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Title:

Design and Implementation of Adaptive Directional Over-current Relay for Smart Micro Grid

Presented by:

- **DERRAR Anes Hani**
- **LEBANNE Sid Ahmed**

Supervisor:

- **Pr.BENTARZI Hamid**

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Abstract

This report details the design and implementation of an Adaptive Directional Over-Current Relay for smart micro-grids, using LabVIEW software and an Arduino Uno microcontroller. The aim is to enhance micro-grid protection and reliability, allowing operation both independently (islanded mode) or in conjunction with the main power grid (connected grid mode).

The relay system features an over-current detection capability to initiate protective actions against excessive current, and a directional feature based on symmetrical components. This directional function ensures the relay responds only to faults or abnormal conditions within a specific zone, improving protection accuracy.

A key innovation is the adaptive feature, enabling the relay to adjust its settings dynamically in response to changing power system conditions. This adaptability is essential for micro-grids with variable renewable energy sources like solar panels and wind turbines, ensuring optimal performance in both islanded and connected modes.

The report covers the design methodology, implementation, and testing of the relay, highlighting the practical use of LabVIEW for control algorithms and the Arduino Uno for hardware interfacing. Experimental results and simulations validate the system's effectiveness, offering a robust solution for enhancing the safety and efficiency of modern micro-grids.

Dedication

To our parents, for always believing in us. To our families, whose unwavering support and love have been our greatest source of strength. To our friends, who shared the journey with us. To our advisor, for his invaluable guidance, patience, and expertise. And to all those who have inspired and supported us along the way, this work is dedicated with heartfelt gratitude.

Acknowledgment

First of all , we want to express our gratitude to Allah the almighty the most merciful for blessing us, and giving us the courage and strength to accomplish this project successfully despite all the difficulties. we would like to express our deepest gratitude to our teacher and supervisor Pr. BENTARZI Hamid for his guidance and patience throughout this journey. Additionally , we are grateful to Dr.Ouadi Abderrahmane for his time and kindness , to our friends for their help whenever we faced difficulties.

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List of Abbreviations

RES	Renewable Energy Sources
SMG	Smart Micro Grid
PV	Photovoltaic
MG	Micro Grid
DG	Distributed Generators
DER	Distributed Generation Resources
EMS	Energy Management System
SOC	State of Charge
AC	Alternating Current
DC	Direct Current
IDM	Islanding Detection Technique
MPPT	Maximum Power Point Tracking
MGCC	Microgrid Central Controller
VTs	Voltage Transformers
RERs	Renewable Energy Resources
HATS	Hybrid Automated Transfer Switch
ESS	Energy Storage Systems
IDMT	Inverse Definite Minimum Time
CTs	Current Transformers
RMS	Root Mean Square
RMU	Ring Main Unit
MCM	Micro-grid Communication Medium
SCC	Signal Conditioning Circuit
VI	LabView
CB	Circuit Breaker

General Introduction

Micro smart grids are a significant innovation in electrical power systems, offering sustainable and resilient energy solutions. These small-scale, localized networks can operate independently or in conjunction with the main power grid, integrating renewable energy technologies like solar panels and wind turbines. Energy storage systems are also used to ensure stable power supply.

The growing adoption of microgrids is driven by their potential to enhance energy security, improve efficiency, and reduce greenhouse gas emissions. However, the dynamic and decentralized nature of these systems poses significant challenges in terms of protection and reliability. To ensure the stability and safety of microgrids, sophisticated protection mechanisms are required.

A critical component in microgrid protection is the relay system, which includes overcurrent protection to detect excessive current flows and initiate protective actions to prevent equipment damage and ensure safety. Directional relays are employed to respond selectively to faults occurring in specific zones, while adaptive relays add an intelligent layer to the protection scheme, allowing the system to adjust its settings and operational characteristics based on real-time conditions and the dynamic nature of the power grid.

Advanced simulation tools such as Simulink and LabVIEW are employed to address these challenges. Simulink allows for detailed analysis and optimization of microgrid components and control strategies, while LabVIEW facilitates the development of comprehensive test scenarios and real-time monitoring of relay performance. This thesis aims to explore the comprehensive framework of microgrid protection, focusing on the role of adaptive relay systems in enhancing the reliability and resilience of these energy networks.

Chapter 1

Smart Micro Grid

1.1. Introduction

The electrical grid evolved from a centralized system in 1896 to a highly interconnected system in the 20th century. By the 1960s, developed world electric grids were large, developed, and highly interconnected. Large coal-, gas-, and oil-fired power plants were strategically positioned near fossil fuel reserves, transportation routes, ports, or rail systems. Hydroelectric dams in mountainous regions also impacted the grid's structure. Nuclear power facilities were located where cooling water was available. Fossil-fired power plants were moved as far away from population centers as economically possible. Only remote rural areas remained "off-grid" by the late 1960s, when most people in developed nations were connected to the electricity system. By facilitating the efficient and dependable use of the resources, optimization techniques help to offset the cost of a microgrid.[1], [2].

1.2. SMART GRID Definition

The term "smart grid" describes the next-generation electrical grid that utilizes advanced technologies and information technology. [3]

A smart grid is a technology that allows electric utility companies and customers to communicate in both directions. In order to deliver the most efficient electric network operations, electric power companies obtain consumer information in a smart grid system. Smart grids allow for the efficient operation of power plants as well as the control of distributed energy, including renewable energy sources and power consumption. Installing an intelligent meter, or smart meter, makes it much easier to monitor energy use and can even assist cut down on carbon dioxide emissions for consumers, particularly homes.[3]

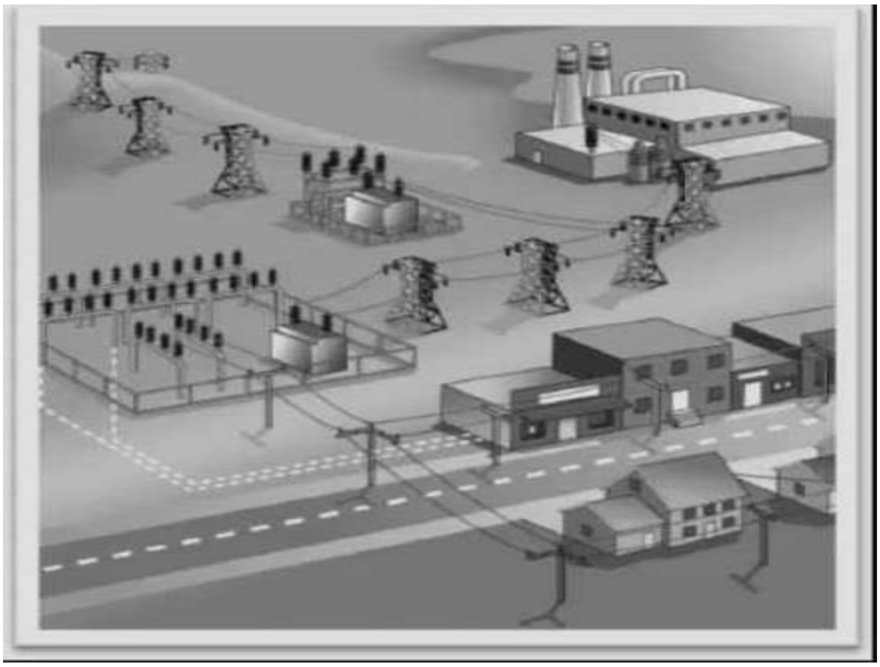


Fig 1.1: *The Main Grid Distribution Network [3]*

A smart grid is an updated electrical system that integrates data, computational intelligence, and two-way cyber-secure communication technologies to power the energy system from power generation to end-user consumption[4],[5].

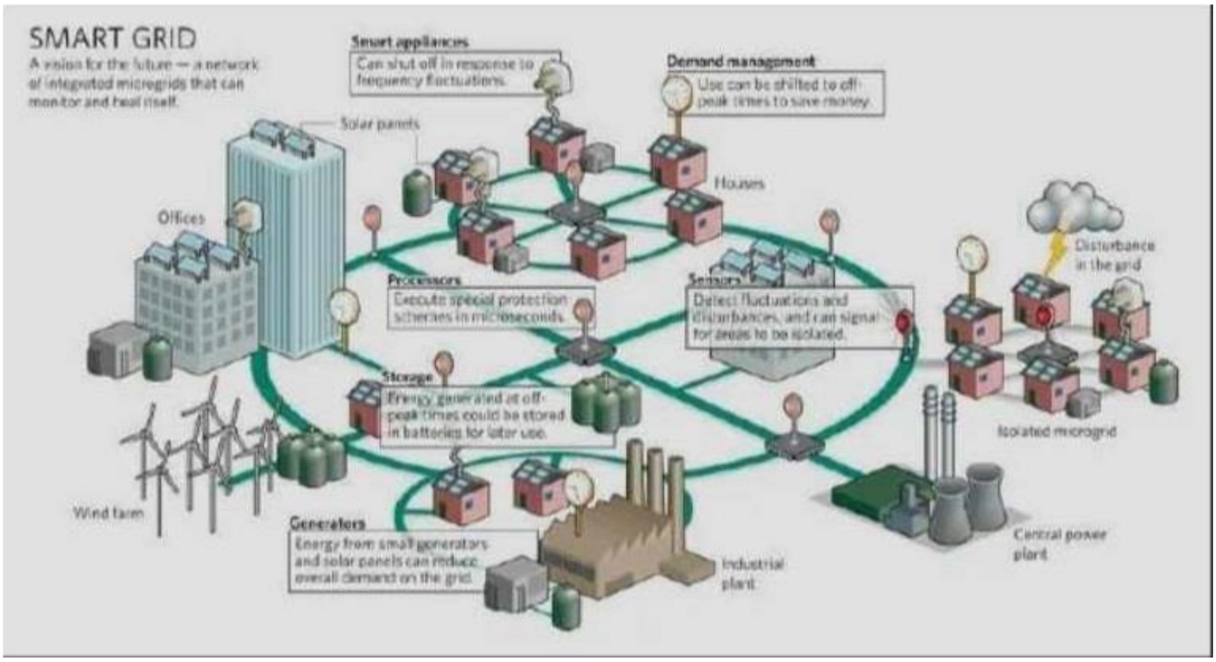


Fig 1.2: *Overview of Smart Grid[3]*

1.3. Features of the smart grid

The smart grid is an amalgam of all the proposed and current solutions to issues related to the supply of power. The large number of elements leads to a wide range of competing taxonomies and a lack of agreement on a universal definition. Nonetheless, this is one possible grouping.[3]

1.3.1. Reliability

The smart grid will include technologies that enhance fault detection and enable network self-healing without the need for technician involvement. As a result, there will be a more consistent supply of electricity and less susceptibility to outside threats or natural disasters.

1.3.2. Flexibility in network topology

The distributed generation from photovoltaic panels on building roofs, fuel cells, charging to and from electric car batteries, wind turbines, pumped hydroelectric power, and other sources will all be possible with next-generation transmission and distribution infrastructure because it will be better equipped to handle potential bi-direction energy flows.

1.3.3. Efficiency

The implementation of smart grid technology is expected to yield numerous benefits, chief among them the enhancement of energy infrastructure efficiency through demand-side management.

1.3.4. Load adjustment

The electricity grid's total load can fluctuate significantly over time, resulting in a fluctuating average power usage. Smart grids can alert individual television sets or larger customers to reduce load, either constantly or temporarily. Mathematical prediction techniques can forecast the number of standby generators needed for a given failure rate. Adding more standby generators could lower the failure rate in conventional grids.

1.3.5. Peak curtailment/leveling and time of use pricing

Smart devices in homes and businesses use communications and metering technologies to monitor energy demand and reduce usage during high-cost periods.

1.3.6. Sustainability

The smart grid's flexibility enables higher renewable energy penetration, even without energy storage, as current network architecture often fails to support dispersed feed-in points and local distribution.

1.3.7. Market-enabling

The smart grid enables efficient communication of energy prices, enhancing operational strategies. It allows strategic use of energy, reducing peak costs for critical loads. Generator flexibility allows for maximum profit, unlike inflexible generators with varying tariffs.

1.3.8. Demand response support

Demand response support in smart meter architectures helps smooth out surges in demand, reducing energy costs, equipment wear, and the need for reserve generators. However, past systems have faced latency issues, allowing up to 24 hours for data flow.

1.3.9. Platform for advanced services

Distributed computers, sensors, and strong communication enhance power transmission efficiency, safety, and enable new services like power-shutting, emergency alarms, and fire monitoring.

1.3.10. Integrated communications

The way that modern communications have evolved over time varies in how modems are used to gather data. Demand response, distribution automation, energy management systems, SCADA, wireless mesh networks, power-line carrier communications, and fiber optics all require improvement.

1.3.11. Sensing and measurement

Grid stability evaluation, equipment health monitoring, energy theft prevention, and management techniques are crucial tasks. Technologies like microprocessor meters, smart meters, monitoring systems, dynamic line rating, electromagnetic signature analysis, time-of-use tools, digital protective relays, and backscatter radio technology are used.

1.3.12. Smart meters

Real-time recording digital meters take the place of traditional mechanical meters in a smart grid. Like Advanced Metering Infrastructure meters, smart meters offer a communication link from power plants to smart sockets and other devices that can be connected to the smart grid. During periods of peak demand, these devices can be configured by the user to shut down.

1.3.13. Phasor measurement units

High-speed PMUs in power networks can check power quality and react automatically. Phasors represent alternating current waveforms, and automated systems can improve power system management by reacting quickly and dynamically. A wide-area measuring system (WAMS) offers real-time monitoring on regional and national levels.

1.3.14. Advanced components

Grids' basic capabilities and features are evolving because of advancements in superconductivity, fault tolerance, storage, power electronics, and diagnostics components.

1.4. Conservation of energy in a micro smart grid

Energy conservation in a micro smart grid refers to the application of technology and tactics designed to reduce energy waste, maximize energy use, and encourage effective energy management in the microgrid. In a micro smart grid, energy conservation can be accomplished in the following ways.[3]:

- Demand Response Programs
- Energy Storage Systems
- Smart Metering and Monitoring
- Efficient Energy Distribution
- Renewable Energy Integration
- Microgrid Optimization Algorithms

1.5. The Energy Management System (EMS)

The Energy Management System (EMS) manages energy consumption by determining when to produce and distribute heat and electricity based on load profiles, meteorological conditions, and available resources. It also advises on investment planning for distributed energy resources, ensuring high power quality and cost-effectiveness. The primary goal is to create a financially viable microgrid using battery banks for energy conservation.[6]

1.5.1. State Of Charge (SOC)

The following relation can be used to compute the battery's state of charge (SOC) throughout the charging process.

$$SOC(t+1) = SOC_t\,(1-\delta_t) + (I_{tES},c\Delta t \eta c/C_{ES}) \tag{1.1}$$

where

δt = The hourly self-discharge rate

C_{ES} = Capacity at the battery’s ambient temperature (Ah)

$I_{tES,c}$ = The charging current at time *t (A)*

Δt= The energy management time step (min)

SOCt= Battery State of charge

η_c = the energy conversion efficiency.

Provided that the hybrid system's power output surpasses the power required for the load, the charging current $I_{tES,c}$ is

$$I_{tES,c} = P_{tExtra}/V_{tES} \tag{1.2}$$

Where $P_{tExtra} = (P_{tHydro} + P_{tDiesel} + P_{tPV}) - P_{tdemand}$ (1.3)

V_{tES} = Battery terminal voltage

The charged quantity of the battery is subject to the following constraints:

$$P_{Extra} \leq \dot{P}_{ES,C} \tag{1.4}$$

$\dot{P}_{ES,C}$= Maximum instantaneous power of charge.

$$SOC_{(t+1)} \leq SOC_{Max} \tag{1.5}$$

If

$$I_t^{ES,e} \leq \max\left\{0, min\left[I^{ES}, \frac{C^{ES}.(SOCmax-SOCt)}{\Delta t}\right]\right\} \tag{1.6}$$

$$V_{tES} \leq V_{float} \tag{1.7}$$

V_{float} = Floating charge of the battery.

SOC_{Max}= The maximum state of charge

When the power generated by the hybrid system cannot meet the load demand completely and the necessary conditions have been satisfied, as a result the discharge process, *SOC* can be computed as follows [6]: *(Marzband, Sumper, Chindris, 2012)*

$SOC_{(t+1)} = SOC_t\ (1 - \delta_t) - (I_{tES,dt} * \Delta t) / C_{ES}$ (1.8)

Where,

$I_{tES,d}$= The discharging current at time *t (A)*

$I_{tES,d} = (P_{tStg}) / V_{tES}$ (1.9)

P_{tStg} = Power shortage

$= P_{tn} - (P_{thydro} + P_{tDiesel} + P_{tPV})$, (1.10)

where P_{tn} = Total demand at each time step

$P_{tES,d}$ = Battery power during discharge

$I_{tES,d}$ = Maximum of continuous discharge current

Meanwhile, the discharged quantity of the battery is subject to the following constraints:

$P^{Stg} \leq P^{ES,d}$ (1.11)

$\dot{P}^{ES,d}$= Maximum instantaneous power of discharge.

$SOC_{t+1} \geq SOC_{MIN}$ (1.12)

If

$$I_t^{ES,e} \geq \max\left\{0, min\left[I^{ES}, \frac{C^{ES}.(SOCmax - SOCt)}{\Delta t}\right]\right\} \qquad (1.13)$$

$V^{ES}_t \geq V_{cuttoff}$ (1.14)

Where

V_{cutoff}= Voltage at which a battery is fully discharged, beyond which further discharge could cause harm.

1.5.2. Floating Charge Voltage of Battery

A battery's terminal voltage is measured in volts, and the voltage drop across the battery's internal resistance is computed as follows. *(Marzband, Sumper, Chindris, 2012).*

For the charging mode, $V^{ES}_t = V_{Oc}^{ES} + I^{ES,c}_t * R_t^{Es}$ (1.15)

For the discharging mode, $VESt = V_{Oc}^{ES} + I^{ES,d}_t * R_t^{Es}$ (1.16)

Both quantities of V_{oc}^{ES} and R_t^{ES} with changing of SOC_t will be changed and their characteristics curves can be achieved in the manual of the used battery and by using interpolation method, the value of these quantities at the moment can be calculated [6]

(Marzband, Sumper, Chindris, 2012)

1.6. Classification of Micro Grid

Based on the features of the electricity that they introduce into a distribution network, microgrids are divided into three groups, which are briefly explained in the subsections that follow.[7]

1.6.1. Ac Micro Grid

In a distribution network, AC microgrids stand in for the ac power supply. They do not require any particular arrangement, such as converters and their control methods, and can be readily connected to an existing grid utility. AC microgrids have been the focus of much research since the notion first emerged, with numerous articles about their operational and control strategies appearing in the literature [8][9]. Single-phase or three-phase distribution systems with or without neutral point lines comprise the three main categories of AC microgrid distribution system [7]. The figure 1.3 shows the scheme of ac micro grid

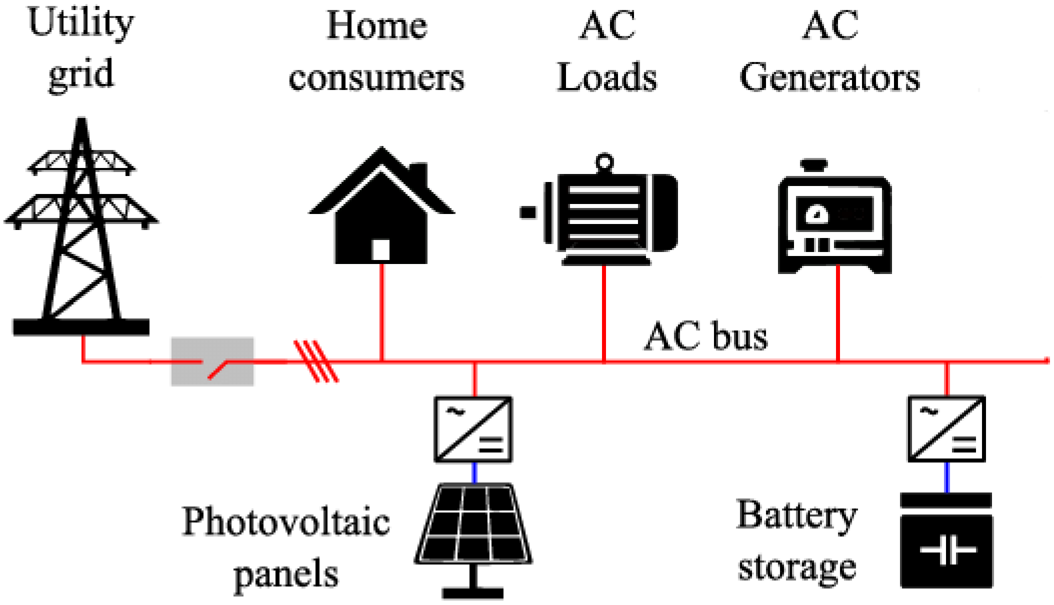


Fig 1.3: *ACMicro Grid Scheme[10]*

1.6.2. DC Micro Grid

The widespread use of contemporary electronic devices and the accessibility of sustainable DC sources (fuel cells and solar panels) have given rise to the idea of a DC microgrid, which offers improved efficiency and short circuit protection. Compared to AC microgrids, these microgrids are more efficient and require less conversion work when applying DC loads [7]. The figure 1.4 shows the design of DC micro grid

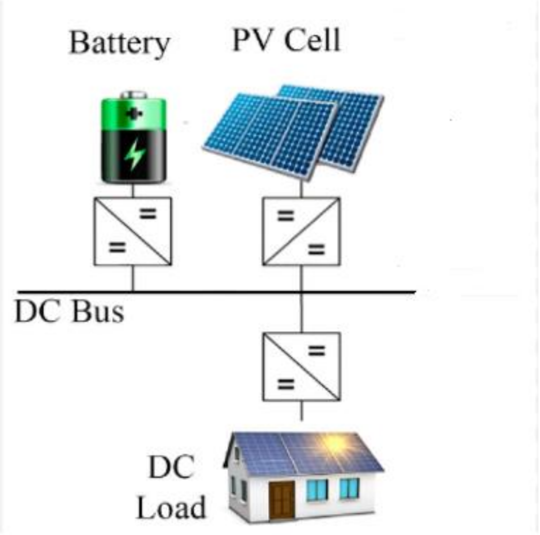


Fig 1.4: *Dc micro grid Scheme[11]*

1.6.3. Difference Between AC Micro Grid and Dc Micro Grid

The difference between AC and DC micro grid can be cited in the following table :

Table 1.1: *Difference Between AC and DC Micro Grid [7]*

Factors	AC	DC
Conversion efficiency	Multiple energy conversions reduce efficiency	Less conversion processes increase efficiency
Transmission efficiency	Continuous reactive current loss reduces efficiency	Absence of reactive components increases efficiency
Stability	Affected by external disturbances	Free from external effects
Synchronization	Synchronization required	No synchronization issues
Power supply reliability	Supply can be affected during seamless transfer	Power supply generally reliable
Microgrid controls	Control process complex due to frequency	Simple control approach
Protection system	Simple, cheap and mature protection schemes	Complex, costly and immature protection components
Suitability	AC loads	DC loads
Calculation methods	Complex numbers involved	Only real numbers used

:

1.6.4. Hybrid Micro Grid

An AC and DC electricity distribution network with a microgrid central controller (MGCC) is what makes up a hybrid microgrid. By building hybrid microgrids, one can improve the network's overall efficiency by minimizing conversion stages, cutting back on interface devices, boosting reliability, and lowering energy costs. With this kind of arrangement, a distribution network can receive both AC and DC power, and customers can consume electricity based on their need (AC or DC).[7]

The figure 1.5 shows the design of hybrid micro grid.

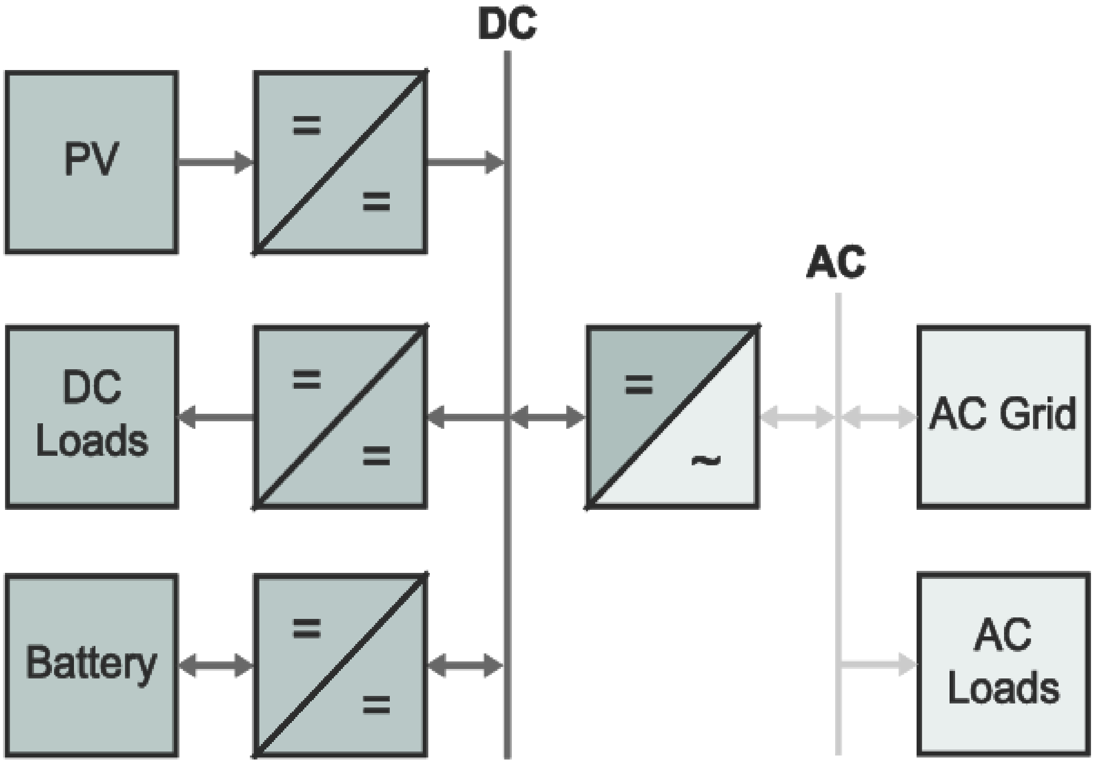


Fig 1.5: *Hybrid Micro Grid Scheme[12]*

1.7. Advantages and Disadvantages of Microgrids

The advantages and disadvantages of microgrids by[3]

1.7.1. Advantages of Microgrids

Microgrids can provide several advantages, including:

1. Improved power reliability
2. Enhanced energy security
3. Increased energy efficiency
4. Improved power quality
5. Environmental benefits
6. Improved market efficiency.

1.7.2. Disadvantages of Microgrids

However, there are also some potential disadvantages to consider with microgrids:

1. High initial costs
2. Technical difficulties
3. Limited scale
4. Complexity
5. Regulation
6. Standardization issues

1.8. Technical Challenges and Possible Solutions

1.8.1. Challenges

Some technical challenges are faced on implementing smart grid which are [3]:

1) Operation

Operation of electric system requires a perfect balance between electricity generation and load at all times.

2) Compatibility

Mixed-generate generators consist of various components, causing compatibility issues due to differences in generation potential, controllability, communication restrictions, and operational cost.

3) Integration of RERs

RERs' are unpredictable, unstable, and climate-dependent nature poses significant challenges to grid integration, potentially causing instability and potential distribution system congestion.

4) Protection

The most difficult technical issue of DGs integrated into MG is system protection. For MGs working in either grid-connected or islanded mode, the protection system must be robust enough to respond to all forms of faults. The protection system should be capable of quickly disconnecting the MG from the main grid during any abnormality, ensuring the DGs, lines, and loads' protection. The following factors should be considered for the protection issues:

1. Integration of distributed generators with the distribution system

2. Current fault level fluctuations

3. Unexpected relay trips

4. Discoordination or reduced position of relays

5. Accidental disconnections.

Thus, the protection strategies must be up to the mark to have an improved and continuous supply. Fault current detection, isolation from the grid network, and an automated re-coordination must all be done with smart devices. Since the fault currents’ magnitudes depend on the MGs’ operating mode, they can differ drastically between grid-connected and standalone modes of operations.

1.8.2. Possible Solutions

Some potential solution for the technical issues facing MGs that have been put out in the literature include the following.[3]

- In order to address stability and reliability issues while incorporating RERs into MGs, Shuai and colleagues researched MG stability classifications and analysis approaches.

- To guard against fault currents, external protection devices such as fault current limiters, quick static switches, and ESS are utilized.

- Installing an intelligent hybrid automated transfer switch (HATS) in conjunction with the islanding detection technique (IDM) is recommended by Papadimitrious et al. The condition and modes of operation of MGs can be identified and controlled using this way.

Chapter2

Protective Relays

2.1. Introduction

Power system protection is one of the trickiest areas of electrical engineering, requiring not only a solid grasp of the various parts of a power system and how they behave, but also a thorough understanding and analysis of the anomalous conditions and potential failures that could arise in any one of the system's components. In addition, the swift evolution of relay principles and technologies are other elements that force professionals in the sector to constantly update and broaden their knowledge.[13]

On a power system, short circuits and other anomalous occurrences frequently happen. If appropriate protective relays and circuit breakers are not supplied for the protection of each segment of the power system, the heavy current associated with short circuits is likely to cause damage to the equipment. To separate the unhealthy portions of the power system from the healthy portions, a protective system consists of circuit breakers, transducers (CTs and VTs), and protective relays. A protective relay's job is to find and identify a defect, then instruct the circuit breaker to cut off the problematic component.[14]

Transmission and distribution networks are both experiencing SHORTFALLS in the protection system's performance. These are caused by a variety of things, including as severe wide area disturbances, varying operational conditions, and growing penetration of distributed generation[15][16].A functional smart grid depends on maintaining appropriate protection performance since these schemes guarantee the dependable and secure operation of the main system. In response to numerous of these variables, adaptive protection—whether through settings groups or more sophisticated setting computation techniques—has been suggested as a way to improve the effectiveness of protection methods.[17]

2.2. Definition

A relay is an electrical device designed to respond to specific input conditions, initiating contact operation or altering control circuits. It may consist of multiple units attuned to a specified input, achieving desired performance characteristics. Inputs can be electrical, mechanical, thermal, or blends.

Protective relaying is essential in electric power systems to disconnect problematic areas during malfunctions, maintaining system operation and servicing.[18]

Short circuits, or faults, can occur from various natural events and accidents. Protective relays and related mechanisms are essential in power systems to isolate issues and allow unaffected components to continue operating. Over the past century, these relays have undergone significant modifications, leading to improvements in both technical and financial aspects. This study provides insight into the evolution of protective relays and predicts potential developments and trends in this field.[18][19].

2.3. Directional relay

2.3.1. Definition

A directional relay is a type of protective relay that operates based on the direction of the power flow in an electrical circuit. It compares the direction of the fault current to a predetermined reference direction and, if the fault current is in the opposite direction of the reference, the relay operates to trip the appropriate circuit breaker. This functionality helps to isolate the faulty section of the network, minimizing disruptions and ensuring system stability. [20]

Three different types of parameters are required for this kind of protection: voltage, current, and the phase angle between the two previous mentioned quantities .[21]

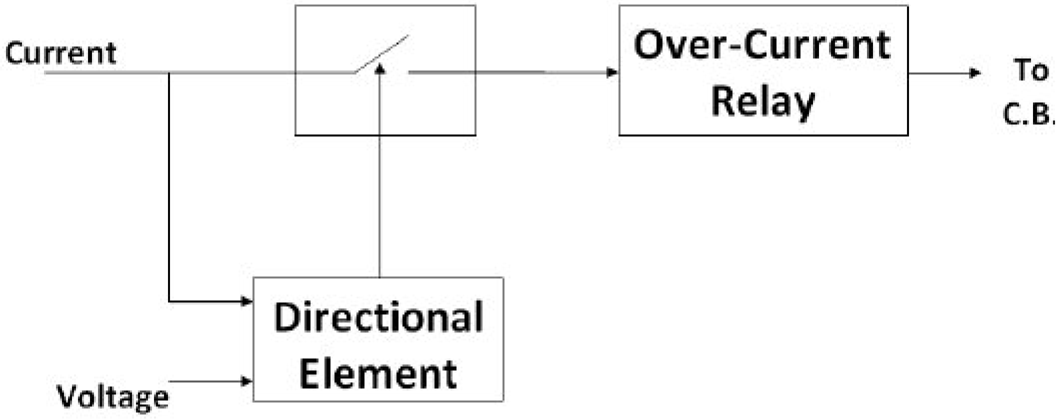


Fig2.1 : *Directional relay principle[22]*

2.3.2. Application of directional relay

2.3.2.1. Feeder Protection:

Directional relays are used to protect radial and parallel feeders from faults such as short circuits, ground faults, and overloads. They help to quickly isolate the faulty section of the feeder, preventing damage to equipment and minimizing service disruptions.

2.3.2.2. Transformer Protection:

Directional relays are employed in transformer protection schemes to guard against internal faults and external faults on connected transmission lines. They work in conjunction with other protective devices, such as differential relays, to provide comprehensive protection to transformers.

2.3.2.3. Generator Protection:

In power generation systems, directional relays are used to protect generators from faults that may occur within the generator or on connected transmission lines. They ensure that faults are quickly isolated to prevent damage to the generator and maintain the stability of the power system.

2.3.2.4. Busbar Protection:

Directional relays can also be used in busbar protection schemes to detect and isolate faults within the busbar zone. They help to maintain the integrity of the power system by quickly disconnecting the faulty section from the rest of the network. [20]

2.3.3. Fundamental of Directional Relay

The relay uses the memorized source voltage V and compares it with the replica current IZ (the actual current I shifted by the impedance angle) to determine the direction of a fault. The replica current IZ is derived from the actual current I flowing in the system. To create the replica current, I is multiplied by the system impedance Z. This multiplication shifts the phase of I by the impedance angle.[21]

The phase relationship between these two phasors (represented by the cosine of their angle difference) helps in identifying whether the fault is in the forward or reverse direction. If V and IZ are in phase, the fault is in the forward direction. If V and IZ are out of phase, the fault is in the reverse direction.[21]

This is described in the equation 2.1 bellow

$$\begin{gathered}\mathrm{COS}(\angle V - \angle IZ) > 0 \text{ (forward fault)} \\ \mathrm{COS}(\angle V - \angle IZ) < 0 \text{ (reversed fault)}\end{gathered} \qquad (2.1)[21]$$

2.3.4. Advantages of Directional Relays

2.3.4.1. Selectivity:

Their ability to operate based on the direction of the fault current allows for improved selectivity in the protection scheme, minimizing the impact of faults on the power system.

2.3.4.2. Coordination:

Directional relays can be easily coordinated with other protective devices in the system, such as non-directional relays and circuit breakers, to provide comprehensive protection against various types of faults.

2.3.4.3. Reliability:

Due to their simple operating principle and well-established design, directional relays are considered highly reliable in detecting and isolating faults within the power system.

The advantages of directional relay are taken from [20]

2.4. Overcurrent relay

2.4.1. Definition

A form of protective relay called an "Over-Current Relay" operates whenever the load current surpasses a predetermined threshold. [23]

The electrical faults include short circuits and overloading. Overcurrent relays can provide protection against all of these faults by detecting when the current exceeds a safe level and then either automatically disconnect the circuit or sending a signal to another device that will take action to protect the circuit. Ideally, this type of current relay consists of two main components: a sensing device and a control device. The sensing device is used to detect the current flowing through the circuit, while the control element determines the tripping current, usually based on user settings.[24]

2.4.2. Application of overcurrent relay

2.4.2.1. Circuit Protection:

Overcurrent relays are primarily employed to protect electrical circuits from damage caused by overloads and short circuits. When the current exceeds a predetermined threshold, the relay operates and trips the circuit breaker, disconnecting the faulty section.[25]

2.4.2.2. Transformer Protection:

Overcurrent relays are used to protect transformers from damage due to overloads and short circuits. They can be applied to both primary and secondary sides of transformers to ensure prompt disconnection in case of a fault. [25]

2.4.2.3. Motor Protection:

Overcurrent relays are crucial for safeguarding electric motors. They are installed in motor control centers or near the motor to trip the power supply in the event of an overload or short circuit, preventing damage to the motor. [25]

2.4.2.4. Feeder Protection:

Overcurrent relays are commonly used for the protection of feeders in distribution systems. They help isolate faulty sections quickly, minimizing the impact of faults on the rest of the distribution network**.**[25]

2.4.3. Advantages of overcurrent Relays

By rapidly cutting off the current source, overcurrent relays can aid in providing protection against electrical problems, which is one of their main benefits. This can lessen the chance of a fire and minimize equipment damage. Overcurrent relays also have the benefit of being more affordable than many other kinds of electrical protection devices due to their relative simplicity. The current relay is employed in a wide range of situations, including transmission line protection, motor current monitoring, and other uses. They can thus be used as adaptable protective devices in various power systems.**[25]**

2.4.4. Types of overcurrent relays

2.4.4.1. Instantaneous Overcurrent Relay

The first type of overcurrent relay is the instantaneous overcurrent relay. This type of relay is designed to protect against very high levels of current for a very short period of time (less than 0.1 seconds). These types of currents can be caused by faults in the system, such as a short circuit.[25]

The instantaneous overcurrent relay will have a very low time delay, meaning that it will trip or open the circuit as soon as the current is detected. This is important, as it can help to prevent damage to the electrical system by quickly removing the source of the overcurrent. Applications for these types of overcurrent relays include outgoing feeders, busbars, and transformers. In these applications, the instantaneous overcurrent relay can provide protection against faults that could otherwise cause extensive damage.[25]

The time-current characteristic curve of instantaneous relay is shown in Fig 2.2.

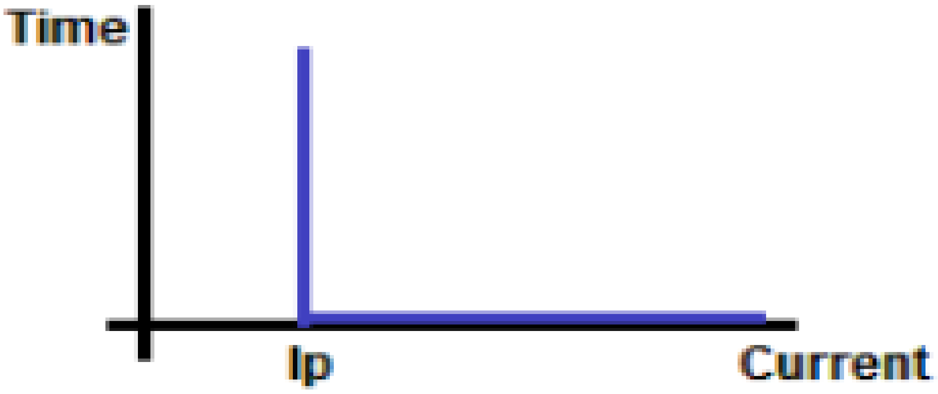


Fig2.2:*Typical time-current characteristic curve of instantaneous relay.[23]*

2.4.4.2. Definite Time Over-current Relay

When distance relays are the primary form of safety for a transmission line, this kind of overcurrent relay is employed as a backup. If the distance relay is unable to recognize a line fault the breaker cannot trip, the overcurrent relay will send a trip instruction to the breaker after a certain amount of time (t1). In this instance, the overcurrent relay is time-delayed by a defined amount of time that is marginally longer than the distance relay's typical running duration plus the time required for the breaker to operate [26].

Fig 2.3 bellow displays the time-current characteristic curve of the specific time over-current relays.

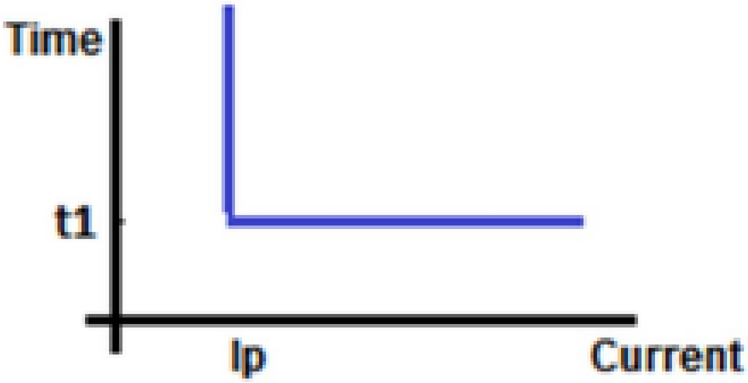


Fig2.3: Typical *Time-current Characteristics curve of definite time relay.[23]*

2.4.4.3. Inverse Time Overcurrent Relay

The third type of overcurrent relay is the inverse time overcurrent relay. Unlike the instantaneous overcurrent relay, the operating time is, as the name suggests, inversely proportional to the current magnitude. That means a high current will reduce the amount of time it takes for the relay to operate, while a lower current will result in a longer operating time, as long as 10 seconds. This is important, as it can help to prevent false trips when there is only a momentary surge of current.[25]

When it comes to application, these types of overcurrent relays are mostly used in distribution lines.

Very Inverse Time Overcurrent Relay

A very inverse time overcurrent relay will have a much greater change in the operating time as the current magnitude changes than the normal inverse time overcurrent relay. They are, therefore, well-suited for use in applications where the fault current is expected to be lower.[25]

Extremely Inverse Time Overcurrent Relay

An extremely inverse time overcurrent relay has the greatest change in operating time as the current magnitude changes of all the inverse time overcurrent relays. They are, therefore, much faster to respond to fault situations. These types of overcurrent relays are commonly used to prevent protecting cables, motors, transformers, and other equipment such as heaters and pumps from overheating.[25]

Long Time Inverse Overcurrent Relay

Based on its name, you can easily tell that the long-time inverse overcurrent relay has an extremely long operating time. In fact, it can take up to 60 seconds for this type of relay to operate. That being said, the long-time relay is not as sensitive as other types of overcurrent relays and is, therefore, mostly used in installations where there is a low risk of faults. These overcurrent relay types are mostly installed to protect against earth faults.[25]

2.4.4.4. Inverse Definite Minimum Time (IDMT) Over-current Relay

There is an inverted time characteristic for this relay. This indicates that the relationship between the relay operating time and the fault current is inverse. When the fault current increases the operating time will decrease. Depending on the necessary tripping time and the properties of other network-wide protection devices, the current/time tripping characteristics of IDMT relays may need to be adjusted. [23]

the mathematical descriptions of IDMT relays are represented with the following equation:

$$T=TMS*\frac{C}{(\frac{I}{Is})^{\alpha}-1} \qquad (2.2)[23]$$

T: Relay operation time.

C: Constant for relay characteristic.

Is: Current Set point.

I: Current Input to the relay.

α: Constant Representing Inverse Time Type ($\alpha > 0$).

TMS: Time Multiplier setting controls the relay tripping time.

The range of TMS is normally changed from 0.1 to 1

By varying in α and C we can obtain different curve for different types of the inverse time over-current relay as shown in figure 2.4 .The values for α and C for each curve are given in Table 2.1 below:

Table 2.1: *Definition of Standard Relay Characteristics[23]*

Relay Characteristic	**α**	**C**
Normal Inverse (NI)	0.02	0.14
Very Inverse (VI)	1	13.5
Extremely Inverse (EI)	2	80
Long Inverse (LI)	1	120

The time-current characteristic curve of the IDMT over-current relays is shown in figure 2.4 :

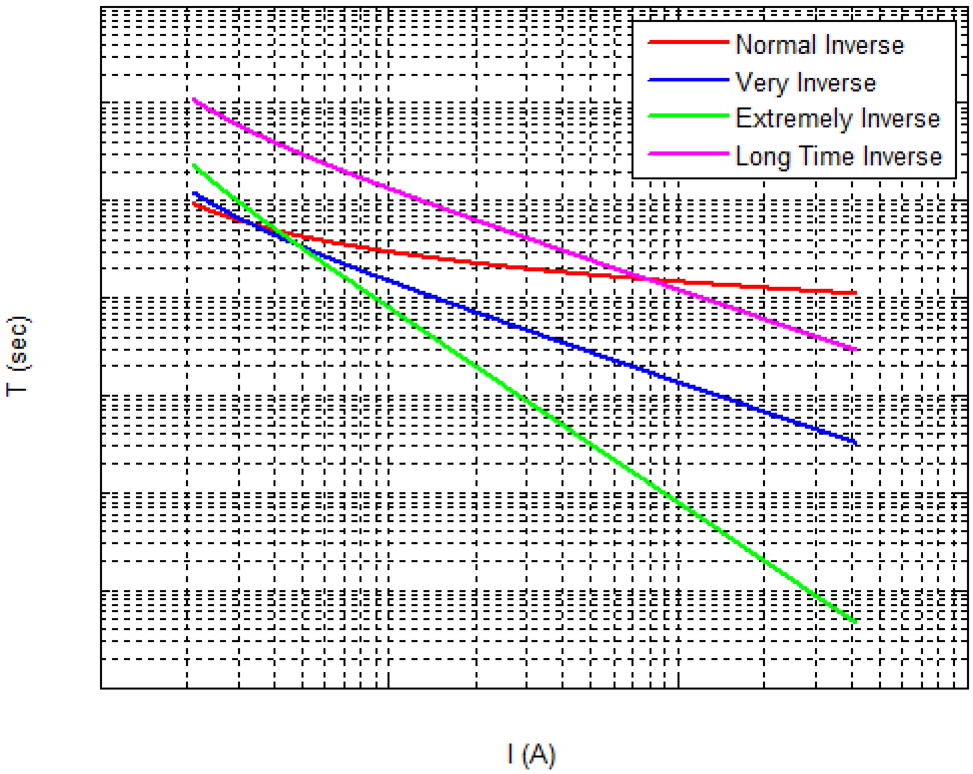


Fig2.4:*Time-current of IDMT Over Current Relaying Characteristics.[27]*

- Proposed modeling:

Figure 2.5 represents a proposed algorithm of an inverse time overcurrent relay with all its types (normal, very inverse, extremely inverse, long inverse). The protection algorithm starts by measuring RMS value of the current in the protected element, then it computes the current ratio (I/I_s), if it is more than 1 this means that the RMS value exceeds the set point.

An output tripping signal will be generated if the RMS value of the current exceeds the set point, the overcurrent relay will trip after exceeding the predetermined delay time calculated using the equation (2.2).

The algorithm requires current setpoint value, TMS and type of inverse characteristics to determine the operation time.

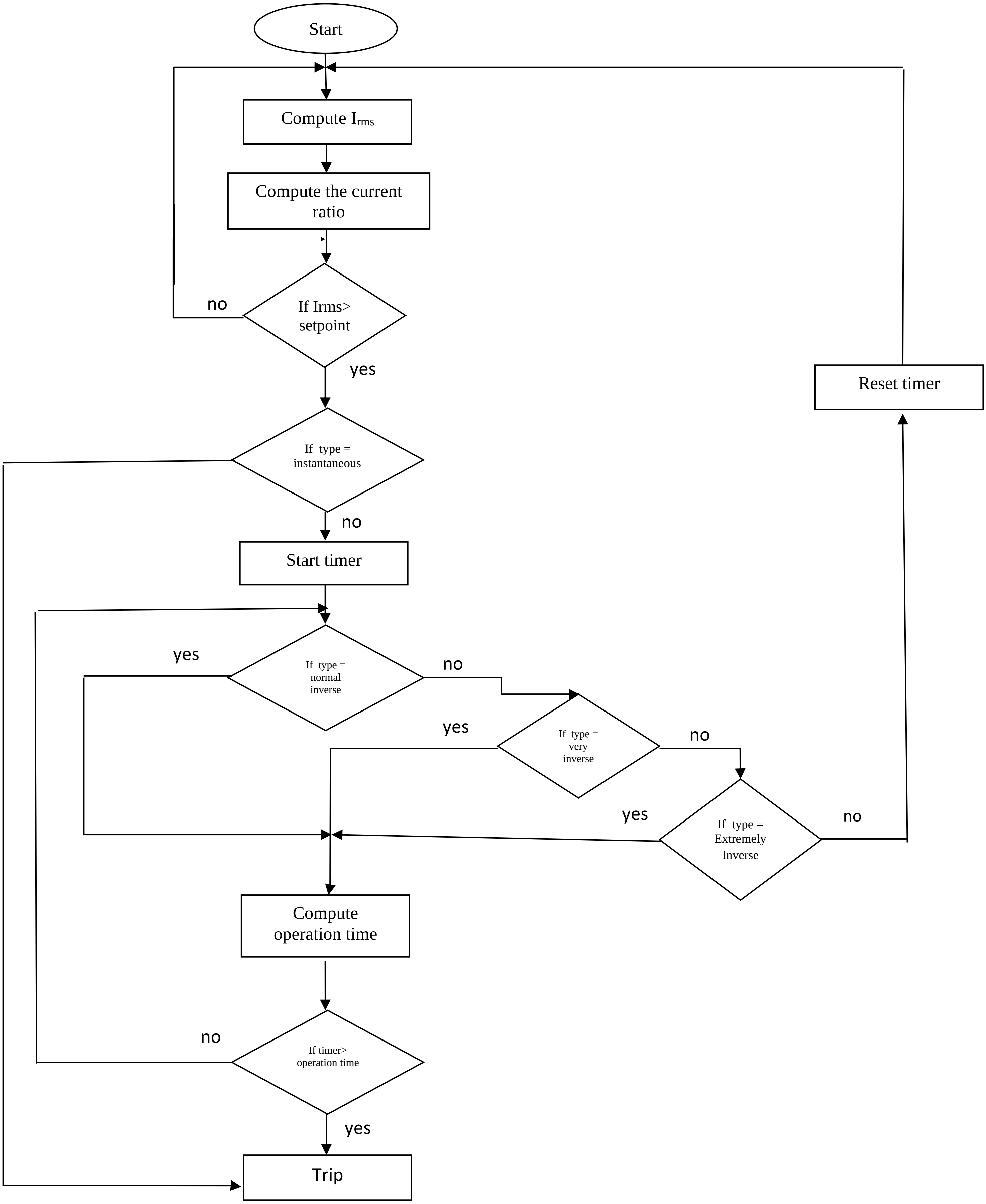


Fig 2.5: *Flow Chart of the Protection Algorithm of the Inverse Time Overcurrent Relay*

2.4.4.5. Directional Overcurrent Relay

Directional overcurrent relays are commonly used to protect against faults in a system where the current may flow in either direction. For example, they may be installed to respond to faults in a ring main system. Directional overcurrent relays are able to detect the direction of the current flow and will only operate when the current is flowing in a certain direction. This helps prevent unnecessary trips or circuit breaker operations in systems with several current paths or power sources [25].Based on its operation, the directional overcurrent relay is used for protection of circuits in these systems:

- Ring Main Unit (RMU)
- Radial Distribution System
- Generator Protection

2.5. Adaptive Protection

2.5.1. Definition

Because conventional relays have predetermined setup settings, it might be challenging to meet protection needs in power systems with changeable operating conditions. Adaptive protection offers a solution to this issue by adjusting its operational characteristics or setting parameters in response to changes in the power supply. "A protection philosophy which permits and seeks to make adjustments to various protection functions in order to make them more attuned to prevailing power system conditions" is how Horowitz, Phadke, and Thorp define adaptive protection.[28]

Adaptive Relaying allows for and attempts to automatically modify a variety of safeguards to better match them to the current state of the power system.[28]

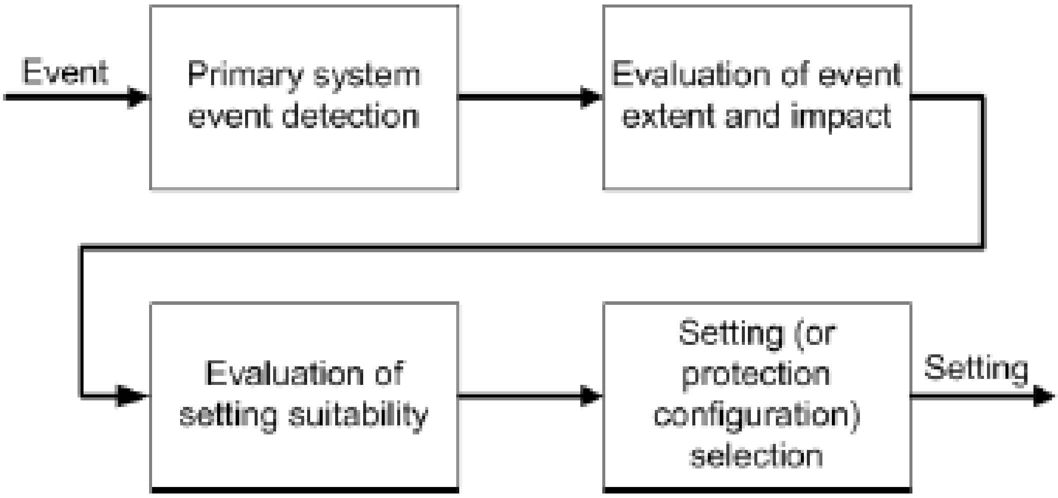


Fig 2.6:*Generic Adaptive Protection Scheme Operation [28]*

2.5.2. Settings and Schemes for Smart Micro Grid

2.5.2.1. Protection strategy for the grid connected mode of operation

The grid connected protection scheme involves continuous measurement of voltage and current of buses and feeders, sent to the Micro-grid Communication Medium (MCM) . When a fault occurs, the MCM detects it using a negative sequence component and initiates the protection algorithm. The MCM then determines the tripping time for the relay using the inverse definite time and over-current relay component. If a fault is detected, the MCM resets the protection algorithm and continues monitoring [29].

If the fault is cleared, the microgrid enters islanding mode and starts its reconnection process. If the fault is not cleared, the MCM shuts down the microgrid and restarts it from a black out. The main protection relay enhances the feeder protection relays.[29]

The flow chart for grid connected protection scheme is shown in Fig 2.7 (a)

2.5.2.2. Protection strategy for the islanded mode of operation

Microgrid operating in the islanded mode has a lower pickup value than the grid linked mode. The MCM monitors and restarts the protection algorithm upon fault detection [30]. The microgrid becomes unstable when the sequence current is negative because the MCM sends a trip command to the feeder CB [29].

A smart microgrid's black start measurement and battery detection procedure is an essential stage in guaranteeing the effectiveness and safety of the system and illustrating the potential of adaptive protection strategies. As a result, following fault clearance, the microgrid enters black start mode and goes through the reconnection procedure as depicted in the flow chart in Figure 2.7(b). By modifying the relay's operating mode in accordance with its mode of operation, the adaptive controller guarantees that the microgrid system is protected against all fault kinds.[29]

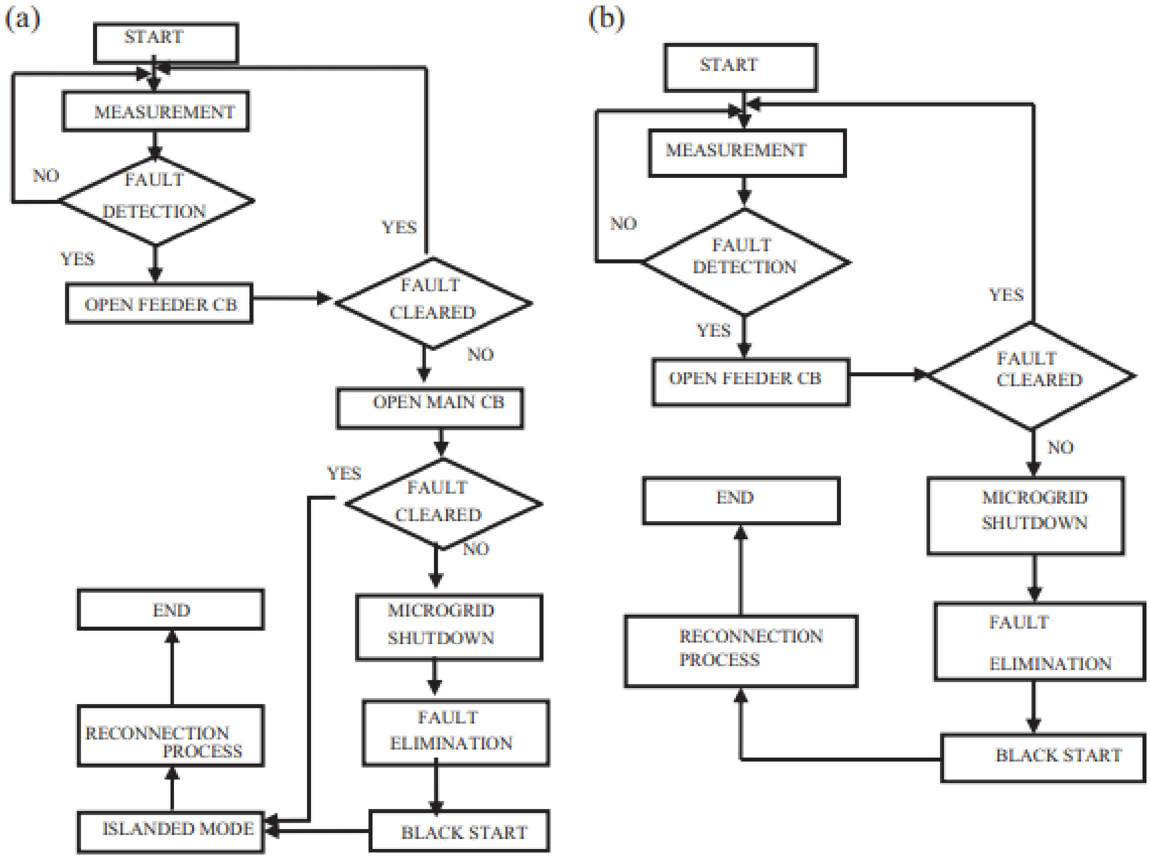


Fig2.7:*(a) Protection Scheme In Grid Connected Mode, (b) Protection Scheme In Islanded Mode of Operation.[29]*

Chapter 3

Simulation and Implementation

3.1. Introduction

This chapter represent the simulation of the smart micro grid using Matlab Simulink and the simulation of directional and overcurrent relay using LabView software. Also, the implementation of directional and overcurrent relay using Arduino uno and LabView software. The implementation part was carried out in the scientific research laboratory of the Institute of Electrical and Electronics Engineering and the University of Boumerdes under the supervision of Prof. Hamid Bentarzi.

3.2. Simulation of Relays Using LabVIEW

Relays can be used for many purposes with a single program environment by utilizing LabVIEW as a software tool development platform. An overcurrent relay of any kind can be selected by the user in LabVIEW using a string control. By manipulating virtual knobs within the LabVIEW software, we can effortlessly modify all parameters.

3.2.1. Block Diagram of Instantaneous Overcurrent Relay

The figure 3.9 illustrates a block diagram which work as a function of an instantaneous overcurrent relay.

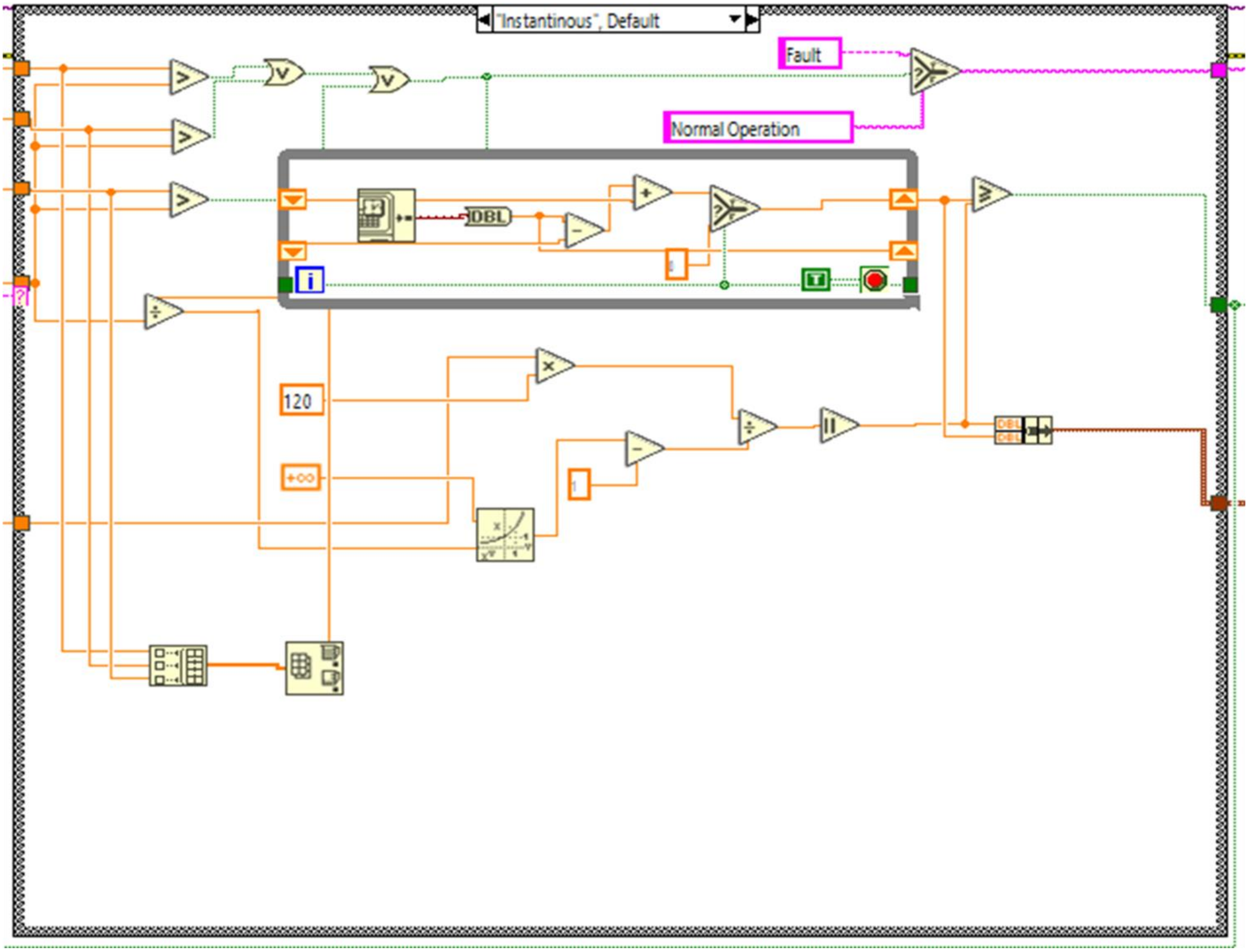


Fig. 3.1 : *Instantaneous Overcurrent Relay*

We can see that there is no time delay to execute the trip, once the input signal is higher than the reference, it will generate a trip signal.

The program is inside "if" statement which means that it asks the type of the relay before start working. The user can select any function as shown in figure 3.10.

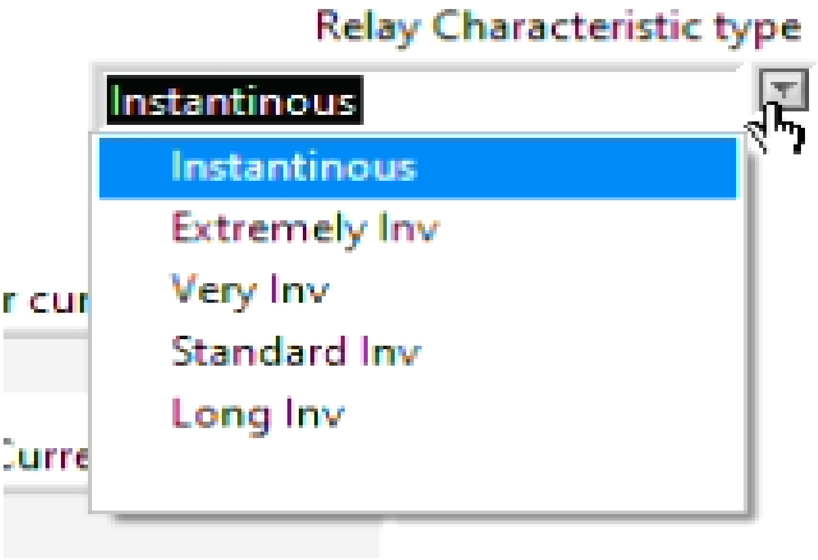


Fig. 3.2 :*Types of Overcurrent Relay*

3.2.2. Very Inverse Overcurrent Relay

The figure 3.11 show the block diagram of the very inverse overcurrent relay. Adding the time delay and changing in the parametersα and C as have seen in table 2.1

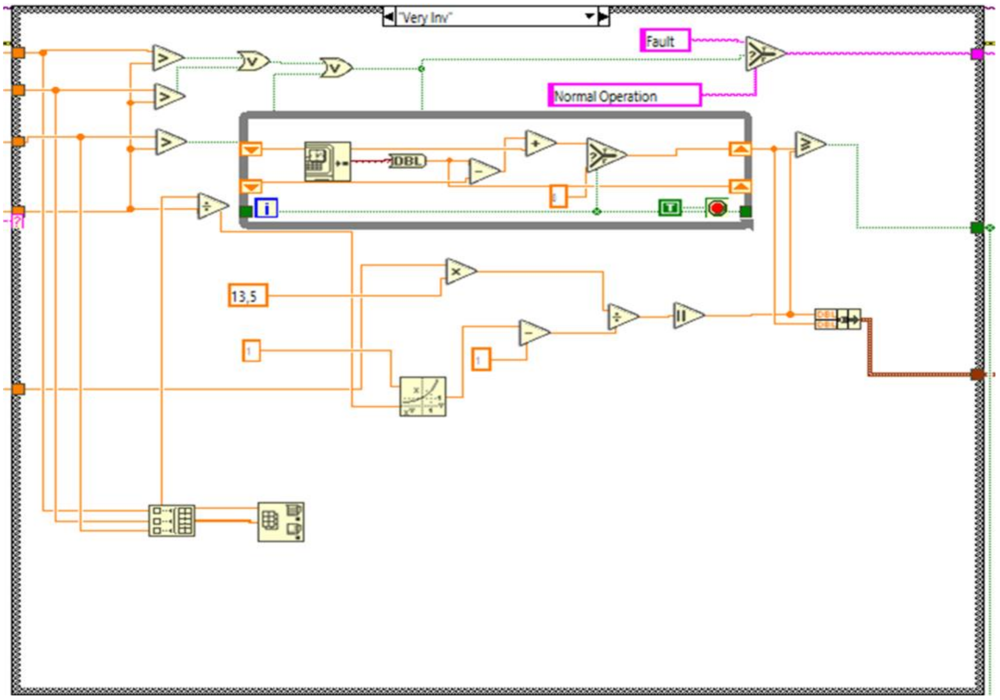


Fig. 3.3 :*very inverse overcurrent relay*

3.2.3. Standard Inverse Overcurrent Relay

The figure 3.12 show the block diagram of the standard (normal) inverse overcurrent relay . the same as the previous one only changing in the parametersα and C as have seen in table 2.1.

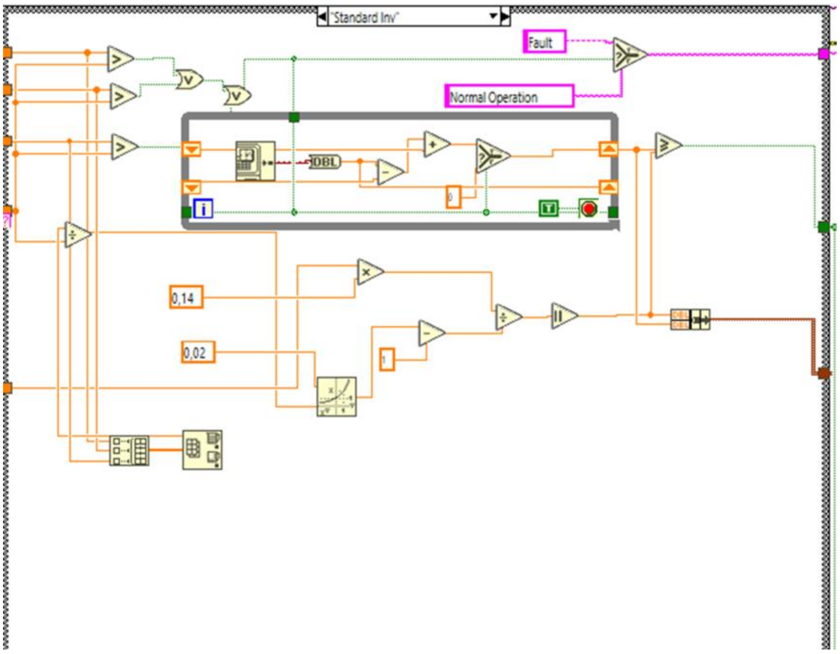


Fig. 3.4: *Standard Inverse Overcurrent Relay*

3.2.4. Long Inverse Overcurrent Relay

The figure 3.13describe the block diagram of the long inverse overcurrent relay.

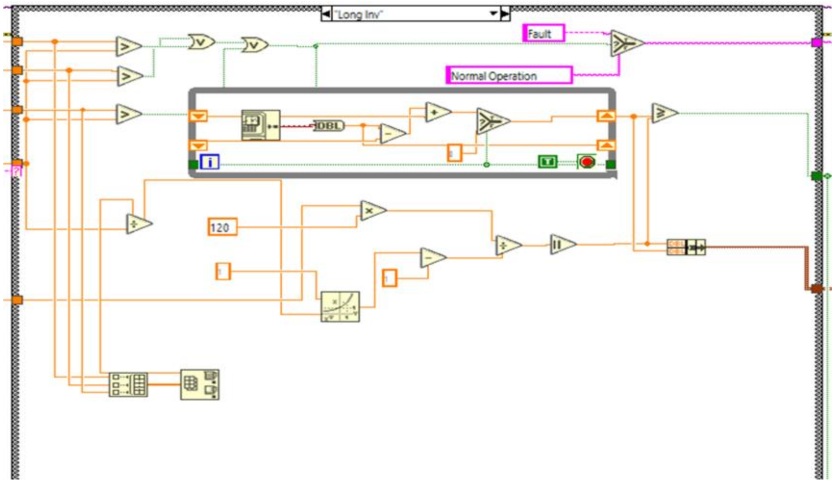


Fig. 3.5 : *Long Inverse Overcurrent Relay*

3.2.5. Extremely Inverse Overcurrent Relay

The figure below illustrates the extremely inverse overcurrent relay function.

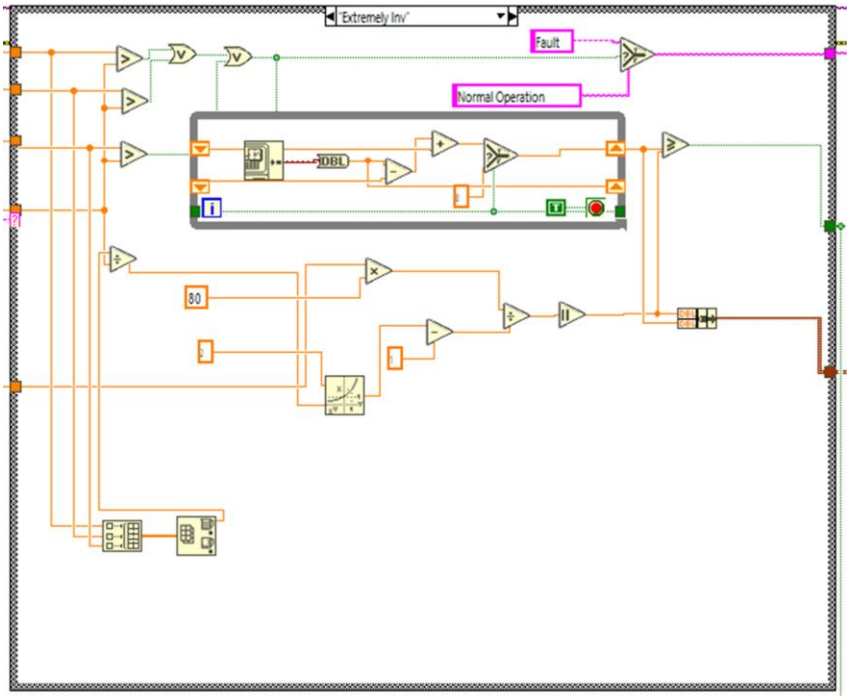


Fig. 3.6: *Extremely Inverse Overcurrent Relay*

3.2.6. Directional Protection

In addition of all this function, we merged the directional function based on the techniques mentioned previously, the fig 3.15 illustrates the directional element used in the simulation.

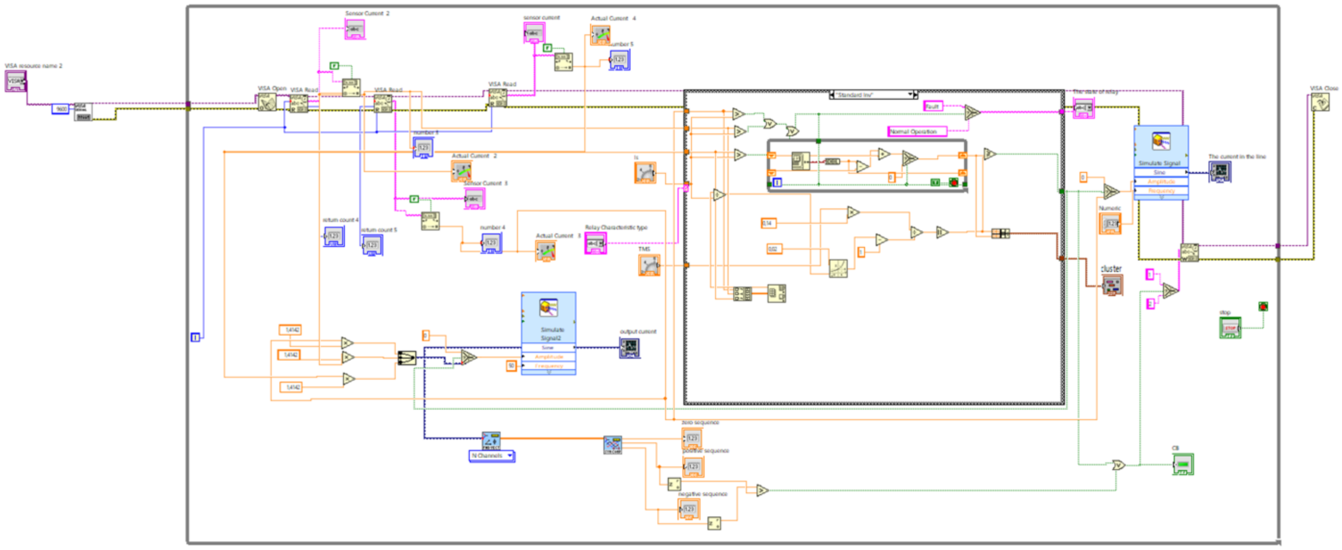
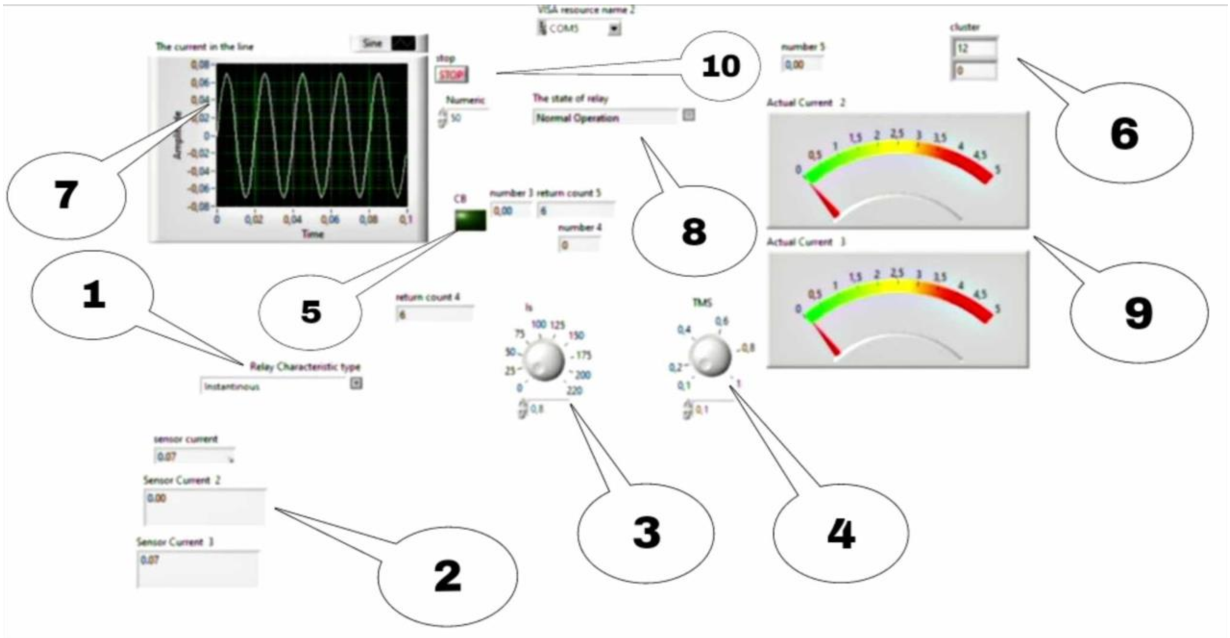


Fig. 3.7 : *Directional Relay*

3.2.7. Front Panel

The front panel window is the user interface for the VI. The front panel has controls and indicators, which are the interactive input and output terminals, respectively, of the VI. In this experiment it shows us the settings, types, setting time and the setting current of the relay .


VISA resource name 2
COM5

stop
STOP

Numeric
50

The state of relay
Normal Operation

number 5
0,00

cluster
12
0

number 3
0,00

return count 5
6

number 4
0

return count 4
6

Relay Characteristic type
Instantinous

Is
0,8

TMS
0,1

sensor current
0.07

Sensor Current 2
0.00

Sensor Current 3
0.07

Fig. 3.8: *Front Panel*

The fig 3.16 shows the user interface to control the relay which can see those parameters

1- The type of the overcurrent relay

2- The measured current from the current sensor (will be shown later)

3- The setting current

4- The required TMS

5- The tripping signal

6- The computed time delay for the overcurrent relay

7- The input signal

8- The state of relay graph

9- The current ratio

10- The stop button

1,3,4,10 are the Parameters that the user can control

2,7 are the input that comes from the Arduino(will be seen later)

5,6,9 are the output signal and parameters of the relay

After setting the current and TMS , the current ratio will be computed in the following formula:

$$K=\frac{I}{Is} \qquad (3.1)$$

I: the measured current

Is: the setting current

K: the current ratio

If K>1 the time delay will be computed using the equation (2.2) and the time will be shown on “6”. After that time the tripping signal will be generated and displayed in “5”.

3.2.8. Adaptive Protection

For the adaptive protection we create a LabView program that automatically switches to islanded mode whenever a disturbance in the system happened and change the pre-determined settings to the off-grid settings. On the other hand, a manual mode is created to allow the user to enter his desired settings any time.

3.2.8.1. Manual mode

For the manual mode we have the block diagram that is shown in the figure 3.17

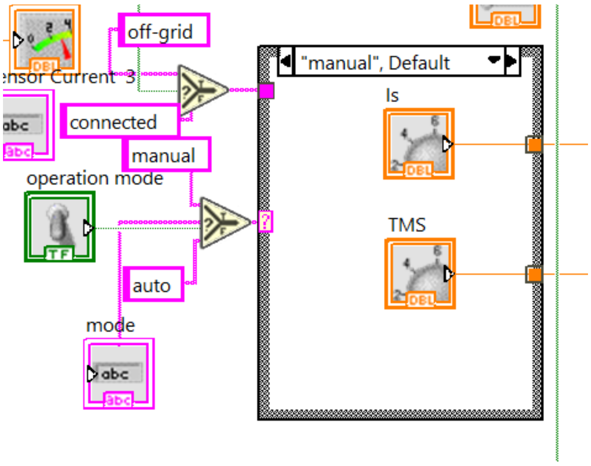


Fig 3.9: *Adaptive Manual Mode*

3.2.8.2. Automatic mode (off grid)

The block diagram of the auto mod off-grid is shown in figure 3.18

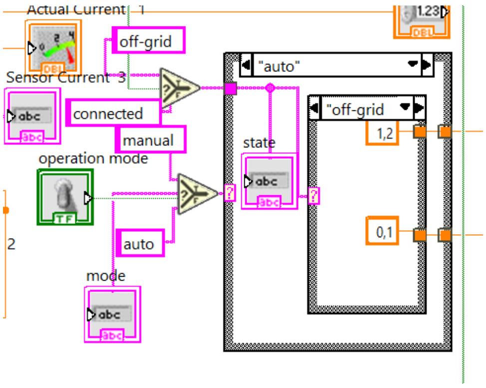


Fig 3.10 :*Adaptive Auto Mode (off grid)*

3.2.8.3. Automatic mode (grid connected)

Also for the automode grid connected we have the following configuration diagram that is shown in the figure 3.19

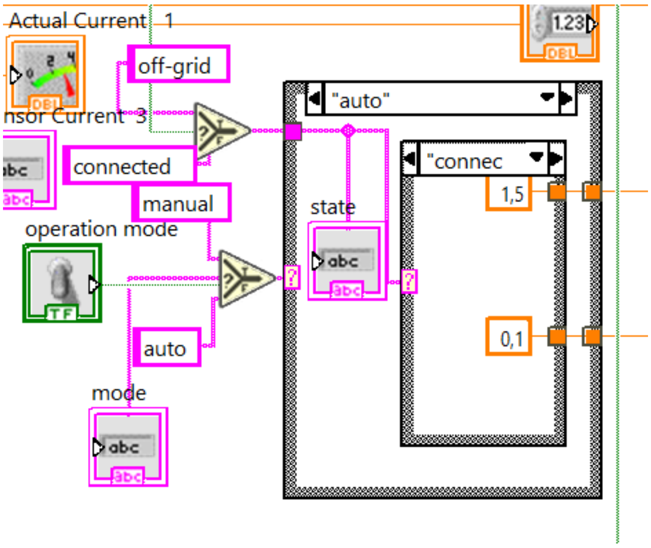


Fig 3.11: *Adaptive Auto Mode (gridconnected)*

3.2.8.4. Adaptive Directional Overcurrent Relay

The figure 3.20 shows the block diagram of the Adaptive Directional Overcurrent Relay

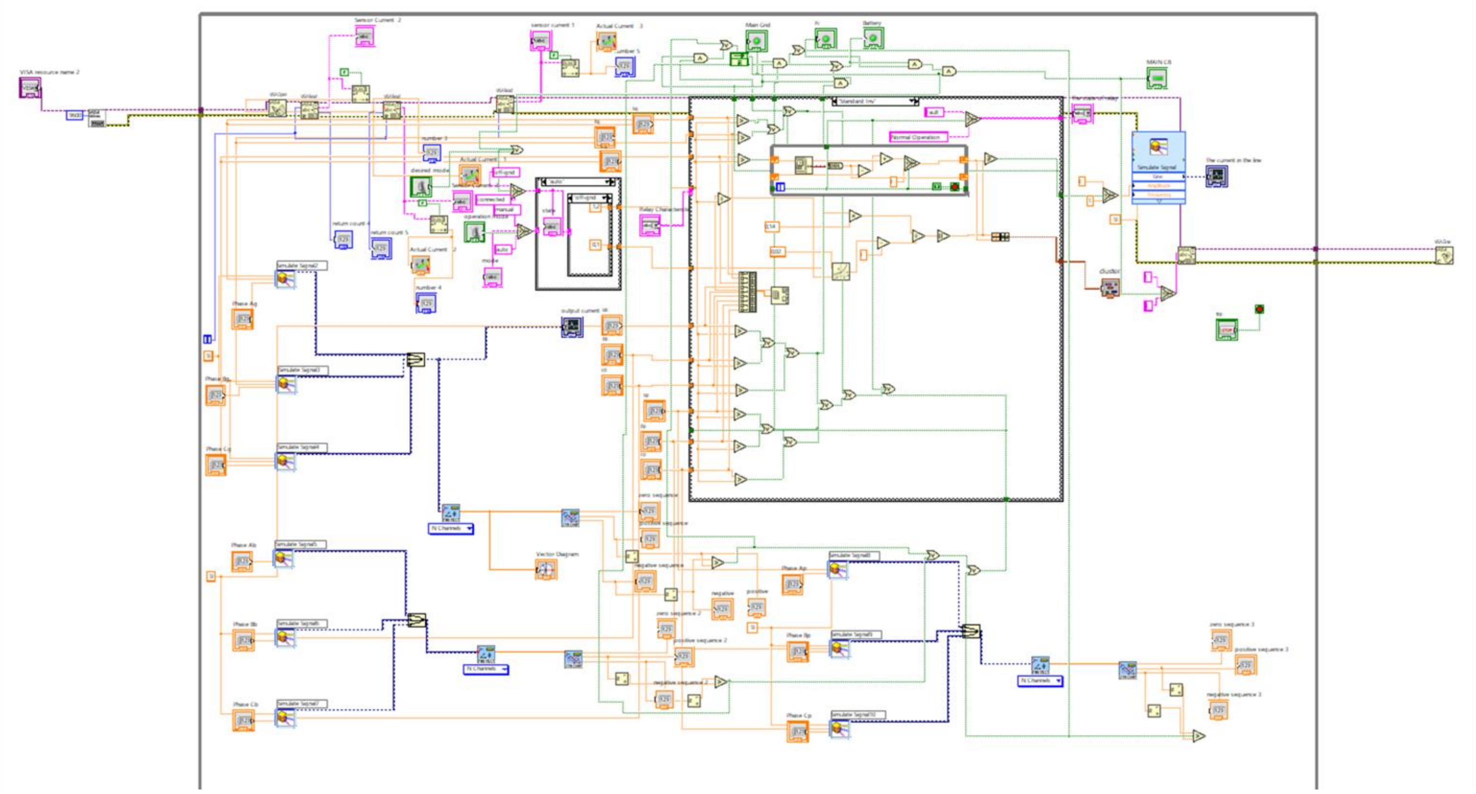


Fig 3.12 :*Adaptive Directional Overcurrent Relay*

3.3. Implementation

As it is mentioned before, the project was implemented in the scientific research laboratory. A specialized material were used in the implementation purposed for scientific researches, to guarantee an accurate results.

3.3.1. Hardware Structure

The materials that used are the following:

- Arduino uno card
- Current sensor ACS712-ELCTR-30A (hall effect-based sensor)
- Potential transformer 240V/6V
- Three phase generator
- Block of resistances
- Block of capacitors
- Block of inductances
- Banana Cables
- DC power supply
- Op-amp

This equipment is used to create some of the circuits that will be shown in the following steps

3.3.2. Signal conditioning circuit (SCC)

The circuit shown in the figure 3.21 is the implementation of voltage sensor, to connect it to the Arduino input for data acquisition

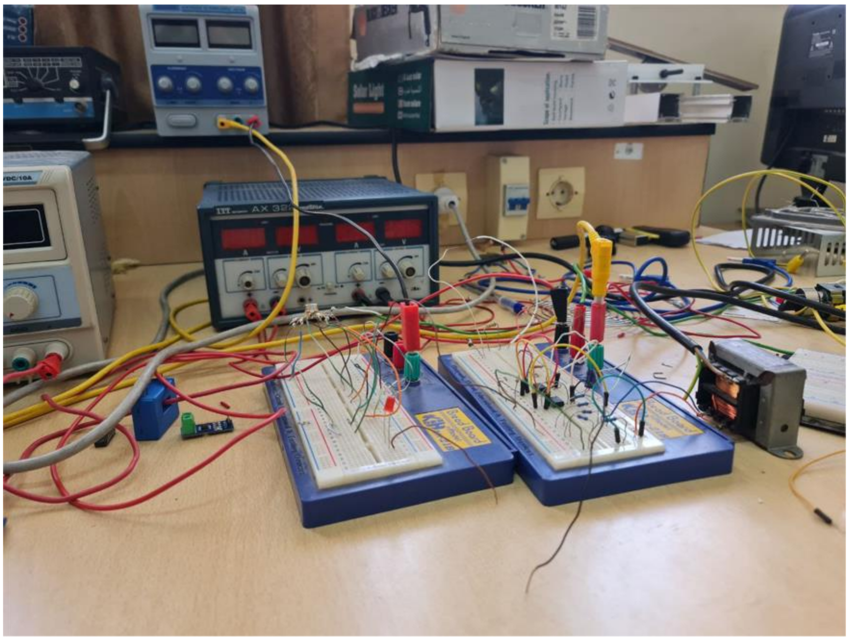


Fig. 3.13: *Signal Conditioning Circuit*

The previous implementation has the electrical circuit diagram shown in the figure 3.22

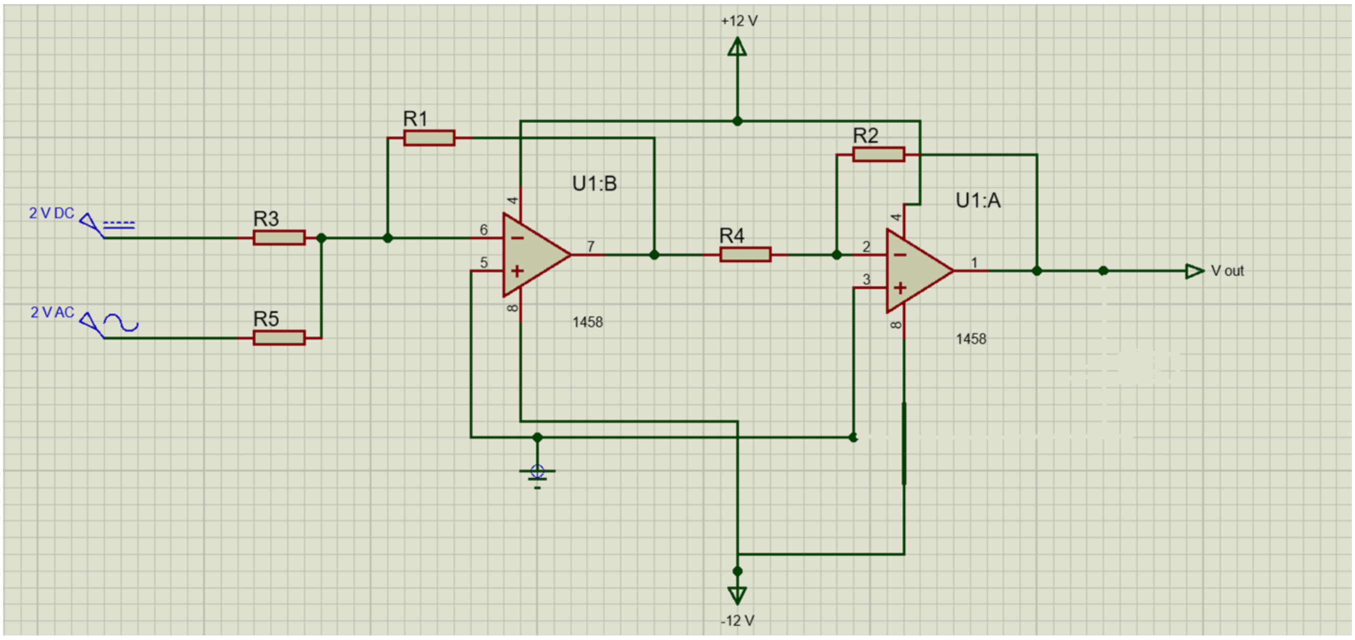


Fig. 3.14 :*Electrical Circuit Diagram of the SCC*

This circuit is essential for the proper reading of voltage since we need it for the directional and adaptive element and it is crucial since the analog input ports of the Arduino UNO ranges from 0 to 5 Volts. First, the input voltage was reduced using 240/6V_{RMS}voltage transformer, then a voltage divider circuit was built in order to get the desired -2 to 2V_{peak} using equation (3.2), and to do so we connected an 8KΩ resistance in series with a 2KΩ taking it as an input for our Operational Amplifier OP07 which will play the role of an inverting summer by adding a DC offset of 2V to our output signal as the equation (3.4) shows.

$$V_{out}=V_{in}*\frac{R8}{R8+R9} \tag{3.2}$$

$$V_{out}=7*\frac{2k}{10k} \tag{3.3}$$

V_{out}= 1.4 V

This is the rms value of the voltage, the maximum value calculated by multiplying V_{rms} with $\sqrt{2}$ it give us a maximum value of approximately 2V .

The inverting summer has the following equation

$$V_{out}= - R_1*(\frac{V1}{R3}+\frac{V2}{R5}) \tag{3.4}$$

By putting $R_1=R_3=R_5$, output voltage will be

$$V_{out1}= - V_1-V_2 \tag{3.5}$$

V_1 is the sinusoidal voltage

V_2=2V , is the DC offset voltage

At this point our output became a -4 to 0 Volts sinusoidal signal and we need to invert it in order to match the range of Arduino UNO input port. For that we used an LM308N Op-amp as an inverting amplifier, the equation (3.6) describes its transfer function.

$$V_{out}= -V_{out1} \tag{3.6}$$

$$V_{out}= V_1+V_2 \tag{3.7}$$

At the end, we had our 0-4V_{peak} voltage with 1.4V_{RMS} which is suitable for our Arduino Uno range.

This above section was about the hardware level, the figure 3.23 shows a flow chart that describes the algorithm used to calibrate the voltage sensor in order to read the real RMS values.

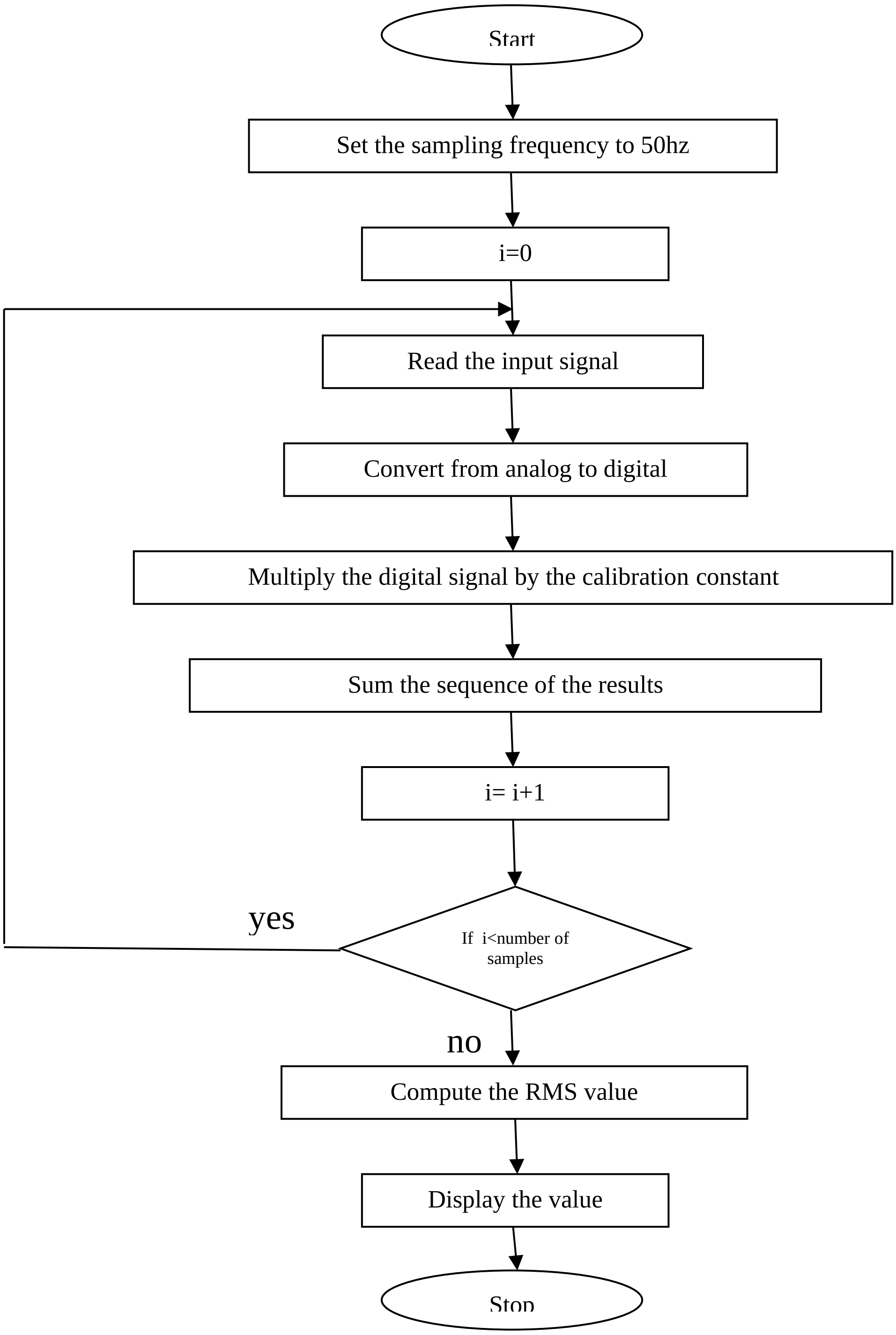


Fig 3.15: *Flowchart of Calibrating Voltage Sensor*

3.3.3. Current sensor

This measuring technique of current was implemented using an ACS712ELCTR-30A-T Hall effect based current sensor connected to the Arduino card and displayed on the computer screen using an algorithm to process the values. Each current sensor is connected to a phase to monitor its current.

The figure 3.24 display how the 3 current sensors connected to the Arduino and measure the phase current.

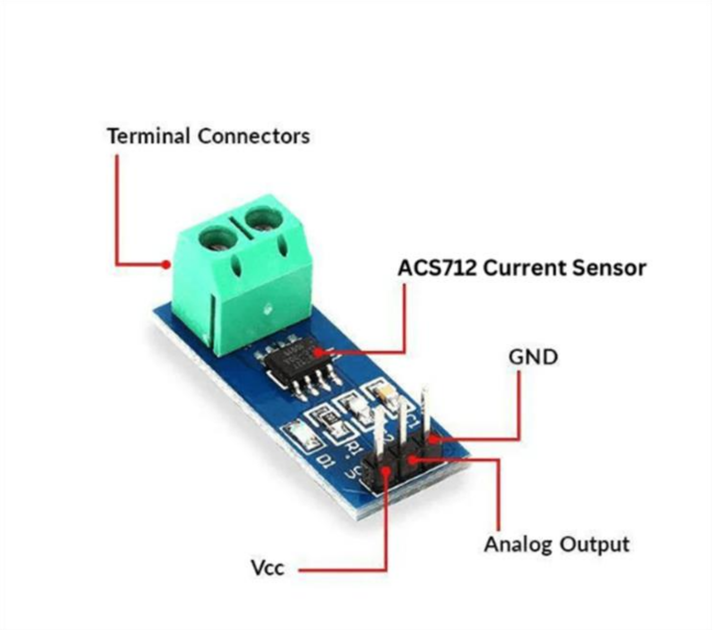


Fig. 3.16 :*ACS712 currentsensor*

3.3.4. Symmetrical Components and Unbalanced system

One of the most used techniques used to determine the direction of the current or the power flow is the continuous monitoring of the voltage and current phase angles and the difference between the two quantities. So, any change or abnormality in the system will create a distortion in the balanced system and by that we mean a change in the symmetrical quantities (positive sequence, negative sequence and zero sequence).

At normal conditions only the positive sequence quantity has a value whereas the two others are weather equals to zero in a perfectly balanced system which is not possible in the real world, or have a very-small magnitude that we can consider it negligible.

Our approach is based on creating a three-phase unbalanced system with a load enough to inverse the current sequence and observe if the proposed algorithm of the directional relay can detect the abnormality and display the phase sequences (positive sequence, negative sequence, zero sequence) using the following relation:

$$\begin{pmatrix} I_0 \\ I_1 \\ I_2 \end{pmatrix} = \frac{1}{3} * \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & \\ & a^2 & \end{pmatrix} \begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix} \qquad (3.8)$$

Where:

I_0: the zero-sequence current

I_1: the positive sequence current

I_2: the negative sequence current

Ia: the current of phase a

I_b: the current of phase b

I_c: the current of phase c

a= $e^{j\frac{2\pi}{3}}$=- $\frac{1}{2}$ +j$\frac{\sqrt{3}}{2}$

the idea here is detecting which type of fault and its direction. According to the following table, each fault has its phase sequences as shown in table 3.1

Table 3.1: *Phase Sequence of Unbalanced System*

Type of fault	I_0	I_1	I_2
Phase to ground	Yes	Yes	Yes
Phase to phase	No	Yes	Yes
2 phase to ground	Yes	Yes	Yes

This method was implemented first using three blocks of resistance. By changing the value of each phase load an unbalanced system will be created, this causes a changing in the magnitudes of both voltage and current but not in their phase angle. The figure 3.25 shows the connection of the load:

Fig. 3.17:*Connection of the Resistive Load*

On the other hand, another approach of an unbalanced system was put under test which is changing the phase angle, we managed to do that by placing the same passive components(resistances, capacitors and inductors) on each phase and started to vary the load until we reached the point of a sever unbalance system.

Using LabVolt software we found the appropriate configuration in order to simulate an unbalance system high enough to inverse the current rotation sequence, then try to make the same configuration in the lab.

The simulation configuration is composed of :

Phase A: R=1.2KΩ; C=15.4µF; L=3.2H

Phase B: R= 240 Ω; C=2.2µF; L=0.45H

Phase C: R=240Ω; C=2.2µF; L=0.45H

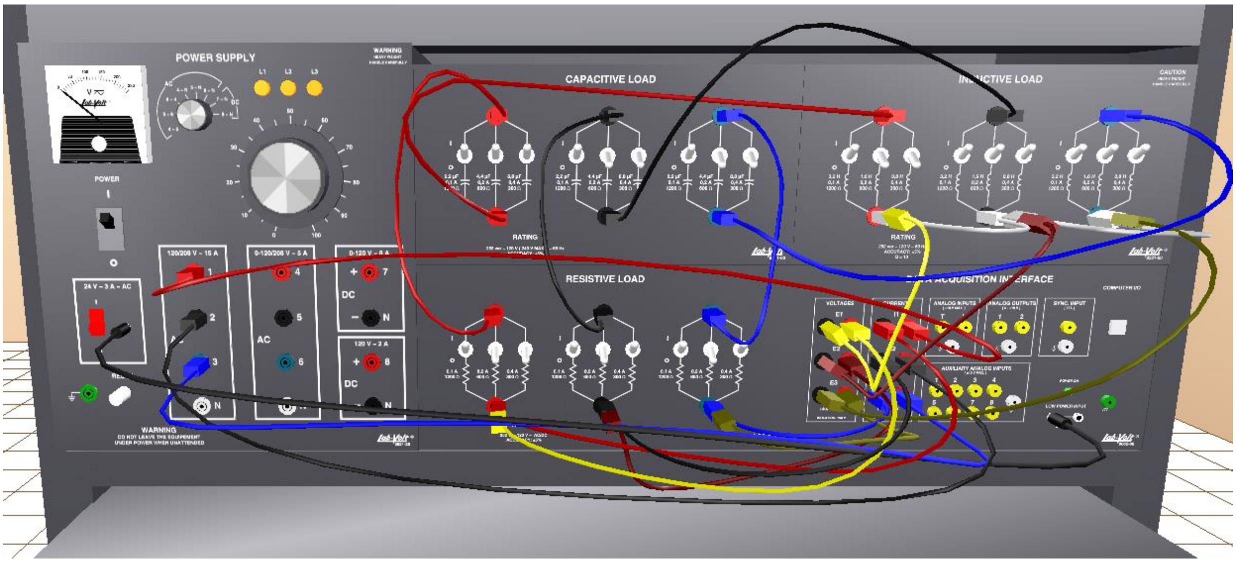


Fig. 3.18 :*the Simulated Connection of the Capacitive and Inductive Load*

The real configuration is composed of:

Phase A: R=880Ω; C=5.06µF; L=14H

Phase B: R= 176Ω; C=0.72µF; L=2H

Phase C: R=176Ω; C=0.72µF; L=2H

The figure 3.27 shows the block of capacitors, inductors and how it is connected to the system .

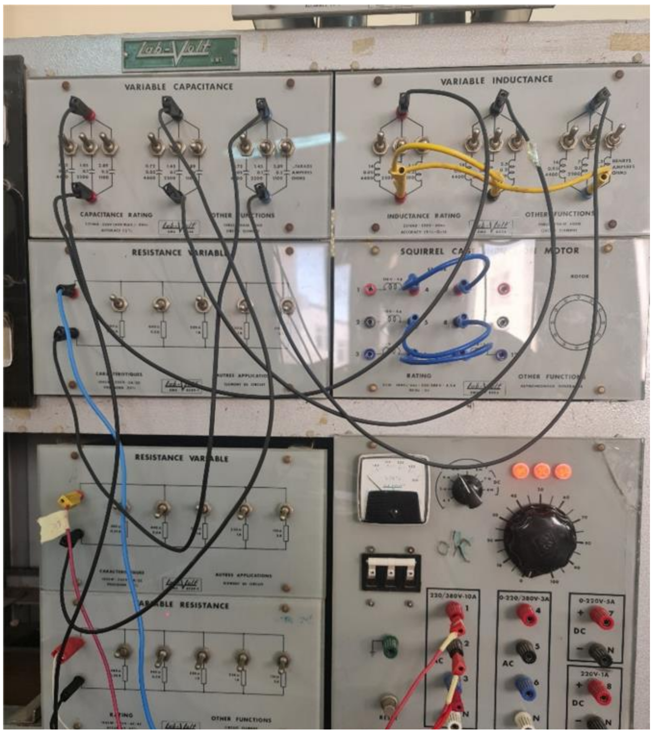


Fig. 3.19 :*the real connection of the capacitive and inductive load*

The figure 3.28 represent a LabView block diagram of computing the phase sequences of the system

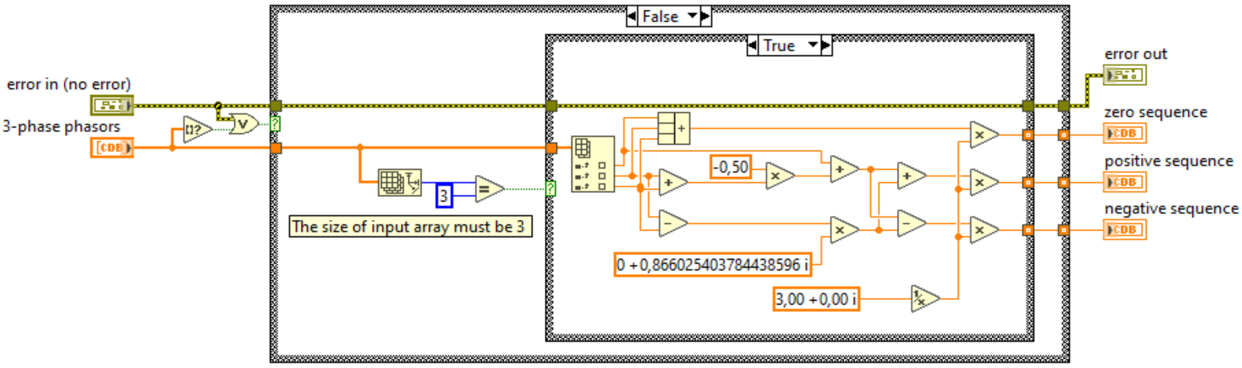


Fig 3.20 :*Block Diagram of Computing the Phase Sequences*

The goal of this experiment is to implement a directional relay using symmetrical component. The idea is to extract the phase sequences (positive, negative and zero sequence) then compare between them as we mentioned before it can deduce the type of the fault. In addition, it can show also the direction of the fault, how? The answer is by comparing the 3 sequences, if the magnitude of positive sequence is much greater than the magnitude of negative sequence (the negative sequence can be neglected) this mean that the power flow in the positive direction. However, if the magnitude of negative sequence is greater than the positive sequence this means that the system is unreliable and must be disconnected immediately to prevent any damages.

Chapter 4

Results and Discussion

4.1. Introduction

This chapter is the final part of the project. After simulating and implementing all project components, various results will be available for discussion and comment, including output signals and values. The simulation results were good and as expected. However, there were slight discrepancies in the implementation results due to the lifetime of the equipment used. The discussion section presents significant perspectives on the system and its protection, highlighting strengths and weaknesses to facilitate improvement, and identifying areas needing future attention.

4.2. Results of Relay Implementation

We used an Arduino Uno as a microcontroller and for data acquisition, VISA interface for communication between the microcontroller and the LabView software which was used for data analyzing and decision making and provide an interface for the user.

4.2.1. Signal Conditioning Circuit (SCC)

The results of the signal conditioning circuit is shown in the following figures

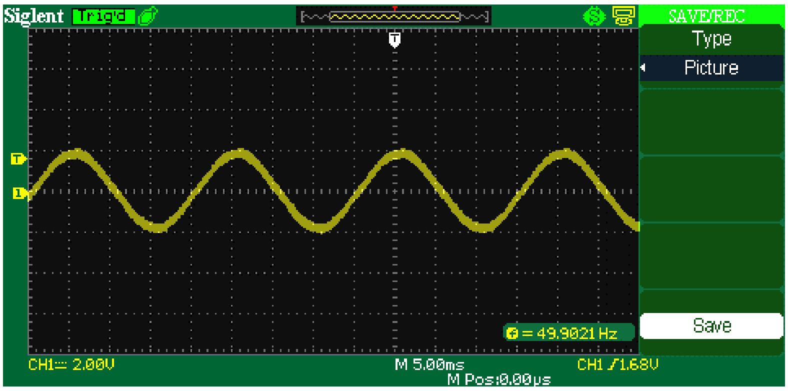
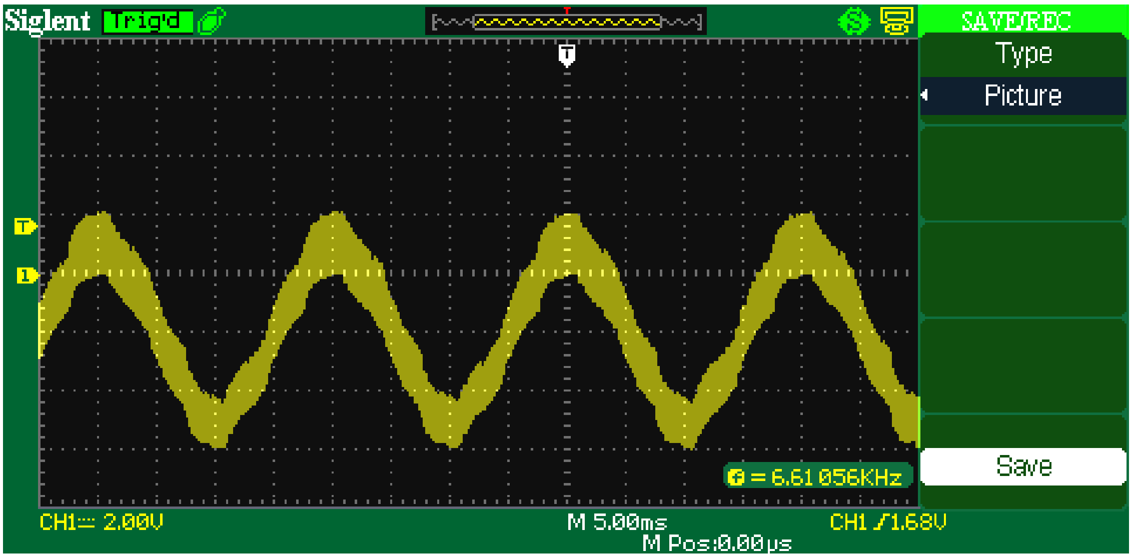


Fig 4.1: *SCC(output of voltage divider)*

We see here that the output voltage is divided from 10V_{peak} to 2V_{peak} because of voltage divider.

The next figure shows the output of inverting summer



f = 6.61 056KHz

CH1 2.00V

M 5.00ms

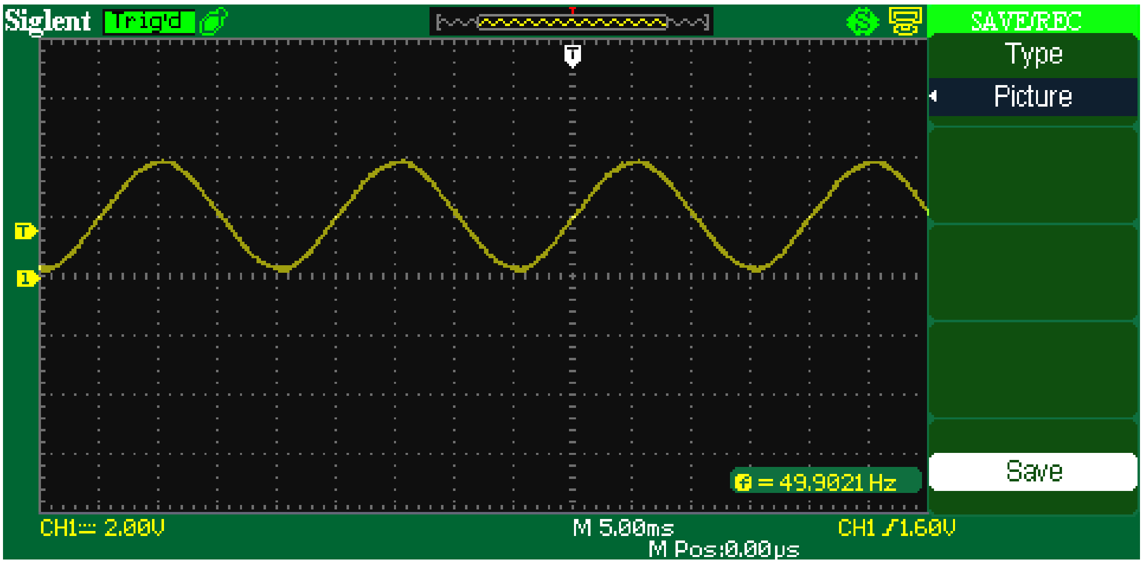
M Pos:0.00μs

CH1 ⁄ 1.68V

Fig 4.2:*SCC(output of inverter summer)*

We see that an offset of 2V was added, and it is inverted due to the inverter summer characteristic.

After that , the figure 4.3 display the final output signal



f = 49.9021 Hz

CH1 2.00V

M 5.00ms

M Pos:0.00μs

CH1 ⁄ 1.60V

Fig 4.3: *The Output Signal of the SCC*

We see that the voltage is varying from 0 to 4V, after installing a capacitor at the output to filter the noise, which is suitable for the Arduino.

4.2.2. Voltage Sensor

Table 4.1: *results of voltage senso**r***

Real voltmeter	**Voltage sensor**	**error**
107.2	111.84	4%
53.42	54	1%
198.9	203.63	2.3%
125	130.11	4%

As noticed in the table above, the voltage sensor designed has a margin error of no more than 4% which is acceptable and we can precede the implementation with it.

4.2.3. Current sensor

Table 4.2: *results of current sensor*

Real Amper meter	Value displayed from current sensor	error
0.34	0.38	11%
0.91	0.89	2.1%
0.21	0.22	4.7%
0.82	0.86	4.8%

Unlike the voltage sensor, the current sensor may exceed a 5% error margin which may reflect on the performance of the relay later, but as mentioned in the ACS712-30A data sheet, this is normal at the low currents.

4.2.4. Instantaneous over-current relay

As it is mentioned before, the instantaneous relay has no time delay, as soon as the current exceeds the pick-up value, a tripping signal will be sent to the CB , the table 4.1 bellow shows the results that we obtained

Table 4.3: *results of instantaneous overcurrent relay*

The measured current	The setting current	Current ratio	State of relay
0.2	0.5	0.4	No trip
0.4	0.5	0.8	No trip
0.6	0.5	1.2	Trip
1	0.5	2	Trip
1.2	0.5	2.4	Trip
1.5	0.5	3	Trip
2	0.5	4	Trip

A tripping signal originating from LabVIEW will be relayed to the circuit via Arduino, indicated by the illumination of an LED. The figure 4.4 shows the illumination of the LED

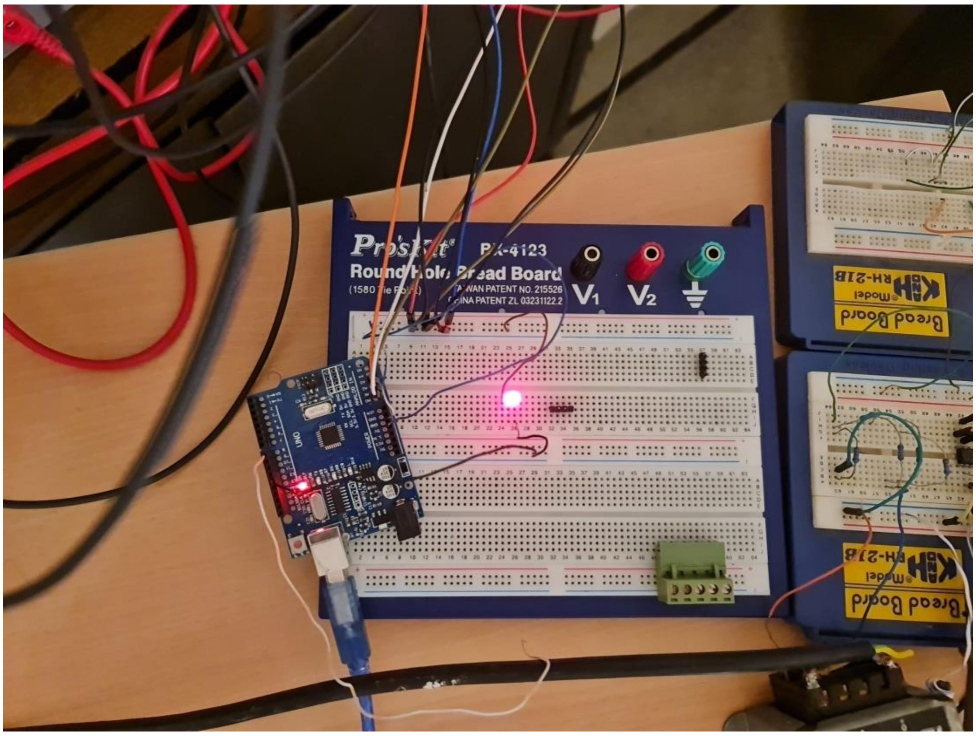


Fig 4.4: *Result of Instantaneous Relay*

4.2.5. Very Inverse Over-current relay

Here the time delay will be considered and computed using the equation (2.2). Setting the parameters C and αas mentioned in table 2.1 and compared them with the results done by [31] under the same conditions (TMS=100ms)

Table 4.4: *results of Very Inverse Over-current relay*

The measured current	The setting current	Computed time delay	Time delay of the experiment	State of relay
0.7	1.25	-	-	No-trip
1.54	1.25	5.82	6.53	Trip
2.16	1.25	1.85	1.96	Trip
1.92	1.25	2.52	2.61	Trip
1.71	1.25	3	3.92	Trip
3.77	1.25	0.67	0.74	Trip
8.17	1.25	0.24	0.33	Trip

4.2.6. Standard Inverse Over-current Relay

Following the same procedure as before we set the values of C and α as in table 2.1 and TMS=0.1sthen we compare them with the experiment in [31] we got the following table

Table 4.5: *results of standard Inverse Over-current relay*

The measured current	The setting current	Computed time delay	Time delay of the experiment	State of relay
1	1.25	-	-	No-trip
1.1	1.25	-	-	No-trip
2.15	1.25	1.28	1.31	Trip
1.69	1.25	2.31	2.93	Trip
1.93	1.25	1.6	1.62	Trip
2.15	1.25	1.28	1.3	Trip
8.84	1.25	0.35	0.42	Trip

4.2.7. Long Inverse over-current Relay

Also, here by setting the values of C and α as mentioned before in table 2.1 and putting the TMS=0.1s we got the following results

Table 4.6: *results of long Inverse Over-current relay*

The measured current	**The setting current**	**Computed time delay**	**Theoretical time delay**	**State of relay**
1	1.25	-	-	No trip
1.35	0.8	17.63	17.45	Trip
2.5	0.8	5.84	5.46	Trip
1.5	1	24.2	24	Trip
2.2	1	10.3	10	Trip
3	1	6.1	6	Trip
2.8	2	30.1	30	Trip

4.2.8. Extremely Inverse Over-Current Relay

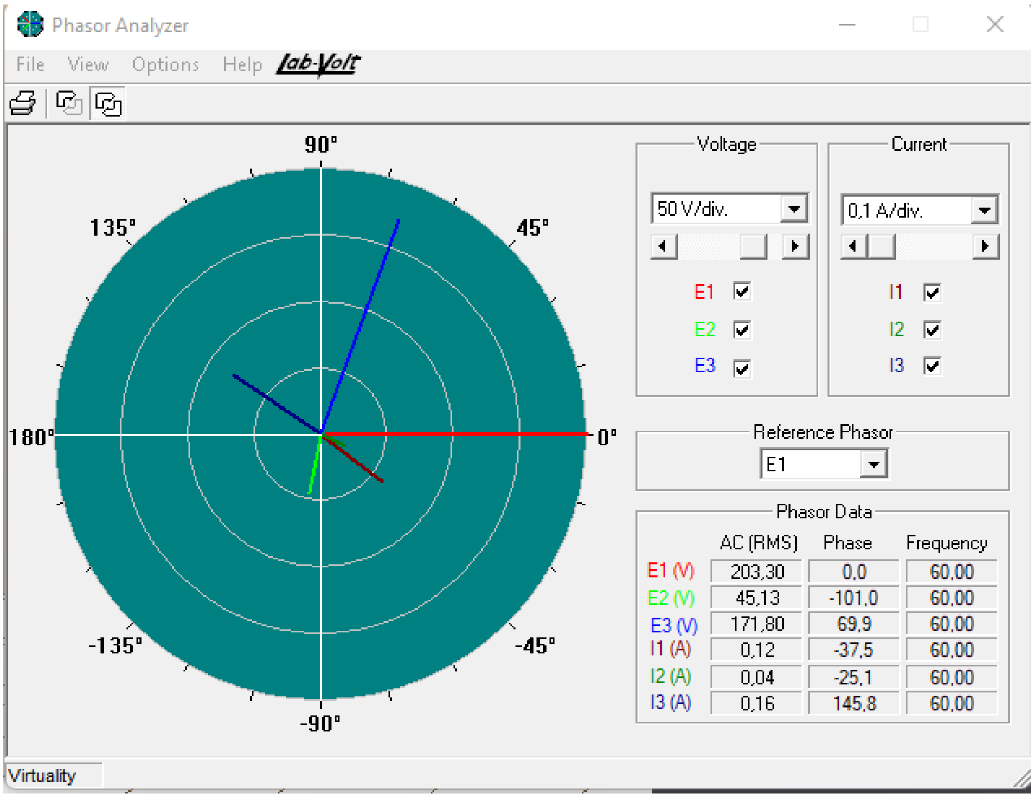
Here in this type also we put TMS=0.1s and setting the values of C and α, then we compared it to the experiment in [31] we got the following table

Table 4.7: ***results of extremely Inverse Over-current relay***

The measured current	**The setting current**	**Computed time delay**	**Time delay of the experiment**	**State of relay**
0.9	1.25	-	-	No trip
1.56	1.25	14.34	14.53	Trip
1.97	1.25	5.38	5.38	Trip
2.58	1.25	2.45	2.47	Trip
2.35	1.25	3.15	3.28	Trip
2.78	1.25	2.02	2.04	Trip
3.18	1.25	1.46	1.65	Trip

4.2.9. Results of symmetrical component method

After creating the unbalanced system we got the following results during simulation,



Voltage: 50 V/div.

Current: 0,1 A/div.

E1 ☑ E2 ☑ E3 ☑

I1 ☑ I2 ☑ I3 ☑

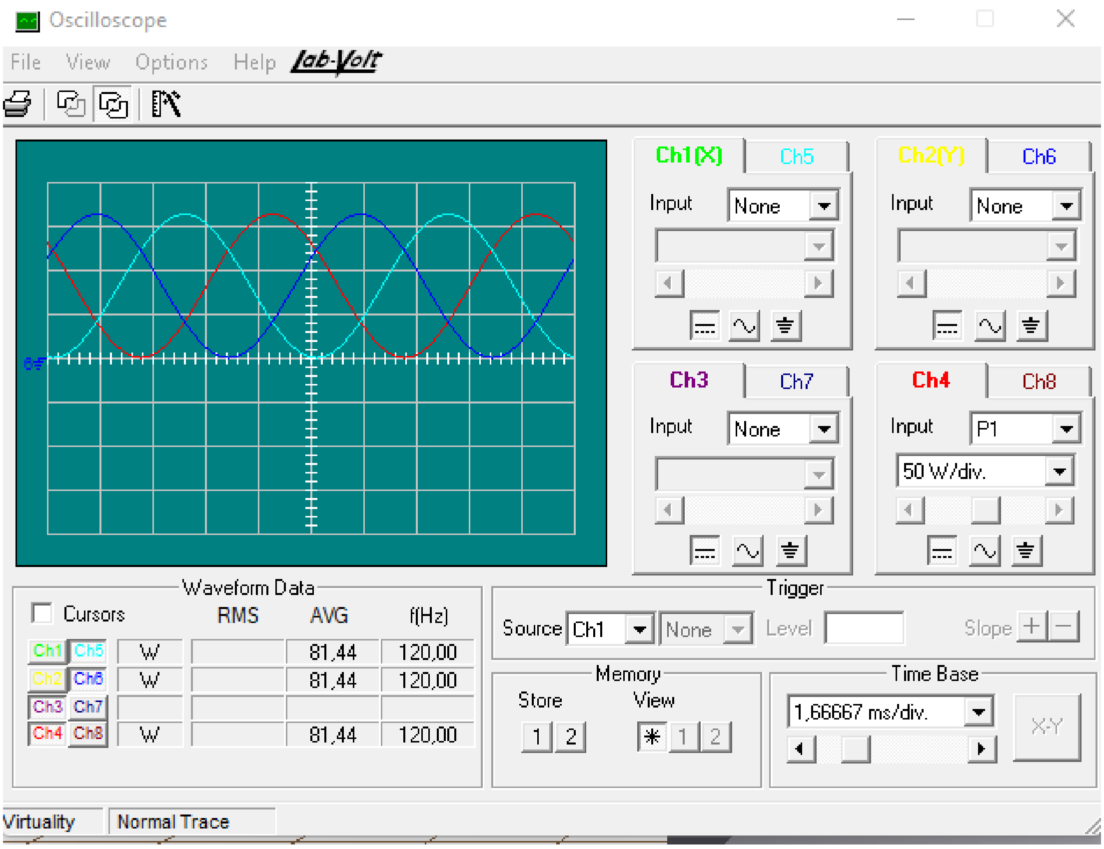
Reference Phasor: E1

	AC (RMS)	Phase	Frequency
E1 (V)	203,30	0,0	60,00
E2 (V)	45,13	-101,0	60,00
E3 (V)	171,80	69,9	60,00
I1 (A)	0,12	-37,5	60,00
I2 (A)	0,04	-25,1	60,00
I3 (A)	0,16	145,8	60,00

Fig 4.5: *Results of Symmetrical Component Simulation*

It is clear that the phase sequence became “ACB” instead of “ABC” which means that the system is not reliable and can cause serious damage to our equipment and must be disconnected.

In the figure 4.6 we can see the difference in the power signal during normal conditions compared with abnormal conditions



Ch1(X) Input: None

Ch2(Y) Input: None

Ch3 Input: None

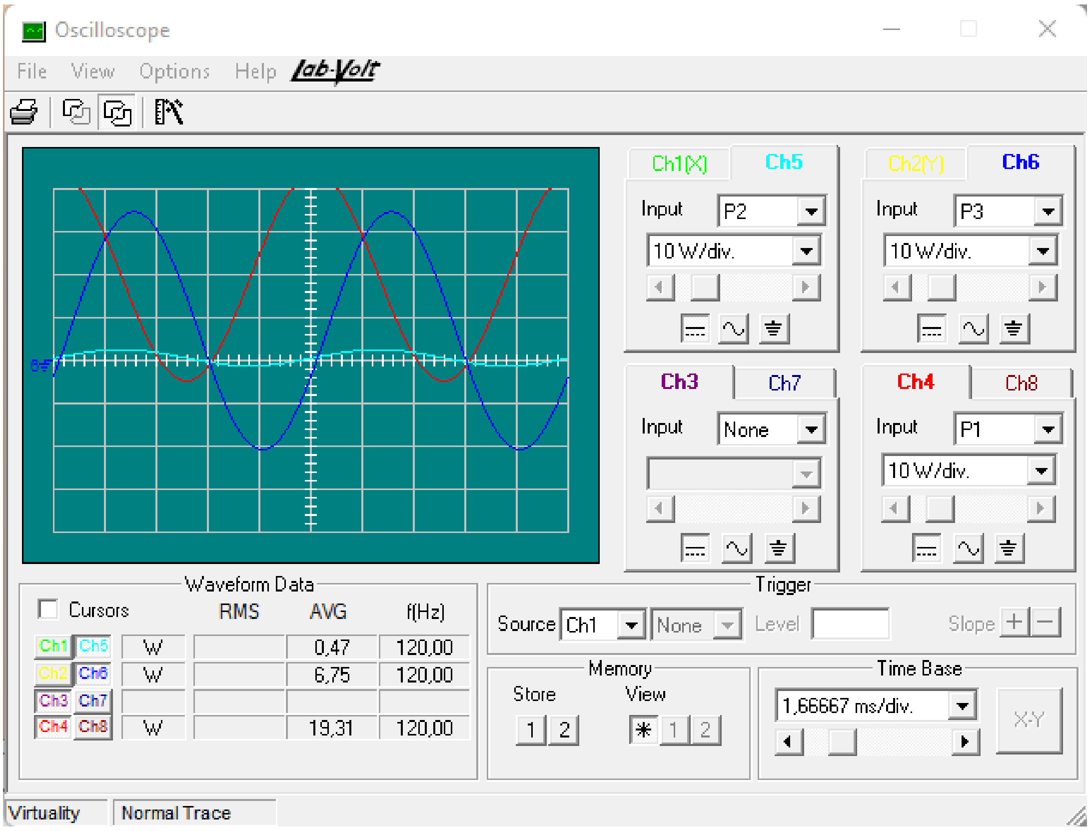
Ch4 Input: P1, 50 W/div.

Waveform Data

Cursors		RMS	AVG	f(Hz)
Ch1 Ch5	W		81,44	120,00
Ch2 Ch6	W		81,44	120,00
Ch3 Ch7				
Ch4 Ch8	W		81,44	120,00

Trigger: Source Ch1, None, Level, Slope

Time Base: 1,66667 ms/div.



Ch5 Input: P2, 10 W/div.

Ch6 Input: P3, 10 W/div.

Ch3 Input: None

Ch4 Input: P1, 10 W/div.

Waveform Data

Cursors		RMS	AVG	f(Hz)
Ch1 Ch5	W		0,47	120,00
Ch2 Ch6	W		6,75	120,00
Ch3 Ch7				
Ch4 Ch8	W		19,31	120,00

Trigger: Source Ch1, None, Level, Slope

Time Base: 1,66667 ms/div.

Fig 4.6: *The Difference in the Power Signal During Normal Conditions and Abnormal Conditions*

It is clear that the power at its best decreased by 75% from the normal condition per phase while it is near to 0Watt in one of the phases which is not acceptable.

The same results appeared in the real experiment using a 243V_{rms} power source where we obtained:

Phase A: 502V / 0.26A

Phase B: 585V / 0.30A

Phase C: 170.4V /0.07A

4.2.10. Directional Relay

By adopting the strategy proposed earlier in (), we compared the magnitudes of the current's positive and negative sequences and voltage's and their phase angle in order to determine if the system is safe enough to be connected to.

The results showed that our designed relay tripped whenever the negative sequence of the current in a specific area is considerably high and the power flow may harm our devices, so it works on isolating the fault or even prevent from a disturbance in the system without necessarily having an event of fault, and this from our point of view is acceptable.

Table 4.8: *results of the designed relay*

				Tripped zone		
	I_0	I_1	I_2	Grid	PV panel	Battery
Grid	✓	✓	✓	✓		
PV panel	✓	✓	✓		✓	
Battery	✓	✓	✓			✓

4.3. Results of Adaptive Protection Simulation

4.3.1. Results of General Fault

In this case we simulate a fault in all busses (PV, Battery , Main Grid) and we obtain the result in figure 4.7

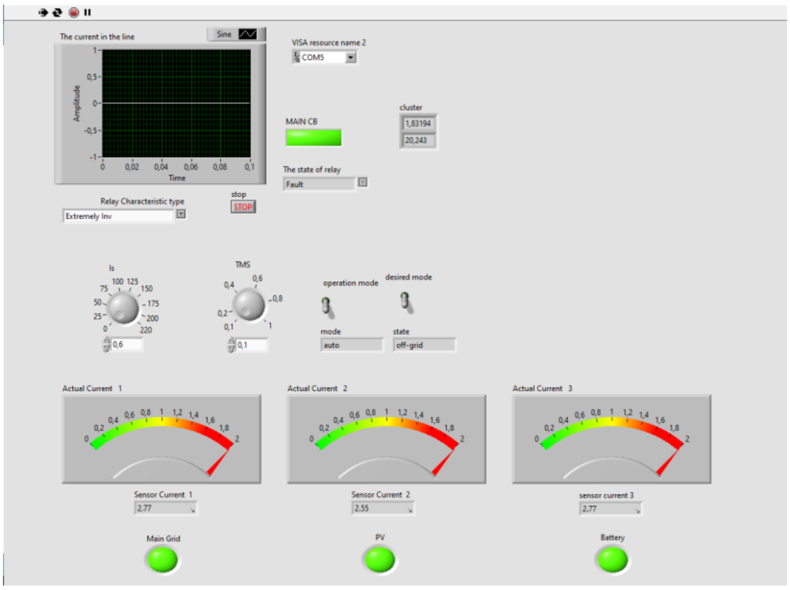

VISA resource name 2
COM5
cluster
1,83194
20,243
The state of relay
Fault
Relay Characteristic type
Extremely Inv
Is
0,6
TMS
0,1
mode
auto
state
off-grid
Sensor Current 1
2.77
Sensor Current 2
2.55
sensor current 3
2.77

Fig 4.7: *Result of General Fault*

4.3.2. Results of Fault at PV

If a fault happened at PV, the output will be as shown in figure 4.8

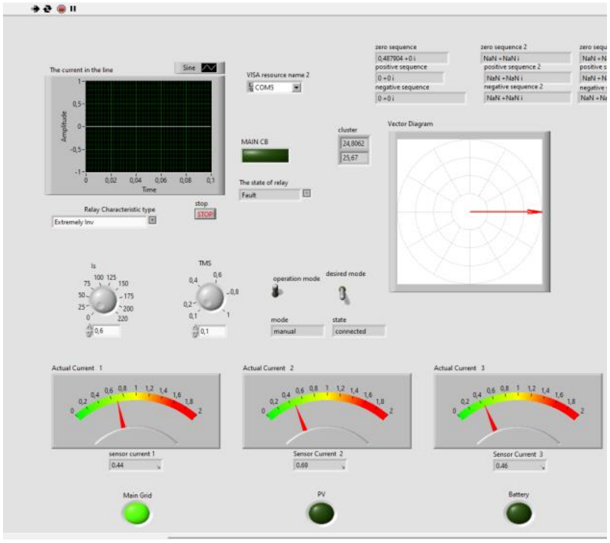

VISA resource name 2
COM5
cluster
15,3518
28,1997
The state of relay
Fault
Relay Characteristic type
Extremely Inv
Is
0,6
TMS
0,1
mode
manual
state
connected
Sensor Current 1
0.49
Sensor Current 2
0.74
sensor current 3
0.51

Fig 4.8: *Result of Fault at PV*

We see that the tripping signal is sent to the PV so CB will disconnect only the PV panel .

4.3.3. Results of Fault at Main Grid

If a fault happened at the main grid, the output will be as shown in figure 4.9



zero sequence: 0,487904 +0 i
positive sequence: 0 +0 i
negative sequence: 0 +0 i
zero sequence 2: NaN +NaN i
positive sequence 2: NaN +NaN i
negative sequence 2: NaN +NaN i
VISA resource name 2: COM5
cluster: 24,8062 / 25,67
The state of relay: Fault
Relay Characteristic type: Extremely Inv
stop
Is: 0,6
TMS: 0,1
mode: manual
state: connected
Actual Current 1
sensor current 1: 0.44
Actual Current 2
Sensor Current 2: 0.69
Actual Current 3
Sensor Current 3: 0.46

Fig 4.9: *Result of Fault at the Main Grid*

We see that the tripping signal is sent to the main grid so CB will disconnect only the main grid .

4.3.4. Results of Fault at the battery

If a fault happened at battery, the output will be as shown in figure 4.10

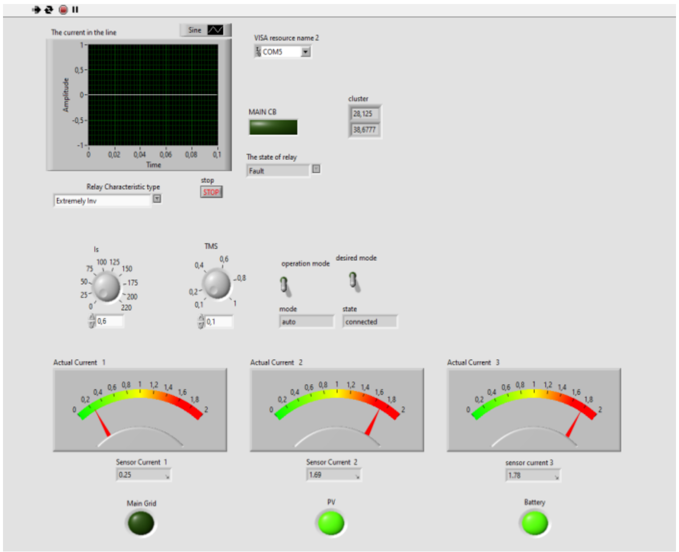
VISA resource name 2: COM5
cluster: 15,3518 / 29,2811
The state of relay: Fault
Relay Characteristic type: Extremely Inv
stop
Is: 0,6
TMS: 0,1
mode: manual
state: connected
Actual Current 1
Sensor Current 1: 0.46
Actual Current 2
Sensor Current 2: 0.40
Actual Current 3
sensor current 3: 0.76

Fig 4.10: *Result of Fault at the battery*

We see that the tripping signal is sent to the battery so CB will disconnect only the battery .

4.3.5. Results of Fault at PV and Battery

If a fault happened at PV and battery , the output will be as shown in figure 4.11



VISA resource name 2
COM5

cluster
28,125
38,6777

The state of relay
Fault

Relay Characteristic type
Extremely Inv

Is
0,6

TMS
0,1

mode
auto

state
connected

Sensor Current 1
0.25

Sensor Current 2
1.69

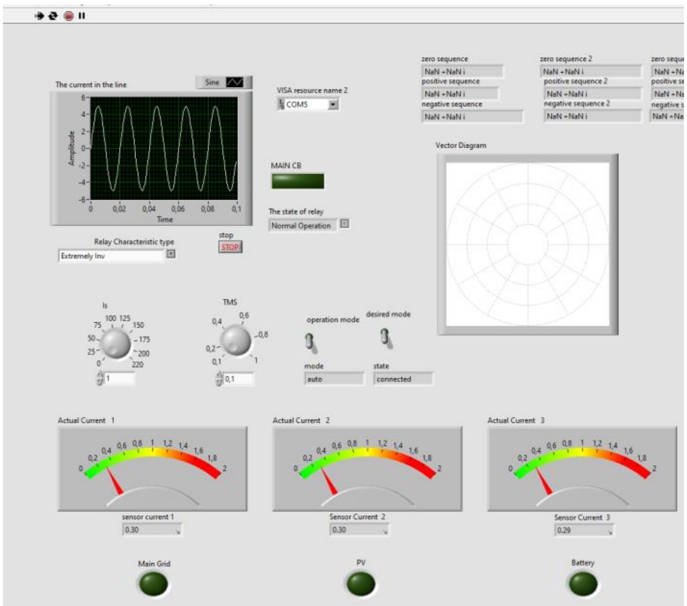
sensor current 3
1.78

Fig 4.11: *Result of Fault at PVand Battery*

We see that the tripping signal is sent to the PV and the battery so CB will disconnect the PV panel and battery.

4.3.6. Results of no-Fault Detection

If there are no fault, the output will be as shown in figure 4.12



zero sequence
NaN +NaN i
positive sequence
NaN +NaN i
negative sequence
NaN +NaN i

zero sequence 2
NaN +NaN i
positive sequence 2
NaN +NaN i
negative sequence 2
NaN +NaN i

zero sequ
NaN +Na
positive se
NaN +Na
negative s
NaN +Na

VISA resource name 2
COM5

The state of relay
Normal Operation

Relay Characteristic type
Extremely Inv

Is
1

TMS
0,1

mode
auto

state
connected

sensor current 1
0.30

Sensor Current 2
0.30

Sensor Current 3
0.29

Fig 4.12: *Result of No Fault Detection*

We see that no tripping signal sent so all buses will stay connected

4.4. Conclusion

In this chapter, we presented a detailed analysis of the results obtained from our implementation of the adaptive directional relay system. This comprehensive evaluation was conducted to assess both the performance and the capabilities of the system in a variety of operational scenarios. The insights gained from this analysis highlight the potential of adaptive relays in enhancing power system protection and reliability.

General Conclusion

This report addresses the research topic of designing and implementing an adaptive directional overcurrent relay for micro smart grids. The study involved simulation and implementation using LabVIEW software, alongside Arduino Uno for data acquisition. Various protection algorithms were integrated and adapted to suit the microgrid context. The research successfully developed a sophisticated relay system tailored for micro smart grids, enhancing reliability and resilience in power distribution.

The findings lay the groundwork for future advancements in microgrid protection. They offer valuable insights into optimizing relay algorithms and integrating machine learning techniques for predictive fault detection. Future work could explore the application of artificial intelligence to further refine the adaptive capabilities of relay systems, as well as the potential for real-time monitoring and automated response mechanisms to improve microgrid efficiency and stability.

The added value for this topic provides a more comprehensive view of the potential future directions and the significance of the research outcomes.

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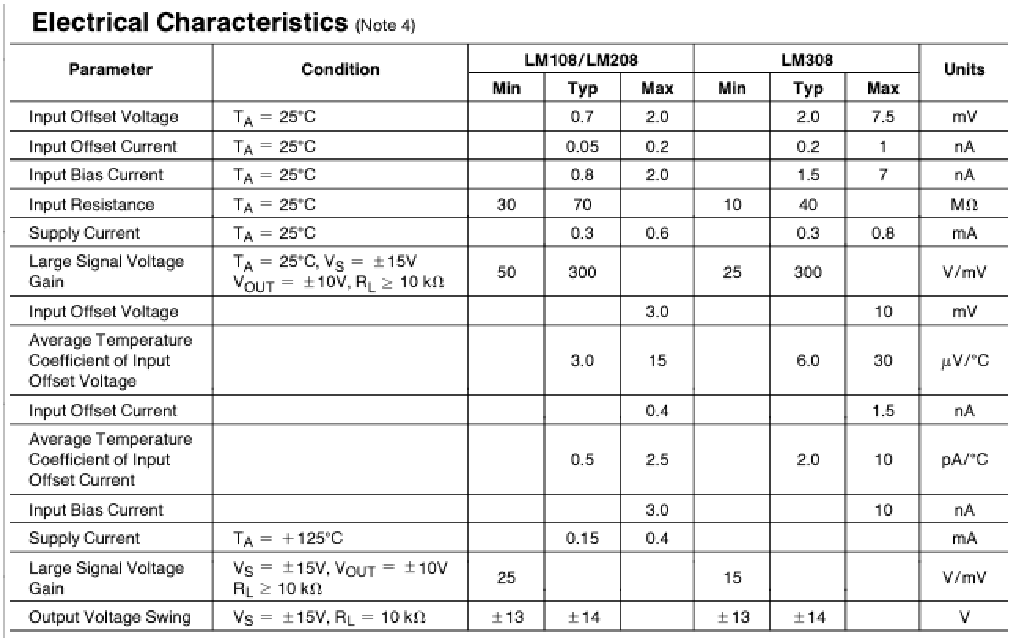
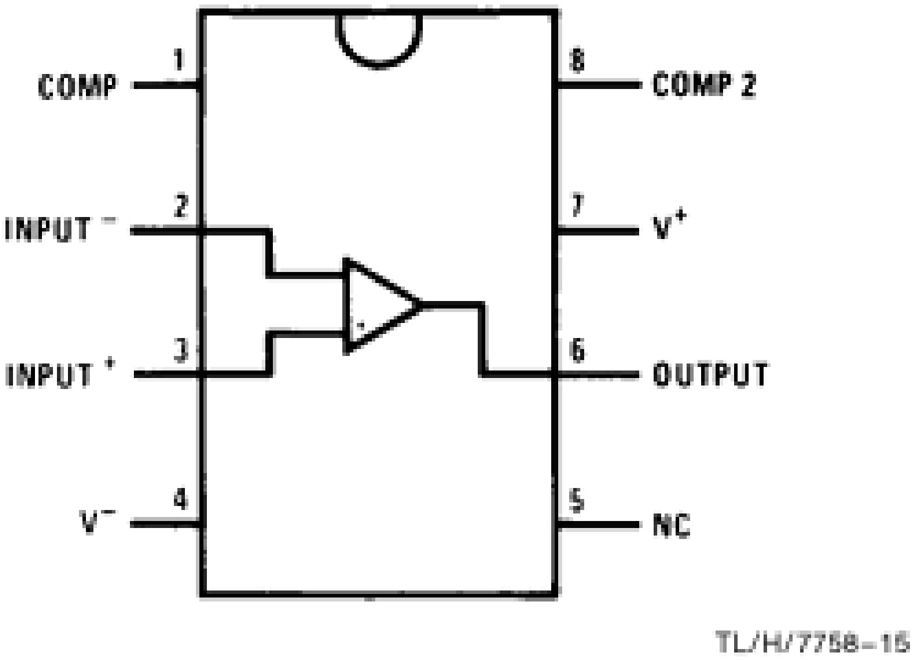
Appendix A: LM308



Electrical Characteristics (Note 4)

Parameter	Condition	LM108/LM208			LM308			Units
		Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	$T_A = 25°C$		0.7	2.0		2.0	7.5	mV
Input Offset Current	$T_A = 25°C$		0.05	0.2		0.2	1	nA
Input Bias Current	$T_A = 25°C$		0.8	2.0		1.5	7	nA
Input Resistance	$T_A = 25°C$	30	70		10	40		MΩ
Supply Current	$T_A = 25°C$		0.3	0.6		0.3	0.8	mA
Large Signal Voltage Gain	$T_A = 25°C$, $V_S = \pm 15V$ $V_{OUT} = \pm 10V$, $R_L \geq 10\ k\Omega$	50	300		25	300		V/mV
Input Offset Voltage				3.0			10	mV
Average Temperature Coefficient of Input Offset Voltage			3.0	15		6.0	30	μV/°C
Input Offset Current				0.4			1.5	nA
Average Temperature Coefficient of Input Offset Current			0.5	2.5		2.0	10	pA/°C
Input Bias Current				3.0			10	nA
Supply Current	$T_A = +125°C$		0.15	0.4				mA
Large Signal Voltage Gain	$V_S = \pm 15V$, $V_{OUT} = \pm 10V$ $R_L \geq 10\ k\Omega$	25			15			V/mV
Output Voltage Swing	$V_S = \pm 15V$, $R_L = 10\ k\Omega$	±13	±14		±13	±14		V

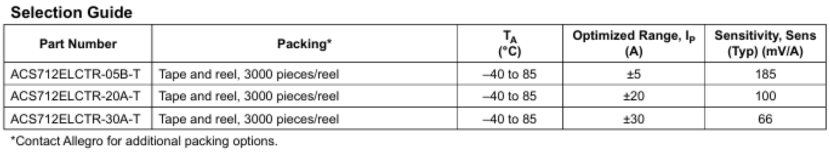
Dual-In-Line Package



Top View

Order Number LM108J-8/883, LM308M or LM308N
See NS Package Number J08A, M08A or N08E

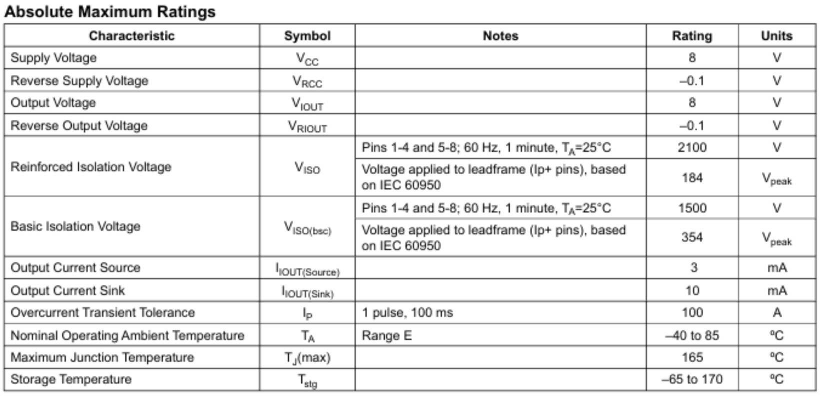
Appendix B: ACS712



Selection Guide

Part Number	Packing*	T_A (°C)	Optimized Range, I_P (A)	Sensitivity, Sens (Typ) (mV/A)
ACS712ELCTR-05B-T	Tape and reel, 3000 pieces/reel	–40 to 85	±5	185
ACS712ELCTR-20A-T	Tape and reel, 3000 pieces/reel	–40 to 85	±20	100
ACS712ELCTR-30A-T	Tape and reel, 3000 pieces/reel	–40 to 85	±30	66

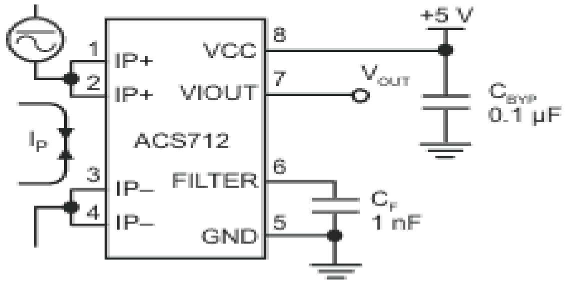
*Contact Allegro for additional packing options.



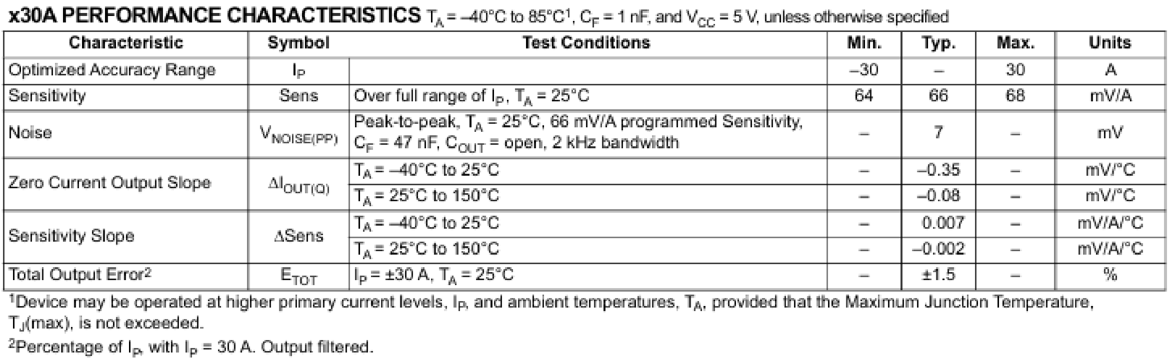
Absolute Maximum Ratings

Characteristic	Symbol	Notes	Rating	Units
Supply Voltage	V_{CC}		8	V
Reverse Supply Voltage	V_{RCC}		–0.1	V
Output Voltage	V_{IOUT}		8	V
Reverse Output Voltage	V_{RIOUT}		–0.1	V
Reinforced Isolation Voltage	V_{ISO}	Pins 1-4 and 5-8; 60 Hz, 1 minute, T_A=25°C	2100	V
		Voltage applied to leadframe (Ip+ pins), based on IEC 60950	184	V_{peak}
Basic Isolation Voltage	$V_{ISO(bsc)}$	Pins 1-4 and 5-8; 60 Hz, 1 minute, T_A=25°C	1500	V
		Voltage applied to leadframe (Ip+ pins), based on IEC 60950	354	V_{peak}
Output Current Source	$I_{IOUT(Source)}$		3	mA
Output Current Sink	$I_{IOUT(Sink)}$		10	mA
Overcurrent Transient Tolerance	I_P	1 pulse, 100 ms	100	A
Nominal Operating Ambient Temperature	T_A	Range E	–40 to 85	ºC
Maximum Junction Temperature	T_J(max)		165	ºC
Storage Temperature	T_{stg}		–65 to 170	ºC

Typical Application



Application 1. The ACS712 outputs an analog signal, V_{OUT}. that varies linearly with the uni- or bi-directional AC or DC primary sensed current, I_P, within the range specified. C_F is recommended for noise management, with values that depend on the application.



x30A PERFORMANCE CHARACTERISTICS T_A = –40°C to 85°C[1], C_F = 1 nF, and V_{CC} = 5 V, unless otherwise specified

Characteristic	Symbol	Test Conditions	Min.	Typ.	Max.	Units
Optimized Accuracy Range	I_P		–30	–	30	A
Sensitivity	Sens	Over full range of I_P, T_A = 25°C	64	66	68	mV/A
Noise	$V_{NOISE(PP)}$	Peak-to-peak, T_A = 25°C, 66 mV/A programmed Sensitivity, C_F = 47 nF, C_{OUT} = open, 2 kHz bandwidth	–	7	–	mV
Zero Current Output Slope	$\Delta I_{OUT(Q)}$	T_A = –40°C to 25°C	–	–0.35	–	mV/°C
		T_A = 25°C to 150°C	–	–0.08	–	mV/°C
Sensitivity Slope	ΔSens	T_A = –40°C to 25°C	–	0.007	–	mV/A/°C
		T_A = 25°C to 150°C	–	–0.002	–	mV/A/°C
Total Output Error[2]	E_{TOT}	I_P = ±30 A, T_A = 25°C	–	±1.5	–	%

[1] Device may be operated at higher primary current levels, I_P, and ambient temperatures, T_A, provided that the Maximum Junction Temperature, T_J(max), is not exceeded.

[2] Percentage of I_P, with I_P = 30 A. Output filtered.