allows us to be alerted if there is any bad wiring. For the other accessory component failure, it can be avoided by using relay with a channel monitor and timer alarm.

c) Human-caused Misoperation

- Vandals during break-in (unauthorized breaker operation) **- 8**
- Transfer trip by accident during maintenance **- 1**
- False trip caused by vibration (from drilling) **- 1**
- RTU was bumped causing it to operate **- 1**
- Wiring dropped into pool of water **- 1**

MTBF = 79.17

Unavailability = 0.0252

Based on the recorded data, it seems that the utility company has been experienced a break-in that occurred on Thursday, May 8, 1997. First, it shows that the area was not guarded well although it is known that the integrity of this area is very important to be remains intact. Also, in the equipment aspect, the security measure was insufficient to prevent breaker operation by unauthorized persons (tripped by the vandals). It is crucial for the security system to be upgraded.

d) Relay Design Hole

- Distance relays operating on either PT failure or a remote fault **- 5**
- Electromechanical differential relays operating on inrush **- 3**
- Solid-state phase comparison relay operated for a fault in parallel line (may be included as setting error) **– 1**

MTBF = 105.56

Unavailability = 0.0189

The false operation that falls into this category is considered based on the event that relay misoperated even though it is tested as OK. The failures in this category can be traced back to the manufacturing but considering that relays are used in large quantity, the number of false operation caused by relay design hole can be say low in number, credit to the qualification testing by relay manufactures.

e) Induced Signal/Noise

- Spike in DC circuit **- 1**
- Noise spike in pilot wire **- 1**
- Voltage spike causing pilot wire relay to operate **- 1**
- Microwave noise **- 1**
- Noise induced into phase comparison relay **- 1**

MTBF = 190
Unavailability = 0.0105

Four of the five instances of induced signal-caused or noise-caused trips were in communications circuits, not in the relays themselves. The problems with using a communications system is that it is subject to noise, such as microwave with a protection scheme dependent on accurate communication. Direct or multiplexed fiber systems would be more appropriate for communication-dependent protection schemes. A circuit breaker operated during a dc ground search with no relay targets recorded. With no record of a device operation available, any corrective action can only be done by guesswork only.

f) Force Majeure

- Water leaked into Buchholz Relay **- 1**
- Rain water leaked into pressure relay **- 1**
- Concussion from explosion cause relay contact to close **- 3**

MTBF = 190

Unavailability = 0.0105

Force Majeure is defined as the natural and unavoidable catastrophes that interrupt the expected course of events and restrict participants from fulfilling obligations which in this case, resulted into the relay failure. Three of the incidents were cause from a nearby industrial explosion that originated from nearby source while the other two were caused by water leaked.

g) Relay Component Failure

- Component failure in electromechanical/solid-state relay **– 3**

MTBF = 316.67

Unavailability, q = 0.0063

There are three relay component failure that caused by system fault. The concern is that these failures are mostly undetectable not until there are false operation happen. To overcome this, we can use a relay with self-checking diagnostics which able to determine that a problem has occurred without having to risk for false operation.

h) Others

MTBF = 475

Unavailability = 0.0042

There are two tripping but cannot be determined the causes of the tripping. This shows the important of recording and keeping the track of the data.

4.2.4 Failure to Operate

a) Setting/Coordination Failure

MTBF = 950

Unavailability = 0.0021

The electromechanical TOC relay did not operate for fault at 110 Amp was caused by a fault below set pickup in a time over-current (TOC) relay. Adjust the setting to prevent this from repeating

b) Accessory Component Failure

- Trip coil and mechanical/electrical failure of breaker **– 5**
- Shorted/mis-wired pilot wires **– 4**
- CT wires in reversed to directional over-current relay **- 1**

MTBF = 95

Unavailability = 0.02

The main cause of the accessory component failure is regarding wiring which has been pointed to be responsible for ten times more failures to trip compared to other causes. All ten failures in this category was related to wiring.

First, the trip coil failures and mechanical/electrical failure can be overcome using the trip coil monitoring which is available in microprocessor relay. As for the failures that caused by shorted/mis-wired pilot wires, either the monitoring of differential communications or replacement of copper wire with optical fiber can be adapted. For the last cause, the usage of microprocessor relay will allows us to be alerted that CT is in reverse with a glance at the meter display.

c) Induced Signal/Noise

MTBF = 950

Unavailability = 0.0021

There was excessive noise from an arching conductor which later blocked a power signal line carrier signal. If we are able to use trending in this situation, we can detect and overcome this problem beforehand.

d) Relay Component Failure

MTBF = 950

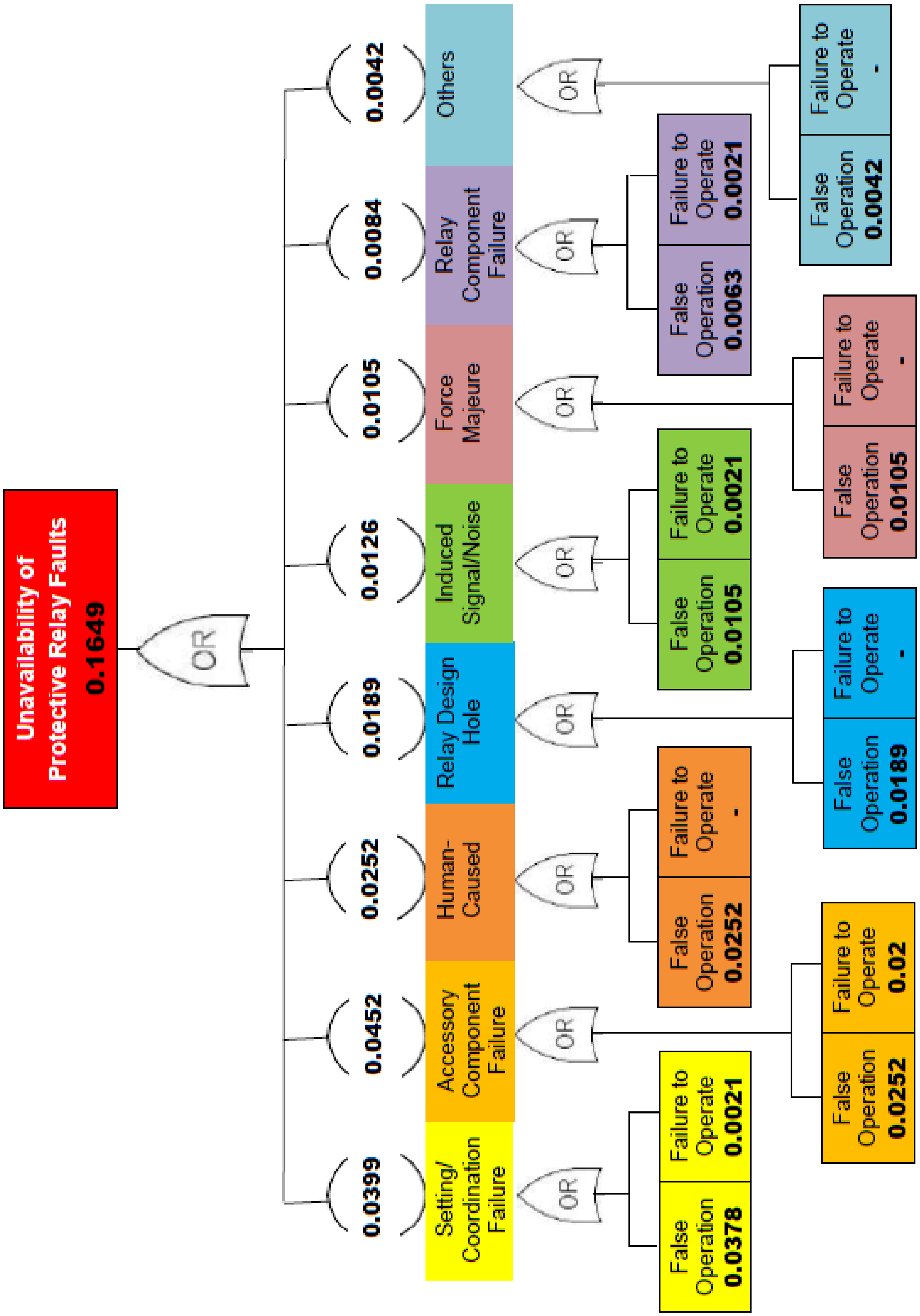
Unavailability = 0.0021

Electromechanical pilot wire differential failed to trip due to aging relay. We just need to replace them with the new relay.

4.2.5 Summary of MTBF and Unavailability

Table 10: Summary of MTBF and Unavailability

	False Operation		Failure to Operate	
	MTBF	**Unavailability**	**MTBF**	**Unavailability**
• **Setting/Coordination Failure**	52.78	0.0378	950	0.0021
• **Accessory Component Failure**	79.17	0.0252	95	0.02
• **Human-Caused**	79.17	0.0252	-	-
• **Relay-Design Hole**	105.56	0.0189	-	-
• **Induced Signal/Noise**	190	0.0105	950	0.0021
• **Force Majeure**	190	0.0105	-	-
• **Relay Component Failure**	316.67	0.0063	950	0.0021
• **Others**	475	0.0042	-	-


Unavailability of Protective Relay Faults
0.1649
OR
0.0399
Setting/ Coordination Failure
OR
False Operation 0.0378
Failure to Operate 0.0021
0.0452
Accessory Component Failure
OR
False Operation 0.0252
Failure to Operate 0.02
0.0252
Human-Caused
OR
False Operation 0.0252
Failure to Operate -
0.0189
Relay Design Hole
OR
False Operation 0.0189
Failure to Operate -
0.0126
Induced Signal/Noise
OR
False Operation 0.0105
Failure to Operate 0.0021
0.0105
Force Majeure
OR
False Operation 0.0105
Failure to Operate -
0.0084
Relay Component Failure
OR
False Operation 0.0063
Failure to Operate 0.0021
0.0042
Others
OR
False Operation 0.0042
Failure to Operate -

4.3 Suitable Components with CBM for protection system

As stated previously, Condition Based Monitoring is still not widely applied into protection system yet but, there are several components which already developed with the capability of condition based monitoring which can be used in the protection system. These components may not specifically built for protection system but still, they can be developed to fit into our objective. This is one stepping stone in achieving our target which is to apply condition based monitoring into protection system. I believe that in later future, we will see that condition based monitoring will be further used into every components and equipment available.

4.3.1 865 Differential Protection Relay by Allen-Bradley

This differential relay is built to provide protection function mainly to protect transformer for distribution networks of utilities, industry, power plants and offshore applications as well as motor and generator differential protection. In addition, it also include several programmable functions such as thermal and circuit breaker protection, communication protocols for various protection and communication situation.[15]

Figure 10: 865 Differential Protection Relay

The protection features that are provided by the relay are including differential over-current protection (87), over-current stage (50/51), current unbalance protection (46), earth fault protection (50N/51G,N), thermal overload protection (49), circuit-breaker failure protection (50BF), arc fault protection (50ARC/50NARC), programmable stages (99) and inverse time operation.

This relay also has the functions that allow it to measure the data and conducting the monitoring of the system. The measured data are including:

- Frequency (Hz)
- Phase currents
- 15-minute average for all phase currents
- Primary value of two zero sequence/residual current CTs
- Positive and Negative sequence currents
- Negative sequence current related to positive sequence current (for unbalance protection)
- Total harmonic distortion of phase currents
- 14 inputs and 9 outputs

As for the monitoring functions, it has:

Event Logs

The event log buffer should have enough room to record the last 50 events. For each trip function, a total of 8 historic events shall be logged

Disturbance Recorder

A 12-channel disturbance recorder will record all the measured signals such as, currents, voltages and the status information of digital inputs and outputs. The recording time shall be up to 12,000 minutes.

Current Transformer Supervision

The device supervises the external wiring between the device terminal and current transformers (CT) and the CT themselves.

Circuit Breaker Condition Monitoring

The relay will have a condition monitoring function that supervises the wearing of the circuit breaker. The condition monitoring can give an alarm for the need of circuit-breaker maintenance before the circuit-breaker condition is critical.

System Clock and Synchronization

The internal clock of the relay is used to time stamp events and disturbance recordings.

Running Hour Counter

This function calculates the total active time of the selected digital input, virtual I/O or output matrix output signal.

Programmable Timers

The relay is to include four programmable timers that can be used together with the user's programmable logic or to control setting groups and other applications that require actions based on calendar time.

Combined Over-current Status

The relay shall include the function to collect faults, faults types and registered fault current of all enabled over-current stages.

Self Supervision

The relay will also have the functions of micro controller and the associated circuitry, as well as the program executions are supervised by means of a separate watchdog circuit.

4.3.2 Line Resonance Analysis (LIRA)

Line Resonance Analysis or LIRA is a method developed based on Frequency Domain Reflectometry. LIRA is still going development systems that aim to be used online, detecting local or global changes in the cable electrical parameters as a consequence of insulation faults or degradation.

Moreover, the Condition Based Monitoring of installed wire systems can able us to check the reliability of the wire system and tackle the aging problem. Aging of a wire system can result in loss of critical functions of the equipment energized by the system or in loss of critical information relevant to the decision making process and operator actions. For further understanding of LIRA, you can refer to the reference [16].

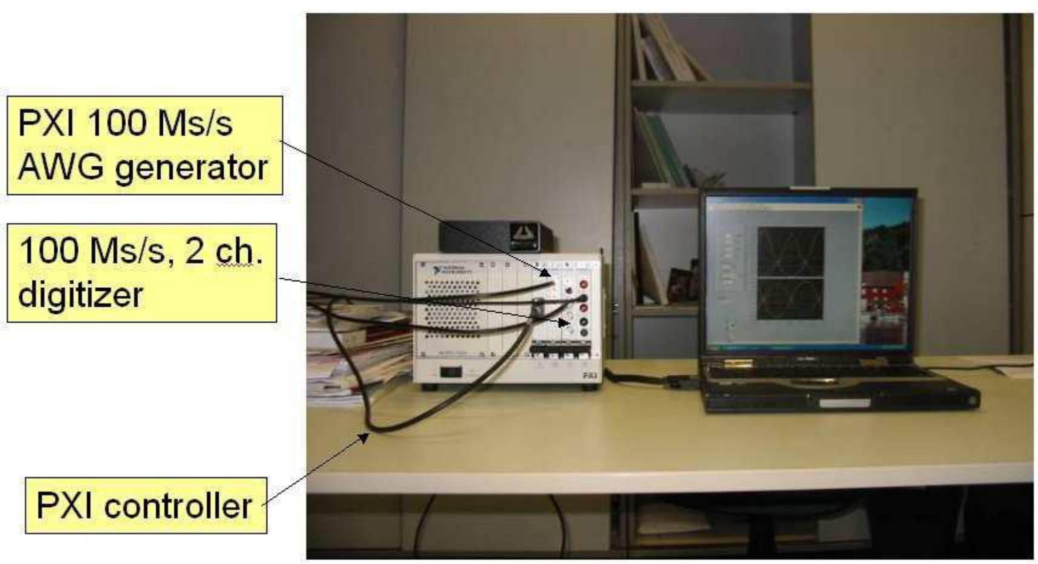


Figure 11: LIRA system (still in development stage)

CHAPTER 5
CONCLUSSION AND RECOMMENDATION

As for this project goes, I realize that online condition based monitoring for protection system is still something uncommon. It still in the research and development stage which make it difficult to obtain the information and data regarding the topic.

Most of the papers that I came across are about reliability analysis which requires us to input the data and conduct several calculations based on the developed formula. Still, this cannot be considered as ‘online’ because the data is collected beforehand.

To applied the analysis to online condition based monitoring, we need to be able to collect the actual real-time data from the system, connect to the computer and analyze them using the specified software based on the existing reliability analysis. The main problem of this is to find the existing device that can collect the information that we need from the equipment that we desire. The current online condition based monitoring is focusing on the rotating machine such as motor by calculating the vibrations and such other parameter of the motor. This is made possible with the existing of the sensors with those functions.

My discovery from the readings that I have done led to several reliability analysis such as using fault tree analysis [13] and reliability analysis using RA (reliability of availability) and RO (reliability of operation) [14].

To perform these analyses, I require a set of actual data of the failure in the protection system. Most of the companies that I contacted stated that they do not have the analyzed data as per my request. This is because the information of the failure in the protection system is not usually sorted in softcopy, they only kept them in hardcopy as it is usually hand-written by the maintenance personnel.

Even for a well-known international research such as Roy Moxley faced the problem of obtaining the required data and only managed to get it from one utility company (which is kept as anonymous due to confidential issues). This shows that data gathering is indeed very difficult to be obtained.

Using the information and the finding that I obtained, I have found several existing equipments that are suitable to be applied in the protection system based on the functions that they provided (condition based monitoring). Despite that, there are still many parts in protection system that cannot be equipped with condition based monitoring and further research and studies need to be done. It is hoped that in future, online condition based monitoring can be fully applied into the protection system.

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[**14**] Hideyuki KAMEDA and Koji YAMASHITA "Reliability Analysis for Protection Relays", Central Research Institute of Electric Power Institute Tokyo, Japan

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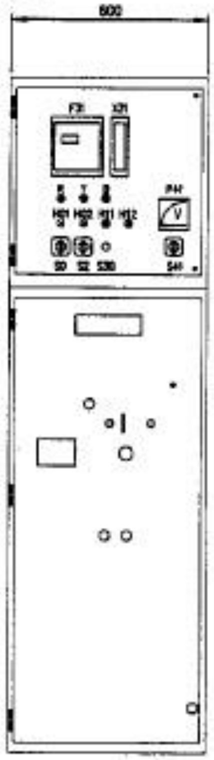
[**16**] Paolo F. Fantoni "Wore System Assessment and Condition Monitoring Using Line Resonance Analysis (LIRA)", 20 April 2006, IFE OECD Halden Reactor Project,Norway

Appendix A

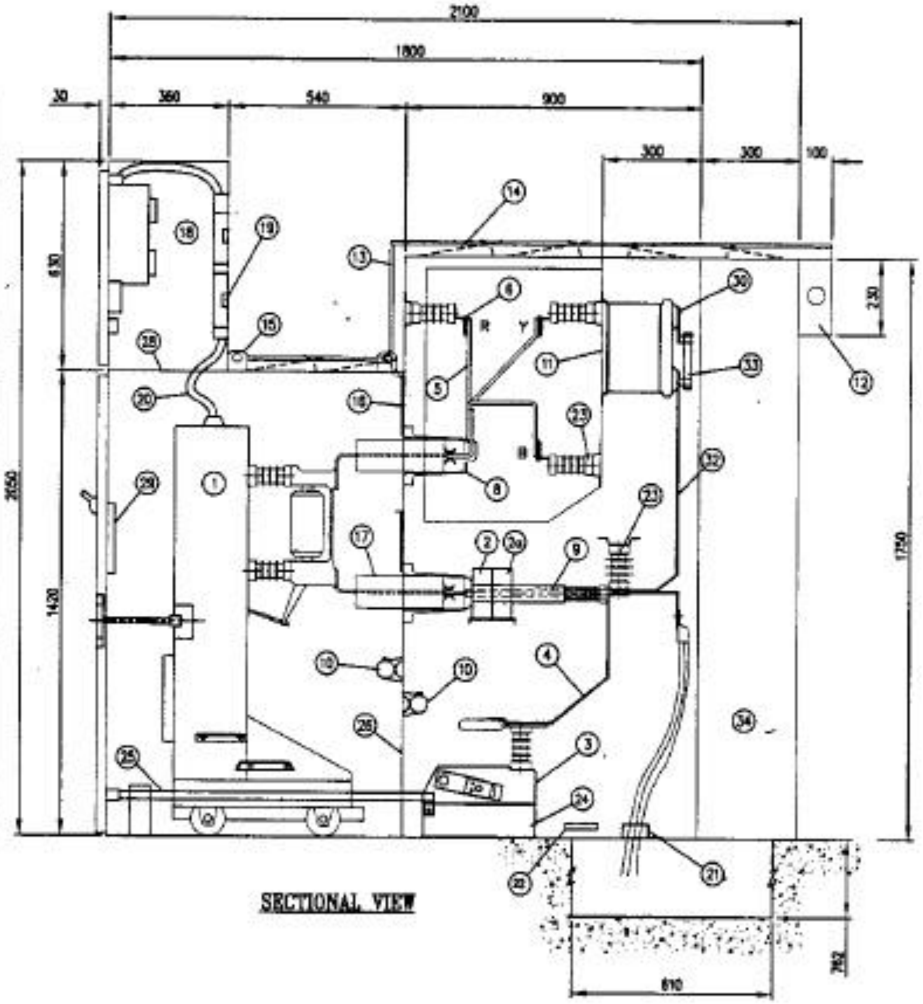
Front and Sectional View of protection system

LEGEND:

F31 - NUMERICAL O/C & E/F PROTECTION
H01 - BREAKER 'OFF' INDICATION LIGHT (GREEN)
H02 - BREAKER 'ON' INDICATION LIGHT (RED)
H11 - BREAKER COMPART.HEATER INDICATION LIGHT (WHITE)
H12 - CABLE COMPART. HEATER INDICATION LIGHT (WHITE)
P41 - VOLTMETER
S41 - VOLTMETER SELECTOR SWITCH
H20 - NEON INDICATOR
S30 - HEATER HEALTHY PUSHBUTTON
S0 - TRIP/N/CLOSE SPRING
RETURN SELECTOR SWITCH (PADLOCKABLE)
S2 - LOCAL/REMOTE SELECTOR SWITCH
X31 - RELAY TEST TERMINAL BLOCK
R,Y,B - PHASE INDICATION LIGHT

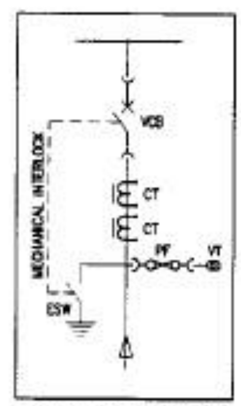


FRONT VIEW



SECTIONAL VIEW

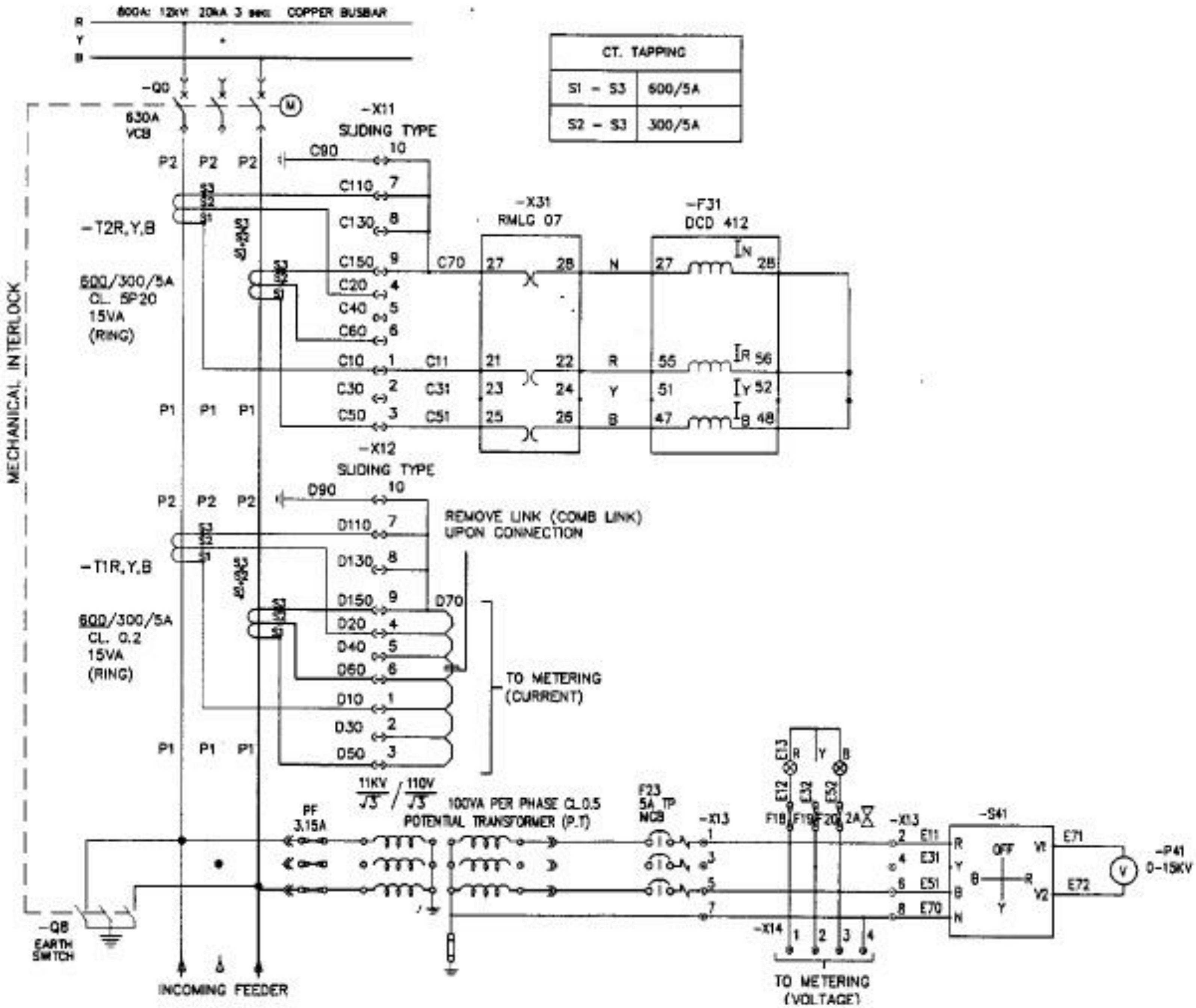
NOS.	DESCRIPTIONS	QTY
1	VACUUM CIRCUIT BREAKER	1 SET
2	CURRENT TRANSFORMER (600/300/5A CL. 5P20 15VA)	3 NOS
2a	CURRENT TRANSFORMER (600/300/5A CL. 0.2 15VA)	3 NOS
3	EARTH SWITCH	1 SET
4	EARTH SWITCH CONNECTION BAR	3 NOS
5	DROPPER BUSBAR	3 NOS
6	MAIN BUSBAR (800A)	3 NOS
7		
8	BUSBAR BUSHING	3 NOS
9	CT BUSHING	3 NOS
10	HEATER	2 NOS
11	BUSBAR PARTITION	3 PLT
12	CONTROL CABLE BOX	1 NOS
13	CONTROL CABLE TRUNKING	1 SET
14	PRESSURE RELIEF FLAP	6 PLT
15	LIFTING HOOK	4 NOS
16	SAFETY SHUTTER	2 PLT
17	POLYPROPYLENE TUBE	6 TUBE
18	LV COMPARTMENT	1 SET
19	TERMINAL BLOCK	1 SET
20	VCB CIRCUIT CONTROL CONNECTION	1 LGH
21	CABLE CLAMP	1 NOS
22	EARTHING BAR	1 NOS
23	INSULATOR	6 NOS
24	ESW PLATFORM	1 NOS
25	ESW LINKAGE	1 SET
26	SHUTTER WALL	1 PLT
28	VCB COMPARTMENT PARTITION PLATE	1 PLT
29	MECHANICAL TRIP & CLOSE MECHANISM	1 SET
30	POTENTIAL TRANSFORMER	3 NOS
31		
32	PT CONNECTION BAR	3 NOS
33	PT FUSE	3 NOS
34	EXTENSION PANEL	1 SET



SINGLE LINE DIAGRAM

Appendix B

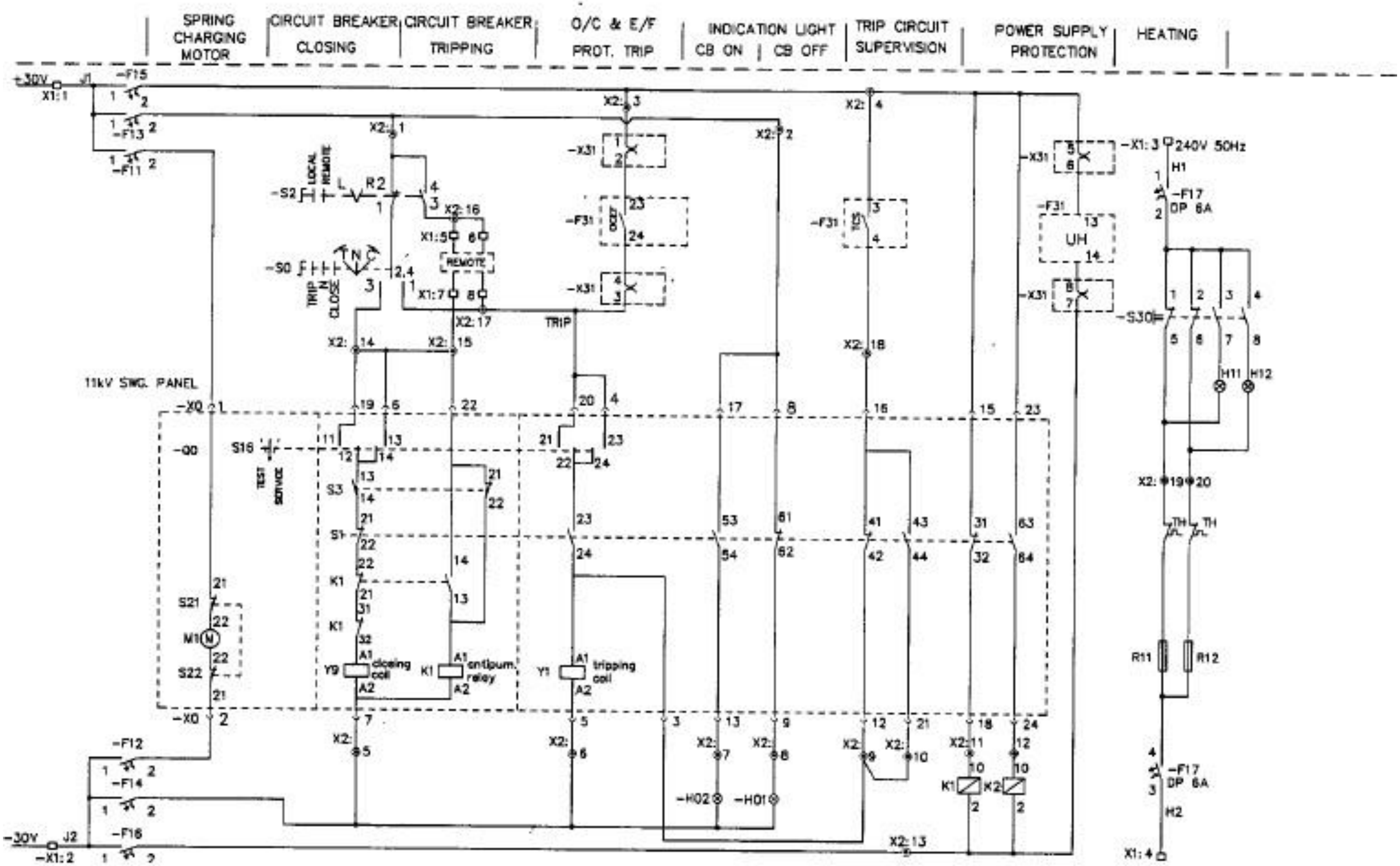
Schematic Diagram of AC Components



CT. TAPPING	
S1 - S3	600/5A
S2 - S3	300/5A

Appendix C

Closing and Tripping Circuit



SPRING CHARGING MOTOR
CIRCUIT BREAKER CLOSING
CIRCUIT BREAKER TRIPPING
O/C & E/F PROT. TRIP
INDICATION LIGHT
CB ON
CB OFF
TRIP CIRCUIT SUPERVISION
POWER SUPPLY PROTECTION
HEATING
+30V
-30V
240V 50Hz
11kV SWG. PANEL
REMOTE
TRIP
closing coil
antipum. relay
tripping coil
DP 6A

Appendix D
False Operation

Relay Component Failure	
4/8/96	Reclosing relay with **shorted diode**, closed in three times, loss of air pressure in circuit breaker caused trip times to increase until backup relay (on 230 kV bank) cleared fault on 34.5 kV feeder.
3/15/96	**Staged fault** caused adjacent 500 kV line to trip by "finding" a faulty component that removed restraint and caused operation on reverse fault. This sent a direct transfer trip to the other end.
6/29/97	230 kV line tripped due to **leaking capacitor** in electromechanical distance relay.
Relay Design Hole	
1/30/96	Two electromechanical distance relays operated for remote bus fault: "the relay contacts have a history of **drifting closed** when the line voltage goes dead." They did not cause outage. The line was already dead.
8/11/96	Solid-state phase comparison relay **tripped for a fault on parallel line**. Relays were tested with no problems found.
9/11/96	Electromechanical distance relays tripped on **PT failure**; line did not trip.
9/23/96	Electromechanical transformer differential **misoperated** during inrush. Relay tested OK.
9/25/96	E/M DCB scheme **misoperated** at one end of line due to **fault detector operating for external faul**t and forward looking **distance relay "drifting"** closed on low voltage (two occurrences on separate lines for same fault).
10/17/96	Electromechanical transformer differential **misoperated** during inrush. Relay tested OK.
11/6/96	Electromechanical transformer differential **misoperated** during inrush. Relay tested OK.
Accessory Component Failure	
1/27/96	9:41 Electromechanical pilot wire **differential false trip** on bad pilot.
1/27/96	9:48 Electromechanical pilot wire **differential false trip** on bad pilot.
8/1/96	E/M POTT scheme false tripped on external fault due to **e/m aux failure** causing transmitter to stay keyed on.
8/1/96	Solid-state bus differential tripped on external fault due to a **ground return wire not installed** during addition of new equipment to station.
9/18/96	Three transformer banks tripped due to false transfer trip during test of breaker failure relays. Blocking switches were **mislabeled** on newly installed equipment.
11/20/96	Directional overcurrent relay opened while switching a capacitor, due to a control **wiring problem**.
1/6/97	Fault on **adjacent line damaged pilot wires**, causing electromechanical pilot wire differential relays to trip three lines.

5/6/97	Electromechanical **pilot wire differential tripped** on external fault. Apparently shorted pilot.
6/24/97	Transformer false tripped on first load because **CT wired backwards**.
7/8/97	Same transformer tripped again due to **one phase wired incorrectly**.
Setting or Coordination Failure	
1/16/96	Electromechanical pilot wire differential operated on fuse-cleared fault. Electromechanical pilot wire differential cannot coordinate with fuse, cleared faults.
3/15/96	500 kV staged fault caused an echo-tripping permissive echo that eventually caused a false trip on that line. Line tripped again on second staged fault test on adjacent line.
3/18/96	Overfrequency relay tripped on transient caused by line tripping. Relay operated correctly, given its settings, but incorrectly, given its application.
3/25/96	Relay operated for a repeated fault on an adjacent 345 kV line. This was a “correct” incorrect operation. Could be described as a coordination failure.
4/5/96	Transfer trip inadvertently sent during disconnect switching 230 kV line.
4/5/96	Electromechanical pilot wire differential tripped after fuse-cleared fault—lack of coordination.
5/17/96	Electromechanical pilot wire differential tripped after fuse-cleared fault—lack of coordination.
7/4/96	Electromechanical pilot wire differential false tripped due to circulating current when transformers were paralleled.
9/19/96	4.8 kV bus tripped on backup due to slow trip of downstream fault (coordination failure).
12/12/96	Overcurrent relay on transformer tripped on back-up when a fault on a feeder did not clear; coordination error.
1/16/97	Underfrequency relays tripped on the transient when a breaker tripped on low SF6 pressure. Settings error
2/27/97	EM TOC relay tripped on circulating current when bus tie closed for routine work.
3/21/97	Electromechanical pilot wire differential overtripped on fault cleared by fuse tapped on line.
4/4/97	Electromechanical pilot wire differential tripped due to circulating current when lines paralleled.
5/19/97	EM directional overcurrent tripped when line was paralleled.
5/23/97	Electromechanical pilot wire differential overtripped on fault cleared by fuse tapped on line.
7/3/97	Transformer relay false tripped on new energization because new settings had not been applied.

Induced Signal/Noise	
3/15/96	Staged fault at a 500 kV line caused false trips due to **noise induced** into phase comparison relay at same station, which sent a transfer trip to other end.
7/23/96	Breaker tripped due to a **spike in the dc circuit** during a dc ground search. No relay targets were reported.
10/16/96	Electromechanical pilot wire differential relay misoperated due to external 230 kV fault sending "**noise spike**" into pilot wires, which tripped one end of 34.5 kV line.
12/17/96	Fault on nearby line created a **voltage spike**, causing a pilot wire relay to operate (line did not have drainage reactor).
8/23/97	500 kV false trip due to **microwave noise**, causing current differential relay to operate.
Mystery	
3/18/96	230 kV line tripped for fault on reverse line. No targets found on any relay.
8/27/96	230 kV bus tripped during transfer of station service. No targets, no cause found.
Human Caused	
4/25/96	500 kV line tripped on transfer trip accidentally sent during maintenance.
11/4/96	Electromechanical pilot wire differential false tripped when "a construction crew was drilling on the adjacent relay panel when the relay was jarred closed."
12/31/96	Transformer tripped when RTU was bumped, causing it to operate. No relay targets (shows advantage of using relay trip contacts for operation).
3/8/97	False trip of transformer due to wiring being dropped into a pool of water during work on transformer pressure relay.
5/8/97	Vandals broke into substation. Tripped 8 breakers. No relay targets. Another reason to use relays to operate breakers. Break-in at 6:04 pm in May.
Force Majoure	
2/20/96	**Water leaked** into Buchholz relay.
11/11/96	"Concussion from a large explosion at X caused the relay contact to close" EM directional overcurrent relay (3 lines).
1/13/97	False trip due to rain **water leaked** into the pressure relay on a LTC.

Appendix E
Failure to Operate

Setting or Coordination Failure	
2/16/96	Electromechanical TOC relay did not operate for fault 1000 Amp. Cleared other end after 63 cycles. Fault self-cleared at 125 cycles.
Accessory Component Failure	
1/29/96	6:36, CB failed to trip (reported as relay failure to trip)
5/5/96	Electromechanical pilot wire differential at 34.5 kV failed to operate due to **miswired** ground lead, which allowed an induced voltage to counteract the tripping voltage. This caused 6 line trips followed by 5 reclosing & trips. Dispatcher could not determine where the fault was and closed in repeatedly to test lines.
12/28/96	Breaker failed during trip for line fault (E/M POTT). Failure caused a bus fault to be detected. Breakers on the bus were blocked from tripping due to a large pump being started causing breaker failure of all incoming 230 kV feeds.
12/28/96	After clearing of the breaker fault, station was attempted to re-energize. Fault was re-initiated and same problems happened again.
1/6/97	E/M directional OC relay failed to trip due to CTs being reversed. Backup tripping cleared 5 incoming lines at 34.5 kV. Fault took approximately 15 seconds to clear.
1/6/97	Failure to trip electromechanical pilot wire differential due to **shorted pilot wires**. Line cleared on time overcurrent backup.
1/6/97	Failure to trip electromechanical pilot wire differential due to **shorted pilot wires**. Line cleared on time overcurrent backup. This was a repeat event 2 minutes following a successful reclose. It could be argued that if the pilot wire relay had tripped, the damage would have been limited and reclose would have held … maybe.
1/6/97	Failure to trip EM TOC due to bad breaker. Breaker would not open until all current flow was interrupted elsewhere. Cleared 2 other lines.
1/6/97	Pilot wire shorted caused failure to trip of electromechanical pilot wire differential. Two lines were cleared in backup.
8/5/97	Failure to trip due to burnt trip coil (EM relays); two lines cleared on backup.
Induced Signal/Noise	
1/6/97	Failure to trip of 230 kV E/M POTT primary protection scheme for the line caused by excessive noise from an arcing conductor swamped out the power line carrier receiver. Line tripped on backup after 24 cycles.
Relay Component Failure	
5/24/96	Electromechanical pilot wire differential failed to trip due to bad “rectox unit” in 55-year-old relay. After failure relays were replaced by similar vintage relays. Six lines tripped as a result of failure to trip.