Interruption reduction at substations using Battery energy storage systems

By

Disebo Cornelia Sesing

212560181

A dissertation submitted in partial fulfillment of the requirements for the degree

Of

Master of Science in Electrical Engineering

College of Agriculture, Engineering and Science, University of KwaZulu-Natal

2019

Supervisor: Dr. A. Saha

As the candidate's Supervisor I agree/do not agree to the submission of this thesis. The supervisor must sign all copies after deleting which is not applicable

Signed: ________________________________

Dr. A Saha

I Disebo Cornelia Sesing declare that

1. The research reported in this thesis, except where otherwise indicated, and is my original research.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) Their words have been re-written but the general information attributed to them has been referenced

b) Where their exact words have been used, then their writing has been placed in italics and inside quotation marks, and referenced.

5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

Signed: ___________________________________

Disebo Cornelia Sesing

ACKNOWLEDGEMENTS

I would like to acknowledge the unending support from my family, friends, and loving partner. I appreciate the help rendered during the year; without them it would have been very difficult to pursue my passion for learning. I would also like to give thanks to Eskom Holdings SOC Ltd -distribution division for the 2 years of training after obtaining my undergraduate (BScEng) qualification. The exposure to the country's power distribution systems/grids empowered the ability to identify some of the major issues surrounding the life-cycle of electricity from generation to distribution and use; such as the large amount of losses that occur when more power than what's needed is produced and the preventative measures that can be taken to mitigate the problems at hand, including but not limited to the use of power storing devices. The topic for the Thesis came about after realizing what lacked in existing power system networks. Lastly, I would like to give my sincerest appreciation to my supervisor Dr. AK Saha. We all need someone who believes in us even when we are doubting ourselves, a person to remind us of how great we can be if we put in sufficient effort. Thank you for the encouragement and guidance throughout this chapter of my life, of all the wise things said "it's okay not to get it right on the first try, you must just never give up", is what I will be taking with me from this point forward.

ABSTRACT

Reliable electrical power supply is vital in the modern society and electrical distribution utilities are responsible for ensuring continuity of supply. South Africa is experiencing a rapid increase in electrical power demand; with the number of people requiring electrification growing continuously. Eskom’s capacity to generate excess electricity is completely used up as the currently installed transformers are of a certain fixed rating and cannot accommodate the rapid continuous growth, resulting in the utility not being able to meet the power demand. The concept of load shedding is utilized when supply cannot meet demand due to certain system constraints and demand reduction is required; it is also regarded as a last resort action taken to prevent the collapse of the power system and protect the current electrical power equipment connected to the system. The constraints are mainly due to the incapability to store the power at any point in the supply, traditionally electrical power generation plants typically produce more energy than necessary to ensure adequate power quality at the points of transmission and distribution as a large percentage of the energy is lost in the power station as waste heat and even more losses occur at the power lines when the generated is transmitted for use; thus raising a need to implement a system to save as much of the discarded energy in between the points of the life-cycle of electricity such as battery energy storage systems (BESS). BESS is useful for its prompt capacity to adjust power well as the characteristics of storage and supply capability. The utilization of BESS for the reduction of network power loss and management of network congestion is the key factor to realize the optimal operation of distribution networks as it can store excess power that can be later utilized when there’s a shortage in the system.

In this dissertation, the integration of BESS into electrical Distribution systems is investigated, with the objective to reduce the power supply interruptions that occur at the substations (planned/unplanned) and know-how BESS can be used to improve the performance of a distribution system. The proposed methodology consists of two main parts.

The first one is of design and simulation of a balanced substation; It’s important to ensure that the substation is operating within its specifications as a standalone before any external features are added to improve the already existing adequate performance. And separately, a BESS with a control method for State of Charge (SoC) for the battery considering the network power loss during both grid and off-grid operation to ensure smooth BESS operation without compromising the voltage regulation performance of the network; as the basis of the investigation, consecutively. The second part consists of integrating the two models (Substation & BESS) and conducting simulation studies to obtain unique scenario-based outcomes. The optimal placement of BESS is investigated as the efficiency of integrating it into large-scale distribution networks depends on it. The substation and BESS are modelled and simulated using MATLAB Simulink to verify the effectiveness of the proposed methodology and based on the research it is evident that BESS integrated distribution systems solutions to overcome shortage created by load shedding or any other interruptions (planned/unplanned) are the best way to go in maintaining continuity of supply to customers.

Table of Contents

ACKNOWLEDGEMENTS iii
ABSTRACT iv
List of Abbreviations vii
List of Figures viii
List of Tables ix
1. Introduction 1
  1.1. Theoretical background 2
    1.1.1. Electrical power systems 2
    1.1.2. Load shedding 4
    1.1.3. Battery Energy storage systems 5
    1.1.4. Control methods to charge/discharge BESS 7
  1.2. Research motivations 8
  1.3. Objectives and Aims 8
  1.4. Dissertation structure 9
Chapter 2 10
2. Literature Review 10
  2.1. Services provided by BESS 10
  2.2. BESS Optimization Techniques 11
Chapter 3 17
3. Methodology 17
  3.1. Assumptions 17
  3.2. Optimization Technique 18
    3.2.1. Genetic Algorithm 18
    3.2.2. Sequential quadratic programming 21
  3.3. Optimal placement of BESS 22
    3.3.1. BESS at primary substation 22
    3.3.2. BESS at secondary substation 22
    3.3.3. BESS at the loads 23
Chapter 4 24
4. Test Model Simulations 24
  4.1. Substation Modelling and analysis 24
    4.1.1. Distribution transformer analysis 25
    4.1.2. Distribution load analysis 27
    4.1.3. Contingency plan analysis 32
  4.2. BESS modelling and analysis 39
    4.2.1. Power conversion system model 39
    4.2.2. Battery management system model 40
    4.2.3. Utility and Load transformer model 43
Chapter 5 47
5. Integrating BESS into Substation 47
  5.1. Busbar 2A supplied by BESS 1 47

  - 5.2. Busbar 2B supplied by BESS 2 49
  - 5.3. Busbar 2C supplied by BESS 3 51

Chapter 6 54

6. Conclusion 54

References 55

Appendix A: Distribution system 62

Appendix B: Battery Energy Storage system 67

List of Abbreviations

A	Ampere
AC	Alternating Current
BESS	Battery Energy Storage System
DC	Direct Current
HV	High Voltage
kV	Kilo Volt
kW	Kilo Watts
LV	Low Voltage
MV	Medium Voltage
MVA	Mega Volts Ampere
MW	Mega Watts
PSO	Particle Swarm Optimization
V	Voltage
W	Watts
GA	Genetic Algorithm
SQP	Sequential quadratic programming
PCS	Power conversion system
BMS	Battery Management system
PWM	Pulse width modulation
RMS	Root means square
IGBT	isolated-gate bipolar thyristor
PLL	phase lock loop
SoC	State of Charge
BB	Busbar
OPF	optimal power flow
MISOCP	Mixed integer second order cone programming
GAMS	General algebraic modelling system
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
p. u	Per unit measurement
d.q	Direct-quadrature transformation

List of Figures

Figure 1: Electrical power system block diagram process 2
Figure 2: Electrical Power Generation Process 2
Figure 3: Electrical Power Transmission Process 3
Figure 4: Electrical Power Distribution Process 3
Figure 5: Main Structure a battery energy storage system 6
Figure 6: Example of Chromosome representation 18
Figure 7: Simple GA process 20
Figure 8: GA process combined with SQP 21
Figure 9: Integrating BESS via the HV busbar block diagram 22
Figure 10: Integrating BESS via the MV busbar block diagram 22
Figure 11: Integration of BESS directly to the loads block diagram 23
Figure 12: 88/11/0.4 kV distribution systems block diagram 24
Figure 13: Distribution Transformer measured Voltage values 25
Figure 14: Mini-Substation Transformer primary parameters 26
Figure 15:Mini-Substation Transformer Secondary parameters 26
Figure 16: Industrial load 1 parameters 28
Figure 17: Industrial load 2 parameters 28
Figure 18: Industrial load 3 parameters 28
Figure 19: Industrial load 4 parameters 29
Figure 20: Residential load 1 parameters 29
Figure 21: Residential load 2 parameters 30
Figure 22: Residential load 3 parameters 30
Figure 23: Residential load 4 parameters 30
Figure 24: Industrial load 5 parameters 31
Figure 25: Industrial load 6 parameters 31
Figure 26: Residential load 5 parameters 31
Figure 27: Residential load 6 parameters 32
Figure 28: Transformer 1 isolation configuration 33
Figure 29: Transformer 2 isolation configuration 33
Figure 30: Connecting busbar 2B to transformer 1 configuration 34
Figure 31: Connecting busbar 2B to transformer 3 configuration 34
Figure 32: Transformer 3 isolation configuration 35
Figure 33: Connecting busbar 2C to transformer 2 configuration 35
Figure 34: Transfer busbar configuration 36
Figure 35: Transformer 1 and 2 simultaneous outage configurations 36
Figure 36: Transformer 2 and 3 simultaneous outage configurations 37
Figure 37: Transformer 1 and 3 simultaneous outage configurations 37
Figure 38: Busbar 2B loads without supply 38
Figure 39: Overview of battery energy storage system implemented 39
Figure 40: PCS Model overview 40
Figure 41: Battery Management system overview 40
Figure 42: PWM Signal 41
Figure 43: Six pulse inverter voltage 41
Figure 44: Six pulse Filter voltage 42
Figure 45: RMS Six pulse Filter voltage 42
Figure 46: BESS overview connected to busbar 2A with Industrial load 43
Figure 47: BESS overview connected to busbar 2B with Residential load 43
Figure 48: BESS overview connected to busbar 2C with Residential and Industrial load 43
Figure 49: Step -up transformer1 secondary phase voltage 44
Figure 50: Step-up transformer2 secondary phase voltage 44
Figure 51: Residential load parameters connected to BESS 45
Figure 52: Industrial load parameters connected to BESS 45
Figure 53: Battery Parameters connected to busbar 2A with Industrial load 46
Figure 54: Busbar 2A BESS connected battery parameters 47
Figure 55: Industrial load 1 supplied by BESS 1 parameters 48
Figure 56: Industrial load 2 supplied by BESS 1 parameters 48
Figure 57: Industrial load 3 supplied by BESS 1 parameters 48

Figure 58: Industrial load 4 supplied by BESS 1 parameters 49
Figure 59: Busbar 2B BESS connected battery parameters.. 49
Figure 60: Residential load 1 supplied by BESS parameters 50
Figure 61: Residential load 2 supplied by BESS parameters 50
Figure 62: Residential load 3 supplied by BESS parameters 50
Figure 63: Residential load 4 supplied by BESS parameters 51
Figure 64: Busbar 2C BESS connected battery parameters.. 51
Figure 65: BESS connected directly to Busbar 2C loads 52
Figure 66: Industrial load 5 supplied by BESS parameters 52
Figure 67: Industrial load 6 supplied by BESS parameters 52
Figure 68: Residential load 5 supplied by BESS parameters 53
Figure 69: Residential load 6 supplied by BESS parameters 53
Figure 70: Incoming line source configuration.. 62
Figure 71: Three phase measuring tool configuration 62
Figure 72: Distribution transformer setup 63
Figure 73: Substation Transformer parameter configuration window.. 64
Figure 74: Industrial Load model setup.. 65
Figure 75: Industrial Load parameter configuration window 65
Figure 76: Mini-Substation Setup... 66
Figure 77: Residential Load Configuration window 66
Figure 78: Battery parameter settings window 67
Figure 79: BESS for busbar 2A 67
Figure 80: BESS for busbar 2B 68
Figure 81: BESS for busbar 2C 68

List of Tables

Table 1: Comparison of different optimization techniques in placement schemes...................... 13
Table 2: Summary of literature based on optimal placement and operation of BESSs 14
Table 3: Calculated 88/11 kV Transformer parameters.. 25
Table 4: Calculated 500kVA 11 kV/400V Transformer parameters 26
Table 5: Expected load current values.. 27

Chapter 1

1. Introduction

The energy demand in the country has been increasing exponentially, and the traditional fossil fuels used as energy resources are depletable with limited supply (i.e. coal). Therefore, it is vital to conserve what the country currently has and scout other prospective energy resources. The use of renewable energy for power generation has increased over the years, but it's the kind of power that is dependent on the weather conditions as it is the nature of the renewable energies [47]. Battery energy storage systems are introduced to the power system to reduce the power quality loss and stabilize the voltage and frequency oscillations. Integrating BESS with distribution network systems may assist in mitigating the majority of problems caused by large scale renewable-energy integration to achieve some economic operation goals caused by power outages. [1]

The existing operation mandate of Electric networks in South Africa is based on the principle of supply meeting the load demands instantaneously, from generation networks to control Centres. Operations are based on the configuration of networks, to ensure optimal energy flow, to minimize technical losses by maintaining the balance between power in and power out across the entire network and maintain an effective quality of supply to all parts of the network under normal and abnormal conditions [47] in real-time. The concept of load shedding is formulated when supply cannot meet demand due to certain system constraints (i.e. slow decline in frequency) and demand reduction is required implying that certain customers are to be without supply which goes against the mandate. The root cause of this constraint has been the inability to store Electricity at any point in the supply chain (Generation-Transmission- Distribution) [2].

Battery energy storage system (BESS) is the fundamental factor to obtain the best possible control and operation of distribution networks, due to its capability to store, supply and adjust power capacity in the system. BESS can contribute to minimizing the ever-increasing energy shortage and environmental pollution problems [3] faced by the country; and can also enable for distribution networks to have flexible power management allowing the load to be supplied by the substation or BESS [4]. There is an increase in the integration of energy storage systems in distribution networks, with the hope of the storage systems offering more technical, economic and environmental solutions. These solutions include improving the power quality, reducing voltage variance, frequency regulation, load shifting and levelling and reducing outage costs [43]. The main aim of embedding BESS in distribution networks is to effectively relieve the problems posed by sudden and unexpected load changes, interruptions that occur at transmission or distribution systems, and most importantly to assist distribution network utilities to provide power demands reliably. Misallocating BESS in distribution network buses can degrade power quality supplied to customers and reduce the reliability of load control while also affecting voltage and frequency regulation. Thus, the optimal placement thereof must be investigated thoroughly beforehand. [5]

1.1. Theoretical background

1.1.1. Electrical power systems

The electrical power system consists of three principal components generation, transmission grid and distribution systems. The electricity is generated at the power stations which is then transferred over large distances to distribution systems via transmission line conductors. Once the power reached the distribution network systems, it gets distributed to large numbers of critical and non-critical loads of various customers.

Figure 1: Electrical power system block diagram process

Electrical energy can be referred to as a manufactured commodity. It involves the conversion of various forms of energy in nature into the electrical nature, referred to as the generation of electrical energy. The electrical energy produced in the generation phase is instantly transmitted to the usage point it’s needed. Many factors need be considered when the instantaneous process of electrical energy production takes place, regarding the technical and economic implications to the electrical power industry [6]. Electricity has become an absolute necessity in modern society, the dependence thereon for the day-to-day operations is enormous. The power stations used to generate the electrical power achieves the economical goal of providing bulk electrical power for the ever-increasing usage thereof in residential and industrial based applications [14]. The design of power systems network should comprise of generating equipment that will maximize the financial returns from minimum spending as far as the working lifespan of the station apparatus are concerned; and even with the minimum expenditure for the systems, the operations should still provide reliable and continuous services at all times [7].

All the various forms of energy can be converted into electrical energy, with the usage of suitable machines and equipment arranged properly [20]. The typical arrangement is made of an alternator coupled to turbine known as the prime mover. The prime mover is operated by the energy obtained from various sources such as the burning of coal. The chemical energy obtained when coal is burnt is utilized to produce the steam to drive the steam turbine at high temperature and pressure. The alternator receives the mechanical energy obtained from the conversion of steam’s heat energy and converts it into electrical energy [25]. Figure 2 depicts the power generation, the electrical energy from the alternator is stepped up to extra-high voltage (EHV) before its transmitted.

Figure 2: Electrical Power Generation Process

Generators in the power plant of power stations produce a relatively low voltage that is not appropriate for long-distance energy transmission- the lower the voltage, the higher the current which will result in high losses. A step-up transformer is utilized to increase the voltage to extra-high voltage (e.g. 500kV) that way the current will be reduced, and the voltage can be transmitted via the transmission line to the transmission substation. The transmission substation consists of a step-down transformer, used to decrease the extra high voltage to just normal high voltage (e.g. 88kV) that is transmitted to the distribution network(s).

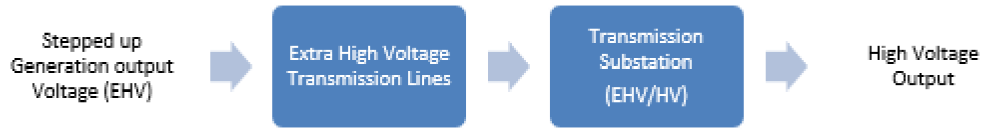


Figure 3: Electrical Power Transmission Process

Distribution systems consist of step-down transformers, that transforms high voltage to medium voltage at substations and medium voltage to low voltage at miniature substations (Mini-substations). Mini substations supply Residential load and industrial loads are supplied directly from the substations.

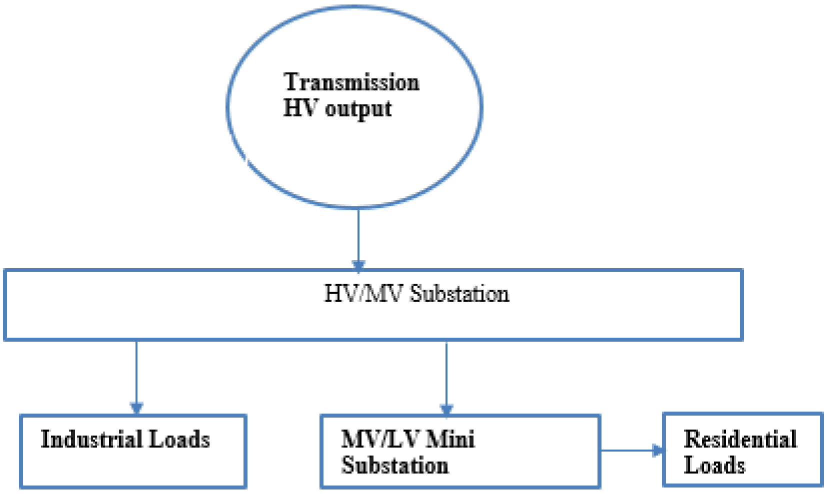


Figure 4: Electrical Power Distribution Process

1.1.2. Load shedding

South Africa has experienced an exponential rate for the need of electricity because of the load and economic growth it is faced with. The continued growth in the economy has completely consumed Eskom’s ability to generate more electricity with the current electrical power systems. The country’s utility company is at the point where additional capacity will only be obtained by building new power stations to accommodate the load growth or by reducing a substantial amount of the national electricity demand in the attempt to stabilize and protect the power system networks. South African Power delivery is balanced by supply and demand and there is no storage of excess power generated at any point in the paradigm. When the supply cannot meet the demand due to certain system constraints then demand reduction is required.

The load growth escalated to a point where there isn’t enough capacity for the supply to meet demand, causing the electrical system to be unstable. The power equipment is being overloaded and being worked towards their life span much quicker than anticipated, which implies the expected maximum returns are not obtained. Load shedding occurs when supply cannot meet demand and it is implemented as the last protection resort to prevent the collapse that will lead to a blackout. Even though the systems are prevented from collapsing, load shedding has negative implications for the country’s economy and the performance indices measurements of the substations. Load shedding schedules are drawn up in advance by the utility’s network security planners to describe the switching sequence plan for the days that load shedding is necessary. parts of the network are switched off in an organized and controlled manner, resulting in the stability of the system throughout the period of load shedding. There are two types of load shedding, more details of what it is about and the process to go about carrying out certain tasks to provide the necessary output are provided in the subsequent subsections.

1.1.2.1.Manual Load shedding (MLS)

Load shedding takes place to reduce load when supply cannot meet demand. In South Africa, the AC operating frequency is 50 Hz. And when the three-phase grid frequency drops below 50 Hz indicating power source/load imbalance, it triggers load shedding which is carried out to balance the power supplied and the load consumed in the power system. When the system is tight and supply is constrained then this causes a slow decline in frequency. Sometimes a constrained system can be predicted based on the forecasted generation and expected load. Manual load reduction is an intervention to arrest the slowly declining frequency. Load shedding guides are used to determine which set of customers are to be shed on certain days and times according to the stage called by National Control. Manual load shedding starts with 5% of the network being switched off and it consists of five stages. The schedule works on an additional principle, that is 5% of each stage is added to the previous stage when the shedding occurs. Stage 5, this includes the 4 blocks shed from stage 4 PLUS an undisclosed amount of load that must be taken off from the network.

1.1.2.2. Automatic Load Shedding/ Under Frequency load shedding (UFLS)

When large amounts of generation are lost in quick succession without warning, the system experiences a sudden shock causing the frequency to decline very rapidly (in the order of milliseconds). This cannot be arrested by manual intervention and must be done automatically to prevent the entire grid from cascading into a complete blackout. UFLS is a protection mechanism which is part of the emergency resources required for system security. It is of utmost importance that this protection mechanism is fully functional, tested and maintained regularly. UFLS is carried out by relays that are strategically placed at certain substations and continuously monitor the system frequency in real-time. Two (2) parameters define the trip signal of a UFLS relay, i.e. frequency setting and time delay. The relays issue a trip signal after the frequency has reached the set point of the relay and lasts for as long as the time delay setting. The seven layers of UFLS are defined according to the two parameters of the relay as follows:

The first 3 layers are traditionally known as Customer Voluntary Automatic (CVA), where customers agreed to have these relays placed on their networks. A total of 10% of the demand at the time of the incident must be shed by CVA; customer sensitivity is also prioritized. Least sensitive customers are pushed towards the later target of CVA. If after all three targets of CVA have been successfully executed and the system frequency has still not yet stabilized, then the next 4 layers of UFLS must kick in. The next 4 layers are known as MANDATORY stages and in total, 40% of the network load must be shed when UFLS is executed. The NRS 048-9 is the guideline by which load reduction should be carried out. It is used for determining which customers in the network must be excluded from the shedding schedule and which customers can be excluded on a special request basis.

The most of the information relating to load-shedding was obtained from Eskom Holdings SOC Ltd -distribution division, which became familiar during the duration spent training in the network optimization department. As mentioned at the beginning of the subsection (1.1.2) regarding load shedding- that it is a tool used for preventative measures to ensure that total blackout (total power shutdown) doesn’t occur. However; the occurrence thereof leaves many customers without supply, which goes against the mandate of providing customers with continuous reliable power supply. The introduction of energy storage into the current power systems will thus eliminate the agony of customers being without supply for the times when the system is not operating under normal conditions as Power delivery is balanced by supply and demand and there is no storage of excess power generated.

1.1.3. Battery Energy storage systems

The accelerated depletion of fossil fuels, increasing power demands, and harmful consequences of fossil fuels on the environment are resulting in the crucial need for the usage of alternate energy resources. An energy storage system is the ability of a system to store energy using the likes of electro-chemical solutions [17]. Solar and wind energy are the top projects the world is embarking on as they can meet future energy requirements, but because they are weather-dependent it is necessary to store the energy generated from these sources [9]. Energy storage systems absorb the excessive energy when generation exceeds predicted levels and supply it back to the grid when generation levels fall short [19]. Electric Storage technologies can be utilized for storing excess power, meeting peak power demands and enhance the efficiency of the country’s power system [18]; these technologies include electrochemical, water electrolysis, compressed air, flywheels and superconducting magnetic energy storage.

Battery energy storage systems (BESS) are a sub-set of energy storage systems that utilize electrochemical solutions, to transform the stored chemical energy into the needed electric energy [11]. A BESS is of three main parts; batteries, inverter-based power conversion system (PCS) and a Control unit called battery management system (BMS). Figure 5 presents the block diagram structure of BESS.

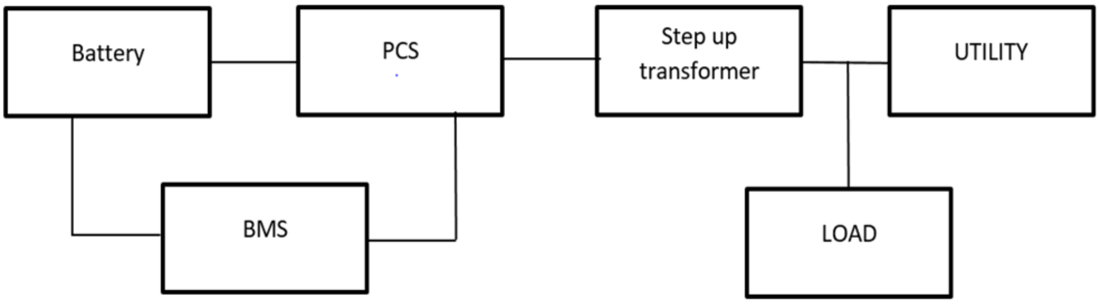


Figure 5: Main Structure a battery energy storage system

Battery systems are made of different types of rechargeable secondary batteries; batteries that can be charged. The following sub-sections discuss the main features of various types of batteries

1.1.3.1. Lead Acid

These are the oldest and evolved batteries. They consist of a sponge metallic lead anode, a lead-dioxide cathode and a sulfuric acid solution electrolyte. They have numerous favourable traits such as relatively affordable, simplicity of manufacturing thereof, and acceptable life cycle under measured conditions [10], with a major drawback of using a heavy metal component that makes them harmful to the environment. Due to the high cost associated with them, the limited life-span and low energy density, these batteries are not advantageous for the large-scale applications [8].

1.1.3.2.Sodium Sulphur (NaS)

They are regarded as the most advanced high-temperature batteries, even though they are relatively new in power system applications [15]. Made of active materials of molten sodium and molten Sulphur, separated by a solid beta alumina ceramic electrolyte. They are favourable to use in relatively large-scale BES applications; due to their inexpensive materials, exceptional high energy density, high-efficiency charge/discharge rate, zero maintenance, and long-life specifications [13]. However, there are a few large-scale application restrictions, such as high-temperature condition that require to maintain Sulphur in its molten form addressed as a small threat to the operators and environment [18]. The system must constantly be monitored, to prevent the reaction with the atmosphere, because the interaction of pure sodium with air will result in a disastrous explosion instantly.

1.1.3.3.Lithium- ion (Li-ion)

These batteries are composed from lithium metal or lithium compounds as an anode. They comprise of advantageous traits such as being lightweight, safety, abundancy and affordable material of the negatively charged electrode “cathode” making them an exciting technology to explore [16]. Li-ion batteries offer higher charge densities and have a minimum environmental impact as the lithium oxides can be recycled. They can provide the much-needed power by the network instantaneously due to the response time that’s in the order of milliseconds [20]. Li-ion batteries are highly reassuring for large grid-scale applications due to their ability to decrease outage costs and desirable functionalities such as providing a high-power capacity, low self-discharge and the highest efficiency. The major disadvantages are that they have capacity loss over time and their ageing is accelerated by high operating temperature [13].

Although various BESS technologies exist with relevant benefits, Li-Ion BESS are more promising for large scale application. Therefore, lithium-ion BESS will be considered for this dissertation

1.1.4. Control methods to charge/discharge BESS

The BESS is operational in two modes; the discharging mode to alleviate the utility when the distribution network is down or during the peak-load period time and charging mode to fill the battery bank during an off-peak period or when the network gets restored. Possible ways to discharge the BESS [14], with the assumption the batteries are fully charged are:

- Time based control with constant discharge rate
- Time-Temperature based control with stable discharge
- Time-Temperature Control with variable discharge
- Power or Voltage control
- Radio-Control (part of SCADA system)

Battery management system (BMS) is an efficient control for the power conversion systems (PCS) in both the charge and discharge storage modes, that is designed for the distribution system operations [15]. The PCS with the help of BMS can supply back-up power with a low distortion AC voltage to the distribution loads via the point of common interconnection via a breaker [16]. The main Control features of PCSs to consider are [15], [16]:

- **Active/Reactive power control**

The PCSs provide both active and reactive power control functions. When the active/reactive command value exceeds the rated value, active power output takes priority over reactive power. PCS controls the charge/discharge flow of the battery bank as required according to the active/reactive power command from the remote SCADA system.

- **Grid Interaction features**

Grid regulations for distribution systems have critical requirements on control functions of PCS, such as low voltage ride-through (LVRT), and the control functions are stored in the control circuit of PCS. The auto-restart function is one of those included in the control circuit, to ensure that the PCS can disconnect from the grid automatically when a grid fault is detected, and also enable for the PCS to restart and reconnect to the grid automatically when the fault is cleared.

- **Stand-alone operation**

When the grid fails, the PCS can switch to stand-alone operation to supply the network loads independently, and when the grid recovers the PCS can switch back to normal operation mode to charge/discharge. The PCS provides the rated AC voltage at the rated frequency to load.

1.2. Research motivations

Eskom is South Africa’s utility, responsible for 95% of the energy supplied within the country. The process of generating and distributing electricity is instantaneous, and this results in a large amount of wasted capacity between the generation, transmission and distribution (for use) of the electricity. The rise in population and industrial ventures, has placed a high demand regarding the electrical needs, which cannot be met from the present generation capacity as the demand is becoming greater than the available supply. The current distribution system is unsatisfactory for its customers, its constantly experiencing load shedding due to the loss of major generators at the power station because of the system operating on overload. Load shedding is designed to distribute the available power to consumers by turning off one area and supplying another in attempt to serve all the customers at different intervals. The process is equivalent to Substation interruptions “outages”. Illegal connections also contribute to substation overloads and trips, as the network is carrying more users than it was originally designed for. As a result of these events, several types of energy storage technologies are evaluated and installation of battery energy storage system to stabilize and improve the overall distribution system, through supplying continuous undisturbed power.

Battery energy storage systems are used to supply the stored energy when needed in the system; therefore, the installation thereof on the large –scale grid may reduce any interruptions on the secondary side of the substation leaving customers- both industrial and residential with a continuous supply of electricity regardless of whether the network is operating under normal or abnormal conditions [24], resulting in the country’s problem of having to switch power off being resolved. There aren’t any large-scale Battery energy storage systems that are currently installed in South Africa as they are very expensive thus low in demand. However, due to the depletion of traditional resources such as fossil fuels and alarming concerns pertaining environmental pollution, the use of renewable energy continues to grow as it provides power security and helps conserve the remaining natural resources. Deploying BESS could be an optimum alternative solution to achieve the reduction of the carbon footprint as well as provide the much-needed continuous supply and also provide lower electricity pricing to customers as demand charges will no longer exist if the need to reduce loads will be eliminated as power will be dispatched to the network at any given time when the need arises. It is vital to research on the power capacity of a system before any implementations take place and how the placement thereof could affect the quality of the existing networks.

1.3. Objectives and Aims

The first objective is to investigate the Merits and operational characteristics of different Battery energy storage technologies. The second objective is to develop the power conditioning system (PCS) for BESS. The third objective is to investigate the optimal placement and operation of Battery Energy Storage system in distribution networks. The fourth objective is to develop approaches for effective sizing and control methods of BESS for multiple distribution network applications. The research aims to attempt to answer the following research questions:

- How can BESS be used to improve the performance of the Distribution Networks?
- What are the key considerations of BESS sizing, placement and control strategies?
- How to design an effective BESS control algorithm to prolong the life of BESS when used for voltage regulation?

1.4. Dissertation structure

The Dissertation is made of six chapters, following this introductory chapter. The rest of the Dissertation is organized as follows:

In chapter 2, literature review of past works on the integration of BESS into distribution networks and BESS control approaches are presented

In chapter 3, the methodology to identify the optimal location to place the BESS when integrated with electrical Distribution system(s) to improve the performance of the network under normal and abnormal operating conditions

In Chapter 4, simulations models of a distribution network system and BESS using MATLAB Simulink are formulated and analyzed. The control method for BESS is such that the distribution voltage performance is not compromised.

In Chapter 5, the simulation studies conducted to investigate the optimum location for the integration of Battery energy storage systems at the substation for emergency backup are presented and analyzed.

In Chapter 6, conclusion of the dissertation is provided, with recommendations for potential future research problems outlined.

Chapter 2

2. Literature Review

This chapter provides the existing research for optimal BESS placement at distribution systems and how the BESS can be used to address operational problems of substations, the algorithms and strategies used, testing bus, and various services provided by BESS. Approaches based on intelligent optimization techniques for optimal BESS placement in distribution networks have been proposed in many works; to be discussed in the sub-sections to follow.

2.1. Services provided by BESS

Ancillary services are the services necessary to support the electric power systems from generation to distribution given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission systems [72]. The technical need for these services is growing daily thus the demand for energy storages to provide these services is growing too. Sustained load growth in the electric power industry has resulted in intensive usage of grid assets, and infrastructure is unable to evolve at the same rate, and this has led to the grid being over-loaded frequently, therefore, congestion management has become vital to maintaining the required level of reliability of power supply [81]. Congestion is traditionally managed by generation rescheduling and/or load shedding that leaves customers without supply and this incurs huge additional costs as distribution companies need to provide huge incentives for changing their pre-committed schedules (usually applies for industrial customers).

Research on BESS technology, development, applications and benefits is reported as follows: [62] presents Congestion Relief Using Grid Scale Batteries. A cost-efficient congestion management scheme using distributed Battery energy storages with minimum adjustment to the pre-committed schedules of loads. Distribution System operators face penalties or pay compensatory costs when they are unable to supply electricity reliably to customers; supply reliability can be increased by employing high-reliability technology (which could be very expensive) or backup supply.

Narayanan A et al [1] presents Interruption Reduction in Secondary Substations. A mixed-integer linear programming model to determine the economic feasibility of installing BESS at the secondary substation in a medium voltage network. A microgrid is assumed to be a portion of the low voltage distribution feeder with a slow response for frequency control. [**63**] Presents a method for determining the optimal size of a battery energy storage system (BESS) for primary frequency control of a Microgrid. Battery Energy storage system due to its very fast dynamic response can play an important role in restoring the balance between supply and demand, provide primary frequency control during a disturbance; Due to variation of environmental conditions, the power generated from renewable energy sources always fluctuates. Therefore, by injecting wind power into the electric grid, some power qualities may start varying due to wind speed fluctuating. Ghorbanian M.J et al [66] presents a Power quality improvement of grid connected doubly fed induction generator using STATCOM and BESS. Static Synchronous compensator and Battery energy storage system implementation to address the issue of voltage stability in wind farms connected to distribution networks by improving transient stability and dynamic behaviour of power systems; BESS was used for mitigation of voltage disturbance caused by the connection of the doubly-fed induction generator wind turbine to the grid.

Wind power has a great impact on the operation and control of the existing power system because of the variability and unpredictability thereof, and; BESSs are expected to mitigate such negative effects as they have great potential for providing energy buffer and additional power regulation capabilities. [67] presents a risk-constrained coordinative dispatching method for BESSs of wind farms, the energy storage of the wind farm will be utilized for multiple applications at the same time including forecast error compensation and short-term volatility control. The proportion of the BESS utilized for different applications will be optimized with a risk-constrained stochastic optimization method.

Integration of energy storage in power distribution systems is expected to be high in the future to manage the power variations from decentralized renewable energy resources and meet the load demand reliably. Karthikeyan N et al [2] presents the utilization of battery storage for flexible power management in active distribution networks. BESS with optimal control method is utilized for peak shaving, reduction of network power loss and network congestion management is addressed for a low-voltage active distribution network. Power quality events during grid disturbances such as feeder tripping and re-closing, voltage sag, swell and load switching have been studied in association with the distribution static compensator (DSTATCOM); Mahela O.P et al [9] presents Power Quality Improvement in distribution network using DSTATCOM with battery energy storage system. The DSTATCOM provides fast control of active and reactive power to enable load compensation, harmonics current elimination, voltage flicker mitigation, and voltage and frequency regulation.

Battery energy storage system (BESS) plays great roles in peak shaving, improving voltage quality and providing active power adjustment capacity. Qing Z et al [3] presents Optimal sitting & sizing of battery energy storage system in an active distribution network. Focuses on the multi-objective optimal model for BESS in Active Distribution Network concerning on peak shaving capacity, voltage quality and active power adjustment capacity. Kein Huat Chua et al [69] have introduced an effective sizing and optimal peak shaving techniques for Energy storage system to reduce the peak load demand. A cost-savings analytical tool is created to provide a quick way for users to determine the optimal energy storage system sizing for various tariff schemes. Alexandre Oudalov et al [70] have proposed BESS sizing technique and optimal operating plan to procure a peak load shaving. The proposed optimization can reduce the payment of power demand with a BESS of a minimum size for maximizing a customer’s economic benefit

2.2. BESS Optimization Techniques

There are different types of algorithms that can be implemented for the optimized BESS usage, which will be discussed in this sub-section. Table 1 depicts the comparison of different optimization techniques used widely for various optimal placement applications. comparison is done based on where is it more suitable to employ each algorithm when incorporating and scrutinizing the advantages and disadvantages. Table 2 provides existing research on BESS placement and operation problems when integrated into the distribution systems and objectives to be fulfilled, based on different techniques/algorithms, testing bus, advantages and limitations [5]. Future research opportunities relating to challenges for optimal placement of BESS are also identified. Numbers of software are used for modelling and simulating power systems networks, such as DIgSILENT, PowerFactory, MATLAB, Gurobi and CPLEX, General algebraic modelling system, to mention a few. MATLAB is found to be the major choice for many researchers. Some of the algorithm applications are implemented as follows:

Maximizing benefit from energy losses reduction and energy shaving enhancement while minimizing investment costs is achieved by implementing an improved genetic algorithm to determine the optimal planning and operation of BESS. Mansuwan K et al [33] presents Optimal Planning and operation of battery energy storage systems in smart grids using improved Genetic Algorithm Based intelligent optimization tool. Double layers’ optimization technique is implemented for determining the BESS placement and sizing in the first layer, while the maximum energy shaving is calculated in the second layer. Karami H et al [34] presents an

Optimal Dispatch Algorithm for Managing Residential Distributed Energy Resources. A scheduling algorithm is developed to generate an efficient look-up table that determines an optimal operation schedule for the distributed energy resources at each time interval so that the operation cost of a smart house is minimized.

The integration of renewable energy into the grid can be used for applications such as peak shaving in low voltage grid and emergency backup; most come with problems of uncertainty and variability. Battery Energy Storage Systems can alleviate the problems associated with renewable energy as well as be used to controlling the power flow and grid minimizing congestion in the distribution network. Salee S et al [44] Presents Optimal Siting and Sizing of battery energy storage systems for grid-supporting in the electrical distribution network, which addresses problems in determining the location and size of BESS by considering network parameters that play an important role for grid-supporting in Electrical Distribution Network using two-steps analyzed methods; the first step describes the use Genetic Algorithm and the second step is installing and testing the placement and sizing of Battery Energy Storage Systems.

Optimal scheduling of the battery charge state is in itself unique; the methods of multi pass dynamic programming are used to accomplish this. Maly D.K and Kwan K.S [35] presents an optimal battery energy storage system (BESS) charge scheduling with dynamic programming. An algorithm (dynamic programming) for the optimal charge/discharge scheduling of BESS energy storage is presented to ensure the minimization of the electricity bill for a given battery capacity while reducing stress on the battery and prolonging the battery life. Jun Xiao et al [68] have presented a bi-level optimization technique for determining the optimal site and capacity of BESS in distribution networks using Genetic Algorithm (GA). The outer optimization determines the total net present value of distribution networks within the project life cycle, and the optimal power flow and BESS capacity adjustment are calculated in the inner optimization.

The minimization of the power losses in the distribution grid is one of the main issues for the Distribution System Operator to reduce the management costs of the grid. The recent development of battery technologies has introduced new possible applications for these systems within the distribution grid. Farrokhifar M et al [50] presents optimal placement of energy storage devices for loss reduction in distribution networks. Particle swarm optimization (PSO) algorithm has been applied for finding the optimal place, along with the related management strategy, of an energy storage device to maximize loss reduction in the network. Lazzeroni P et al [51] presents Optimal Planning of Battery Systems for Power Losses Reduction in Distribution Grids; with the focus being on the optimal siting and sizing of the energy storage solutions, considering battery management capable to reduce network power losses and considering battery installation costs. A Mixed Integer Quadratically Constrained Quadratic Programming is implemented to identify possible batteries optimal management strategies capable to minimize the power losses.

The optimal placement of distributed BESSs is investigated in distribution network systems, with high penetration of renewable energy (i.e solar and wind) to minimize voltage deviation, line loading and power losses thereby significantly improve distribution network performance. Das C.K et al [52] presents optimal placement of distributed energy storage systems in distribution networks using artificial bee colony Algorithm. An effective strategy for the optimal placement of distributed ESSs in distribution networks using the ABC meta-heuristic optimization technique is implemented. The artificial bee colony optimization approach is employed to optimize the objective function parameters through a Python script automating simulation events to verify the system results obtained from the ABC approach.

Table 1: Comparison of different optimization techniques in placement schemes

No	**Algorithm**	**Advantages**	**Disadvantages**
1	Genetic Algorithm (GA)	Easy to implement; Suitable for placement problems	Takes a long time to solve the placement and sizing problems
2	Particle swam optimization (PSO)	Simple computation and ability to find near-optimal solution	Premature convergence; possibility of being stuck in local optima
3	Ant colony optimization (ACO)	Positive feedback accounts for rapid discovery of good solutions	Time to convergence is uncertain
4	Greedy Algorithm	Fast and guaranteed to produce feasible solutions	The obtained solution is normally a sub-optimal solution
5	Integer (linear) programming	Solves many diverse combinations of problems simply	Only works on linear variables; cannot potentially solve stochastic problems
6	Cplex optimization software package	Efficiently solves linear, convex or non-convex constrained problems	Difficulty in modifying optimization routines

Embedding BESS in distribution networks will be done to offer technical support to the existing power systems. They are expected to alleviate the problems that come with the sudden and unexpected load changes and any form of interruptions (i.e. load shedding, outages) to the distribution systems. Although BESS can be installed at any point on a distribution system, not conducting proper studies and misallocating BESS can lower the power quality of the system even more and reduce reliability, while also affecting voltage and frequency balancing. For this research, the aim amongst others is to investigate the optimal location to place the battery energy storage system(s) at a substation, for the optimal power usage thereof.

The control of BESSs using different algorithms is very important for obtaining optimal operating results. Control strategies are utilized to navigate the optimal BESS operation in distribution system networks. Based on most of the literature reviewed, BESS operations are commonly navigated via the control method to provide voltage and frequency support. To obtain solutions for the optimum placement, performance and reliability of BESS; these various factors relating to the network should be considered:

- Reliability Indices i.e. SAIDI, SAIFI
- System size and topology

The Factors are Considered through case study simulations for low voltage, medium voltage and high voltage distribution network. It can be concluded that the usage of battery energy storage systems is a significant avenue for maximizing the energy efficiency of a distribution network based on the literature discussed above; and overall network performance can be enhanced by placing the BESS in the location that will be easier to supply the loads from, which will enable the storage system to provide power quality management and reducing distribution network congestion and outage costs, and maintain the system stability and continuous supply.

Table 2: Summary of literature based on optimal placement and operation of BESSs

Grid Scenario	**Targeted Objectives**	**Applied Algorithm**	**Test Bus**	**Advantages**	**Limitation/Future Research opportunities**
Active distribution network [71]	Optimal allocation of distributed BESSs and grid reconfiguration	Convex optimal power flow (OPF), Gurobi and MATLAB interface- YALMIP used for implementation	6-bus and 70-bus	Minimization of voltage deviation, line congestion, energy supply and BESS investment costs, and network losses	Only photovoltaic (PV) is considered as a RES, and more optimal gird reconfiguration is also possible
Distribution networks [72]	Multi-objective energy management with BESSs	Hybrid of grey wolf optimizer and PSO, pareto-optimal and fuzzy decision-making strategies, MATLAB	IEEE 84	Operational cost reduction and reliability improvement	RES uncertainties are not considered, performance indices other than reliability can be addressed
Active distribution system [73]	Scheduling and operation of mobile BESSs	PSO, energy management system, MISOCP, Gurobi	41 bus (radial)	Cost minimization of imported grid power and profit maximization of network operators, voltage supports	Power quality issues can be investigated for mobile BESSs, application of hybrid meta heuristic optimization approaches
European LV distribution networks [74]	Optimal allocation and sizing of ESSs integrating RESs	Non-dominated sorting genetic algorithm II (NSGA-II)	IEEE 906	Voltage profile improvement, DG and BESS cost reduction, BESS lifetime maximization	Overall power quality improvement is not investigated
Distribution Networks [75]	Optimal ESS integration (ESS number, sizes, and locations	NSGA-II and Pareto dominance concept	94-bus (radial)	Network reliability improvement (i.e. SAIDI and MAIFI), equipment cost minimization	Modelling of specific ESS types are not presented, other reliability indices, e.g., SAIFI, CAIFI, ASIFI, ASAI, CTAIDI, and CAIDI are not addressed

A radial distribution network [84]	Optimal allocation of ESSs to mitigate risks for distribution companies (DISCOs)	Fuzzy PSO (FPSO) and a cost-benefit analysis method	IEEE 15	Maximizing the DISCO's profit from energy transactions and operational cost savings	Power quality issues are not considered
A distribution network [78]	Optimal and flexible ESS operation to maximize the profit compared to fixed ESS operation	A two stage framework- (1) optimization of integer variables (2) active reactive OPF problem, MATLAB, GAMS	41-bus rural network	Achievement of higher profit than fixed ESS operation, price reduction	More than one ESS cycling is not allowed, only wind is considered as a RES, ESS types are not specified
Distribution Systems [83]	Optimal ESS allocation and determination of loads to be shed, network reliability improvement	GA combined with LP solver, a sequential MCS	33-bus (radial)	Minimization of interruption cost and improvement of distribution system reliability, annual cost reduction	Wind is the only RES considered as DG
Smart grid [85]	Optimal ESS operation addressing real-time pricing	Integer coded GA, Auto regression moving average (ARMA) modelling technique, MATLAB	-	Minimization of daily net costs	Optimization parameters other than real time pricing can be addressed and analyzed

European medium voltage (MV) distribution Network [84]	Optimal ESS scheduling	Markov chain decision process, MATPOWER	14-bus	Voltage profile improvement, cost minimization in terms of energy and network losses	Investigations need for different network scenarios having larger solar DG or multiple ESSs
Active distribution networks [76]	Optimal ESS siting and sizing by handling voltage deviations, line congestion, cost of supplying loads and ESSs, network losses, load curtailment, and stochasticity of RESs and loads	AC-OPF and MISOCP, YALMIP-MATLAB interface	IEEE 34	Mitigation of voltage deviations and improvement of supply quality, elimination of load curtailment and line congestions, minimization of network cost and electricity cost	The analysis is not carried out with specific ESS technologies
A distribution network [79]	Optimal ESS installation site and capacity determination	A novel bi-level optimization solution algorithm, OPF, and GA	IEEE 33	Minimization of total NPV by integrating DG	Analysis is not accomplished with specific ESS types; other optimization approaches can be applied
Smart grid with grid scale ESSs [80]	Characterization of optimal value-lifetime performance pair for ESSs	Constrained stochastic shortest path (CSSP), Pareto optimal approach	-	Balancing the economic value and lifetime of ESSs, energy arbitrage application of ESSs under dynamic pricing	Although, the analysis is done for four types of batteries, the ESS types are not specified

Chapter 3

3. Methodology

The proposed methodology, designed for the identification of the best location to place the BESS when integrated with electrical substations to improve the performance of the network under normal and abnormal operating conditions and reduce interruptions at the Secondary side of substations, is discussed in this section. The following steps will be followed:

- Selection of the network topology and scenario.
- Simulation and analysis of a Distribution system using MATLAB Simulink
- Investigate the robustness of the distribution system by creating contingency plan scenarios
- Identification of valuable buses/busbars for the installation of the BESS.
- Selection of the control function to be applied for the management of the BESS.
- Simulation of the BESS model including the power conversion system and battery management system using MATLAB Simulink
- Integrate the BESS Model with the Distribution network model, at the optimal location(s)
- Create case studies (for both Residential and industrial loads) that evaluates how BESS improves the performance of the Distribution system
- Analysis of simulation results for the Distribution system with and without the integration of BESS.
- Conclude with regards to the initial Aims and objectives of the dissertation

3.1. Assumptions

The following assumptions are made for the methodology:

- The Distribution network is balanced
- Controlling the operation of BESS is based on achieving constant voltage output for the specified objectives
- Annual load growth rate is considered to not be rapid
- All secondary buses and Busbars can be used for BESS placement

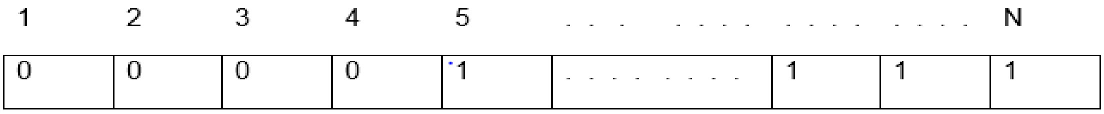
3.2. Optimization Technique

In this sub-section, using an algorithm to obtain optimum placement of battery energy storage is investigated by evaluating Genetic Algorithm for its best operation during times when faced with different load levels at the buses. Genetic algorithm is chosen based on the two most important features, that is its robustness and ability to provide good results in optimization processes. As the optimization technique will be utilized to identify the potential battery size and location combinations that increase the BESS hosting capacity of the distribution network [34]. The results on the work studies conducted in table 2 show that voltage profiles can be improved and grid power losses reduced by optimally placing and sizing a BESS

3.2.1. Genetic Algorithm

Genetic Algorithm (GA) is an adoptive optimization technique based on the principles and mechanisms of natural processes related to evolution, genetics and natural selection [30], [31]. GAs present stochastic optimization methods for solving problems; they work with a population of individuals, each representing a possible solution to a given problem [32]. GA permits a population including many strings to evolve under specified selection rules to a state that maximizes or minimizes the fitness [33]. Information about these local maxima is interchanged when applying the GA mechanism, not to terminate the algorithm in one of them but to recognize which one is also a global maximum [35].

Genetic Algorithms try to find the best chromosome, by manipulating the chromosomes material, and not denting too much into the problem that is being solved [36]. Binary record of one of the analyzed features is what's considered under the term chromosome, regarding GAs. The processes of manipulating binary records can solve extremely complex problems without addressing the complexity and nature of the problem that is being solved [37]. The basic element that the Genetic Algorithm manipulates is the string and each string represents the binary code of the parameter in the search field, that way each string is a point in the search field [38]. A binary string of dimensions N is introduced as a chromosome of GA, which represents the operation schedule of BESS. In the string [1,0] denotes the charge or discharge status of the BESS [39], shown in figure 6.



1	2	3	4	5	. . . .	. . . .	. . . .	N
0	0	0	0	1	. . . .	1	1	1

Figure 6: Example of Chromosome representation

There are three main operators of Genetic Algorithm, which are described as follows:

- **Reproduction Operator**

The best chromosome (binary string) solution is passed on to the generation to follow concerning their standard functions, which can be any linear/non-linear, differential/non-differential, or continuous /discontinuous, as long as it's a positive function to lead to a more feasible solution in each iteration of the GA [40]

- **Crossover Operator**

Crossover is key a operator of the genetic algorithm; unlike the reproduction operator that only considers the best individuals but does not generate new quality in terms of chromosomes, the crossover operator uses the best ones and generates upgraded individuals [41], [42]. Crossover operates on two chromosomes at a time, the operator randomly looks for "01" or "10" in one parent chromosome and sets it as crossover point. The string from one parent up to the crossover point is exchanged with the other parent, resulting in two new members of the next generation being created.

- **Mutation Operator**

The Reproduction and Crossover operators lead to favourable results in general. However, they do not produce new quantity/information on a bit level. Mutation replaces the genes lost during the evolutionary process in a new form or produce new genes which were nor explored before in the initial population. Mutation operator selects the mutation point randomly, therefore the level of mutation should be chosen carefully [41], [42]. The operator looks for "01" or "10" combination in chromosomes and then changes the combination randomly to "00" or "11"

GAs typically works by iteratively generating and evaluating individuals using an evaluation function, consisting of the following steps made up of technical aspects of the creation of GA: Create initial population, evaluate fitness, Selection, Crossover, Mutation, select next generation, check to stop and obtain the best solution. Figure 7 depicts the simple GA working scheme given by [43]. The crucial aspects that need to be addressed when creating a GA are given by [41] as follows:

Fitness function

The function evaluates the string bits individually and indicates whether the solution is feasible or not [44]. The performance of the algorithm depends mainly on the selection of the function [45]. The creation of the fitness function should satisfy at least the following conditions to be able to optimize the problems and produce solutions:

- It can be implemented in the Genetic algorithm processes
- must be inclusive of the objective function the algorithm is attempting to satisfy

The following constraints must always be satisfied, where the evaluation function is concerned**:**

- The per unit Voltages at all busbars must fall into the minimum and maximum range (0.95-1.05)

$$Vmin \leq \mathrm{V}i \leq Vmax$$

- Active BESS power is limited by its rated minimum and maximum power capacity

$$P\mathrm{BESS}min \leq P\mathrm{BESS} \leq P\mathrm{BES}Smax$$

- Energy stored in the BESS must fall into an admissible range,

$$\mathrm{EBESS}min \leq \mathrm{EBESS} \leq \mathrm{EBES}Smax$$

- **Termination Criteria**

Selection is the process which guides the evolutionary algorithm to the optimal solution by preferring chromosomes with high fitness. Assuming the total number of iterations will be reached at the maximum of the string dimension, the optimal BESS placement methodology has come to an end; else the selected operator procedure will be reiterated until the criterion is fulfilled.

Genetic Algorithms are popular due to the following attributes; taking into consideration that they are greatly dependent on the technical aspects discussed [45], [46]:

- GAs can handle both continuous and discrete optimization problems.
- They require no derivative information about the fitness criterion.
- GAs have the advantageous over others algorithms since it is less likely to be trapped by local minimum.
- GAs provide a more optimal and global solution
- GAs use probabilistic operators not deterministic ones.

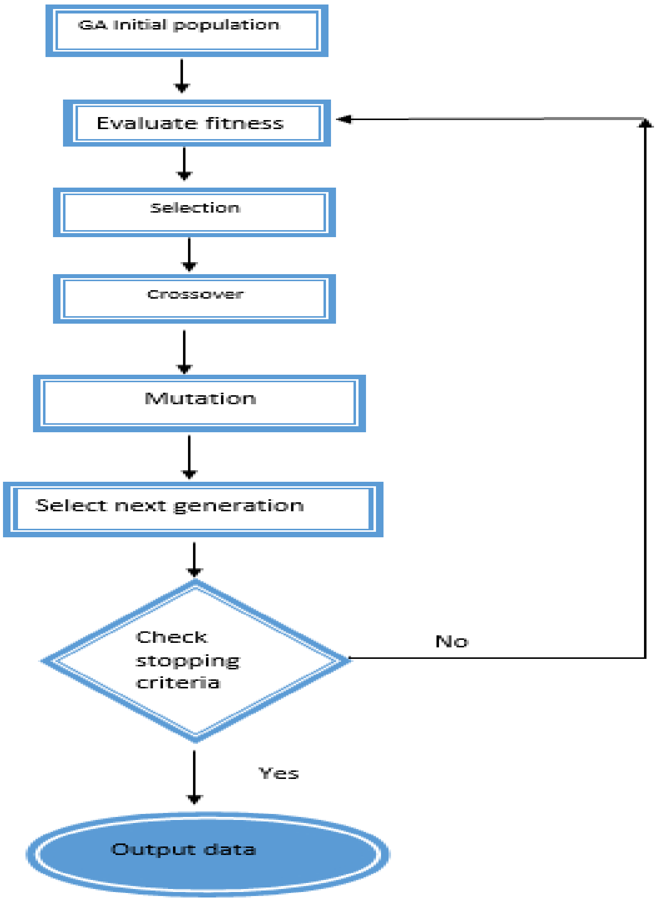


Figure 7: Simple GA process

3.2.2. Sequential quadratic programming

The sequential quadratic programming algorithm is a powerful technique for solving non-linear constrained optimization problems [47], [48]. In solving an optimization problem, normally search for feasible solutions for the problem. During the evolutionary process, many unfeasible solutions appear. This is because some individual in the population due to crossover and mutation operation might produce solutions outside the feasible search space [47], [48]. SQP is proposed to handle the unfeasible solution.

Figure 8 below depicts a general structure of GA incorporated with SQP, which is a more powerful duo to obtaining the best location to place the BESS on the distribution network.

The GA creates an initial string population characterized by the allocation nodes of BESS and the size of the loads. Upon the completion of the initial population generation, the inner algorithm performs an optimization aimed at finding the daily charge/discharge cycles of BESS including initial and final state of charge that is more feasible and the reactive power that BESS can provide for each individual in the string population. The fitness function of the population is calculated individually by using the inner optimization (SQP) output. If GA does not converge, the next population is provided [49].

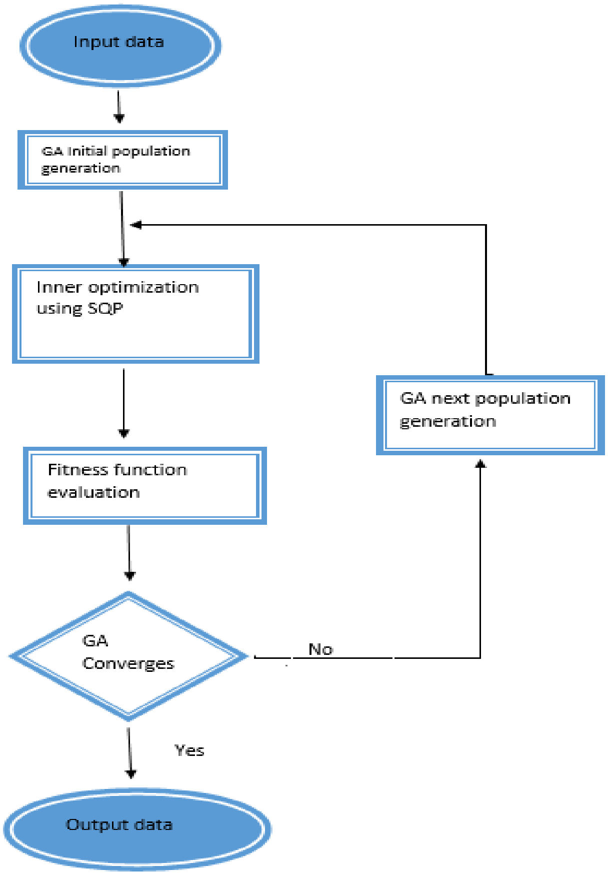


Figure 8: GA process combined with SQP

3.3.Optimal placement of BESS

BESS can be placed at different locations on the power system network to ensure continuity of supply for all customers under any abnormal conditions, the potential locations are; the high voltage side of the substation, Secondary side of the substation or at the secondary side of the mini-substation and act as a residential community focused system.

3.3.1. BESS at primary substation

Battery energy storage system may be connected to the high voltage busbar(s) or the high voltage feeders with voltage ranges of 132kV-44 kV; for the reliability of supply, substations upgrades deferral and/or large-scale back-up power supply. Figure 9 depicts a block diagram showing an example of how the BESS can be integrated into the distribution system via the High voltage busbar.

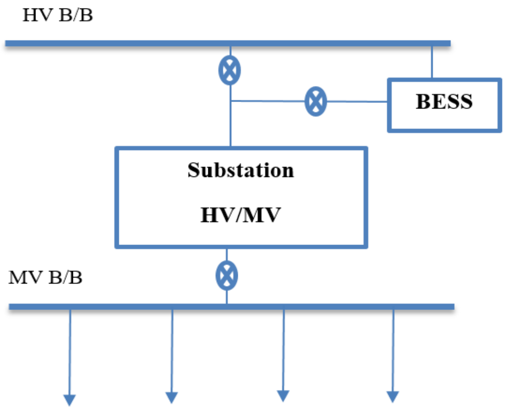


Figure 9: Integrating BESS via the HV busbar block diagram

3.3.2. BESS at secondary substation

Battery Energy storage system may be connected to the medium voltage busbar(s) or to the medium voltage feeders with voltage ranges of 33kV-1kV; for peak-shifting, substation upgrades deferral, additional capacity, or medium-scale back-up-supply. Figure 10 depicts a block diagram showing an example of how the BESS can be integrated into the distribution system via the medium-voltage busbar.

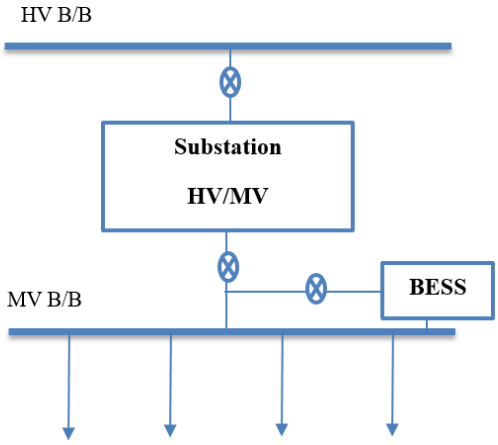


Figure 10: Integrating BESS via the MV busbar block diagram

3.3.3. BESS at the loads

The BESS may further be connected as close as possible to the loads, by either being placed by the mini-substations (MV/LV TRFR) or at the customer's point of connection 400V-230V for residential loads and at the medium voltage feeders with voltage ranges of 33kV-11 kV (depending on the voltage the customer requires) for industrial loads. For voltage support, frequency stabilization, solar smoothing for networks with PV systems, or back-up-supply. Figure 11 depicts a block diagram showing an example of how the BESS can be integrated into the distribution system directly to the loads.

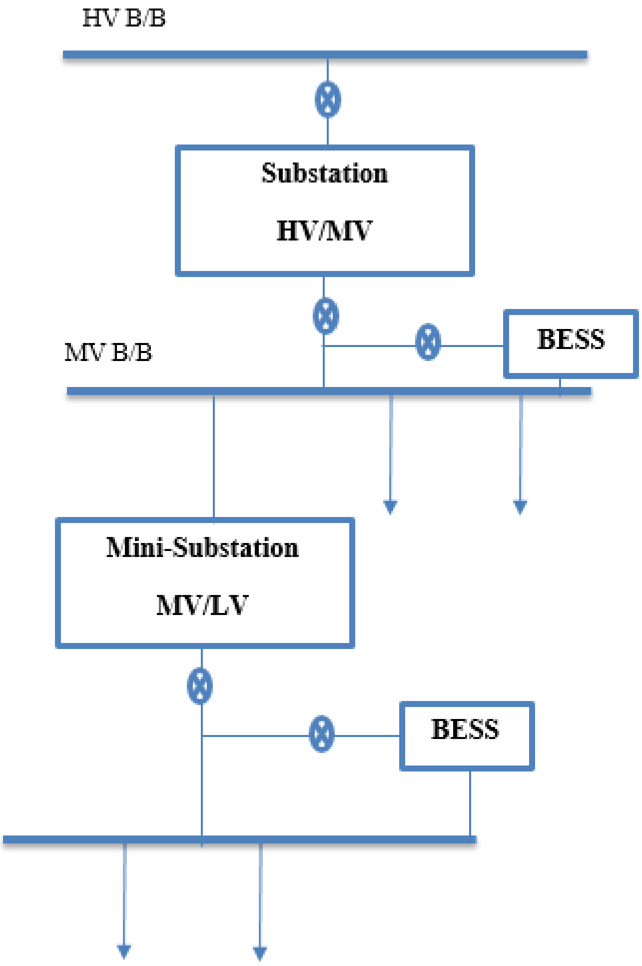


Figure 11: Integration of BESS directly to the loads block diagram

From the above block diagrams of possible BESS placement, the diagrams shown in figures 10 and 11 are the best fit with regard to the objective of reducing outages in substations and continuously supplying customers, as they offer voltage support, additional capacity and backup-supply. Therefore, both block diagrams will be implemented and simulated using MATLAB Simulink the preliminary and main research to be presented in chapters 4 and 5.

Chapter 4

4. Test Model Simulations

This chapter consists of the Simulink based simulation models of the substation and the BESS. It is important to identify the failure risks regarding distribution systems that are more likely to occur and consider the consequences thereof, and shouldn’t only consider single contingency (n-1) but also consider the double contingency and the impact thereof. Distribution systems aim to maximize the benefits of electricity to customers and provide sustainable and cost-effective networks. Multiple interruptions occur on the systems causing customers to be without supply, and some loads are critical and are less tolerant of even short interruptions. The interruption of supply affects the key performance indices of substations negatively. The BESS is modelled and simulated, to enable the usage thereof to provide uninterrupted backup supply to the distribution system. The contingencies and the BESS operation will be further discussed in this chapter.

4.1. Substation Modelling and analysis

The substation is made of three incoming lines and three distribution transformers. The sub-station consists of three 11kV busbars, and each consists comprises of four feeders. The system is designed in such a way that for contingencies ((n-1) or (n-2)), n being the number of transformers or incoming lines in the network, the remaining component(s) will be able to sustain the network and supply power to all the loads combined. Figure 12 depicts a single line block diagram of an 88kV/11 kV that is used to evaluate basic functions of a balanced distribution network, see the model simulated in Appendix A. A scenario-based investigation will be conducted, where the effect of putting each transformer offline and a combination of two transformers offline at a time to observe the state of the substation at each event. The results will be analysed and discussed in the subsections to follow.

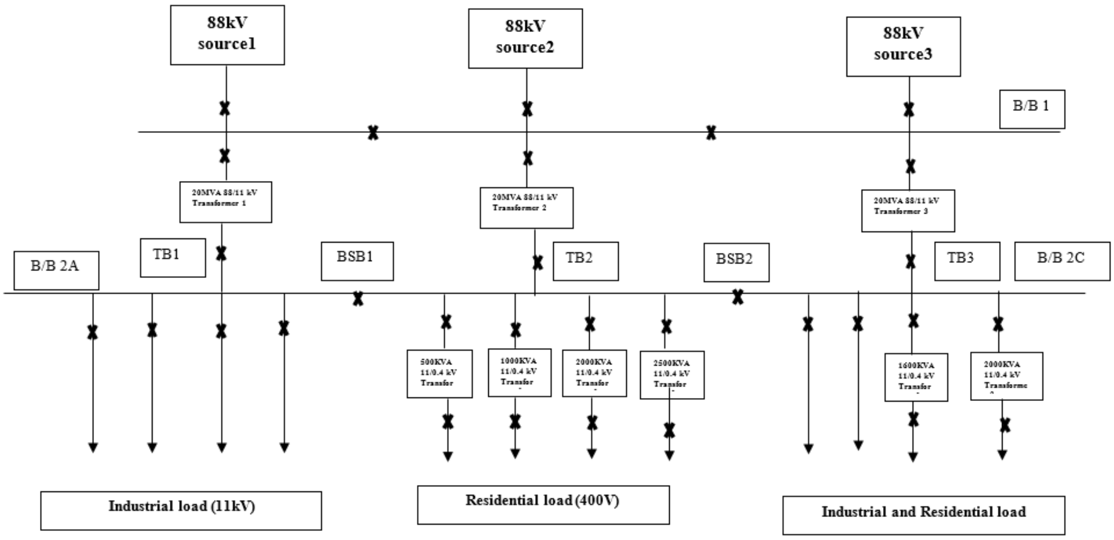


Figure 12: 88/11/0.4 kV distribution systems block diagram

Figure 12 depicts a step-down distribution network; Stepping down the 88kV line voltage from the transmission systems to 11kV and 400V line voltages that can be utilized in the distribution networks. The three-phase system will be analysed per phase. Using the basic voltage and current three-phase equations, the simulation results will be compared to the calculated expected values, to deduce whether the system is modelled correctly, and the equipment parameters are set appropriately.

Firstly, the results to be presented in the sub-sections to follow will first be when the system is operating under normal conditions, to get the exact voltage and current values are expected when there aren’t any disturbances for the transformers and the loads, and secondly, disturbances will be added to investigate just how robust the substation is.

4.1.1. Distribution transformer analysis

Each substation Transformer of the three has the following parameters: 20MVA 88/11 kV and they all have the same reactance therefore under normal operating conditions, the measurements are expected to be equal. The primary side of the transformer is supplied from the incoming line busbar, therefore the per phase value of the incoming line voltage is equivalent to that of the primary side of the transformer(s). Table 3 shows the calculated values of the transformer; they will be compared to the values measured from the simulated model. Both the results are expected to be the same.

Table 3: Calculated 88/11 kV Transformer parameters

Transformer Primary Side	**Transformer Secondary Side**
$\boldsymbol{Vph = 50.8kV}$	$Vph = 6.35kV$

Figures 13 and 14**,** show the phase voltages of the primary and secondary side of the transformer respectively. The measured and calculated values correlate with each other, therefore the transformer settings in the simulation model of the distribution system are set correctly. Regarding the Distribution transformer, the secondary voltage needs to be precise as the busbar voltage solely depends thereon if it’s incorrect the loads would not be supplied with the correct voltage value thus affecting the load current readings as well.

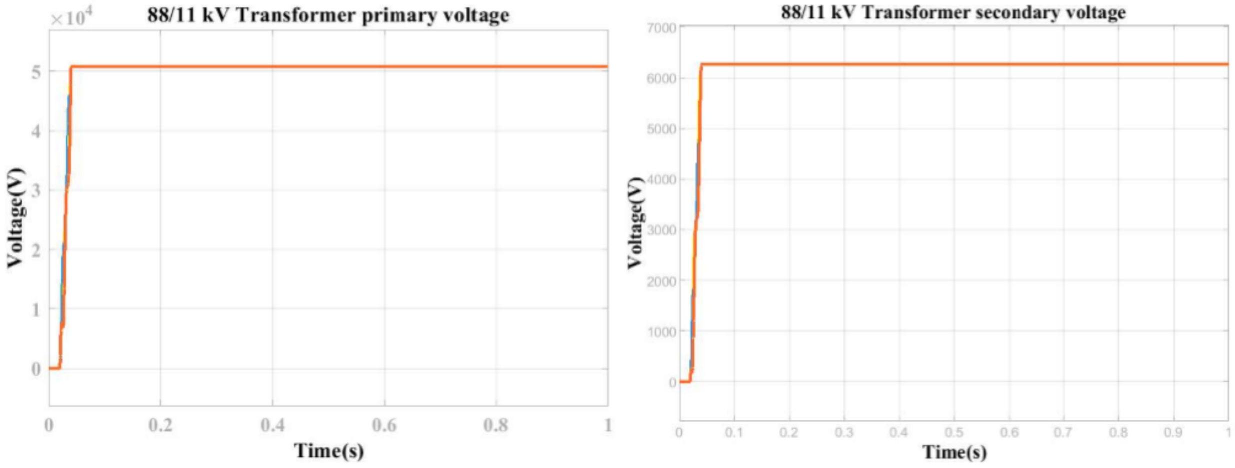


Figure 13: Distribution Transformer measured Voltage values

Mini-substations are used to step the medium voltage further down to Low voltage, the voltage used for residential loads. Each mini-substation transformer consists of the 11kV/400V voltage ratio, only with different loadings depending on the size of the loads connected to it. Table 4 shows calculations done for both the primary and the secondary side of the 500kVA $11kV$ /400V transformer.

Table 4: Calculated 500kVA 11 kV/400V Transformer parameters

Transformer Primary Side	**Transformer Secondary Side**
Vph = 6.35kV	Vph = 230 .94V
Iph = 26.24A	Iph = 721 A

Figures 14 and 15 depict the phase voltage and current of the primary and secondary side of the mini-substation transformer respectively. The measured and calculated values correlate with each other, therefore the medium/low voltage transformer settings in the simulation model (figure 12) are proven to be set correctly

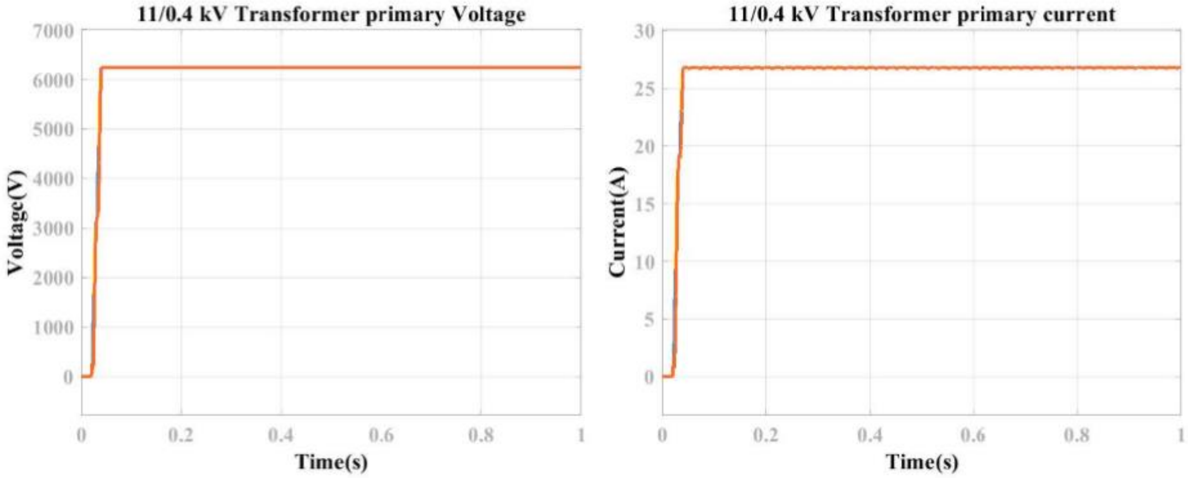


Figure 14: Mini-Substation Transformer primary parameters

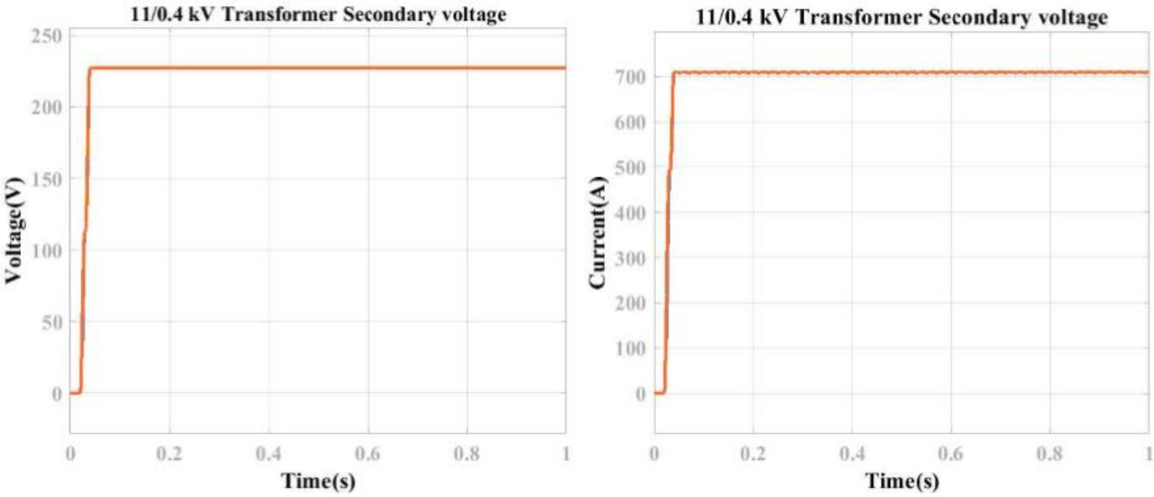


Figure 15:Mini-Substation Transformer Secondary parameters

4.1.2. Distribution load analysis

The distribution system in figure 12 is made up of two types of loads, Industrial loads which require 111kV Voltage supply and the residential/commercial load that require 400V voltage supply, therefore another step-down transformer must be introduced at the 11kV busbar to make a residential load feeder. The loads on each busbar are such that the sum of all loads should be less or equal to the transformer MVA rating of the transformer connected to the respective busbar.

The substation (figure 12) is made of three incoming lines and three distribution transformers. The sub-station is made of three 11kV busbars, and each busbar comprises of four feeders, with the total sum of each feeder load less than the transformer MVA rating. The system's load is distributed such that, should one or two transformer(s) of the three be out of service, the remaining one or two of the three be able to supply their own load plus the additional load of the transformer(s) out of service. This is known as an n-Contingency plan. Table 5 depicts the expected current measures at different loadings and voltage levels, for all the busbar loads.

Table 5: Expected load current values

Load Rating	**Calculated Current Value (A)**
500 kVA @ 400V	721
1000 kVA @ 400V	1443
1600 kVA @ 400V	2309
2000 kVA @ 400V	2886
2500 kVA @ 400V	3608
2500 kVA @ 11kV	131
3150 kVA @ 11kV	165.33

Under normal operating conditions, the busbar(s) section breakers will remain in the normally open state and the high voltage secondary transformer breakers remain closed; meaning that each transformer is to supply its own busbar load.

The busbar 2A of the substation consists of industrial loads only, meaning the loads are supplied directly from the busbar at 11kV. All the loads are rated at 2.5MVA. The figures 16 -19 depict the voltage and current values of each load on the busbar 2A, with the load rating equal the graphs are expected to follow the same pattern with the exact same readings.

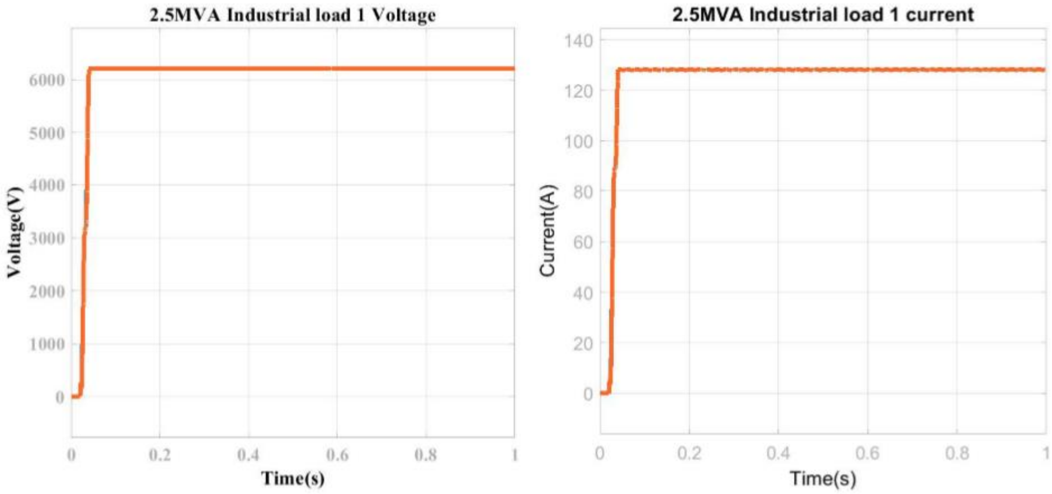


Figure 16: Industrial load 1 parameters

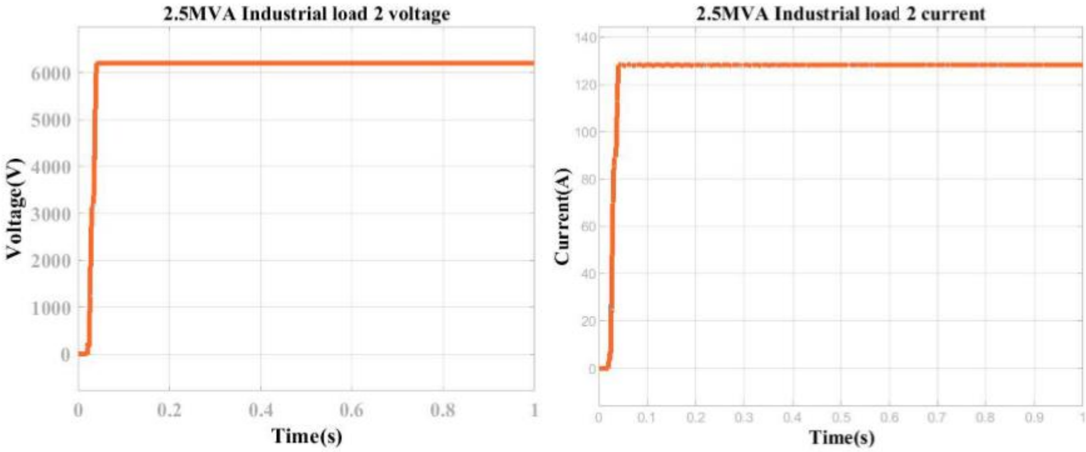


Figure 17: Industrial load 2 parameters

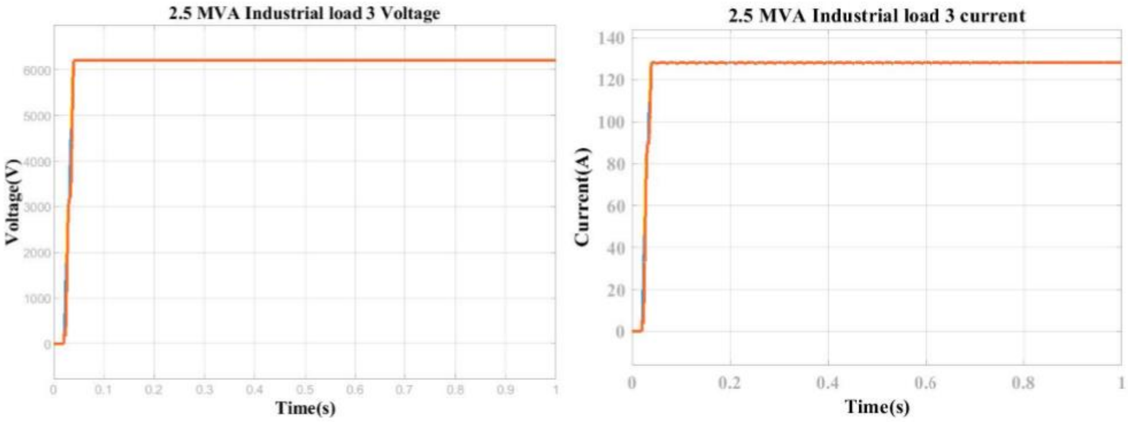
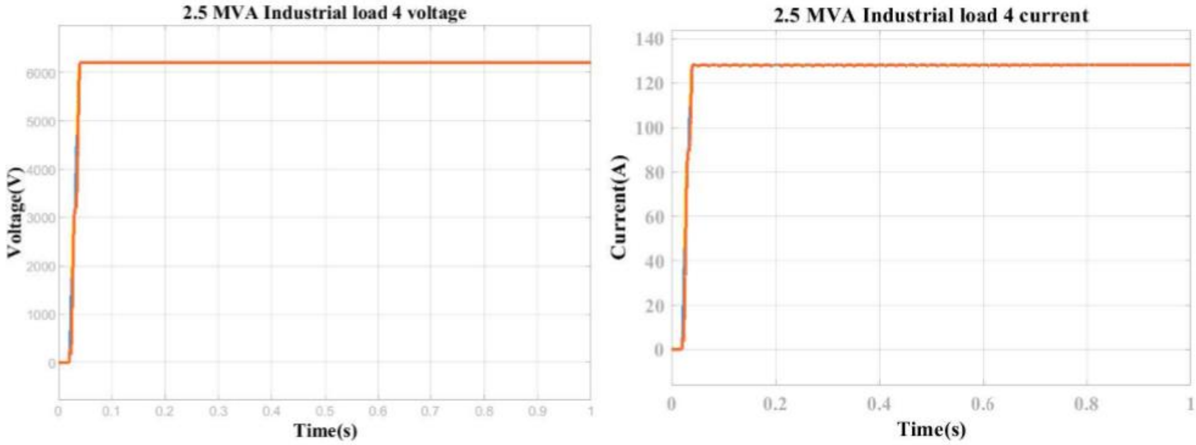


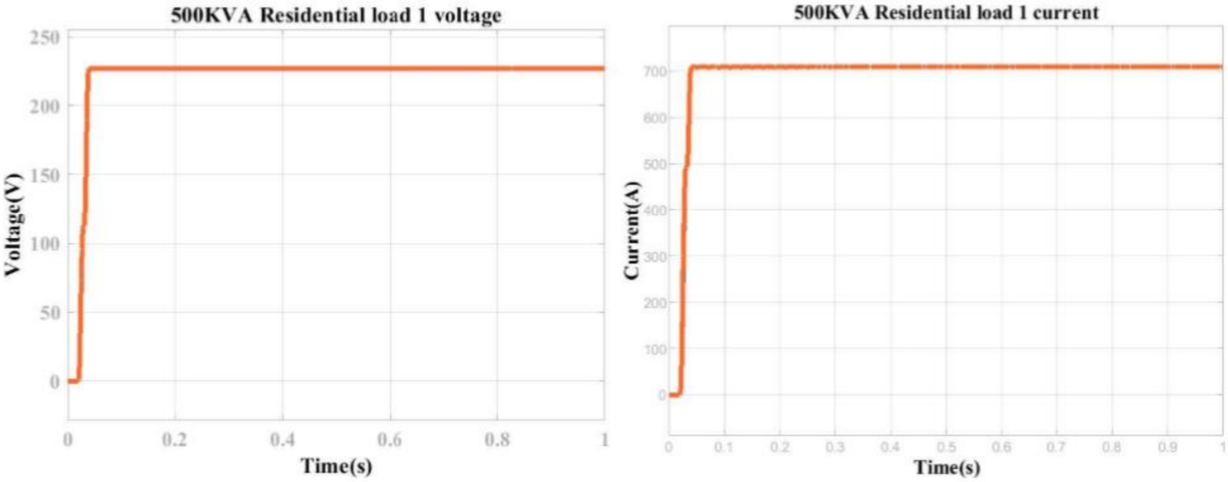
Figure 18: Industrial load 3 parameters


2.5 MVA Industrial load 4 voltage

2.5 MVA Industrial load 4 current

Figure 19: Industrial load 4 parameters

The busbar 2B of the substation only has residential loads. The loads are supplied from the mini-substation transformers that steps the 11k V to 400V. The loadings of the four loads are rated as follows for load 1 to 4: 500kVA, 1000kVA, 2000kVA, 2500kVA, in that order. The Figures 20-23 depict the voltage and current measures of residential loads 1 -4 respectively, of Busbar 2B. The voltage of the loads will be equal as all the mini-substation transformers have the same voltage ratio, and only the current will differ as the load loading s are not the same.


500KVA Residential load 1 voltage

500KVA Residential load 1 current

Figure 20: Residential load 1 parameters

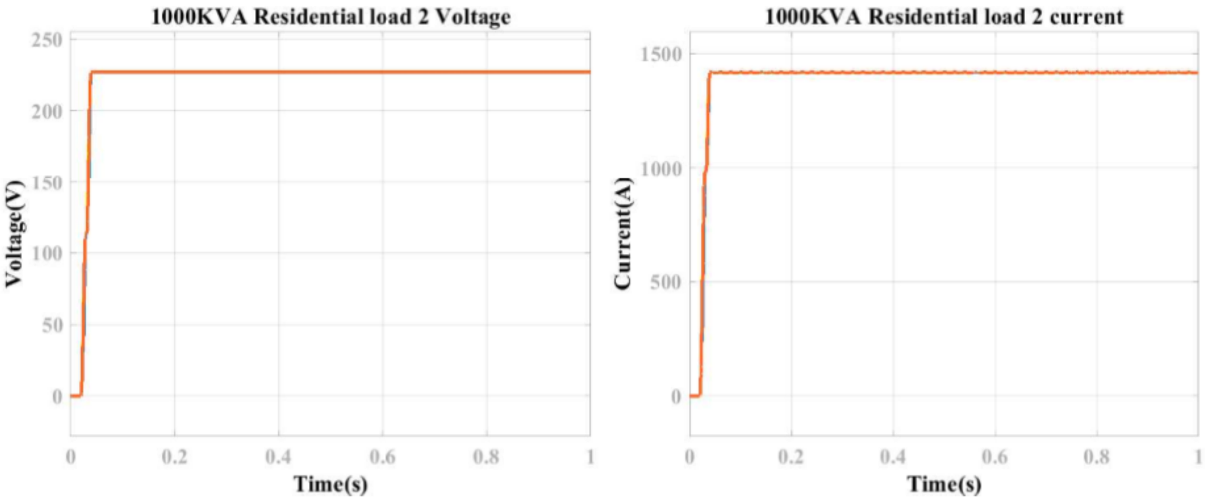


Figure 21: Residential load 2 parameters

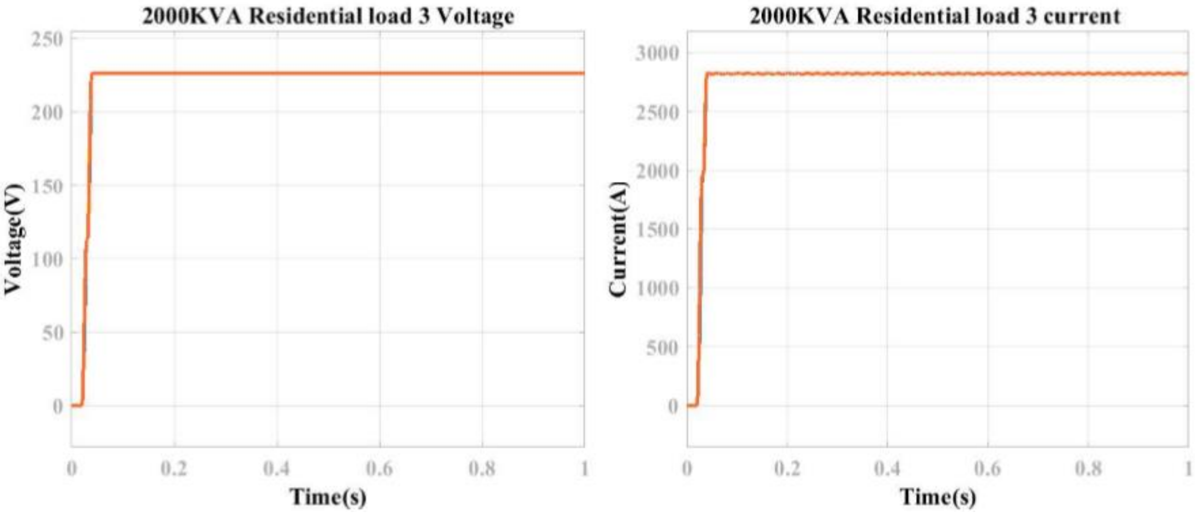


Figure 22: Residential load 3 parameters

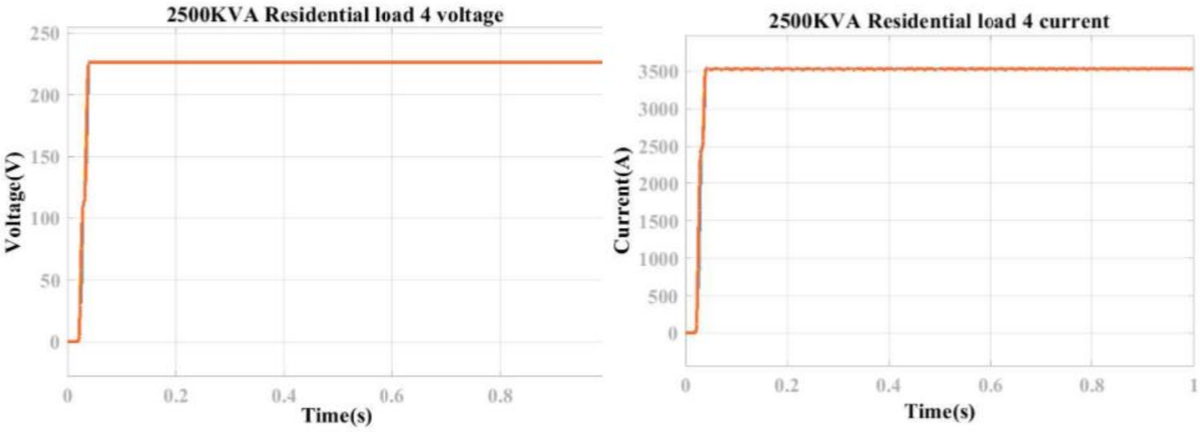


Figure 23: Residential load 4 parameters

The busbar 2C consists of a mixture of industrial and residential loads. The industrial loads are supplied directly from the busbar and the residential loads are supplied from the mini-substation transformers. The two industrial loads are both loaded at 3.15 MVA and the residential loads are rated at 1600kVA and 2000kVA respectively. The figures 24 -25 depict the voltage and current measures of the industrial loads and figures 26-27 depict that of the residential loads. Both the voltage and currents for the industrial loads will be equal as they are loaded the same way; the residential loads will only have voltage in common, but the currents will differ.

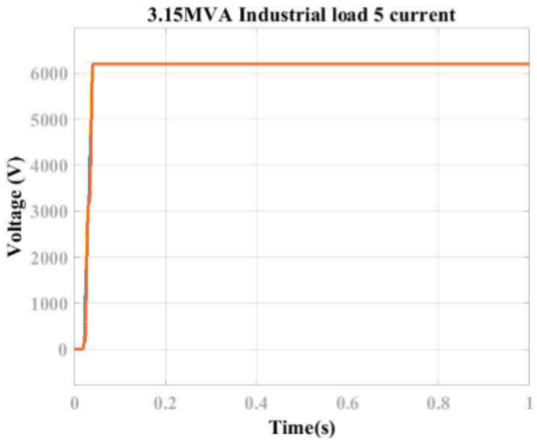


Figure 24: Industrial load 5 parameters

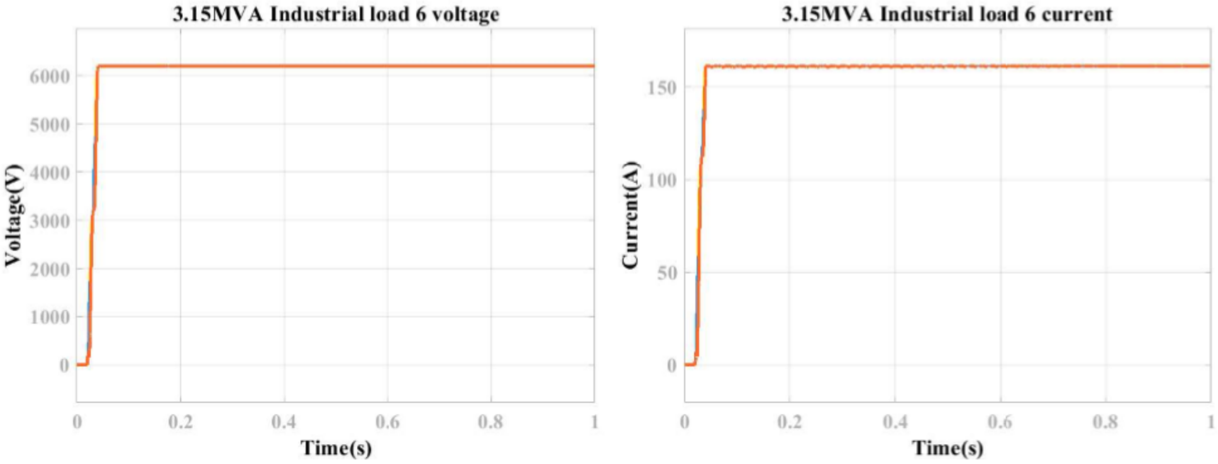


Figure 25: Industrial load 6 parameters

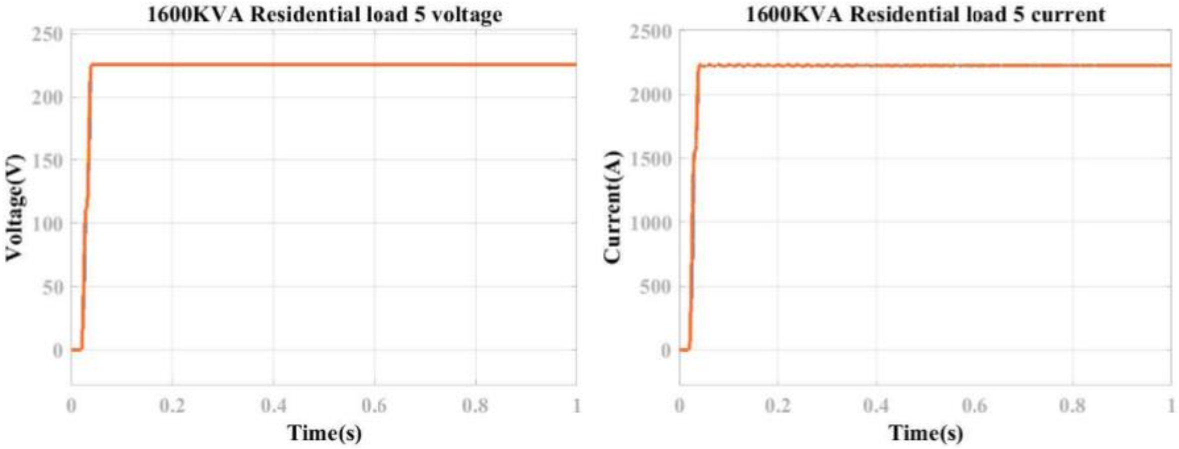


Figure 26: Residential load 5 parameters

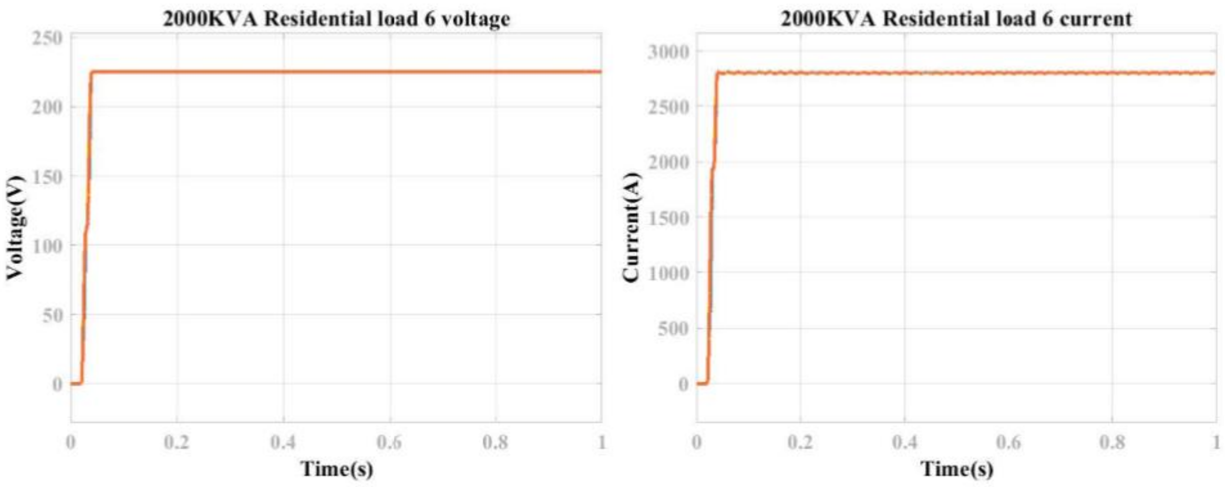


Figure 27: Residential load 6 parameters

It can be seen from the tables and figures in the sub-section that the calculated voltages and currents correlate with the measured voltage and current values as shown on the figures. The values are within the allowable 2% error margin. Therefore, proving the system to be configured properly. Appendix A will have the relevant simulation models of all the cases that were discussed as well as the parameters settings of all the equipment.

4.1.3. Contingency plan analysis

Contingencies on the electricity supply network arise when some component of the supply chain malfunctions or when switching needs to be done. The network is then in an abnormal state and the supply to customers is influenced. The contingency is normally indicated as the supply to a single customer or a network.

Substation contingency plans are done to evaluate the stability and robustness of the transformers. That is to ensure that the transformers installed can be able to supply power in the worst-case scenarios regarding equipment failure. the substation in figure 12 is of ring main bus scheme, busbar arrangement, as it has the provision that if a power interruption occurs to one of the busbars, power can be fed from another side of the system. The contingencies that will be analysed in this sub-section are (n-1), where each transformer will be isolated from the system to evaluate if the remaining transformers can continue supplying the entire loading and (n-2) to evaluate if the remaining transformer can single headedly supply the loads.

4.1.3.1. (N-1) Contingency scenario

In this case, the customer or network described will continue operating when one element in the network is not available. In case of a network fault, the customer might see a dip in the supply until the protection operates and clears the fault.

- **Scenario 1: Transformer 1 outage**

When Transformer 1 is out of service, it is required that it gets isolated from the rest of the network, that way the fault doesn’t spread to the rest of the system and cause any more damage. By so doing, the transformer breaker will be opened cutting off supply to the loads. Figure 28 depicts the transformer taken out service configuration. With the bus section breaker 1 open, the busbar 2A is left without supply when the transformer one is out of service.

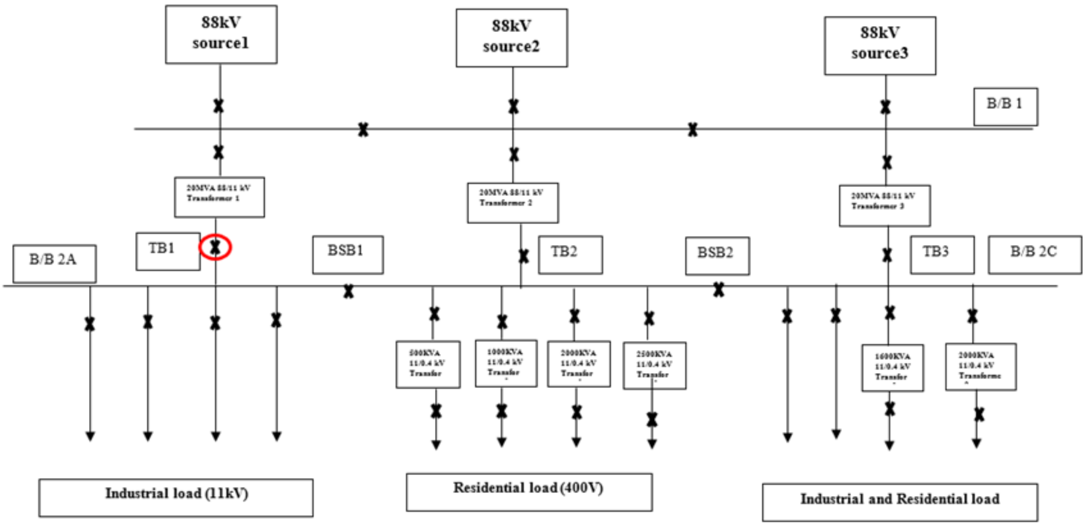


Figure 28: Transformer 1 isolation configuration

- **Scenario 2: Transformer 2 outage**

When transformer 2 is out of service, its breaker contacts will be opened, isolating it to the rest of the system shown in figure 29. And just as in scenario one, at the instance transformer 2 is out of service, busbar 2B will be without any voltage resulting in the load being without any supply. Being that it’s the middle transformer in the system it can be supplied by either one of the other two transformers as the section breakers are both nearby.

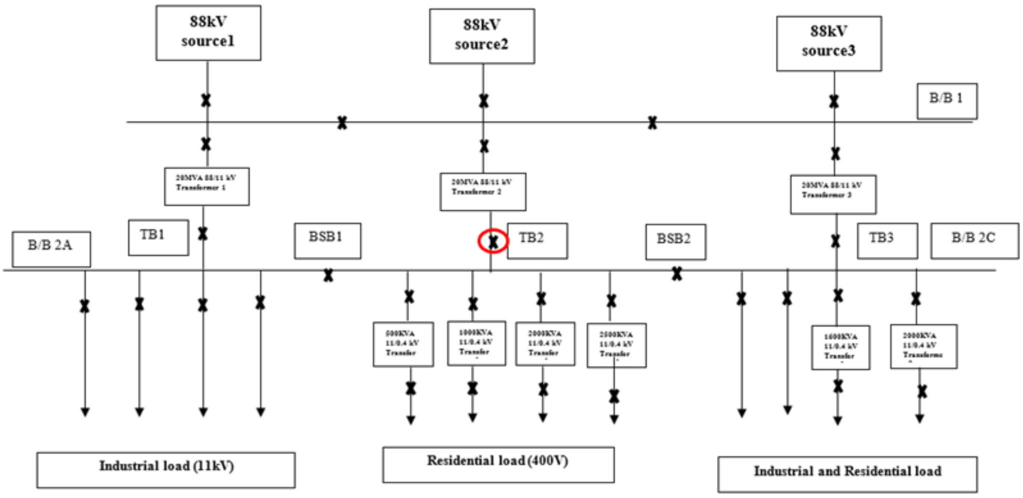


Figure 29: Transformer 2 isolation configuration

Loads of Transformer 2 can be supplied by Transformer 1 when the bus section 1 is closed and bus section 2 is left open (Figure 30) and/or Transformer 3 can supply loads of transformer 2 when the bus section breaker 2 is closed and 1 is left open (figure 31); both are expected to deliver the same results, supplying the all the busbar loads.

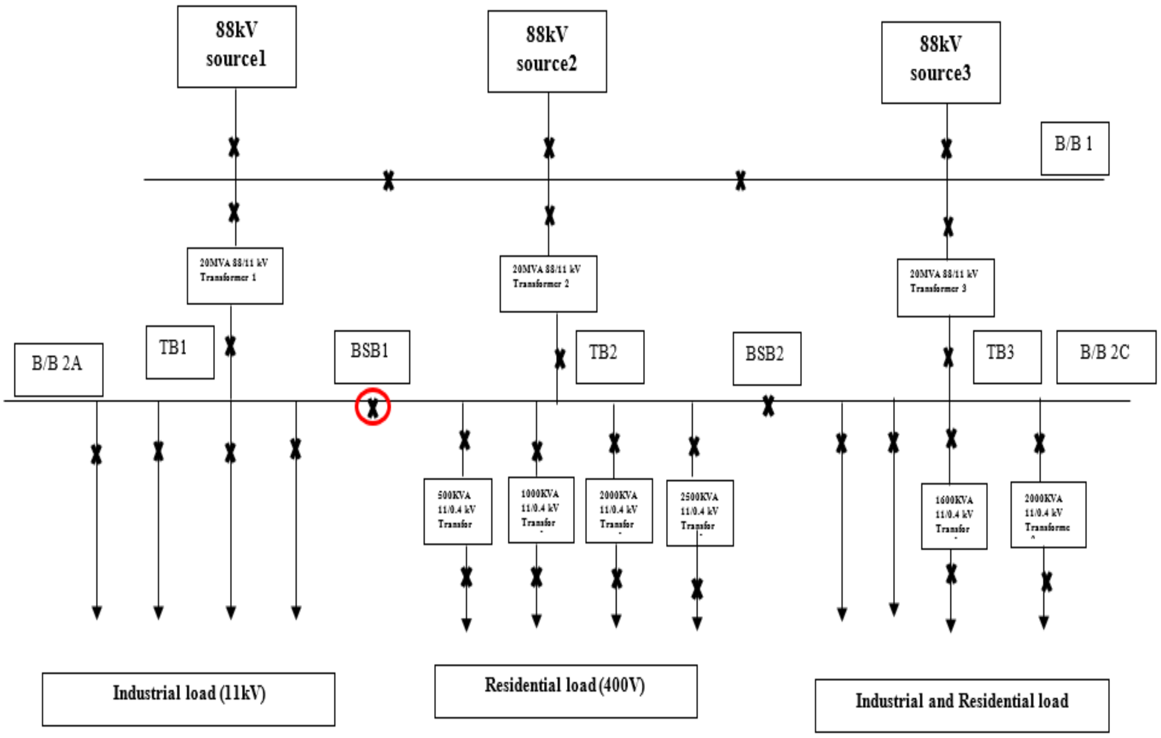


Figure 30: Connecting busbar 2B to transformer 1 configuration

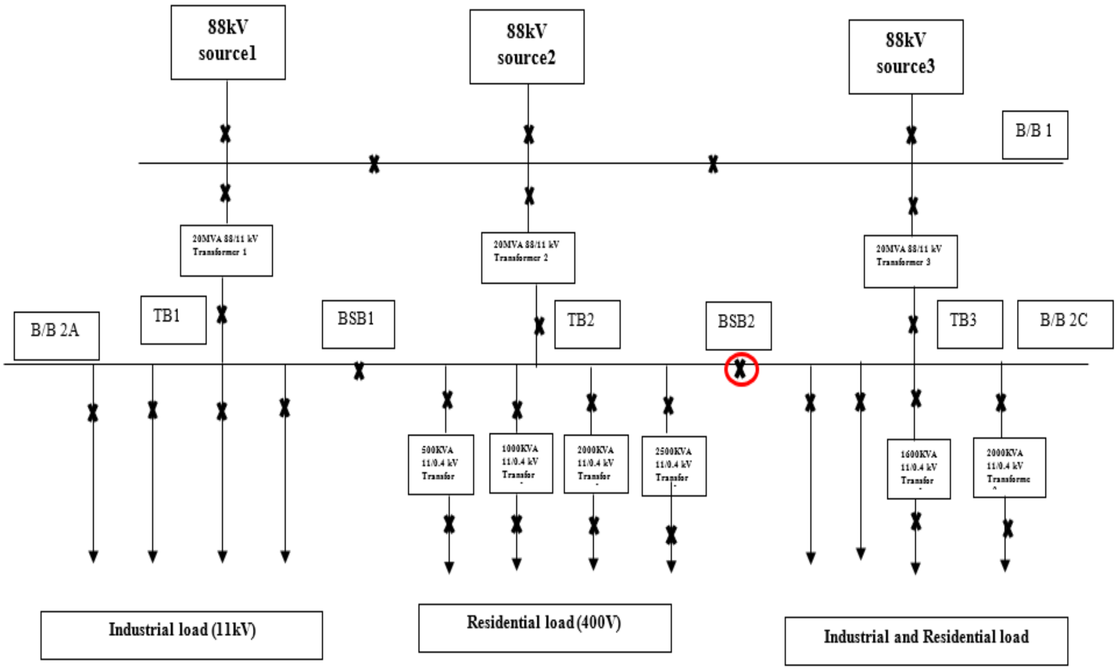


Figure 31: Connecting busbar 2B to transformer 3 configuration

- **Scenario 3: Transformer 3 outage**

When transformer 3 is out of service, just as with the previous scenarios, the transformer 3 breaker will be opened to get it isolated from the rest of the system (see figure 32), leaving the loads connected to the B/B 2C without any supply. The bus section breaker 2 is closed to connect the B/B 2B and 2C and both be supplied by transformer 2, shown in figure 33.

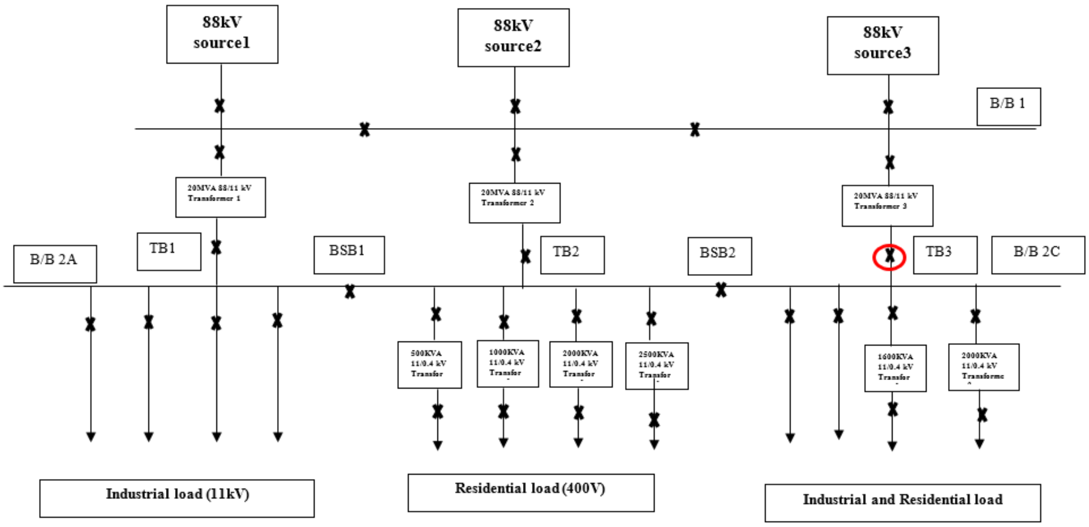


Figure 32: Transformer 3 isolation configuration

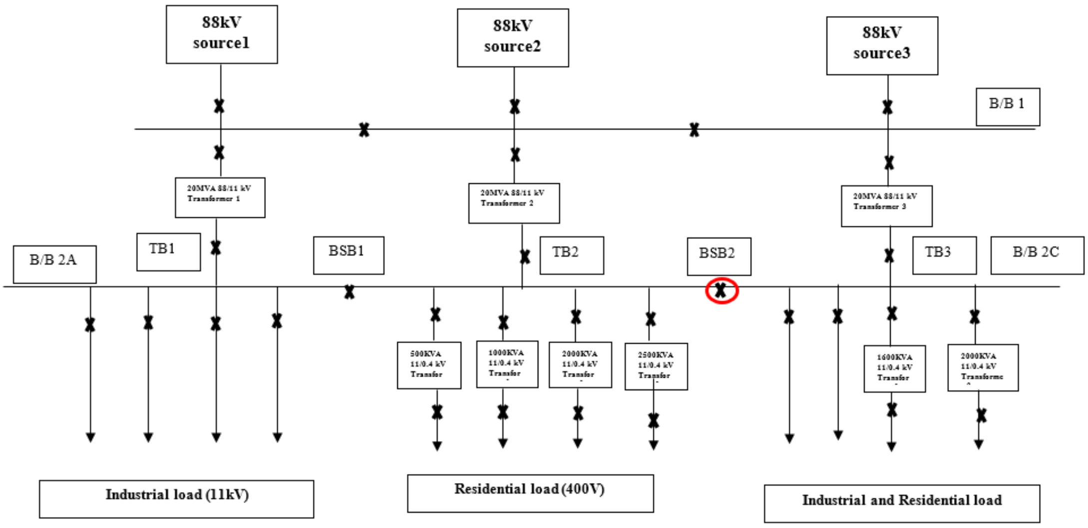


Figure 33: Connecting busbar 2C to transformer 2 configuration

One of the most important characteristics of pairing transformers in a network is that if the transformers have the same MVA rating they can be connected in parallel and be used to double the MVA rating thus being able to supply a larger load. Therefore, in all the scenarios, when one transformer is not connected to the grid, the remaining two can be connected in parallel through closing both section breakers as opposed to only 1 and suppling all the loads together. From the above scenarios, the (n-1) contingency is passed by all the transformers. That is if any one of them were to be out due to planned or unplanned outages, the remaining transformers would be able to hold the fort for the one that is out of services until the outage is resolved without compromising themselves and their loads.

4.1.3.2. (N-2) Contingency scenario

A double contingency is when the network will allow the failure of two items in the supply network where these items are not in series. For the (n-2) contingency investigation(s), the 11kV bus section breakers will remain closed (see figure 34), as only one transformer will be utilized in the attempt of supplying power to all the loads, single headedly. And the effects of not having any supply through having transformer breakers and the bus section breakers open have already been investigated in the previous sub-section.

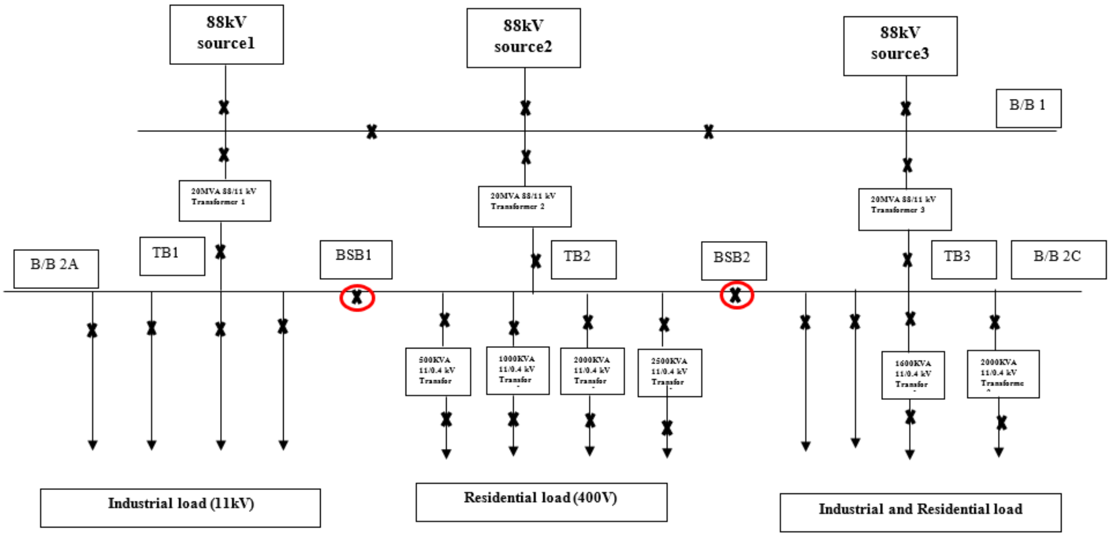


Figure 34: Transfer busbar configuration

- ### Scenario 1: Transformer 1 and 2

Transformer 1 and 2’s breakers will be opened, to isolate the two transformers and only transformer 3 will be left connected to supply all the loads.

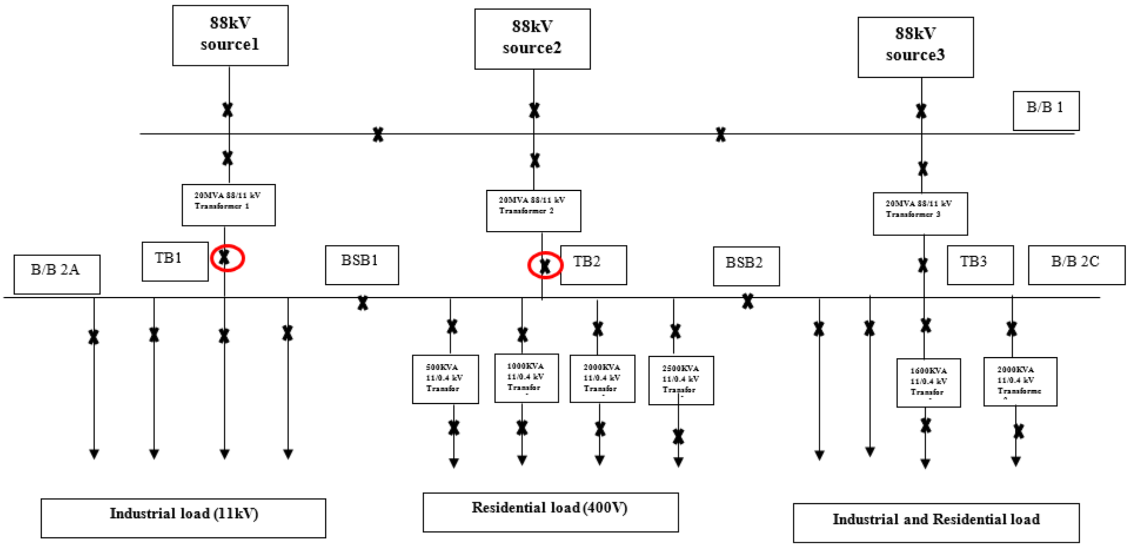


Figure 35: Transformer 1 and 2 simultaneous outage configurations

- **Scenario 2: Transformer 2 and 3**

Transformer 2 and 3's breakers will be opened, to isolate the two transformers and only transformer 1 will be left connected to supply all the loads.

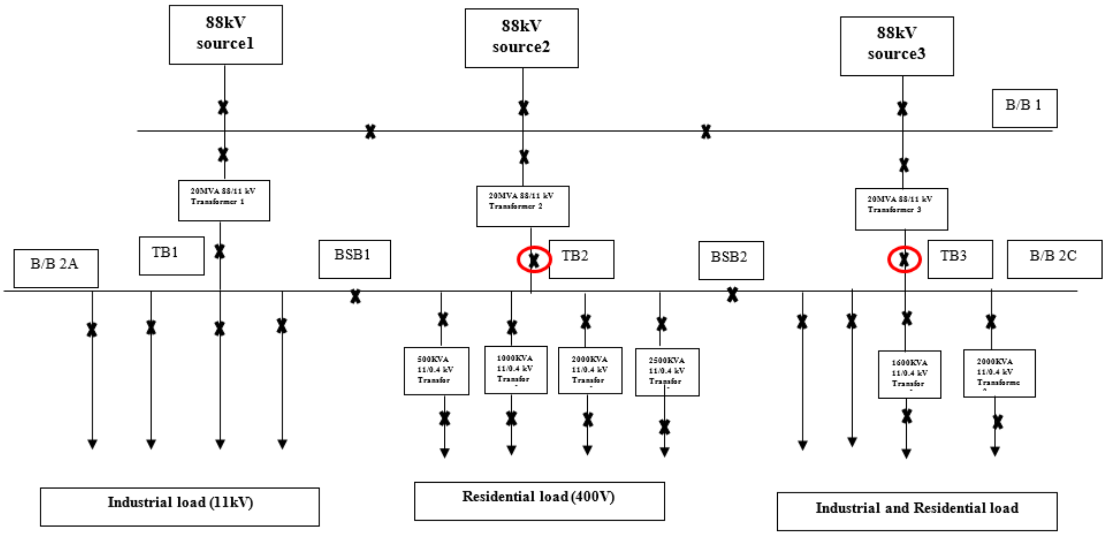


Figure 36: Transformer 2 and 3 simultaneous outage configurations

- **Scenario 3: Transformer 1 and 3**

Transformer 1 and 3's breakers will be opened, to isolate the two transformers and only transformer 2 will be left connected to supply all the loads.

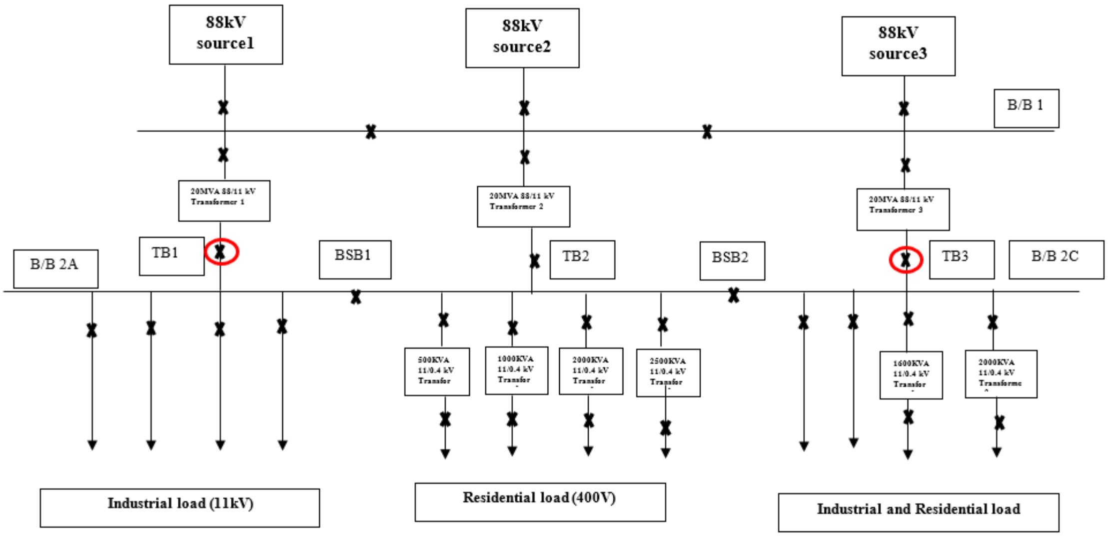


Figure 37: Transformer 1 and 3 simultaneous outage configurations

After running the simulations, the results of each busbar loads were the same for all scenarios- resultant graphs for when the contingency scenarios are evaluated are the same at each busbar as in figures 16-27. When the busbars are without supply, the graphs remain at zero see figure 38, with busbar 2B loads without any supply. Therefore, the distribution system model designed was indeed balanced, as a single transformer was able to handle all the loads without running to failure. However, the system will remain balanced only if the load remains fixed.

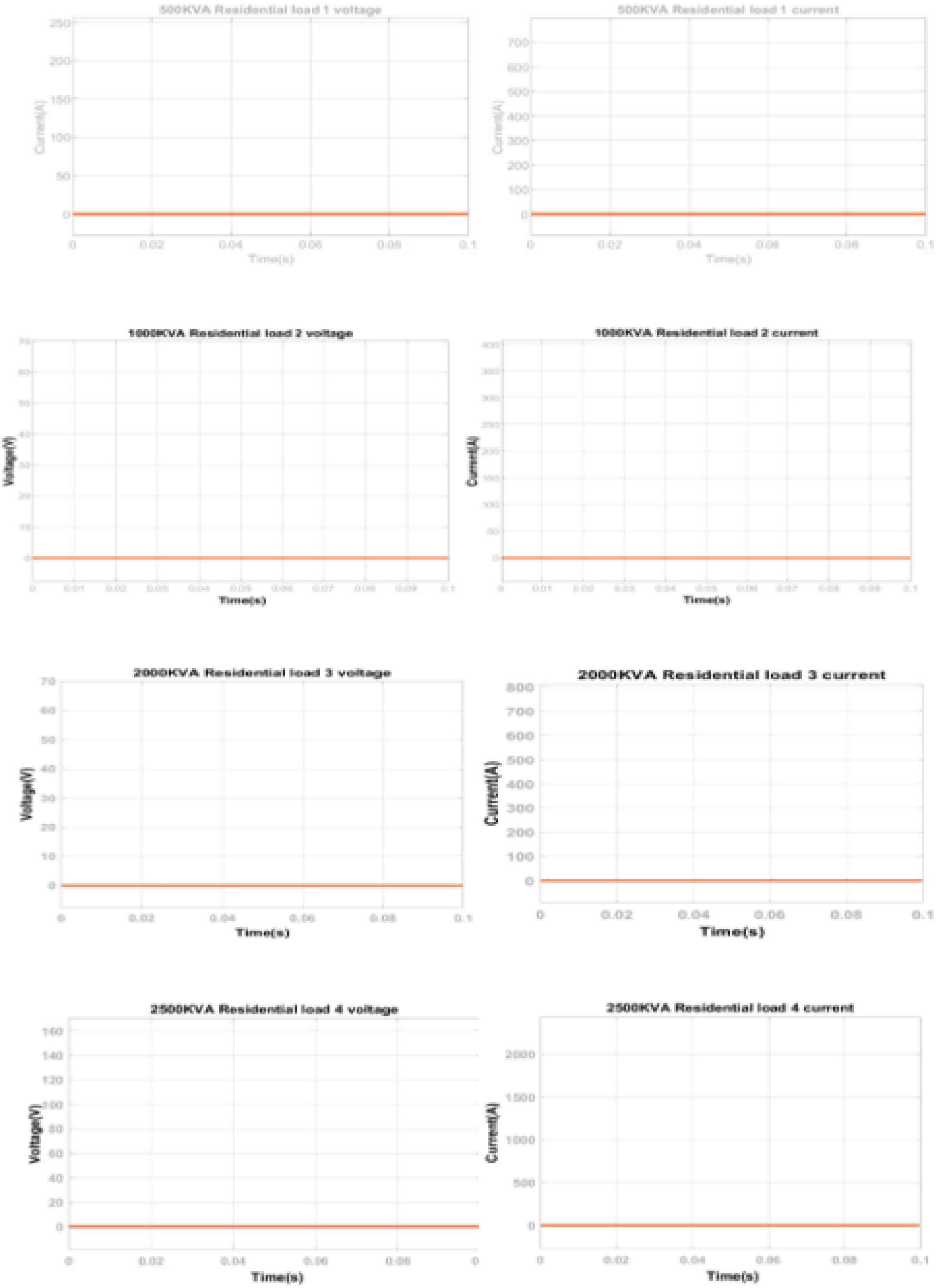


Figure 38: Busbar 2B loads without supply

Ideally, for the distribution networks to supply continuous power to the customers as investigated above. However, loading increases daily to a point that the provisions that were made in the design phase of the network can no longer be adhered to, leading to the Transformer(s) being overloaded in cases of emergencies which might lead to the explosion thereof and ultimately no means of supplying electricity to customers. From the above investigation of the contingency plans; it's easily noted that should all three incoming lines or transformers be out of service, the will be no means of maintaining continuity of supply to the customers. Meaning total blackout. The topic of introducing Battery Energy storage systems to Electrical power systems came about at the realization of the previous statement. Which is what will be fully investigated in Chapter 5.

Following sub-section analyses and investigates a BESS model on its own, to understand its characteristics and behaviours, and check if it will be a good fit for the integration and it will be able to fulfil its designated purpose, to increase the reliability of the network.

4.2. BESS modelling and analysis

The flexibility of the BESS results in the usefulness thereof at any stage of the power system energy process; addressing different issues as it can adapt to different activities quickly but having in common the possibility of increasing the network's safety and reliability [13]. Figure 39 depicts the Overview model of BESS implemented in the dissertation; the model is made of the battery, the DC/AC conversion, the control system of the BESS and a transformer to match the utility and load/s. The model is connected to a load and a voltage source that sends the control signal to decide if the battery should charge or discharge. The MATLAB Simulink implemented model can be found in appendix B.

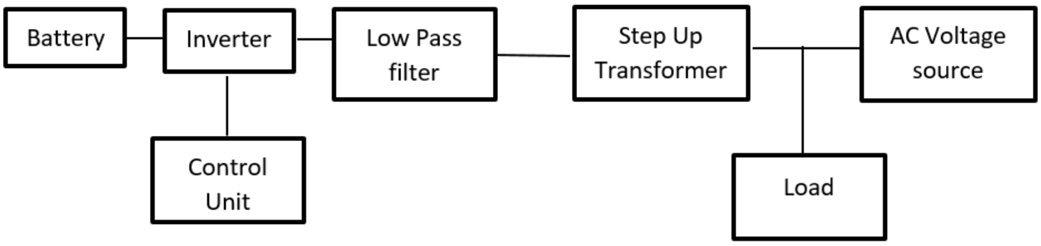


Figure 39: Overview of battery energy storage system implemented

The battery is the main component of the system, provide the flexibility of storing and releasing the energy to the grid at different time intervals and conditions. A lithium-ion battery is implemented in this sub-section with a set output voltage of 48 V. The PCS is used to manage the conversion and power flow for both charge and discharge process of the BESS. The BMS is the control unit system for the batteries and the PCS, as it decides which way power flow should be. The voltage control method will be implemented in the BMS and used to switch the inverter in the PCS for this dissertation.

4.2.1. Power conversion system model

The PCS is made of two components, the converter/inverter and low-pass filter. The power electronic component used in the PCS depends on the kind of electrical system the BESS is connected to, there are two types of PCS method that can be utilized. The first method being to implement a buck/boost converter and the second being to implement an inverter. The converter is connected to the DC part of the grid from the DC system (battery) if the BESS is connected to a DC grid. On the second method, the battery is connected to an inverter that converts the DC voltage to AC voltage, and vice-versa [90].

In this dissertation the BESS will be connected to the AC source; therefore, the charge/discharge process will be controlled by a 6-pulse bridge bi-directional inverter and each phase of the inverter will be connected to a low-pass LR filter to mitigate harmonics. Figure 40 depicts the PCS part of the BESS.

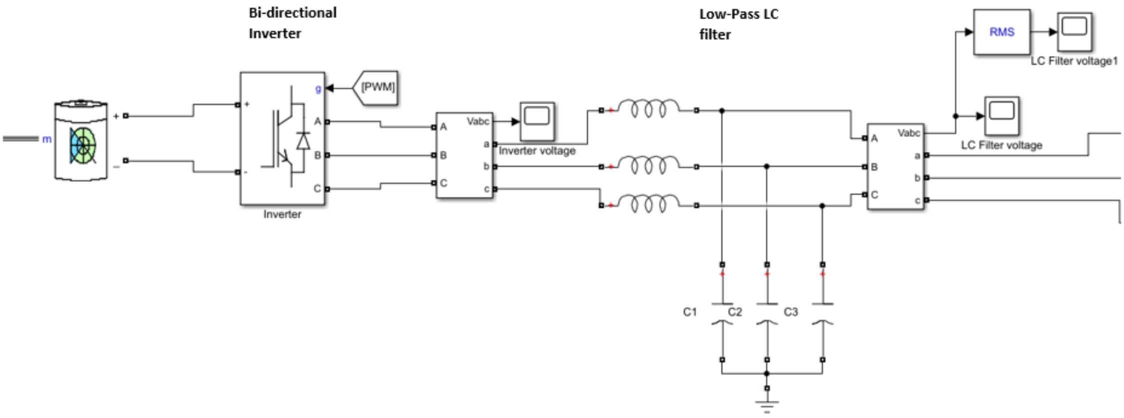


Figure 40: PCS Model overview

4.2.2. Battery management system model

The BESS is controlled by the SoC to prevent the over-saturation of the battery or it experiences over-discharging. The BMS creates pulse width modulation (PWM) signals that are used to switch the isolated-gate bipolar thyristors (IGBT) on and off to convert the voltage between DC and AC. Figure 41 depicts the overview of the BMS.

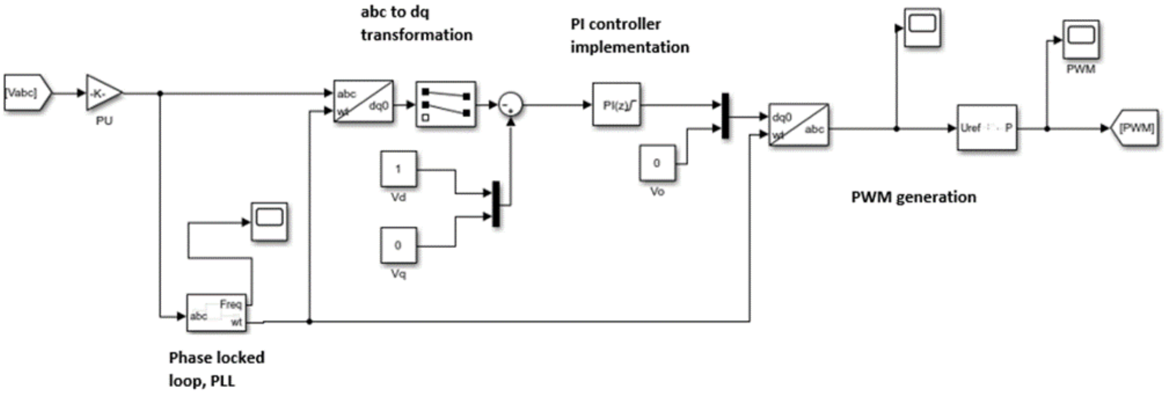


Figure 41: Battery Management system overview

The actual voltage measured after the step-up transformer is used as an input in the creation of the PWM signal. The voltage is converted to per unit (p.u) measurement using the gain block. The gain block value will be a fraction of the expected transformed voltage per phase depending on the load ($\frac{1}{230}$ for residential load and $\frac{1}{6.35X10^3}$ for industrial load).

The p.u ABC phase voltage is converted into dq axes to simplify the analysis. The error signal is created by subtracting the actual value from the reference value and the error value in the implemented PI controller. The dq reference system is transformed back to the abc reference system, the new abc p.u voltage together with the phase lock loop (PLL) is used to create the PWM signal, which is the input that controls the inverter to decide if the battery should charge or discharge.

Figure 42 depicts the PWM pulse signal generated by the BMS. Figure 43 depicts a six-pulse wave created when the IGBTs converts from DC to AC. The low pass filter is used to smooth the inverter pulse. Figure 44 depicts the AC voltage wave after the filter and Figure 45 depicts an RMS AC voltage graph at the filter. The battery input 48Vdc is successfully inverted to 48Vac. Therefore, the PWM signal created is working as it should.

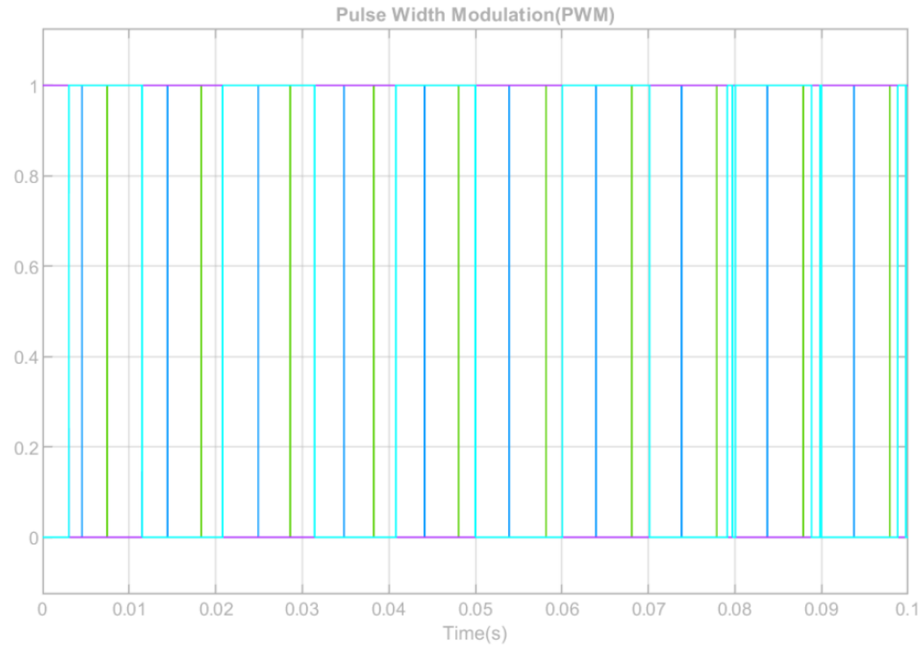


Figure 42: PWM Signal

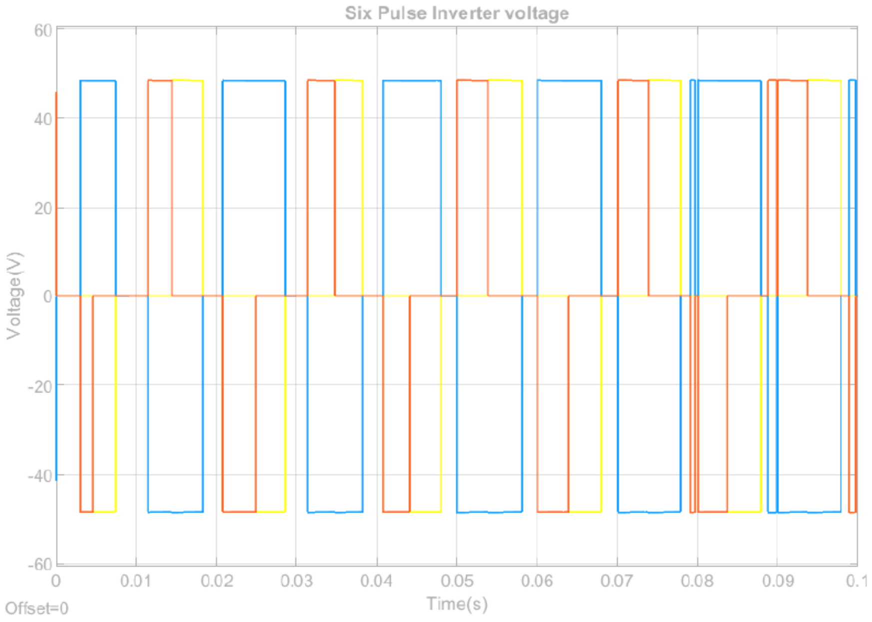


Figure 43: Six pulse inverter voltage

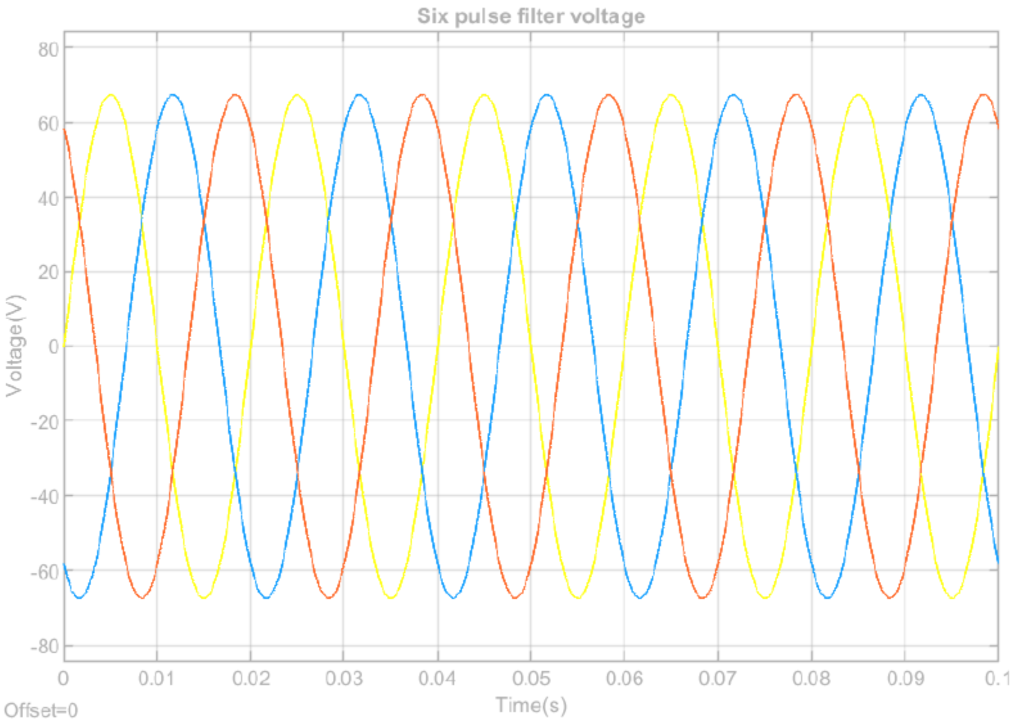


Figure 44: Six pulse Filter voltage

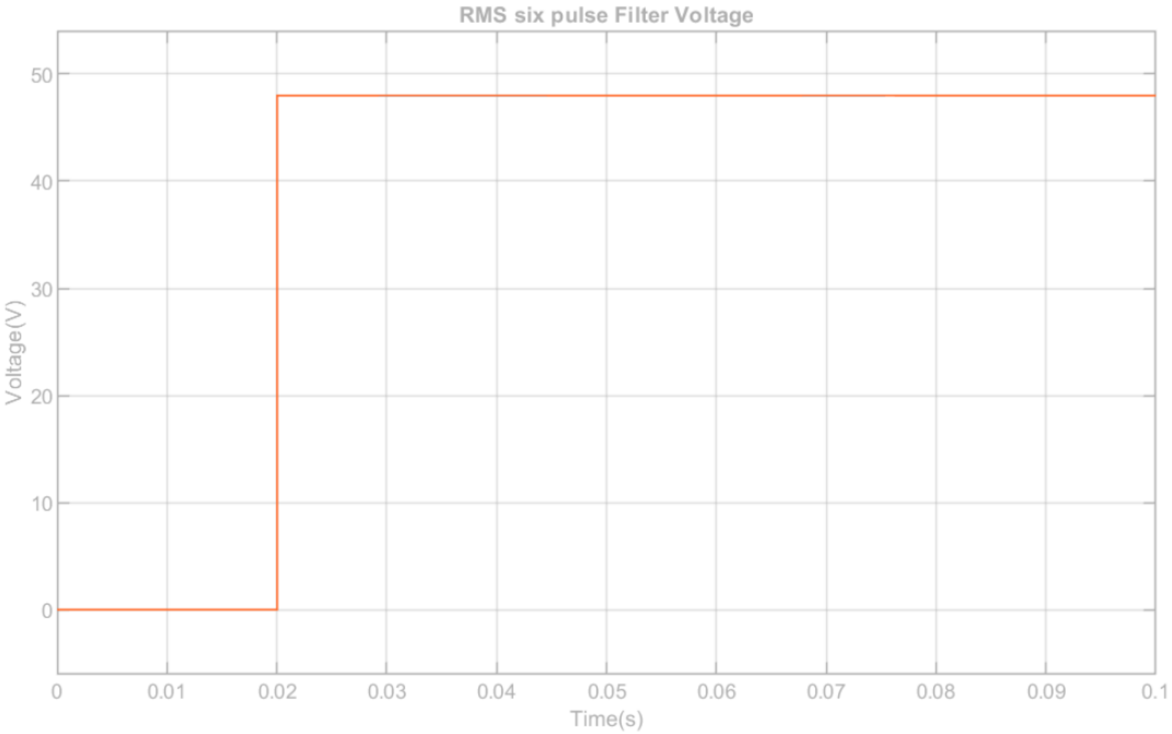


Figure 45: RMS Six pulse Filter voltage

4.2.3. Utility and Load transformer model

To obtain a complete BESS system, a transformer is added after the filter, this is to boost up the low battery inverted voltage to a voltage that matches the grid-connected load. Based on the distribution model (figure 12), there are two types of loads connected across three medium voltage busbars, residential and industrial. Therefore, there will be three BESS models that will be implemented using two different step-up transformers to accommodate each load. Figures 46, 47 and 48 depict block diagrams for the BESS connected to the three busbar loads in the distribution model in 4.1

The BESS unit depicted by the block diagram in figure 49 will be used to supply the 11kV busbar connected to industrial loads only; the one in figure 50 will supply the residential loads directly after the mini-substation transformers. And from figure 51, busbars that consist of both the loads that require 11kV and 400V.

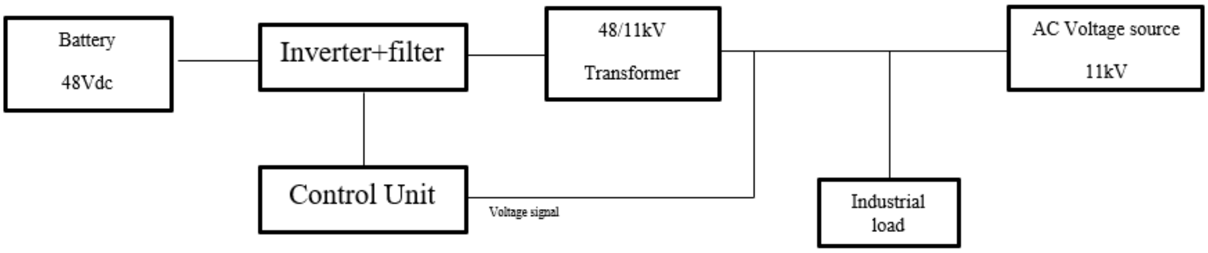


Figure 46: BESS overview connected to busbar 2A with Industrial load

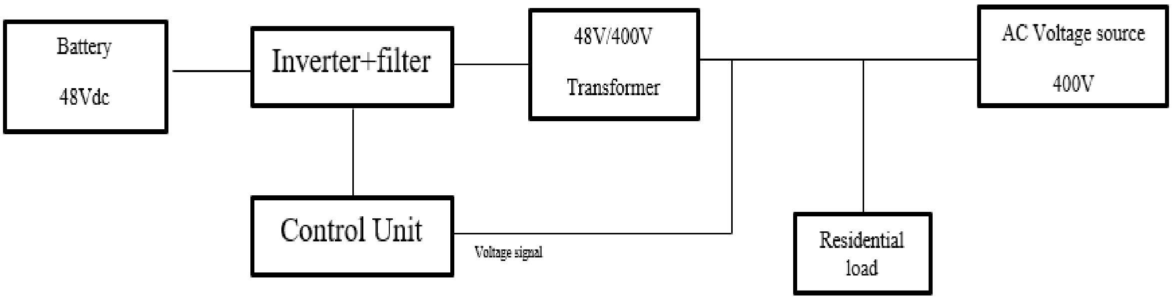


Figure 47: BESS overview connected to busbar 2B with Residential load

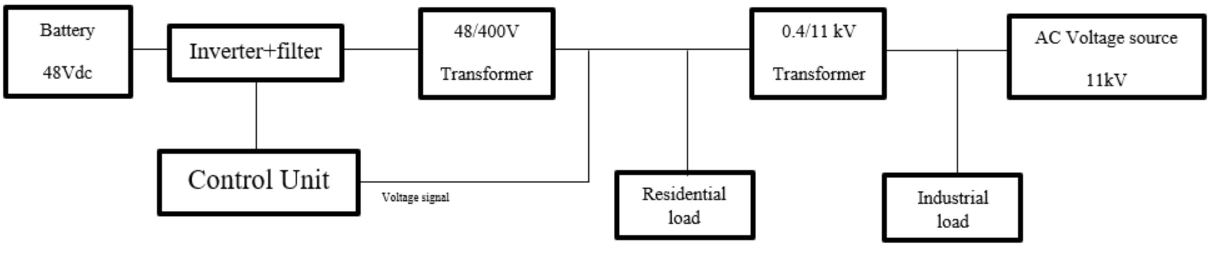


Figure 48: BESS overview connected to busbar 2C with Residential and Industrial load

Before the BESS units can be integrated with the substation, they will first be tested with a single load, set at the maximum transformer loading, to investigate if the designed systems can still supply the capacity needed at different loadings.

The figures that are to follow results from the BESS connected to the grid and the load with two transformers that steps-up the 48 V of the battery to 230V and 6.35kV per phase, respectively; which will be more suitable for busbar 2C as it has a combination of the industrial and residential load. The purpose is to observe if the loads and transformers are operating as intended or not via their voltage and current readings.

Figure 49 and figure 50 depict the voltage graphs of the transformers. The first transformer is to step up the 48 V to 400V, therefore the expected secondary measured value is 230V per phase. The second transformer is to step the 400V up to 11kV to match the source and loads, and the expected secondary voltage is 6.35 kV. It is found that the measured voltages correlate with the actual expected voltages, therefore the BESS is functioning as it should and the transformers are configured properly.

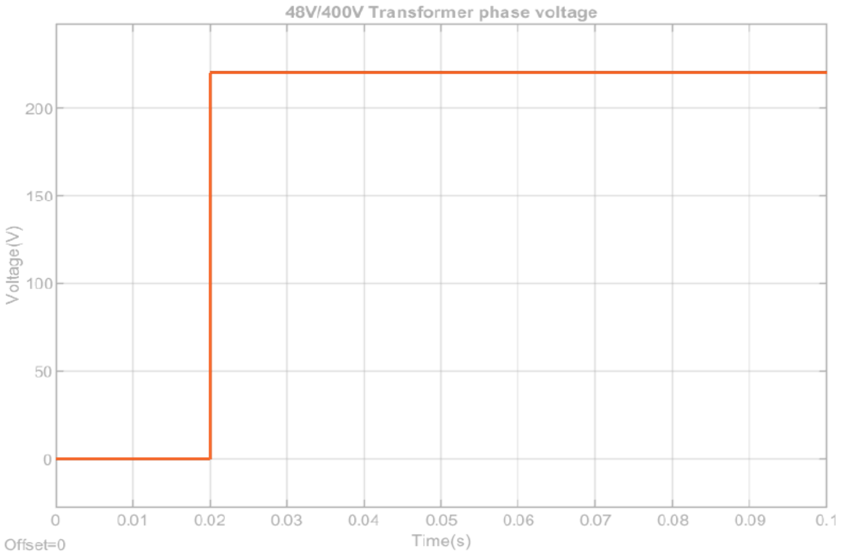


Figure 49: Step -up transformer1 secondary phase voltage

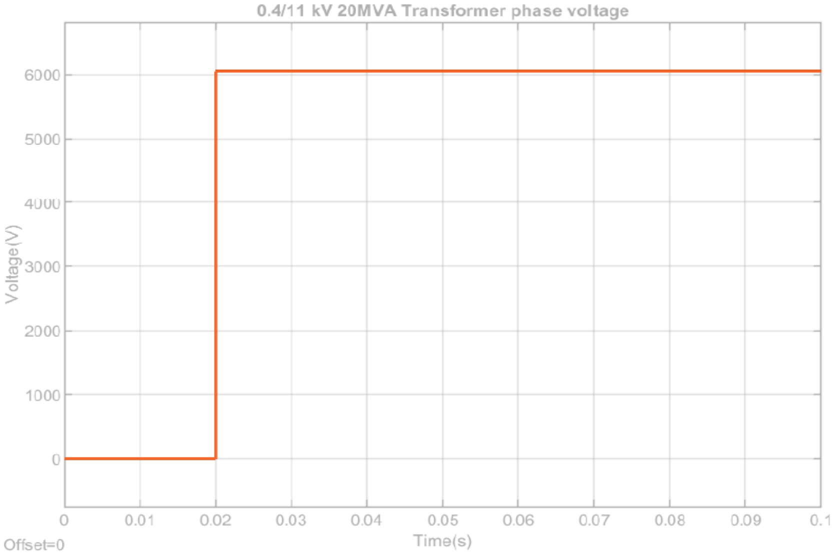


Figure 50: Step-up transformer2 secondary phase voltage

For residential loads, the transformer is measuring 230V which is the expected phase voltage and the current measured at the load is equivalent to the calculated load current for 474kW load at 230V see figure 51, and for Industrial load, the transformer is measuring 6.35kV which is the expected phase voltage and the current measured at the load is equivalent to the calculated load current for a 19MW load at 6.35kV see figure 52.

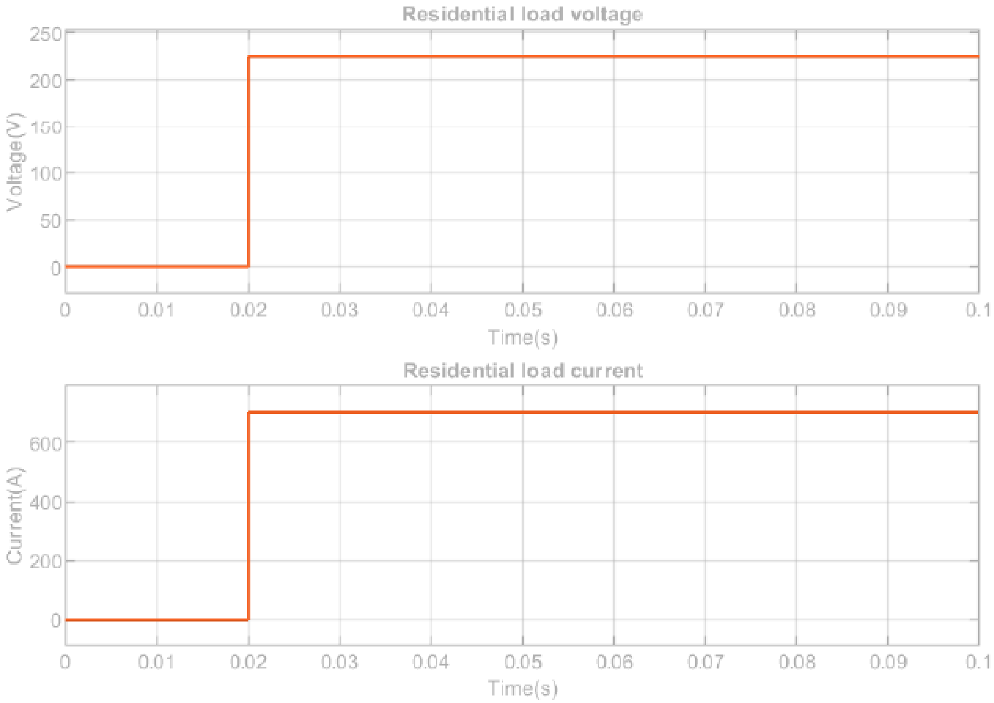


Figure 51: Residential load parameters connected to BESS

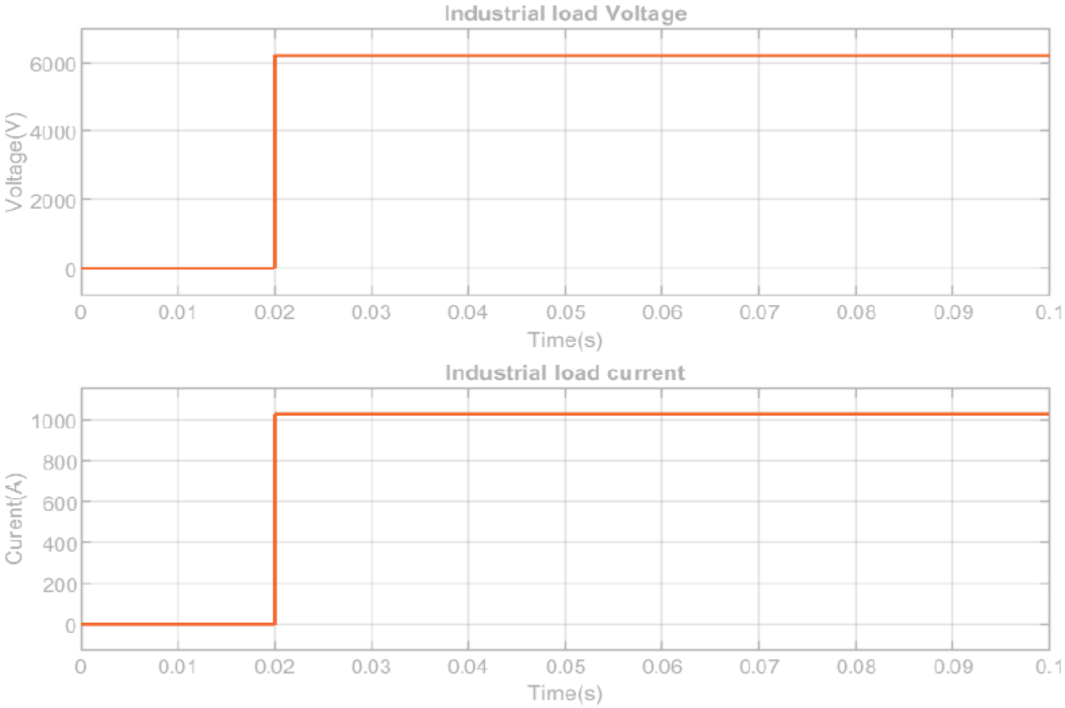


Figure 52: Industrial load parameters connected to BESS

The battery being the main component of BESS, it is very important to monitor it and see to it that it functions accordingly. The charging and discharging process of the BESS is noted from the current graph of the battery. When the SoC is in the charging mode, the battery current increases (negative axis) over a certain period. When the SoC is in the discharging mode, the battery current increases (positive axis) over a certain period. Figure 53 depicts the battery parameters, current and state of charge and from the graphs, when the battery is charging (SoC increasing) the battery current is negative, and when the battery is discharging (SoC decreasing) the battery current is positive, thus demonstrating the correct BESS model operation.

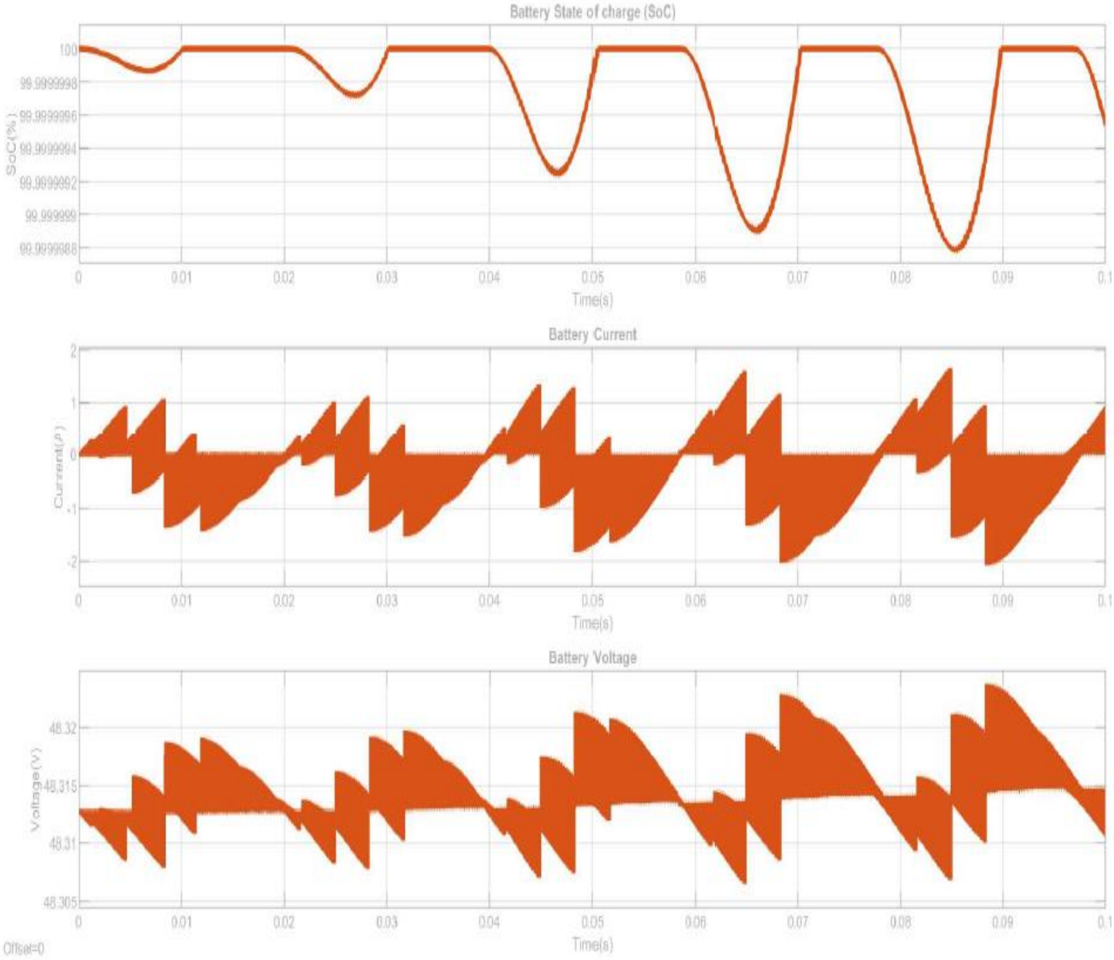


Figure 53: Battery Parameters connected to busbar 2A with Industrial load

Based on the figures obtained in this sub-section, it is without a doubt that the BESS is modelled appropriately, and parameters are set correctly as the values obtained were as expected. The BESS can act as both the voltage source and the load during its charge and discharge process; this makes it possible for it to act as a power balance unit on the power grid. The size-range of BESS is large and will keep on growing. The grid-connected BESS can be everything from the range that accommodates the Transmission power rating to the distribution rating, making it possible to supply and balance the power from low to large scale distribution grids.

Chapter 5

5. Integrating BESS into Substation

This section is dedicated to investigating the optimum placement of BESS in the distribution system to allow customers to receive backup supply during an outage. The distribution test system formulated (see figure 12) is a three-phase balanced radial distribution feeder with 12 loads; the system contains technical parameters for loads, transformers and breakers. The three busbars at the substation (figure 12) consist of different loads, therefore it is deemed better to have BESS suitable for each busbar load voltage as all the loads are a priority. The BESS models were simulated following the block diagrams depicted in figures 46-48.

The integration of BESS into the distribution system for backup purposes is so that during a system event, the faulted sub-system will be disconnected, and the non-faulted sub-system will begin to operate in isolated mode with customers being supplied by the local BESS. The subsections to follow will demonstrate each load being supplied by the BESS and as each busbar operates in an island-like mode.

5.1. Busbar 2A supplied by BESS 1

Industrial loads are supplied directly from the busbar. In case of any outages that leave the busbar without supply, the BESS will be connected to the busbar to enable all the loads to have an electrical power supply. Figures 55- 58 depict the voltage at which the loads are supplied and the load currents that are expected and figure 54 is of the battery parameters as it supplies the busbar, the battery supplies the loads when it is in the discharging mode, hence the voltage increases as opposed to decreasing when the battery is charging.

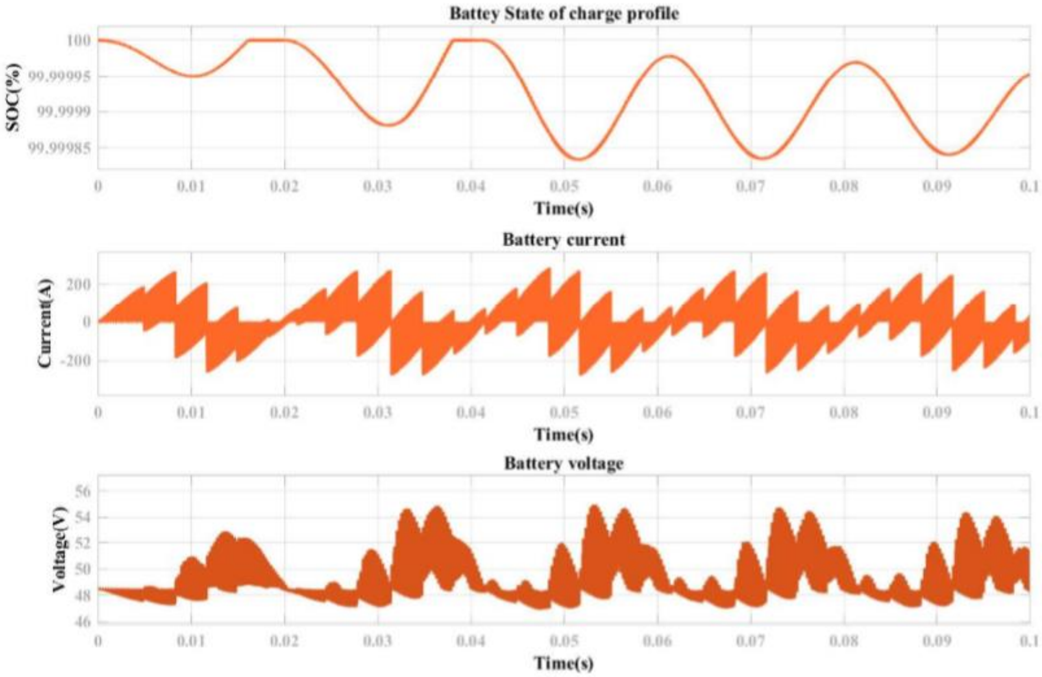


Figure 54: Busbar 2A BESS connected battery parameters

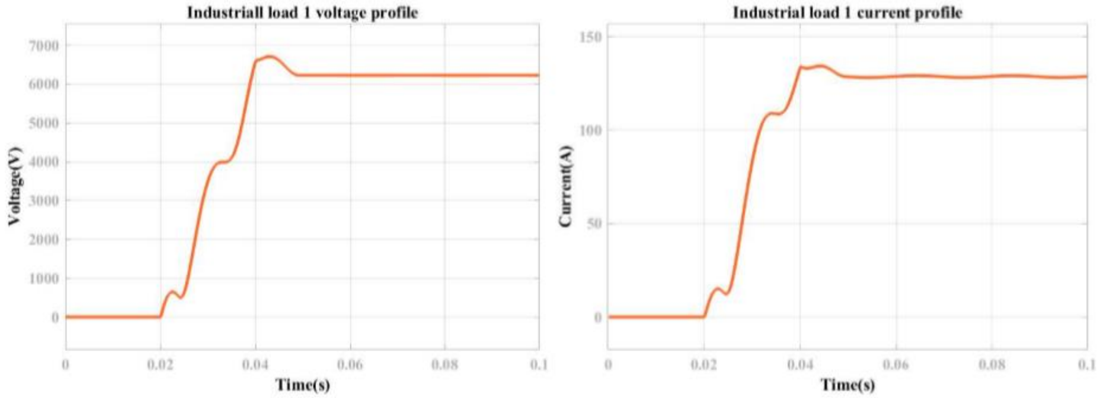


Figure 55: Industrial load 1 supplied by BESS 1 parameters

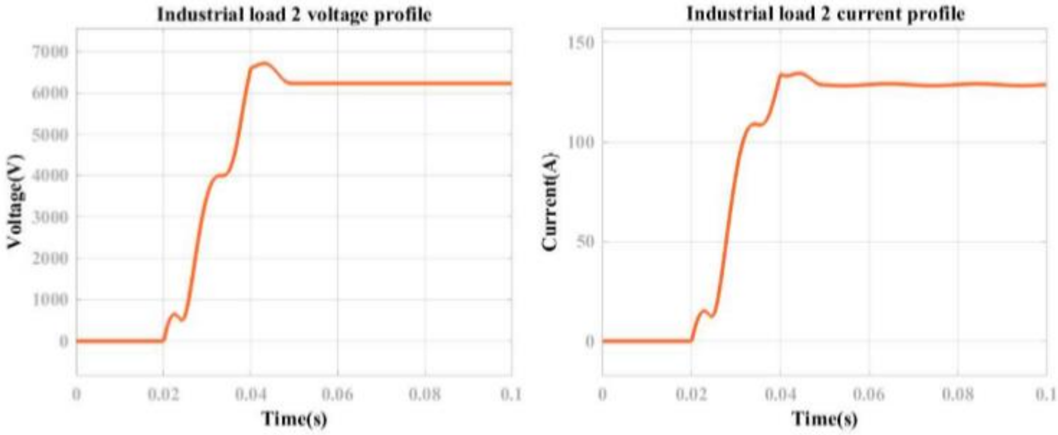


Figure 56: Industrial load 2 supplied by BESS 1 parameters

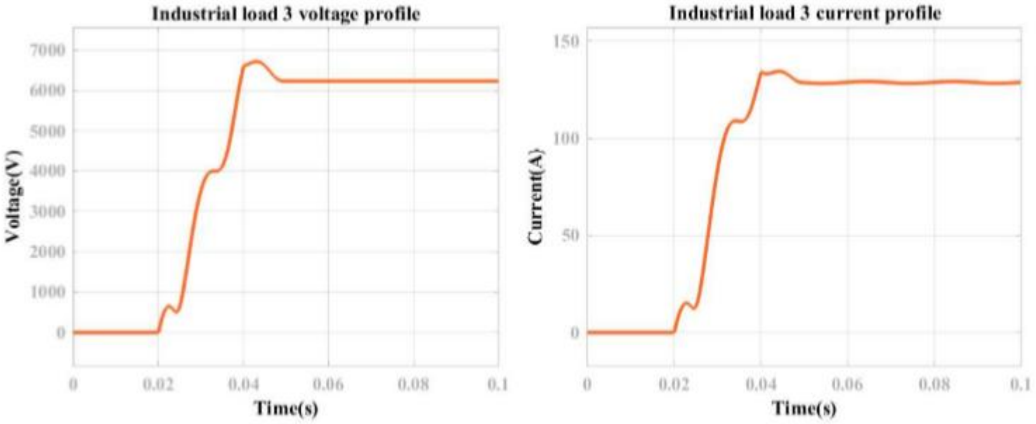


Figure 57: Industrial load 3 supplied by BESS 1 parameters

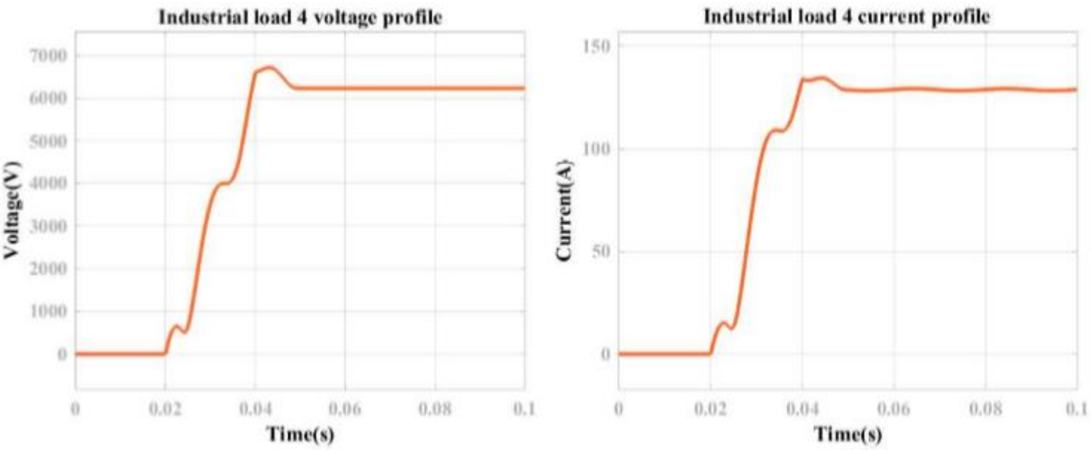


Figure 58: Industrial load 4 supplied by BESS 1 parameters

5.2. Busbar 2B supplied by BESS 2

Residential loads can be supplied from the busbar as there is a step-down power transformer to lower the busbar voltage to the level required by residential users. And it can also be supplied directly after the load breakers. Therefore, the two types of BESS configurations can be utilized for this busbar at a time; the first configuration being from figure 46, connecting it directly to the busbar. The second being depicted in figure 50, connecting it directly to the load after the load breaker. With the two different connecting points, the operation of the battery system remains the same shown in figure 59. Figures 60-63 depict the voltage at which the loads are supplied and the load currents that are expected.

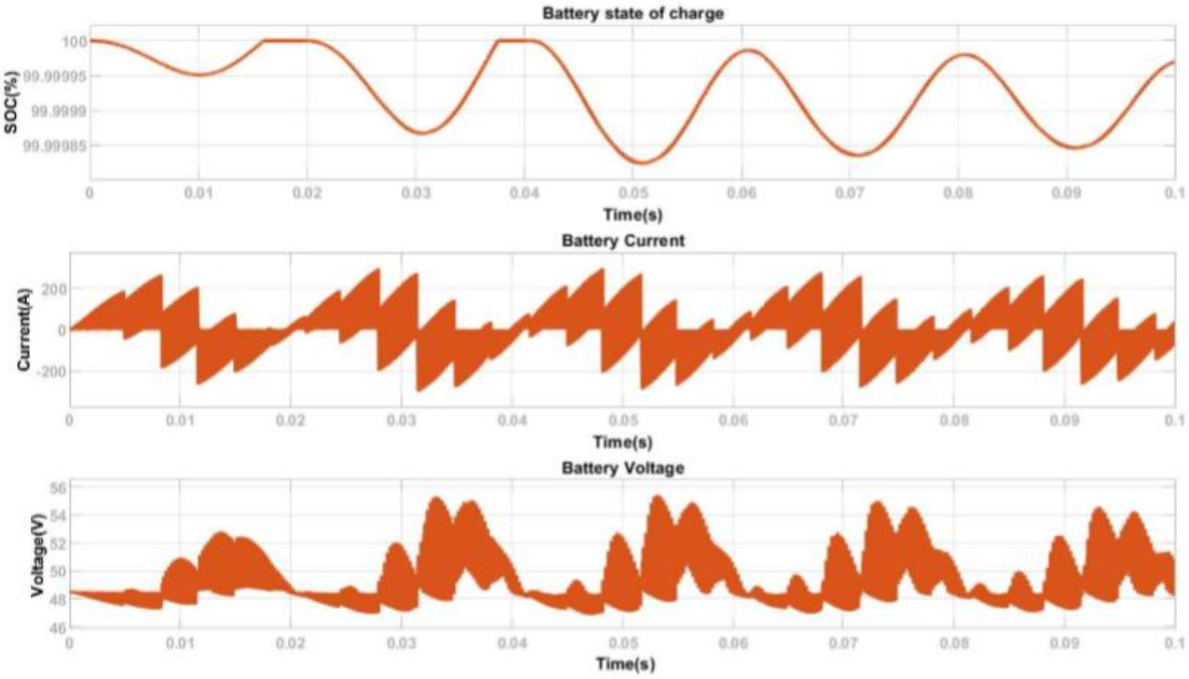


Figure 59: Busbar 2B BESS connected battery parameters

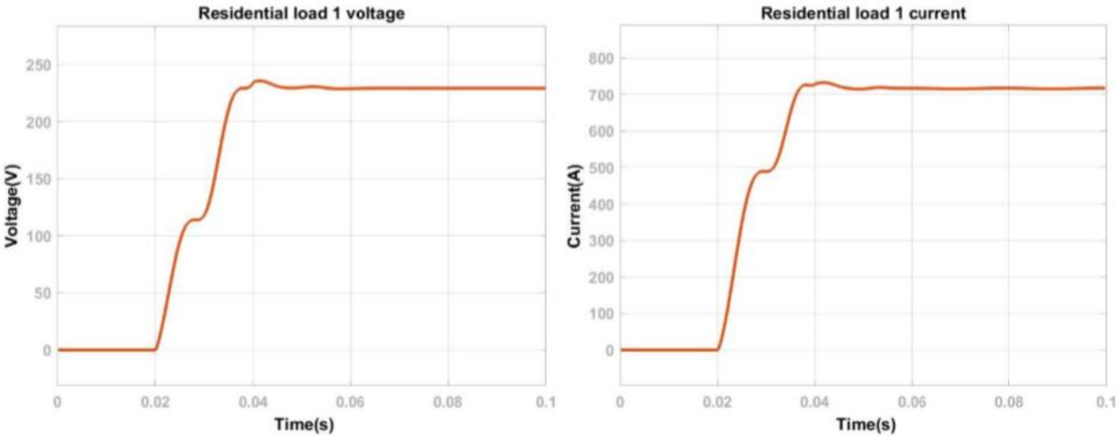


Figure 60: Residential load 1 supplied by BESS parameters

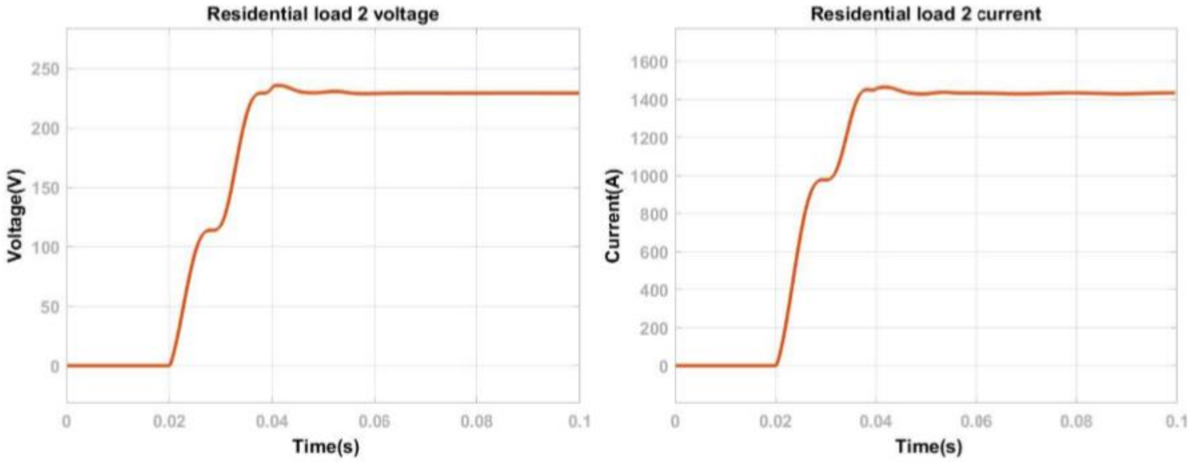


Figure 61: Residential load 2 supplied by BESS parameters

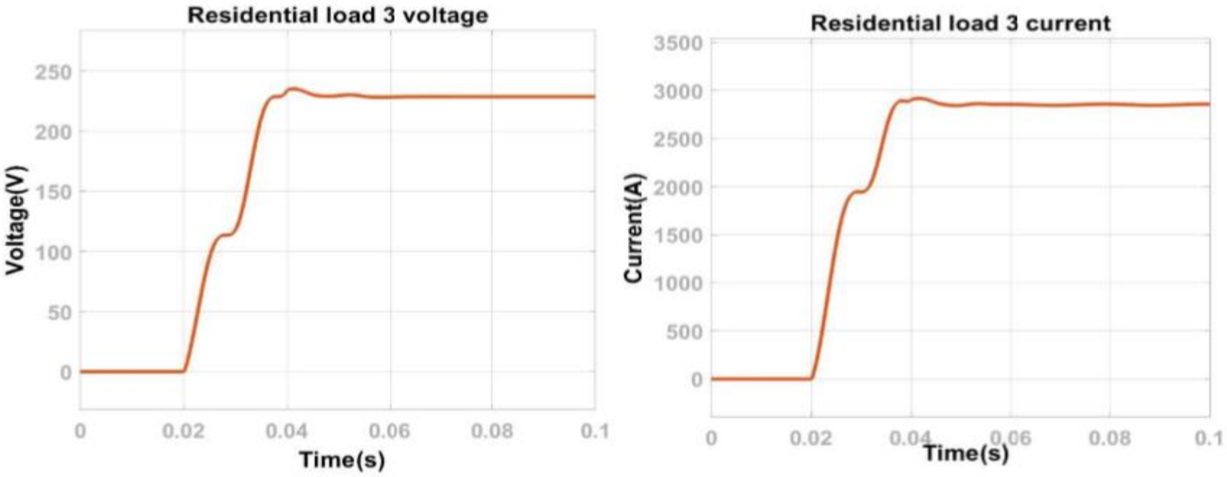


Figure 62: Residential load 3 supplied by BESS parameters

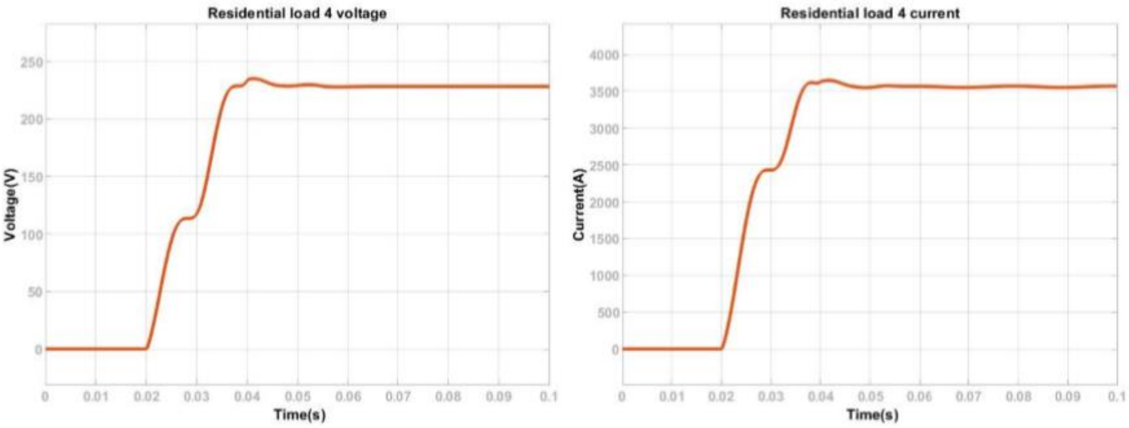


Figure 63: Residential load 4 supplied by BESS parameters

5.3. Busbar 2C supplied by BESS 3

With the busbar having two types of loads, the one solution is to have two BESS to accommodate the loading; that is to connect the industrial load as shown in figure 46 and connect the residential load as in figure 47. However, this method will not be cost efficient. The BESS configuration shown in figure 48, is the better option with regards to the financial side of things as a single battery unit will be used, However, the battery ought to reach its lifespan much quicker as it will be used to supply at different voltages at once. Which is going to result in the battery being changed frequently, and this is also not cost-efficient. Figures 66-69 depict the voltage at which the loads are supplied and the load currents that are expected, and the same for the two BESS configuration. But the difference is that the battery system’s operation differs, and one takes a lot of strain at supplying the load.

The battery parameters in figure 64, on the voltage graph it is noticeable that the battery voltage is a lot higher than the set value, meaning that connecting the BESS on the busbar with different loads is not a good idea, as this leads to the battery working harder, which will lead to a shorter life span. However, when connected directly to the loads, the parameters remain within the set value. See figure 65.

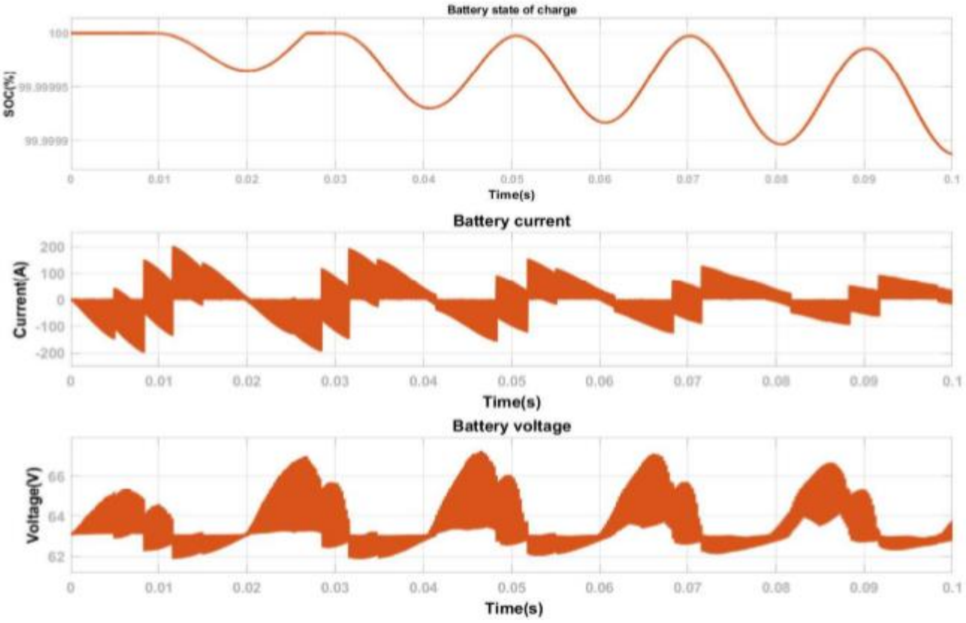


Figure 64: Busbar 2C BESS connected battery parameters

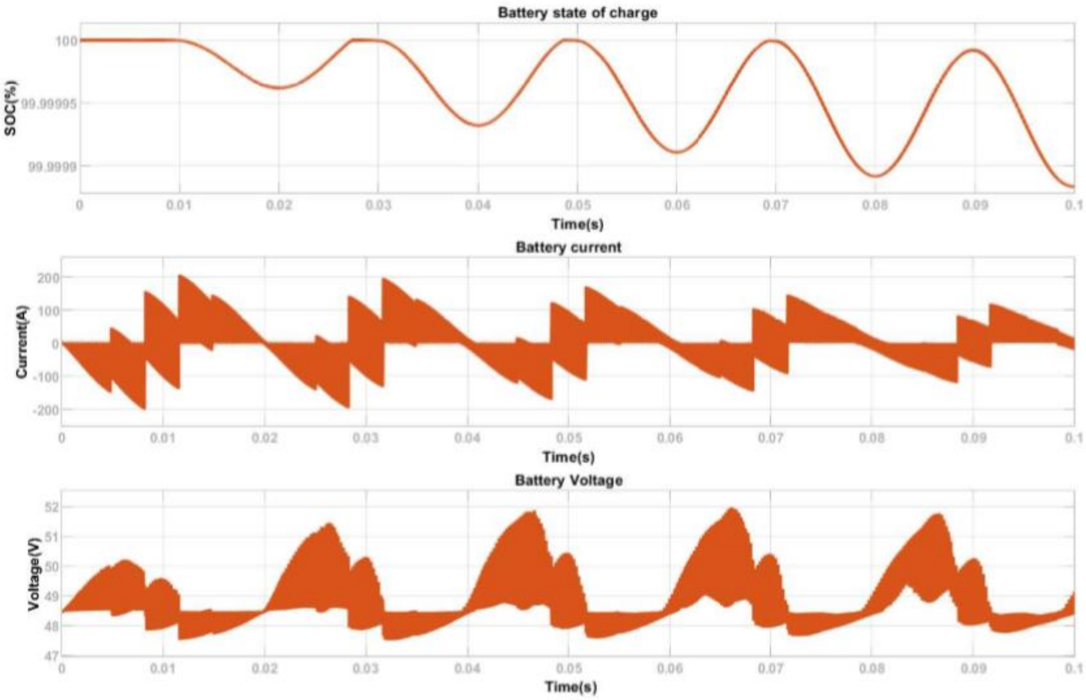


Figure 65: BESS connected directly to Busbar 2C loads

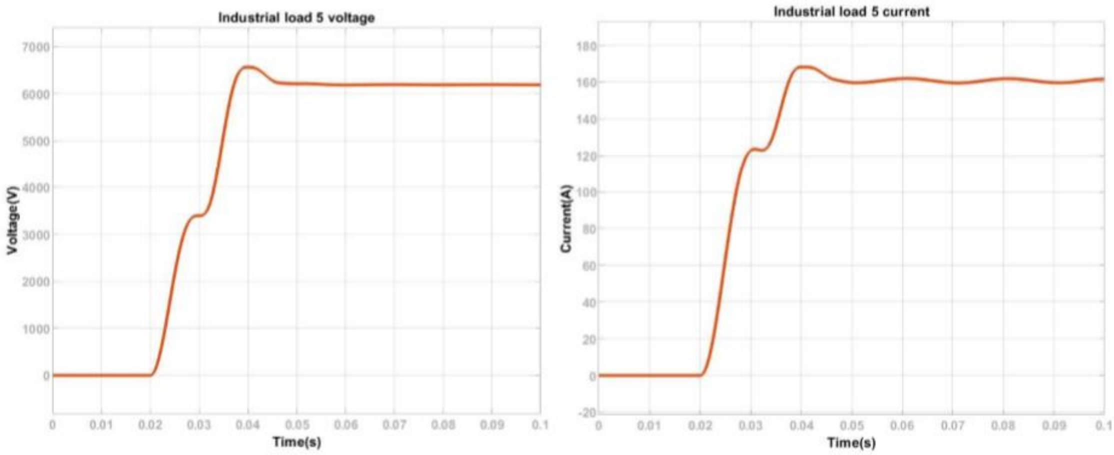


Figure 66: Industrial load 5 supplied by BESS parameters

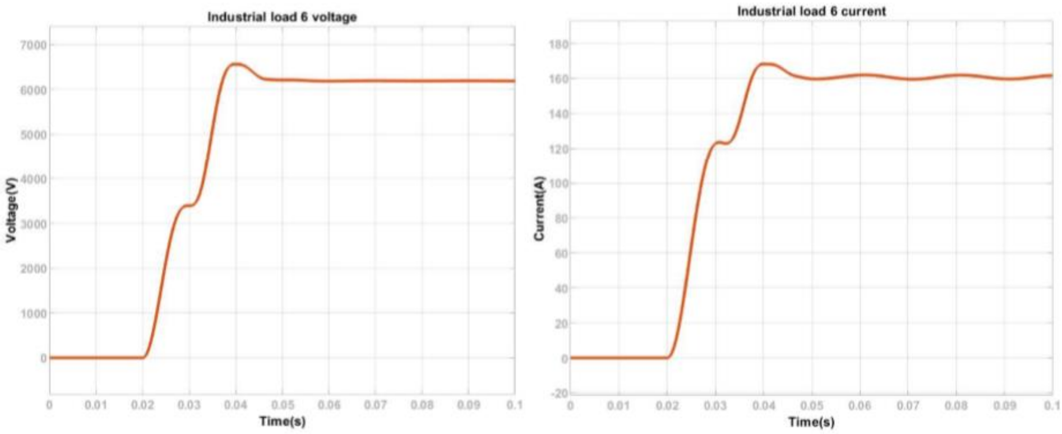


Figure 67: Industrial load 6 supplied by BESS parameters

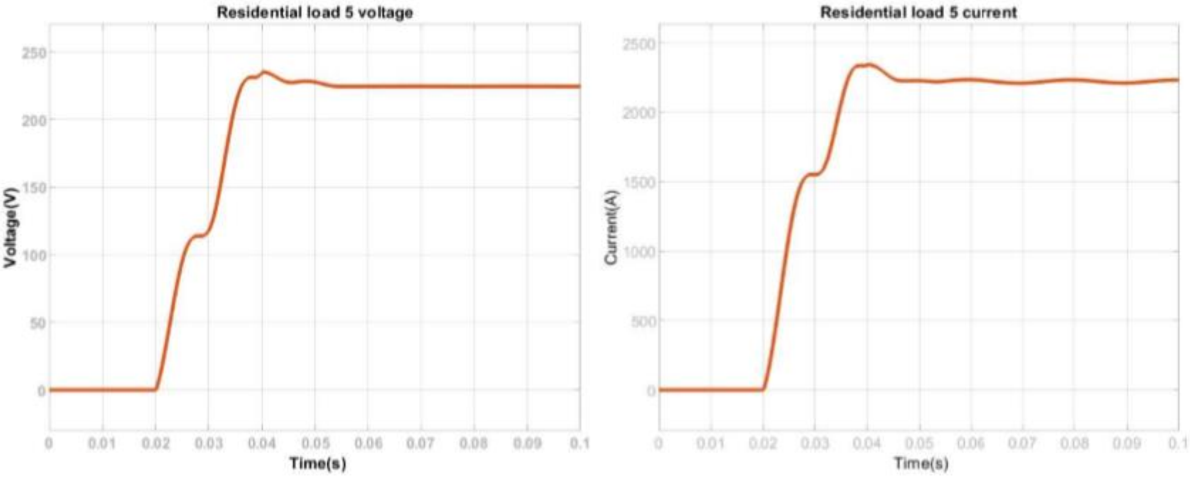


Figure 68: Residential load 5 supplied by BESS parameters

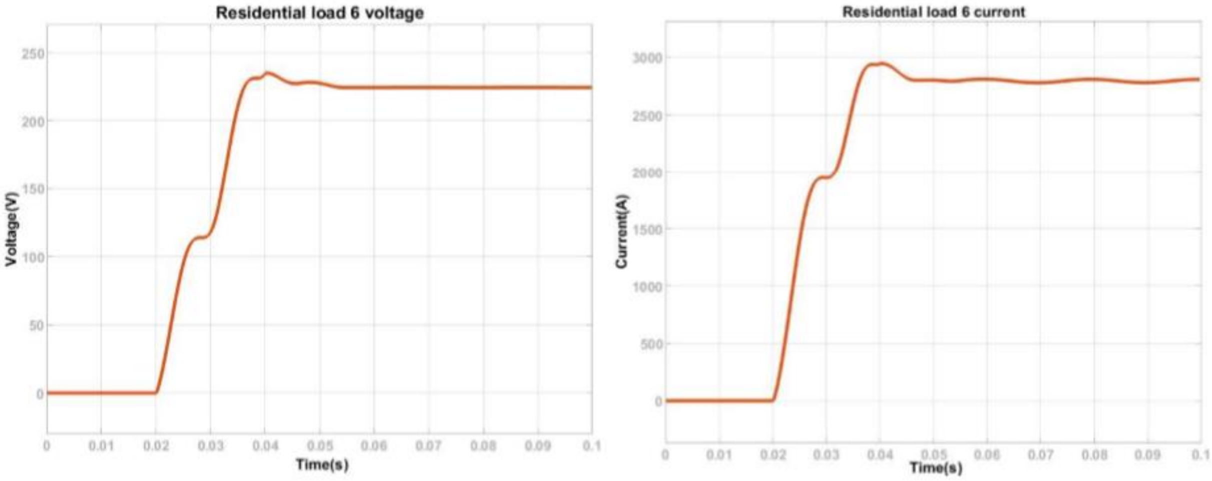


Figure 69: Residential load 6 supplied by BESS parameters

The 11kV side of the transformer should be connected to the BESS unit(s) as a source of AC power. The PCS links the battery system to the network’s utility, and the BMS is used to monitor and measure the battery systems’ performance parameters such as voltage, currents and SoC/temperature and control the PCS for optimum results. The main function of the BMS is to ensure that the battery’s output is matched to the distribution network and prevents any current strays from impacting the distribution system. From the figures, the BESS supplies the loads with the needed voltage and the current measured is the same as when the loads are supplied by the distribution transformers. The results show that BESS can be very valuable. The implementation thereof in the distribution systems reduces the overall outages, improving the key performance indices of the substation. The distortions observed on the load current and voltage graphs are caused by the inverter as it acts as a non-linear load and doesn’t draw current that is sinusoidal only. Being the coupling point between the DC and AC GRID, it draws both the DC and AC current depending on the direction of its operation. Thus, it takes milliseconds for the system to stabilize once the supply switchover occurs as shown in the figures.

Chapter 6

6. Conclusion

The load growth that South Africa is experiencing and results in the power equipment being overloaded is due to the high residential (high electrification) and industrial (agriculture and mining) developments; the illegal connections also contribute to problems, as this is an additional load that was not planned for. There are two methods currently being utilized to normalize the power systems; to reduce demand (load shedding) and upgrade substations to accommodate the new load that is constantly being added. However, both methods cannot be implemented without interfering with the supply of power to the customers. Any interference that leaves the customers without electricity results in a negative impact on the key performance indices (KPI) of the network; the System average interruption duration index (SAIDI) and System average interruption frequency index (SAIFI). BESS provides demand reduction, power reliability, it’s used to improve the quality of the network’s supply and defer outages at the customers’ endpoint, allowing consumers to be always connected. The BESS provides the grid with the opportunity to reduce outages that affect the customers if not eliminate them. When outage or fault occurs at the substation, the BESS acts quickly at any slight change in the frequency of distribution system, by allowing the loads to be supplied while the battery is discharging; when the utility power is restored, the BESS disconnects from the loads and starts charging. The loads will draw from the BESS unit located close to it because it is impossible to predict the exact point(s) where disturbances will occur. Therefore, the optimal placement/connection point of BESS is at the secondary busbars or directly to the load. When determining the optimum size in the network, must consider whether increasing the number of BESSs and arranging for them to work in a coordinated manner would reduce the overall cost and/or decrease network losses as well as provide power capacity and total availability of energy; More especially for busbars with a mixture of Industrial and residential loads, as they contain multiple BESS units.

The main objectives set out for the dissertation regarding the integration of BESS onto the distribution system were successfully addressed. Sub-section 4.2 covered the development of the power conditioning system and the effective control method via the battery management system for the BESS. Voltage control was the method utilized, it enabled for the loads to be supplied by the grid as well as the BESS when the grid is unable to do so. The research aimed to attempt to answer a few research questions; it was found that the strengthening of the network by integrating BESS onto it provides the opportunity to improve customer and network quality and reliability of supply. This may lead to a solution that is marginally more expensive but leads to a substantial quality of supply improvement and increased performance of the system, measured by duration the outage lasted and the number of times the outage occurs in the system that left customers without supply, and the BESS reduces the interruptions that occur at the secondary substation by suppling the loads when there’s an outage on the grid, acting as an uninterruptable backup power supply. Based on the simulations works done in chapters 4 and 5, it can be concluded that BESS can be used to supply the distribution system loads when the network is unable to do so due to any outages or faults that may occur at any of the critical points of the substation and leave the loads without any electrical supply. Thus, reducing interruptions at the secondary side of the substation. For future works, a method to use BESS for peak shaving instead of keeping it without effect when there are no outages in the network will be implemented; as well as a method that monitors BESS health status and approximate the possible future failure date, to increase the reliability and life cycle of the overall system and eliminate surprises. The next step is to conduct an in-depth study BESS economic performance issues and evaluate specific cost effects on the economic performance of BESS for an HV/MV substations and create a scaled model to validate the research work done; by Building a prototype of the BESS and embedding it to a real-time distribution network to demonstrate the effect it will have on the performance of the substation under normal and abnormal operating conditions.

References

[1] Narayanan A, Kaipia T, Partanen J, “Interruption Reduction in Secondary Substations”, IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 26-29 September 2017

[2] Karthikeyan N, Pokhrel B.R, Pillai J.R, Bak-Jensen B, “Utilization of Battery Storage for Flexible Power Management in Active Distribution Networks”, IEEE Power & Energy Society General Meeting (PESGM), 5-10 August 2018

[3] Qing Z, Nanhua Y, Xiaoping Z, Yi Y, Dong L, “Optimal Siting & Sizing of Battery Energy Storage System in Active Distribution Network”, 4th IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), 6-9 October 2013

[4] Shi W, Jiang J, Li S, Lin S, Lin P, Wen F, “Applications of Battery Energy Storage System (BESS) for Energy Conversion Base in Expo 2010”, The second International Symposium on Power Electronics for Distributed Generation Systems, IEEE, 16-18 June 2010

[5] Kim GH, Bae HH, Kim SS, Hwang C, Lee HG, Kim N, Seo HR, Park JD, Yi DY, Lee S, “Application of Battery Energy Storage System for Power Quality Improvement of Jeju Power System”, International conference on Electrical Machines and Systems, IEEE, 10-13 October 2010

[6] Desanti JD, Schwetz G, “Decreasing Owning Costs of MV/LV Substations Backup Batteries”, INTELEC 06-Twenty-Eight International Telecommunications Energy Conference, 10-14 September 2006

[7] Xia T, Li M, Zi P, Tian L, Qin X, An N, “Modelling and Simulation of Battery Energy Storage System (BESS) Used in Power System”, 5th International Conference on Electric Utility Deregulation and Restructuring and power Technologies (DRPT), IEEE, 26-29 November 2015

[8] Yamabe K, Komatsu H, Iijima Y, “Requirements Analysis and Development of MW-Range PCS for Substation-Scale Battery Energy Storage Systems”, 19th International Conference on Electrical Machines and Systems (ICEMS), 13-16 Nov 2016

[9] Mahela O.P, Shaik A.G,” Power Quality Improvement in distribution network using DSTATCOM with battery energy storage system”, Electrical Power and Energy Systems 83, pp 229-240, 2016

[10] Bucciarelli M, Paoletti S, Vicino A,” Optimal Sizing of energy storage systems under uncertain demanding and generation “, Applied Energy 225, pp 611-621, 2018

[11] Das C.K, Bass O, Kothapalli G, Mahmoud T.S, Habibi D, “Overview of energy storage systems in distribution networks: placement, sizing, Operation and operation and power quality”, Science direct, Renewable and sustainable Energy Reviews, Volume 9, pp 1205-1230, August 2018

[12] Akhil A, “Trends and Status of Battery Energy Storage for Utility Applications”, Proceedings of the Tenth Annual Battery Conference on Applications and Advances, IEEE, 10-13 January 1995

[13] Tiara, Ziadi Z, Funabashi T, “Assessment of Impact Distributed Generators, Plug –in Electric Vehicle and Battery Energy Storage System on Power Distribution Losses”, 1st international Future Energy Electronics Conference (IFEEC), IEEE, 3-6 November 2013

[14] Hatta H, Omine E, Takahashi N, "Proposal of Impact Assessment Method for Autonomous Operation of Smart Community Using Battery Energy Storage Systems", IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia), 28 Nov- 01 Dec 2016

[15] Roberts B.P, "Sodium-Sulfur(NaS) Batteries for Utility Energy Storage Application", IEEE Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 20-24 July 2008

[16] Hayashiya H, Suzuki T, Hino M, Hara D, Tojo M, "Effect evaluation of Li-ion battery for regenerative energy utilization in traction power supply system", 17th European Conference on Power Electronics and Application, 8-10 September 2015

[17] Divya K.C, Ostergaard J, "Battery Energy Storage Technology for power systems-An overview", Science Direct, Electric Power Systems Research 79, pp 511-520, 2009

[18] Dehghani-Sanij A.R, Tharumalingam E, Dusseault M.B, Fraser R, "Study of Energy storage systems and environmental challenges of batteries", Science Direct, Renewable and Sustainable Energy Reviews 104, pp 192-208, 2019

[19] Azzuni A, Breyer C, "Energy security and energy storage technologies", Science Direct, 12th International Renewable Energy Storage Conference, IRES, pp 237-258, 2018

[20] Mahlia T.M.I, Saktisahdan T.J, Jannifar A, Hasan M.H, Matseelar H.S.C, "A Review of available methods and development on energy storage; technology update", Science Direct, Renewable and Sustainable Energy Reviews 33, pp 532-545, 2014

[21] Chacra F.A, Bastard P,Fleury G, Clavreul R,"Impact of Energy Storage Cost and Economical Performance in a Distribution Substation", IEEE Transactions on Power Systems, Vol.20, No.2, May 2005

[22] Jian C, Yutian L, Guanman Bao, "Optimal Operating Strategy for Distribution Networks with PV and BESS Considering Flexible Energy Storage", IEEE Power and Energy Society General Meeting (PESGM),17-21 July 2016

[23] Daly D.F,"20 MW Battery Power Conditioning System for Puerto Rico Electric Power Authority", Proceedings of the Tenth Annual Battery Conference on Applications and Advance, 10-13 January 1995

[24] Casadei D, Grandi G," Power Quality and Reliability Supply Improvement Using a Power Conditioning System with Energy Storage Capability", 2004 IEEE International Symposium on Industrial Electronics, 4-7 May 2004

[25] Bhati R.S, Jain D.K, Singh B," Battery Energy Storage System for Power Conditioning of Renewable Energy Sources" 2005 International Conference on Power Electronics and Drives Systems, IEEE, 28-1 December 2005

[26] Van Voorden A.M, Paap G.C, van der Sluis L, "The Use of Batteries in Stand-Alone Renewable Power Systems", 2005 IEEEE Russia Power Tech, 27-30 June 2005

[27] Casadei D, Grandi G, Serra G, "Power Quality Improvement and Uninterruptible Power Supply Using a Power Conditioning System with Energy Storage Capability", 2005 IEEE Russia Power Tech, 27-30 June 2005

[28] Li H, Iijima Y, Kawakami N, "Development of power Conditioning System (PCS) for Battery Energy Storage Systems", 2013 IEEE ECCE Asia Downunder, 3-6 June 2013

[29] Chen C, Liu B, Duan S, Zou C, “Centralized Control of Parallel Connected Power Conditioning System for Battery Energy Storage System in Charge-Discharge Storage Power Station”, 2013 IEEE Energy Conversion Congress and Exposotion, 15-19 Sept 2013

[30] Kollimalla S.K, Ukil A, Gooi H.B, Manandhar U, Reddy N, “Optimization of charge/Discharge Rates of Battery Using a Two Stage Rate-Limit Control”, IEEE PES Transactions on Sustainable Energy, April 2017

[31] Yun-feng D”, Optimal Allocation of Energy Storage system in Distribution systems”,Science Direct, Procedia Engineering 15,pp 346-351, 2011

[32] Farsadi M, Sattarpour T,Nejadi AY, “Optimal Placement and Operation of BESS in a Distribution Network Considering the Net Present Value of Energy Losses Cost”, 2015 9th International Conference on Electrical and Electronics Engineering (ELECO),IEEE, 26-28 November 2015

[33] Mansuwan K, Jirapong P, Burana S. Tharak P, “Optimal Planning and Operation of Battery Energy Storage Systems in Smart Grids Using Improved Genetic Algorithm Based Intelligent Optimization Tool”, IEEE, 24-26 October 2018

[34] Karami H, Sanjari M.J, Hosseinian A.H, Gharehpetian G.B, “An Optimal Dispatch Algorithm for Managing Residential Distributed Energy Resources”, IEEE Transactions on Smart Grid, Vol.5, No.5, 5 September 2014

[35] Maly D.K, Kwan K.S, “Optimal Battery Energy Storage System (BESS) Charge Schedule with Dynamic Programmimg”, IEE Proceedings-Science, Measurement and Technology, Vol.142, Issue 6, November 1995

[36] Biswas S, Bera P, “GA Application to optimization of AGC in Two-Area Power System Using Battery Energy Storage”, 2012 International Conference on Communication, Devices and Intelligent Systems (CODIS), IEEE, 28-29 December 2012

[37] Swarup K.S, Yamashiro S, “Unit Commitment solution methodology using Genetic Algorithm”, IEEE Transactions on Power Systems, Vol 17, Issue 1, Feb 2002

[38] Senjyu T, Saber A.Y, Miyagi T, Shimabukuru K, Urasaki N, Funabashi T, “Fast technique for unit commitment by Genetic Algorithm based om unit clustering”, IEE Proceedings-Generation, Transmission and Distribution, Vol. 152, Issue 5, 9 Sept. 2005

[39] Yuan Y, Zhang X, Ju P, Li Q, Qian K, Fu Z”, Determination of economic dispatch of wind farm-battery energy storage system using Genetic Algorithm”, Int. Trans. Electr. Syst. 2014; 24:264-280, 8 October 2012

[40] Yu F, Fu X, Li H, Dong G, “Improved Roulette Wheel Selection-Based Genetic Algorithm for TSP”, 2016 International Conference on Network and Information Systems for Computers (ICNISC), IEEE, 15-17 April 2016

[41] Koyuncu N, “Computation of Parameters Using Genetic Algorithm and Sequential Quadratic Programming in Sampling”, International Journal of Computer Theory and Engineering, Vol 7, No. 5, October 2015

[42] Sheta A, Turabieh H, “A comparison between Genetic Algorithms and Sequential Quadratic Programming in Solving Constrained Optimization Problems”, AIML Journal, Vol 6, Issue 1, January 2006

[43] Carpinelli G, Celli G, Mocci S, Mottola F, Pilo F, Proto Daniela, “Optimal Integration of Distributed Energy Storage Devices in Smart Grids”, IEEE Transactions on Smart Grid, Vol 4, No 2, June 2013

[45] Salee S, Wirasanti P, “Optimal Siting and Sizing of Battery Energy Storage Systems for Grid-Supporting in Electrical Distribution Network”,2018 International ECTI Northern Section Conference on Electrical, Electronics, Computer and Telecommunications Engineering (ECTI-NCON), IEEE, 25-28 February 2018

[46] Bose S, Gayme D.F, Topcu U, Chandy K.M “Optimal placement of Energy Storage in the Grid”, IEEE Conference on Decision and Control (CDC), 10-13 December 2012

[47] Karanki S.B, Xu D, Venkatesh B, “Optimal Location of Battery Energy Storage Systems in Power Distribution Network for Integrating Renewable Energy Sources”,2016 National Power Systems Conference (NPSC), IEEE, 19-21 December 2016

[48] Abbey C, Joos G, “Sizing and Power Management Strategies for Battery Storage Integration into Wind-Diesel Systems”,2008 34th Annual Conference of IEEE Industrial Electronics, IEEE, 10-13 November 2008

[49] Kihara H, Yokoyama A, Liyanage K.M, Sakuma H, “Optimal Placement and Control of BESS for Distribution System Integrated with PV Systems”, Journal of international Council on Electrical Engineering, Vol. 1, No. 3, pp. 298-303, 2011

[50] Farrokhifar M, Grillo S, Tironi E, “Optimal Placement of Energy Storage Devices for Loss Reduction in Distribution Networks”, 4th IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe),6-9 October 2013

[51] Lazzeroni P, Repetto M, “Optimal Planning of Battery Systems for Power Losses Reduction in Distribution Grids”, ScienceDirect, Electric Power Systems Research 167, pp 94-112, 2019

[52] Das C.K, Bass O, Kothapalli G, Mahmoud T.S, Habibi D, “Optimal placement of distributed energy storage systems in distribution networks using Artificial bee colony Algorithm”, ScienceDirect, Applied Energy 232, pp 212-228,2018

[53] Dubarry M, Baure G, Pastor-Fernándezb C, Yu T.F, Widanage W.D, Marco J, “Battery energy storage system modelling: A combined comprehensive approach”, ScienceDirect, Journal of Energy Storage 21, pp 172-185

[54] Tang X, Gao F, Zou C, Yao K, Hu W, Wik T, “Load-responsive model switching estimation for state of charge of lithium-ion batteries”, ScienceDirect, Applied Energy 238, pp 423-434, 2019

[55] Wu J, Li T, Zhang H, Lei Y, Zhou G, “Research on modelling and SOC Estimation of Lithium Iron Phosphate Battery at Low Temperature”, CUE2018-Applied Energy Symposium and Forum 2018: Low carbon cities and urban energy systems, pp 556-561, 5-7 June 2018

[56] Tang X, Wang Y, Zou C, Yao K, Xia Y, Gao F, “A novel framework for Lithium-ion battery modelling considering uncertainties of temperature and aging”, ScienceDirect, Energy Conversion and Management 180, pp 162-170,2019

[57] Zou C, Klintberg A, Wei Z, Fridholm B, Wik T, Egardt B, “Power capability for lithium-ion batteries using economic nonlinear model predictive control”, ScienceDirect, Journal of Power Sources 396, pp 580-589, 2018

[58] Wang X, Wei X, Dai H," Estimation of state of health of lithium-ion batteries based on chare transfer resistance considering different temperature and state of charge", ScienceDirect, Journal of Energy Storage 21, pp 618-631, 2019

[59] Weyers C, Bocklisch T, "Simulation-based investigation of energy management concepts for fuel cell-battery-hybrid energy storage systems in mobile applications", ScienceDirect, 12th International Renewable Energy Storage Conference, IRES, pp 295-308,2018

[60] Yamchi H.B, Shahsavari H, Kalantari N.T, Safari A, Farrokhifar M, "A cost-efficient application of different battery energy storage technologies in microgrids considering load uncertainty", ScienceDirect, Journal of Energy Storage 22, pp 17-26, 2019

[61] Wong L.A, Ramachandaramurthy V.K, Taylor P, Ekanayake J.B, "Review on the optimal Placement, Sizing and Control of an energy storage System in the distribution network", ScienceDirect, Journal of Energy Storage 21, pp 489-504, 2019

[62] Hazra J, Padmanaban M, Zaini F, "Congestion relief using grid scale batteries", Innovative Smart Grid Technologies Conference (ISGT), 2015 IEEE Power & Energy Society. IEEE, 2015

[63] M. R. Aghamohammadi and H. Abdolahinia, "A new approach for optimal sizing of battery energy storage system for primary frequency control of islanded Microgrid", ScienceDirect, International journal Electrical Power Energy Systems, vol. 54, pp. 325–333, 2014

[64] Yih-Der L, Jiang J-L, Su H-J, Ho Y-H, Chang Y-R, "Ancillary voltage control for a distribution feeder by using energy storage system in microgrid." Power Electronics for Distributed Generation Systems (PEDG), 2016 IEEE 7th International Symposium on. IEEE, 2016

[65] Petinrin, J. O, Shaaban M. "A voltage control scheme in a distribution feeder with wind energy sources." 2015 IEEE Conference on Energy Conversion (CENCON). IEEE, 2015

[66] Ghorbanian, M. J, Goodarzvand F, Poudaryaei A, Mahadi W.N.L "Power quality improvement of grid connected doubly fed induction generator using STATCOM and BESS." Engineering Technology and Technopreneuship (ICE2T), 2014 4th International Conference on. IEEE, 2014

[67] Huang Y, Hu W, Min Y, Zhang W, Luo W, Wang Z, Ge W, "Risk-constrained coordinative dispatching for battery energy storage systems of wind farms", 2013 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC). IEEE, 2013

[68] Xiao J, Zhang Z, Bai L, Liang H, "Determination of the optimal installation site and capacity of battery energy storage system in distribution network integrated with distributed generation",IEEE, IET Generation, Transmission & Distribution, Vol 10,No.3, pp 601-607, 03 March 2016

[69] Oudalov A, Cherkaoui R, Beguin A, "Sizing and optimal operation of Battery Energy Storage System for peak shaving applications", IEEE Lausanne Power Tech, pp 621-625,2007

[70] Burana S, Thararak P, Jirapong P. Mansuwan K, "Optimal Allocation of distributed generation with FACTS controller for Electrical Power Loss Reduction Using Genetic Algorithm", IEEE,9th International Conference on Information technology and Electrical Engineering (ICITEE),12-13 October 2017

[71] Nick M, Cherkaoui R, Paolone M, "Optimal Planning of Distributed Energy Storage Systems in Active Distribution Networks Embedding Grid Reconfiguration", IEEE Transactions On Power Systems, Vol. 33, No. 2, March 2018

[72] Azizivahed A, Naderi E, Narimani H, Fathi M, Narimani M.R, “A nEw Bi-Objective Approach to Energy Management in Distribution Networks with Energy Storage Systems”, IEEE Transactions On Sustainable Energy, Vol. 9, No. 1, January 2018

[73] Abdeltawab H.H, Mohamed Y.A.R.I, “Mobile Energy Storage Scheduling and Operation in Active Distribution Systems”, IEEE Transactions on Industrial Electronics, Vol. 64, No. 9, September 2017

[74] Mehmood K.K, Khan S.U, Lee S.J, Haider Z.M, “Optimal sizing and allocation of battery energy storage systems with wind and solar power DGs in a distribution network for voltage regulation considering the lifespan of batteries”, IEEE, IET Renewable Power Generation, May 2017

[75] Kim I, “A Case Study on the Effect of Storage Systems on a Distribution Network Enhanced by High-Capacity Photovoltaic Systems”, ScienceDirect, Journal of Energy Storage, Vol 12, pp 121-131, April 2017

[76] Babacan O, Torre W, Kleissi J, “Siting and Sizing of Distributed Energy Storage to Mitigate Voltage Impact by Solar PV in Distribution Systems”, ScienceDirect, Solar Energy, vol 146, pp 199-208, February 2017

[77] Ahmadian A, Sedghi M, Aliakbar-Golkar M, Elkamel A, “Optimal Probalistic Based Storage Planning in Tap-Changer Equipped Distribution Network Including PEVs, Capacitor Banks and WDGs: A Case Study for Iran”, ScienceDirect, Energy, Vol 112, pp 984-997, March 2016

[78] Chen Y, Zeng Y, Luo F, Wen J, Xu Z, “Reliability Evaluation of Distribution Systems with Mobile Energy Storage Systems”, IEEE, IET Renewable Power Generation, July 2016

[79] Kahrobaee S, Asgarpoor S, “Reliability-Driven Optimum Standby Electric Storage Allocation for Power Distribution Systems”, 1st IEEE Conference on Technologies for Sustainability (SusTech), 2013

[80] Xiao J, Zhang Z, Bai L, Liang H, “Determination of the optimal installation site and capacity of battery energy storage system in distribution network integrated with distributed generation”,IEEE, IET Generation, Transmission & Distribution, Vol 10,Issue 3, pp 601-607, March 2016

[81] Nick M, Cherkaoui R, Paolane M, “Optimal Allocation of Dispersed Energy Storage Systems in Active Distribution Networks for Energy Balance and Grid Support”, IEEE Transactions on Power Systems, Vol.29, No.5, September 2014

[82] Pombo AV, Murta-Pina J, Pires VF, “Multi-objective formulation of the integration of storage systems within distribution networks for improving reliability”, ScienceDirect, Electric Power Systems Research, Vol 148, pp 87-96, July 2017

[83] Awad ASA, El-Fouly THM, Salama MMA, “Optimal ESS Allocation and Load Shedding for Improving Distribution System Reliability”,IEEE Transactions on Smart Grid, Vol 5, Issue 5, pp 2339-2349, September 2014

[84] Zheng Yu, Dong ZY, Luo FJ, Meng K, Qiu J, Wong KP, “Optimal Allocation of Energy for Risk Mitigation of DISCOs with High Renewable Penetrations”, IEEE Transactions On Power Systems, Vol 29, No 1, January 2014

[85] Lujano-Rojas JM, Dufo-Lopez R, Bernal-Augustin JL, Catalao JPS. “Optimizing Daily Operation of Battery Energy Storage Systems Under Real-Time Pricing Schemes”, IEEE Transactions on Smart Grid, VoL. 8, No 1, January 2017

[86] Tan X, Wu Y, Tsang DHK, “Pareto Optimal Operation of Distributed Battery Energy Storage Systems for Energy Arbitrage under Dynamic Pricing”, IEEE Transactions on Parallel and Distributed Systems, Vol 27, No 7, July 2016

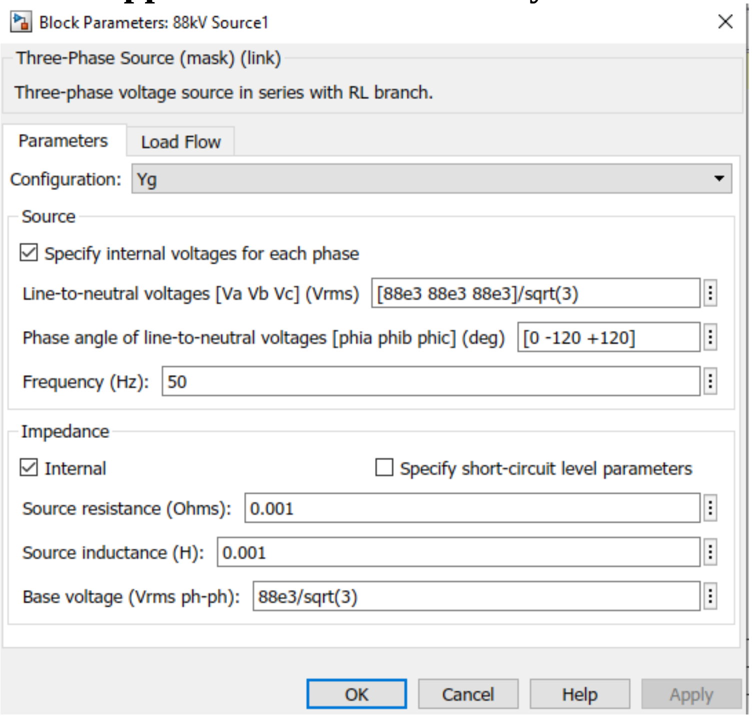
[87] Gabash A, Li P, “Flexible Optimal Operation of Battery Storage Systems for Energy Supply Networks”, IEEE Transactions on Power Systems, Vol 28, No 3, August 2013

[88] Grillo S, Pievatolo A, Tironi E, “Optimal Storage Schedulling Using Markov Decision Processes”, IEEE Transactions on Sustainable Energy, Vol 7, No 2, April 2016

[89] Thulasi J.A, Anuja V, Mary M.A, “A novel voltage regulator-Battery energy storage system for renewable energy system”, IEEE, International conference on electrical, electronics, and optimization techniques (ICEEOT), 3-5 March 2016

[90] Gao D.W, “Energy storage for sustainable microgrid”, ScienceDirect, chapter 3, pp 79-121, Academic press, 2015

Appendix A: Distribution system



Block Parameters: 88kV Source1

Three-Phase Source (mask) (link)

Three-phase voltage source in series with RL branch.

Configuration: Yg

Source

☑ Specify internal voltages for each phase

Line-to-neutral voltages [Va Vb Vc] (Vrms) [88e3 88e3 88e3]/sqrt(3)

Phase angle of line-to-neutral voltages [phia phib phic] (deg) [0 -120 +120]

Frequency (Hz): 50

Impedance

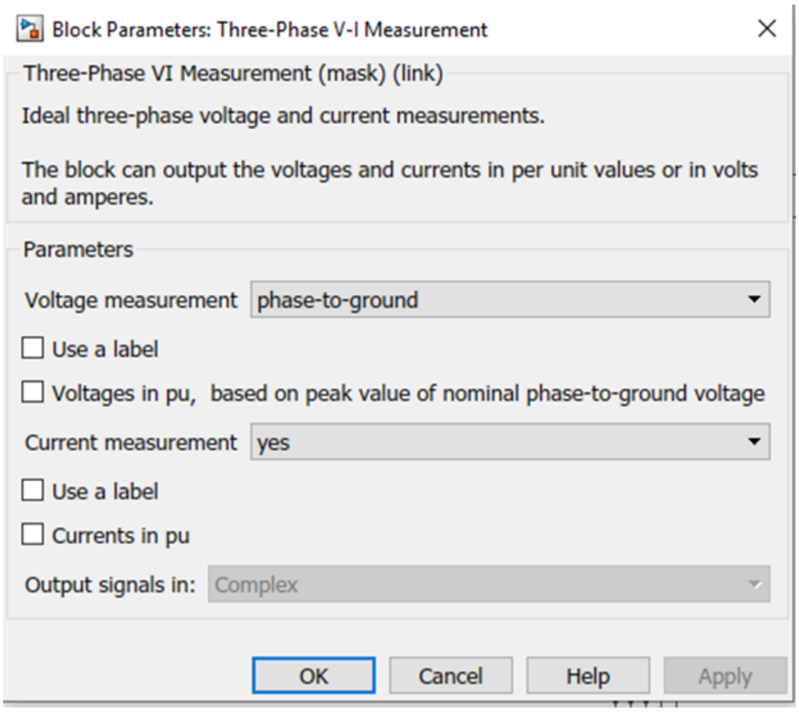
☑ Internal ☐ Specify short-circuit level parameters

Source resistance (Ohms): 0.001

Source inductance (H): 0.001

Base voltage (Vrms ph-ph): 88e3/sqrt(3)

Figure 70: Incoming line source configuration



Block Parameters: Three-Phase V-I Measurement

Three-Phase VI Measurement (mask) (link)

Ideal three-phase voltage and current measurements.

The block can output the voltages and currents in per unit values or in volts and amperes.

Parameters

Voltage measurement phase-to-ground

☐ Use a label

☐ Voltages in pu, based on peak value of nominal phase-to-ground voltage

Current measurement yes

☐ Use a label

☐ Currents in pu

Output signals in: Complex

Figure 71: Three phase measuring tool configuration

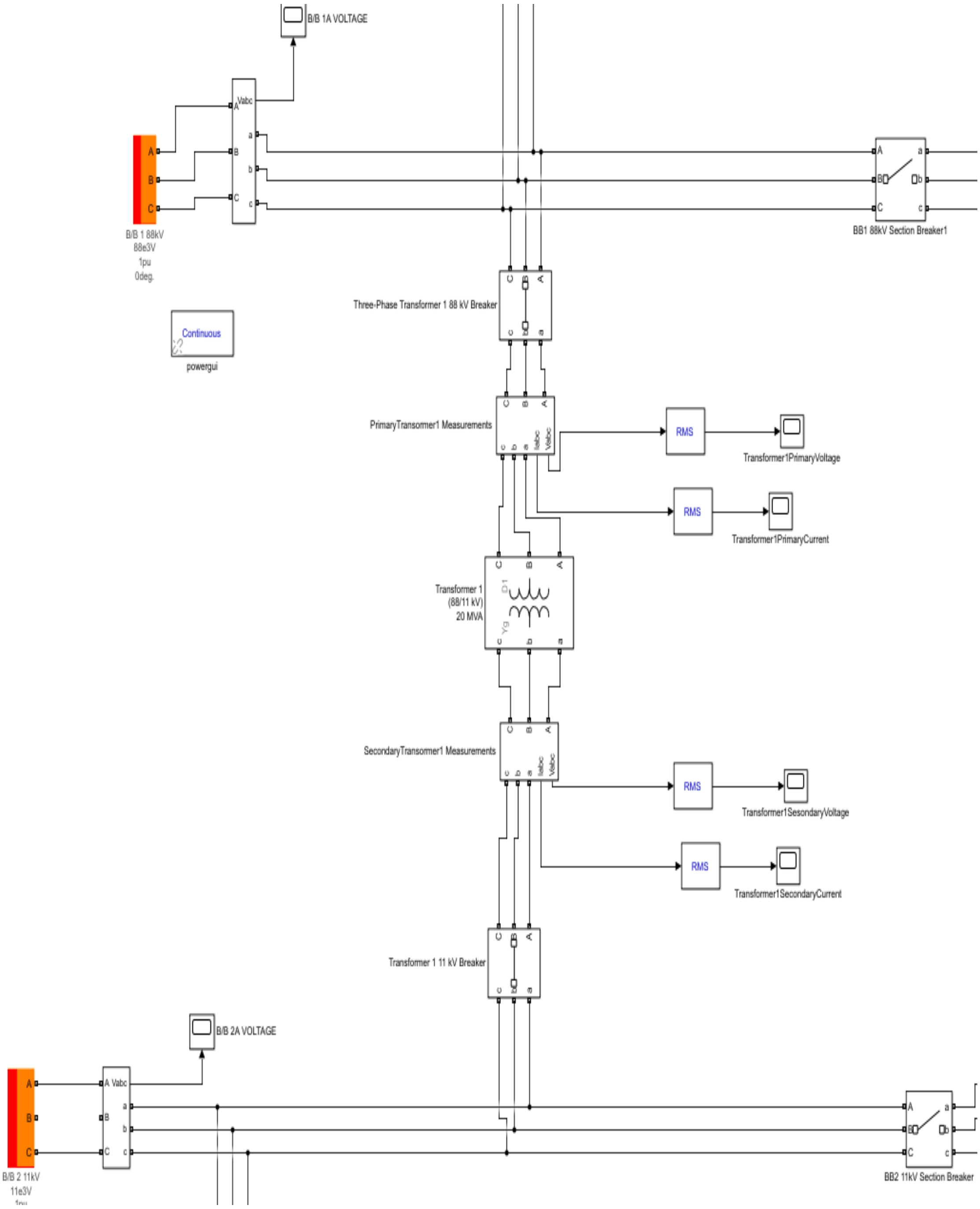
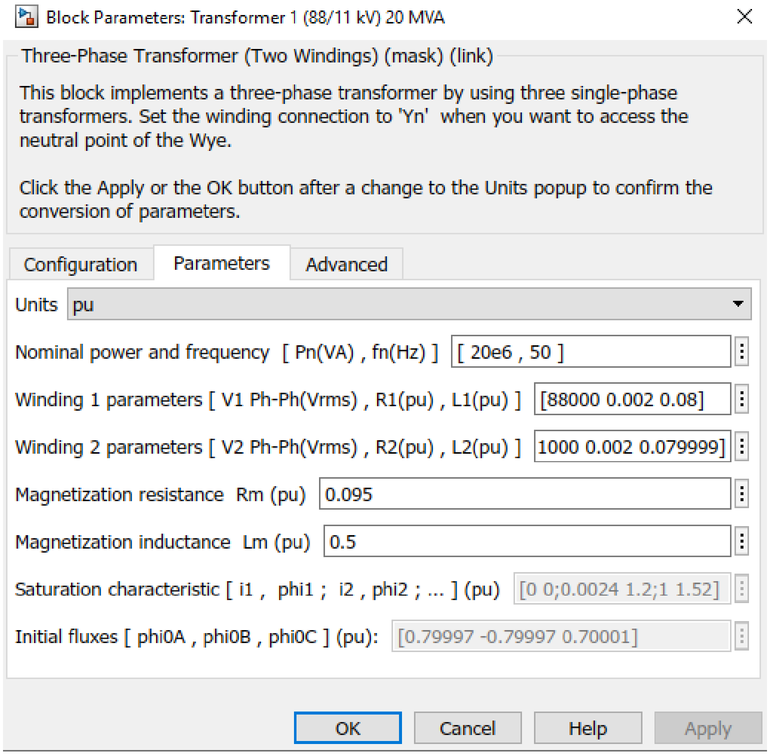


Figure 72: Distribution transformer setup



Block Parameters: Transformer 1 (88/11 kV) 20 MVA

Three-Phase Transformer (Two Windings) (mask) (link)

This block implements a three-phase transformer by using three single-phase transformers. Set the winding connection to 'Yn' when you want to access the neutral point of the Wye.

Click the Apply or the OK button after a change to the Units popup to confirm the conversion of parameters.

Units: pu

Nominal power and frequency [Pn(VA) , fn(Hz)]: [20e6 , 50]

Winding 1 parameters [V1 Ph-Ph(Vrms) , R1(pu) , L1(pu)]: [88000 0.002 0.08]

Winding 2 parameters [V2 Ph-Ph(Vrms) , R2(pu) , L2(pu)]: 1000 0.002 0.079999]

Magnetization resistance Rm (pu): 0.095

Magnetization inductance Lm (pu): 0.5

Saturation characteristic [i1 , phi1 ; i2 , phi2 ; ...] (pu): [0 0;0.0024 1.2;1 1.52]

Initial fluxes [phi0A , phi0B , phi0C] (pu): [0.79997 -0.79997 0.70001]

Figure 73: Substation Transformer parameter configuration window

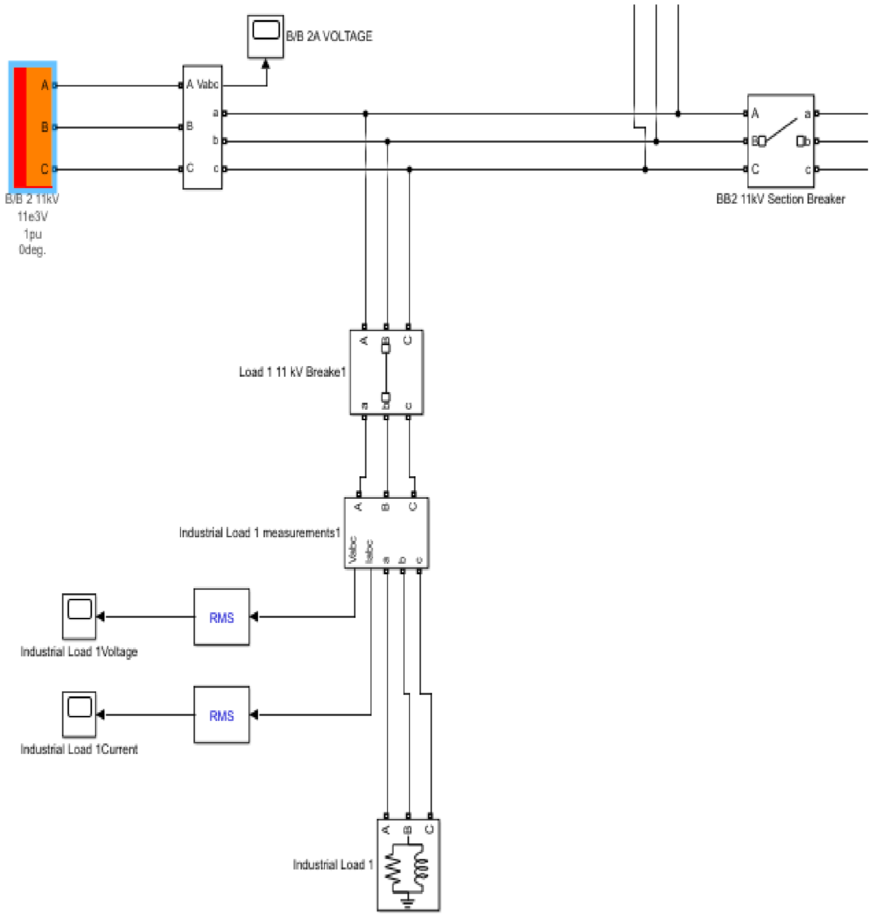
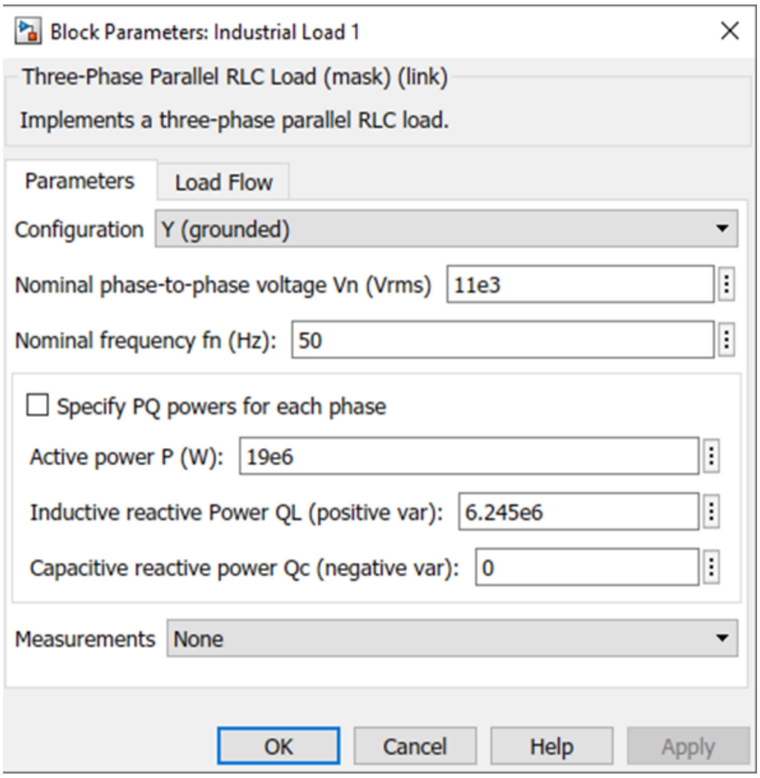


Figure 74: Industrial Load model setup


Block Parameters: Industrial Load 1

Three-Phase Parallel RLC Load (mask) (link)

Implements a three-phase parallel RLC load.

Configuration: Y (grounded)

Nominal phase-to-phase voltage Vn (Vrms): 11e3

Nominal frequency fn (Hz): 50

☐ Specify PQ powers for each phase

Active power P (W): 19e6

Inductive reactive Power QL (positive var): 6.245e6

Capacitive reactive power Qc (negative var): 0

Measurements: None

Figure 75: Industrial Load parameter configuration window

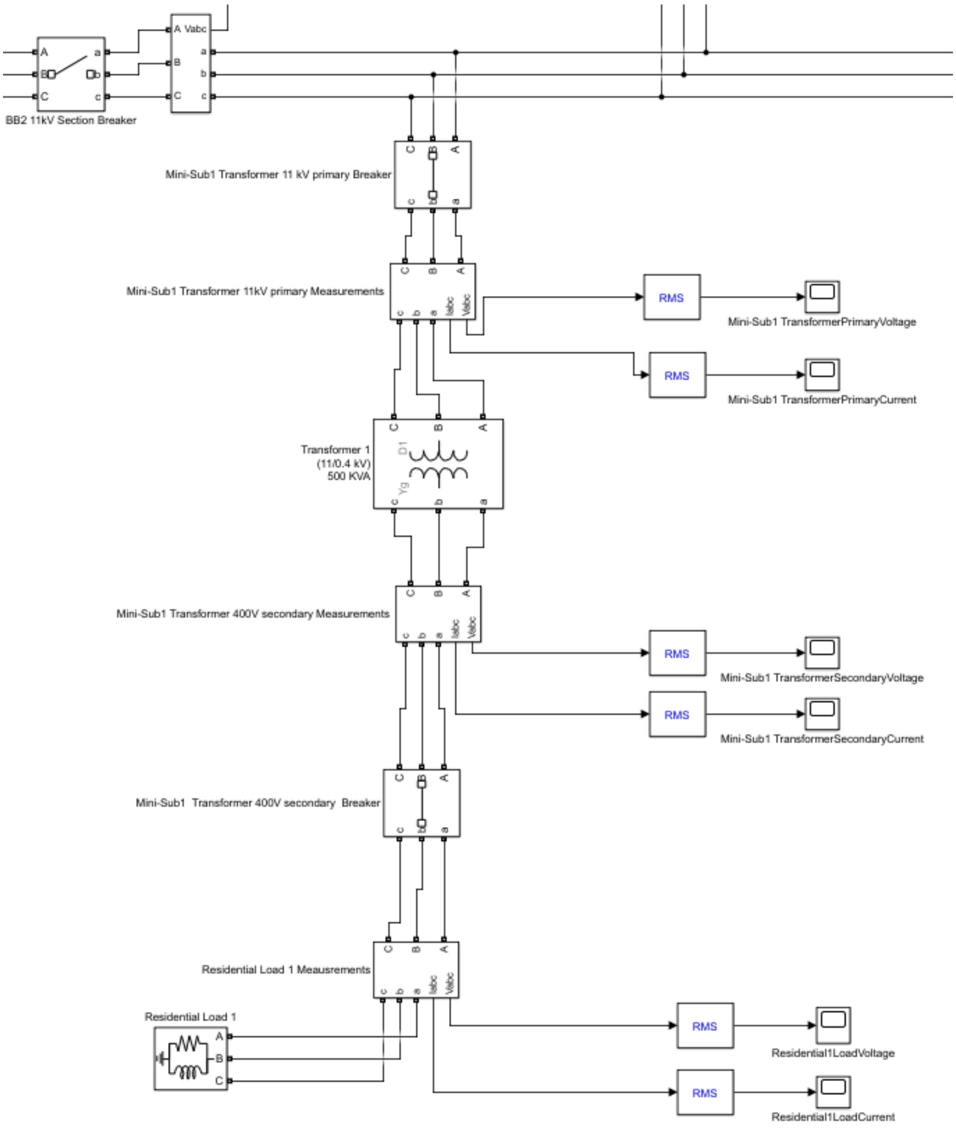
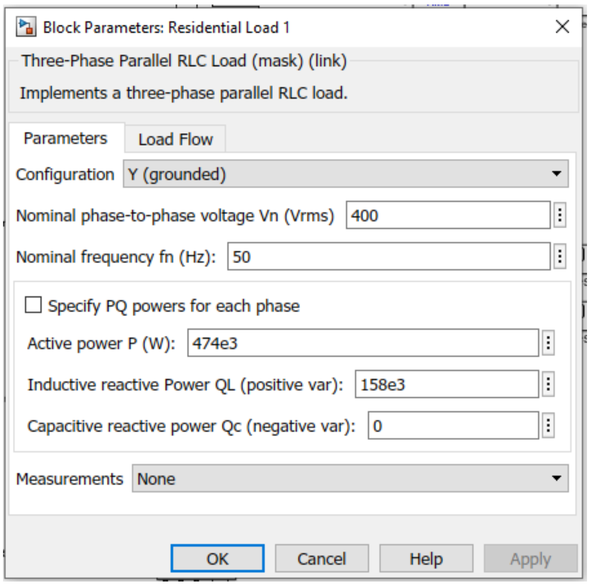


Figure 76: Mini-Substation Setup



Three-Phase Parallel RLC Load (mask) (link)

Implements a three-phase parallel RLC load.

Configuration: Y (grounded)

Nominal phase-to-phase voltage Vn (Vrms): 400

Nominal frequency fn (Hz): 50

☐ Specify PQ powers for each phase

Active power P (W): 474e3

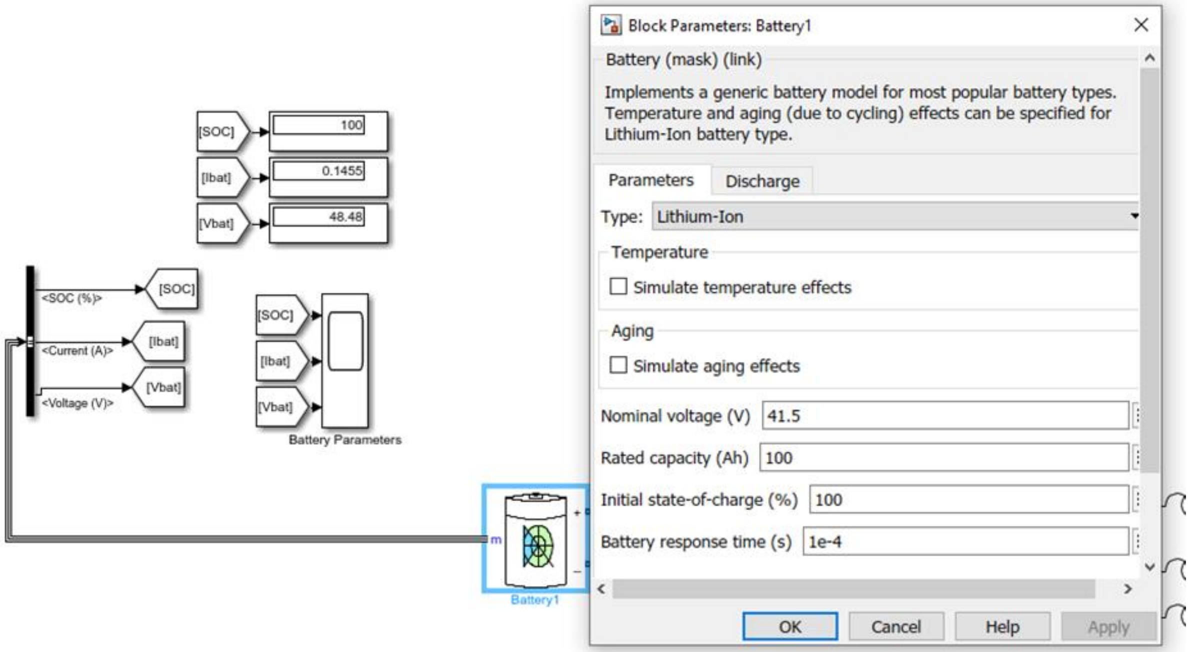
Inductive reactive Power QL (positive var): 158e3

Capacitive reactive power Qc (negative var): 0

Measurements: None

Figure 77: Residential Load Configuration window

Appendix B: Battery Energy Storage system



Block Parameters: Battery1

Battery (mask) (link)

Implements a generic battery model for most popular battery types. Temperature and aging (due to cycling) effects can be specified for Lithium-Ion battery type.

Parameters | Discharge

Type: Lithium-Ion

Temperature

☐ Simulate temperature effects

Aging

☐ Simulate aging effects

Nominal voltage (V) 41.5

Rated capacity (Ah) 100

Initial state-of-charge (%) 100

Battery response time (s) 1e-4

Figure 78: Battery parameter settings window

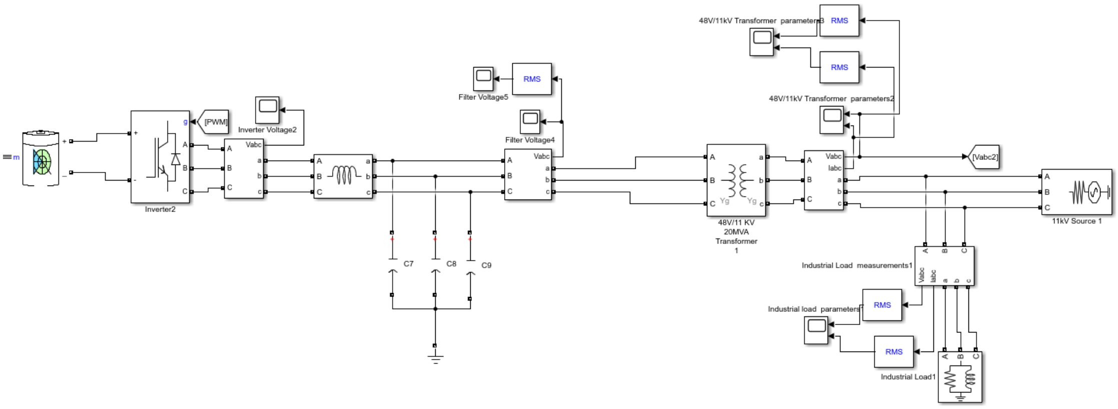


Figure 79: BESS for busbar 2A

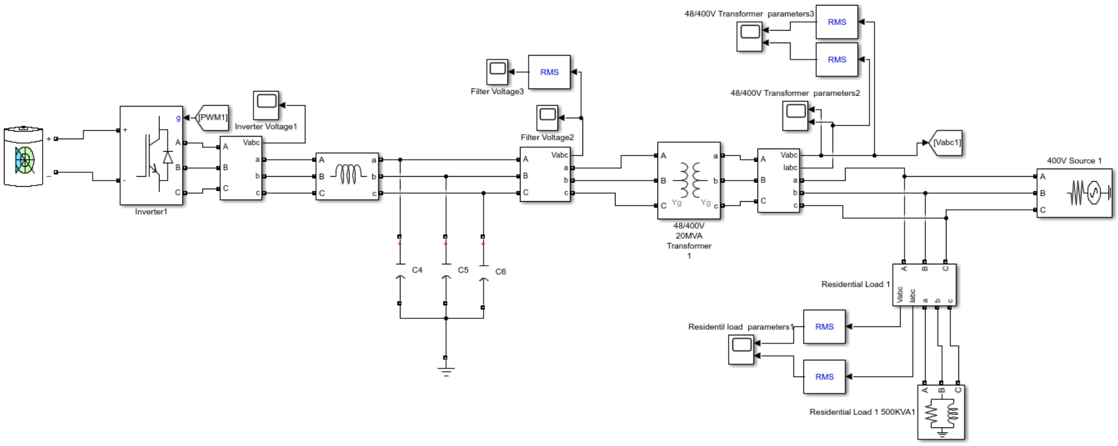


Figure 80: BESS for busbar 2B

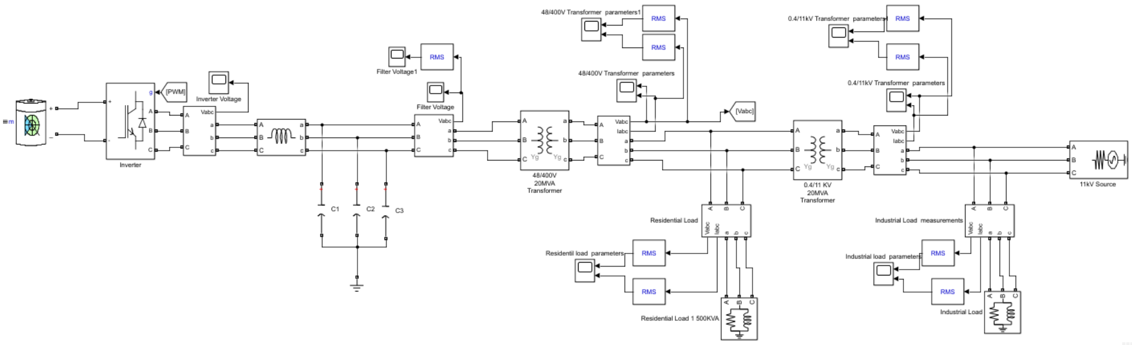


Figure 81: BESS for busbar 2C