DESIGN OF A BAY CONTROL UNIT IN A SUBSTATION AUTOMATION SYSTEM

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Abstract

A bay of is a part of a substation containing extra-high (or high) voltage switching devices and connections of a power line, a power transformer, etc., to the substation busbar. It forms a vital node in power networks, for that a responsive automation system is needed for controlling, protection and monitoring of substations.

Interlocking is a method of preventing undesired states in a substation, that is achieved by a series of conditions must be met to affect an output condition. An improper switching operation can damage equipment and can affect the quality of the electrical system.

Traditionally, Bay Control Units (BCUs) and Remote Terminal Units (RTUs) were used in substations to act as the link between the switchgear (devices) and the control centre for monitoring and controlling, now that more and more they are being replaced by another electrical devices, more efficient in measurements and protection, like Programmable Logic Controllers (PLC).

The project concerned the software interlocking system applied for mutual interlocking disconnectors, circuit breakers and earthing switches at a bay to avoid consequences, that is to ensure safety of switching operations carried out in the substation during operation and maintenance, using a control solution with PLC for a model that simulates a bay of substation. The project also allows operators to interface with the control system in an evident way, using PC-Access human machine interface (HMI).

PLC interlocking is used all over the world and is very reliable, and from safety point of view, some PLCs are now safety rated, with these, PLC can be used for safety interlocking and controlling.
المستخلص

الحوض المحطة هو جزء من المحطة الكهربائية تحتوي على مفاتيح كهربائية ذات جهد عالي وتعمل كوصلة بين خطوط القدرة والمولدات. وتعتبر الحملة المجمعة في المحطة جزءًا أساسيًا في شبكات الكهرباء، لذلك فهي تحتاج إلى أنظمة تحكم آليات منظمة سريعة الاستجابة.

قد تمكّنت المحطاتوالوحدات البعيدة والوحدات المحلية للتحكم المحلية لتربط بين الأجهزة ومراكز التحكم. ولكن الآن أصبحت تستخدم جهاز كبير التحكم في القيادة الأخرى لها المقدار على القياس والحماية في نفس الوقت بفعالية أكبر، مثل المحكمة المنطقية القابلة للبرمجة.

الغلق التبادلي هو طريقة يتم منع حدوث أي حالة غير مرغوب فيها في المحطة. ويجب ذلك بسلسلة من الشروط المتداخلة مع بعضها البعض لكي لا يحدث خلل على الخروج المطلوب. إذا لم تتم عملية الفتح والغلق الكهربائي بصورة غير مفيدة، فقد تؤدي الخسائر في المعدات وتؤثر على كفاءة النظام ككل.

يهدف المشروع لتصميم وتنفيذ نظام برمجي محاكي لعملية الفتح والغلق بشكل منظم لضمان عملية فتح وغلق المحافظ الكهربائية أثناء التشغيل والصيانة، وذلك باستخدام المحكمة المنطقية ونموذج لزاكى لأجزاء المحطة. كما أن المشروع يهدف لتسهيل عمليات التحكم والمراقبة.

عملية الغلق التبادلي باستخدام المحكمة المنطقية دقيقة ومواد تكنولوجية، لذلك فهي من التقنيات الاجهزة المستعملة على نطاق واسع عالمياً. أيضاً من أكبر التحديات التي تواجه عملية تصميم نظام تحكم آلي هو تقليل زمن الاستجابة في حالات استقبال ورسائل الإشارة من المحافظ، وإجهزة جنرالية، وتزويد المحكمة المنطقية بصورة كبيرة في تحسينه.
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Chapter 1

Introduction

1.1 Overview

The electric power industry is going through a period of dramatic changes caused by restructuring, deregulation, downsizing, requirements for improved power quality and operation close to the stability limits. All of this makes Substation Automation (SA) systems a key factor in the efficient operation of electric power systems. Substation automation (SA) was successfully introduced over the last 30 years. Successful design and implementation of Substation Automation Systems is possible only with a good understanding of their functionality, the hierarchy of the different functions, the devices being integrated and the tools used in the engineering process.

The bay control unit (BCU) performs control in accordance with control commands from network to control equipment and monitoring the bay power apparatus. Electrical substation consists of two parts, main circuits and auxiliary circuits, that the BCU integrates all of the auxiliary functions in a single unit.

1.2 Problem definition

In the single breaker-double bus configuration, the sequence of interlocking conditions accomplished by International Electrotechnical committee (IEC) in IEC 61850 standard. These conditions must be met to achieve proper operation of electric power system (EPS), as detailed in subsequent chapters.

Switches are opened and closed by operators using pre-generated guidelines for avoiding human errors, for design reasons, disconnectors used in substations disconnected parts of a circuit breaker, which due to design restrictions cannot be ensured by a circuit breaker. Disconnectors are able to switch on or off only very little currents, and they are not able to switch on or off a loaded line, and are only used to ensure the required isolation clearance between circuit breaker ends. Depending on the state of a given EPS at the moment of performing switching operation, incorrect sequence of switching operation could cause a large power system failure resulting for example in a collapse of a part of the EPS referred to as black out. It could also cause disturbance in substation operation and interruption of energy supply to
consumers. Sprayed melted metal could seriously injure personnel if some personnel was close to the exploding disconnector accidently.

1.3 Project objectives

The objective of this project is to apply Bay interlocking scheme for air insulated switchgear in double bus–single breaker configuration, which is achieved by:

- Creating a software program, using PLC.
- Interfacing the operator to the Bay using Human Machine Interface (HMI).
- Design a model that simulates the Bay.

1.4 Tools

The project must be accomplished in three steps, as described in the objective. Tools required for the development of the project are:

- SIMATIC S7-200 Micro PLC, using a MicroWin ladder diagram.
- PC-Access server.
- Visual basic program.
- Mimic model.

1.5 Thesis Layout

The thesis is organized as follows:

**Chapter 1 Introduction**: Problem definition and its solution are discussed here.

**Chapter 2 Theoretical background**: This chapter deals with the theoretical background needed throughout the project.

**Chapter 3 Implementation and design**: In this chapter, the system design in terms of design goal implementation and components are covered.

**Chapter 4 Results**: This chapter covers results obtained from the project.

**Chapter 5 Conclusion**: Conclusions and recommendations for future work are presented in this chapter.
Chapter 2

Theoratical Background

2.1 Substations

A substation is the part of an electricity transmission and distribution system where voltage is transformed from low to high and vice versa using transformers. Transformation may take place in several stages and at several substations in sequence, starting at the generating plant substation where the voltage is increased for transmission purposes and is then progressively reduced to the voltage required for household use. The word substation comes from the days before the distribution system became a grid. The first substations were connected to only one power station, where there was the generator, and were entirely dependent on it, hence the name.

A substation that has a step-up transformer increases the voltage whilst decreasing the current, while a step-down transformer will decrease the voltage while increasing the current for domestic and commercial distribution. It is more efficient to transmit electricity over long distances at very high voltages; the function of the substation is to reduce the voltage from transmission level to values suitable for local distribution.

Substations may be on the surface in fenced enclosures, underground, located in special-purpose buildings, located on power poles (aerial substations) or located in the service areas of the buildings they service. Substations located within the buildings they serve are particularly a feature of high-rise buildings.

2.1.1 Types of substations:

i. A step-up transmission substation

Receives electric power from a nearby generating facility and uses a large power transformer to increase the voltage for transmission to distant locations. A transmission bus is used to distribute electric power to one or more transmission lines. There can also be a tap on the incoming power feed from the generation plant to provide electric power to operate equipment in the generation plant.

ii. Step-down transmission substations

Are located at switching points in an electrical grid. They connect different parts of a grid and are a source for subtransmission lines or distribution lines. The step-down substation can change the transmission voltage to a subtransmission voltage. The subtransmission voltage lines can then serve as a source to distribution substations. Sometimes, power is tapped from the
subtransmission line for use in an industrial facility along the way. Otherwise, the power goes to a distribution substation.

iii. **Distribution substations**

Are located near to the end-users. Distribution substation transformers change the transmission or subtransmission voltage to lower levels for use by end-users. From here the power is distributed to industrial, commercial, and residential customers.

iv. **Underground distribution substations**

An underground system may consist of these parts:

- Conduits
- Duct Runs
- Manholes
- High-Voltage underground cables
- Transformer
- Riser

![Figure 2.1 : Underground Distribution Substation](image)

2.1.2 Substation components

Electric power substations consist of two essential parts:

- Primary circuits
- Auxiliary circuits.

2.1.2.1 Main circuits:

The main circuit of a substation is composed of a busbar system and connections of power lines, power transformers, etc. to the busbar system through switching devices. Substations are divided into bays. A bay of a substation is a part of a substation containing extra-high (or high) voltage switching devices and connections of a power line, a power transformer, etc., to the substation busbar system(s) as well as protection, control, and measurement devices for the power line, the power transformer, etc. If it is a bay used to connect a power line to the busbar system, it is called a line bay, if it is used for connecting a power transformer to the busbar system.
system; it is called a transformer bay. Normally, a substation contains a number of line and transformer bays and also other bays. All bays are similar to the line bay. Auxiliary circuits are electrical circuits containing measurement, signaling, control and protection devices.

2.1.2.2 The secondary circuit:

Consists of three subsystems:

- Protection which is composed of busbar protection, feeder protection and transformer protection.
- Automation which involves load shedding (frequency control), load restoration, sequential switching, synchronization and tap-changer control.
- Control/operation: this represents a very important section which is bay interlocking, and whole substation interlocking.

2.1.2.3 SUBSTATION BUS

It is an aluminium or copper conductor supported by insulators that interconnects the loads and the sources of electric power in an electric power system, there are six types of substation bus:

i. **Single Bus** :

This arrangement involves one main bus with all circuits connected directly to the bus. The reliability of this type of an arrangement is very low. When properly protected by relaying, a single failure to the main bus or any circuit section between its circuit breaker and the main bus will cause an outage of the entire system. In addition, maintenance of devices on this system requires the de-energizing of the line connected to the device. Maintenance of the bus would require the outage of the total system, use of standby generation, or switching to adjacent station, if available.
ii. **Double Bus, Double Breaker**:

This scheme provides two separate breakers available to each circuit. In addition, with two separate buses, failure of a single bus will not impact either line. This scheme provides a very high level of reliability by having two separate breakers available to each circuit. In addition, with two separate buses, failure of a single bus will not impact either line. Maintenance of a bus or a circuit breaker in this arrangement can be accomplished without interrupting either of the circuits.

This arrangement allows various operating options as additional lines are added to the arrangement; loading on the system can be shifted by connecting lines to only one bus.

![Figure 2.3: Double bus-Doublbreaker](image)

iii. **Main and Transfer Bus**:

This scheme is arranged with all circuits connected between a main (operating) bus and a transfer bus (also referred to as an inspection bus). Some arrangements include a bus tie breaker that is connected between both buses with no circuits connected to it. Since all circuits are connected to the single, main bus, reliability of this system is not very high. However, with the transfer bus available during maintenance, de-energizing of the circuit can be avoided.

![Figure 2.4: Main and transfer bus](image)
iv. **Ring Bus**:

In this scheme, all breakers are arranged in a ring with circuits tapped between breakers. For a failure on a circuit, the two adjacent breakers will trip without affecting the rest of the system. Similarly, a single bus failure will only affect the adjacent breakers and allow the rest of the system to remain energized. However, a breaker failure or breakers that fail to trip will require adjacent breakers to be tripped to isolate the fault.

Maintenance on a circuit breaker in this scheme can be accomplished without interrupting any circuit, including the two circuits adjacent to the breaker being maintained. The breaker to be maintained is taken out of service by tripping the breaker, then opening its isolation switches. Since the other breakers adjacent to the breaker being maintained are in service, they will continue to supply the circuits.

Relaying is more complex in this scheme than some previously identified. Since there is only one bus in this scheme, the area required to develop this scheme is less than some of the previously discussed schemes. However, expansion of a ring bus is limited, due to the practical arrangement of circuits.

![Figure 2.5: Ring bus](image)

v. **Breaker-and-a-Half**:

The breaker-and-a-half scheme can be developed from a ring bus arrangement as the number of circuits increases. In this scheme, each circuit is between two circuit breakers, and there are two main buses. The failure of a circuit will trip the two adjacent breakers and not interrupt any other circuit. With the three breaker arrangement for each bay, a center breaker failure will cause the loss of the two adjacent circuits. However, a breaker failure of the breaker adjacent to the bus will only interrupt one circuit. Maintenance of a breaker on this scheme can be performed without an outage to any circuit. Furthermore, either bus can be taken out of service with no interruption to the service.
This is one of the most reliable arrangements, and it can continue to be expanded as required. Relaying is more involved than some schemes previously discussed. This scheme will require more area and is costly due to the additional components.

![Diagram of Breaker and a half]

**Figure 2.6: Breaker and a half**

vi. **Double Bus, Single Breaker:**

This scheme has two main buses connected to each line circuit breaker and a bus tie breaker. Utilizing the bus tie breaker in the closed position allows the transfer of line circuits from bus to bus by means of the switches. This arrangement allows the operation of the circuits from either bus. In this arrangement, a failure on one bus will not affect the other bus. However, a bus tie breaker failure will cause the outage of the entire system.

Operating the bus tie breaker in the normally open position defeats the advantages of the two main buses. It arranges the system into two single bus systems, which as described previously, has very low reliability.

Relay protection for this scheme can be complex, depending on the system requirements, flexibility, and needs. With two buses and a bus tie available, there is some ease in doing maintenance, but maintenance on line breakers and switches would still require outside the substation switching to avoid outages.
2.1.2.4 Components of a bay

A bay generally contain one or more transformers, and have switching, protection and control equipment. In a large substation, circuit breakers are used to interrupt any short-circuits or overload currents that may occur on the network. Smaller distribution stations may use recloser circuit breakers or fuses for protection of branch circuits. Substations do not (usually) have generators, although a power plant may have a substation nearby. A typical substation will contain line termination structures, high-voltage switchgear, one or more power transformers, low voltage switchgear, surge protection, controls, grounding (earthing) system, and metering. Other devices such as power factor correction capacitors and voltage regulators may also be located at a substation.

2.1.2.5 Circuit breakers

A circuit breaker is defined as "a mechanical switching device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying and breaking for a specified time, and breaking currents under specified abnormal circuit conditions such as a short circuit" (IEEE Std. C37.100-1992).

Electrical power transmission networks are protected and controlled by high-voltage breakers. The definition of "high voltage" varies but in power transmission work is usually thought to be 72,500 V or higher, according to a recent definition by the International Electrotechnical Commission (IEC). High-voltage breakers are broadly classified by the medium used to extinguish the arc:

- Bulk oil
- Minimum oil
Sulfur Hexafluoride (SF6) high-voltage circuit-breakers

Sulfur hexafluoride (SF₆) is an inorganic, colorless, odorless, and flammable gas under standard conditions, used in the electrical substations as a gaseous dielectric medium for high-voltage circuit breakers, switchgear. These breakers are available for indoor or outdoor applications, the latter being in the form of breaker poles housed in ceramic insulators mounted on a structure. Current interruption is obtained by separating two contacts in medium, of SF₆, having arc quenching properties. After contact separation, current is carried through an arc and is interrupted when this arc is cooled by a gas blast of sufficient intensity. Gas blast applied on the arc must be able to cool it rapidly so that gas temperature between the contacts is reduced from 20,000 K to less than 2000 K in a few hundred microseconds, so that it is able to withstand the transient recovery voltage that is applied across the contacts after current interruption.

2.1.2.6 Disconnect Switches

A disconnect switch is a mechanical device used to change connections within a circuit or isolate a circuit from its power source, and is normally used to provide isolation of the substation equipment for maintenance. Typically a disconnect switch would be installed on each side of a piece of equipment to provide a visible confirmation that the power conductors have been opened for personnel safety. Once the switches are placed in the open position, safety grounds can be attached to the de-energized equipment for worker protection. Switches can be equipped with grounding blades to perform the safety grounding function.

Disconnect switches are designed to continuously carry load currents and momentarily carry higher capacity for short-circuit currents for a specified duration. They are designed for no load switching, opening or closing circuits where negligible currents are made or interrupted, or when there is no significant voltage across the open terminals of the switch. They are relatively slow-speed operating devices and therefore are not designed for arc interruption. Disconnect switches can also be used for bus sectionalizing or for other equipment for maintenance. Interlocking equipment is available to prevent inadvertent operating sequence by inhibiting operation of the disconnect switch operation until the fault and/or load currents have been interrupted by the appropriate equipment.
2.1.2.7 **Contactors:**

To define a contactor, we must define the operation of a relay first. A relay is an electrically operated switch. Current flowing through the coil of the relay creates a magnetic field which attracts a lever and changes the switch contacts. The coil current can be on or off so relays have two switch positions and they are double throw (changeover) switches. Relays allow one circuit to switch a second circuit which can be completely separate from the first. There is no electrical connection inside the relay between the two circuits, the link is magnetic and mechanical.

![Circuit symbol for a relay](image)

When a relay is used to switch a large amount of electrical power through its contacts, it is designated by a special name: contactor. Contactors typically have multiple contacts, and those contacts are usually (but not always) normally-open, so that power to the load is shut off when the coil is de-energized.
The top three contacts switch the respective phases of the incoming 3-phase AC power, typically at least 480 Volts for motors 1 horsepower or greater. The lowest contact is an "auxiliary" contact which has a current rating much lower than that of the large motor power contacts, but is actuated by the same armature as the power contacts.

2.2 Substation Automation (SA)

2.2.1 Definition

Substation automation (SA) is used for controlling, protecting and monitoring substations. At least from a logical point of view, SA systems comprise three levels, the station level with the substation host, the substation HMI and the Gateway (GW) to the remote control centre, the bay level with all the control and protection units and the process level with more or less intelligent process interfaces to the switchgear. Extended implementations show all three levels equipped with IEDs, where for example a conventional RTU comprises all three levels in one unit. All implemented levels are interconnected by serial communication links. There is not only vertical communication between the levels (e.g. between bay and station level), but also horizontal communication within the level (e.g. in the bay level between bay units for functions like interlocking).
Substation automation can mean different things to different electric utilities. To one, it could mean adding a supervisory control and data acquisition (SCADA) system for remote monitoring and control to a traditional substation with mimic panels and an annunciator. Another utility may replace the mimic panel and annunciator with a station human machine interface (HMI). A third utility might use substation automation to replace all interlocks, cutouts and other controls so that all station control is performed and monitored using a combination of microprocessor-based relays, substation controllers and HMIs. Finally, a utility could take a more literal interpretation of the term and define it as actual station automation, including such items as automatic voltage control, power fail actions, intelligent load transferring between stations, load tap. The BCU is the unit responsible of automation in a bay of substation.

2.2.2 Bay Control Unit (BCU)
2.2.2.1 Function of a BCU

i. Monitoring
To monitor the whole system remotely away. The status of primary equipment or auxiliary devices can be obtained from auxiliary contacts. Therefore it is possible to detect and indicate both the OPEN and CLOSED position or a fault or intermediate circuit-breaker or auxiliary contact position.

ii. Control
In addition to the monitoring functions, BCU also support all control functions that are required for operating medium-voltage or highvoltage substations. The main application is reliable control of switching and other processes.

With integrated logic, the user can set, via a graphic innterface (CFC), specific functions for the automation of switchgear or substation. Functions are activated via function keys, binary input or via communication interface.

Switching authority is determined according to parameters, communication or by LOCAL/REMOTE switch .If it is set to " LOCAL" , only local switching operations are possible. The following sequence of switching authority is laid down: " LOCAL" ; DIGSI PC program, " REM OTE"

Every switching operation and change of breaker position is kept in the status indication memory. The switch command source, switching device, cause (i.e. spontaneous change or command) and result of a switching operation are retained.

iii. Command processing
All the functionality of command processing is offered. This includes the processing of single and double commands with or without feedback, sophisticated monitoring of the control hardware and software, checking of the external process, control actions using functions such as runtime monitoring and automatic command termination after output.

2.2.3 IEC 61850
The International Electrotechnical Committee (IEC) Technical Committee (TC) 57 was established in 1964 because of an urgent need to produce international standards in the field of communications between the equipment and systems for the electric power process, including telecontrol, teleprotection, and all other telecommunications that control the electric power system.

The new communication standard IEC 61850 is introduced in Substation Automation replacing almost all traditional wires by serial communication. Based on mainstream
communication means like Ethernet it provides a high flexibility regarding communication architectures. The scope of the standard IEC 61850 is to support the communication for all functions being performed in substation. The goal of the standard is interoperability. Up to now, the communication for SA was based on proprietary serial communication mechanisms complemented with conventional parallel copper wiring. The latter is used especially from the process to the switchgear. With the advent of IEC 61850 there is a comprehensive global standard for all communication needs in the substation being introduced now.

2.3 Programmable Logic Controller (PLC)

The term 'programmable Logic Controller' is defined as:

"A digitally operating electronic system, designed for use in an industrial environment, which uses a programmable memory for the internal storage of user-oriented instructions for implementing specific functions such as logic, sequencing, timing, counting and arithmetic, to control, through digital or analogue inputs and outputs, various types of machines or processes.”[3]

A programmable logic controller (PLC) or programmable controller is a digital computer used for automation of electromechanical processes, such as control of machinery on factory assembly lines, amusement rides, or lighting fixtures. The functionality of the PLC has evolved over the years to include sequential relay control, motion control, process control, distributed control systems and networking. The data handling, storage, processing power and communication capabilities of some modern PLCs are approximately equivalent to desktop computers. PLC-like programming combined with remote I/O hardware, allow a general-purpose desktop computer to overlap some PLCs in certain applications. Unlike general-purpose computers, the PLC is designed for multiple inputs and output arrangements, extended temperature ranges, immunity to electrical noise, and resistance to vibration and impact. The functionality of the PLC has evolved over the years to include sequential relay control, motion control, process control, distributed control systems and networking. The data handling, storage, processing power and communication capabilities of some modern PLCs are approximately equivalent to desktop computers. PLC-like programming combined with remote I/O hardware, allow a general-purpose desktop computer to overlap some PLCs in certain applications.

The first Programmable Logic Controller (PLC) was developed by a group of engineers at General Motors in (1968). Before the PLC, control, sequencing, and safety interlock logic for manufacturing automobiles was accomplished using hundreds or thousands of relays, cam timers, and drum sequencers and dedicated closed-loop controllers. The process for updating such facilities for the
yearly model change-over was very time consuming and expensive, as the relay systems needed to be rewired by skilled electricians. Today As PLC technology has advanced, so have programming languages and communications capabilities, along with many other important features. Today's PLCs offer faster scan times, space efficient high-density input/output systems, and special interfaces to allow non-traditional devices to be attached directly to the PLC. Not only can they communicate with other control systems, they can also perform reporting functions and diagnose their own failures, as well as the failure of a machine or process.

2.3.1 Operation of PLC

A PLC consists of two basic sections: the central processing unit (CPU) and the input/output interface system. The CPU, which controls all PLC activity, can further be broken down into the processor and memory system. The input/output system is physically connected to field devices (e.g., switches, sensors, etc.) and provides the interface between the CPU and the information providers (inputs) and controllable devices (outputs).

The function of an input module is to convert incoming signals into signals, which can be processed by the PLC, and to pass these to the central control unit. The reverse task is performed by an output module. This converts the PLC signal into signals suitable for the actuators, in accordance with the program stored in the memory.

To operate, the CPU "reads" input data from connected field devices through the use of its input interfaces, and then "executes", or performs the control program that has been stored in its memory system. Programs are typically created in ladder logic, a language that closely resembles a relay-based wiring schematic, and are entered into the CPU's memory prior to operation. Finally, based on the program, the PLC "writes", or updates output devices via the output interfaces.

IEC 61131-3 (is the third part of the open international standard IEC 61131, and was first published in December 1993 by the IEC, The purpose of the new standard was to define and standardise the design and functionality of a PLC and the language required for proogramming to the extent where users were able to operate using different PLC systems without any particular difficulties) currently defines five programming languages for programmable control systems:

FBD (Function block diagram):

A function block diagram is a diagram, that describes a function between input variables and output variables. A function is described as a set of elementary blocks. Input and output variables are connected to blocks by connection lines. An output of a block may also be connected to an input of another block. Inputs and outputs of the blocks are wired together with connection lines, or links. The connection is oriented, meaning that the line carries associated
data from the left end to the right end. The left and right ends of the connection line must be of the same type.

**LD (Ladder diagram):**

Ladder logic is a programming language that represents a program by a graphical diagram based on the circuit diagrams of relay-based logic hardware. It is primarily used to develop software for Programmable Logic Controllers (PLCs) used in industrial control applications. The name is based on the observation that programs in this language resemble ladders, with two vertical rails and a series of horizontal rungs between them...Many of the earliest PLCs expressed all decision making logic in simple ladder logic which appeared similar to electrical schematic diagrams. This program notation was chosen to reduce training demands for the existing technicians.

**ST (Structured text):**

Structured text is a high level language that is block structured and syntactically resembles Pascal.

**IL (Instruction list):**

It is a low level language and resembles assembly. All of the languages share IEC61131 Common Elements. The variables and function call are defined by the by the common elements so different languages can be used in the same program. The file format has now been standardized to XML by PLCopen.

**SFC (Sequential function chart):**

SFC programming offers a graphical method of organizing the program. The three main components of an SFC are steps, actions and transitions. Steps are merely chunks of logic, i.e., a unit of programming logic that accomplishes a particular control task. Actions are the individual aspects of that task. Transitions are the mechanisms used to move from one task to another. Control logic for each Step, Action and Transition is programmed in one of the other languages such as Ladder Diagram or Structured Text.

![SFC chart symbol](image-url)

**Figure 2.12**: SFC chart symbol
Many PLCs can be expanded by means of additional input/output, analogue, positioning and communication modules. Special PLCs are available for safety technology, shipping or mining tasks.

### 2.3.2 User interface

PLCs may need to interact with people for the purpose of configuration, alarm reporting or everyday control. A Human-Machine Interface (HMI) is employed for this purpose (e.g.: PC_Access, WinCC). A simple system may use buttons and lights to interact with the user. Text displays are available as well as graphical touch screens. More complex systems use a programming and monitoring software installed on a computer, with the PLC connected via a communication interface.

### 2.3.3 PLC compared with other control systems and its benefits

The main difference from other computers is that PLCs are armored for severe conditions (such as dust, moisture, heat, cold) and have the facility for extensive input/output (I/O) arrangements. The input/output arrangements may be built into a simple PLC, or the PLC may have external I/O modules attached to a computer network that plugs into the PLC. PLCs also contain input and output devices compatible with industrial pilot devices and controls; little electrical design is required, and the design problem centers on expressing the desired sequence of operations in ladder logic (or function chart) notation. PLC applications are typically highly customized systems so the cost of a packaged PLC is low compared to the cost of a specific custom-built controller design.

A microcontroller-based design would be appropriate where hundreds or thousands of units will be produced and so the development cost (design of power supplies and input/output hardware) can be spread over many sales, and where the end-user would not need to alter the control. Automotive applications are an example; millions of units are built each year, and very few end-users alter the programming of these controllers.

Many PLCs can be expanded by means of additional input/output, analogue, positioning and communication modules. PLCs have built in communications ports usually 9-Pin RS232, and optionally for RS485 and Ethernet. Modbus, BACnet or DFI is usually included as one of the communications protocols. Others' options include various fieldbuses such as DeviceNet or Profibus. Most modern PLCs can communicate over a network to some other system, such as a computer running a SCADA (Supervisory Control And Data Acquisition) system or web browser.
2.4 Micro Automation SIMATIC S7-200

The SIMATIC S7-200 series of micro-programmable logic controllers (Micro PLCs which perform maximum power at minimum size) can control a wide variety of devices to support any automation needs. The S7-200 monitors inputs and changes outputs as controlled by the user program, which can include Boolean logic, counting, timing, complex math operations, and communications with other intelligent devices. The compact design, flexible configuration, and powerful instruction set combine to make the S7-200 a perfect solution for controlling a wide variety of applications.

The table below shows S7-200 series and their features:

<table>
<thead>
<tr>
<th>S7-200 CPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU 221 DC/DC/DC 6 Inputs/4 Outputs</td>
</tr>
<tr>
<td>CPU 221 AC/DC/Relay 6 Inputs/4 Relays</td>
</tr>
<tr>
<td>CPU 222 DC/DC/DC 8 Inputs/6 Outputs</td>
</tr>
<tr>
<td>CPU 222 AC/DC/Relay 8 Inputs/6 Relays</td>
</tr>
<tr>
<td>CPU 224 DC/DC/DC 14 Inputs/10 Outputs</td>
</tr>
<tr>
<td>CPU 224 AC/DC/Relay 14 Inputs/10 Relays</td>
</tr>
<tr>
<td>CPU 224XP DC/DC/DC 14 Inputs/10 Outputs</td>
</tr>
<tr>
<td>CPU 224XP AC/DC/Relay 14 Inputs/10 Relays</td>
</tr>
<tr>
<td>CPU 226 DC/DC/DC 24 Inputs/16 Outputs</td>
</tr>
<tr>
<td>CPU 226 AC/DC/Relay 24 Inputs/16 Relays</td>
</tr>
</tbody>
</table>

Table 2.1: S7-200 Series

It is in a class by itself: Exceptionally compact yet remarkably capable – especially with respect to its real-time performance – it is fast, features great communication options, and comes with easy to operate hardware and software. But there's more to it than that: The SIMATIC S7-200 Micro PLC has a consistently modular design – for customized solutions which are not too large for the present but open-ended enough to be expanded anytime in the future. All this makes the SIMATIC S7-200 Micro PLC a highly effective and economical solution for automated control in the compact performance range. The S7-200 CPU combines a microprocessor, an integrated power supply, input circuits, and output circuits in a compact housing to create a powerful Micro PLC.
Inputs to S7-200 are devices such as switches, pushbuttons, and other sensor devices, they are connected to the terminal strip under the bottom cover of the plc.

Outputs devices such as relays, leds, so on are connected to the output terminals under the bottom cover of the plc.
2.4.1 Communications options

Siemens provides two programming options for connecting computer to S7-200: a direct connection with a PPI Multi-Master cable, or a Communications Processor (CP) card with an MPI cable.

The PPI Multi-Master programming cable is the most common and economical method of connecting computer to the S7-200. This cable connects the communications port of the S7-200 to the serial communications of the computer. The PPI Multi-Master programming cable can also be used to connect other communications devices to the S7-200.

2.4.2 Selecting the operating mode for the S7-200 CPU

The S7-200 has two modes of operation: STOP mode and RUN mode. The status LEDs on the front of the CPU indicates the current mode of operation. In STOP mode, the S7-200 is not executing the program, and can download a program or the CPU configuration. In RUN mode, the S7-200 is running the program.

If a power cycle occurs when the mode switch is set to either STOP or TERM, the S7-200 goes automatically to STOP mode when power is restored. If a power cycle occurs when the mode switch is set to RUN, the S7-200 goes to RUN mode when power is restored. STEP 7-Micro/WIN also allows to change the operating mode of the online S7-200. To enable the software to change the operating mode, by using the PLC > STOP or PLC > RUN menu commands or the associated buttons on the toolbar to change the operating mode.
2.5 Human Machine Interface (HMI)

It is a graphical, object oriented method by which an operator is capable of communicating with the system. Human-machine interfacing allows the operator to visualize, manage, command, and program the system. Also known as GUI (graphical user interface) or MMI (man machine interface). This is a process that displays graphics and allows people to interface with the control system in graphic form. It may contain trends, alarm summaries, pictures, or animation. The user interface provides means of:

- Input: allowing the users to manipulate a system
- Output: allowing the system to indicate the effects of the users' manipulation.

2.5.1 Types of HMI

Currently (as of 2009) the following types of user interface are the most common:

- **Graphical user interfaces (GUI)**: Accept input via devices such as computer keyboard and mouse and provide articulated graphical output on the computer monitor. There are at least two different principles widely used in GUI design: Object-oriented user interfaces (OOUIs) and application oriented interface.

- **Web-based user interfaces or web user interfaces (WUI)**: Accept input and provide output by generating web pages which are transmitted via the Internet and viewed by the user using a web browser program.

User interfaces that are common in various fields outside desktop computing:

- **Command line interfaces**: Where the user provides the input by typing a command string with the computer keyboard and the system provides output by printing text on the computer monitor. Used for system administration tasks.

- **Tactile interfaces**: Supplement or replace other forms of output with haptic feedback methods. Used in computerized simulators.

- **Touch user interface are graphical user interfaces**: Using a touchscreen display as a combined input and output device. Used in many types of point of sale, industrial processes and machines, self-service machines etc.
Chapter 3

Design and Implementation

3.1 Preamble

This chapter covers in details every step performed until the completion of the project including software and hardware tools used.

3.2 Design goals

Due to the increasing no of applications performed by PLCs in substations, it is desired to implement the bay interlocking scheme in a double bus-single breaker configuration using the PLC as a controller for such a problem.

In the path until completion, four different independent sections were performed. These sections were integrated to exit with a final picture; these will be verified in details.

I. Step (1): Implementation of the interlocking concept using MicroWin to convert this logic into a ladder diagram.

II. Step (2): Connecting the controller to the computer through OPC server (S7-200 PC-Access).

III. Step (3): Integration between OPC server (S-7200 PC ACCESS) and a program written in visual basic (VB) in order to provide sort of user interfacing.

IV. Step (4): The final step is to build a MIMIC diagram its switching operation simulates the physical bay switching functions.

3.3 Implementation

3.3.1 Step (1): Construction of the ladder diagram

To ensure reliable control, the high voltage switching devices within each bay, and at a higher level within the entire installation, are interlocked with respect to each other. The interlock conditions depend on the circuit configuration and status of the installation at any given time. The interlock conditions must be defined according to the station layout, such as in the following case under consideration of a double bus single breaker bus/switching configuration.

In order to implement the logic (interlocking) needed to gain a system with higher reliability SIEMENS STEP7-200 PLC is used for this purpose. It’s appended with a software
(V4.0 step7 MicroWin SP1), through which the logic is translated into a ladder diagram understood by the PLC CPU (224 XP).

![Figure 3.1: A mimic diagram of a double busbar substation with branch coupling and bus earthing switch.](image)

The following conditions are satisfied in this case:

1. Disconnectors Q1, Q2 and Q9 is operated only when breaker Q0 is open (protection against switching under load).
2. Breaker Q0 cannot be closed with disconnectors Q1, Q2 and Q9 in the intermediate position (intermediate position indication).
3. Disconnectors Q1 and Q2 are mutually interlocked so that only one is closed at a time.
4. When the bus-tie is closed, a second bus disconnector (Q1 or Q2) belonging to the tied system is closed. One of the two closed disconnectors is then be opened (change of bus under load).
5. Disconnectors Q1 and Q2 is operated only if the related bus earthing switch Q15 or Q25 is open.
6. Disconnector Q9 is operated only when earthing switch Q8 is open (taking account of other end if necessary) and vice versa is tue.
7. The tie-breaker Q0 can be opened only if not more than one bus isolator in each branch is closed (tie-breaker lock-in).
8. One bus earthing switch Q15 or Q25 can be operated if in the respective bus section all bus disconnectors of the corresponding bus system are open.
9. An interlock release switch cancels the interlock conditions. Switching operations are then the responsibility of the person authorized.

The following flow charts show clearly the conditions above.
Setting breaker Q0.0:

![Flowchart for Setting breaker](image)

Figure 3.2: Flowchart for Setting breaker

Mutual interlock between Isolator (Q0.3) and earthin switch (Q0.4):

![Flowchart for Mutual interlock](image)

Figure 3.3: Flowchart for mutual interlock

3: Flowchart for mutual interlock
Setting buses isolators (Q0.1/Q0.2):

Figure 3.4: Flowchart for Setting isolators
Resetting buses isolators (Q0.1/Q0.2):

![Flowchart for resetting isolators](image)

**Figure 3.5: flowchart for resetting isolators**

The Ladder diagram is appended in the appendix A.

### 3.3.2 Step (2)

The ladder is tested to assure that the logic is correct using an appended simulator with the PLC software. When it is cleared that interlocking is achieved, the ladder is downloaded to the PLC.

A series of wiring is performed which is verified in the mimic diagram construction. An OPC server is used in order to create sort of real-time monitoring of the PLC status by connecting this PLC to the computer through PC/PPI cable. The OPC server suitable for Siemens drivers only which is S7-200 PC-Access is used to perform this job. S7-200 PC-Access is software capable to bring the state of the predefined items which refer to the physical input, outputs or memories which is either fixed or variable.

Consequence steps are performed for items definition in S7-200 PC-Access, these items in this case refer to the switchgears in the bay (breakers, isolators, etc.) as will be shown in the mimic diagram construction where the switchgears in the real bay are replaced by contactors.
Items in the OPC server are defined as follows:

Figure 3.6: Window of s7-200 PC Access

Figure 3.7: Creation of a new a PLC in the S7-200 PC Access
i. The properties of the PLC is modified as desired to meet the consistency of the whole design.

![Figure 3.8: Determination of the PLC characteristics in S7-200 PC Access](image1)

Figure 3.8: Determination of the PLC characteristics in S7-200 PC Access

ii. Variables in the diagram the needs to be monitored to perform the suitable and desired action are defined in the server with its physical addresses in the PLC.

![Figure 3.9: definition of desired variables that need to be monitored or manipulated](image2)

Figure 3.9: definition of desired variables that need to be monitored or manipulated
Figure 3.10 definition of the breaker item in order to be monitored through.

Figure 3.11: Definitions of all items
Test client is started which gives full information about each item including its value, time stamp which is time at which real time monitoring is begun or even the quality which is an indication that the server is acquiring data from PLC. These brought data are manipulated by writing new values to its corresponding defined items which reflect its new values to the physical input or outputs in the S7-200 PLC.

![Figure 3.12: All items are defined.](image)

3.3.3 Step 3

Controlling the bay can be either local or remote. Remote control is performed using a user friendly human machine interface as mentioned above. It is chosen to use visual basic (VB) program in order to create HMI.

Code is written in VB each item defined in PC-Access is defined in VB program with two sub functions for reading and writing. A bay with bus coupler, three earthing switches, breaker and three isolators is drawn to represent the HMI, as follows:
3.3.4 STEP 4: Mimic Model

It is designed so that its switching operations simulates the real life bay switching operations. Each switchgear in a real bay of a substation is replaced by a contactor, functionality of contactors is controlled by the logic embedded in the PLC, each O/P of the PLC is connected to a contactor energizing coil. Switches of the actual switch in a real bay is replaced by an OFF/ON switch.
In a substation the control panels consist of indicator lamps. Indicator lamp is used as an indicator for the operation of the interlock. In the mimic diagram they are placed adjacently to the contactor.

Fig 3.15 : An ON/OFF switch, an indicator lamp, a contactor
The indicator lamp connection: A contactor has a Normally Opened (NO) switch, this switch is closed when the contactor coil is energized, when it is closed a path for current is established, then the indicator is lightened, this connection is performed to replace the first connection in which the indicator lamps are connected in parallel with the contactor, because the first connection had small indication efficiency, it is sensed that OFF state indicators is emitting light with the ON state indicators, probably due to the mutual inductance caused by the contactor coils.

3.4 Local/Remote switch

Control must be either local or remote, when control is local, HMI has no authority to either close or open any of the switchgears, and when it is remote, switchgears are only controlled by HMI. This problem is solved as follows:

An I/P (switch) of a PLC (I1.5) has two positions either ON or OFF, depending on its state only one control can be authorized, i.e.:

I1.5 = OFF___________________________ Local control
I1.5 = ON ___________________________Remote control
Ladder for this switch:

![Ladder Diagram](image)

Figure 3.17: ladder for LOCAL/REMOTE switch

### 3.5 The difference between V memory and M memory

I. **V memory (variable memory):** Its value can be altered externally, this property is used to solve the problem of writing to the PLC since I and Q are external to the PLC, cannot be accessed directly internally.

II. **M memory:** Fixed memory, its value depends on the logic of the ladder, can be setted or resetted externally, not accessible.
Chapter 4

Results

4.1 Ladder Diagram

In order to investigate whether the ladder diagram worked appropriately, a LD was tested using the appended simulator with the PLC software, the simulation results haven’t been ideal, therefore an excessive error detection was adopted to debug the errors. Finally, after many trials the interlocking was achieved and the ladder was doing well. After that the ladder was downloaded the PLC. The tests carried out in this section have proved that the ladder performed as desired.

![Operating PLC](image)

Figure 4.1: Operating PLC

4.2 HMI

4.2.1 Using PC-Access Server

When the items are defined to PC_Access server, the data displayed on screen matched the data initially fed to the PLC (inputs).
The interlocking conditions were met, for example, Figures (4.3) and (4.4) shows achievement of breaker Q0.0 setting and resetting conditions respectively.

**Figure 4.3: Breaker Closing Is Only Achieved When 3 And 1 Are Closed**
Figure 4.4: Breaker is opened directly

Figure (4.5) shows the permeability of closing bus Q0.1 and Q0.2 when the tie is closed:

<table>
<thead>
<tr>
<th>Test Client</th>
<th>value</th>
<th>Time Stamp</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Image 98x615 to 513x785]</td>
<td>[Image 72x323 to 488x524]</td>
<td>[Image 296x52]</td>
<td>[Image 299x52]</td>
</tr>
<tr>
<td>MicroWin.writing2.TIE ISOLATOR-1</td>
<td>0</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.TIE BREAKER (1)</td>
<td>0</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.TIE BREAKER</td>
<td>0</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.ISOLATOR-3 (1)</td>
<td>1</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.ISOLATOR-3</td>
<td>0</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.BUS-2 ISOLATOR (1)</td>
<td>0</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.BUS-2 ISOLATOR</td>
<td>0</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.BUS-2 EARTHING SWITCH (1)</td>
<td>0</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.BUS-2 EARTHING SWITCH</td>
<td>0</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.BUS-1 ISOLATOR (1)</td>
<td>1</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.BUS-1 ISOLATOR</td>
<td>0</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.BUS-2 EARTHING SWITCH</td>
<td>1</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.BUS-2 EARTHING SWITCH (1)</td>
<td>0</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.BUS-1 EARTHING SWITCH</td>
<td>0</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
<tr>
<td>MicroWin.writing2.TIE BREAKER (1)</td>
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<td>15:12:13:139</td>
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</tr>
<tr>
<td>MicroWin.writing2.BUS-2 BREAKER</td>
<td>0</td>
<td>15:09:54:812</td>
<td>Good</td>
</tr>
</tbody>
</table>

Figure 4.5: Breaking of the mutual interlock condition when the tie is closed

Figure (4.6) depicts tying the two buses together, in order to change from one bus to another under load.
4.2.2 Visual Basic

The connection between OPC and VB was completed successfully, users or operators in the control centre can access their interface; the users can monitor status of O/Ps and I/Ps of the Bay and PLC and they can change it, as shown in Figure (4.7).

Figure 4.6: changing of bus under load

Figure 4.7.a: HMI, VB window
4.3 Mimic model

When the mimic model has been built and tested and the PLC, switches and contactors and indication lamps are connected together, the switches have controlled the PLC’s I/Ps and the actual outputs of the PLC are reflected via the indication lamps. An emission problem with the indication lamps has been encountered and resolved as described in section (3.3.4).
Chapter 5

Conclusion And Recommendation

5.1 Conclusion

- PLC proved to be safer and much more efficient than the old RTUs and BCUs, and provides an excellent and very reliable control that makes it best candidate to completely replace those RTUs and BCUs.
- The S7-200 PLC used in this project is small for real-life application Bays, that is due to its low rated voltage, but it is suitable for educational purposes. 
- PLCs are very reliable in control application but when it comes to protection it is not that reliable. A small shortcoming is that even though; it is a computer program and can crash or be damaged. When such a thing happens the security circuit may fail and causes untolerable system failure.
- The HMI greatly facilitated the remote control in the Bay eliminating the need to go to the Bay and provided easy monitoring and caused all the Bay to be viewed within a small monitor display.
- There are PLCs specially constructed for safety applications that do have the necessary hardware to detect and deal with I/O failures and to precisely locate the failure to be in the Input or the Output in case they were tied together.
- Although PLC is very trustable, yet it is not used for human safety; because human safety worth to much, so it is used only with machines.

5.2 Future Work

- Bus coupling in this project was performed in steps; (i.e. : Isolator Q0.1 then Isolator Q0.2 and then the tie breaker). But for further work this can be done with a circuit that can perform the sequencing procedure and with single ON/OFF switch the whole thing is accomplished.
- The case study was about partial Bay interlock automation, but it can be extended for the whole automation using PLCs.
- One important note is that before proceeding to tying the Double Bus-Single Breaker the PLC must synchronize the 
  \- Voltage 
  \- Phase 
  \- Frequency 
  \- Phase sequence (R,Y,B) 
For the two buses, this is done in real life Bays using Synchro-Check.
References


[4]"Switchbay Protection and Control unit ,Ref 542 Plus”,ABB


### APPENDICES

**Appendix A: Ladder Diagram**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Var Type</th>
<th>Data Type</th>
<th>Comment</th>
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</thead>
<tbody>
<tr>
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<td>BREAKER(Q0) SWITCH</td>
</tr>
<tr>
<td>I0.1</td>
<td>TEMP</td>
<td></td>
<td>ISOLATOR(Q1) SWITCH</td>
</tr>
<tr>
<td>I0.2</td>
<td>TEMP</td>
<td></td>
<td>ISOLATOR(Q2) SWITCH</td>
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<tr>
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<td>TEMP</td>
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<td>ISOLATOR(Q9) SWITCH</td>
</tr>
<tr>
<td>I0.4</td>
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<td>BUS1 EARTHING SWITCH(Q15)</td>
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<tr>
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<td>BUS 2 EARTHING SWITCH</td>
</tr>
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<td>I1.0</td>
<td>TEMP</td>
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<td>TIE BREAKER(Q0)</td>
</tr>
<tr>
<td>I1.1</td>
<td>TEMP</td>
<td></td>
<td>TIE ISOLATOR(Q1)</td>
</tr>
<tr>
<td>I1.2</td>
<td>TEMP</td>
<td></td>
<td>TIE ISOLATOR(Q2)</td>
</tr>
<tr>
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<td>REMOTE/LOCAL CONTROL</td>
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</tr>
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<td>TEMP</td>
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<td>ISOLATOR(Q1)</td>
</tr>
<tr>
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<td>ISOLATOR(Q2)</td>
</tr>
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<tr>
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<tr>
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<td>Q1.0</td>
<td>TEMP</td>
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<td>TIE ISOLATOR(Q1)</td>
</tr>
<tr>
<td>Q1.1</td>
<td>TEMP</td>
<td></td>
<td>TIE ISOLATOR(Q2)</td>
</tr>
</tbody>
</table>
Network 1
Setting breaker Q0.0

Network 2
(resetting breaker Q0.0 (independent))

Network 3
Network Title
(output to Q0.0)
Network 14
Setting ES Q0.4
M2.4 M0.4
\[ R \]
\[ 1 \]

Network 15
To O/P Q0.4
M0.4 Q0.4

Network 16
Setting ES Q0.5
M2.5 Q0.1 M0.5
\[ S \]
\[ 1 \]
M2.7

Network 17
Resetting ES Q0.5
M2.5 M0.5
\[ R \]
\[ 1 \]

Network 18

Network 19
Setting ES Q0.6
M2.6 Q0.2 M0.6
\[ S \]
\[ 1 \]
M2.7
Appendix B: Eidbabiker Single Line Diagram