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IoT Based Optimal Coordination of Protective Devices for FREEDM System

BSc. Project

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2020

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Acknowledgement

We would like to express our deepest appreciation to all those who provided us the possibility to complete this project. We are highly indebted to Prof. Dr. Magdi El-Saadawi for his guidance and constant supervision as well as for providing necessary information regarding the project and also for his support in completing the project. A special gratitude we give to our final year project supervisor, Dr. Bishoy Elkis Sedhom Beshay, whose contribution in stimulating suggestions and encouragement, helped us to coordinate our project especially in writing this book. It would not have been possible without that kind of support and help of him to complete this project.

Furthermore, we would also like to acknowledge with much appreciation the crucial role of the staff of our faculty, who gave the permission to use all required equipment and the necessary materials to complete the project. Last but not least, we would like to thank all of our engineering professors, doctors and assistants who taught us, may Allah bless them.

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INTRODUCTION

1. Introduction

1.1 Distribution system

1.1.1 Electric power distribution

It is the final stage in the delivery of electric power; it carries electricity from the transmission system to individual consumers. Distribution substations connect to the transmission system and lower the transmission voltage to medium voltage ranging between 2 kV and 35 kV with the use of transformers. Primary distribution lines carry this medium voltage power to distribution transformers located near the customer's premises. Distribution transformers again lower the voltage to the utilization voltage used by lighting, industrial equipment or household appliances. Often several customers are supplied from one transformer through secondary distribution lines. Commercial and residential customers are connected to the secondary distribution lines through service drops. Customers demanding a much larger amount of power may be connected directly to the primary distribution level or the subtransmission level.

The transition from transmission to distribution happens in a power substation, which has the following functions:
- Circuit breakers and switches enable the substation to be disconnected from the transmission grid or for distribution lines to be disconnected.
- Transformers step down transmission voltages, 35 kV or more, down to primary distribution voltages. These are medium voltage circuits, usually 600–35000 V.[1]

- From the transformer, power goes to the busbar that can split the distribution power off in multiple directions. The bus distributes power to distribution lines, which fan out to customers.

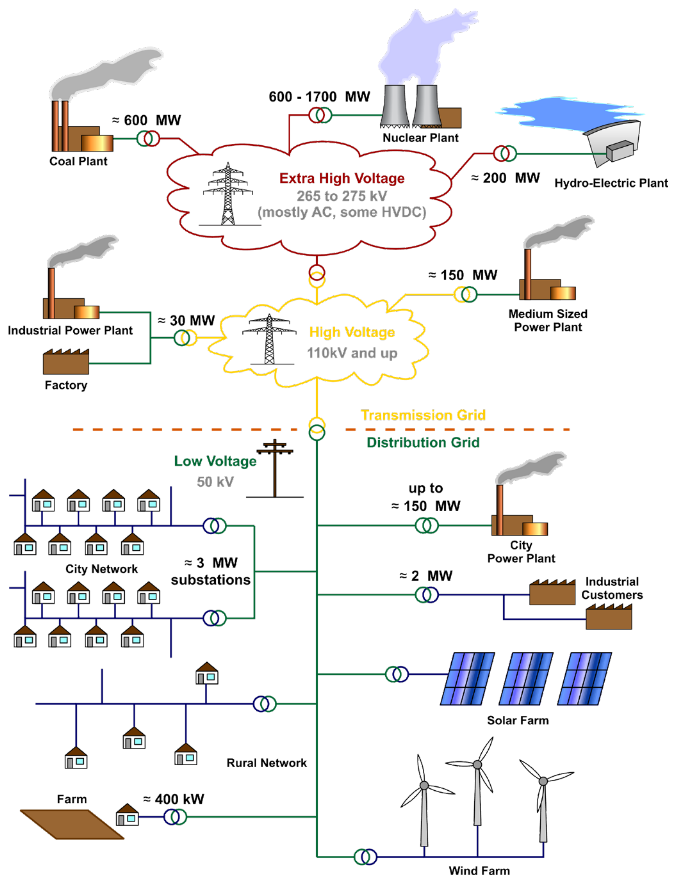


Figure 1.1 Schematic of Electricity Grid

Urban distribution is mainly underground, sometimes in common utility ducts. Rural distribution is mostly above ground with utility poles, and suburban distribution is a mix. Closer to the customer, a distribution transformer steps the primary distribution power down to a low-voltage secondary circuit, usually 120/240 V in the US for residential customers. The power comes to the customer via a service drop and an electricity meter. The final circuit in an urban system may be less than 15 metres (50 ft), but may be over 91 metres (300 ft) for a rural customer.

1.1.2 Introduction of the transformer

Transmitting electricity a long distance at high voltage and then reducing it to a lower voltage for lighting became a recognized engineering roadblock to electric power distribution with many, not very satisfactory, solutions tested by lighting companies. The mid-1880s saw a breakthrough with the development of functional transformers that allowed the AC voltage to be “stepped up” to much higher transmission voltages and then dropped down to a lower end user voltage. With much cheaper transmission costs and the greater economies of scale of having large generating plants supply whole cities and regions, the use of AC spread rapidly.


Figure 1.2 Power Tarnsformer

In the US the competition between direct current and alternating current took a personal turn in the late 1880s in the form of a “war of currents” when Thomas Edison started attacking George Westinghouse and his development of the first US AC transformer systems, pointing out all the deaths caused by high voltage AC systems over the years and claiming any AC system was inherently dangerous. Edison’s propaganda campaign was short lived with his company switching over to AC in 1892.

AC became the dominant form of transmission of power with innovations in Europe and the US in electric motor designs and the development of engineered universal systems allowing the large number of legacy systems to be connected to large AC grids.

In the first half of the 20th century, in many places the electric power industry was vertically integrated, meaning that one company did generation, transmission, distribution, metering and billing. Starting in the 1970s and 1980s, nations began the process of deregulation and privatisation, leading to electricity markets. The distribution system would remain regulated, but generation, retail, and sometimes transmission systems were transformed into competitive markets

1.1.3 Primary distribution & Secondary distribution

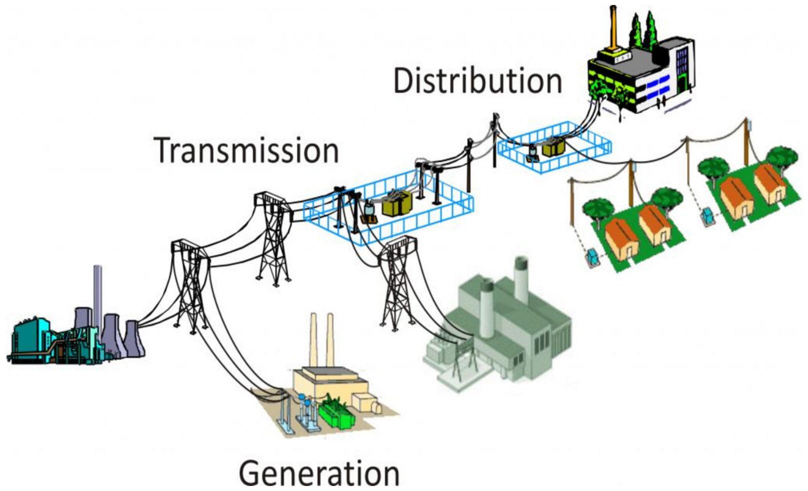


Figure 1.3 Electric Power System

In Primary Distribution At the sub station, the level of secondary transmission voltage (132kV, 66 or 33 kV) reduced to 11kV by step down transforms. Generally, electric supply is given to those heavy consumer whose demand is 11 kV, from these lines which caries 11 kV and a separate sub station exists to control and utilize this power. For heavier consumer (at large scale) their demand is about 132 kV or 33 kV, they take electric supply from secondary transmission or primary distribution (in 132 kV, 66kV or 33kV) and then step down the level of voltage by step-down transformers in their own sub station for utilization (i.e. for electric traction etc). While in Secondary Distribution the Electric power is given by (from Primary distribution line i.e.11kV) to distribution sub station. This sub station is located near by consumers areas where the level of voltage reduced by step down transformers 440V by Step down transformers. These transformers called Distribution transformers, three phase four wire system). So there is 400 Volts (Three Phase Supply System) between any two phases and 230 Volts (Single Phase Supply) between a neutral and phase (live) wires. Residential load (i.e. Fans, Lights, and TV etc) may be connected between any one phase and neutral wires, while three phase load may be connected directly to the three phase lines

1.3.1 Network configurations

Distribution networks are divided into two types, radial or network. A radial system is arranged like a tree where each customer has one source of supply. A network system has multiple sources of supply operating in parallel. Spot networks are used for concentrated loads. Radial systems are commonly used in rural or suburban areas.
Radial systems usually include emergency connections where the system can be reconfigured in case of problems, such as a fault or planned maintenance. This can be done by opening and closing switches to isolate a certain section from the grid.Long feeders experience voltage drop (power factor distortion) requiring capacitors or voltage regulators to be installed.

Reconfiguration, by exchanging the functional links between the elements of the system, represents one of the most important measures which can improve the operational performance of a distribution system. The problem of optimization through the reconfiguration of a power distribution system, in terms of its definition, is a historical single objective problem with constraints. Since 1975, when Merlin and Back] introduced the idea of distribution system reconfiguration for active power loss reduction, until nowadays, a lot of researchers have proposed diverse methods and algorithms to solve the reconfiguration problem as a single objective problem. Some authors have proposed Pareto optimality based approaches (including active power losses and reliability indices as objectives). For this purpose, different artificial intelligence based methods have been used: microgenetic, branch exchange, particle swarm optimization] and non-dominated sorting genetic algorithm.

1.3.2 Rural services

Rural electrification systems tend to use higher distribution voltages because of the longer distances covered by distribution lines (see Rural Electrification Administration). 7.2, 12.47, 25, and 34.5 kV distribution is common in the United States; 11 kV and 33 kV are common in the UK, Australia and New Zealand; 11 kV and 22 kV are common in South Africa; 10, 20 and 35 kV are common in China. Other voltages are occasionally used.

Rural services normally try to minimize the number of poles and wires. It uses higher voltages (than urban distribution), which in turn permits use of galvanized steel wire. The strong steel wire allows for less expensive wide pole spacing. In rural areas a pole-mount transformer may serve only one customer. In New Zealand, Australia, Saskatchewan, Canada, and South Africa, Single-wire earth return systems (SWER) are used to electrify remote rural areas.

Three phase service provides power for large agricultural facilities, petroleum pumping facilities, water plants, or other customers that have large loads (Three phase equipment). In North America, overhead distribution systems may be three phase, four wire, with a neutral conductor. Rural distribution system may have long runs of one phase conductor and a neutral. In other countries or in extreme rural areas the neutral wire is connected to the ground to use that as a return (Single-wire earth return). This is called an ungrounded wye system.

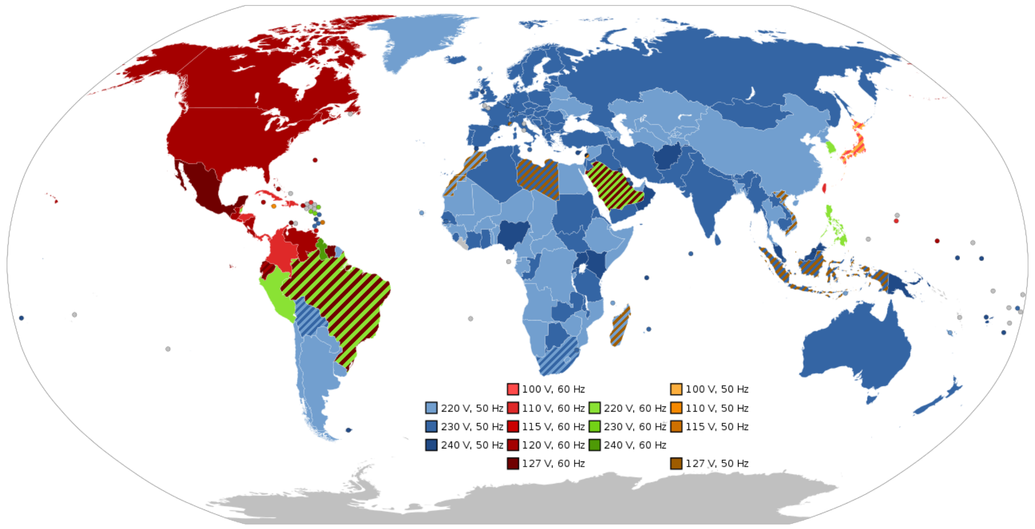


Figure 1.4 World map of mains voltage and frequencies

Electricity is delivered at a frequency of either 50 or 60 Hz, depending on the region. It is delivered to domestic customers as single-phase electric power. In some countries as in Europe a three phase supply may be made available for larger properties. Seen with an oscilloscope, the domestic power supply in North America would look like a sine wave, oscillating between −170 volts and 170 volts, giving an effective voltage of 120 volts RMS. Three-phase electric power is more efficient in terms of power delivered per cable used, and is more suited to running large electric motors. Some large European appliances may be powered by three-phase power, such as electric stoves and clothes dryers.

A ground connection is normally provided for the customer's system as well as for the equipment owned by the utility. The purpose of connecting the customer's system to ground is to limit the voltage that may develop if high voltage conductors fall down onto lower-voltage conductors which are usually mounted lower to the ground, or if a failure occurs within a distribution transformer. Earthing systems can be TT, TN-S, TN-C-S or TN-C.

1.3.3 Regional variations

1.3.3.1 220–240 volt systems:

Most of the world uses 50 Hz 220 or 230 V single phase, or 400 V 3 phase for residential and light industrial services. In this system, the primary distribution network supplies a few substations per area, and the 230 V / 400 V power from each substation is directly distributed to end users over a region of normally less than 1 km radius. Three live (hot) wires and the neutral are connected to the building for a three phase service. Single-phase distribution, with one live wire and the neutral is used domestically where total loads are light. In Europe, electricity is normally distributed for industry and domestic use by the three-phase, four wire system. This gives a phase-to-phase voltage of 400 volts wye service and a single-phase voltage of 230 volts between any one phase and neutral. In the UK a typical urban or suburban low-voltage substation would normally be rated between 150 kVA and 1 MVA and supply a whole neighbourhood of a few hundred houses. Transformers are typically sized on an average load of 1 to 2 kW per household, and the service fuses and cable is sized to allow any one property to draw a peak load of perhaps ten times this. For industrial customers, 3-phase 690 / 400 volt is also available, or may be generated locally.[19] Large industrial customers have their own transformer(s) with an input from 11 kV to 220 kV.

1.3.3.2 100–120 volt systems:

Most of the Americas use 60 Hz AC, the 120/240 volt split phase system domestically and three phase for larger installations. North American transformers usually power homes at 240 volts, similar to Europe's 230 volts. It is the split-phase that allows use of 120 volts in the home.

Most household appliances are made to work on either frequency. The problem of incompatibility came into the public eye when the 2011 Tōhoku earthquake and tsunami knocked out about a third of the east's capacity, and power in the west could not be fully shared with the east, since the country does not have a common frequency.

There are four high-voltage direct current (HVDC) converter stations that move power across Japan's AC frequency border. Shin Shinano is a back-to-back HVDC facility in Japan which forms one of four frequency changer stations that link Japan's western and eastern power grids. The other three are at Higashi-Shimizu, Minami-Fukumitsu and Sakuma Dam. Together they can move up to 1.2 GW of power east or west.

1.3.3.3 240 volt systems and 120 volt outlets:

Most modern North American homes are wired to receive 240 volts from the transformer, and through the use of split-phase electrical power, can have both 120 volt receptacles and 240 volt receptacles. The 120 volts is typically used for lighting and most wall outlets. The 240 volt outlets are usually located to service the oven and stovetop, water heater, and clothes dryer (if they are electric, rather than using natural gas). Sometimes a 240 volt outlet is mounted in the garage for machinery or for charging an electric car.

1.2 What is smart grid

1.2.1 Definition of smart grid

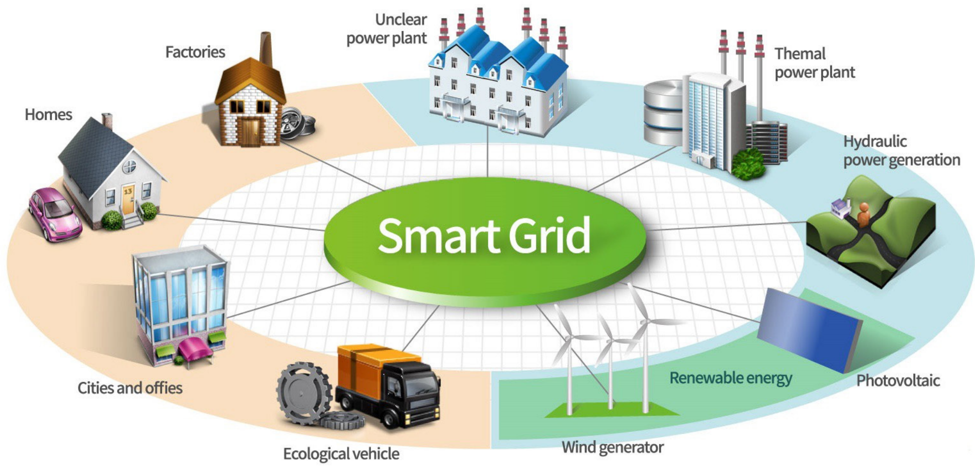


Figure 1.5 Smart Grid System

In the past, electricity grids were simple pipes through which electricity flowed from the producer to consumers. They have however evolved gradually to become 'smart'. This has enabled them to solve the growing issue of managing the balance of the grid.

The term "smart grid" describes an electrical grid that's integrated with a computerized, two-way communication network. Older electrical grids send electrical power one direction, from a power plant to homes and offices. A smart grid improves on that network by providing instantaneous feedback on system-wide operations, power interruptions and electrical use back to electrical plant and regional power grid operators.

A smart grid can use real-time monitoring to modify and tune itself to an optimal state of performance, delivering electricity evenly even during peak-usage hours and anticipating problem areas and service disturbances. It can also isolate parts of the electrical network that are at risk of failure, to prevent small-scale, brief interruptions from turning into region-wide, long-term blackouts.smart grid will permit more efficient transmission of electricity, lower operating and kilowatt costs, quicker restoration of electricity after outages and reduced energy use during peak-demand hours.

1.2.2 Smart grid features

Figure 1.6 Smart Grid Features

The Smart Grid is a collection of technologies, all communicating and interacting with each other, grid operators, producers, and consumers. Utilizing the existing infrastructure and adding functionality to it, the overall feature set of Smart Grids is significantly greater than the sum of its component parts as, with every new individual technology integrated into the whole, new synergistic benefits develop. While these benefits are what the Smart Grid actually offers, it is prudent to first look at the major components of Smart Grids before delving into how they interact with one another.

1.2.2.1 Metering and real time monitoring

Metering technology is the foundation upon which Smart Grids function. Smart meters measure and analyze electricity usage, constantly communicate the data they collect to central locations, and, differentiating them from past technologies, are capable of two-way communication with the grid as a whole, influencing and being influenced by other components in the Smart Grid. Advanced Metering Infrastructure, AMI, is the networking of devices and protocols that allows for this two-way communication, representing the collective advances in metering and communications technologies.One immediate result of this improvement in metering is the potential for a shift away from flat-rate fees for electricity in favor of time-of-use pricing, where the cost of using electricity reflects the cost of producing that electricity at that very moment, financially incentivizing the voluntary shifting of demand away from peak hours

1.2.2.2 Stability and automated management and faster restoration

Smart Grids include a series of features designed to improve stability and mitigate the effects of unavoidable damage. As mentioned, Demand Response seeks to balance demand and supply across the grid. However, what Demand Response addresses is not the only concern of grid operators, as potential problems range from downed trees, unexpected failures at power plants, or even attacks by malevolent parties. The extensive metering network can identify problematic conditions before any service disruption or equipment damage occurs, act accordingly, and prevent issues that today would need independent resolutions. This ranges from pattern recognition, the nuanced identification of grid conditions that are known to precede problems, combined with preemptive solutions, to immediate damage control, such as the sectioning off of damaged areas to prevent the spread of damage. While the responses mentioned so far have all been either remote or automatic, not everything can be done remotely. The information provided by the Smart Grid also illuminates those problems that can only be resolved by dispatching repairmen, both reducing the time delay between the occurrence of a problem and when the repairmen know about it and providing them with more information before they arrive at the scene. This way, whether the problem is a surge in demand, a fallen tree, a power plant failure, or an attack, the Smart Grid can mitigate or even completely eliminate service disruptions or (additional) equipment damage.

1.2.2.3 Security and Standards

Recognizing that improperly designed Smart Grids are vulnerable security risks, the involved industries have collaborated to assemble a large collection of standards, detailing secure protocols, mechanisms, and procedures for equipment interconnecting distributed resources with electric power systems, communication networks and systems in substations, power system management and the associated information exchange, distributed networks, intelligent electronic devices, advanced metering infrastructure, as well as the integration and upgrading of relevant existing standards.

Energy efficiency and renewable energy

The smart grid scores over the traditional grid where energy efficiency is concerned. While the traditional power grid has little means at hand to achieve energy efficiency, the smart grid employs smart meters and associated ICT infrastructure to ensure efficiency. It also allows for integration of renewable/distributed energy resources wherever possible, thereby lightening the onus on the grid for energy generation. The renewable resources contribute to greener environment by reducing the greenhouse gas emissions. They also help to alleviate the losses caused by transmission over very long distances, because they cause the energy generation to be decentralized.The distribution network architecture plays a part in determining the energy efficiency. A hierarchical architecture from cognitive radio domain for the distribution network is proposed to manage consumption, intermittent production, storage and grid monitoring.The architecture helps to reduce the peak power consumption to a fraction of its original value. This gain is due to the management of storage facilities, sheddable, and adjustable load.

IOT enabled smart grid

The IoT is a system of interrelated computing devices, mechanical and digital machines, objects or people that are provided with unique identifiers and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction. IoT has evolved from the convergence of wireless technologies, micro-electromechanical systems, micro services, and the internet. IoT has plenty of applications including smart grid. Urban IoTs are designed to support the Smart City vision, which aims at providing added-value service, like structural health of buildings, waste management, noise monitoring, air quality, traffic congestion, and smart parking, for the administration of the city and for the citizens

1.3 Overview on FREEDM

1.3.1 Definition of FREEDM

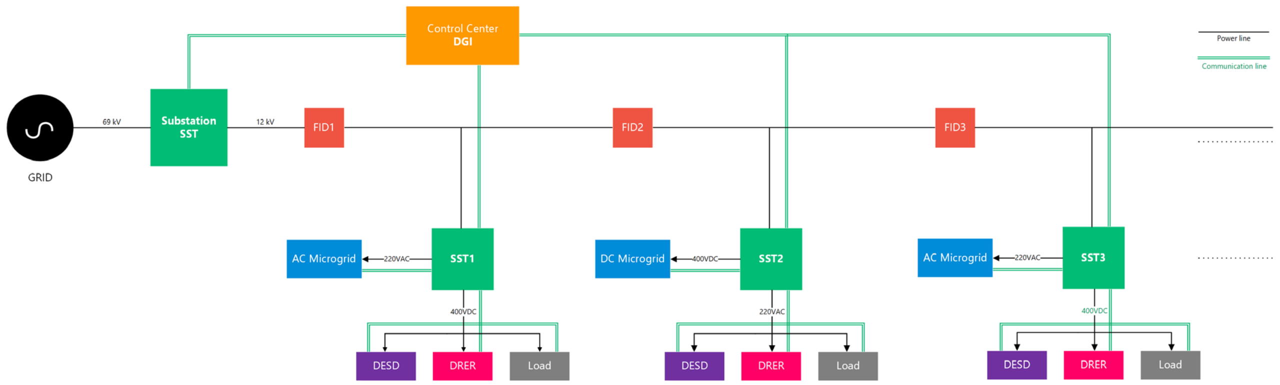


Figure 1.7 Diagram of FREEDM System

FREEDM stands for Future Renewable Electrical Energy Distribution Management. it is an efficient power grid integrating highly distributed and scalable alternative generating sources and storage with existing power systems. Targeted as a grid suitable for large-scale integration of distributed resources. The future renewable electric energy (FREEDM) system has several renewable energy resources and energy management facilities with loss minimization and operation flexibility. It has the plug-and-play feature to control and integrate the various sources available in the distribution system.FREEDM systems has high reliability and power quality.

1.3.2 FREEDM advantages

The proposed FREEDM system merges advanced power electronics technology and information technology to form a future distribution power grid with the following capabilities:

- Allow plug and play of any distributed renewable energy resource (DRER) or distributed energy storage device (DESD), anywhere and anytime.
- Manage load, DRER and DESD through Distributed Grid Intelligence (DGI) software.
- Interface the load, DRER and DESD through a revolutionary interface (solid state transform).
- Have a communication infrastructure backbone.
- Have a revolutionary protection device called Fault Isolation Device (FID).
- Have the capability of being totally isolated from the main grid, if necessary, autonomous continuing to operate based on 100% renewable energy.
- Have perfect power quality and guaranteed system stability.
- Have improved system efficiency, operating the alternating current system with unity power factor.

1.3.3 FREEDM system features

1.3.3.1 Solid State Transformer (SST)

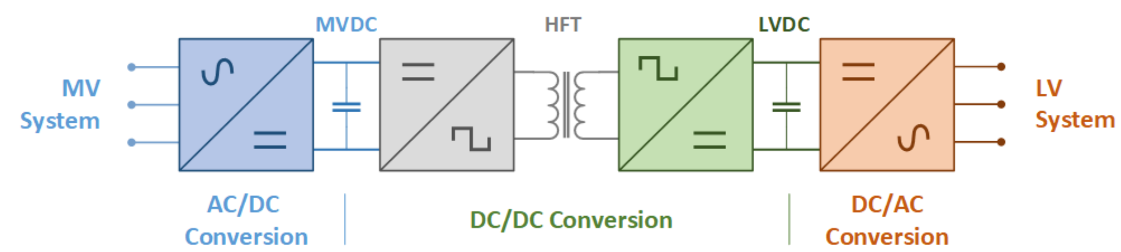


Figure 1.8 Three-stages Solid State Transformer

Solid-state transformer (SST) is a collection of high-powered semiconductor components, conventional high-frequency transformers and control circuitry which is used to provide a high level of flexible control to power distribution networks. Add some communication capability and the entire package is often referred to as a smart transformer.

When SSTs are implemented, they will radically change the way utility power is distributed. They will also become integral components in the future Smart Grid - enabling it to direct power from any source to any destination by the most efficient route possible.

1.3.3.2 distributed grid intelligence (DGI)

Distributed operation of microgrid architectures consists of energy management, power management, power electronic management, and fault detection and recovery. Traditionally, Supervisory Control And Data Acquisition (SCADA) architectures have been used to manage energy resources, but these centralized architectures may be conceptually and practically infeasible due to questions of reliability and ownership. A Distributed Operating System architecture is proposed to manage power and computational resources within a smart microgrid, using the FREEDM system architecture as a model. In this concept, there are control elements not generally present in traditional distribution systems. And, the distribution primaries are assumed to be networked. The DGI comes with everything needed to implement distributed algorithms for power device control in the smart grid.

- Real-time scheduling for execution of distributed algorithms using an integrated round-robin scheduler.
- Automatic detection and configuration for DGI processes. The DGI automatically manages groups. Every module receives a list of available peers to use for executing algorithms. Updates are pushed to each module on change.
- Device management and integration with PSCAD and RSCAD/RTDS simulations. Physical devices can be easily integrated by implementing our Plug n' Play protocol.
- Casually consistent global snapshot capturing. This can be used to capture the state of a smart-grid using a method that compensates for latency.

1.3.3.3 Fault isolation device (FID)

Compared to conventional mechanical circuit breakers (MCB), solid-state circuit breakers (SSCB) provide faster and more accurate switching operations to cope with power systems transients or faults. These devices potentially enhance the reliability of distribution systems, reduce the downtime of power outages, and minimize possible damages to utilities or load customers. One major challenge with SSCBs in conventional distribution systems is the high fault current interruption capability needed for solid state devices. For this reason, distribution systems with inherent current limiting capability is desirable for the application of the SSCB. Such a SSCB will no longer need extremely high interruption current capability and for this reason we will call this type of SSCB fault isolation device (FID). Future Renewable Electric Energy Distribution and Management (FREEDM) System is a power electronics based distribution system suitable for large scale integration of renewable energy and energy storage. Its fault current is inherently limited due to the use of power electronics interfaces. The FREEDM MVAC bus is powered by a substation SST from transmission grid. Several distribution class SSTs are connected to the MVAC bus and transform the AC voltage to low voltage AC and DC voltages.

1.3.3.4 DESD & DRER

Figure 1.9 Solar and Wind Power Energy

Renewable energy has been a buzz in the electricity sector for the past few years. it is any system that allows clean energy to be generated from a natural and sustainable source that can constantly be replenished. FREEDM system allow distributed renewable energy resources (DRER) such as pv panels and wind turbines and distributed energy storage devices (DESD) such as batteries to be plugged and played through a protocol that gives the system the most economical and efficient results.

02

OPERATION
OF SOLID STATE TRANSFORMER

2. Operation of Solid State Transformer
2.1 Solid-State Transformer (SST)

What is (SST)? Solid-state transformer (SST) is a collection of high-powered semiconductor components, conventional high-frequency transformers and control circuitry which is used to provide a high level of flexible control to power distribution networks. Add some communication capability and the entire package is often referred to as a smart transformer. SST technology can step-up or step-down AC voltage levels just like that of the traditional transformer but it also offers several significant advantages. These include:

- allow two-way power flow
- input or output AC or DC power
- actively change power characteristics such as voltage and frequency levels
- improve power quality (reactive power compensation and harmonic filtering)
- provide efficient routing of electricity based on communication between utility provider, end user site and other transformers in the network
- greatly reduce the physical size and weight of individual transformer packages with equivalent power ratings

When SSTs are implemented, they will radically change the way utility power is distributed. They will also become integral components in the future Smart Grid - enabling it to direct power from any source to any destination by the most efficient route possible.

2.2 Solid-State Transformer Stages

In this thesis we will talk about a 3-stage SST as shown in figure 2.1

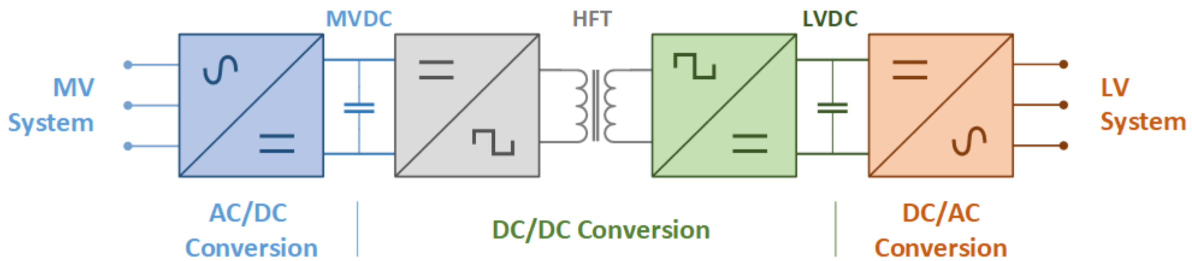


Figure 2.1 Stages of Solid State Transformer

(1) AC-DC Stage

This stage is connected to a three phase AC grid via RL filters, if it is assumed the power flows from the MV side to the LV side of the SST, this stage acts as a rectifier, in case of power flow reversal, this stage acts as an inverter.

(2) DC-DC Isolation Stage

This stage consists of three major parts, (1) DC-AC conversion stage, (2) High-Frequency transformer (HFT), (3) AC-DC conversion stage. The DC-AC stage acts as an inverter and generates high frequency to (HFT). High frequency transformer is required to achieve electric isolation, it also has to allow large voltage and current ratios between input and output. The usage of HFT in SST is the main reason for size reduction in comparison with the conventional transformer operating at power frequency (50-60 Hz), Therefore, an optimized design of HFT in DAB is necessary to utilize the advantages of SST.

AC-DC conversion stage rectifies the output current of the HFT and controls the LV-side dc link voltage at the desired value.

(3) DC-AC Stage

This stage is proposed for the LV side of the SST, with an RL impedance for filtering currents and a capacitor bank for filtering voltages, the main task of LV-side converter controllers is to obtain balanced voltages at capacitor terminals with stable frequency and voltage, independently of the load/generation level and the unbalance of LV-side currents.

2.3 Simulation of Solid-State Transformer

The system simulation is done using MATLAB Simulink to test the operation of the solid-state transformer with grid connected modes. The grid connected mode is first tested followed by the startup of the solid-state transformer in mode of operation.

A system diagram showing a simple solid-state transformer system, the diagram reviews the overall operation of the converters and is shown in Figure 2.2.

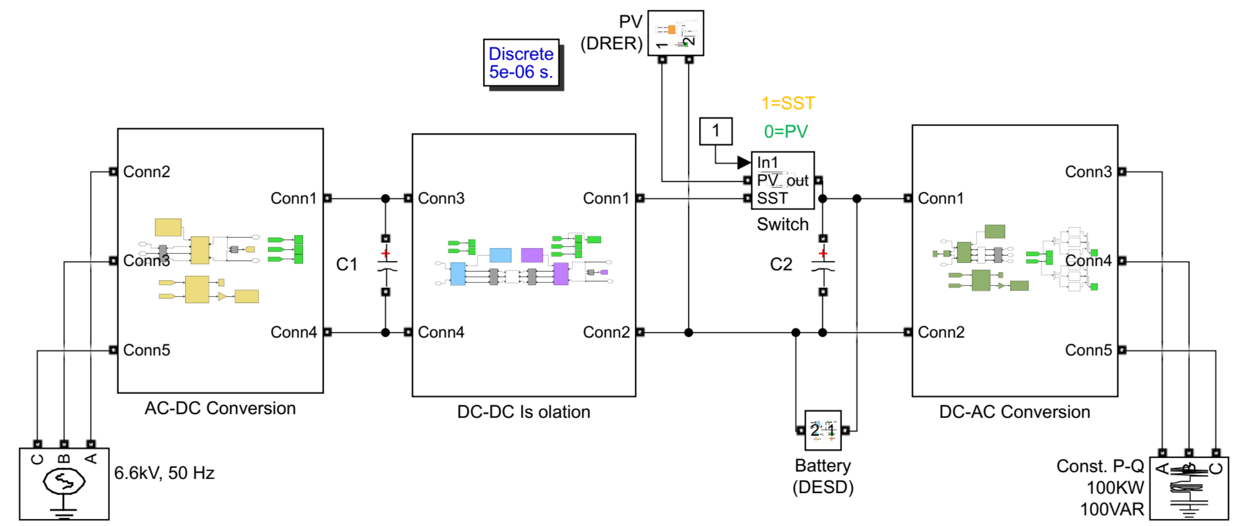


Figure 2.2 SST System diagram

2.3.1 Simulink Parameters

(a) Powergui

Simulation type: Discrete
Sample time: 5e-06s
Variable step solver

(b) Grid Source

Three phase, Yg, 6.6KV(ph-ph, rms) and 50Hz frequency.

(c) Converters Switches(for all stages)

IGBT / Diodes, 3 bridge arms,
inf. Capacitance and 100KΩ snubber resistance.

(d) Isolation Transformer

Yg-Yg, 13860 MVA, 50Hz, V1:V2 = 10.8 : 1
Rm=200pu and Lm=200pu

(c) Load

Constant P-Q, 100Kw, 100VAR, 50Hz
Nominal Voltage of 380v(ph-ph, rms).

(e) IGBTS Control

Simple PWM pulse generator, producing 3 sine wave signals, the first signal depending on the fundamental frequency of the system and the other 2 signals is shifted, then the signals is multiplied by Modulation Index, then a sawtooth signal is compared with the sine wave signals to produce the pulses controlling the IGBT. The Modulation Index is used to determine the desired value of the output.

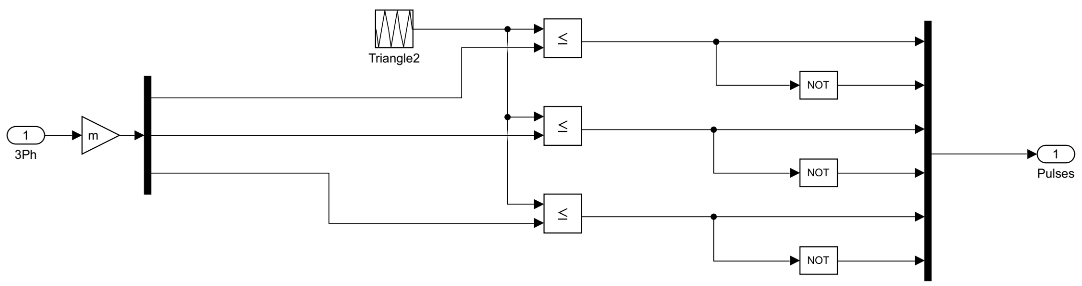


Figure 2.3 Control Scheme

2.3.2 Simulation Results

The simulation is done over a period of 2 seconds, and here the waveforms of the results of the 3 stages.

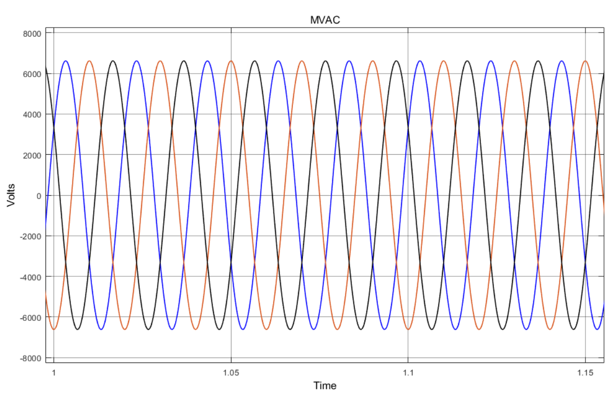


Figure 2.4 AC intput voltage (MVAC)

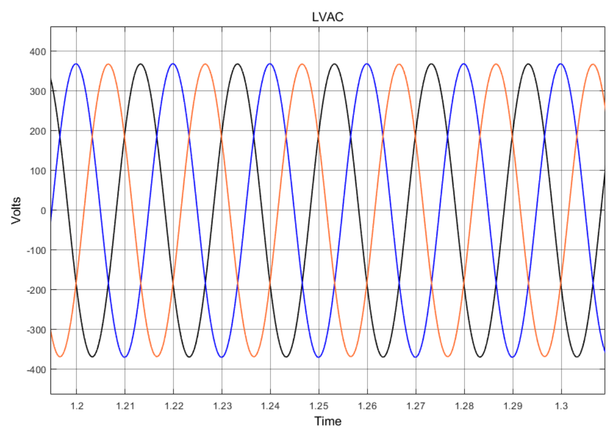


Figure 2.5 AC output volatge (LVAC)

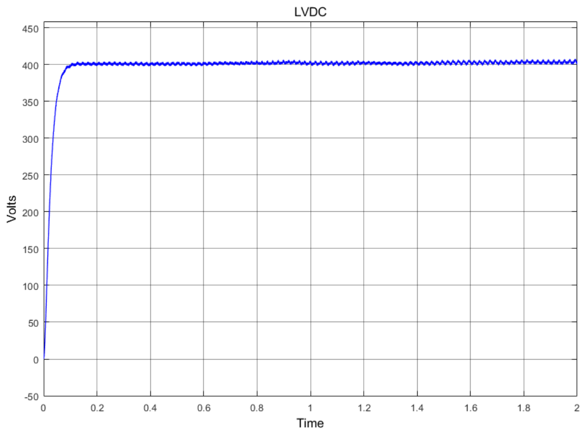


Figure 2.6 LVDC

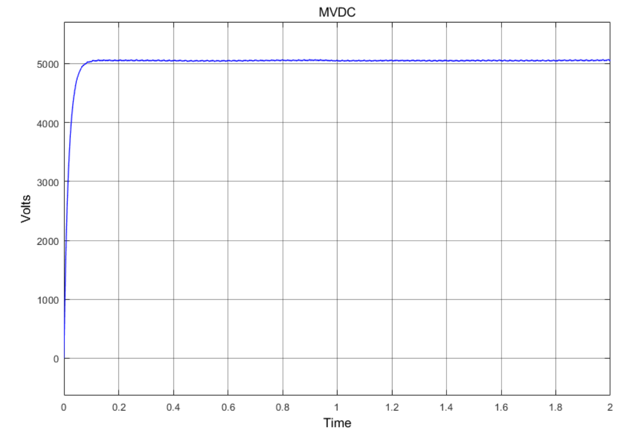


Figure 2.7 MVDC

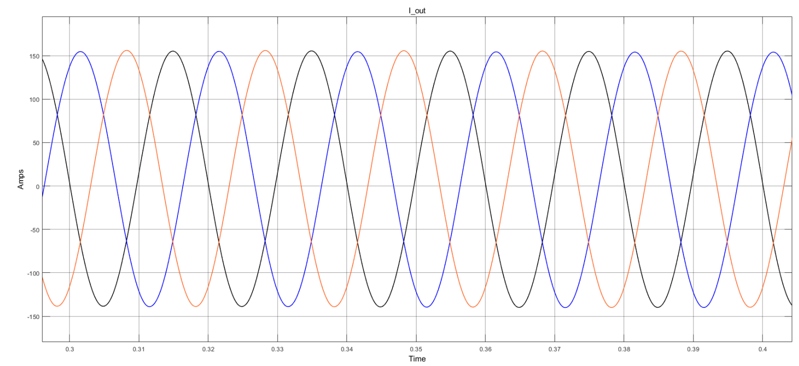


Figure 2.8 Output current

2.4 Simulation of SST Modes

In this thesis we will talk about 2 modes of SST, PV mode (DRER) and Battery mode (DESD), The system simulation is done using MATLAB Simulink to test the effect of the two modes on the load voltage. The parameters of this simulation are the same as the parameters of simulation of SST in standalone mode.

2.4.1 SST-PV mode

The simulation is done over a period of 2 seconds, and here the waveforms of the voltage of the load in figures 2.9 and 2.10 with the fact that, the first second the load is fed by SST and the remaining period the load is fed by PV. As shown in figure 2.2. The switch is used to determine either the load will be fed by SST or PV.

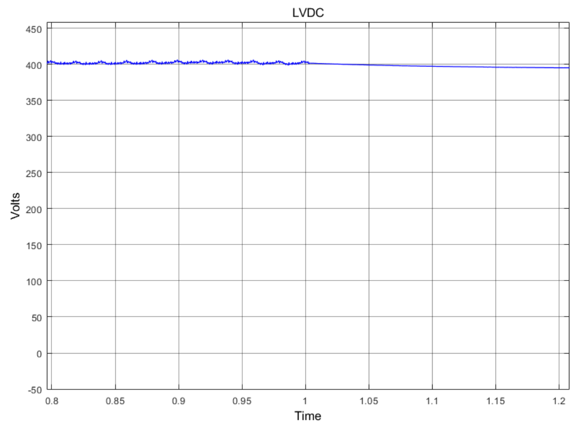


Figure 2.9 LVDC

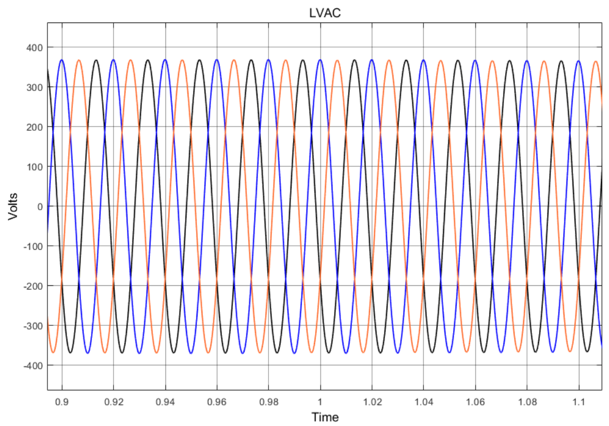


Figure 2.10 LVAC

As noticed from the results, the dc voltage of the PV is smoother than of SST. because no power electronics switches are used to control the voltage in the PV.

2.4.2 SST-Battery mode

This mode allows the bi-directional power flow, the simulation is done over a period of 2 seconds, and here the waveforms of the voltage of the load in figures 2.11and 2.12, with the fact that, the first second the state of battery is charging and the remaining period the battery is discharging. The switch is used to determine the state of the battery as charging or discharging as shown in figure 2.2.

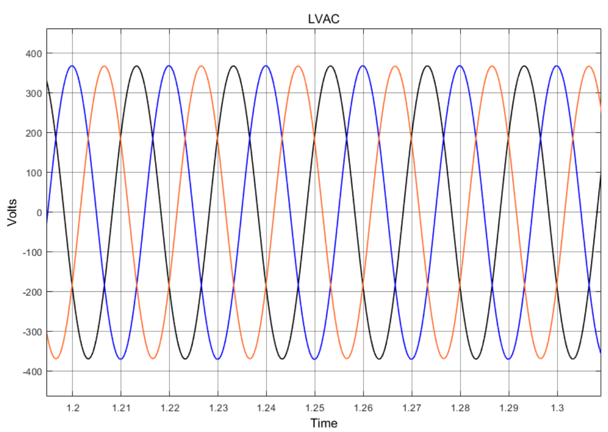


Figure 2.5 LVAC

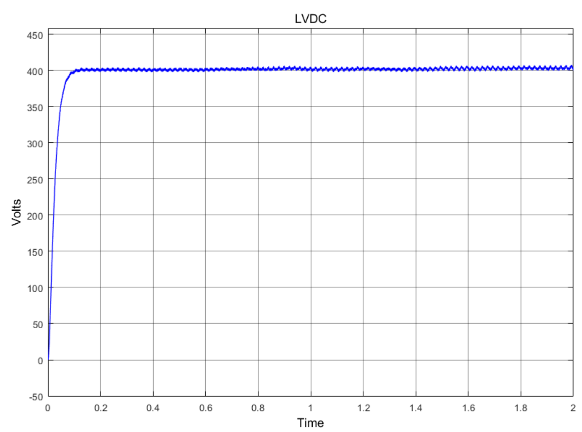


Figure 2.6 LVDC

2.5 Renewable Resources

2.5.1 Photovoltaic Solar Energy

2.5.1.1 Energy conversion

Solar energy offers many advantages, with benefits similar to wind energy: it is renewable (restored by nature), sustainable (non-depleting or non-permanent damage), clean (non-polluting), and ubiquitous (abundantly available anywhere in the world; in fact, the most abundant energy resource on planet Earth), besides being today cost-effective (it is one of the lowest-priced renewable energy technology available today after wind energy). Another important advantage of PV is its modularity, permitting a very flexible system sizing for integration into buildings and for decentralized applications down to minimal load demands. In general, no moving parts and no specific thermal stresses are involved. Therefore, photovoltaic systems operate quietly and can offer extremely high reliability, low maintenance requirements, and a long lifetime. Due to the nature of the conversion process, according to the PV system type, it can be utilized directly as well as diffuse radiation, which also allows applications in moderate climates with higher fractions of diffuse radiation.

The main drawbacks of photovoltaics are that it is intermittent (limited controllable variability and partial unpredictability although not as complex as wind power) and has low power-density (PV systems in the range of few kW), which translates into high initial investment costs. Furthermore, solar modules efficiency levels are relatively low (between 14 and 25%) compared to the efficiency levels of other renewable energy systems.

Photovoltaic solar energy conversion systems convert sunlight directly into electricity by using the photovoltaic effect. The basic building block of a PV system is the PV solar cell, which is a device (typically a semiconductor) that converts solar energy into DC electricity. A wide variety of materials are photoelectric, i.e., light is absorbed, and an electron acquires kinetic energy to move it to another energy level within the material. Nowadays, the primary elements for PV cells are semiconductors although researchers are trying other materials including organic polymers.

The conversion efficiency of the PV cell is the ratio of electrical energy produced over the insolation on the cell. Today, PV devices convert 7–17% of light energy into electric energy. However, multiple layers and other improvements have raised efficiencies into the 35–40% range for laboratory tests. About 55% of the energy of sunlight cannot be used by most PV cells because this energy either is below the band gap or carries excess energy, which results in heat.

There are mainly four different types of PV cells, i.e., crystalline silicon with its two variations monocrystalline and polycrystalline, thin-film, and hybrid cells, which are presented in the figure 2.15.

Monocrystalline (single crystal) silicon cells are saw-cut from a single cylindrical crystal of silicon. The entire cell is aligned in one direction, which means that when the sun is shining brightly on them at the right angle, they are extremely efficient. So, these cells work better in bright sunshine with the sun shining directly on them. They have a uniform blacker color because they are absorbing most of the light. Pure cells are octagonal, although there are round and semi-round cells, so there is unused space in the corners when lots of cells are made into a solar module.

The main advantage of monocrystalline cells is their high efficiencies of about 14–16% although the manufacturing process is complicated and expensive. The cost of producing pure silicon wafers is a little more than for polycrystalline cells but there is not much difference in price these days.

Polycrystalline (or multicrystalline) silicon cells are cut from a metal of melted and recrystallized silicon. In the process, molten silicon is cast into ingots of polycrystalline silicon. These metals are then saw-cut into very thin wafers and assembled into complete cells. Because the individual crystals are not necessarily all perfectly aligned together, as the previous case of monocrystalline cells, and there are losses at the joints between them, they are not quite as efficient. However, this misalignment can help in some circumstances because the cells work better from light at all angles, especially in low light, etc. The appearance is also different, the random crystal arrangement and the panels look a little bluer as they reflect some of the light. Since they are cut into rectangular blocks, there is very little wasted space on the panel so there are not little diamonds that are typical of mono or hybrid panels.

Multicrystalline cells used to be a bit cheaper than monocrystalline cells due to their simpler manufacturing process, but nowadays their price is very similar to monocrystalline cells although they have slightly lower efficiency (about 13–15%). Thick Film silicon is a multicrystalline technology where the silicon is deposited in a continuous process onto a base material giving a fine-grained, sparkling appearance. The cell is encapsulated in a transparent insulating polymer with a tempered glass cover and usually bound to a sturdy aluminum frame.

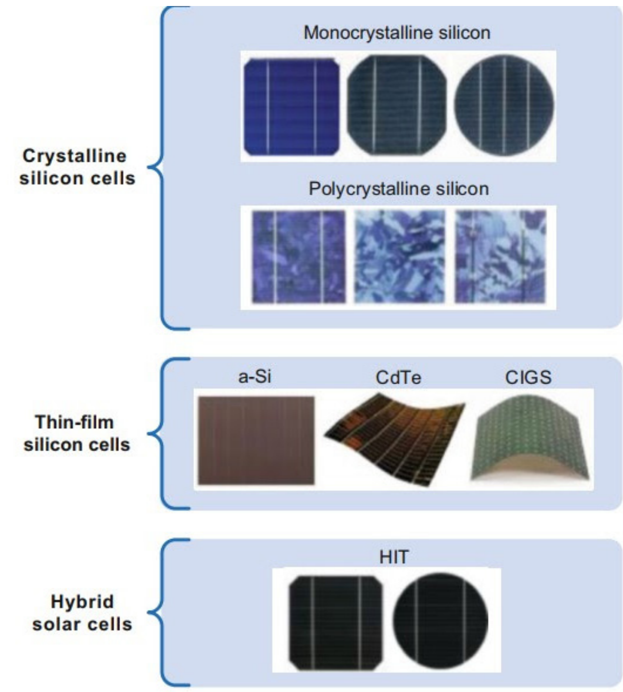


Figure 2.15 Types of solar cells

Thin-film cells are second-generation solar cells made by depositing one or more thin layers, or thin-film (TF) of photovoltaic material on a substrate, such as glass, plastic, or metal rather than a crystal structure. Film thickness varies from a few nanometers (nm) to tens of micrometers (μm). Thus, this photovoltaic material layer is much thinner than any other rival technology, such as the crystalline silicon solar cell (c-Si) which uses wafers of up to 200 μm for the first generation of c-Si cells. This is the reason why they are called "thin-film" PV solar cell technology. This feature allows thin-film cells to be flexible, versatile, lower in weight, and have good performance in indirect light and high temperature applications. Typical efficiency is around 6–12%, but they are easier and consequently cheaper to produce than crystalline silicon solar cells. However, there is a reason why thin-film solar modules have not replaced older types yet. Apart from efficiency, there are some thin-film materials that have shown degradation of performance over time with stabilized efficiencies of 15–35% lower than initial values.

The solar cell is the basic building block of a PV system. Individual cells can vary in size from about 1 to 10 cm; however, one cell only produces 1–2 W with about 0.5 V of DC voltage, which is not enough power for most applications.

Consequently, cells are combined into a module, sometimes called a panel, typically with 36 cells to reach up to 50–300 W. PV modules can also be grouped in series to create a string with the aim of increasing their voltage to attain higher voltage applications. Eventually, a group of modules in a system can be combined in series/parallel, at low/high voltage, on a single/multiple rack to form a PV array with up to tens of MW (or more) for large power applications, as depicted in the figure 2.16.

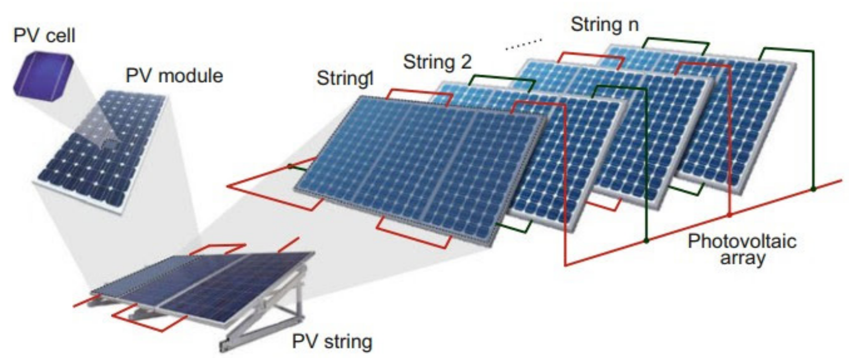


Figure 2.16 PV system

2.5.1.2 Photovoltaic System Concepts

One of the major challenges of a grid-connected PV solar system is to attain optimal compatibility of the PV array with the electricity grid. Since a PV array produces an output DC voltage with variable amplitude, additional conditioning is required to meet the amplitude and frequency requirements of the roughly stiff utility AC grid and inject synchronized power into the grid. As the output of PV panels is direct current, it is typically a DC-AC converter (or inverter) which inverts the DC output current generated by the PV arrays into a synchronized sinusoidal waveform. This power electronic interface must generate high-quality electric power and simultaneously be flexible, efficient, and reliable. Another key challenge of grid-connected PV systems is the procedure employed for power extraction from solar radiation and is mostly related to the nature of PVarrays.

Each PV module is a nonlinear system with an output power influenced mainly by atmospheric conditions, such as solar radiation and temperature. To Transfer the maximum solar array power into the utility grid for all operating conditions, an MPPT technique is usually implemented. To this aim, the MPPT system can be implemented using a power electronic converter with a different number of power processing stages.

Thus, grid-tied PV power conditioning system (PCS) topologies can be firstly classified (whether or not they employ a transformer) according to the number of converter stages as follows:

- Single-stage topology
- Two-stage topology

The MPPT system can be implemented using a single-stage converter topology, i.e., connecting the PV array directly to the DC bus of a power inverter or using a dual-stage converter (two cascade stages), e.g., adding a DC-DC converter (or chopper) between the PV array and the static power inverter, with or without galvanic isolation provided by a step-up transformer. The advantages of the single stage topology are good efficiency, lower price, and easier implementation since the maximum power point tracking of the PV modules and the inverter control loops (current and voltage control loops) are handled all in one single stage by the inverter itself. However, the inverter employed in this single-stage conversion must be designed to handle peak power of twice the nominal power. Nevertheless, the double-stage topology offers an additional degree of freedom in the operation of the grid-connected PV solar system as the additional DC-DC converter in between the PV panels and the inverter handles the MPPT and the control loops are applied to the inverter. This division of tasks between the DC-DC converter and DC-ACconverter allows the overall system to pursue various additional control objectives simultaneously and independently of the PV array normal operation, such as reactive power compensation, voltage regulation, and power oscillations damping among others.

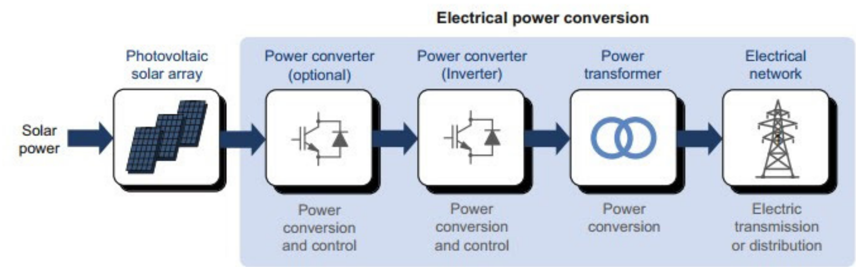


Figure 2.17 PV solar energy conversion system

The Figure summarizes the significant parts included in the electrical power conversion of a typical grid-tied PV solar energy conversion system. PV panels are electrically combined in series and sometimes stacked in parallel to form an array with the appropriate output power required for the specific DG application. The PVsystem power electronic converter can be implemented with a different number of power processing stages, i.e., including or not an additional DC-DC converter. In the case of stand-alone (also known as off-grid or isolated from the utility grid) PV solar systems, the power electronic interface is typically made up of a DC-DC converter.

2.5.2 Wind energy

Wind energy offers many advantages, which explains why it is one of the fastest growing energy sources in the world. Its benefits are similar to most other renewable energy resources: it is renewable (restored by nature), sustainable (non-depleting or non-permanent damage), clean (non-polluting), and ubiquitous (availability in many regions of the world). In addition, it is cost-effective (it is one of the lowest-priced renewable energy technologies available today). The main drawbacks are that it is intermittent (limited-controllable variability and partial unpredictability) and has low power-density (wind turbine generators in the range of few MW), which translates into high initial investment costs. In general, good wind sites are located in remote locations distant from load centers where the electricity is needed, which in these cases means that transmission could be a problem for large-scale installation of wind farms.

A wind turbine is a rotary engine that captures power from a fluid flow (the wind) using aerodynamically designed blades and converts it into useful mechanical power. The available power depends on the wind speed, but it is essential to be able to control and limit the power at higher wind speeds so as to avoid the damage to the unit. Some of the three following methods may do the power limitation, namely stall control (the blade position is fixed but stall of the wind appears along the blade at higher wind speed), active stall (the blade angle is adjusted in order to create stall along the blades), or pitch control (the blades are turned out of the wind at higher wind speed)

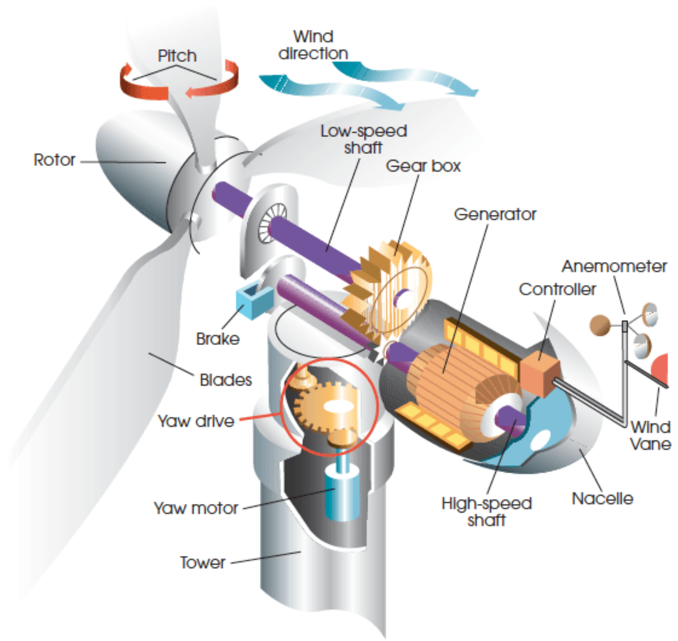


Figure 2.18 Wind turbine components

Essentially, three types of typical wind generator systems are the most widely spread. The first type is a constant-speed wind turbine system with a standard squirrel-cage induction generator (SCIG) directly connected to the grid. The second type is a variable speed wind turbine system with a doubly fed induction generator (DFIG). The power electronic converter supplying the rotor winding has a power rating of approximately up to 30% of the rated power; the stator winding of the DFIG is directly connected to the grid. The third type is a variable speed wind turbine with the full-rated power electronic conversion system and a synchronous generator or a SCIG. A multi-stage gearbox is used with the first two types of generators. Synchronous generators, including permanent magnet synchronous generators (PMSG), may be directly driven through a low-ratio gearbox system; one or two-stage gearbox, becomes an interesting option. The figure summarizes the major parts included in the mechanical and electrical power conversion of a typical wind turbine system.

2.5.3 Energy Storage

The energy storage system is a key component of the microgrid, so it must be carefully considered and designed for its successful operation. The size of the energy storage system depends on several factors such as:

- Amount of energy that is required by the load when there is no production
- Consistency of resources
- Desired days of autonomy
-

Choosing the correct storage system will determine not only the reliability of the microgrid but also the initial investment and maintenance costs, thus affecting the cost of the energy production directly. There are several ways to store energy in different forms:

- Chemical energy: Batteries, hydrogen generation, and subsequent conversion to methane
- Kinetic energy: High-speed flywheels
- Electric energy: Capacitors
- Potential energy: Water pumping, air compressing
- Thermal energy: High-temperature molten salts

Each of these alternatives of energy storage has its advantages, problems, minimum working scales, and cost-effectiveness. In this chapter, batteries are considered as the principal alternative for energy storage in rural microgrids, distinguishing two main chemistries: lead-acid and lithium.

2.5.3.1 Lead-Acid Batteries

Lead-acid batteries belong to a technology that has more than 100 years of existence, with a significant amount of accumulated knowledge and experience. It is a product of a large-scale and well-consolidated industry. When lead and lead oxide plates (electrodes) are submerged in a solution of sulphuric acid (electrolyte), an electric potential of approximately 2,12 V is generated. Several plates in parallel will increase current capacity, and several in series will increase voltage.

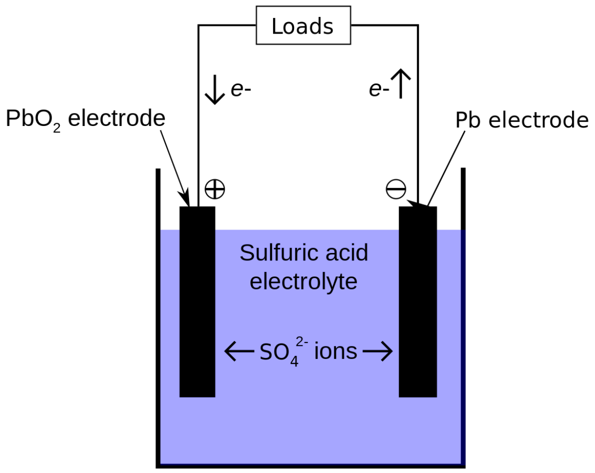


Figure 2.19 Lead-acid bateery

Typical commercial batteries have six sets of plates, or cells, in series to generate 12.75 V. The most common type of battery is automotive, which are designed to provide powerful bursts of cranking power to start the internal combustion engine. Once the engine has started the battery is quickly recharged by the vehicle's alternator, so the battery spends most of its time in a fully charged state. This is very different in the case of a microgrid in which batteries are subjected to long charging and discharging cycles, once or several times a day. If batteries are to withstand this much heavier work, they have to be built accordingly: with stronger and specially formulated plates, being called "Deep Cycle Batteries,"

2.5.3.2 Lithium Batteries

It was during the 1990s that lithium battery technology started to develop. It is still a very active and intense field of research in which new combinations of chemistries are generated seeking to optimize key parameters like cost, specific energy, energy density, durability, safety, and environmental impact. Some technologies are so recent that it is difficult to know the performance level that can be obtained shortly. At present, it is evident that lithium batteries have already revolutionized the concept of wireless tools, appliances, and electric vehicles. This industry is in a very active process of growth and innovation that will certainly bring ever better products to be used in microgrids. There are six main chemistries for lithium batteries: lithium cobalt oxide (LiCoO2), lithium manganese oxide (LiMnO4), lithium nickel manganese (NMC), lithium iron phosphate (LiFePO4), lithium nickel cobalt aluminum oxide (LiNiCoAlO2), and lithium titanite (Li4Ti5O12). To be able to compare the parameters of these different alternatives and assess their convenience for a particular application.

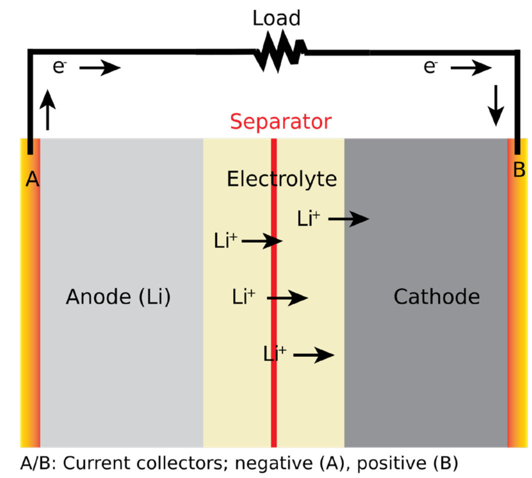


Figure 2.20 Lithium battery

Lithium batteries are composed of a huge number of individual units of cylindrical shape, similar to the commercial AA batteries. These individual units are manufactured massively, with the lowest possible cost, assembled in series and parallel to reach the required voltage and capacity. The whole set is then encased in a protective metallic case.

2.6 FREEDM System Simulation

The FREEDM System simulation is done with MATLAB Simulink, using a power system of 3 buses, bus no.1 is considered as slack bus and connected with SST no.2 only, bus no.2 is connected with SST no.1 and load, bus no.3 is connected with load only, the three buses is connected with 3 RL transmission lines as shown in figure.

The simulation is done over a period of 0.5 seconds to test the voltages and currents of the buses, and to test the effect of the faults done in the transmission lines on the voltages and currents of the buses. The parameters of the SSTs, Powergui and loads are the same of the SST Standalone simulation mode, and here the waveforms of the voltages of the 3 buses.

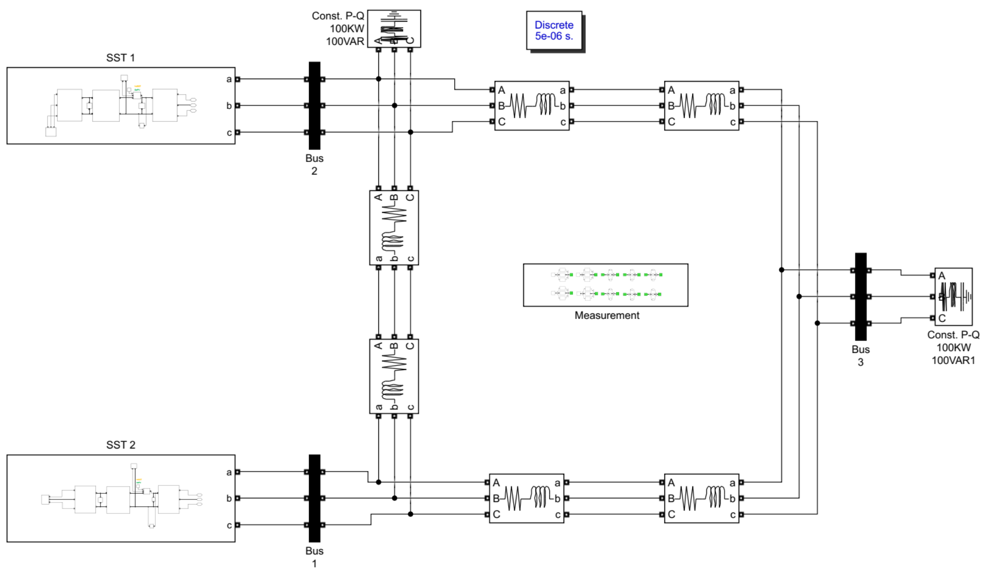


Figure 2.21 FREEDM System

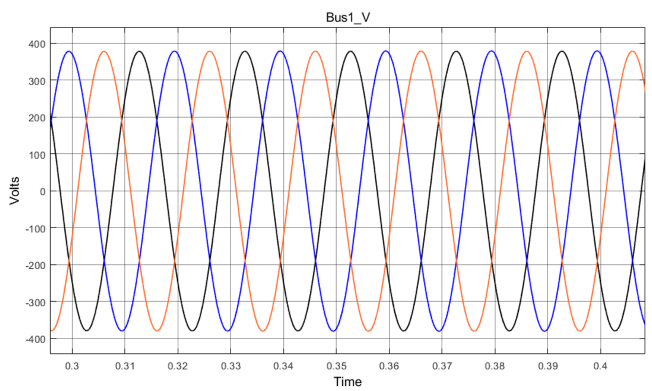


Figure 2.22 Voltage of bus 1

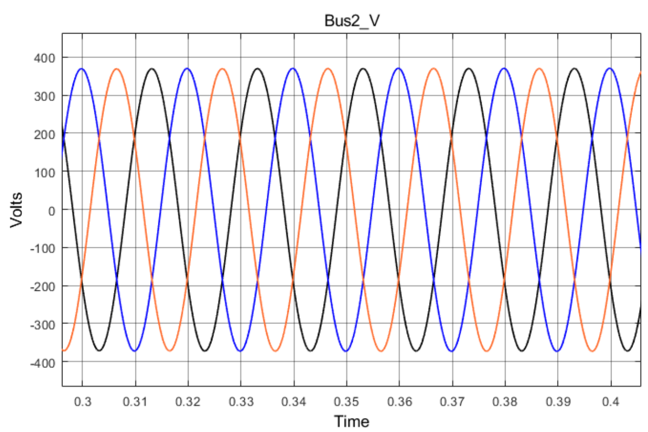


Figure 2.23 Voltage of bus 2

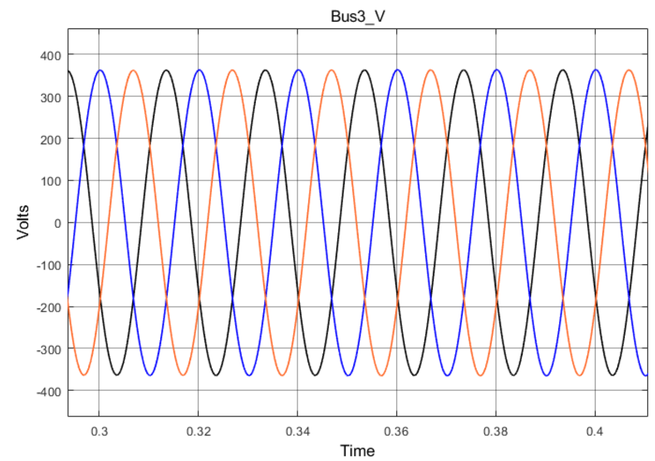


Figure 2.24 Voltage of bus 3

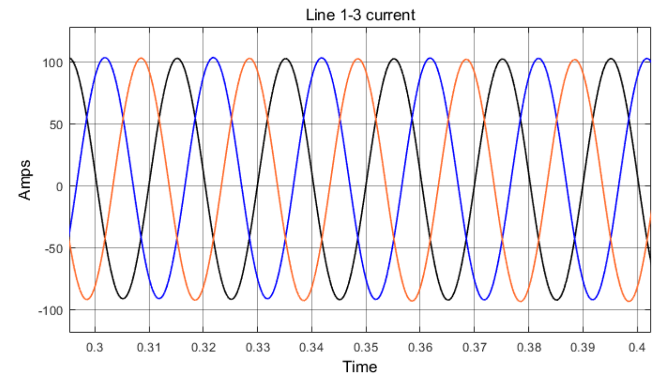


Figure 2.25 Current of line 13

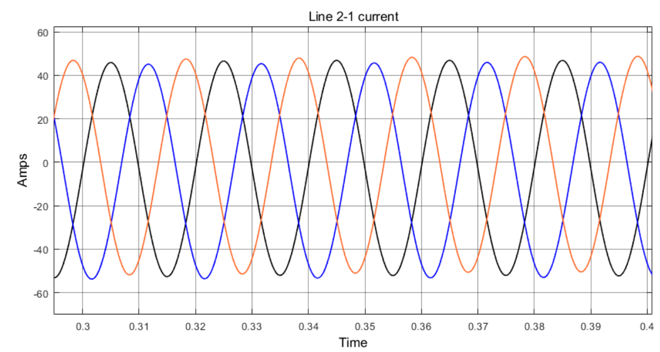


Figure 2.26 Current of line 21

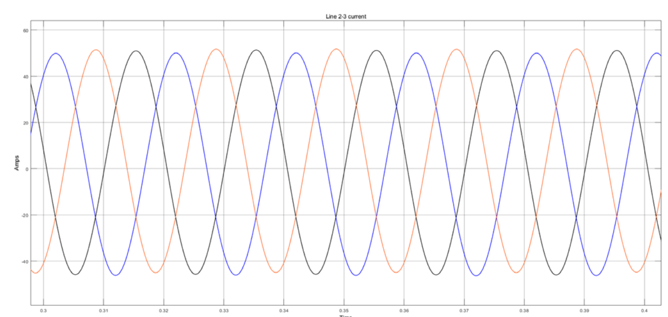


Figure 2.27 Current of line 23

03

FREEDM
SYSTEM PROTECTION

3. FREEDM System Protection
3.1 introduction

Electric energy is one of the fundamental resources of modern industrial society. Electric power is available to the user instantly, at the correct voltage and frequency, and exactly in the amount that is needed. This remarkable performance is achieved through careful planning, design, installation and operation of a very complex network of generators, transformers, and transmission and distribution lines. To the user of electricity, the power system appears to be in a steady state: imperturbable, constant and infinite in capacity. Yet, the power system is subject to constant disturbances created by random load changes, by faults created by natural causes and sometimes as a result of equipment or operator failure. In spite of these constant perturbations, the power system maintains its quasisteady state because of two basic factors: the large size of the power system in relation to the size of individual loads or generators, and correct and quick remedial action taken by the protective relaying equipment.

Relaying is the branch of electric power engineering concerned with the principles of design and operation of equipment (called 'relays' or 'protective relays') that detects abnormal power system conditions, and initiates corrective action as quickly as possible in order to return the power system to its normal state. The quickness of response is an essential element of protective relaying systems response times of the order of a few milliseconds are often required. Consequently, human intervention in the protection system operation is not possible. The response must be automatic, quick and should cause a minimum amount of disruption to the power system. To accomplish correct diagnosis of trouble, quickness of response and minimum disturbance to the power system, we must examine all possible types of fault or abnormal conditions which may occur in the power system. We must analyze the required response to each of these events, and design protective equipment which will provide such a response. We must further examine the possibility that protective relaying equipment itself may fail to operate correctly, and provide for a backup protective function. It should be clear that extensive and sophisticated equipment is needed to accomplish these tasks.

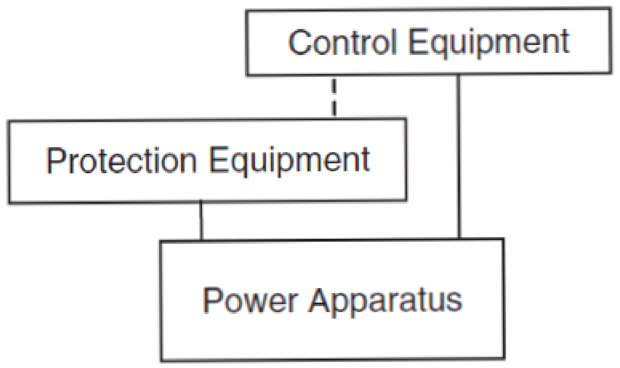


Figure 3.1 Three-layered sturcture of power systems

3.2 Power system bus configurations

The manner in which the power apparatus is connected together in substations and switching stations, and the general layout of the power network, has a profound influence on protective relaying. It is therefore necessary to review the alternatives, and the underlying reasons for selecting a particular configuration. A radial system is a single-source arrangement with multiple loads, and is generally associated with a distribution system (defined as a system operating at voltages below 100 kV) or an industrial complex (Figure 3.2). Such a system is most economical to build; but from the reliability point of view, the loss of the single source will result in the loss of service to all of the users. Opening main line reclosers or other sectionalizing devices for faults on the line sections will disconnect the loads downstream of the switching device. From the protection point of view, a radial system presents a less complex problem. The fault current can only flow in one direction, i.e. away from the source and towards the fault.

Since radial systems are generally electrically remote from generators, the fault current does not vary much with changes in generation capacity. A network has multiple sources and multiple loops between the sources and the loads. Subtransmission and transmission systems (generally defined as systems operating at voltages of 100–200 kV and above) are network systems (Figure 3.3). In a network, the number of lines and their interconnections provide more flexibility in maintaining service to customers, and the impact of the loss of a single generator or transmission line on service reliability is minimal. Since sources of power exist on all sides of a fault, fault current contributions from each direction must be considered in designing the protection system. In addition, the magnitude of the fault current varies greatly with changes in system configuration and installed generation capacity.

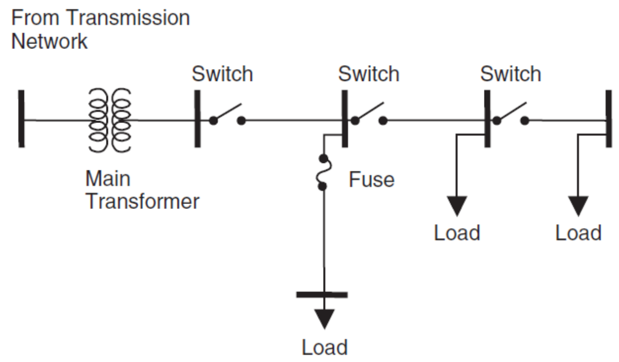


Figure 3.2 Radial power system

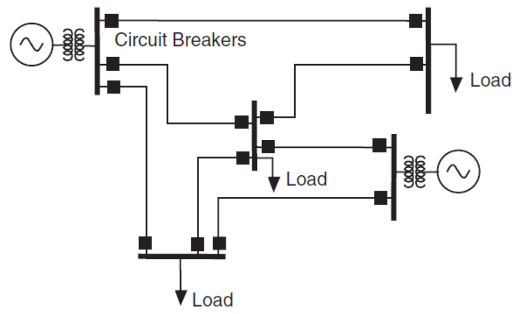


Figure 3.3 Network power system

Substations are designed for reliability of service and flexibility in operation, and to allow for equipment maintenance with a minimum interruption of service. The most common bus arrangements in a substation are (a) single bus, single breaker, (b) two bus, single breaker, (c) two bus, two breakers, (d) ring bus and (e) breaker-and-a-half. These bus arrangements are illustrated In Figure 3.4.

A single-bus, single-breaker arrangement, shown in Figure 3.4(a), is the simplest, and probably the least costly to build. However, it is also the least flexible. To do maintenance work on the bus, a breaker, or a disconnect switch, de-energizing the associated transmission lines is necessary.

A two-bus, single-breaker arrangement, shown in Figure 3.4(b), allows the breakers to be maintained without de-energizing the associated line. For system flexibility, and particularly to prevent a bus fault from splitting the system too drastically, some of the lines are connected to bus 1 and some to bus 2 (the transfer bus). When maintaining a breaker, all of the lines that are normally connected to bus 2 are transferred to bus 1, the breaker to be maintained is bypassed by transferring its line to bus 2 and the bus tie breaker becomes the line breaker. Only one breaker can be maintained at a time. Note that the protective relaying associated with the buses and the line whose breaker is being maintained must also be reconnected to accommodate this new configuration.

A two-bus, two-breaker arrangement is shown in Figure 3.4(c). This allows any bus or breaker to be removed from service, and the lines can be kept in service through the companion bus or breaker. A line fault requires two breakers to trip to clear a fault. A bus fault must trip all of the breakers on the faulted bus, but does not affect the other bus or any of the lines. This station arrangement provides the greatest flexibility for system maintenance and operation; however, this is at a considerable expense: the total number of breakers in a station equals twice the number of the lines.

A ring bus arrangement shown in Figure 3.4(d) achieves similar flexibility while the ring is intact. When one breaker is being maintained, the ring is broken, and the remaining bus arrangement is no longer as flexible.

Finally, the breaker-and-a-half scheme, shown in Figure 3.4(e), is most commonly used in most extra high voltage (EHV) transmission substations. It provides for the same flexibility as the two-bus, two-breaker arrangement at the cost of just one-and-a-half breakers per line on an average.

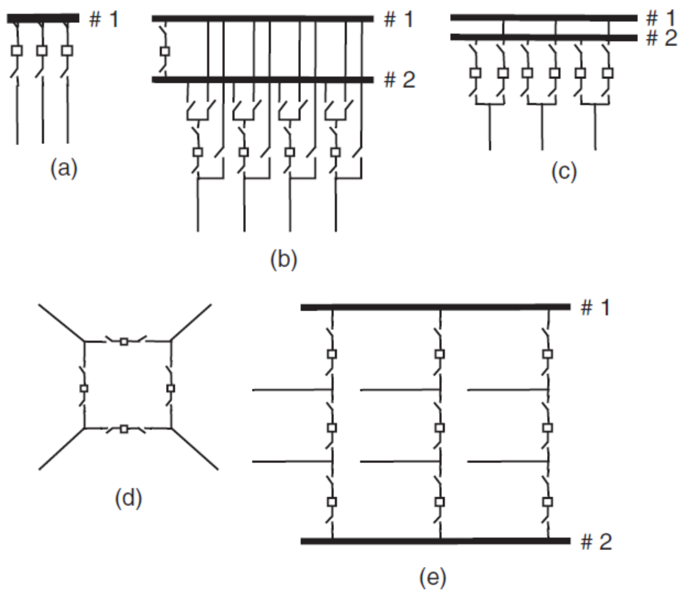


Figure 3.4 Substation bus arrangements

3.3 Elements of a protection system

Although, in common usage, a protection system may mean only the relays, the actual protection system consists of many other subsystems which contribute to the detection and removal of faults. As shown in Figure 1.11, the major subsystems of the protection system are the transducers, relays, battery and circuit breakers. The transducers, i.e. the current and voltage transformers.

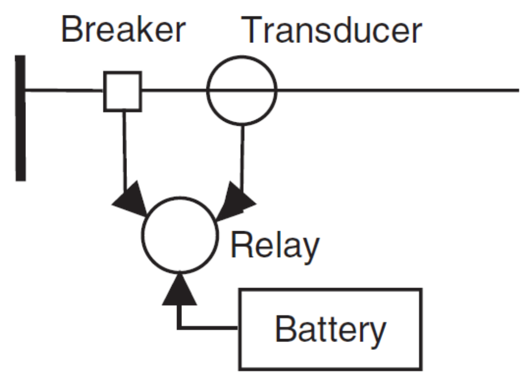


Figure 3.5 Elements of a protection system

3.3.1 Battery and DC supply

Since the primary function of a protection system is to remove a fault, the ability to trip a circuit breaker through a relay must not be compromised during a fault, when the AC voltage available in the substation may not be of sufficient magnitude. For example, a close-in three-phase fault can result in zero AC voltage at the substation AC outlets. Tripping power, as well as the power required by the relays, cannot therefore be obtained from the AC system, and is usually provided by the station battery.

The battery is permanently connected through a charger to the station AC service, and normally, during steady-state conditions, it floats on the charger. The charger is of a sufficient volt–ampere capacity to provide all steady-state loads powered by the battery. Usually, the battery is also rated to maintain adequate DC power for 8–12 hours following a station blackout. Although the battery is probably the most reliable piece of equipment in a station, in EHV stations it is not uncommon to have duplicate batteries, each connected to its own charger and complement of relays. Electromechanical relays are known to produce severe transients on the battery leads during operation, which may cause mis-operation of other sensitive relays in the substation, or may even damage them. It is therefore common practice, insofar as practical, to separate electromechanical and solid-state equipment by connecting them to different batteries.

3.3.2 Circuit breaker

Circuit breakers are electrical switches that are automatically activated to avoid damage to circuits which happens due to short circuits or overload. Miniature circuit breakers (MCB) carry out this function in specific applications. Its basic operation is to detect the fault current and interrupt the current flow. Unlike a fuse which must be replaced after one use. This type of circuit breakers are not economical when current rating exceed more than 1000 amps. The bimetallic strip present in such type wear as time passes on and the response become very slow. Changes in temperature diminishes the current capacity of the circuit breaker. MCB's reacts very slow during overloading results in damage to the equipments. The primary goal is to ensure that the circuit breakers plays a vital role in carefully protecting the electrical distribution. The ratings, performance, features, and testing of circuit breakers and switchgear are governed by electrical standards.

3.3.3 Voltage transformer

It is not possible to connect the voltage coils of the protective device directly to the system in case of high voltage systems. So it is necessary to step down the voltage, also to insulate the protective equipment from primary circuit. This is achieved by using a voltage transformers. Also known as potential transformer (PTs) which is similar to a power transformer. The voltage transformer is rated in terms of the maximum burden (VA) output it delivers without exceeding specified limits of errors. Whereas the power transformer is rated by the secondary output it delivers without exceeding a specified temperature rise. The output of PTs is usually limited to a few hundred volt amperes and the secondary voltage is usually 110V between phases. Ideally a VT should produce a secondary voltage exactly proportional to the primary voltage and exactly in phase opposition. This cannot obviously be achieved in practice owing to the voltage drops in the primary and secondary
coil due to the magnitude and power factor of the secondary burden. Thus ratio errors and phase angle errors are introduced.

3.3.4 Currnt transformer

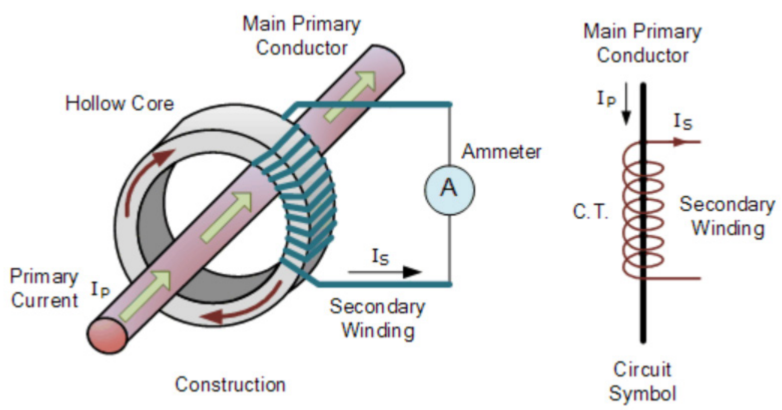


Figure 3.6 Current transformer

The Current Transformer (C.T.), is a type of "instrument transformer" that is designed to produce an alternating current in its secondary winding which is proportional to the current being measured in its primary. Current transformers reduce high voltage currents to a much lower value and provide a convenient way of safely monitoring the actual electrical current flowing in an AC transmission line using a standard ammeter. The principal of operation of a basic current transformer is slightly different from that of an ordinary voltage transformer. There are three basic types of current transformers:

3.3.4.1 Wound Current Transformer

The transformers primary winding is physically connected in series with the conductor that carries the measured current flowing in the circuit. The magnitude of the secondary current is dependent on the turns ratio of the transformer.

3.3.4.2 Toroidal Current Transformer

These do not contain a primary winding. Instead, the line that carries the current flowing in the network is threaded through a window or hole in the toroidal transformer. Some current transformers have a "split core" which allows it to be opened, installed, and closed, without disconnecting the circuit to which they are attached.

3.3.4.3 Bar-type Current Transformer

This type of current transformer uses the actual cable or bus-bar of the main circuit as the primary winding, which is equivalent to a single turn. They are fully insulated from the high operating voltage of the system and are usually bolted to the current carrying device.

3.3.5 relay

When any abnormal condition develop, the main function of a protective relay is to isolate the faulty section with the least interruption to the service by controlling or operation the circuit breaker.The relay may be designed to detect and to measure abnormal condition and close the contacts of the tripping circuit. The two categories of relay are most commonly used in protective relay:

3.3.5.1 Secondary indirect acting relays

Example: Current, Voltage, Power, Impedance, Reactance and frequency whether minimum or maximum

3.3.5.2 Secondary directing acting relay

A group of over current and under voltage relays designed to operate immediately or with time lag. These are relays of the electromagnetic type which are built into circuit breaker operating mechanism.

3.4 Operation and Design of FID

In Power Electronics Distribution Systems (PEDS), a solid state transformer (SST) will be used to enable active management of distributed renewable energy resources and loads, rather than a traditional transformer. With an advanced high voltage power semiconductor device such as a 15 kV Silicon Carbide (SiC) IGBT, a much higher frequency (~15 kHz instead of 60 Hz) can be used to reduce transformer size and weight, making the SST lightweight, and easy to manufacture. The SST is a digitally controlled converter that is capable of controlling power flow, voltage magnitude, and various phase relationships of current and voltage. Since the SST is a power electronics device, it can provide current limiting for the entire distribution system though the system voltage will lower significantly. Hence, it is an important requirement that the circuit breaker be able to disconnect the faulted section as fast as possible to allow for the SST to restore the system voltage quickly after a fault. Despite the usage of these fast acting mechanical circuit breakers, short disruptions of power flow during faults on an AC distribution system can lead to significant disturbances at critical loads. One way to develop a fast fault isolation device is to replace mechanical circuit breakers with semiconductor switches. In this sense, a Solid State Fault Isolation Device (SSFID) serves the dual purpose of a recloser and sectionalizer. It has already been proven that the usage of power semiconductor devices can mitigate short circuit currents and voltage sags during a short circuit event.

Design

The SSFID topology has the IGBTs in series, with the Diodes connected together. By making use of a commercially available, emitter connected IGBT module, the topology does not require separate driver circuits or series diodes. In SSFID operation, the balancing of the series IGBT modules and the control of turn-off over-voltages at their collectors under all operating conditions are the most important tasks to be mastered, as they are directly responsible for the system reliability.

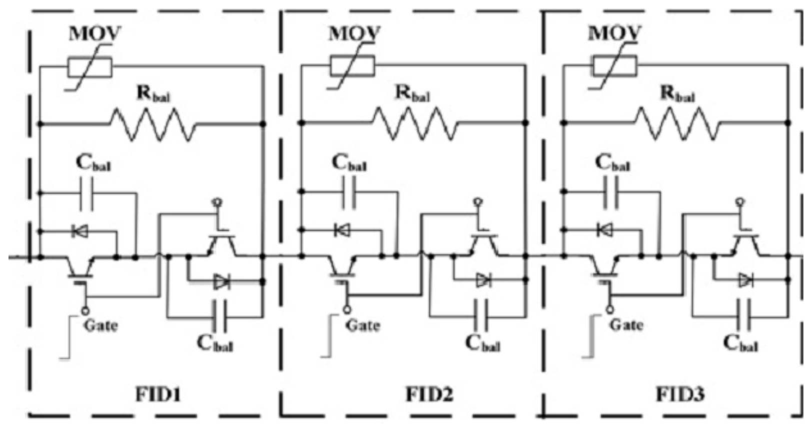


Figure 3.7 FID topolgy

IGBT modules are placed in series to construct a SSFID with an operating voltage higher than any of the rated voltages of the single IGBT modules of which it is comprised. In this series connection, the operating voltage of the SSFID must be perfectly balanced across each of the individual IGBT modules, else when the SSFID opens the short circuit current flow under fault conditions, the resulting overvoltage that the SSFID will have to block will not be evenly distributed across each module, thus requiring one module to block a voltage that is higher than what it is rated for, thus risking damage to the module.

Simulink design

In order to examine the SSFID interaction with the grid voltage and current. The FID is designed with Matlab Simulink using two IGBT blocks and two diodes blocks.

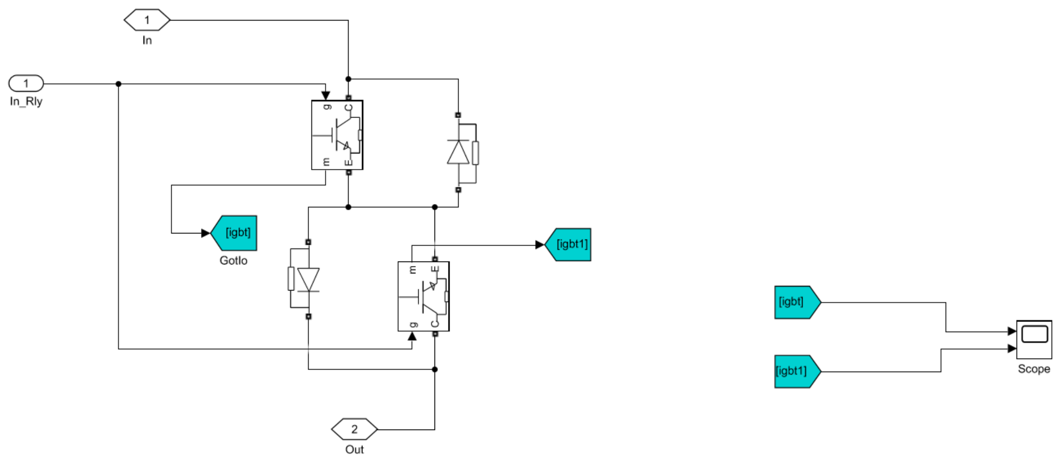


Figure 3.8 Block diagram of FID circuit

3.5 Transmission Lines Protection

In this part we will discuss three different types of line faults which are: single phase to ground fault, double phase fault and three phase to ground fault and how this fault affects the voltages and current flow through the line. In addition, the protection schemes applied for clearing these faults. Using three phase fault block in Simulink which locates in Simscape / Electrical / Specialized Power Systems / Fundamental Blocks / Elements, We will apply each type of fault on line 12 which is between SST1 and SST2.

3.5.1 At fault operation

The fault is set to occur at 0.5 as shown in below figure.

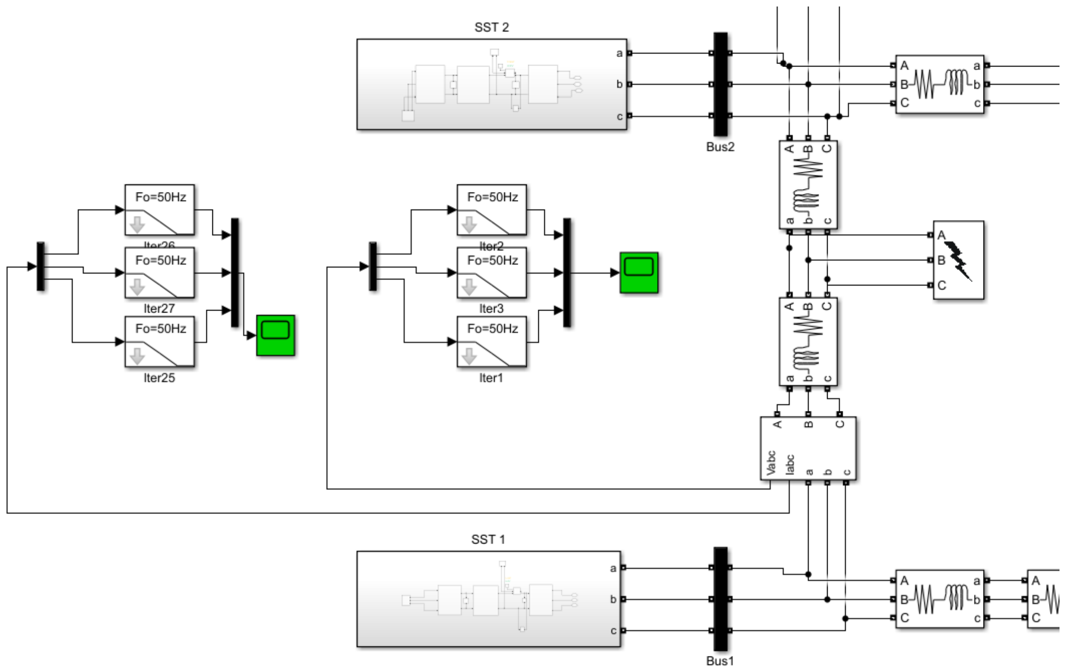


Figure 3.9 Fault operation

Three Phase to Ground Fault

a. Line 12

Transient current occur and current increases to nearly 200 A , while voltage dropped to 25 v

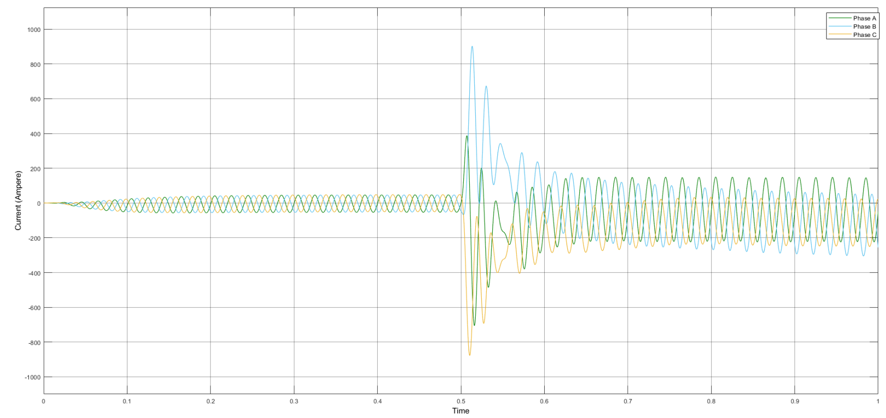


Figure 3.10 Current of line 12

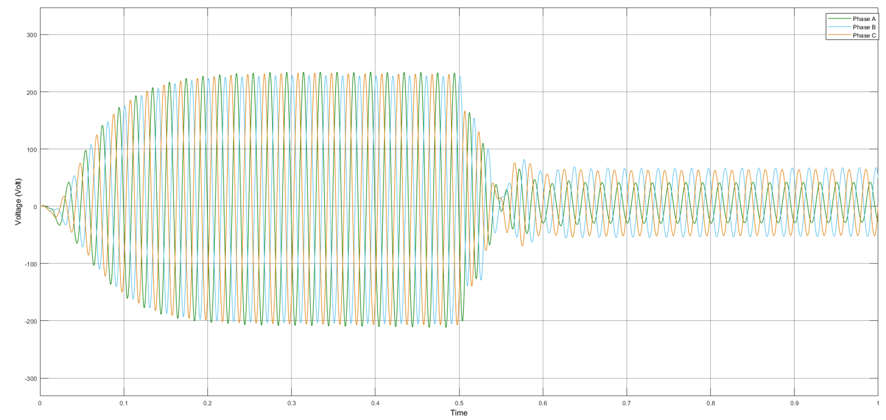


Figure 3.11 Volatge of line 12

b. Line 13

A notable collapse in both current and voltage which both decrease to nearly 25 A and 50 V respectively

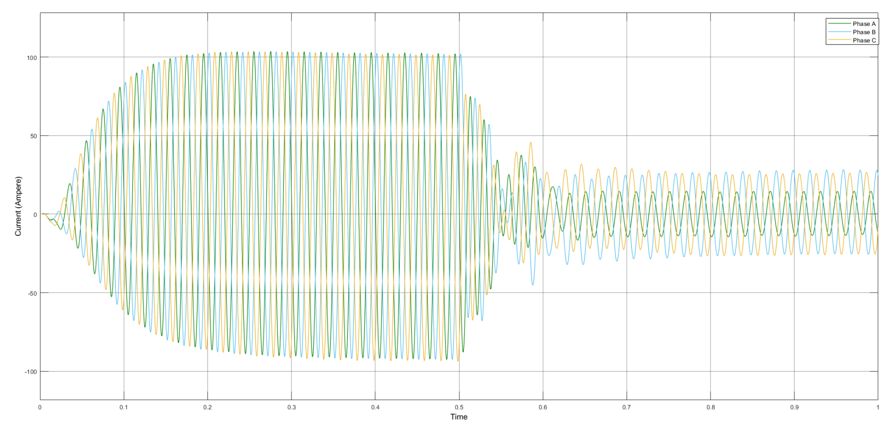


Figure 3.12 Current of line 13

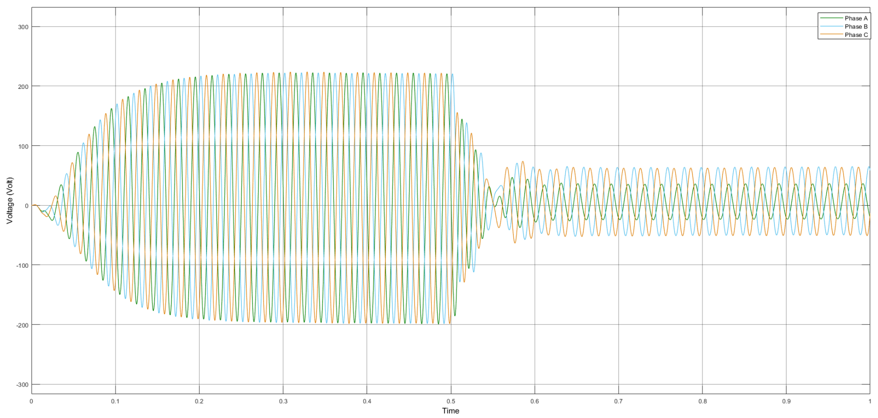


Figure 3.13 Voltage of line 13

c. Line 23

A notable collapse in both current and voltage which both decrease to nearly 18 A and 50 V respectively

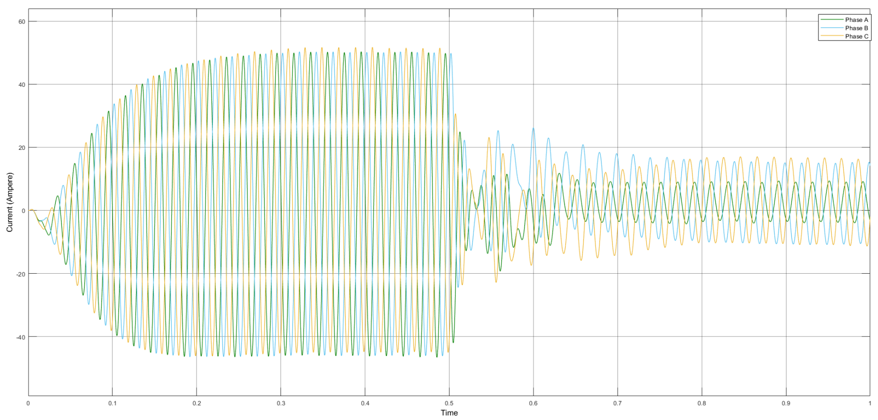


Figure 3.14 Current of line 23

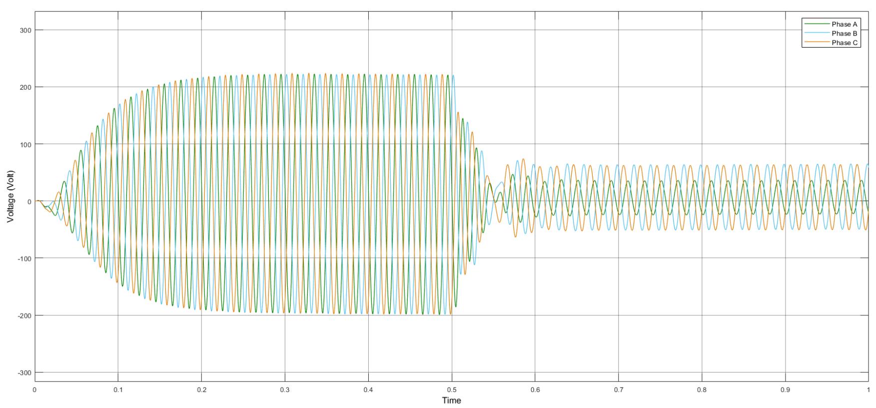


Figure 3.15 Voltage of line 23

Single Phase to Ground Fault

By setting a fault at phase A

a. Line 12

The current at phase A increases significantly at the instant of fault occurance while voltage collapsed

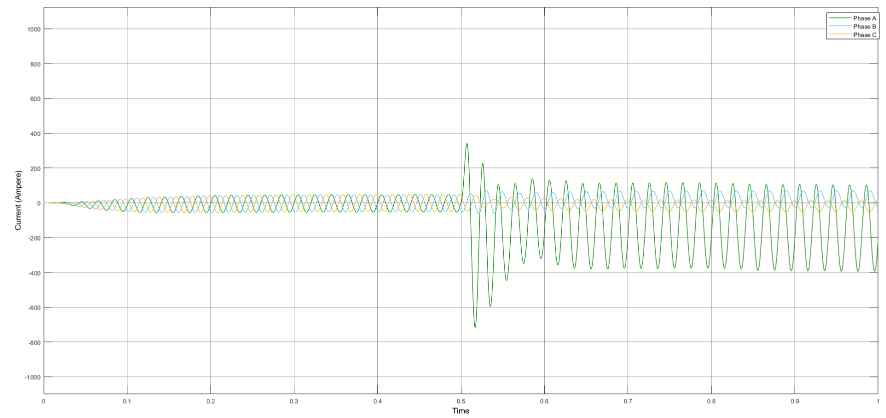


Figure 3.16 Current of line 12

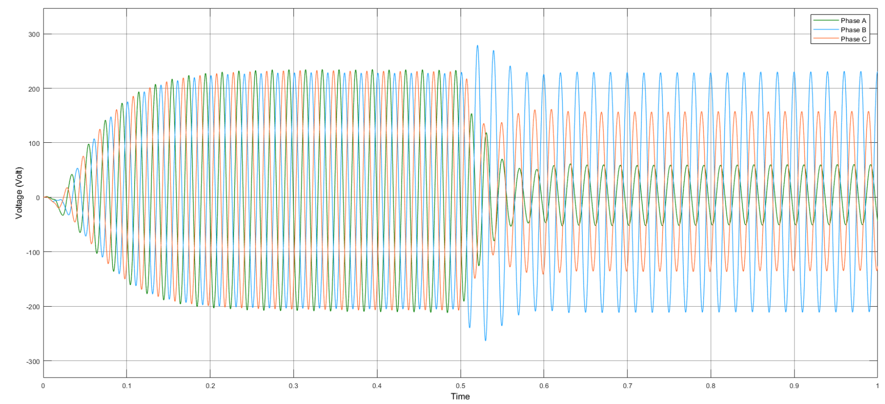


Figure 3.17 Voltage of line 12

b. Line 13

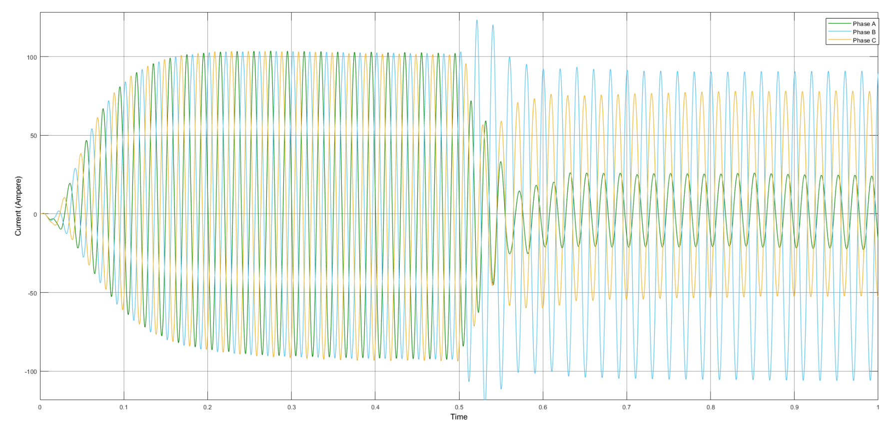


Figure 3.18 Current of line 13

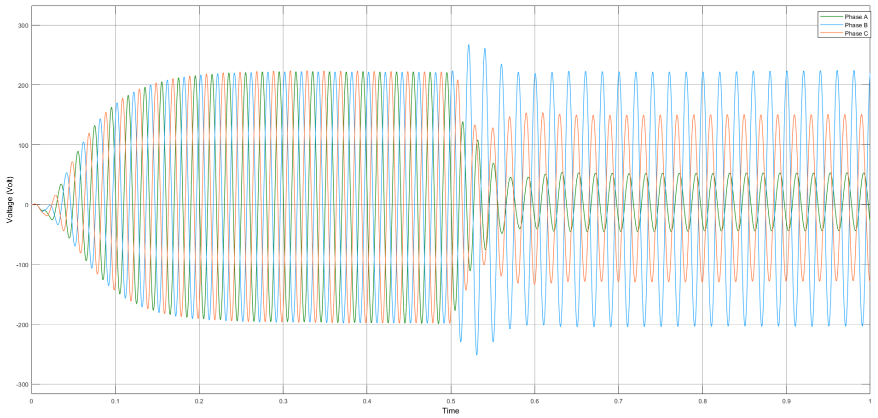


Figure 3.19 Voltage of line 13

c. Line 23

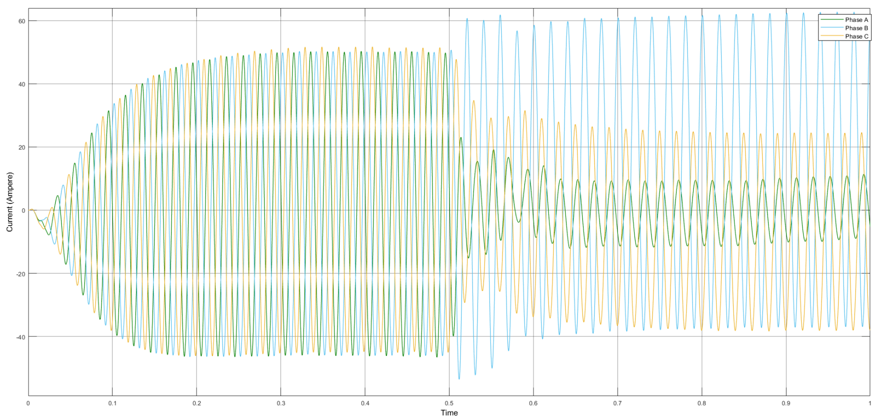


Figure 3.20 Current of line 23

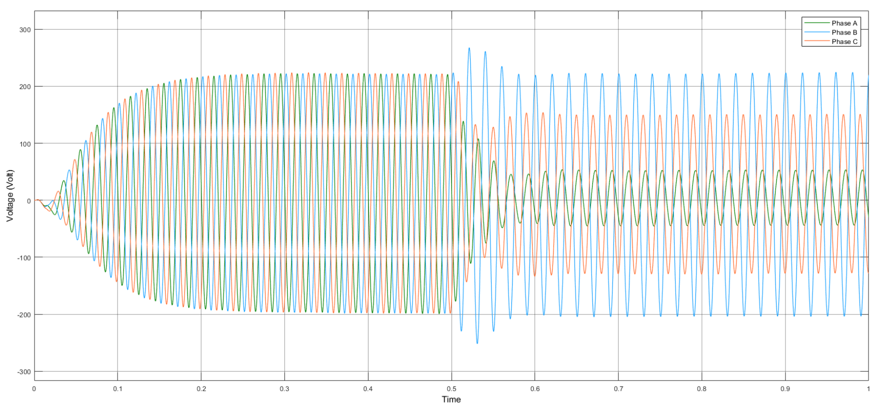


Figure 3.21 Voltage of line 23

Double phase fault

The fault is set between phase A and Phase B

a. Line 12

The two faulted phases current increased to 200 A while a breakdown in voltage occured to 100 v

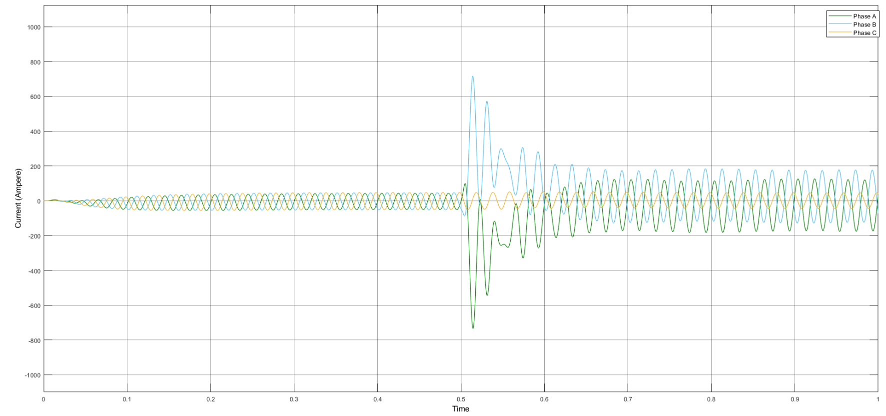


Figure 3.22 Current of line 12

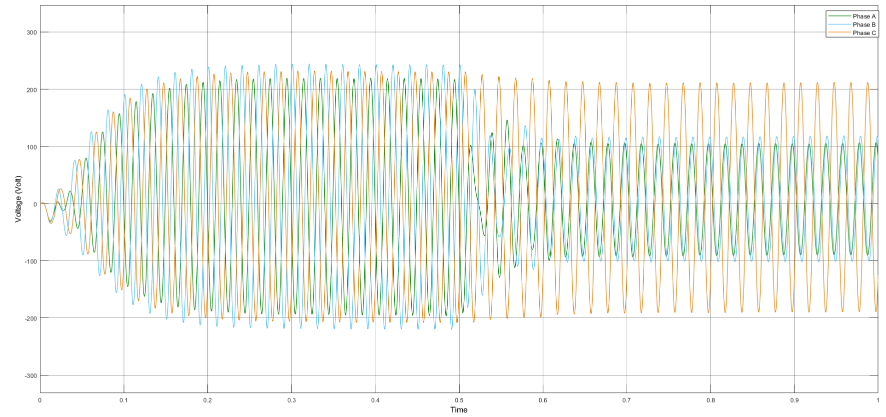


Figure 3.23 Voltage of line 12

b. Line 13

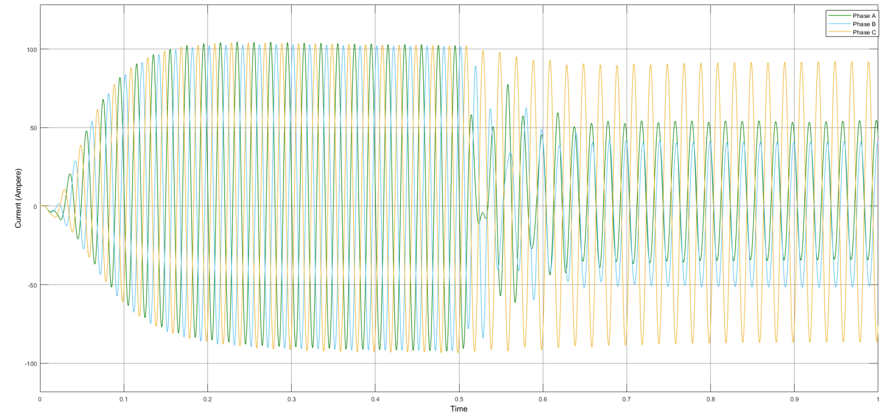


Figure 3.24 Current of line 13

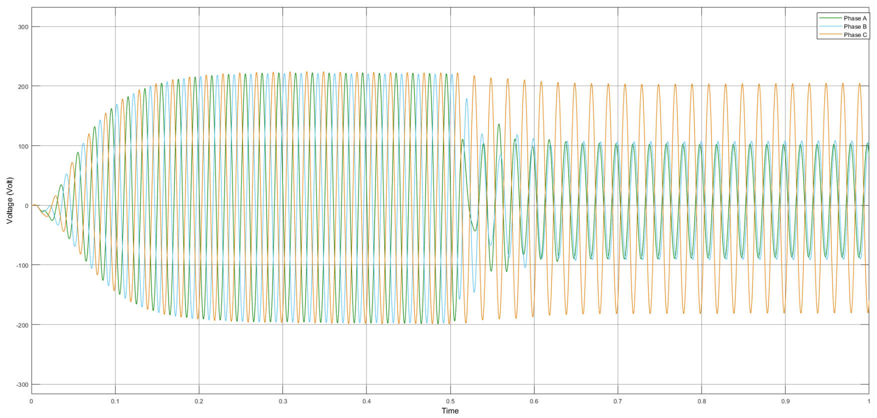


Figure 3.25 Voltage of line 13

c. Line 23

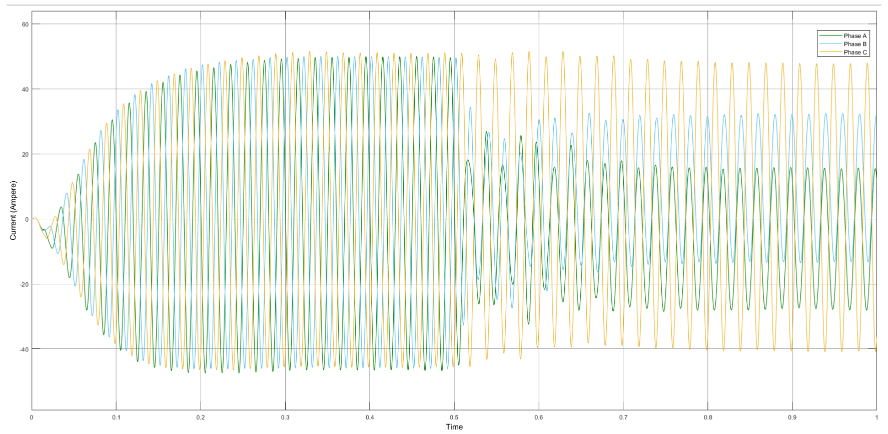


Figure 3.26 Current of line 23

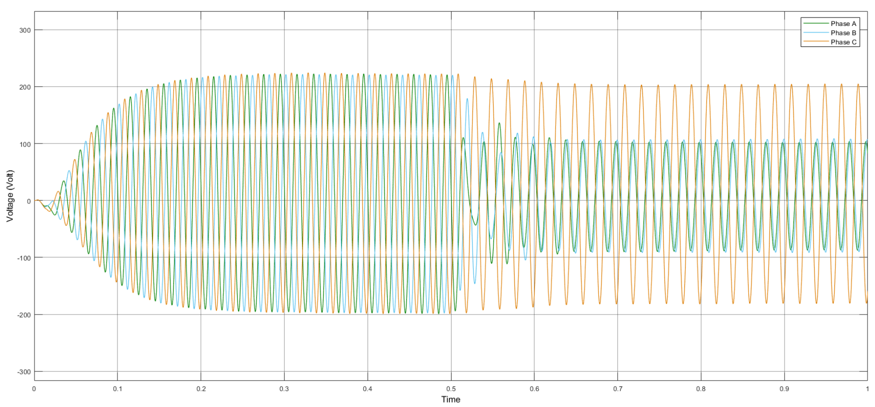


Figure 3.27 Voltage of line 23

3.5.2 Differential Protection

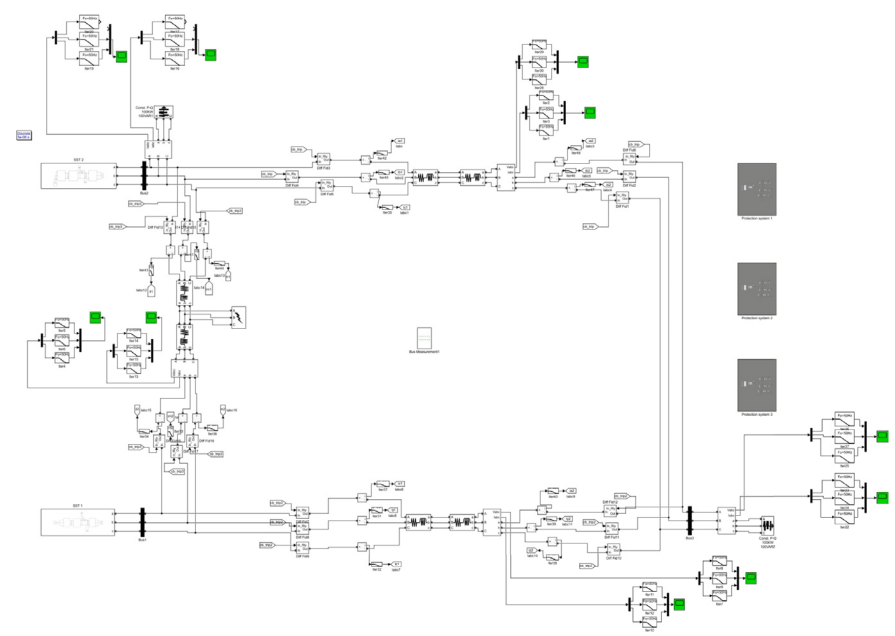


Figure 3.28 Diffential protection scheme

The protection scheme is designed by using two current measurement in the beginning and the end of every line

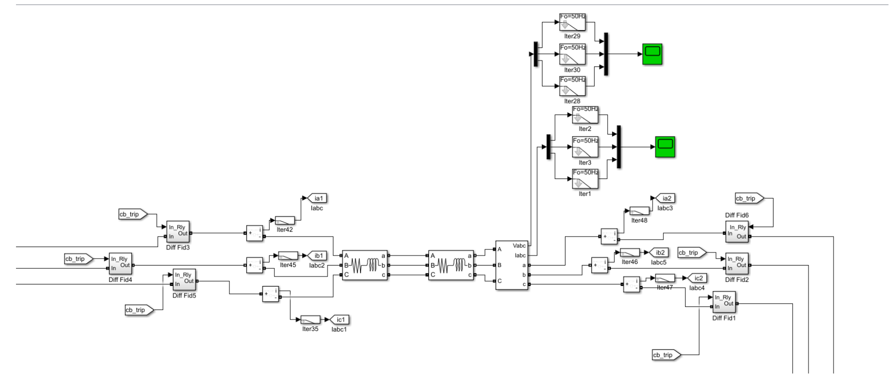
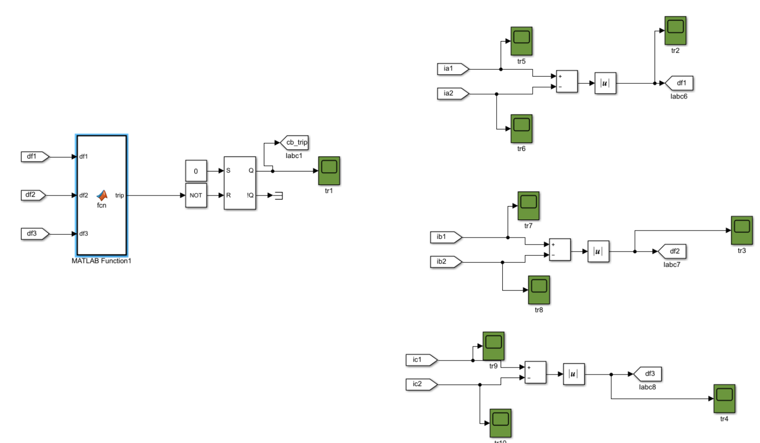


Figure 3.29 Differential protection of line



3.30 Differential relay

The absolute of difference of two values is obtained

This current difference is compared to the pick up by using a code of matlab function to send trip signal to FID

```
function trip  = fcn(df1,df2,df3)
        trip=1;

        if (df1 >0 || df2 >0 || df3 >0)                              % fault occurs
                trip=0;
        end

```

Figure 3.31 Matlab function code

Fault trip using differentail relay

When the fault occurs the current difference increases significantly which makes the relay send trip=0 signal to FID to clear fault at line 12

Three phase to ground fault

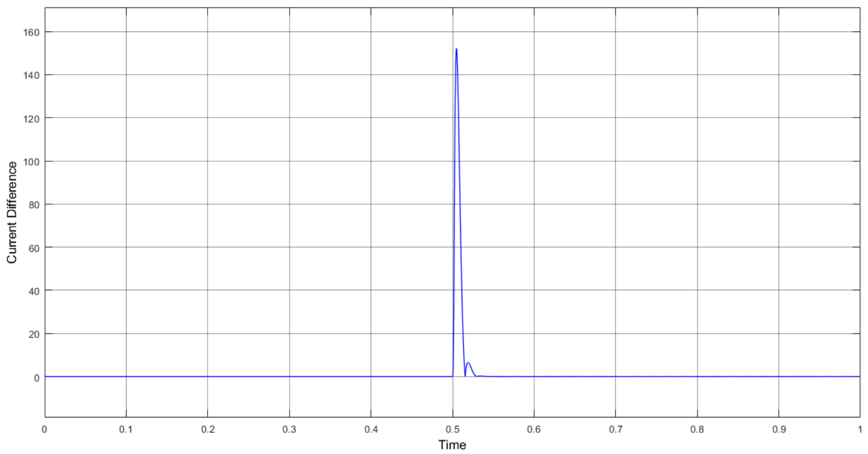


Figure 3.32 Current difference in line 12 during fault

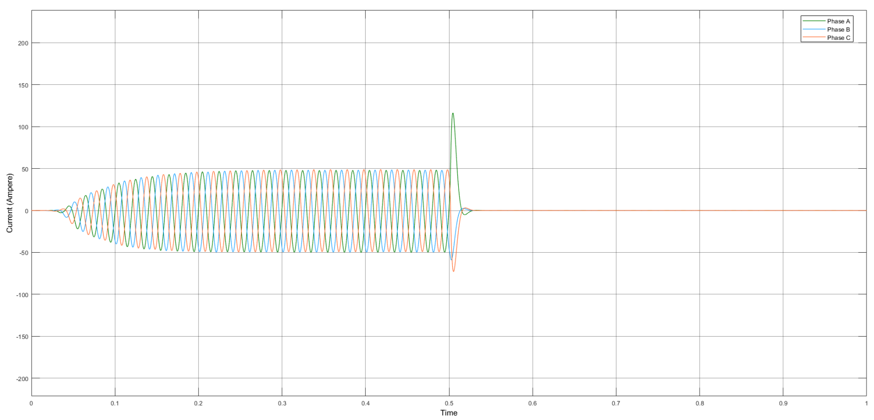


Figure 3.33 Current of line 12 during fault

Single phase to ground fault

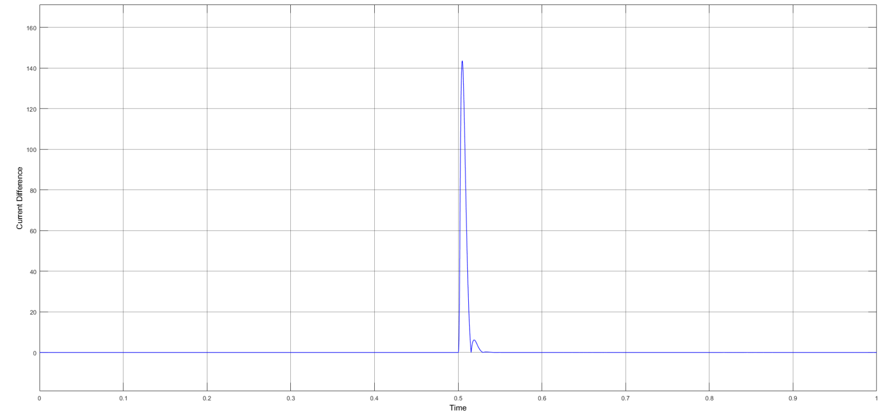


Figure 3.34 Current difference in line 12 during fault

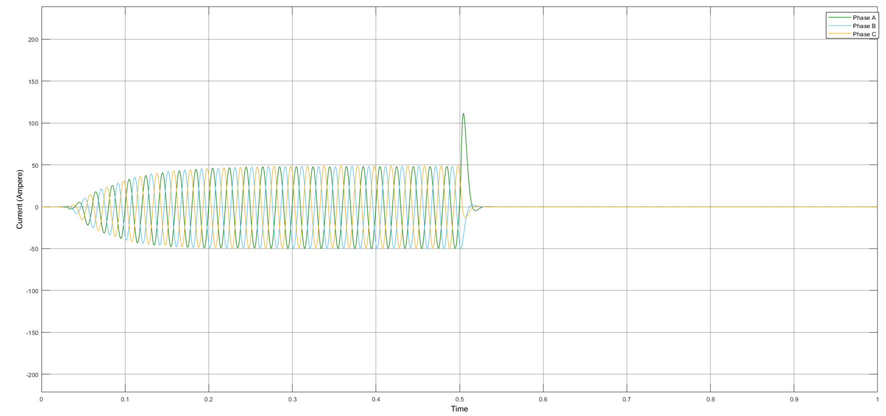


Figure 3.35 Current of line 12 during fault

Double phase to ground fault

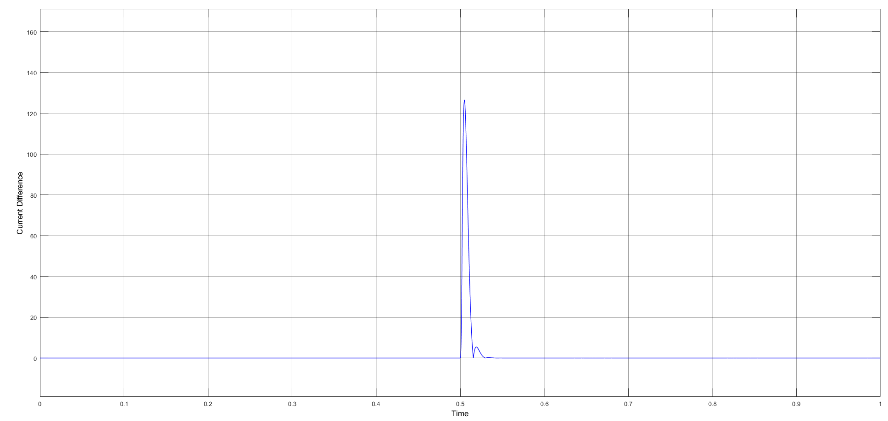


Figure 3.36 Current difference in line 12 during fault

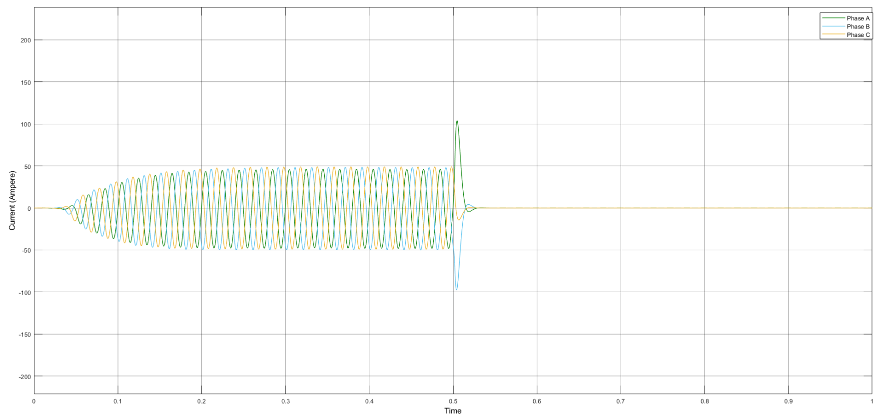
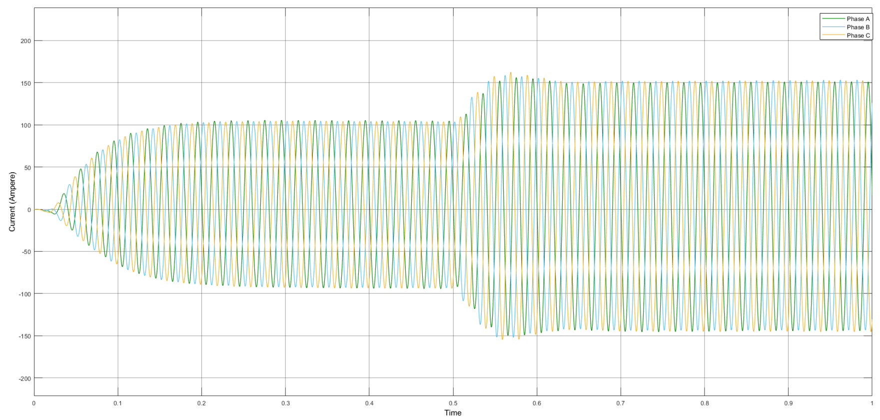


Figure 3.37 Current of line 12 during fault

The two other line line 13 and line 23 will continue to carry the current to the loads

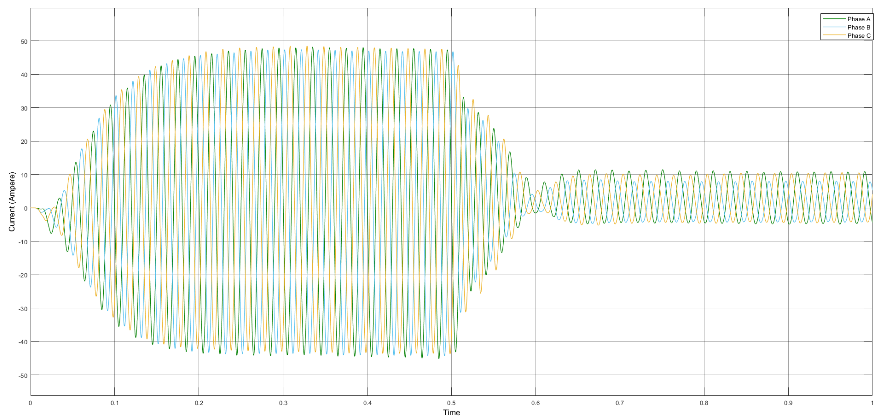
Line 13

It is obvious that the current flow increases to 150 A fulfill the loads needs as the line between the two SST is out



Fgure 3.38 Current of line 13 during fault

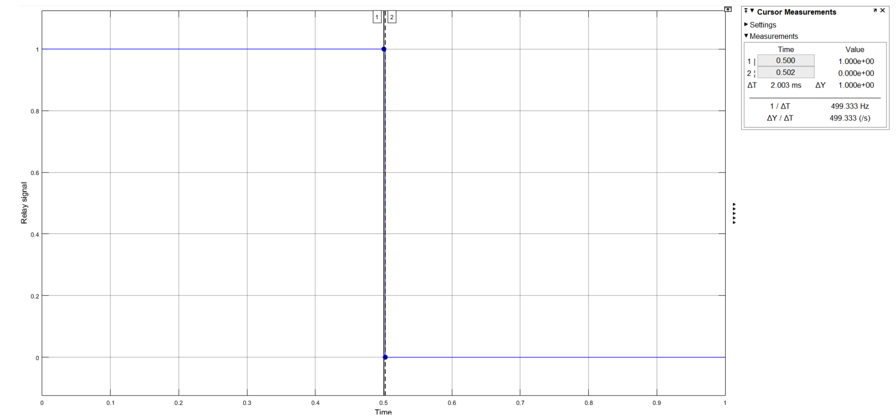
Line 23



Fgure 3.39 Current of line 13 during fault

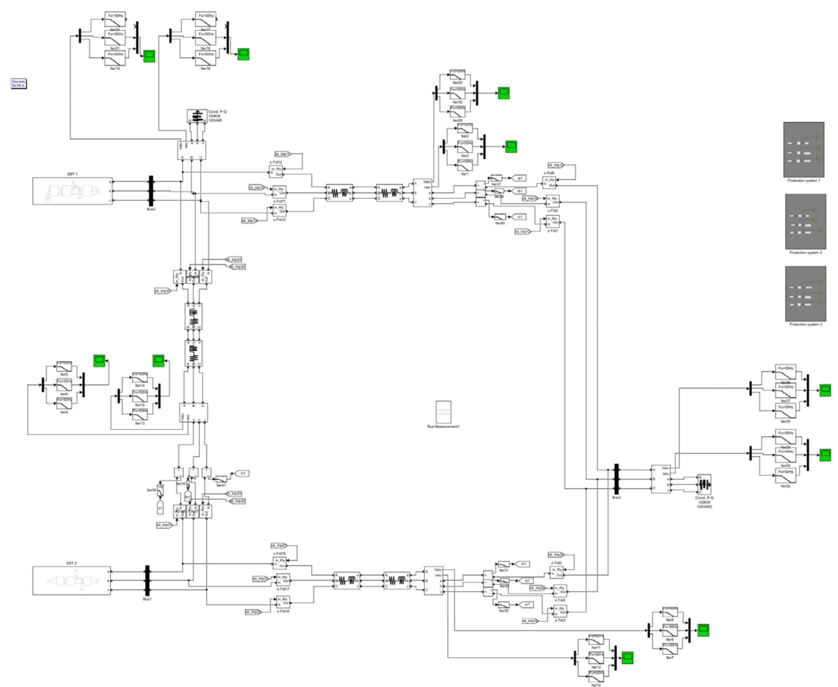
Clearance time

the clearance time of our designed relay to eliminate error is 0.002 sec

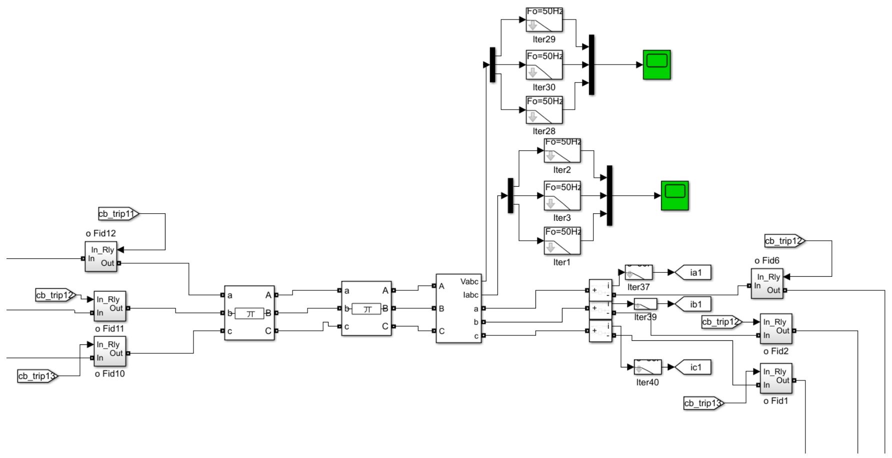


Fgure 3.40 Clearnce time of diifrential relay

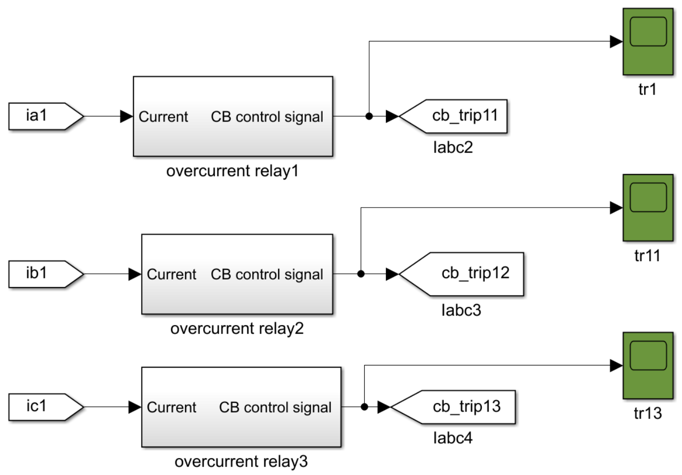
3.5.3 Over current protection



Fgure 3.41 Over Current protection scheme



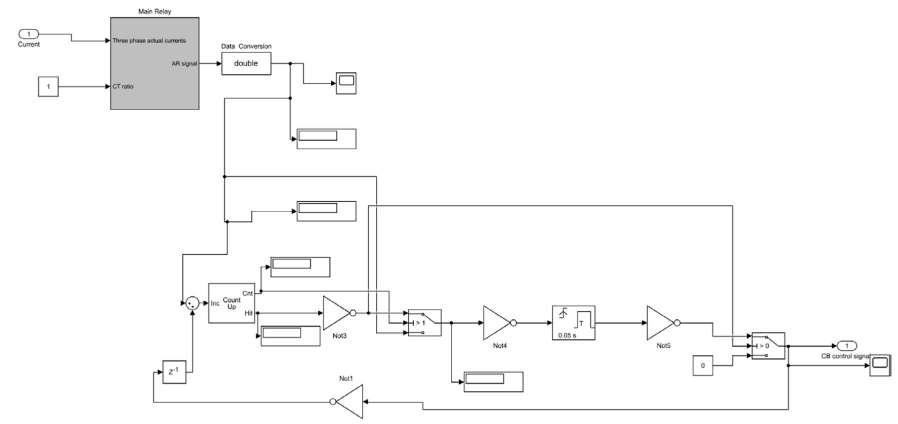
Fgure 3.42 Over Current line protection



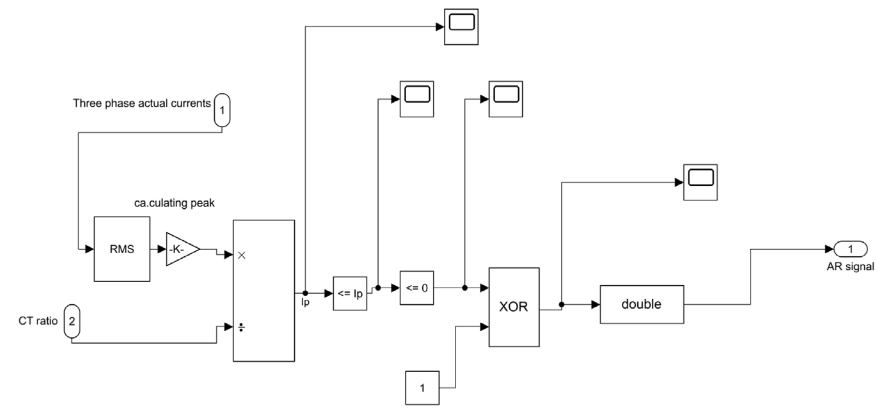
Fgure 3.43 Over Current relay

The designed relay consists of many blocks which are:

- **RMS:** to get rms value of input current
- **Divide:** to divide current over CT ratio
- **Compare to constant:** to compare input current with pick up current if current smaller than pick up it gives 1 and if the current greater than pick up it gives 0
- **Compare to zero:** operates as not gate
- **Logical Operator (XOR):** to send 0 or 1 signal according it is truth table where the gate has two input, a constant which equal 1 and the output of compare to zero block which gives 1 or 0
- **Counter up:** define the number of allowed times to send a reclosing signal for circuit breaker then block circuit breaker and cannot receive a closing signal
- **Delay:** it delays the input signal for a constant time
- **Monostable:** it is rising kind and if the input signal 0:1 or 1 ;the output will be 1 for a constant time (pulse duration=0.05 sec)
- **Switch:** it has 3 points with condition at point 2 and when the input at point 2 achieves the condition then the output will be at point 1 and if it does not achieve the condition the output will be at point 3



Fgure 3.44 Design of over current relay

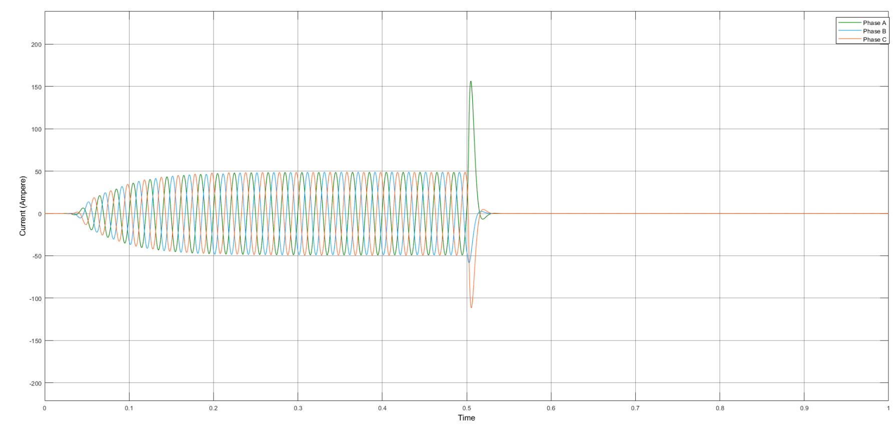


Fgure 3.45 Main relay block

Fault trip using overcurrent relay

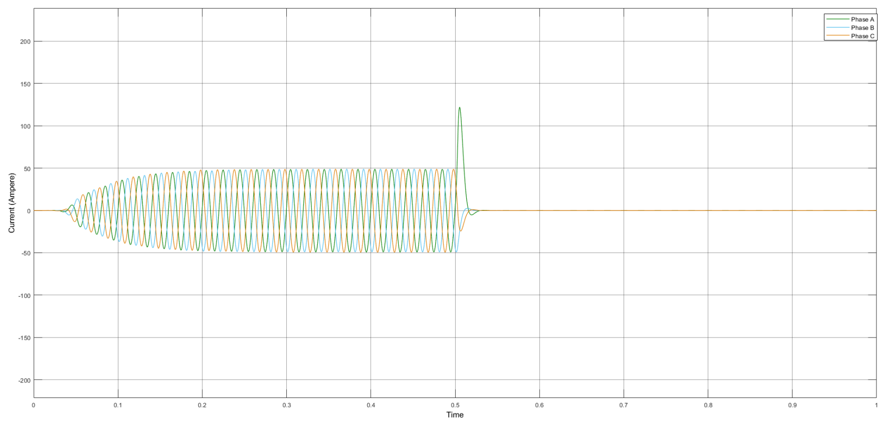
When the fault occurs the current exceeds the pick up current adjusted in the relay which makes the relay send trip=0 signal to FID to clear fault at line 12

Three phase to ground fault



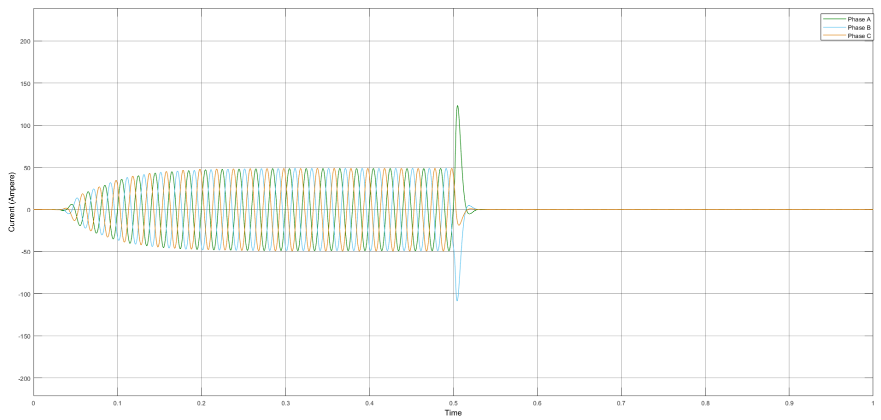
Fgure 3.46 Current of line 12 during fault

Single phase to ground fault



Fgure 3.47 Current of line 12 during fault

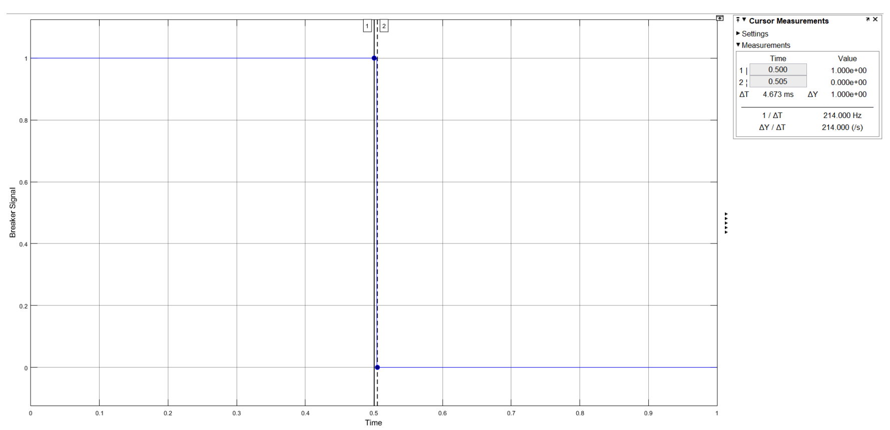
Double phase to ground fault



Fgure 3.48 Current of line 12 during fault

Clearance time

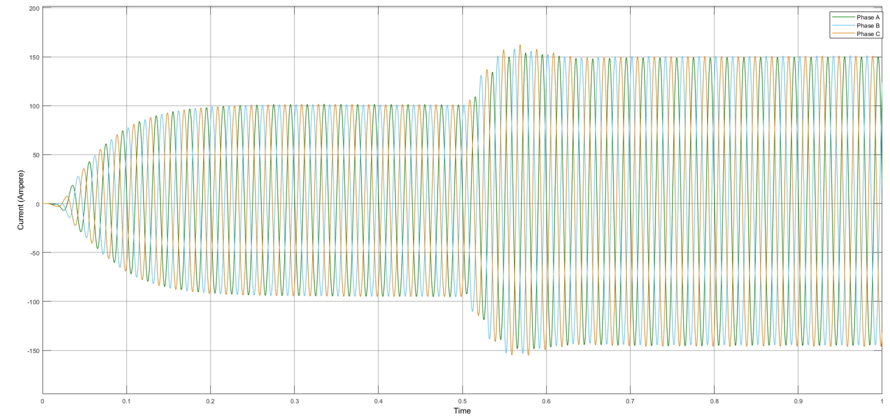
The clearance time for the relay designed is 0.005 sec to trip and eliminate the fault



Fgure 3.49 Clearance time of over current relay

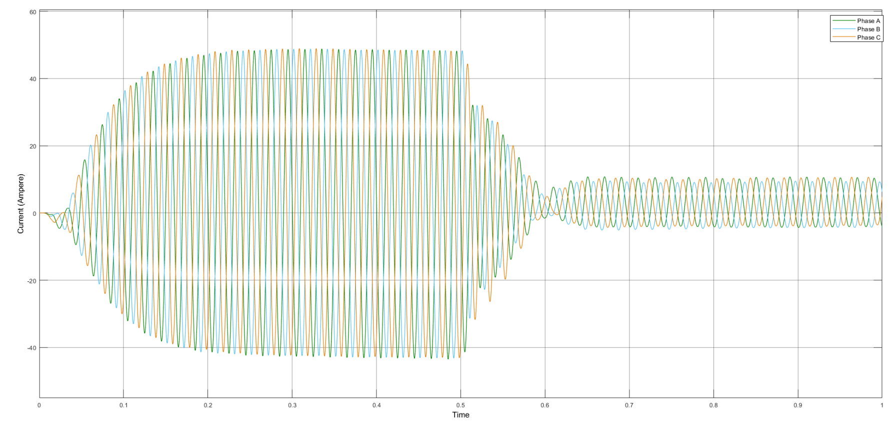
The two other line line 13 and line 23 will continue to supply the current to the loads

Line 13



Fgure 3.50 Current of line 13 during fault

Line 23



Fgure 3.51 Current of line 23 during fault

04

INTERNET of THINGS

4. Internet of Things

4.1 Introduction to IoT

Basically, **IoT is a network in which all physical objects are connected to the internet** through network devices or routers and exchange data. IoT allows objects to be controlled remotely across existing network infrastructure. IoT is a very good and intelligent technique which reduces human effort as well as easy access to physical devices. This technique also has autonomous control feature by which any device can control without any human interaction.

Figure 4.1 IoT features

"Things" in the IoT sense, is the mixture of hardware, software, data, and services. "Things" can refer to a wide variety of devices such as DNA analysis devices for environmental monitoring, electric clamps in coastal waters, Arduino chips in home automation and many other. **These devices gather useful data with the help of various existing technologies and share that data between other devices.** Examples include Home Automation System which uses Wi-Fi or Bluetooth for exchange data between various devices of home. The versatility of IoT has become very popular in recent years. **Mckinsey Global Institute reports that IoT business will reach 6.2 trillion in revenue by 2025.** There are lots of applications are available in the market in different areas.

4.2 IoT in Power Systems

Integration of renewable energy and optimization of energy use are key enablers of sustainable energy transitions and mitigating climate change. Modern technologies such the Internet of Things (IoT) offer a wide number of applications in the energy sector, i.e, in energy supply, transmission and distribution, and demand. IoT can be employed for improving energy efficiency, increasing the share of renewable energy, and reducing environmental impacts of the energy use.

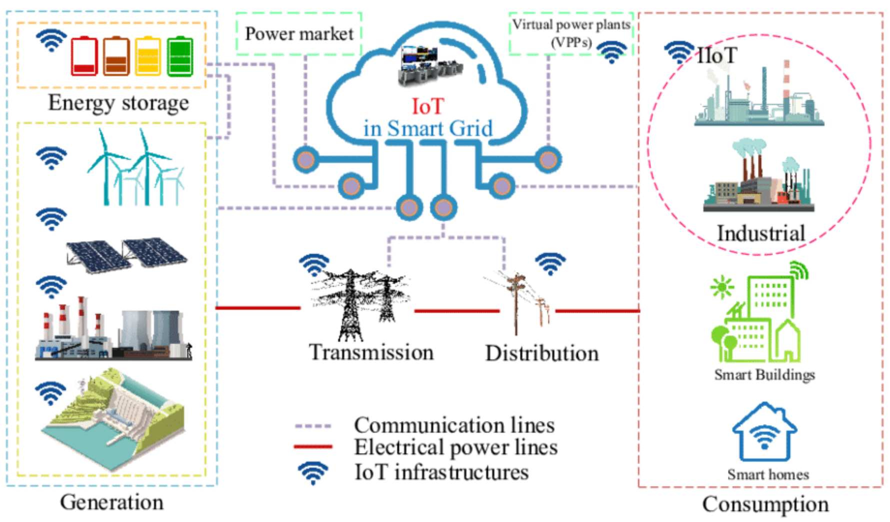


Figure 4.2 IoT Applications in Power Systems

IoT is an emerging technology that uses the Internet and aims to provide connectivity between physical devices or "things" [1]. Examples of physical devices include home appliances and industrial equipment. Using appropriate sensors and communication networks, these devices can provide valuable data and enable offering diverse services for people. For instance, controlling energy consumption of buildings in a smart fashion enables reducing the energy costs [2]. IoT has a wide range of applications, such as in manufacturing, logistics and construction industry [3]. IoT is also widely applied in environmental monitoring, healthcare systems and services, efficient management of energy in buildings, and drone-based services.

4.2.1 Smart Cities

Nowadays, the staggering rate of urbanization as well as overpopulation has brought many global concerns, such as air and water pollution [4], energy access, and environmental concerns. In this line, one of the main challenges is to provide the cities with clean, affordable and reliable energy sources. The recent develop-ments in digital technologies have provided a driving force to apply smart, IoT based solutions for the existing problems in a smart city context [5]. Smart factories, smart homes, power plants, and farms in a city can be connected and the data about their energy consumption in different hours of the day can be gathered. If it is found that a section, e.g., residential areas, consumes the most energy in the afternoon, then automatically energy devoted to other sections, e.g., factories, can be minimized to balance the whole system at a minimum cost and risk of con-gestion or blackout.

4.2.2 Smart Grid

Smart grids are modern grids deploying the most secure and dependable ICT technology to control and optimize energy generation, T&D grids, and end usage. By connecting many smart meters, a smart grid develops a multi-directional flow of information, which can be used for optimal management of the system and efficient energy distribution [6].

In traditional grids, batteries were recharged by adapters through electricity cables and AC/DC inverter [6]. These batteries can be charged wirelessly in a smart grid, using an inductive charging technology. In addition, in a smart grid, the energy demand pattern of end users can be analyzed by collecting data through an IoT platform, for example, the time of charging of mobile phones or electric cars. Then, the nearest wireless battery charge station can allocate the right time-slot and that device/vehicle can be charged. Another advantage is that the use of IoT will lead to better control and monitoring of the battery equipped devices, and therefore, first, the energy distribution can be adjusted, and second, the delivery of electricity to these vehicles can be guaranteed. This will reduce unnecessary energy con-sumption considerably.

Moreover, IoT can be applied in isolated and microgrids for some islands or organizations, especially when energy is required every single moment with no exception, e.g., in databases. In such systems, all the assets connected to the grid can interact with each other. Also, the data on energy demand of any asset is accessible. This interaction can assure the perfect management of the energy distribution whenever and everywhere needed.

4.3 Distributed Grid Intelligence DGI

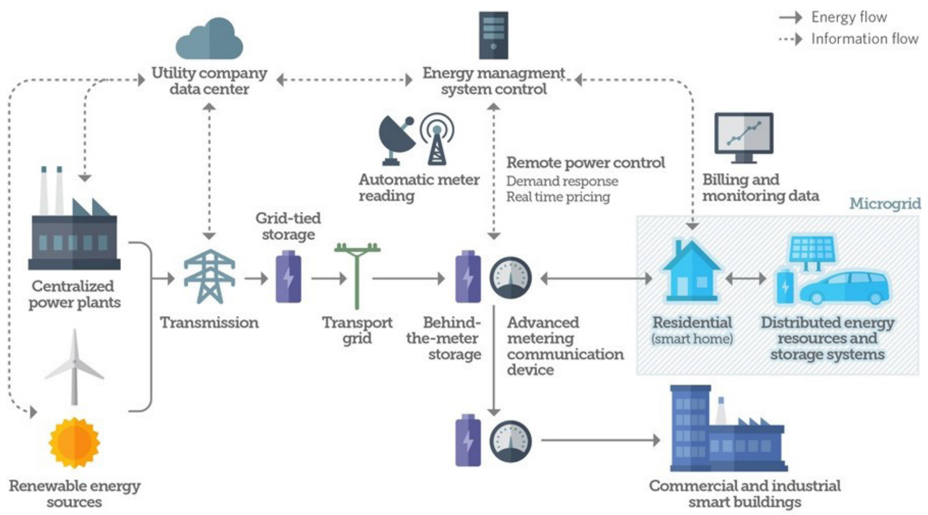


Figure 4.3 DGI Features in smart grid

The FREEDM microgrid is a smart grid solution with Distributed Grid Intelligence (DGI) to efficiently manage the power distribution and storage of renewable energy. Within the FREEDM system, DGI applies distributed control method in a unique way to achieve feasible load balancing in microgrid by migrating power between renewable energy generation and storage at each node.

DGI also plays a vital role acting as the communication backbone of the system. It's responsible for connecting various nodes (SST/FID/...etc.) in the system and to make the ideal coordination between system parts like protection and energy control and management which are critically important for the stability of the system.

Moreover, the ability to connect the smart grid into the cloud is trivial thanks to the Distributed Grid Intelligence. Communication between system nodes can be done wirelessly or using conventional wired links which can be various mediums depending on the communication protocol used. For instance, Ethernet cables can be used as the wired physical links between system nodes.

4.3.1 DGI as Raspberry PI

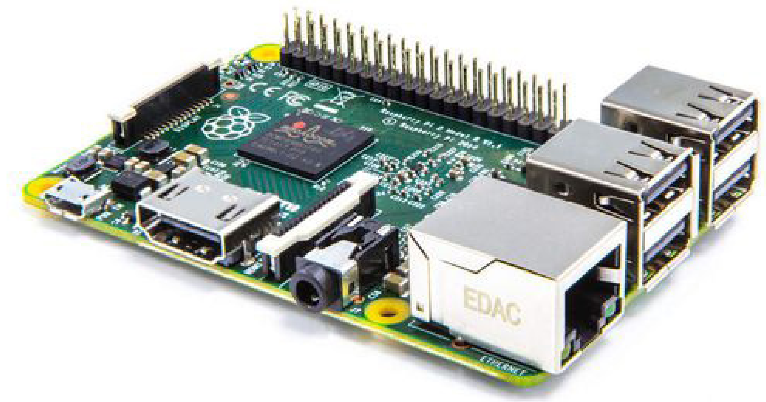


Figure 4.4 Raspberry Pi 3 B+

Choosing the propriate brain of the system is not an easy choice. That's because there are many available options out there in the market. However, when looking at the technical specifications of the Raspberry Pi 3 Model B+ and its exceptional computational power, it gave us no hesitation time to select it. Inspecting it:

- Broadcom BCM2837B0, Cortex-A53 (ARMv8) 64-bit SoC @ 1.4GHz
- 1GB LPDDR2 SDRAM
- 2.4GHz and 5GHz IEEE 802.11.b/g/n/ac wireless LAN, Bluetooth 4.2, BLE
- Gigabit Ethernet over USB 2.0 (maximum throughput 300 Mbps)
- Extended 40-pin GPIO header
- Full-size HDMI
- 4 USB 2.0 ports
- CSI camera port for connecting a Raspberry Pi camera
- DSI display port for connecting a Raspberry Pi touchscreen display
- 4-pole stereo output and composite video port
- Micro SD port for loading your operating system and storing data
- 5V/2.5A DC power input
- Power-over-Ethernet (PoE) support (requires separate PoE HAT)

The Raspberry Pi 3 Model B is the most popular Raspberry Pi computer made, and the Pi Foundation knows you can always make a good thing better! And what could make the Pi 3 better? How about a faster processor, 5 GHz WiFi, and updated Ethernet chip with PoE capability?

4.3.2 Fault Isolation Device as Arduino

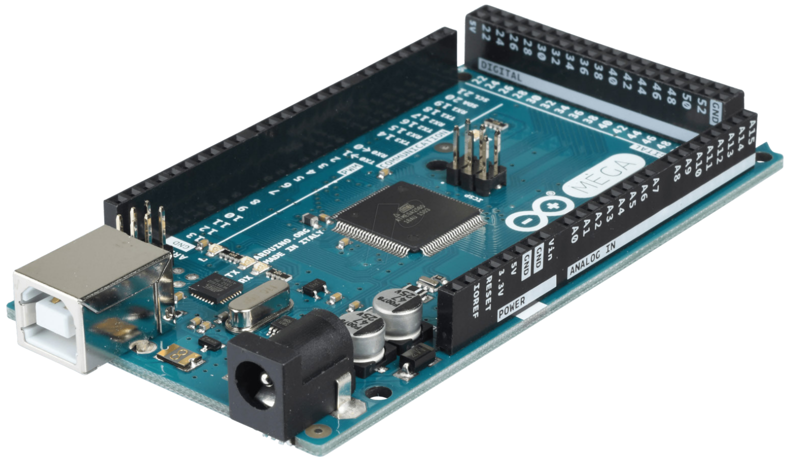


Figure 4.5 Arduino MEGA

For the sake of simplicity, Arduino MEGA was chosen to play the part of the rest intelligent nodes in the system which will be connected to the main DGI. With its technical specifications, it is more than enough for our purposes. Inspecting it:

- Microcontroller: ATmega2560
- Operating Voltage: 5V
- Digital I/O Pins: 54 (of which 15 provide PWM output)
- Analog Input Pins: 16
- DC Current per I/O Pin: 20 mA
- DC Current for 3.3V Pin: 50 mA+
- Flash Memory: 256 KB of which 8 KB used by bootloader
- SRAM: 8 KB
- EEPROM: 4 KB
- Clock Speed: 16 MHz
- LED_BUILTIN: 13
- Length: 101.52 mm
- Width : 53.3 mm
- Weight: 37 g

Each node is responsible for a certain task. That's because this is a programmable circuit board which can be instructed to do whatever we want based on the C language code burned into its internal chips. For instance, one Arduino MEGA is responsible for the over-current protection. To illustrate, selecting the **ACS712 Current Sensor** and connecting it as input to the Arduino ports, the equipment's circuit breakers also connected as output to the Arduino ports and with the right code in hand which simply tells the Arduino if the measured amount of current exceeds a certain predefined value, send a signal through the output ports to open the circuit breaker and protect the equipment.

Not to forget, the Arduino will also be connected to the Distributed Grid Intelligence to be in standby state to receive orders, whether to disable over-current protection or to modify the threshold current value or simply to collect all measured points to create a logged monitoring window for all nodes in the system.

4.3.3 DGI Main Roles

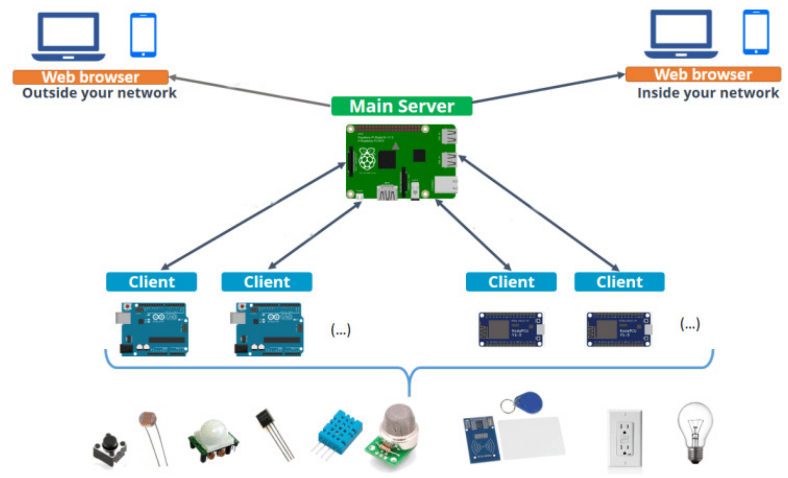


Figure 4.6 DGI main roles

In our case -regarding the system prototype-, the DGI will be the centralized node where we can control everything in our system. Furthermore, acting as a web server to be easily interfaced via internet using a simple web browser from even a mobile phone.

The DGI has the following important main roles:

- Managing all system components using automated coded algorithm or user direct commands via internet.
- Communicating with multiple nodes at once or a single node for specific task.
- Building a centralized log server to keep track of every measured quantity in the system in order to implement a high reliable monitoring window.

In the coming chapter, the detailed implementations for the system nodes will be discussed.

05

PROTEUS IMPLEMENTATION of FREEDM SYSTEM

5. Proteus Implementation of FREEDM System

5.1 System Structure

Regarding prototype simulation, we are going to work on the DC grid sub-system in which we will apply all the operation and protection algorithms. Similarly, the same concepts apply for the AC grid sub-system with minor changes or no changes at all. The same hardware components remain almost the same in both grids.

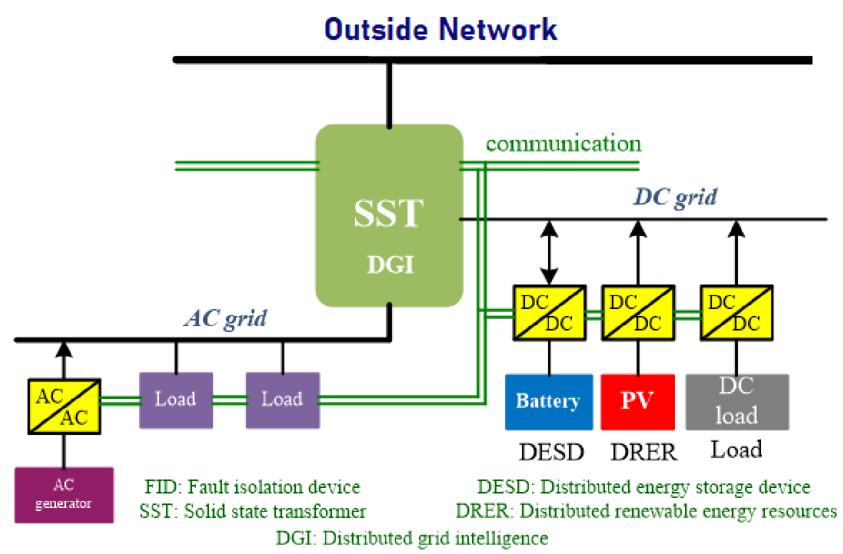


Figure 5.1 System structure

5.1.1 DC Grid Single Line diagram

Focusing on the DC grid sub-system – our main prototype- in this chapter, below are the single line diagram which consists of:

1.Simulating the SST DC stage as DC source: input for the sub-system.
2.Simulating the PV unit as current source.
3.Battery unit. 4. DC Motor.

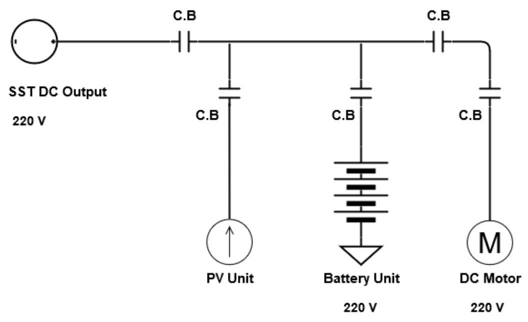


Figure 5.2 DC grid single line diagram

5.1.2 Proteus Software Simulator

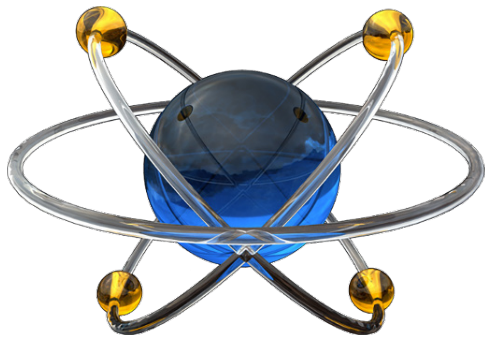


Figure 5.3 Proteus software simulator

The Proteus Design Suite is a proprietary software tool suite used primarily for electronic design automation. The software is used mainly by electronic design engineers and technicians to create schematics and electronic prints for manufacturing printed circuit boards. It was developed in Yorkshire, England by Labcenter Electronics Ltd and is available in English, French, Spanish and Chinese languages.

As seen in the below figure; Proteus fits perfectly in design and simulation for our FID circuits; integrating sensors with the microcontrollers and electronics can never be easier in any other way. Unfortunately, the IoT functionality for Proteus is not free. Consequently, we will not provide simulation for the networking features in our system implementation which we believe it's far easier in real life hardware implementation.

Microcontroller Simulation:

One of the best features available in Proteus. The micro-controller simulation in Proteus works by applying either a hex file or a debug file to the microcontroller part on the schematic. It is then co-simulated along with any analog and digital electronics connected to it. This enables its use in a broad spectrum of project prototyping in areas such as motor control, temperature control and user interface design. It also finds use in the general hobbyist community and, since no hardware is required, is convenient to use as a training or teaching tool.

Support is available for co-simulation of:

- Microchip Technologies PIC10, PIC12, PIC16,PIC18,PIC24,dsPIC33 Microcontrollers.
- Atmel AVR (and Arduino), 8051 and ARM Cortex-M3 Microcontrollers
- NXP 8051, ARM7, ARM Cortex-M0 and ARM Cortex-M3 Microcontrollers.
- Texas Instruments MSP430, PICCOLO DSP and ARM Cortex-M3 Microcontrollers.
- Parallax Basic Stamp, Freescale HC11, 8086 Microcontrollers.

5.2 Power Sources

Power sources are the main node in our system design. Everything we are trying to de here is to harness them in a clever way to provide our loads with enough required power. Furthermore, the power delivered will need much intelligent way to be controlled and maintained in order not to damage our loads or not to waste the power we have. According to FREEDM system standards, these are our sources of power:

1. Main DC grid which comes from the outside grid provided by the SST.
2. 220 Volts PV -solar panel- as our distributed renewable energy resource (DRER).
3. 220 Volts Battery unit as our distributed energy storage device (DESD).

These power sources are controlled and coordinated wisely to get the best efficiency of them. Below are how these power sources are implemented and simulated in our Proteus design.

5.2.1 DC Grid 220 V

The distributed power from the outside network which is converted to DC using the SST. It’s implemented in our Proteus design using DC generator tool with 220 V.

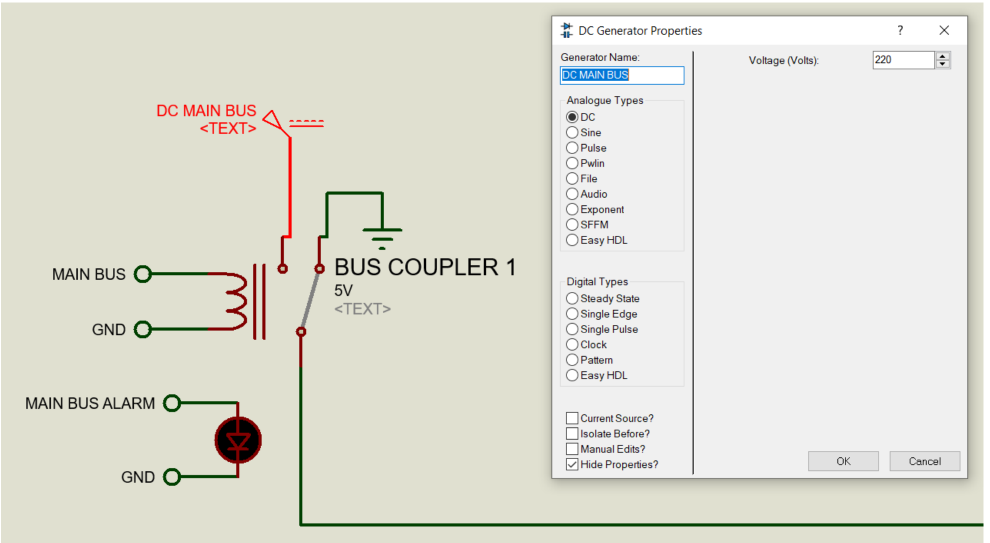


Figure 5.4 DC grid 220 V

Bus coupler is a device which is used to couple one bus to the other without any interruption in power supply and without creating hazardous arcs. The bus coupler is controlled by a 5V signal from the DGI in order to connect the inner DC system to the outside network. Moreover, an auxiliary alarm system is used to indicate the operation of the DC grid bus coupler.

5.2.2 DRER: Solar Panel 220 V

The Distributed Renewable Energy Resource in our system is a 220 Volts PV unit with a series potentiometer to simulate its power fluctuations.

A circuit breaker controlled by the DGI is used to commit the PV unit into the system as well as its opposite circuit breaker -coupled by inverter- to maintain the short circuit structure explained previously. The two circuit breakers can never be in the same status because of the inverter between them. For instance, if the first circuit breaker is closed to commit the PV unit, the second one is being opened to prevent the short circuit path from excluding the PV source from the system.

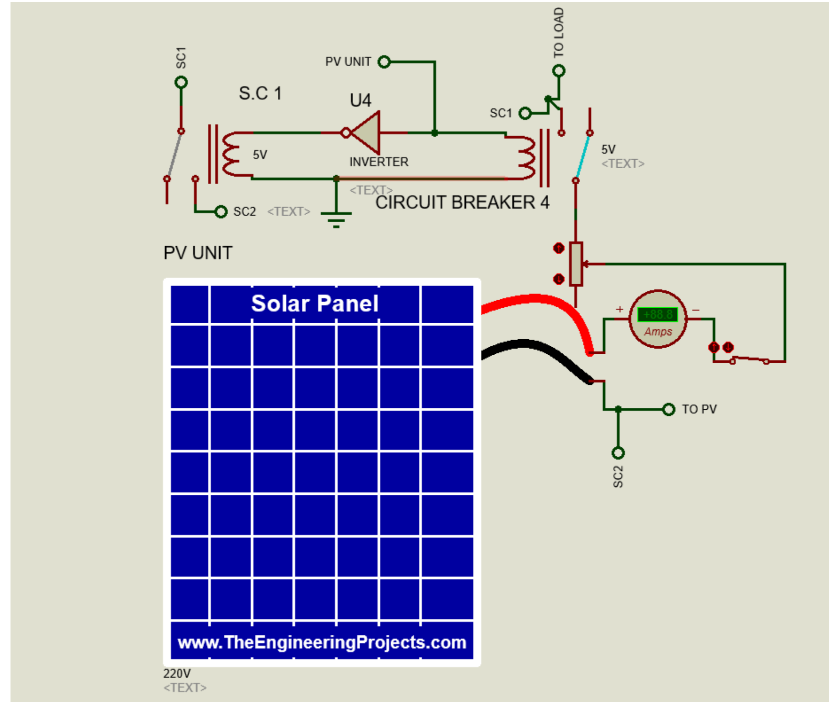


Figure 5.5 DRER: solar panel 220 V

5.2.3 DESD: Battery Unit 220 V

The Distributed Energy Storage Device in our system is a 220 Volts Battery unit consisting of four 110 Volts batteries with a series potentiometer to simulate its power fluctuations.

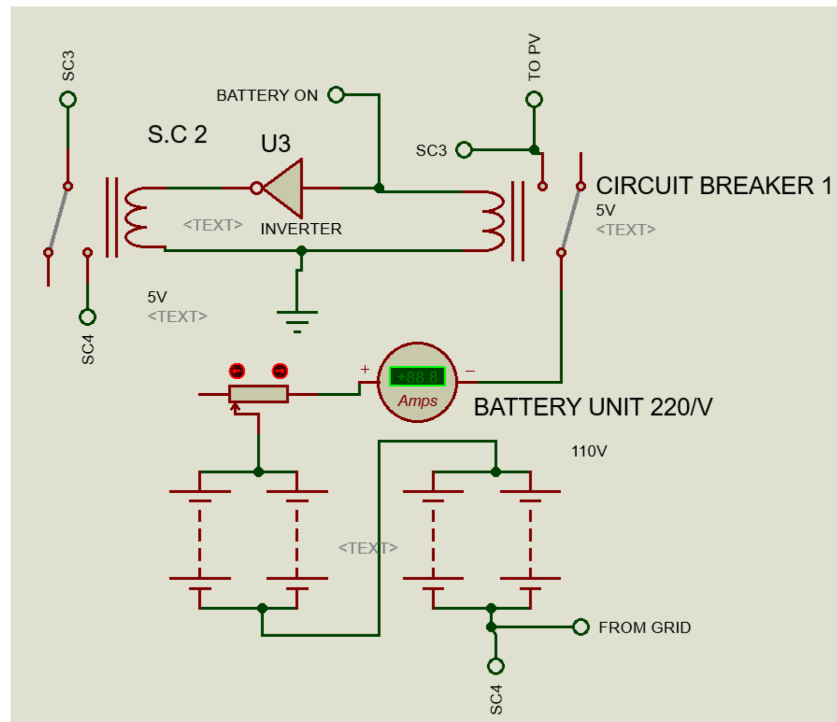


Figure 5.6 DESD: battery unit 220 V

Again, a circuit breaker controlled by the DGI is used to commit the battery unit into the system as well as its opposite circuit breaker -coupled by inverter- to maintain the short circuit structure explained previously.
The battery unit is being charged continuously by the PV and ready to be plugged into the system to provide power in times of need.

5.2.5. Prioritization of power sources.

The power sources in our FREEDM system is assigned a certain set of rules in order to optimize the load reliability and the economic cost.
Power sources priority:

- PV unit.
- Battery unit.
- DC grid.

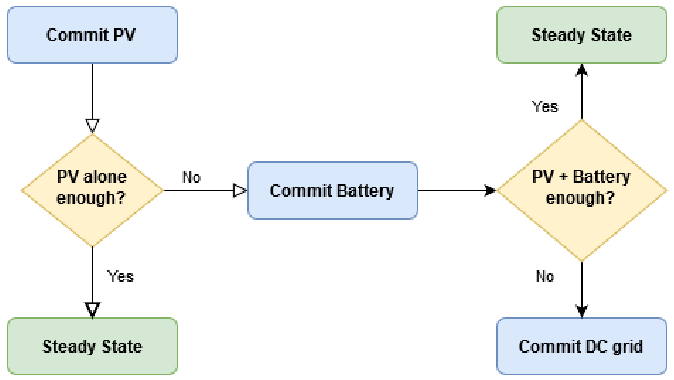


Figure 5.7 Flowchart: prioritization of power sources

This priority order assigns the maximum priority to the PV unit. In other words, this means that whenever the PV unit is available and enough to the load, there is no need to commit any other sources. If the load varies and requires more power, then the next power source to be added is the battery unit before our last resort which is the power coming from the DC grid. We have defined the steady state as the state when the load is operating without any interruptions within the stable limits .

5.3 Protection Schemes

The second main task in our FREEDM system is to maintain a healthy operation with minimal faults and errors. In electrical engineering, faults can be disastrous with heavy costs in terms of money and personnel life. Thus, it's a must to design an error-free protection schemes that work together in a defined coordination rules to achieve the best of the best. Leading to high secure and reliable system with optimized economical cost. Within our system, there two types of protection methods are being used:

1. Differential protection for the main line.
2. Over current protection for the load.

These two methods vary in design, implementation and theory of course. But, the one common factor between them is that each method is sensing the current flowing in a conductor. We chose a suitable sensor with high reliability and low error rate.

5.3.1 Current sensor implementation

The ACS712 is our chosen sensor for measuring current in our FREEDM system.

This ACS721 current module is based on ACS712 sensor, which can accurately detect AC or DC current. The maximum AC or DC that can be detected can reach 30A, and the present current signal can be read via analog I / O port of Arduino. Costs only 3.98 $.

- Supply Voltage: 4.5V~5.5V DC
- Measure Current Range: -30A~ 30A
- Sensitivity: 66mV/A

This module is put in series within the circuit and outputs analog voltage to indicate the amount of current measured. It outputs 2.5 volts to indicate zero current. The output of the sensor is sent to the FID to be processed.

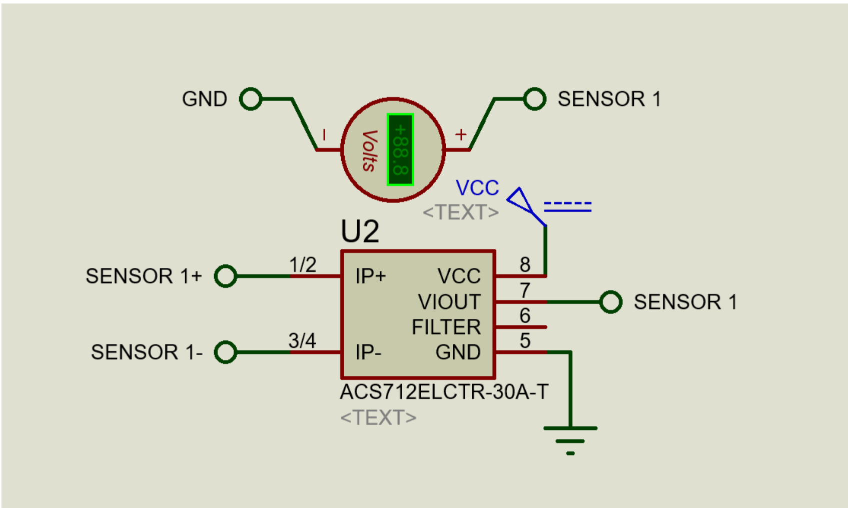


Figure 5.8 ACS712 current sensor

5.3.2 FID implementation and design

The purpose of the Fault Isolation Device (FID) project is to develop a device that minimizes the time needed to isolate and clear faults in the FREEDM system as part of the system's intelligent fault management functionality. Due to the current-limiting nature of the FREEDM system, grid voltage will decrease quickly in the event of a fault; this makes ultra-fast fault isolation a necessity.

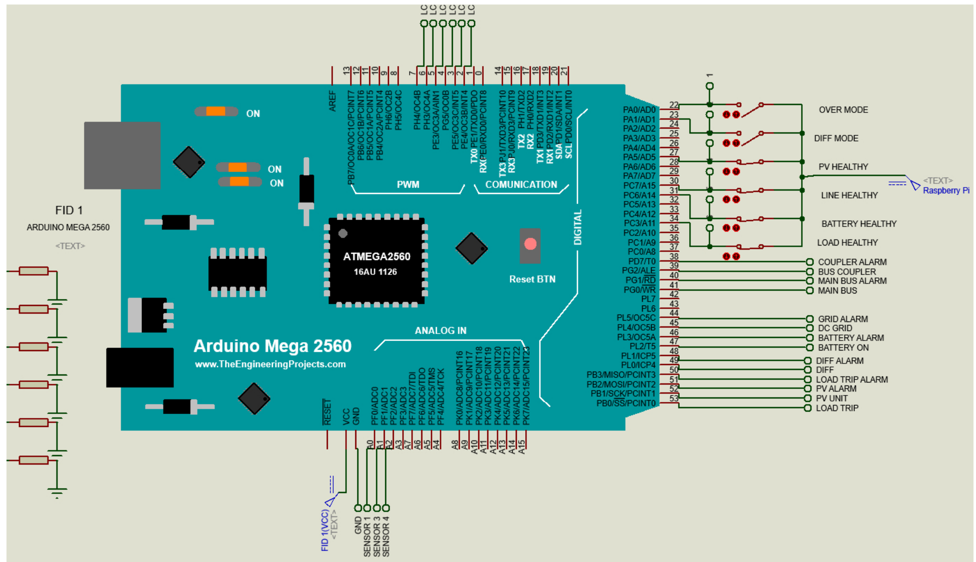


Figure 5.9 Arduino MEGA in Proteus

The fault isolation device in our system is the Arduino Mega 2560 as mentioned in the previous chapter. It's responsible for taking the input signals from the current sensors and processing them according to the C language code embedded in it, then tripping circuit breakers or removing and adding certain nodes in the system.

Based on the processing happened, all what it takes is a 5 V signal from the Arduino to control the circuit breaker that is assigned to that FID.

Also, it's crystal clear that the FID is always in touch with the main DGI for direct control commands by the administrator like disabling or enabling protection modes.

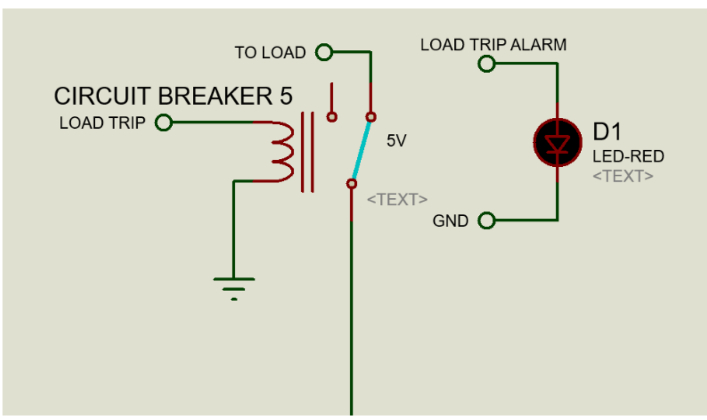


Figure 5.10 Relay in Proteus

5.3.3 Differential protection

An alternative principle for line protection that is quickly becoming the norm is differential protection. Differential protection is based on Kirchhoff's laws, stating that all current into a network node shall add up to zero in an ideal system. What this practically means for a line protection application is that the current that is measured to flow into the line should also be measured to come out.

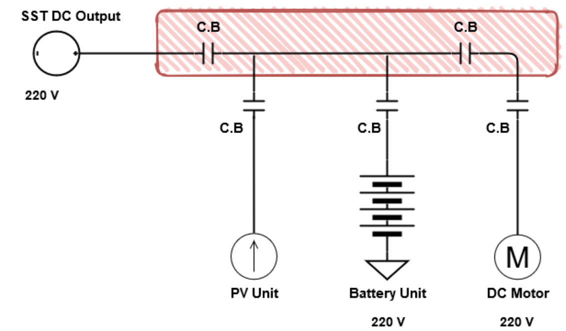


Figure 5.11 Differential protection zone

The most important advantage of transmission line differential protection function is unaffected to external faults. By simply deploying two FIDs at each end of the zone we want to protect, measuring the difference between them. If the difference is higher than a defined pickup value, the line is tripped. The protection zone is shown above in red. Below are the Proteus implementation for them:

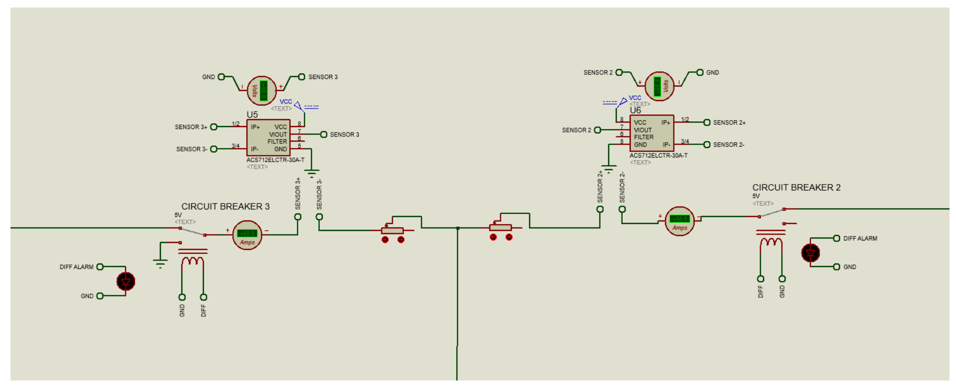


Figure 5.12 Differential protection zone in Proteus

5.3.4 Overcurrent protection.

An overcurrent protection device protects the circuit by opening the device when the current reaches a value that will cause an excessive or dangerous temperature rise in conductors. Most overcurrent protection devices respond to both, short-circuit or ground-fault current values as well as overload conditions.

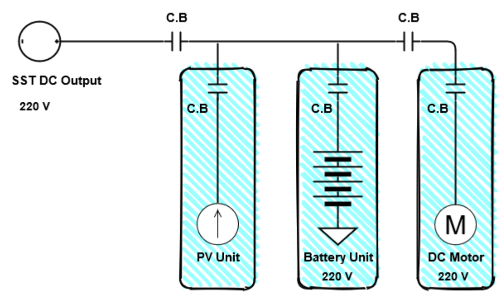


Figure 5.13 Overcurrent protection zone

As seen in the previous figure, the protection zone is in blue. In our system, the overcurrent protection is assigned to the load instead of the line. The load is a simple DC motor operating at 220 Volts.

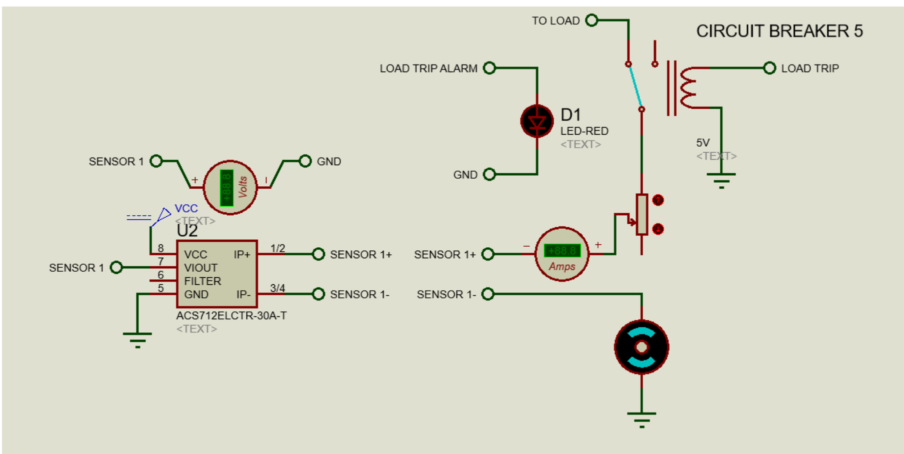


Figure 5.14 Overcurrent protection zone in Proteus

5.3.5 Protection coordination algorithm

One critical task for our FREEDM system is to correctly coordinate the protection system with the management control system. Leading to more secure, reliable and healthy system with no false positives that can trigger the protection equipment in normal operation.

The purpose of the protection scheme is to make sure that any sudden fault has no effect on the grid equipment and the load of course. Assigning the differential protection to guard the line between the bus and the load. Leaving the overcurrent protection to protect the load from excessive currents. The over current protection acts like a backup for the differential protection due to its slower response time compared to the differential protection.

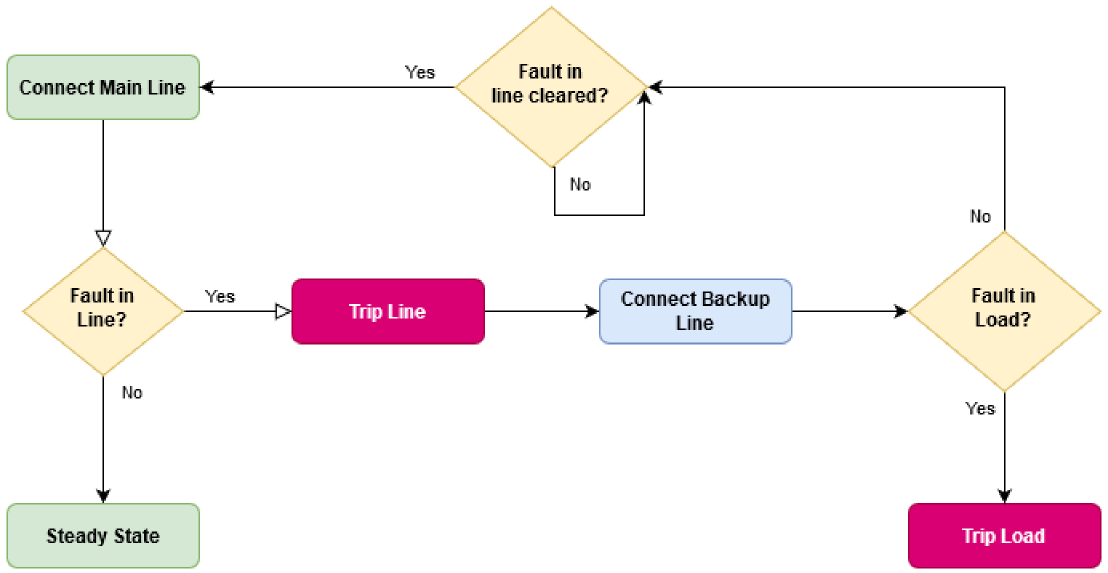


Figure 5.15 Flowchart: protection coordination

06

CONCLUSION

6. Conclusion

In conclusion implementing FREEDM systems whether it's grid connected or not can help with the energy generation, transmission and distribution as :

- FREEDM system is a smart distribution system that facilitates seamless integration of high-penetration DRER and DESD with the existing distribution system.
- FREEDM systems accommodate high-penetration of renewable energy resources, it can decrease the consumption of fossil fuel and consequently reduce the amount of greenhouse gas emissions.
- It can improve overall system efficiency, operating the alternating current system with unity power factor.
- High reliability and power quality can be achieved by applying the FREEDM systems
- There are many benefits that electric distribution networks can get by integrating this system including:

- It provides real-time monitoring and control
- It provides a resiliency of the microgrid
- Reduce peak demand and energy demand
- Minimize the fault impact on the system
- Reduced operation and maintenance costs

The world's electric energy demand will be doubled by 2050 and the carbon emissions need to be halved by 2050. That's what's called "The energy dilemma". The potential of FREEDM systems mentioned above could help with energy dilemma in developing countries as well as developed industrial countries which is hard to solve without a flexible system that allow integration of various types of renewable energy resources efficiently while maintaining its stability, availability and reliability, all those conditions are met with using FREEDM systems at any scale.

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