IMPACT OF CHARGING OF BACKUP BATTERIES BY RESIDENTIAL CONSUMERS ON THE LOW VOLTAGE DISTRIBUTION NETWORK

By

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A dissertation submitted in partial fulfillment of the requirements for the degree of Masters of Engineering in Electrical Power Engineering

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DECLARATION

I, Greenwell Malindi declare that this dissertation was composed by myself, that the work contained herein is my own, original work except where explicitly stated otherwise in the text, that I am the sole author thereof and that this has not been submitted for any other degree or professional qualification except as specified.

Signature: .... Date:..

APPROVAL

This dissertation of Greenwell Malindi has been approved as fulfilling partial fulfillment of the requirements for the award of the degree of Masters in Power Electrical in Engineering at the University of Zambia.

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ABSTRACT

Battery-charging units are appreciably being used in residential application as power back-up in the face of power shortages. The study investigated the effects of backup battery-charging units on the low voltage distribution network. The investigation focused on examining the supply voltage drop, total harmonic distortions (THD) and dc component produced at the point of common coupling by backup battery-charging using Simulink.

Fourteen performance parameters which determined the quality of low voltage distribution network were reviewed. Eight of the performance parameters (namely supply voltage, supply current, harmonics, voltage imbalance, notches, direct current mains signaling interference and noise) were found to be affected by backup battery-charging units.

Three out of 8 performance parameters affected by backup battery-charging units can be investigated using Simulink. Performance parameters investigated are the voltage drop, harmonics and dc component.

Supply voltage drop of 0.13 to 2.48%, supply voltage THD of 0.02 to 0.17%, current THD of 0.41 to 0.61%, dc voltage component of 0.0000318 to 0.0008757V and dc current component of 0.00002763 to 0.00017417A were obtained by simulating up to 10 backup battery-charging units. Additionally, supply voltage drop of 2.74 to 12.93%, supply voltage THD of 0.18 to 0.83%, current THD of 0.63 to 3.65%, voltage dc component of 0.0009713 to 0.0087291V and current dc component of 0.00019423 to 0.00084623A were obtained by extrapolating 11 to 50 backup battery-charging units.

By extrapolation, the maximum number of backup battery-charging units required to produce maximum permissible supply voltage drop of 10% and THD of 5% were found as being 39 for supply voltage drop, 57 for current THD and 300 for voltage THD. The voltage drop above 10% and the THD above 5% require mitigation to maintain the values at the acceptable limit according to Institute of Electrical and Electronics Engineers (IEEE) 519 standard.

Overall, the least number of backup battery-charging units found to violate the standard was considered as the maximum number of backup battery-charging units which can be connected simultaneously. Therefore, 39 backup battery-charging units was considered as the maximum number of backup battery-charging units to be connected on the low voltage distribution network where neither supply voltage drop nor THD limits would be violated.

Keywords: Backup battery-charging unit, distribution, network, supply voltage/current, total harmonic distortion.

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DEDICATION

To

My wife Esther, your encouragements, patience and prayers gave me strength to write this dissertation.

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TABLE OF CONTENTS

CHAPTER 2

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

ABBREVIATIONS

TOU	Time Of Use
EV	Electric Vehicles
PQ	Power Quality
SOC	State of Charge
V2G	Vehicle to Grid
PP	Performance Parameters
IEEE	Institute of Electrical and Electronics Engineers
TSO	Transmission System Operators
IEC	Internal Electroelectronical Commission
MEN	Multiple Earth Neutral
THD	Total Harmonic Distortion
THDi	Current Total Harmonic Distortion
THDv	Voltage Total Harmonic Distortion
TV	Television
PCC	Point of Common (Coupling) Connection
DC	Direct Current
AC	Alternating Current
FFT	Fast Fourier Transforms

CHAPTER 1

INTRODUCTION

Of late, integration of backup battery-charging units on the low voltage power distribution network by residential consumers has been increasing. The increase in the use of backup battery-charging units is due to electrical energy deficit experienced in the country. However, backup battery-charging units are non linear devices which influence power quality on the distribution network.

1.1 Background

In Zambia, as the population increases and the economy expands, the power supply utility company faces the challenge of meeting the obligation to serve electrical consumers - both residential and commercial consumers. This problem was made more prominent by reduced generation output arising from low water levels at Kariba and Itezhi-tezhi reservoirs during the 2014/2016 rain season. Power generation in Zambia relies heavily on water from rainfall and so, in the event of adverse weather as it was, generation was severely affected. As a result, Zambia faced massive load shedding lasting up to 5-8 hours per day for each residential consumer areas between 2014 and 2016. That seriously affected industries, commercial undertakings, offices and domestic consumers alike.

Whenever a shutdown of electricity supply occurs, all electrical equipment could not be used unless they were connected to a backup supply. In order to maintain the use of electrical equipment during such periods, there were a number of methods that were used. One of the most common methods used to maintain power when the electricity supply was cut-off was the use of backup batteries. Backup batteries were charged using the utility supply line, see Figure 1.1.

The backup batteries were charged during the time when power was available. When power was cut-off, backup batteries provided energy for lighting and other light loads such as radios, TVs, computers, phone charging and so on, as the residential consumers wait for power supply restoration. But, heavy loads such as cooking and water heating were usually done by using either charcoal or gas stoves.

Charging of backup batteries from the utility supply posed power quality issues due to the production of polluting harmonic components into the distribution network.

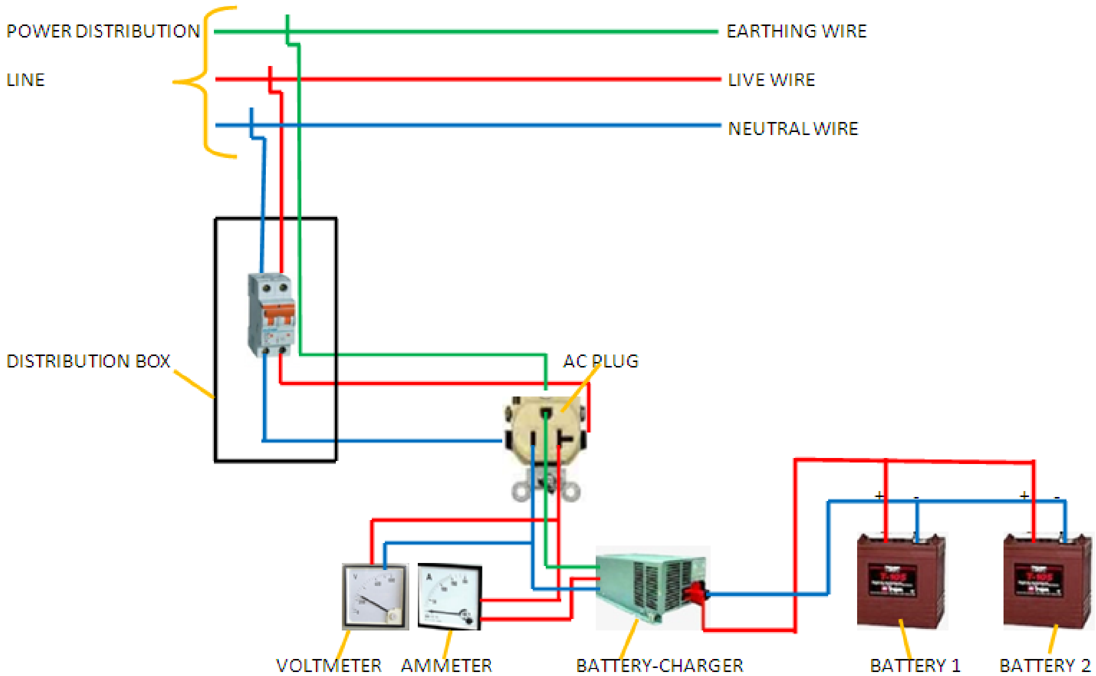

Figure 1.1 Typical household battery-charging unit connections:

(https://tosunelectric.en.made-in-china.com/product/EvcQSDnxJehb/China-Isolating-Switch-for-Individual-Eletric-Circuits.html).

Load demand also increases necessitated by the increased number of backup battery-charging units being used in particular highly populated communities. Backup battery-charging units added up some load onto the low voltage power distribution transformers and also to the distribution network. The extent to which the backup battery-charging units could be tolerated was of great interest to electric power utilities in ensuring sustainable power supply throughout.

To that effect, the aim of this research was to investigate the impact of backup battery-charging units on the low voltage power distribution network in terms of harmonic injection.

1.2 Statement of the problem

The Gross Domestic Product (GDP) for Zambia had been growing at a steady rate of 5% per annum as depicted by Central Statistics Office (Central Statistics Office, 2007). At the same time the mining sector and agricultural activities continued expanding. Meanwhile little expansion had taken place in electrical power generation, which failed to match with the industrial expansion taking place in the country. Minor improvement on the existing plants had resulted in a negligible addition of power to the Zambian national power transmission line.

Rural electrification programme had led to many rural communities being connected to the Zambian national power transmission line enabling more and more people to access electricity supply. That was a welcome development for the country. But, that had brought new challenges by increasing daily power demand being drawn from the Zambian national power transmission line since generation capacity had basically remained the same. Since the utility company was unable to supply adequate power to all its consumers at the same time that led to introduction of load shedding so as to distribute power to some communities while ours were temporally shut-off. The scheduled power supply was problematic to residential consumers who had since resorted to charge backup batteries from the low voltage power distribution network as the power supply backup. Once a given community was on load shedding, the residential consumers used their stored energy from the backup batteries for lighting up the homes, TV, radio and phone charging.

The backup battery charging units influenced the functionality of low voltage power distribution network performance parameters. Once the performance parameters were negatively altered, the power quality on the distribution network was also negatively affected.

1.3 Aim of the study

This research was aimed at investigating the effects of charging of backup batteries by residential consumers on the low voltage distribution network.

1.4 Research hypothesis

Backup battery-charging units, containing power electronic switching devices, can result in several power quality problems such as voltage drops, power imbalances and voltage /current disturbances on the low voltage distribution network.

1.5 Study objectives

i) To assess the impact of backup battery chargers on identified performance parameters on the low voltage distribution network.

ii) To review low voltage power distribution performance parameters affected by backup battery charging.

iii) To select low voltage power distribution performance parameters affected by backup battery charging.

1.6 Research questions

i) What performance parameters are associated with the low voltage distribution network?

ii) How is the low voltage distribution network affected by backup battery chargers used by residential consumers?

1.7 Delineation and limitations

This research was confined to a low voltage power distribution network in which the maximum voltage was 400VAC for three phase network. But only a single phase nominal input voltage of 220VAC would be considered for supplying the backup battery-charging units.

The backup battery-charging units would convert 220VAC to 12VDC only and only 12VDC, 50 AH batteries were considered in this research.

1.8 Significance of the study

If the research hypothesis would be proved, then the results would be used to formulate policies. The policies would used to regulate backup battery-charging unit usage by residential electricity consumers on the low voltage distribution network. In addition, the results of this study would help power distribution designers on how best to deal and plan for harmonics produced by backup battery-charging units.

Furthermore, the results would promote other research to find ways of improving the performance of low voltage power distribution network. In particular when the distribution network is subjected to multiple backup battery-charging units.

1.9 Organisation of the Dissertation

This dissertation consists of 5 chapters. Chapter 1 outlines the background of the current work, the definition and scope of the research work, delineation and limitation of the research work. Chapter 2 gives detailed literature review from various sources which were related to the research work being undertaken. Chapter 3 describes the methods employed to achieve the objectives, while Chapter 4 is dedicated for results, and discussions. Chapter 5 contains the conclusions and recommendation of the entire study.

1.10 Summary

This research work was undertaken to investigate the impact of backup battery-charging units on the low voltage power distribution network. The research focused on the voltage drop, harmonics and DC components produced by the backup battery-charging units on low voltage distribution network. Low voltage power distribution network performance parameters were reviewed, taking particular attention to those performance parameters influenced by backup battery-charging units. Selected performance parameters influenced by backup battery charging units were examined to establish their contribution to the power quality problems on the distribution network, by analysing simulations results obtained in Simulink software.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews the works of different researchers who did something related to the current research. Also included in this chapter is selection of low voltage performance parameters affected by backup battery charging units. Selected performance parameters would be assessed by Matlab/Simulink for their impact on the distribution network.

In nearly all electronic equipment, the devices directly connected with the power network are converters. Therefore, their characteristics determine the harmonics produced on the complete system and the impact on the power supply depends on the topology and the type of devices employed.

The integration of backup battery-charging units by residential consumers on the low voltage power distribution network had prompted the interest of many researchers. to investigate their impact on low voltage distribution network. Therefore, better understanding of interoperability phenomena would be required. In particular, the impact that large scale integration of battery-charging units would have on the low voltage distribution network is of great importance. With the increase of number of people owning home based backup battery-charging units, those may affect existing electricity distribution infrastructure in various ways. Hence there was need to understand the impact of backup battery-charging units had on the low voltage power distribution network.

Some studies which had been conducted in the recent past years analyzed the impact of charging electric vehicle batteries on the low voltage distribution network, but none concerning backup battery-charging units. In foregone studies, the impact analysed were divided into three main groups: generation adequacy, transformer aging due to loading and distribution network power quality. The researchers further proposed several mitigation schemes on their findings such as time- of- use (TOU) and direct control using smart charging algorithms.

In the existing literature, studies on battery charging were those conducted on by various researchers to evaluate the effect on electricity generation adequacy, transformer aging and distribution system power quality.

2.2 Impact of battery charging on electricity generation adequacy

A number of battery charging integration studies (Farmer et al, 2010; Taylor et al, 2009; Taylor et al, 2010; Chen et al, 2011) had adequately analysed the existing and planned generation capacity to meet current and future battery demands. Those studies pointed out that if batteries were charged during the off-peak load, no new power plants would be required to meet battery charging demands. They emphasised that if battery charging was controlled and shifted to off-peak hours, no peak load demand increase would be experienced on the distribution network, and the process would prevent construction of new power plants. In addition, (Hadley, 2007) concluded that, depending on the time and place of the charging, battery charging could require additional power or increase the utilization of the existing capacity and possibly reduce the reserve margins. In these cases, generation reliability was a serious concern.

2.3 Impact of battery charging on transformer aging

High usage of battery charging was likely to cause problems on the low voltage distribution network because of additional load, additional network losses and increased voltage drops (Chen et al, 2011; Hadley, 2007; Shao et al, 2009; Warweg et al, 2011; Clement et al, 2010; Boulanger et al, 2011; Pillai and Bak-Jensen, 2010; Putus et al, 2009; Dubey et al, 2013; Leon et al, 2014; Gray et al, 2015; Bohn et al, 1015). The increased load demands due to battery loads overloaded service transformers, deteriorate the transformers' life and increased network losses. Furthermore, battery charging could create new load peaks exceeding the service transformers' rated capacity, thereby accelerating equipment aging (Shao et al, 2009; Warweg et al, 2011). In particular, (Shao et al, 2009) characterized the impact of battery charging harmonics on the distribution transformers' life. The analysis portrayed a quadratic relationship between the transformers' life and the total harmonic distortion (THD) of the battery charger current. For a transformer to work properly, to its normal life expectancy, (Shao et al, and 2009) suggested that the current THD should not exceed 25-30%. Mitigating transformer overload problems greatly improved its service life. Furthermore, (Warweg et al, 2011) evaluated the impact of battery charging on the transformer capacity overload and conclude that a time controlled battery charging successfully mitigated transformers overload concerns.

In addition, the study conducted by (Farmer et al, 2010) pointed out that battery charging affected transformer aging either positively or negatively. For example, an increased peak load demand may decrease transformer life expectancy. However, if batteries were primarily charged during off-peak hours, a flatter load profile would reduce the daily expansion and contraction of the transformers' windings, resulting in a positive effect of transformers' life.

2.4 Impact of battery charging loads on power quality

Battery charging cause power quality problems in the low voltage distribution network, such as under-voltage conditions, power unbalances, and voltage and current harmonics. As the number of battery chargers increased so did the electricity demand required to charge respective batteries. Any battery load charged by 18kWh chargers (3phase level 2 chargers) almost double increased the peak load demand of the homeowner (Dubey et al, 2013). The battery charging will unfortunately increase the load demand that led to additional voltage drops in distribution network, thus affecting the service voltage quality. The impacts of the additional load demand due to battery charging on the distribution network increased power losses and voltages deviations which affected our uses. In (Boulanger et al, 2011), the impacts of quick battery charging on the power distribution network particularly on the power system harmonics were evaluated and the maximum battery penetration level while avoiding serious harmonic imparts was determined. To mitigate the effects of battery charging, (Clement et al, 2010) recommended controlled charging methods.

Furthermore, in (Wu, 2011), the impact of integration of battery chargers on power system loading and voltage profile were evaluated and the benefits of the several charging scenarios, such as dumb charging, timed charging and controlled charging, on service voltage quality were quantified. (Pillai and Bak- Jensen, 2010), also investigated the effects of battery charging on the distribution network regarding line voltages, line drops and system losses, while (Putus et al, 2009) evaluated battery charging impacts on the voltage limits, power quality and power imbalance. In (Dubey et al, 2013), several network parameters; both at local and global level were analysed those affecting distribution voltages during battery chargers. Based on the above analysis, it was concluded that a large scale battery charging deployment could violate recommended limits for the secondary voltages and could cause voltage imbalance. (Dubey et al, 2013), used actual measurements and survey data to determine battery charging characteristics, on feeder load demand, battery charging starting time, battery state of charge (SOC), and proposed a stochastic approach to analyse the impact of battery charging. A Monte Carlo approach to evaluate the impact of battery charging on feeder voltage quality, including under/over- voltages and voltage unbalances was proposed in (Gray and Morsi, 2015).

Maintaining of appropriate voltage level for residential consumers was of great importance to utility companies, as such there were various schemes designed to mitigate the impact of battery charging on distribution voltages. Time of use pricing and smart charging algorithms were widely used schemes to mitigate the impact of battery charging on the low voltage distribution network.

2.5 Time of use (TOU) pricing to mitigate battery charging load impacts

Several studies had concluded that battery charged during peak hours led to undesirable grid impacts, in which the peak load demand went up coupled with under-voltage conditions, thereby necessitating grid expansion and upgrades. Studies in (Chen et al, 2011; Hadley, 2007; Shao et al, 2009; Warweg et al, 2011; Clement et al, 2010; Boulanger et al, 2011; Pillai and Bak-Jensen, 2010; Putus et al, 2009; Dubey et al, 2013; Leon et al, 2014); Gray et al, 2015; Bohn et al, 1015) concluded that uncontrolled charging of battery loads limited the number of battery loads on the distribution network. Therefore, to avoid battery charging during peak hours, utility companies deployed TOU pricing structure. In the TOU scheme, the electricity usages were rated differently during peak and off- peak hours. Off- peak hour's rates were lower than the peak hours rates, that motivated the consumers to utilize the electricity generated during off-peak hours. The study in Cook et al, investigated the response of consumers towards TOU, the conclusion was that consumers responded positively to that type of tariff structure. As such most of the EVs owners adjusted their charging schedule to charge during the off-peak tariff periods. Therefore, TOU pricing successfully stimulated EV battery charging during off-peak hours, hence a flatter load demand profile was maintained.

Implementation of TOU pricing was useful to the side of utility company to maintain and predict the load demand. Nevertheless, if during designing the TOU scheme, the total demand and load profile of the EV battery loads was not taken into consideration, the effect of EV battery charging under TOU schedule might get worse (Schey et al, 2012; Shao et al, 2010; Gao et al, 2012). The reduced electricity rates during off-peak hours result in simultaneous charging of multiple battery loads. That caused an even higher increase in the load demand because EV batteries were charged during the off-peak period. Thus larger additional voltage drop were encountered during off-peak periods. To date, the implementations TOU schemes do not consider EV battery loads when setting up the TOU schedule. That necessitated development of optimal TOU schedule that considers the EV battery load demand and thus minimizes the effect of battery load charging.

An optimized TOU schedule that considered battery load demand was developed by (Gao et al, 2012). Nevertheless, the proposed TOU in (Gao et al, 2012) did not take the convenience of battery owners into consideration. Another optimal TOU schedule that benefits both utility companies and consumers, while taking battery charging into consideration was developed and presented in (Cao, 2012).The objective was to develop a practice approach for setting up TOU schedule based on customer load demand, battery charging demand and service transformer loading constraints. The selected time to begin off-peak rates in a TOU scheme was designed to minimize the effect of battery charging on the secondary service voltages, while ensuring that batteries were fully charged by 7am (worst case). Both grid and consumer benefits were maximized in that way. The analysis suggests that the optimal time to begin off-peak rates was between 11p.m and 12a.m (Dubey et al, 2015).

2.6 Smart charging algorithms to mitigate battery load impacts

When there was high level of battery charging, TOU pricing scheme structure did not give optimal results because the line voltage deviated beyond standard limits. That fact was pointed out in (Schey et al, 2012), who stated that under TOU pricing the simultaneous charging of several EV battery loads created a second peak in load demand during off-peak hours. The second peak load demand was even worse than the first, as the result some battery loads were prevented from accessing power due to overload. TOU pricing essentially encouraged residential customers to charge simultaneously at the beginning of off-peak hours. To that effect (Mets et al, 2010) said that power network could be utilized more efficiently if the battery charging rate and charging start time were controlled to optimize desired distribution objectives. The objective of the distribution network was to maintain a stable power supply throughout the distribution network by providing a flatter overall load demand profile. In addition, it minimizes the power losses and to reduce as much as possible the cost of battery charging. To achieve those objectives a smart battery charging algorithms were proposed that took into account the higher battery charging penetration without causing negative impacts on the distribution network.

2.7 Smart charging scheme

Several studies had been conducted on smart charging structures or algorithms to determine appropriate schedule to address distribution network malfunctions due to battery charging. Smart charging scheme was designed to benefit both the utilities and the owners.

2.7.1 Controlled battery charging - benefits utility

A smart charging scheme that was designed to benefit the utility was decided upon by fixing the charging rates and charging start time in accordance with the current load demand /or electricity generation costs. In view of that, (Clement et al, 2010) proposed a coordinated charging scheme to minimize system power losses. In the process dynamic programming algorithms was developed to determine the EV battery charging profile for each battery load under both deterministic and stochastic settings. In (Mets et al, 2010) a charging technique was proposed that minimized the load peak demand, it controlled battery charging based on the local load information and overall global information. Furthermore, (Sortomme et al, 2011) discovered the relationship between load variance, load factors and feeder losses and designed several optimal charging algorithms to minimize the impact of battery charging of the distribution network. A real time battery charging strategy was proposed in (Deilami et al, 2011) to minimize total generation cost and associated distribution energy losses. In addition, (Shao et al, 2011) proposed a demand response strategy to decrease the likely impact of new loads created by battery integration, while minimizing the cost of upgrading the infrastructure. Another type of demand response was proposed in (Shao et al, 2012) which accommodated battery charging while keeping the peak demand unchanged therefore maximizing distribution network usage. In (Gan et al, 2012), the scheme was proposed that aimed at flattening the total load demand, designed the optimal battery charging scheduling problems as discrete optimization problems. In (Han and Sezaki, 2010), the proposed optimal charging control that optimizes the energy usage of the battery charging on distribution network for vehicle to grid (V2G) frequency relation services. In (Hoogde et al, 2015), the author proposed a near real-time algorithm that took account of the dynamic nature of the battery charging demands.

In order for consumers to benefit more, a real-time electricity market pricing/TOU was proposed. In that scheme, battery charging rate and time were controlled following the TOU/real-time structure while minimizing the cost for the battery owners. To that several authors had proposed to adjust the battery charging rates and charging start times according to the real- time electricity market. That prompted (Li et al, 2014) to propose a control model for battery charging that followed real -time electricity price information.

In addition, (Shretha and Chew, 2007) proposed a quadratic programming techniques used to optimize charging - discharging process such that the charging cost was minimized while maximizing discharging profit. In (Cao, 2012) a heuristic method to control the battery charging rate and time in response to the TOU pricing schedule was formulated. In (Shi and Wong, 2014), another real-time scheme was proposed named vehicle to grid (V2G) control algorithm with price uncertainty to maximize the profit of each EV owner. In that scheme, the owners were awarded for selling power to the utility company at a higher price than it was bought. Similarly, (He et al, 2012), both global and local optimal battery control techniques proposed to minimize the total cost of electricity that battery owner paid for charging. Also, (Jin et al, 2013), proposed a scheme that looked at the battery charging schedule problems by simultaneously maximizing aggregator's profit minimizing the battery owner's costs. That was a linear programming based on optimal control strategy for static charging scenario, and a heuristic for the dynamic charging scenario. Similarly, (Richardson et al, 2011) proposed battery charging strategy aimed at delivering the maximum amount of energy to the battery loads while maintaining the circuit parameters within the specified limits, thus benefiting consumers to optimizing the grid level constraints.

In this section, the authors formulated various smart charging algorithms designed to directly control battery charging, hence the mutual benefits discussed above. However, there were some challenges to the smart charging algorithms. For example, while scheduling battery charging rate and time to maximize utility benefits, the proposed algorithm ignored consumer inconvenience. The other challenge was that a number of utility companies did not implement real-time pricing for their residential consumers. As the result, the optimal battery charging methods formulated to benefit battery consumers' were of little or no use.

Batteries are high capacity storage (in the range of 2 - 4kWh) devices that draw great amount of current from the distribution network when they a being charged. Because of that charger are connected to the high voltage distribution network.

The studies mentioned above looked at the impacts that arise due to charging on the high voltage distribution network. The studies on charging were normally done on designated places, therefore, the impact of charging on the grid were much easy to monitor and control. Charging was normally conducted during off peak with limited number of charging connected to the grid at a time, hence there was little distribution network interferences. In addition, charging were conducted on fixed stations, thus monitoring and control were not complicated.

In this research work, backup battery charging units were purchased and owned by private individuals randomly distributed among the residential consumers. Harmonics were produced when residential consumers connected their backup battery-charging units on the low voltage distribution network. Backup battery-charging units produced harmonics because they are non-linear devices. The amounts of total harmonic distortions produced by backup battery-charging units on the distribution network were unknown. The maximum number backup battery-charging units to produce worst effect on the distribution network is also unknown. The unknown amount of total harmonic distortion produced by multiple backup battery-charging units on the low voltage distribution network was the gap being investigated in this research work. In view of that, this research work was focused on power quality issues on the low voltage power distribution network.

2.8 Review of performance parameters

Integration of backup battery-charging units by residential consumers on the low voltage distribution network had prompted the interest of many researchers to investigate the impacts thereof on the low voltage distribution network. The dynamic behaviour of backup battery-charging units affected the state of performance parameters. Therefore, better understanding of interoperatability phenomena, especially the impact that large scale integration of backup battery-charging units had on the low voltage distribution network was of great importance to the power supply network providers.

A backup battery-charging unit presents an electric power quality issues on the low voltage distribution network. They manipulate some performance parameters which play pivotal role in maintaining electric power quality. In this regard, the purpose of this section was to review performance parameters affected by backup battery-charging units on the low voltage distribution network. But before proceeding to review performance parameters affected by backup battery-charging units, a general overview of performance parameters associated with low voltage power distribution network was outlined and discussed. The low voltage power performance parameters determine the quality of electricity supplied to the consumers. The performance parameters for the low voltage distribution network were outlined and as follows:

2.8.1 Frequency of supply

In an electrical power system, a constant equilibrium between active power generation and consumption has to be maintained for a smooth operation of the distribution system. The frequency of supply is a measure of the rate in cycles per second (Hertz) at which the alternating voltage or current oscillates between peak forward and reverse values. In other words frequency of supply is a measure for the rotation speed of the synchronized generators. The rotation speed of the synchronize generators determines the frequency of supply of an electrical system; by increasing the total load demand on the electrical power system, the speed of the generators would reduce and hence lowering the system frequency. On the other hand, decreasing the load demand would lead to an increase in the system frequency (European Network of Transmission System Operators for electricity handbook, 2009). Therefore, a balanced supply and demand of active power had to be maintained to keep system frequency constant, a task performed and achieved by frequency regulator system. In order to maintain frequency stability, power generated had to be coordinated and controlled to the required power consumption. Frequency deviations could not only damage electronic devices connected to the low voltage distribution network but also endangers the stability of the entire electrical network within a given distribution network. For example, German transmission system operators (TSOs) were legally obliged to maintain the system frequency within the strict limits of 50 Hz ± 1% (Soni et al., 2016; Conrad et al., 1991). In order to achieve that primary goal of the system operators, a certain amount of active power reserve was required to re-establish the equilibrium between demand and generation in case of unbalances. Despite the active power reserve being present, there were times when an unbalance between instantaneous power consumption and generation occurred because of other major power disturbances in the low voltage distribution network. The nominal frequency of the supply of electricity to the consumers via low voltage distribution system was 50Hz. That frequency was maintained automatically by the generators provided there was a limited load various between the generated power and that being consumed, the frequency remains stable at or very close to 50Hz. The nominal operating frequency range as provided by (Zambia Standard 378-1, 2009) was set between 49Hz and 51Hz. Nevertheless, operations outside the set limits occurred from time to time and in rare circumstances the supply was interrupted if the frequency deviates excessively. Zambian power electricity supply system frequency is directly controlled by Southern African Grid. Frequency of supply as a performance parameter is vital for the smooth operation of electrical devices. Any electrical device connected to the low voltage power distribution network should conform to the supply frequency for the distribution network.

2.8.2 Range of supply voltage

Supply voltage is the voltage available at the point of common coupling accessible to all electrical devices, instrument or machines connected to the distribution network. International Electroelectrical Commission (IEC) 61000-3-2, 2018) embarked on a programme to achieve an international standard of supply voltage of 230/400V at 50Hz by the year 2003, which was accomplished on time. The standard required, under normal service conditions, that the voltage at the point of common coupling should not differ from the normal voltage of 230/400 V by more than ±10%. That programme automatically led many electrical devices manufacturers in different places to stick to the standards international voltage level to avoid individual voltage transformations at the distribution points to suit equipment voltage level, thereby preventing equipment failures due to excessive voltage levels implications on the windings or conductor insulations.

Automatic voltage regulation equipment (tap changing transformers, capacitors and reactors) were employed on the transmission and distribution network to maintain the supply voltage within the desired range by compensating load variations on the distribution network. Without the use of automatic voltage regulation equipment, voltage would sag to unacceptable level during the time of peak load demand or could be excessively swell at time of low load demand. Voltage variations due to distribution network load switching may oscillate a few minutes until the high voltage regulations equipment operates to attain a steady state voltage.

Electrical power consumers desire that their equipment operate reliably within the standard range of supply voltage or would take appropriate measures within their installations to maintain voltage within the excepted range to prevent their equipment malfunction or failure. Brown outs or voltage levels outside the standard range can occur if a distribution transformer losses supply to one phase generally through one high voltage fuse blowing. The supply voltage will be maintained to the health phases resulting in low voltage phase to neutral voltage of approximately 100%, 50%, 50%. The reduced voltage will continue until the problem is rectified by the utility company. The importance of constant voltage level for the low voltage distribution network cannot be over emphasized because electrical equipment are usually designed and set to operate normally at standard frequency and voltage range. To this effect, low voltage distribution network voltage must not be allowed to deviate excessively beyond its prescribed limit as stated in IEEE Standard 519-2003 or IEC 61000-4-7 otherwise unprotected consumers' equipment connected to the power supply system may fail to work accordingly or totally be damaged.

2.8.3 Voltage fluctuations

Voltage fluctuations are short duration variations in supply voltage levels due to changes in loads or switching of heavy loads on the distribution network. Voltage fluctuations are also caused by rapid and repetitive variations of consumer loads. In an active distribution network, the supply voltage falls as the load increases and vice versa. The common causes of voltage fluctuations are the equipment when plugged-in on the distribution network because they tend to draw high current from the distribution network during starting. Equipment such as motors, arc furnaces and arc welding plants are the main cause of voltage fluctuations. For instant, during arc welding, current consumption from the distribution network continuously vary. The equipment is being loaded on and off repeatedly during its operation which results in voltage fluctuations on the low voltage distribution network. The voltage fluctuations can easily be observed as a flickering of light on lighting bulb. Voltage fluctuations can also be caused switching of large electrical load because a high current is suddenly drawn from the low voltage distribution network.

The high level of voltage fluctuations at the consumers' point of common coupling can affect nearby installed equipment as well the consumers' own equipment. Even though it is not mandatory, consumers must ensure that their equipment have an in- built protection to voltage fluctuations or take appropriate measures within their installations to prevent voltage fluctuations from spreading to other nearby distribution networks. The voltage fluctuation influences the operation of sensitive equipments such as photocopiers, fax machines and computers due to errors in transmitting of signals during their time of operation. The utility company usually provides supply voltage free of voltage fluctuations so that electrical equipment connected on the low voltage distribution network could operate effectively and efficiently.

2.8.4 Voltage dip

Voltage dip or sag is a single short duration reduction in the supply of voltage levels generally due to short circuit faults on the distribution network or motor starting (Conrad et al., 1991). Thus, voltage dip is a sudden reduction of the supply voltage to a value 1% - 90% of the declared voltage followed by a voltage recovery after a short period of time that should not last more than 1 minute. Conventionally the duration of a voltage dip is between 20 ms and 3 s. The depth of a voltage dip is defined as the difference between the minimum root mean square voltage during the voltage dip and the declared voltage. Voltage changes which do not reduce the supply voltage to less than 90 % of the declared voltage is not considered as a voltage dip (ZABS, 2009), see Figure 2.1 below for the voltage dip illustration.

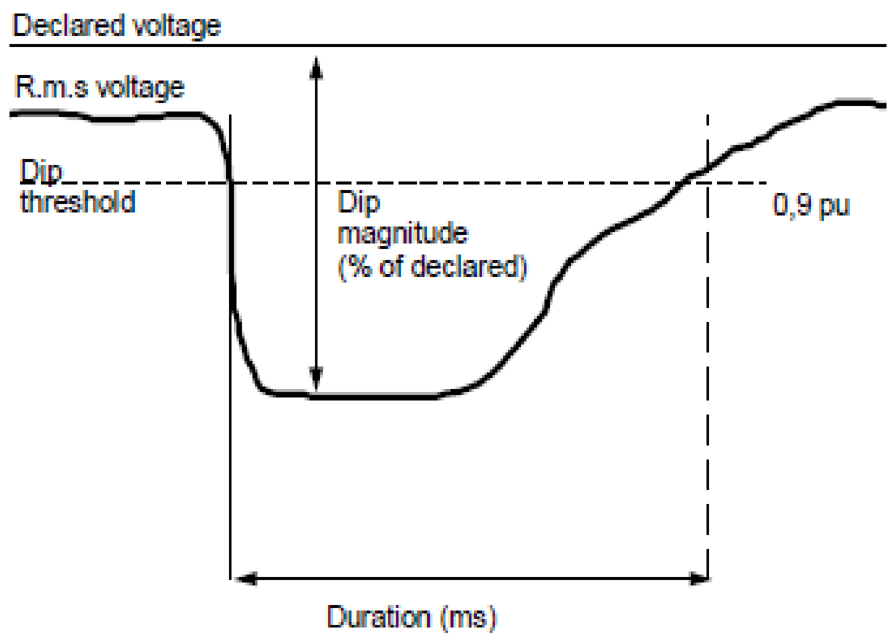

Figure 2.1 Measured voltage dip parameters (Zambia Bureau of Standard 378-1, 2009).

Voltage dips on the distribution network may be caused by short circuit faults which may occur due to accidents, vehicles collisions, birds, trees, wind, and lightning hitting the distribution network or connection of heavy loads on the distribution network. The voltage levels reached during faults depend on the nature of the fault, where the fault occurred, and the location of the consumer relative to the fault. The voltage on the affected part(s) of the distribution network can collapse to a fraction of its nominal value until protection system operates thus preventing connected electrical equipment from receiving further reduced supply voltage which is capable of damaging them.

Voltage dips occur more frequently in rural areas because rural distribution network are more exposed to environmental hazards. In addition, rural distribution networks are generally less robust than the urban distribution networks due to the increased length of spans. Hence, voltage dips are more severe and are more experienced across a wider section of the rural distribution networks. A distribution network corrupted with voltage dips cannot deliver to its design expectation because the voltage is not in conformity with what the equipment are designed to feed on. Hence, some electrical equipment ceases operation during the time of voltage dip because their operating temperature is exceeded. Such phenomena led into high degree of premature failure or damage of the installed electrical equipment. A distribution network free of voltage dip is desirable for the smooth operation of electrical devices at all times.

2.8.5 Voltage differences neutral to earth

The multiple earth neutral (MEN) system connects the low voltage neutral conductor to earth at the distribution transformer and at each consumer's installation for the purpose of personnel protection. A low voltage neutral conductor interconnects to all the surrounding of a MEN system along with neighboring distribution substation. Despite this arrangement being in place a small steady state voltage differences may occur between neutral and earth. These voltages may rise to higher levels during some fault situations. Some electronic equipment may be unable to continue their normal operation if the voltage differences between neutral and earth, generated within the consumer's premises, exceeds 10V. The voltage differences between neutral and earth affects the smooth operation of the low voltage distribution network due to circulating current in the distribution network.

2.8.6 Voltage transients

Transients are fast travelling spikes on the voltage/current waveform. Voltage transients can have so much energy such that sensitive electronic equipment can be affected or even be damaged. The transient are short lived waveform shock on the distribution network as they last for about 5 microseconds.

The most common voltage transients are caused by lightning and to a much lesser extent by distribution network faults or load switching operations in the distributions network. The voltage transients from lightning do occur when lightning strikes the low voltage distribution network or just the ground nearby the low voltage distribution network. Lightning strikes cause a storm related voltage transients, however strong winds and debris can also cause overhead conductors to clash or to contact trees which can also generate a voltage transient.

Another form of transient is known as switching transient, it is a short-term distortion to the voltage waveform caused by switching operations. Voltage transients caused by switching operation of electronic devices are of low energy compared to that generated by the lightning. A voltage transient is propagated on the low voltage distribution network and influences the performance parameters of a low voltage distribution network. The majority of switching transients are generated within consumer premises. A distribution system which is experiencing switching transients will cause malfunction of electrical devices connected to it because transients are capable of burning out insulation to the devices or they may be felt as control signal hence activate/deactivate devices when in fact should not be.

2.8.7 Step and touch voltages

During distribution network faults, substantial voltage differences referred to a step and touch voltages can occur within the ground or between metallic systems and earth, in the immediate area of the fault or associated supply equipment.

Earth system is designed to minimize step and touch voltages in the vicinity of metallic or conductive structures in close proximity to electrical equipment. Structures such as metallic fences, swimming pools, flammable gas or liquid storage tasks, electric railway lines, medical facilities, communication facilities, pits, pillars, transformers kiosks and metallic plumbing system are best installed away from the distribution network equipment to assist in limiting the risk from step and touch voltages.

2.8.8 Voltage imbalance

Voltage imbalance is a ratio of maximum voltage deviation from the average line voltage to the line voltage by (Dharmakeerthi et al., 2012; Kothandabhany, 2011). The change in terminal voltage at the PCC depends on the load impedance. As the number of backup battery-charging units increase, the voltage drop also increases. The voltage drop expressed in percentage was computed by Tarnekar et al as shown in equation (1) below.

$$\%\text{Voltage drop} = \frac{(\text{numerical difference } V_2 \text{ and } V_2')}{V_2} x100\% \ldots\ldots\ldots\ldots\ldots\ldots 1$$

$$\%\text{Voltage drop} = \frac{V_2' - V_2}{V_2} \text{ x } 100\%$$

where V_2 is terminal voltage at load, V'_2 is terminal voltage at no load.

The author (Kothandabhany, 2011) recommended that the maximum voltage imbalance of the electrical supply system must be restricted to 3%. In addition, authors in (International Electroelectrical Commission 61000-4-7, 2014) highlight allowable permissible maximum voltage imbalance specifically for the induction motors to be as low as 1%.

The authors (Ahmed and Mohammed, 2005), defined voltage imbalance as a ratio of negative sequence voltage to the positive sequence voltage. Voltage imbalance is a power quality problem because of its detrimental effects on the performance and efficiency of three phase equipment on the distribution network such as induction motors. Voltage imbalance is frequently encountered in weak low voltage distribution networks at the industrial as while as residential distribution networks due to weak power generating sources. Voltage imbalance is caused by uneven distribution of single phase loads over the three phase supply system and by asymmetry of impedances over three phase lines. This problem is expected to worsen if a large number of single phase backup battery-charging units are connected on the low voltage distribution network. Residential backup battery-charging units are more likely to cause severe phase voltage imbalance problem because these devices are not evenly distributed across all three phases voltage supply.

Generally speaking, a widespread usage of backup battery-charging units presents a concern about their unfavorable impacts on all of the electrical power system sectors such as generation, transmission, and distribution. The distribution network is mainly affected by the backup battery-charging units based on the level of penetration as well as the length of time to which the backup battery-charging units remain connected on to the distribution network. Practically, increasing the number of backup battery-charging units connected on to the distribution network affects the distribution network performance in terms of reducing the distribution network efficiency, reliability, power quality, and voltage regulation (Conrad et al., 1991). The backup battery-charging units also increase the voltage deviation and voltage unbalance in the distribution network. Additional power demands due to uncontrolled backup battery charging either increase peak load demand or introduce a new peak load of the low voltage distribution network which eventually influences the performance of the low voltage distribution network's efficiency. An uncontrolled load as a result of backup battery charging has a negative impact on the service transformers. It increases the transformer losses and the thermal loading, which leads to insulation breakdown; consequently, the lifespan of the transformer is reduced, the process of backup battery charging trickles down to power quality challenges. Power electronics devices such as, dc/dc, dc/ac converters, which used in backup battery chargers designs inevitably produce harmonic distortion in both voltage and current waveforms. This could harmfully affect the quality of the utility distribution network (Richardson et al., 2010). The author (Liu et al., 2011) affirm the impact of increased backup battery charging phenomena on the distribution network by saying that the load shifting effectively reduce peak load, whose task can be achieved by charging coordination. The purpose of controlled backup battery charging is to shift load demand of energy and leveling the peak load, thereby minimizing voltage imbalance to maintain a constant voltage supply reaching the equipment on the distribution network.

The voltage imbalance between the phases of the distribution power supply network occurs because of imbalance in consumer loads' on the distribution network. A distribution network where there is a predominance of single-phase or two-phase consumers' electrical loads, the assessed unbalance may be up to 3 % (Zambia Standard 378-1, 2009). Excessive imbalance in supply voltages is undesirable for consumers as it results in overheating of induction motors. Furthermore, nuisance tripping can also occur in motor loads equipment once the protection system notices the voltage unbalance in the distribution system.

2.8.9 Direct current

Direct current may flow in the alternating current neutral conductor of the low voltage distribution network due to consumer's equipment with non-linear load characteristics installed on the distribution network. A normal alternating current low voltage distribution network should not contain direct current component because the flow of direct current on the alternating current network causes corrosion on the distribution network and the consumer's earthing system. Direct current is generated as a side effect of operation of non-linear loads; this should be limited during the initial design of equipment or installation. The DC components were computed using Fourier series analysis as obtained in Mohan et al which are shown in equation 2 and 3.

DC component for current:

$$I_{DC} = \frac{1}{T}\int_0^T i(t)dt \quad \ldots\ldots 2$$

$$I_{DC} = \frac{1}{2\pi}\int_0^{2\pi} i(t)dt$$

where I_{DC} is the DC component for current, $T = 2\pi$ = period, i(t) is the instantaneous current.

Similarly, the DC component for voltage:

$$V_{DC} = \frac{1}{T}\int_0^T v(t)dt \quad \ldots\ldots 3$$

$$V_{DC} = \frac{1}{2\pi}\int_0^{2\pi} v(t)dt$$

where I_{DC} is the DC component for voltage, $T = 2\pi$ = period, v(t) is the instantaneous voltage.

2.8.10 Harmonic content of voltage and current waveforms

Harmonics are frequencies of voltage/current at the integer multiples of their fundamental frequency. The harmonic distortions are created by consumers' equipment with nonlinear loads characteristics such as solid state rectifiers and variable speed motor drives. Harmonic distortion in the current drawn from the low voltage distribution network by the consumer's equipment also creates distortions in the supply voltages which may affect other nearby consumers connected on the same line.

Measurement of harmonics is essential to establish their impact on the distribution network. Harmonic current produced by consumers' electrical equipment into distribution network distorts the original sinusoidal supply voltage from the Utility. If the harmonics are not confined within acceptable limits as stated by (Dharmakeerthi et al., 2012; Kothandabhany; Nguyenet al., 2013), then it is the responsibility of electricity supply utility to provide sinusoidal supply voltage which is difficult to attain without consumer co-operation. Nonlinear loads produce harmonics which distort the supply voltage and current waveforms. Total harmonic distortion (THD) is a measure of the distortion to the supply voltage and current waveforms. In IEEE 519-2014 standards, the THD is defined as ratio of the root mean square of the harmonic content, considering components up to the 50th order. The amounts of distortion in the voltage or current waveform were computed by (Mohan et al, 2003) as shown below:

The input current in steady is the sum of its Fourier (harmonic) components as

$$i_s(t) = i_{s1}(t) + \sum_{h\neq 1}^{\infty} i_{sh}(t) \qquad \ldots\ldots 4$$

Therefore, the distortion component i_{dis} of the current was generated from equation (4) as

$$I_{dis}(t) = i_s(t) - i_{s1}(t) = \sum_{h\neq 1}^{\infty} i_{sh}(t) \ldots\ldots 5$$

In terms of the rms values,

$$I_{dis} = [I_s^2 - I_{s1}^2]^{1/2} = \left(\sum_{h\neq 1} I_{sh}^2\right)^\wedge\tfrac{1}{2} \ldots\ldots 6$$

The THD in the current is defined as

$$\%THD_i = 100 \text{ x } \frac{I_{dis}}{I_{s1}} \ldots\ldots 7$$

$$=100 \text{ x } \frac{\sqrt{I_s^2 - I_{s1}^2}}{I_s}$$

$$= 100 \text{ x} \sqrt{\sum_{h\neq 1}\left(\frac{I_{sh}}{I_{s1}}\right)^\wedge 2},$$

where the subscript i indicates the THD in current.

In a similar, the THD in the voltage can be expressed from equation (4) as

$$\%THD_v = 100 \text{ x } \frac{V_{dis}}{V_{s1}} \ldots\ldots 8$$

$$= 100 \text{ x } \frac{\sqrt{V_s^2 - V_{s1}^2}}{V_s}$$

$$= 100 \text{ x} \sqrt{\sum_{h\neq 1}\left(\frac{V_{sh}}{V_{s1}}\right)^\wedge 2},$$

where the subscript v indicates the THD in voltage.

Backup battery-charging units employ power electronic converters in converting voltage which produce harmonics on the low voltage distribution network that affect both supply voltage and current waveforms.

The presence of harmonics on the low voltage distribution network cause overheating of equipment and disruption to communication facilities. Since EV battery charger employs power electronics components for its charging operation; the switching on/off of the power electronics components that converts alternating current to direct current yields power quality issues onto the power distribution network. Thus, authors (Moeed and Salam, 2014) stated that the process of converting alternating current to direct current inject current harmonics. This is the main challenge faced by power utility companies because harmonics could lead to system components de-rating if it is not controlled and managed, phenomena that would demand power system components upgrade for the distribution network to remain sustainable. This fact is supported by authors (Jimenez and Garcia, 2010) who pointed out that EV battery charging increases voltage total harmonic distortion (THD) on distribution network which may automatically de-rate transformer capacity. Therefore, backup battery charging will affect the distribution network power due to injection of harmonic in the low voltage power distribution network.

Studies in (Deilami et al 2010); Liu et al., 2013) reviewed that EV battery charging could cause unacceptable level of voltage THD For instance (Liu et al., 2013) performed their studies on high penetration level of EV battery chargers on random charging during peak demand hours results in approximately 45% of voltage THD. This study shows that EV battery charging inject significant amount of harmonic on the power distribution network. Thus the level of harmonics produced on the distribution network heavily dependent on the type of EV battery charger and the nature of power electronic device designs and operations.

Harmonic orders may vary from 2 to 100 or more, would be analysed. Power electronic devices such as furnaces, energy saving lamps and transformers are the key sources of harmonics. Widespread emergences of harmonics were first noted in 1970s after introduction of power electronic converters in consumer electronics and industries (Du et al., 2010). Since then several researcher have been attracted to study this subject in various angles. The advent of integrated circuits, computers and electronic devices further worsened the power quality problems in 1980s (Nguyen and Lee, 2012). Harmonics vary in magnitude over time but a certain minimum level of pollution always exists in distribution system which distorts utility supply waveform. Harmonics worsen the power factor, increase line losses and utility apparent power supply demand. Different loads connected to the distribution network shows different current waveforms upon simulation (Kuperman et al., 2013; Yang et al., 2013). Waveform distortion and periodic resonance events is the source of wary to power system engineers. Utility is mandated to provide acceptable quality power to its consumers. Harmonics produced by consumers, especially large industries, affecting smaller consumers and utilities. Power utility companies are forced to supply more apparent power to account for lost distortive power. In order to neutralize harmonics, large industries install filters for their lower order harmonics but small consumer electronic devices continue injecting higher order harmonics to the distribution network. Utilities install static variable compensators on distribution network to improve power factor by reducing reactive and distortive power losses. Lower order harmonics (h=2 to 25) awfully distort sinusoidal waveforms due to their high magnitudes but higher order harmonics (h=26 to 50 or higher) are usually perceived too low to be considered for harmonic analysis.

EV battery chargers are high power nonlinear devices which generate significant amount of current harmonics distortion of up to 50% during the charging time (IEEE 519 standard, 2003). It is expected that the backup battery chargers will become an integral component to the operation of low voltage distribution network, as such their power quality impacts concerning voltage profile, fundamental and harmonic losses, current total harmonic distortion and current unbalance are issues that cannot be avoided. Increased use of EV battery chargers nowadays necessitates large number of massive battery packs regardless of their charging level. These EV battery chargers could have a disruptive impact on the distribution network, if their design did not meet the regulatory requirements for the power quality of the charging voltage and current during charging process (Kuperman et al., 2013; IEEE 519 standard, 2003). Since EV battery chargers represent a huge load, the impact on the low voltage distribution network will generate significant amount of current harmonics distortion of the input current can vary from more than 13% to less than 52% (Zhang et al, 2012) depending on charging time, charging rate and penetration level.

2.8.11 Interharmonics

The frequencies, which are not an integer multiples of the fundamental frequency are called inter-harmonics (International Electroelectrical Commission 61000-4-7, 2014). Interharmonics interference is caused by the presence of sinusoidal waveforms at frequencies lying between multiples of the supply frequency of 50 kHz.

Interharmonics could cause severe resonances and may affect power line carrier signals, and induce visual flickers in fluorescent, arc lightning's and computer display devices.

2.8.12 Mains signaling interference

The main signaling interference are basically control signals injected and carried on the distribution network at various frequencies primarily to switch appliances on and off remotely. These control signals have a frequency that is higher than normal 50 or 60Hz line frequency and range up to 3 kHz. The control signals are designed only to be injected at a moment when remote appliances need to be controlled. These signals cause interferences similar to those generated by interhamonics if the level is excessive, the most common and noticeable problem is noise from ceiling fans.

Failure to receive appropriate signals at the designated point and time can cause incorrect activation/deactivation of remote controlled appliances. This can occur due to interference, low signal levels, distribution system fault and signal equipment failure.

2.8.13 Noise

Noise is unwanted voltage or current superimposed on the low voltage distribution power system voltage or current waveform. Noise can be generated by power electronic devices, control circuits, arc welders, switching power supplies and radio transmitters. Poorly grounded sites make the system more susceptible to noise. Noise can cause technical equipment problems such as data errors, equipment malfunction, long-term component failure, hard disk failure, and distorted video displays.

Power system components can cause audible and electronic noise interference. Audible noise can be generated by transformers (cores and / or cooling equipment), by discharges in wet weather and by faulty equipment such as damaged insulators.

Power line interference can also be generated by discharges occurring in faulty power line equipment, particularly insulators or connections. Power line interference is propagated through the low voltage distribution system. This generally results in interference to TV and radio receptions.

2.8.14 Voltage notching

Notching of the voltage waveforms occur when the solid state rectifiers are short-circuited momentarily across two phases during voltage conversion when the polarity of supply voltage is reversed. The harmonic voltage distribution limits should not be exceeded at the point of common connection (PCC) for the notching to have less impact on the low voltage distribution network. The maximum depth of the notch, that is the average of start notch depth and end notch depth, should not exceed 20% of the fundamental peak voltage and the peak amplitude of oscillation due to communication at the start and end of voltage notch should not exceed 20% of the nominal fundamental peak voltage.

The notched waveform is presented in Figure 2.2 below.

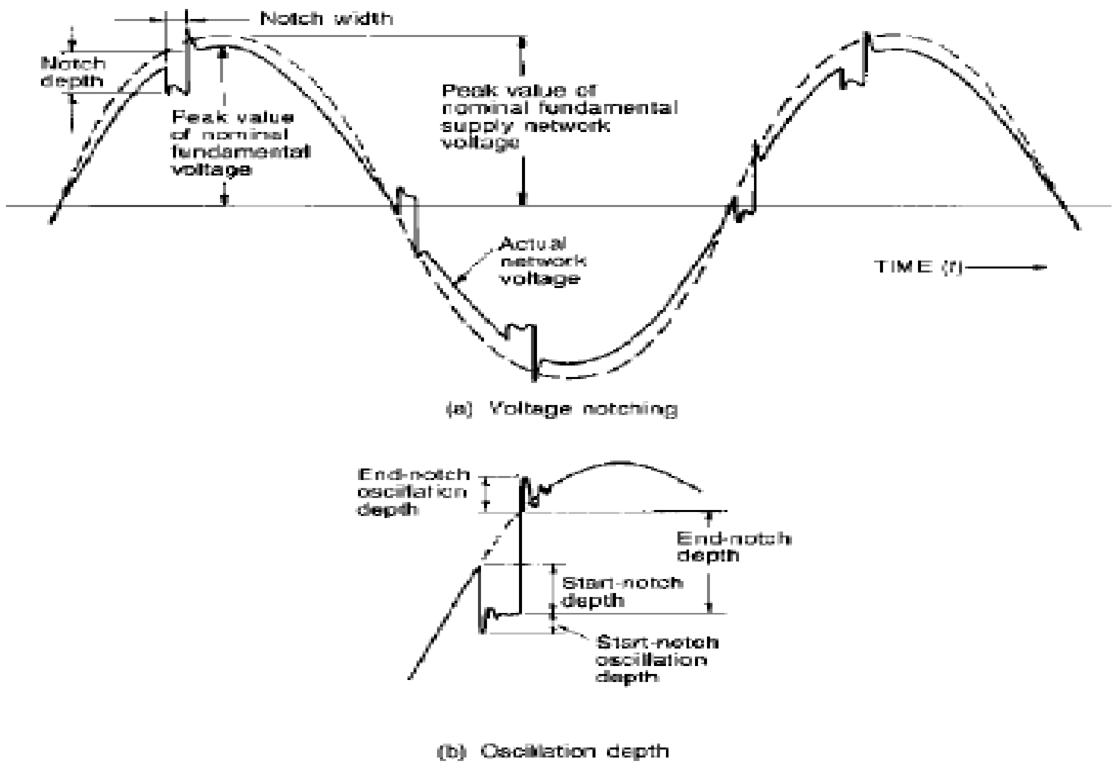

Figure 2.2 (a) Voltage notching, (b) Oscillation depth (Operational procedures: Electricity supply standards CEOP8026).

In this section, a number of performance parameters for the low voltage power distribution network were reviewed. These affect the well being of low voltage power distribution network which is normally gauged by the smooth operations of sensitive electrical equipment. If one of the performance parameter of low voltage power distribution network is affected in one way or another, sensitive electrical equipment will malfunction in their operation.

The summary of the low voltage power distribution network performance parameters is given in Table 2.1. These performance parameters determine the well being of the distribution network. Hence the performance parameters should be maintained at optimum levels for proper functioning of modern loads.

Table 2.1: Low voltage power distribution network performance parameters

No.	Performance parameter	Description, causes, penalties of performance parameter
1	Frequency of supply	Description: Frequency of supply is a measure of the rate in cycles per second (Hertz) at which the alternating voltage or current oscillate between peak forward and reverse values. Causes: Start/stop of heavy load, interruption on the generators alters the system frequency. Penalties: Malfunction, stoppage and damage of electric equipment. Tripping of protection devices, loss of information and malfunction of data processing equipment, if is excessive loss of electrical supply.
2	Supply voltage	Description: Supply voltage is the voltage available at the common point of connection accessible for all electrical devices, instrument or machines connected to the distribution line. Causes: Failure of equipment in the power system network, storms and objects striking distribution network or poles, fire or human error. Penalties: All electrical machines stop operations.
3	Voltage Fluctuations	Description: Voltage fluctuations are short duration variations in supply voltage levels. Causes: Due to changes in loads as in arc furnaces or switching of heavy loads within the distribution

		supply network. Penalties: Most penalties are noticed during undervoltages as flickering of lighting and screen, indicating unsteadiness of supply voltage.
4	Voltage dip	Description: Voltage dip or sag is a single short duration reduction in the supply of voltage levels. Causes: Short circuit faults on the Transmission or distribution network. Fault in consumer installation. Connecting of large loads or huge motor starting. Penalties: Malfunction of data processing equipment that may stall the process. Tripping of protection devices and contactors. Disconnection and loss of efficiency in electric machines.
5	Voltage Differences Neutral to Earth	Description: Unexpected voltage difference that might exist between neutral and earth conductors in a Multiple Earth Neutral (MEN) type of connection. MEN system is provided at the distribution transformer and at each consumer's installation for the purpose of personnel protection. Causes: Leakage currents. Penalties: Stoppage of sensitive electronic equipment
6	Voltage swell	Description: Voltage swell is momentarily increased of voltage at the power system frequency beyond acceptable tolerances, with duration of more than one

		cycle and less than a few seconds. Causes: Stop of heavy load, badly regulated transformer. Penalties: Stoppage or damage of sensitive electronic equipment if the voltages swell too high, data loss, flickering of lighting and screen.
7	Step and Touch Voltages	Description: During distribution network faults, substantial voltage differences referred to a step and touch voltages can occur within the ground or between metallic systems and earth, in the immediate area of the fault or associated supply equipment. Causes: Distribution network faults. Penalties: Failure, malfunction of equipment, danger of personal of being electrocuted.
8	Voltage imbalance	Description: Voltage imbalance is a voltage deviation from the average line voltage in 3-phase system in which the three voltage magnitudes or phase angles are different. Causes: Connection of huge single phase loads, incorrect distribution of single phase loads on the 3-phase power system, fault line(s). Penalties: Stoppage or damage to all 3-phase loads. The most affected loads are three phase induction machines.
9	Direct Current	Description: Direct current may flow in the alternating current neutral conductor of the low

		voltage distribution network due to consumer's equipment with non-linear load characteristics installations on the distribution network. Causes: Non-linear loads. Penalties: Corrosion of consumers' earth system.
10	Harmonics distortion	Description: Harmonics distortion is voltage/current non-sinusoidal shape waveforms. The waveform is equal to the sum of different sine waves with different magnitude and angle, having frequencies that are multiples of power system frequency. Causes: The harmonics distortion are created by consumers' equipment with nonlinear loads characteristics such as solid state rectifiers and variable speed motor drives; Arc furnaces, welding machines, rectifiers, switched mode power supplies, high efficiency lighting and data processing equipment. Penalties: Neutral overloads of 3-phase system, overheating of equipment and cables, loss of electrical machines, increased chances in occurrences of resonance, electromagnetic interferences with communication system, errors in measurements when using average reading meters, nuisance tripping of thermal protection.
11	Inter-harmonics	Description: Sinusoidal waveforms with frequencies which are not an integer multiples of the fundamental frequency are called inter-harmonics.

		The harmonics distortion are created by consumers' equipment with nonlinear loads characteristics such as solid state rectifiers and variable speed motor drives; Arc furnaces, welding machines, rectifiers, switched mode power supplies, high efficiency lighting and data processing equipment. Penalties: Neutral overloads of 3-phase system, overheating of equipment and cables, loss of electrical machines, increased chances in occurrences of resonance, electromagnetic interferences with communication system, errors in measurements when using average reading meters, nuisance tripping of thermal protection.
12	Mains Signaling Interference	Description: The main signaling interference is basically control signals injected and carried onto the distribution network at various frequencies primarily to switch appliances on and off remotely. Causes: Pollution on the supply voltage due to non-linear devices connected on the distribution network. Penalties: Failure to receive appropriate signals at the designated time can result in incorrect switching off remote devices.
13	Noise	Description: Noise is unwanted voltage or current superimposed on the low voltage distribution power system voltage or current waveform. Causes: Improper grounding, electromagnetic interference due to usage of microwaves, television diffusion and radiations due arc furnaces, welding

		machines and electronic equipment. Penalties: Disturbance on sensitive electronic equipment, loss of data and data processing errors.
14	Notching	Description: Notching of the voltage waveforms Causes: When the solid state rectifiers are short-circuited momentarily across two phases during voltage conversion when the polarity of supply voltage is reversed. Penalties: Distortion of sinusoidal waveform, reduction in efficiency.

Some consumers connect their non-linear loads to the distribution network which eventually affect fundamental performance parameters, thereby rising power quality problems. Non-linearity of loads cause disturbance to the sinusoidal voltage/current waveforms. Section 2.9 was dedicated for selection of performance parameters reviewed in section 2.8 which can be investigated using Simulink.

2.9. Selection of performance parameters

In this section, selection of performance parameters for the low voltage distribution network was conducted by referring to section 2.1. The criteria for selection of low voltage power distribution network performance parameters affected by backup battery-charging units were based on two criteria. Firstly it was done by establishing the capability of the investigation tool. The second was by obtaining information from the literature.

2.9.1 Frequency of supply

The increasing number of backup battery-charging units on the low voltage power distribution network may results in growing amount of fluctuations of active power being experienced on the low voltage power distribution network. This may lead to active power imbalance and consequently the need for additional control reserves to maintain a balance between input power and that being consumption. Small islanded systems will be highly influenced by power unbalance and as a result, the frequency of supply can suffer severe fluctuations (European Network of Transmission System Operators for electricity handbook, 2009; Sony et al., 2016). An example of an islanded system is a micro-grid detached from the main grid or operated as an autonomous system. In such systems, the frequency of supply is more sensitive to changes in power balance as the power balance changes in the distribution network; so does the frequency. This may lead to limitations on the number of backup battery-charging units connected on islanded systems and ultimately also in larger power systems. Connection of backup battery-charging units on the low voltage distribution network with uncontrolled charging schemes can cause larger power unbalances in the system which may affect the behaviour of frequency of supply. The control measures should be taken by varying the loads the same way the generating units are varied at the generating plants to match the present load demand for the distribution network.

In this study, a single backup battery-charging unit would be considered for analysis. As such a 1 backup battery-charging unit is too small to provide noticeable power difference in the system. Unless a considerable number of backup battery-charging units were connected onto the distribution system and act as a huge load (Marra et al., 2012), the frequency of supply may not be altered. The effects of a backup battery-charging unit on the frequency of supply was unnoticed because the power drawn from the low voltage distribution network was too small. As the backup battery-charging unit was charging the battery bank, the frequency of supply is not affected. Hence this performance parameter was chosen for further investigation on a model in Simulink.

2.9.2 Range of supply voltage

The low voltage power distribution network supply voltage is normally maintained at a given value. But due to unseen eventualities a range between minimum and maximum values is maintained in which connected electrical equipment/loads should operate in accordance to their design specifications. The standard requires, under normal service conditions, that the voltage at the point of common supply should not differ from the normal voltage of 230/400V by more than ±10% according to (International Electroelectrical Commission 61000-3-2, 2014). When a backup battery-charging unit was introduced on the low voltage power distribution network, supply voltage was likely change. The variation of supply voltage beyond the prescribed limits as earlier stated in this section would yield operational constraints on the electrical equipment and other nearby connected electrical components on the distribution system. The operation of the backup battery-charging unit draws current from the low voltage distribution network at a point of common connection, the phenomena that may alter the supply voltage. Simulink was capable of investigating the impact of backup battery-charging units on supply voltage. Hence, supply voltage was selected for further investigation in Simulink.

2.9.3 Voltage fluctuations

Voltage fluctuations on the low voltage distribution network were encountered due to variations of loads connected in or switching of loads within the supply network. It is probably difficult to maintain a uniform supply voltage in an operating distribution system because of feedback from the electrical equipment as they perform their respective functions. Voltage fluctuations are also caused by rapid and repetitive variations of consumer loads. Since the backup battery charger unit operates by way of converting alternating supply voltage to direct supply voltage by switching on/off of bridge diodes repetitively, a phenomenon that is likely to impact negatively on the supply voltage is created on the low voltage distribution network. As long as the backup battery charger unit is plugged-in on the distribution network the repeated switching operation continues going on, hence voltage fluctuations may be borne in this way which later traverse along the distribution network affecting other nearby consumers' equipment.

The aim of this study is to investigate how much voltage fluctuations due to backup battery charging at the point of common coupling on the low voltage power distribution network. In order to ascertain what amount of voltage fluctuation, a study will be conducted using a model is designed in Simulink to simulate the results. If the supply voltage fluctuates beyond acceptable limit, sensitive electrical devices would begin malfunctioning in their operation and that may lead to premature electrical equipment failures.

2.9.4 Voltage dip

A voltage dip or sag is the common supply disturbance causing interruption on the low voltage distribution network. The impact of voltage dips on the consumers may range from non-periodic light flickers to the tripping of sensitive loads and stalling of motors. Although the main known causes of voltage dips are short circuit faults caused by accidents, vehicles collisions, birds, wind, lightning network equipment failure or the connection of heavy loads, introduction of backup battery charging units along with their battery banks also present a new electrical loads onto a low voltage distribution network that may bring about voltage dip or sag. It is worthy to state that a single backup battery-charging unit may not develop a noticeable voltage dip on low voltage distribution network because it draws little current. But if a high penetration level of backup battery-charging units were allowed, a noticeable voltage dip may be seen on the distributions system.

Voltage dips are more prevalent in heavily loaded distribution networks and in areas where distribution transformer tap settings were set incorrectly, as the current transformer tap setting do not match with the consumers' load demand shift. Consequently, voltage dip are common in seasonal regions where communities increase in power usage during peak-season while the output of the transformer is set for the low load usage part of the season; the power requirement becomes much higher than usual resulting into unsuspected voltage dip. Voltage dip conditions can create high current being drawn from the supply line thus causing unnecessary tripping of downstream circuit breakers, dimming of lights, data errors delivery as well as overheating of motors thus imparting undue stress on the equipments which may lead to their premature break down.

In order to establish the impact of backup battery charging on voltage dips, a model formulated in Simulink would be employed to capture information regarding this performance parameter.

2.9.5 Voltage differences neutral to earth

This performance parameter was not investigated further because of inadequacy of the investigation tool.

2.9.6 Voltage transients

The process of converting alternating current to direct current which occurs in the backup battery-charging unit requires that the diodes on the bridge rectifiers be switched on/off repeatedly. The switching in the backup battery-charging units cause voltage transients on the low voltage distribution network and distort the voltage waveforms.

2.9.7 Step and touch voltages

The effect of step and touch voltages on the low voltage distribution network due to backup battery-charging units was not examined because the tool used was unable to investigate this performance parameter.

2.9.8 Voltage imbalance

Voltage imbalance is a voltage quality issue on the low voltage distribution network with high penetration level of backup battery charger units. Ideally, electric utility companies are mandated to generate and supply balanced three phase voltages on the low voltage distribution network to the consumers' satisfaction. But the voltage levels at the consumers' side may not be balanced due to uneven consumption of power from the phases.

Despite of single phase backup battery chargers being supplied from the balanced three phase system, they may not be uniformly distributed on feeder lines since a single phase battery charger only connects to single phase. Furthermore, residential consumers do not choose which line to connect their battery charging units. Consequently, one phase may have more single phase loads than others, a situation that would promote voltage unbalance in the distribution network. The situation becomes more complex to control because different backup battery-charging units may draw different amount of current from the feeder lines necessitating voltage unbalance on the distribution network. In essence the complexity of backup battery charger unit connection on the low voltage distribution network in relation to the other consumers' connectivity results in a voltage unbalance between the phases of the distribution supply system that adversely affect three phase loads consumers on the low voltage distribution network. On a distribution networks where there is dominance of single-phase or two-phase consumers, the assessed voltage unbalance may be up to 3 % (Zambia Standard 378-1, 2009). Excessive voltage unbalance in supply voltages is undesirable for consumers as it results in overheating of induction motors. In addition, voltage unbalance may be accompanied by nuisance tripping of protective devices so as to prevent burning of three phase loads and equipments.

The voltage unbalance has negative impacts on the low voltage power distribution network and the equipment connected on the distribution network. The power distribution network would heat up and experience more losses in case of unbalanced conditions. Moreover, under unbalanced conditions, the induction machines fail to operate. Furthermore, the temperature of winding conductors would be increased which results in reduced efficiency and decreased lifespan of the machines because the windings risk burnout any time. Any other electromagnetic equipment connected on the malfunctioning distribution network would suffer similar consequences just as induction motors. Voltage imbalance and voltage drop adversely affect distribution network as it hinder smooth operation of a number of electrical devices since the magnitudes of line or phase voltages are different. Uneven distribution of single phase backup battery-charging units over the three phase system causes voltage imbalance on the distribution network. Uncoordinated single phase backup battery charging would significantly increase the voltage unbalance of the distribution system. Residential consumers' backup battery-charging units connected on the low voltage distribution network reveals a high load demand which causes a high voltage drop due to battery load demands in the process of charging. The minimum voltage drop reached during the peak demand was 0.9691 per unit, 0.16% lower than the case without battery charging and higher than the lower limit of 0.90 per unit (Ahmed and Mohammed, 2005). Therefore, backup battery-charging units affect the quality of power on the distribution network and this can be transferred back to the transformers and cause lack of capacity to the electricity distribution network which results in distortion of performance parameters. Voltage drop negatively impact on the distribution conductor and increases the power losses on the on the distribution network. Voltage drop also causes equipment malfunction. On the worst case scenario, voltage drop will bring operation of the electrical equipment to a halt.

Due to the limitations of the investigation tool, this performance parameter was not further investigated.

2.9.9 Direct current

Non-linear loads consumers' equipments inherently generate direct current which flows in the neutral conductor during their operation. Direct current has the adverse affect of corroding conductors for the low voltage distribution network and consumers’ earthing system. Once the neutral and earthing conductors are destroyed not only is personnel contact protection lost, but also the distribution network could not operate single phase devices, and the distribution network becomes a hazard to the consumers. Direct current can be induced into an alternating current distribution system, often due to failure of rectifiers. Direct current can traverse along the ac power system and add unwanted current to devices already operating at their rated level. Overheating and saturation of transformers can be one of the results of circulating direct currents. When a transformer saturates, its temperature rises above normal and is unable to deliver full power to the load. The quality of the supply voltage becomes distorted; the subsequent voltage waveform distortion can create further instability in electronic load equipment. Direct current will analysed further using the model designed in Simulink software.

2.9.10 Harmonics content of voltage and current waveforms

A sinusoidal voltage is a conceptual quantity produced by an ideal alternating current generator, built with finely distributed stator and field windings, operating in a uniform magnetic field which does not exist in practice. Neither the winding distribution nor the magnetic field can be uniform in an alternating current machine. Generator voltage distortion is very small which is increased in transformers and nonlinear loads. Power electronic load causes the current to vary disproportionately with the voltage during each cyclic period. Current and voltage waveforms distortion is due to distribution network impedance between source and nonlinear load at the point of common coupling. Harmonics are generally produced by generators, transformers, nonlinear loads and the power electronic switched devices. Backup battery chargers are nonlinear load which uses electronic power switches during charging process which inevitably produce and inject harmonics current on the low voltage power distribution network. Harmonics current increase hysteresis, eddy current and core losses in generators, transformers and induction motors; even multiply line losses in the conductors and cables due to higher frequencies; causing malfunction of circuit breakers, fuses, protective relays and control systems (Masoum et al., 2011). Harmonics currents increase root mean square (rms) values which cause power losses.

Simulink software tool would be used to analyse the effects of backup battery-charging units on the low voltage distribution network, were voltage and current waveform forms distortion signifies the presence of harmonics.

2.9.11 Mains signaling interference

The main signaling is carried on the low voltage power distribution network to act upon a remote appliance either to switch it on or switch it off. The main control signal can be interfered with if the distortion on the voltage sinusoidal waveform is excessive. That would prevent the control signals from reaching the intended control unit meant to control remote equipment. If the backup battery-charging units generates high interhamonics that would act in the same way as the main control signal would, since interharmonics are also propagated on the distribution network the same way as the main signals are propagated. This would result into malfunctioning of remote equipment.

This performance parameter would not be investigated further because the investigation tool employed is unable to examine it.

2.9.12 Noise

Noise is unwanted voltage or current superimposed on the power system voltage or current waveform. Noise can be generated by power electronic devices, control circuits, arc welders, switch mode power supplies and radio transmitters. Poorly grounded sites make the system more susceptible to noise. Noise can cause technical equipment problems such as data errors, equipment malfunction, long-term component failure, hard disk failure, and distorted video displays.

Due to limitation of Simulink software being used to examine performance parameters on the low voltage power distribution network, noise was not selected for further examination.

2.9.13 Voltage notching

Simultaneous conduction of switches in an alternating current/direct current converter during the commutation period causes a two-phase short circuit via switching elements. The voltage loss that results from this short circuit in the converter voltages causes disturbances in the voltage waveform, which is called the voltage notch. These abrupt and regular changes in the voltage of the converter distort the sinusoidal voltage waveform, which causes the excitation of the natural frequencies of the electrical network. The excitation of system's natural frequencies via the voltage notch can generate noticeable oscillations in the voltage and the current characteristics of the converter (de Lima et al., 2007). These oscillations can cause some problems, such as damage to capacitor banks, parallel resonance, radio disturbances, and electronic device malfunction. The frequency and magnitude of such oscillations depend on the circuitry structure of the network, the size of the system impedance as seen from the converter bus, and the size of the capacitor banks (International Electroelectrical Commission 61000-4-7, 2014). If the capacitor banks of the network are neglected, then the capacitors of the snubber circuits will produce some high-frequency oscillations in the voltage and current waveforms (Ghandehari et al., 2007). The notch depth and area are proper indices of the voltage notch phenomenon, which is noticeable in the study and investigation of power quality. The depth of the voltage notch and its area in the converter bus depends on the impedance value between the converter and the point of common coupling (PCC), and on the system impedance, as seen from PCC. When the impedance between the converter and PCC is high, a lower value of voltage notch depth is experienced on the distribution network; as such power quality is improved. But if the impedance between converter and PCC is low, a high value of voltage notch depth is experienced resulting in low power quality.

Since the operation of backup battery-charging units highly depends on the switching on and off of solid state devices in the rectifiers there occur momentarily short circuits during the two crossover phases. The power losses during phase crossover generates short falls on the voltage and current waveforms hence, creating a notch, harmonics are also produced during the process thus distorting voltage and current waveforms. Despite all the above highlighted challenges of a backup battery-charging unit, it cannot be done away with because it is the heart of battery charging system. As a result, voltage and current waveform notching are encountered in backup battery charging, therefore notching is power quality concerns (Zambia Standard 378-1, 2009).

Notches would be investigated further by simulation using Matlab/Simulink software.

In this chapter, performance parameters for the low voltage distribution network were discussed to examine if at all, they were affected by backup battery-charging units. Tables: 2.2, 2.3 and 2.4 present summary of the performance parameters on the low voltage power distribution network.

Table 2.2: Classification of low voltage power distribution network performance parameters

No	**Steady state performance parameters**	**Transient state performance parameters**
1	Frequency of supply	Noise
2	Voltage supply	Notching
3	Voltage dip(sag)	Mains signalling interference
4	Voltage swell(rise)	Voltage fluctuations
5	Voltage unbalance	Voltage transients
6	Supply current	
7	Harmonics distortion	
8	Inter-harmonics	
9	Step and touch voltage	
10	Voltage differences between neutral and earth	
11	Direct current	

Table 2.3: Low voltage power distribution network performance parameters affected by backup battery charging.

No	Performance parameters affected by backup battery charging
1	Supply voltage
2	Supply current
3	Harmonics distortion
4	Voltage unbalance
5	Noise
6	Notching
7	Mains signaling interference
8	Direct current

Table 2.4: Low voltage power distribution network performance parameters critically affected by backup battery charging.

No	Performance parameters affected by backup battery charging
1	Supply voltage
2	Supply current
3	Voltage imbalance
4	Voltage notching
5	Direct current /voltage component

The performance parameters for the low voltage power distribution network affected by 12V dc backup battery chargers were summarized in Tables 2.3 and 2.4. A full list of performance parameters affected by backup battery chargers was captured in Table 2.3, the voltage notch presented in this table is not further investigated because the model used in Matlab/Simulink platform eliminate it, while the other transient performance parameters listed in Table 2.3 cannot easily be investigated using the Matlab/Simulink software. As such, this research would only focus on steady state performance parameters provided in Table 2.4, which are the voltage supply, harmonic distortion and voltage unbalance because these are highly affected by backup battery chargers and they can be investigated on the Matlab/Simulink software. For this reason, a further research study is suggested in which transient performance parameters could be investigated using other investigation tools.

Selected performance parameters would be subjected to a further study in Matlab/Simulink software platform to establish their affect on the low voltage power distribution networks by simulation in Chapter 3.

CHAPTER 3

MATERIALS AND METHODS

3.1 Introduction

This research was computer based focusing on electric power quality problems on low voltage distribution network due to battery charging. This chapter highlights the research design and steps taken to arrive at a conclusion on the research topic. The research design was based on two approaches the extended literature review and simulations modeling. The extended literature approach was undertaken in chapter 2 which looked at the first and second objectives; reviewed various performance parameters affected by backup battery-charging units. The simulations modeling was employed (focused o third objective) to assess performance parameters affected by backup battery-charging units.

The purpose of this research was to investigate the impact of charging of backup batteries by residential consumers on the low voltage distribution network. Therefore, this chapter outlines the general methods and methodology (specific procedures) that were used in order to achieve intended objectives.

The chapter is structured as follows: the general methods, methodology, data collation, data analysis, limitations and summary.

3.2 Research design

3.2.1 Extended literature review

The extended literature review approach was used to establish various performance parameters for the low voltage distribution network. In the extended literature review approach a lot of reading was conducted to obtain information required for the present research. In order to establish various performance parameters for low voltage distribution network , extensive reading were conducted on the recent (a) journal papers, (b) conference papers and (c) books.

To obtain quality piece of information, the researcher only considered renowned sources , mainly the IEEE materials. The information gathered were highly accurate because they were obtained from credible and reliable sources.

The information presented here lack most recent information from 2017 or 2018 publications because they were not available for the topic under consideration. However, the information gathered from various sources covered recent works which reflected the current state of affairs.

3.2.2 Simulations modeling

The simulations modeling approach was used to assess performance parameters affected by backup battery-charging units. As stated by (Hofstee, 2010) the simulations modeling attempts to capture the essence of a process by identifying key variables and creating a representation of it. Simulations are used to imitate the behaviour operation of a real-world system, where system is a collection of entities. For example, people or machines that act and interact together towards accomplishment of some logical end. The approach have wide application for both practical and theory. There are several software packages and platforms available in building simulation models. These software packages include Matlab, Matlab/Simulink , PSIM, Simplorer, Pspice, Multsim etc. The advantage of this method is that you can easily generalise the results obtained to mean similar results for another similar case of expanded or reduced scope. In this research Matlab/Simulink was preferred to the rest of available platforms because of its numerous capabilities to control and regulate simulation processes. In additional, Matlab/Simulink software is widely used for simulations based study because of its availability and advanced tools with system functionality simulation capability. Furthermore, Matlab/Simulink software was chosen to help in conducting investigation because of its reliability and easy accessibility. Matlab/Simulink software is widely accepted internationally by researchers because it known to yield accurate and reliable results once the model is set right.

However, the approach has its weaknesses. Firstly, no model is real. Therefore, a model cannot replicate real results in totality but all most the same. The other drawback is the difficulty to obtain sufficient and sufficiently complete data to build and test the model. Human error in constructing the model is another disadvantage of this method. Nevertheless, the above weaknesses were taken care of. First and foremost the components used in building the model were carefully configured. Secondly, every component was tested and found to mimic a real component. The model was suitably constructed to yield reliable results worthy being considered.

3.3 Methodology

3.3.1 Research instruments

3.3.1.1 Questionnaire

In order to ascertain how many sinetech backup battery-charging were being used in the area, a systematic questionnaire was designed as shown in appendix C. The questionnaire was meant to review sinetech backup battery- charging unit penetration level. It was also intended to confirm prevailing load shedding for justification of current research. The sinetech type of backup battery-charging units are small in size compared to the conventional type. Leading questions to describe the sinetech backup battery- charging units were designed. Such as when and where was it bought, does lighting intensity reduce in the house charging. The questionnaire was initially served onto 10 respondents of the surveyed area at random to review its clarity. It showed 100% clarity. Most of the low class residents hardly buy sinetech backup battery-charging units because of the cost involved. Therefore, a middle class residential community was chosen where they could afford to buy this type of battery charger. In this case, Buyantashi township was chosen for this survey. One hundred questionnaires were served to this residential community. The data collected was meant to establish the number of backup battery-charging units used by the residents. The number of backup battery-charging units connected at same time determine the degree to which the distribution network would be affected.

3.3.1.2 Simulation model

In the real life experiment the results of this research could have been accomplished by taking readings on a physical system at the PCC. The Fluke power quality analyzer; or oscilloscope digital analyzer could be used to determine readings of the performance parameters affected by battery-charging units.

However, on this research data was obtained from FFT analysis tool on Simulink. To that effect, initial theoretical information pertaining the components involved in construction of a model in Matlab/Simulink were collected. The main components for the model being the power source, backup battery-charging units and the battery.
To ensure that the designed model (shown Figure 3.2) was capable of achieving its aim, and third objective, all its components were configured from ideal to real with exact precision. To this effect, all the model components were configured in such a way to mimic a physical component as much as possible. For instant, the cable from PCC to the household (battery-charging unit) was assumed to be 50 meters. Hence the cable was modeled as being equivalent to resistance of 10mΩ and inductance of 0.3mH. Later on, individual the components were assembled to form a model which was used in this research. The power source was tested to ascertain its supply voltage and harmonics emissions. The supply voltage was found to be 220VAC on no-load condition and free of harmonics. This steady supply voltage was then supplied to the backup battery-charging unit. The backup battery-charging unit was tested for its output voltage, it was 12VDC.

The backup battery-charging unit under consideration had the following technical specifications shown in Table 3.1.

Table 3.1: Technical specification for backup battery charging unit - model

NO	DESCRIPTION	LIMIT
1	Input voltage	220V AC
2	Frequency	50Hz

3	Output voltage	12V DC
4	Current	10A

To obtain data using the model, 10 separate computer based experimental investigations were conducted. The examinations were focused on supply voltage drop, voltage and current THD and DC components produced by backup battery-charging units at the PCC. A computer based power system model was designed and implemented in Simulink. The block diagram for model is shown in Figure 3.1, while the implementation circuit diagram is shown in Figure 3.2. The first experiment was setup and conducted by applying the model shown in Figure 3.2. In this research work, examination of performance parameters affected by backup battery-charging units was restricted by the capability of the Matlab/Simulink software used.

Figure 3.2 was used to obtain simulation results for the first experiment. The other experiments were setup by adding an extra backup battery-charging unit in parallel to the previous experimental setup from 1 to 10.

The measurements of voltage drop, voltage and current THD and DC component were conducted at the PCC. For other experimental setups 2-4, see Appendix G

The following were the steps taken to assess performance parameters of a low voltage distribution network using simulation model:

Experiment 1:

In the first experiment a model involving supply voltage (power source), 1 backup battery-charging unit and a battery was setup as shown in Figure 3.1 on Simulink platform. The model was run to obtain simulation results for the voltage drop, voltage and current total harmonic distortions and the direct components. The results were captured on the Fast Fourier Transform (FFT) analysis unit which represented 10 cycles of operation. These results were recorded.

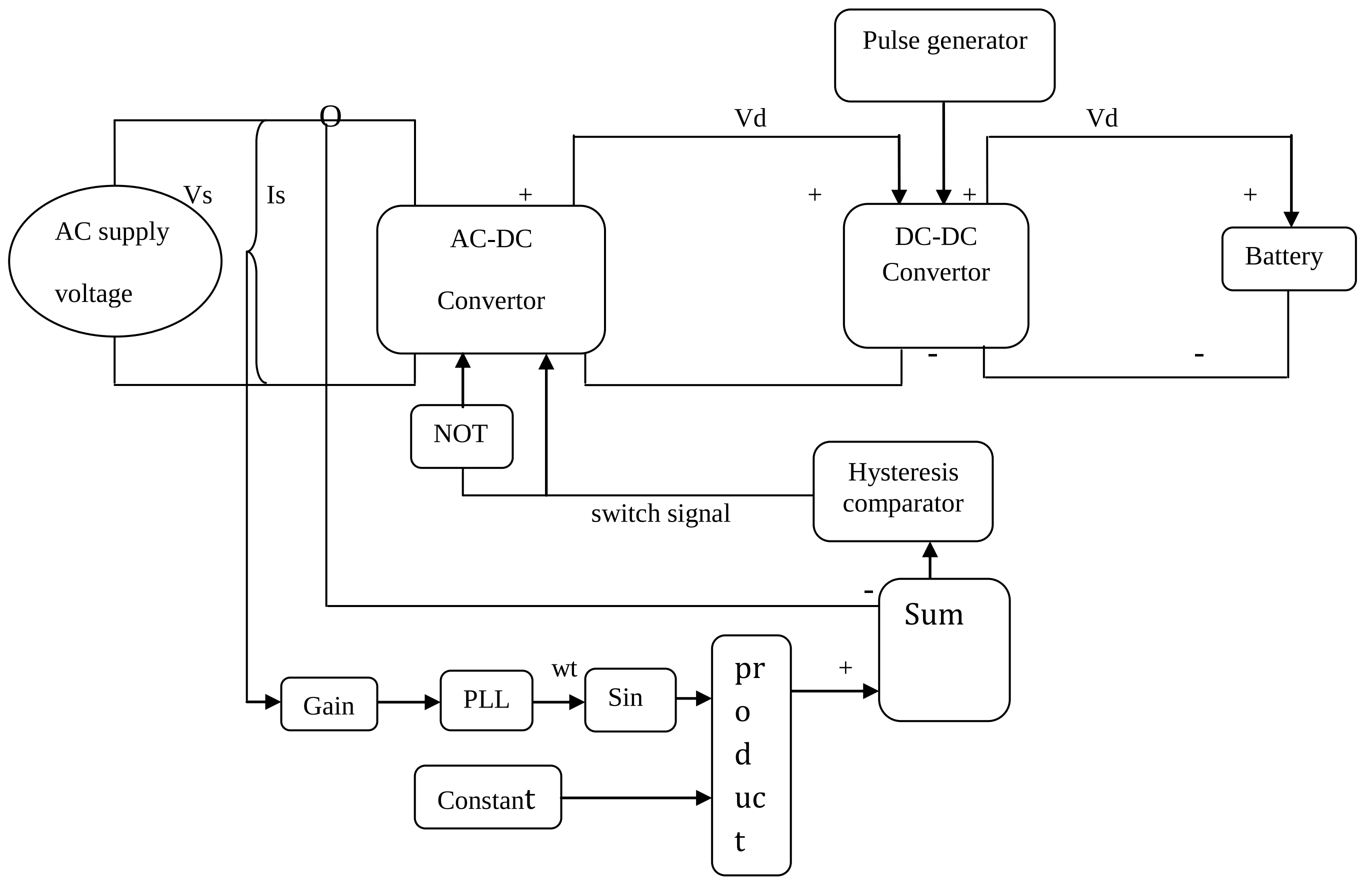

Figure 3.1 Backup battery-charging unit block diagram; where V_s=supply voltage; I_s=supply current; V_d= direct voltage; PLL=phase locked loop; wt=angular velocity; AC=alternating current; DC=direct current.

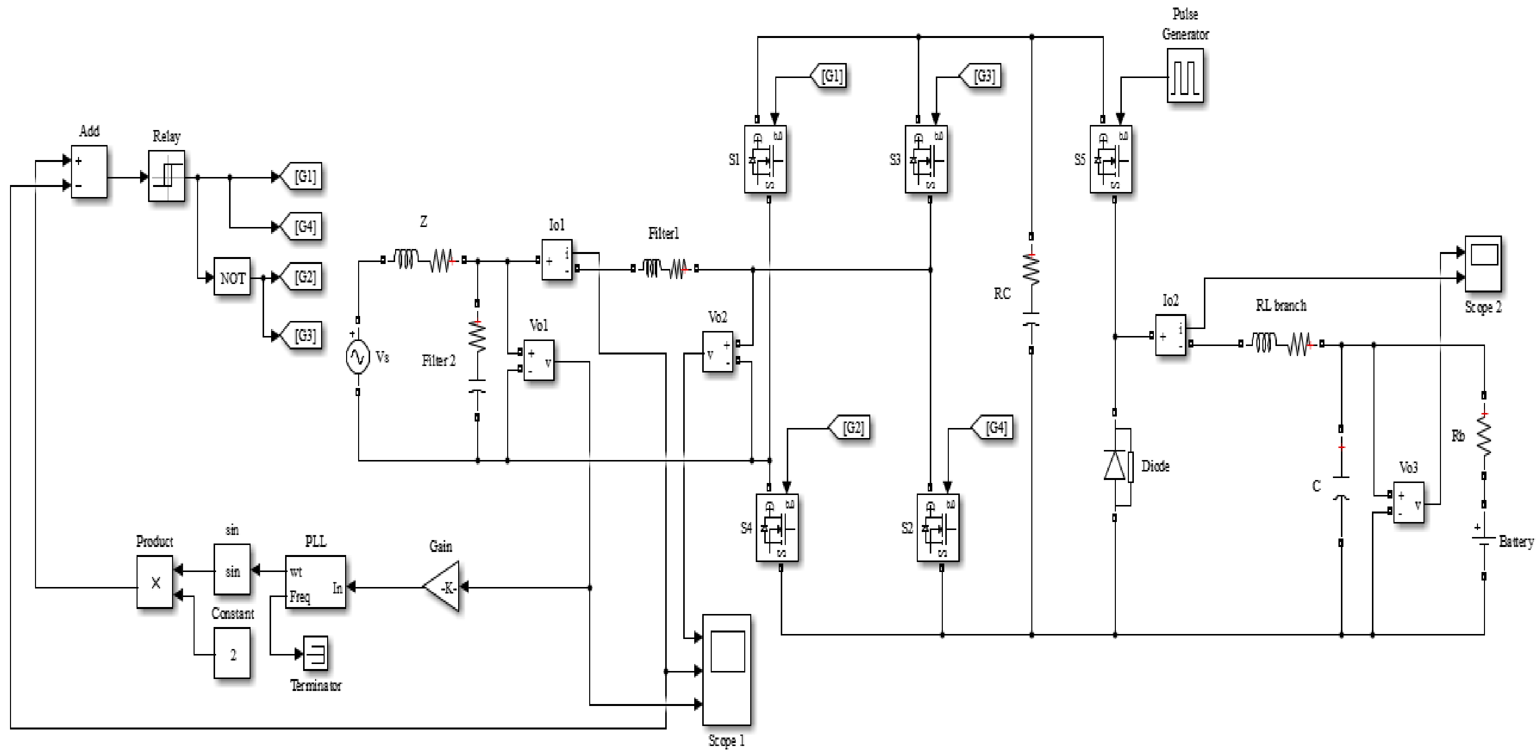

Figure 3.2 **Experimental setup for 1 backup battery-charging unit** implementation circuit diagram ; where Vs=supply voltage; Z= line impendence; Io1, Io2=Ammeter; Vo1,Vo2,Vo3=Voltmeter; RC=resistor capacitor branch; RL=resistor inductor branch; C=capacitor; Rb=internal battery resistor; S1,S2,S3,S4,S5=Mosfet; PLL=phase locked loop; wt=angular velocity; Freq= frequency

Experiment 2:

For the second experiment a model involving supply voltage (power source), 2 backup battery-charging units and a battery was setup as shown in Figure F2, Appendix F. The model was run to obtain simulation results for the voltage drop, voltage and current total harmonic distortions and the direct components. The results were captured on the Fast Fourier Transform (FFT) analysis unit which represented 10 cycles of operation. These results were recorded.

Experiment 3:

In the third experiment a model involving supply voltage (power source), 3 backup battery-charging units and a battery was setup as shown in Figure F3 Appendix F. The model was run to obtain simulation results for the voltage drop, voltage and current total harmonic distortions and the direct components. The results were captured on the Fast Fourier Transform (FFT) analysis unit which represented 10 cycles of operation. These results were recorded.

Experiment 4:

In the fourth experiment a model involving supply voltage (power source), 4 backup battery-charging units and a battery was setup. The model was run to obtain simulation results for the voltage drop, voltage and current total harmonic distortions and the direct components. The results were captured on the Fast Fourier Transform (FFT) analysis unit which represented 10 cycles of operation. These results were recorded.

Experiment 5:

In the fifth experiment a model involving supply voltage (power source), 5 backup battery-charging units and a battery was setup. The model was run to obtain simulation results for the voltage drop, voltage and current total harmonic distortions and the direct components. The results were captured on the Fast Fourier Transform (FFT) analysis unit which represented 10 cycles of operation. These results were recorded.

Experiment 6:

In the sixth experiment a model involving supply voltage (power source), 6 backup battery-charging units and a battery was setup. The model was run to obtain simulation results for the voltage drop, voltage and current total harmonic distortions and the direct components. The results were captured on the Fast Fourier Transform (FFT) analysis unit which represented 10 cycles of operation. These results were recorded.

Experiment 7:

In the seventh experiment a model involving supply voltage (power source), 7 backup battery-charging units and a battery was setup. The model was run to obtain simulation results for the voltage drop, voltage and current total harmonic distortions and the direct components. The results were captured on the Fast Fourier Transform (FFT) analysis unit which represented 10 cycles of operation. These results were recorded.

Experiment 8:

In the eighth experiment a model involving supply voltage (power source), 8 backup battery-charging units and a battery was setup. The model was run to obtain simulation results for the voltage drop, voltage and current total harmonic distortions and the direct components. The results were captured on the Fast Fourier Transform (FFT) analysis unit which represented 10 cycles of operation. These results were recorded.

Experiment 9:

In the ninth experiment a model involving supply voltage (power source), 9 backup battery-charging units and a battery was setup. The model was run to obtain simulation results for the voltage drop, voltage and current total harmonic distortions and the direct components. The results were captured on the Fast Fourier Transform (FFT) analysis unit which represented 10 cycles of operation. These results were recorded.

Experiment 10:

In the tenth experiment a model involving supply voltage (power source), 10 backup battery-charging units and a battery was setup. The model was run to obtain simulation results for the voltage drop, voltage and current total harmonic distortions and the direct components. The results were captured on the Fast Fourier Transform (FFT) analysis unit which represented 10 cycles of operation. These results were recorded.

The results from all the 10 experiments were tabulated. The graphs were drawn, which were later used to obtain Microsoft excel curve-fitting equations. The equations were used to extrapolate results up to 50 backup battery-charging units. Since the Matlab/Simulink software used in the experiments was unable to process more than 10 backup battery-charging units.

3.4 Data collection

3.4.1 Extended literature review

Data collected in the literature search reviewed various performance parameters on the low voltage distribution network. Performance parameters affected by the backup battery charging units were selected. Selected performance parameters were chosen for investigation depending on the capabilities of Matlab/Simulink software. To this effect, some performance parameters affected by backup battery-charging units were not chosen for assessment. Finally, the voltage drop, voltage and current THD and DC components were selected for examination.

3.4.2 Questionnaire

One hundred questionnaires were served to a residential community which represented 40% of the households in the area surveyed. The data obtained from the questionnaires reviewed that 20 households own smart battery-charging units in that community. Five out of 100 questionnaires served were not collected because they were misplaced in the process. Uncollected questionnaires could have introduced a small error in results obtained. However, the data collected was big enough to generate reliable information because it was based on simple and straight forward questionnaire.

3.4.3 Simulation modelling

Data collected from 10 experimental simulations were a representation of the impact of smart backup battery-charging units because other electrical loads were excluded. The voltage drop, voltage and current THD results reflected the effects of backup battery-charging unit on the low voltage distribution network. The sample size was low to yield reasonable results on which to base the final conclusion. That was due to the limitation of the Matlab/Simulink software used in this study. Therefore, the results from 10 experiments were extrapolated up to 50 backup battery-charging units using Microsoft excel tools. The Microsoft excel trend lines is capable of developing smooth curve- fitting equations from as low as 3 points. In this research, 10 points obtained from simulations were considered to produce curve-fitting equations. A sample size of 50 backup battery-charging units was reasonable enough to represent urban residential community. The results from 50 backup battery-charging units was used to arrive at a balanced conclusion.

3.5 Data analysis

3.5.1 Extended literature review

Data collected from the extended literature review were textually analysed.

3.5 .2 Questionnaire

Data collected from the questionnaire were textually analysed.

3.5.3 Simulations modeling

Data collected from simulations for each experiment was analysed quantitatively by using simple statistical analysis to interpret and draw some inferences. Quantitative data was transferred into Microsoft excel sheets, from which graphs were then plotted for analysis. Simulation results obtained by using Simulink models were compared with the results stipulated in IEEE 519 standards and the Zambian Standards 378 for voltage drop and harmonics emissions. The comparisons of results helped to draw up conclusions on the research topic.

3.6 Limitations

Physical experiments were not conducted on physical smart backup battery-charging units because the owner of equipment did not permit to carry out measurements. Gathering of battery chargers to setup physical experimental arrangements as those shown in simulation experimental setups 1-10 were not feasible because of its complexity. This was because the owners backup battery-charging units were scattered all over the area. The other limitation on this research was that pointed out by (Pawlikowski, 2002) of the collected sample size of the output data can be too small. Because of that, it may not represent real world system. Despite of the limitations mentioned above, simulations results were worthwhile because they were obtained from a model precautionary constructed, tested and used proper of simulation output analysis.

3.7 Conclusion

As shown in Figure 3.3, the sequence of steps in simulations modeling approach for chapter 3 is displayed. This the road map, it depicts all the necessary steps for easy follow up what was done.

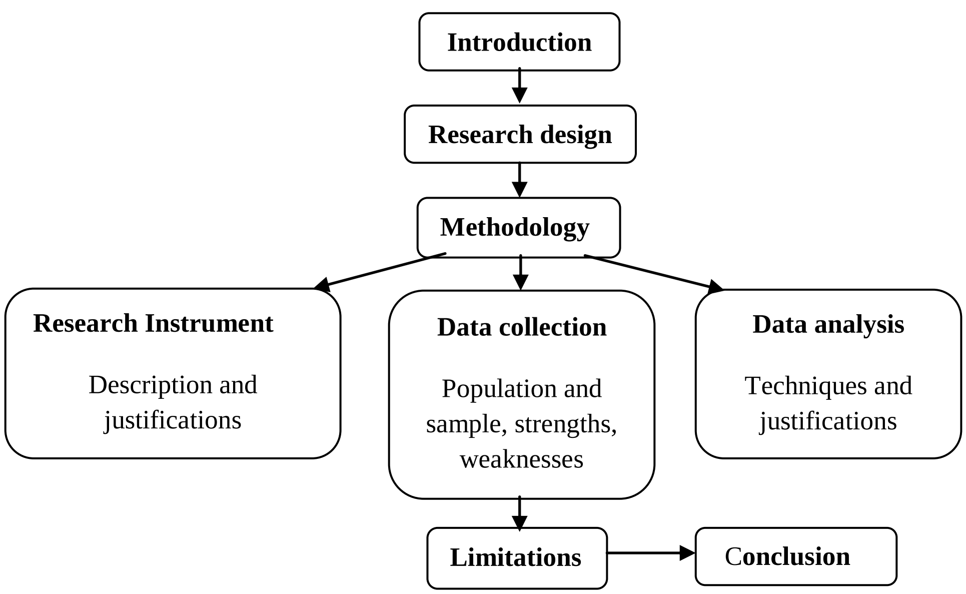

Figure 3.3 Material and Method flow chart

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter is divided into three parts. The first part reviews and discusses various performance parameters on the low voltage power distribution network, the second part discusses selected performance parameters which were examined using Simulink. Thirdly, the chapter discusses the simulation results obtained in the experiments conducted based on a model designed in Simulink. Furthermore, the chapter discusses extrapolated results. The conclusions were drawn up by comparing results obtained from experiments with the standard specifications stipulated in IEEE 519 standard.

4.1 Review of performance parameters

The reviewed performance parameters were supply voltage, supply current, harmonics, voltage dip, voltage swell, voltage notch, voltage imbalance, voltage transient, spikes, noise, voltage fluctuations, main signalling interference and direct current. These performance parameters were divided into two groups, that is fundamental and non- fundamental performance parameters. Fundamental performance parameters are the supply voltage and supply current, while the rest are non-fundamental performance parameters.

Both fundamental performance parameters and some non-fundamental performance parameters are affected by backup battery-charging units as found from literature. Some of the non-fundamental performance parameters are not affected by backup battery-charging units. Non-fundamental performance parameters affected by backup battery-charging unit are the voltage imbalance, voltage notch and the dc component. Non-fundamental performance parameters not affected by backup battery-charging units are the voltage dip, voltage swell, spikes, voltage fluctuation, noise and the main signalling interference. Non-fundamental performance parameters which are not affected by backup battery-charging units are not discussed furthermore in this research work. Furthermore, some non- fundamental performance parameters unable processed by Simulink; these are voltage imbalance and voltage notch. Voltage imbalance was unable to be examined because only 1 phase out of 3 phases is being used to run the model. Voltage notch unable to be examined due to the type of switching devices being used in the model which do not promote notches.

Reviewed performance parameters affected by backup battery-charging units are discussed below as follows: supply voltage drop, harmonics, supply voltage and current dc component.

4.1.1 Supply voltage drop

Backup battery-charging units depend on the supply voltage drawn from the distribution network for its operation. The supply voltage should be supplied at fairly constant value throughout for efficient operation of devices connected to the distribution network. However, during battery charging, the supply voltage at PCC is reduced. For example, if multiple backup battery-charging units were allowed to be connected on the distribution network, supply voltage is expected to drop. Eventually a point is reached at which the voltage drop produced on the distribution network would more than 10%, the value at which power quality would be affected.

4.1.2 Supply voltage and current total harmonic distortions

4.1.2.1 Supply voltage total harmonic distortion

Backup battery-charging units converts alternating current supply to direct current supply suitable for battery (battery bank) charging. During convention of voltage, harmonics are produced on the distribution network. Therefore, when the voltage harmonic components interacts with the fundamental supply voltage; the fundamental supply voltage is affected. Distorted supply voltage affects the operation of equipment in neighbourhood connected on the same PCC of the distribution network. With the increase of backup battery-charging unit usage by the residential consumers, supply voltage total harmonic distortion would increase probably exceeding acceptable THD level of 5% according to IEEE 519 standard. If the supply voltage THD goes beyond 5% it would require correction measures to keep the values within acceptable levels. The supply voltage THD higher than 5% affects electrical equipment as they may start malfunctioning due to poor quality of supply voltage.

4.1.2.2 Supply current total harmonic distortion

Backup battery-charging units converts alternating current supply to direct current supply suitable for battery (battery bank) charging. During convention of current, harmonics are produced on the distribution network. Therefore, when the current harmonic components interacts with the fundamental supply current; the fundamental supply current is affected. Distorted supply current affects the operation of equipment in neighbourhood connected on the same PCC of the distribution network. With the increase of backup battery-charging unit usage by the residential consumers, supply current total harmonic distortion would increase probably exceeding acceptable THD level of 5%. The supply current THD of less than or equal to 5% is acceptable according to IEEE 519 standard. If the supply current THD goes beyond 5% it would require correction measures to keep it within acceptable levels. Supply current THD higher than 5% affects sensitive electrical equipment as they may start malfunctioning due to poor quality of supply current.

Distorted supply current is a problem because it degrades the quality of power on the distribution network. The pollution of supply current due to backup battery-charging also affects other electrical consumers on the distribution network. Utility companies whose mandate is to supply pollution free power are forced to correct the situation to normal at a cost.

The level of supply current distortion caused by backup battery would be examined in section 4.3.

4.1.3 Supply voltage and current DC components

The non-linear switching devices such as backup battery-charging unit inevitably produce dc voltage and current components on the distribution network. The dc current component untimely imposed on the ac network is undesirable because it overloads and heats up the distribution line conductors. Consequently, the line protection devices may trip because the dc component could signal the presence of fault current.

4.2 Selected performance parameters

Based on the 14 performance parameters reviewed in chapter 3.1 and also shown in Table 3.1, some performance parameters were found to be affected by backup battery charging, while others were not. Performance parameters which were found to be affected by backup battery-charging units were identified in section 4.1 as the supply voltage, supply current, harmonics, voltage notch, noise, main signaling interference, voltage imbalance, and the direct current. Of the 8 performance parameters indentified as being affected by backup battery-charging units. Three performance parameters out of 8 were selected for examination in Simulink using a model shown in Figure 3.5. Those selected for examination were the supply voltage drop, harmonics and dc components. The voltage imbalance and voltage notch were not selected for examination due to software limitation.

The results of performance parameters selected for examination in Simulink are shown and discussed in section 4.3.

4.3 Assessment of selected performance parameters

The examination of selected performance parameters were conducted using Simulink so as to establish their impact on the low voltage distribution network. Simulation results were obtained by running the model shown in Figure 3.5.

Ten sets of models were prepared for examining the impact of backup battery-charging units on the selected performance parameters. The first model comprised of 1 backup battery-charging unit, the second model comprised of 2 backup battery-charging units, the third model comprised of 3 backup battery-charging units. The fourth model comprised of 4 backup battery-charging units and the fifth model comprised of 5 backup battery-charging units. The list of models goes on up to the tenth. The software used in this research work was unable to process more than 10 backup battery-units at the same time. Therefore, extrapolation was used to determine the supply voltage drop, supply voltage and current THD of 20 backup battery-charging units own by Buyantashi resident in Kitwe.

In this dissertation, only three sets of experimental simulation results for 1, 3 and 10 backup battery-charging unit connections are displayed. But the rest of simulation results are shown in the Tables 4.1, 4.3 and 4.5,while extrapolated values are shown in the Tables 4.2, 4.4 and 4.6.

4.3.1 Supply voltage drop

4.3.1.1 Supply voltage drop: Simulation results

The supply voltage drop produced by 1 backup battery-charging unit was 310.6V (0.13%) as shown in Figure 4.1. But, before the backup battery-charging unit was switched-on, the supply voltage(peak) was 311V. Only highly sensitive electric equipment connected on to the same distribution line as to where the backup battery-charging unit was connected could react to such a small voltage variation. Generally speaking, such voltage variation did not affect the operation of other devices connected on to the same distribution line where the backup battery-charging unit was connected. Since the supply voltage drop obtained was far below the minimum value of 10% of its fundamental value as guided by the Zambian standard, the supply voltage was of high quality. As far as the standard measure is concerned, the supply voltage drop did not warrant any mitigation because it was far below the critical value.

One backup battery-charging unit connected to the distribution network was unable to produce a noticeable supply voltage drop as shown in Figure 4.1. Therefore, supply voltage produced by 1 backup battery-charging unit did not affect the distribution network beyond limit. The supply voltage remained basically the same during battery charging process.

The voltage drop of 0.13% could not be noticed by consumers because most equipment operate normally. Therefore, 1 backup battery-charging units does not produce supply voltage drop that would affect the distribution network.

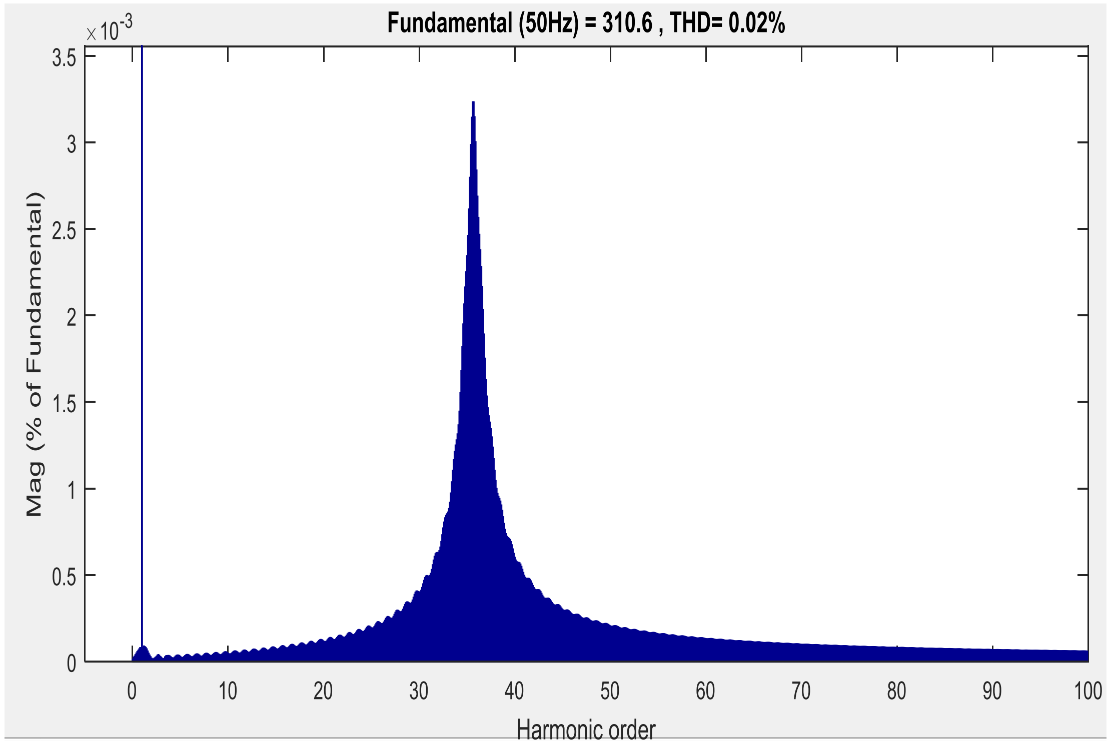

Figure 4.1: Supply voltage drop and harmonic spectra for 1 battery-charging unit; where 310.6=supply voltage(peak) drop; THD= total harmonic distortion; obtained from Simulink software.

To further examine the impact of backup battery-charging units on supply voltage drop, the number of backup battery-charging units were increased consecutively from 1 to 10.

The supply voltage reading for 3 backup battery-charging units was 309.0V (0.64%) shown in Figure 4.2. Before the backup battery-charging units were switched-on, the supply voltage(peak) reading was 311V.

The supply voltage drop of 0.64% was far below the minimum standard specification that would affect the distribution network. Therefore, 3 backup battery-charging units does not produce supply voltage drop that would affect the distribution network because equipment were not affected.

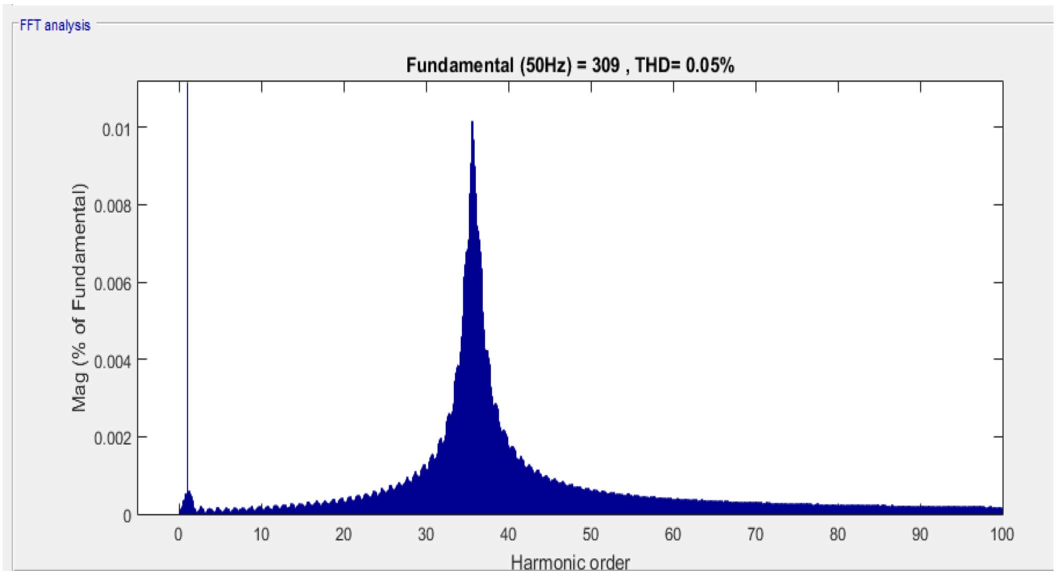

Figure 4.2: Supply voltage drop and harmonic spectra for 3battery-charging units; where 309=supply voltage(peak) drop; THD= total harmonic distortion; obtained from Simulink software

The supply voltage reading at the PCC for the operating 10 battery-charging units was 303.3V (2.48%) shown in Figure 4.3. The supply voltage drop of 2.48% was within the safe standard limit of 10% according to Zambian Standards 378-1.

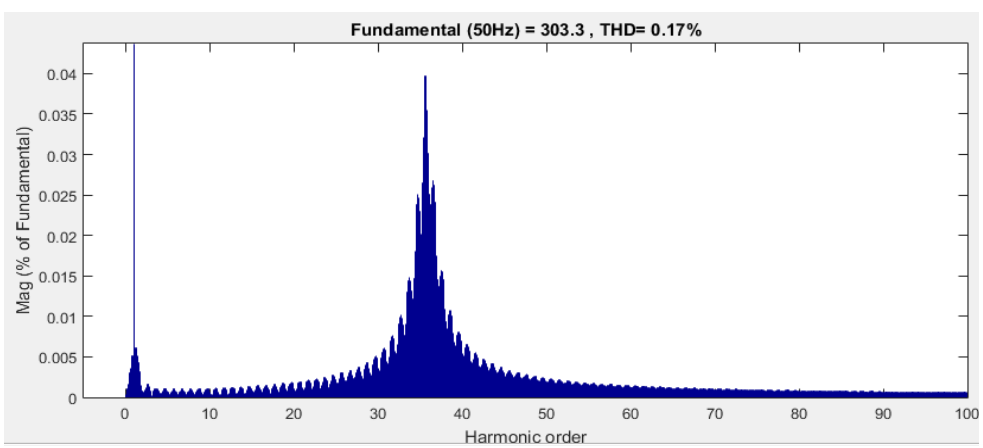

Figure 4.3: Supply voltage drop and harmonic spectrum for 10 battery-charging units; where 303.3=supply voltage(peak) drop; THD= total harmonic distortion; obtained from Simulink software.

Ten backup battery-charging units connected to the same distribution network produced a supply voltage drop of 303.3V. In terms of percentage, the supply voltage drop was 2.48%. It was safe for 10 residential consumers to connect and operate their battery-charging units at the same time because they produced supply voltage drop which falls within standard specification.

The supply voltage drops (%) obtained from 10 different experiments involving 10 different numbers of backup battery-charging units are as outline in Table 4.1.

Table 4.1: Simulation results for 1-10 backup battery-charging units at the point of common coupling.

		THD		**DC component**	
No Battery Charger	**Voltage drop (%)**	**Voltage (%)**	**Current (%)**	**Voltage (V)**	**Current (A)**
1	0.13	0.02	0.41	0.0000318	0.00002763
2	0.39	0.03	0.42	0.0000755	0.00004352
3	0.64	0.05	0.44	0.0001369	0.00006005
4	0.90	0.06	0.45	0.0002029	0.00007559
5	1.16	0.08	0.47	0.0002861	0.00009187
6	1.42	0.1	0.5	0.0003806	0.00010765
7	1.71	0.11	0.52	0.0004857	0.00012491
8	1.96	0.13	0.55	0.0006061	0.00014174
9	2.22	0.15	0.58	0.0007315	0.00015865
10	2.48	0.17	0.61	0.0008757	0.00017417

The supply voltage drops obtained for up to 10 backup battery-charging units were all below 10% as shown in Table 4.1. The supply voltage drop obtained for 10 backup battery-charging was 2.48%. If the supply voltage drop exceeds 10%, mitigation measures would be required so as to keep the values below 10%. The voltage drop results shown in Table 4.1 were translated into a graph shown in Figure 4.4.

Ten backup battery-charging units connection produced little voltage variation which all were within the standard specification. Hence, supply voltage on the low voltage distribution network was still of high quality.

The voltage drop produced increases as the number of backup battery-charging units were increased (as shown Figure 4.4). Excel software was used to generate equation shown in Figure 4.5. The equation was afterwards used to obtain extrapolated values for up to 50 backup battery-charging units. The values obtained reviewed that 39 backup battery-charging units would be required to produce voltage drop equal to 10%.

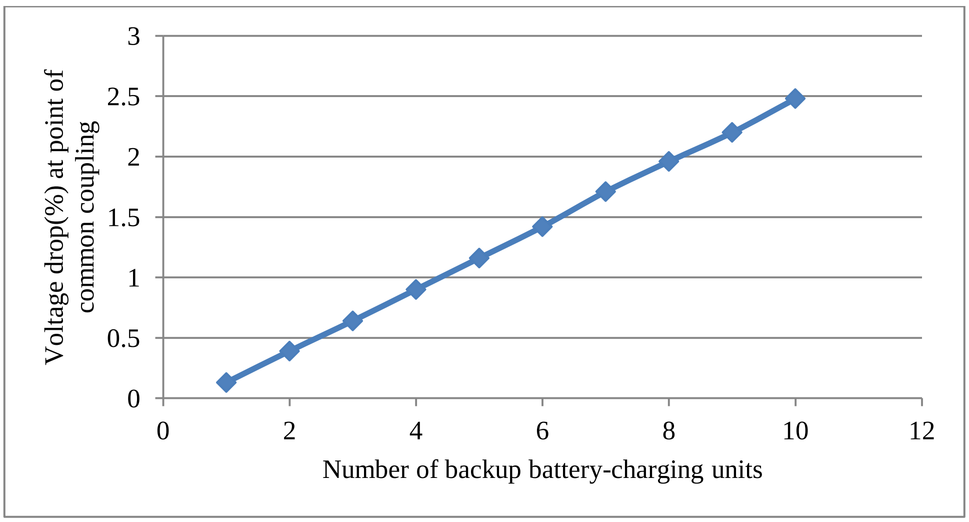

Figure 4.4: Supply voltage drop at the point of common coupling for 1 to 10 backup battery-charging units.

From Figure 4.4 it shows that the supply voltage drop increases linearly as the number of the backup battery-charging units increase.

Figure 4.5 shows a linear equation which was generated by excel software. The equation(1) fitted very well on the simulated supply voltage drop values for up 10 backup battery-charging units. The equation(1) was used to calculate extrapolated values by simply replacing the number of backup battery-charging units.

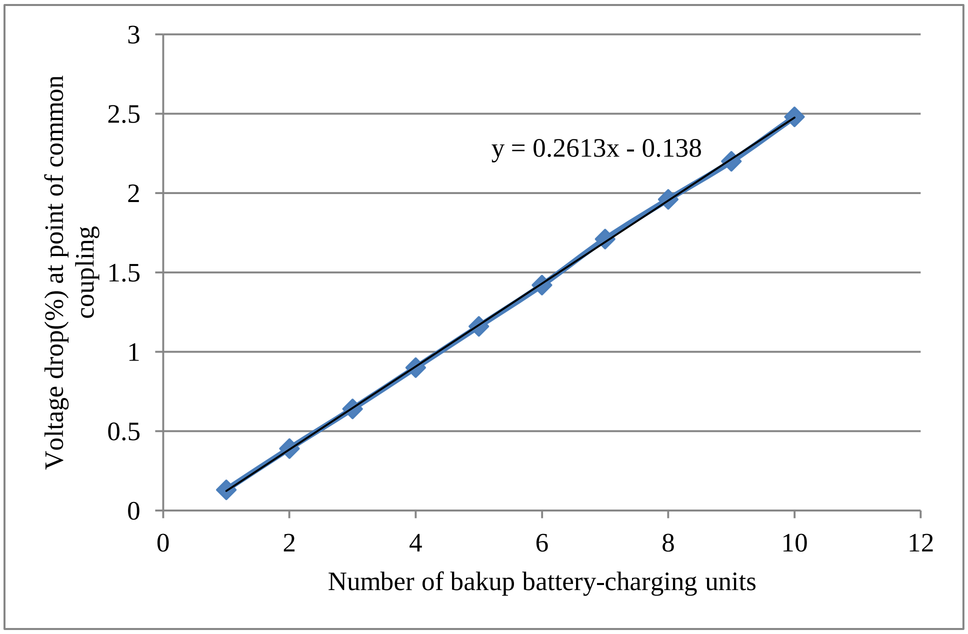

Figure 4.5: Supply voltage drop at the point of common coupling for 1 to 10 backup battery-charging units indicating curve fitting equation generated in excel.

$y = 0.2613x - 0.138$..9

In equation 9; where y= calculated voltage regulation; x= a variable representing the number of backup battery-charging units; 0.2613=coefficient of x; -0.138= constant at the y-axis crossing.

4.3.1.2 Extrapolated results

Below is Table 4.2 which shows extrapolated results for the voltage drop, THD and DC components for 8-50 battery-charging units.

Table 4.2: Extrapolation results for 8-50 backup battery-charging units at the point of common coupling

		THD		**DC component**	
No Battery charger	**Voltage drop (%)**	**Voltage (%)**	**Current(%)**	**Voltage(V)**	**Current(A)**
8	1.95 (1.96)	0.13 (0.13)	0.55 (0.55)	0.0006061	0.00014174
9	2.21 (2.22)	0.15 (0.15)	0.58 (0.58)	0.0007315	0.00015865
10	2.48 (2.48)	0.17 (0.17)	0.61 (0.61)	0.0008757	0.00017417
11	2.74	0.18	0.63	0.0009713	0.00019423
12	3.00	0.20	0.66	0.0011021	0.00021041
13	3.26	0.22	0.69	0.0012382	0.00022463
14	3.52	0.23	0.72	0.0013781	0.00023993
15	3.78	0.25	0.75	0.0015232	0.00025953
16	4.04	0.27	0.79	0.0016723	0.00027423
17	4.30	0.28	0.82	0.0018264	0.00028923
18	4.57	0.30	0.86	0.0019845	0.00030797
19	4.83	0.32	0.9	0.0021457	0.00032423
20	5.09	0.33	0.94	0.0023114	0.00034212
21	5.35	0.35	0.99	0.0024809	0.00035423
22	5.61	0.37	1.03	0.0026541	0.00037423
23	5.87	0.38	1.08	0.0028307	0.00038923
24	6.13	0.40	1.13	0.0030109	0.00040423
25	6.40	0.42	1.18	0.0031946	0.00041923
26	6.66	0.43	1.24	0.0033815	0.00043813
27	6.92	0.45	1.29	0.0035718	0.00045523

28	7.18	0.47	1.35	0.0037652	0.00047423
29	7.44	0.48	1.42	0.0039618	0.00049622
30	7.70	0.50	1.48	0.0041614	0.00051213
31	7.96	0.52	1.55	0.0043641	0.00052423
32	8.22	0.53	1.62	0.0045697	0.00054425
33	8.48	0.55	1.7	0.0047783	0.00056433
34	8.75	0.57	1.77	0.0049897	0.00057923
35	9.00	0.58	1.85	0.0052039	0.00059623
36	9.27	0.60	1.94	0.0054209	0.00061403
37	9.53	0.62	2.03	0.0056406	0.00062523
38	9.79	0.63	2.13	0.0058631	0.00064421
39	10.05	0.65	2.22	0.0060881	0.00066223
40	10.31	0.67	2.33	0.0063158	0.00068423
41	10.58	0.68	2.43	0.0065461	0.00069923
42	10.84	0.70	2.55	0.0067789	0.00071627
43	11.10	0.72	2.66	0.0006061	0.00014174
44	11.36	0.73	2.79	0.0007315	0.00015865
45	11.62	0.75	2.91	0.0008757	0.00017417
46	11.88	0.77	3.05	0.0009713	0.00019423
47	12.14	0.78	3.19	0.0011021	0.00021041
48	12.40	0.80	3.34	0.0012382	0.00022463
49	12.67	0.82	3.49	0.0013781	0.00023993
50	12.93	0.83	3.65	0.0015232	0.00025953

In Table 4.2 the supply voltage drop shown in brackets for 8,9 and 10 are simulation results, whilst the rest of the results not in brackets are extrapolated values (8- 50 backup battery-charging units).

Extrapolated values reviewed 39 (shown Table 4.2) as the maximum number of backup battery-charging units to be connected simultaneously to avoid exceeding supply voltage drop limit of 10%.

Figure 4.6 below shows the graph for the supply voltage drop against battery-charging units.

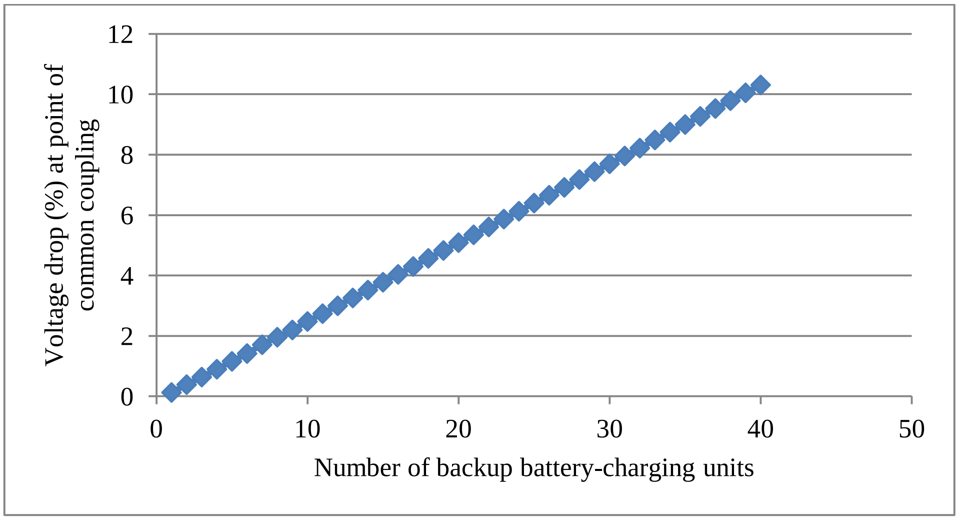

Figure 4.6: Supply voltage drop at the point of common coupling for 1 to 40 backup battery-charging units - indicating maximum charging units required to attain maximum allowable voltage drop of 10% .

Figure 4.7 below shows supply voltage drop graph for up to 50 backup battery-charging units. If 50 backup battery-charging were operated at the same time, it would produce supply voltage drop of 12.93%. It was not safe to connect 50 backup battery-charging units at the same time they produce supply voltage drop more than 10%.

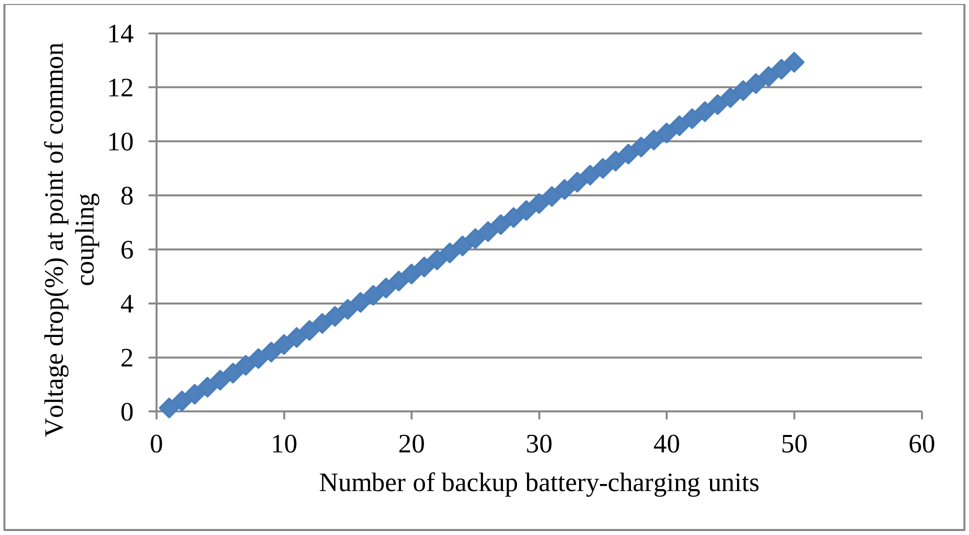

Figure 4.7: Supply voltage drop at the point of common coupling for 1 to 50 backup battery-charging units.

Twenty backup battery-charging units found in Buyantashi township would be safe to operate at the same time because they would produce voltage drop of 5.09%. The value is below 10%, implying that it would be safe to operate them all at the same time without affecting the distribution network.

Extrapolated values in Table 4.2 shows that 39 backup battery-charging units would produce maximum permissible supply voltage drop of 10%.

Therefore, the maximum number of backup battery-charging units required to be operated at the same time was found to be 39.

4.3.2 Supply voltage and current total harmonic distortion

4.3.2.1 Supply voltage total harmonic distortion - simulation results

During the process of ac voltage convention to dc voltage, the backup battery-charging unit produced harmonics which would affect power quality on the low voltage power distribution network. The supply voltage total harmonic distortion (THDv) of 0.02% was produced by 1 backup battery-charging unit as shown in Figure 4.1. When the supply voltage waveform interacts with the harmonics, the supply voltage become affected.

A very small supply voltage THD was observed at the point common of coupling; as such the power quality was unaffected. In such a circumstance, the distribution network was negligibly polluted and no harmonics disturbances were felt on nearby residential consumers' equipment connected on the same distribution line. The main harmonic component observed on the supply voltage was the 36th harmonic to the value of 0.005% of its fundamental supply voltage, the value which had no bearing on the supply voltage. The low pass filter removed all the odd harmonics (for example, 3rd, 5th, and 11th etc) which if present would severely affect the supply voltage waveform.

The supply voltage THD produced was far below the minimum level of 5% of fundamental component as stipulated in IEEE 519 standard.

From Figure 4.1 simulation results, the supply voltage harmonic distortion caused by 1 backup battery-charging unit was within the safe limit. It was concluded that 1 backup battery-charging unit had very little effect on the supply voltage. Although it was difficult to make final conclusion as to what amount of THD would be produced if the number of backup battery-charging units utilisation was raised to 50. Fifty was chosen as a realistic number to present an urban Zambian residential community for the purpose of this research work.

In Figure 4.2, the THDv of 0.05% was produced by 3 backup battery-charging units. The THDv produced was far less than the minimum value 5% stated in the IEEE 519 standards which if exceeded would require mitigation. Low harmonic components such as 3^{rd} to 12^{th} were all filtered, but 36^{th} harmonic managed to escape to the distribution network. The magnitude of THDv produced was too small to affect the distribution network.

It was concluded that 3 backup battery-charging units could not produce supply voltage total harmonic distortion that would affect power quality on the distribution network. The next simulation involves 10 backup battery-charging units.

Figure 4.3 shows experimental results involving 10 backup battery-charging units, THDv of 0.17% was produced. The THDv value was far less than 5% minimum value stated in the IEEE 519 standards that. Hence, the low voltage distribution network did not receive high amount of harmonics that would require correction measures. The THDv of this magnitude had no impact on the distribution network.

It was concluded that 10 backup battery-charging units were safe to use at the same time because they did not produce THDv value that would affect power quality to the distribution network.

Overall, the total harmonics distortion experimental results obtained for connecting up to10 backup battery-charging units were all below minimum value 5%. It is safe to use 10 backup battery-charging units simultaneously because they would not produce THD beyond 10%..

4.3.2.2 Supply current total harmonics distortion - simulation results

The supply current total harmonic distortion (THDi) produced by 1 backup battery-charging units was 0.41% as shown in Figure 4.8. The individual harmonics produced lies between 0.01% and 0.3%. Thus, current harmonics were all below maximum allowable levels. The supply current total harmonics distortion was less than 5%. In comparison to IEEE 519 standard, the current total harmonic distortion produced by 1 backup battery-charging unit did not require mitigation as it was far less than 5%.

Fundamental (50Hz), 2A, THD= 0.41%

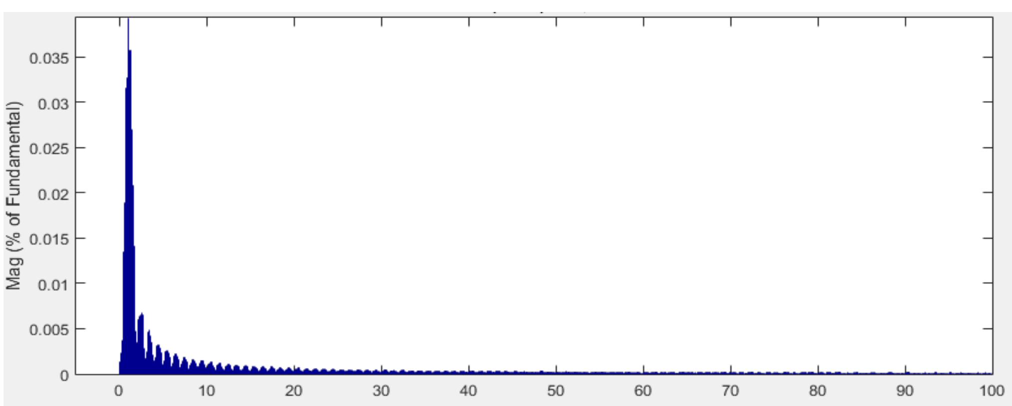

Figure 4.8: **Supply current total harmonic distortion** for 1 battery-charging unit; where 2A=supply current; THD=total harmonic distortion; obtained from Simulink.

Therefore, supply current total harmonic distortion (THDi) produced by 1 backup battery-charging was not sufficient to distort supply current.

It was difficult to make a final conclusion on the current total harmonics distortion depending on the results obtained by connecting 1 backup battery-charging unit on the low voltage distribution network.

To that effect, the number of backup battery-charging units connected to the same distribution line were gradually increased from to 1 to 10 consecutively. But, only 1, 3 and 10 backup battery-charging unit current simulation results were displayed in Figure 4.4, 4.5 and 4.6 respectively. Figure 4.4 shows the simulation results of connecting 1 backup battery-charging unit.

Supply current Total harmonic distortion of (THDi) of 0.44% was produced by 3 backup battery-charging units as shown in Figure 4.9. The individual harmonic distortion contributions lies between 0.01% and 0.3%.

Fundamental (50Hz), 2A, THD= 0.44%

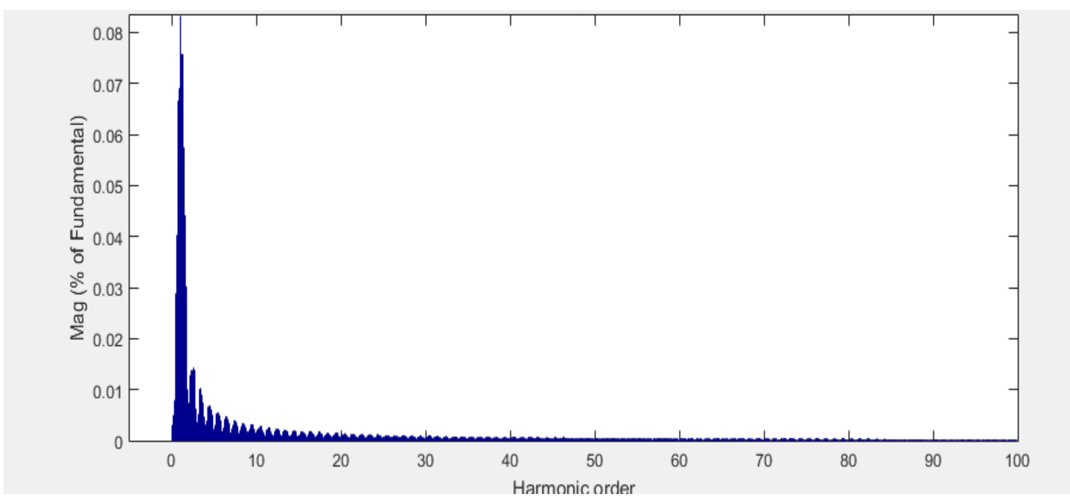

Figure 4.9: Supply current harmonics spectrum for 3 battery-charging units; obtained from Simulink software

The supply current total harmonic distortion produced by the 3 backup battery-charging units were lower than 5%, a level that do not requires mitigation measures. Three backup battery-charging units were safe to operate at the same time because they produce THD less than 5%.

Simulation results involving 10 backup battery-charging units is as shown in Figure 4.10. The supply current total harmonic distortion of 0.61% was produced . The current supply THD obtained was far below the minimum level that would require mitigation in accordance to IEEE 519 standard.

It was safe to operate 10 backup battery-charging units. However, it was not possible to draw up a final conclusion on the current total harmonic distortion basing on 10 backup battery-charging units because it was possible to have more than 10 consumers connected at the same time. For example, in the community surveyed there were 20 households owing backup battery-charging units. If 20 backup battery-charging units were connected at the same time, the supply current THD would differ from that obtained for 10 backup battery-charging units.

Fundamental (50Hz), 2A, THD= 0.61%

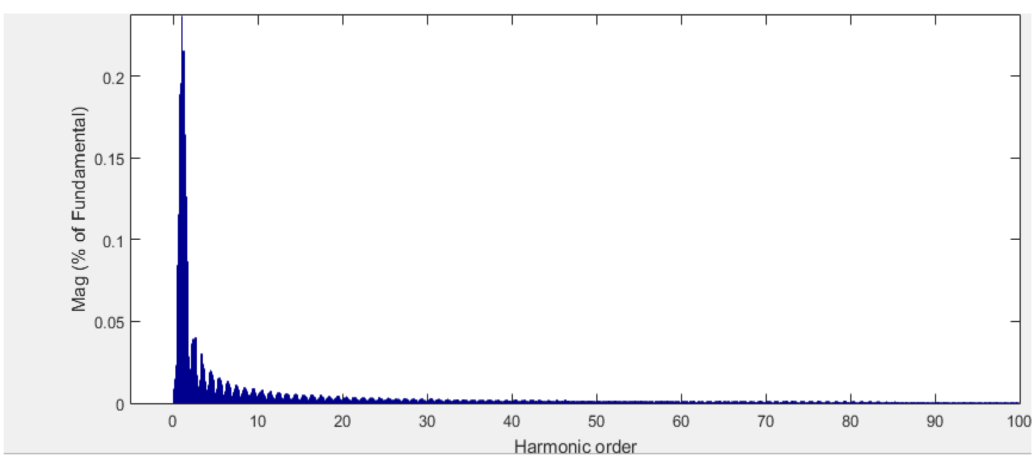

Figure 4.10: Supply current total harmonic distortion for 10 battery-charging units; obtained from Simulink software

The current total harmonic distortions produced on the low voltage distribution network by using up to 10 backup battery-charging units were all below 5%. Therefore, it was safe to connect up to 10 backup battery-charging units on the distribution network.

The voltage and current THD simulation results for up to 10 backup battery-charging units were tabulated in Table 4.1.

The THD for supply voltage and current were both increasing as the number backup battery-charging units were increased. As the backup battery-charging units were linearly increased, so was the supply voltage THD, but the supply current THD increased exponentially.

Simulation results shown in Table 4.3 were used to draw graphs shown in Figure 4.11. The supply current total harmonic distortions (THDi) graph started at higher value than the supply voltage total harmonic distortions (THDv) graph. For example, when 1 backup battery-charging unit was connected to the distribution network, THDv and THDi produced were 0.02% and 0.41% respectively. The graphs in Figure 4.11 reviewed that more current THD than voltage THD were produced at a time. The THDi had a stepper gradient than the THDv.

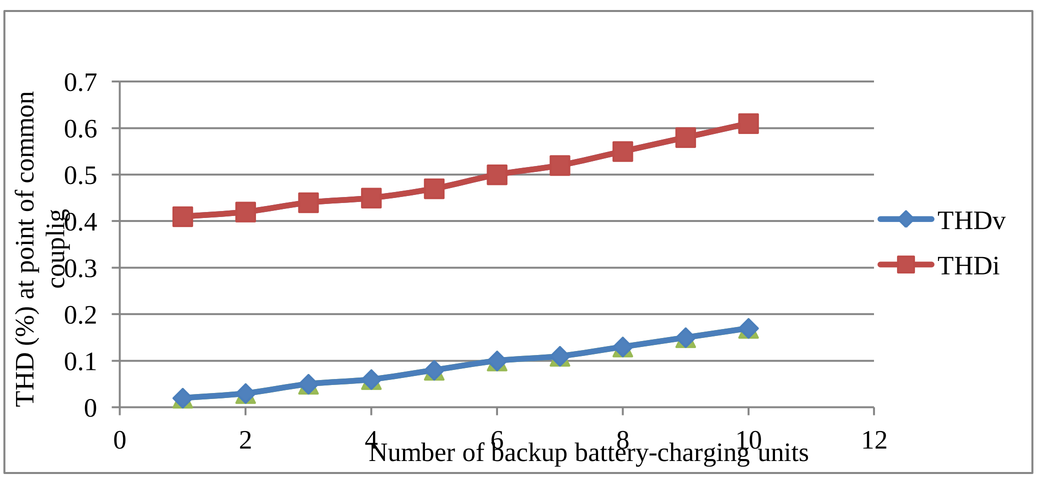

Figure 4.11: Simulation results: Graphs for total harmonic distortions (THD) against 1-10 backup battery-charging units; where THDv = total harmonic distortions for voltage; THDi = total harmonic distortions for current.

As such when 10 backup battery-charging units were connected at the same time the THDv and THDi produced were 0.17% and 0.61% respectively.

The software used in this research work was unable to simulate more than 10 backup battery-charging units. Therefore, to examine the impact of 11 to 50 backup battery-charging units extrapolation was used. From THDi and THDv graphs shown in Figure 4.11, two smooth curves and two equations were generated by excel software as shown in Figure 4.12. The equation 8 was used to calculate THDi, while equation 9 was used to calculate THDv for 8 to 50backup battery-charging units (shown in Table 4.2).

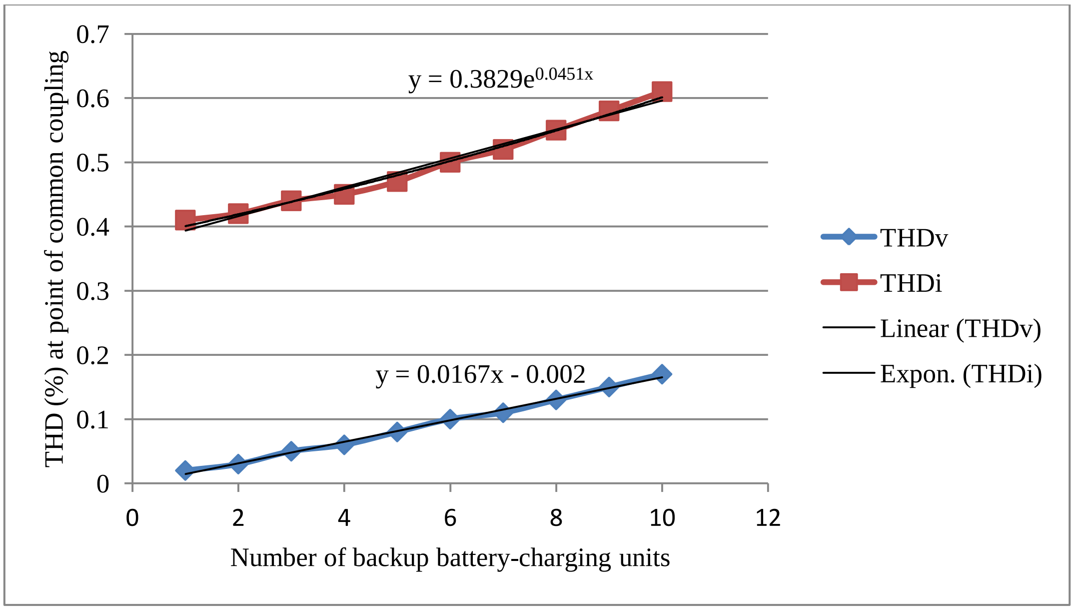

Figure 4.12: Simulation results: Graphs for total harmonic distortions (THD) against 1-10 backup battery-charging units with equations generated in excel; where THDv = total harmonic distortions for voltage; THDi = total harmonic distortions for current.

y = 0.3829e^ 0.0451x...10

In equation 10; where y= calculated current total harmonics distortion; e= exponential value; x= a variable representing the number of backup battery-charging units.

An algorithm for equation 10 is found in Appendix E(i)

y = 0.0167x - 0.002..11

In equation 11; where y= calculated voltage total harmonic distortion; x= a variable representing the number of backup battery-charging units; 0.0167=coefficient of x; -0.002= constant at the y-axis crossing.

An algorithm for equation 11 is found in Appendix E(ii)

4.3.2.3 Extrapolated results: Supply voltage and current total harmonic distortions

The software used in this research work was unable to process more than 10 backup battery-charging units. In order to determine the supply voltage and current total harmonic distortions produced by connecting 11-50 backup battery-charging units extrapolation was conducted using generated equations (8, 9).

To test the accuracy of the equations 8 and 9, calculated and simulated (shown in brackets) values for 8-10 backup battery-charging units are written side by side for comparison in Table 4.2. The equations fitted well because they reproduced simulated value.

Table 4.2 shows that the supply voltage and current THD produced by operating 8 to 50 backup battery-charging units were all below 5%; the THD in brackets for 8-10 backup battery-charging units are simulated values , while the rest of THD for 8-50 backup battery-charging units are extrapolated values.

The supply voltage THD of 0.50% was produced for operating 30 backup battery-charging units, while the supply current THD of 1.42% was produced. THD levels produced did not require any mitigation because they were within the safe limit of 5%.

At 50 backup battery-charging unit connections, the supply voltage total harmonic distortion of 0.83% was produced, while supply current total harmonic distortion of 3.65% was produced.

The simulation and calculated values in Table 4.3 and Table 4.4 respectively, were combined to draw Figures 4.13 & 4.14. The graphs showed how the THD were increasing as the backup battery-charging units were being increased.

Figure 4.13 display graphs for total harmonic distortions against 1 to 30 backup battery-charging units.

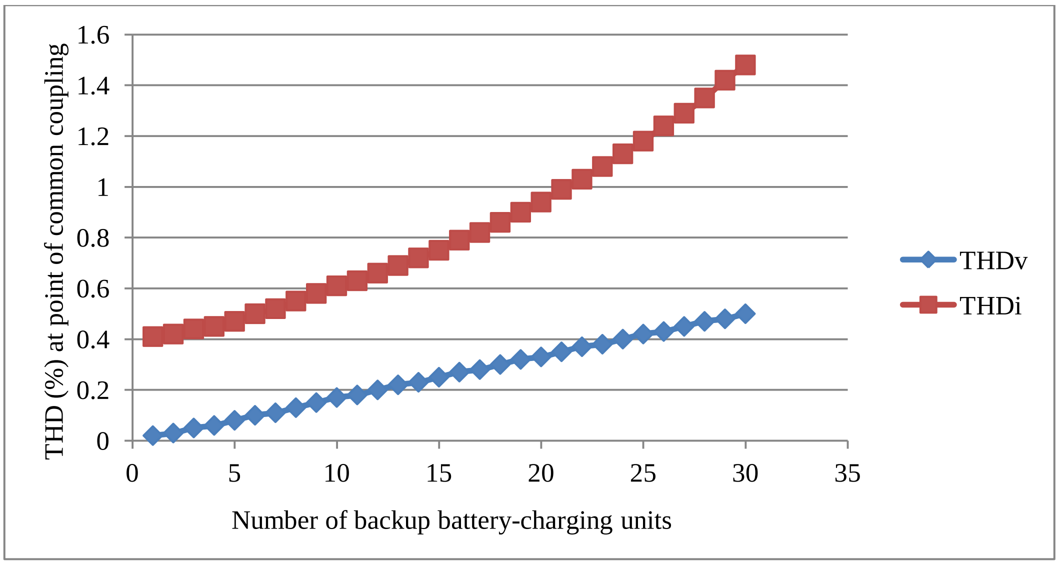

Figure 4.13: Graphs for extrapolated total harmonic distortions (THD) against 1to 30 backup battery-charging units; where THDi = total harmonic distortions for current; THDv = total harmonic distortions for voltage.

The THDi increased exponentially, whilst THDv increased linearly all the way. Both the THDi and THDv produced were below 5%, there was no need of mitigation measures.

Figure 4.14 display graphs for total harmonic distortions against 1to50 backup battery-charging units. There were more THDv produced than THDi from 30 to50 backup battery-charging unit connections.

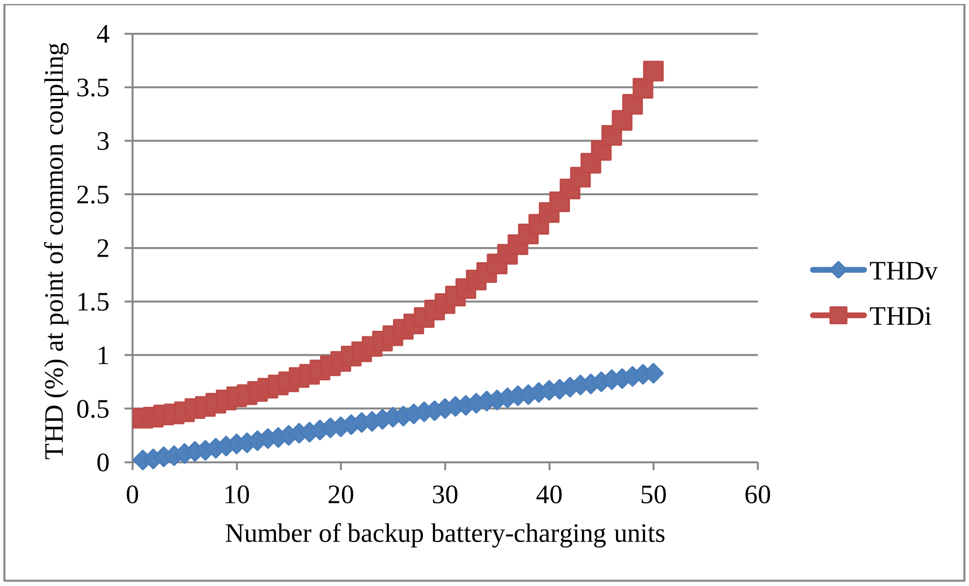

Figure 4.14: Graphs for extrapolated total harmonic distortions (THD) against 1-50 backup battery-charging units; where THDi = total harmonic distortions for current; THDv = total harmonic distortions for voltage.

At 50 backup battery-charging unit connections, voltage total harmonic distortion was to 0.83%, while current total harmonic distortion was 3.65%.

As observed in Table 4.4, from 1 to 50 backup battery-charging unit connections, the THD produced for voltage and current were less than 5%. The THD produced did not require any mitigation in accordance to the requirements of IEEE 519 standards.

By extrapolating up to 57 backup battery-charging units, the maximum permissible THDi value of 5% was obtained. In addition, by extrapolating up to 300 backup battery-charging units, the maximum permissible THDv value of 5% was obtained.

Overall, the least number of backup battery-charging units to violate THD standard specification determines the maximum number of backup battery-charging units required to be connected simultaneously. Therefore, the maximum number of backup battery-charging unit connections was found to be 57.

4.3.3 Supply voltage and current DC components

4.3.3.1 Supply voltage DC component - simulation results

Before the backup battery-charging unit was switched-on, the supply voltage DC component was 0V. When 1 backup battery-charging unit was operated the supply voltage DC component of 0.0000318V was produced as shown in Figure 4.15.

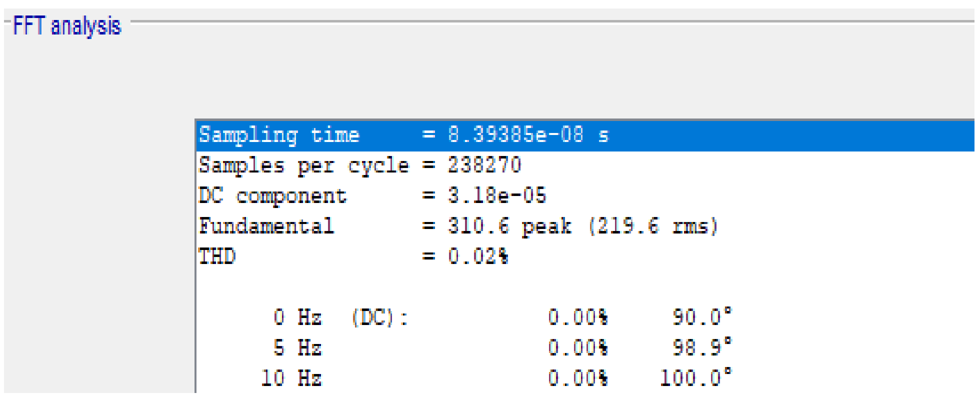

Figure 4.15: Supply voltage DC component for 1 backup battery-charging unit; where DC component=0.0000318V; Fundamental=310.6V(peak); THD=total harmonic distortion; obtained from Simulink software.

The voltage DC value obtained by simulating 1 backup battery-charging unit was too small to affect the power quality on the distribution network.

When 2 backup battery-charging units were operated the supply voltage DC component of 0.0000755V was produced as shown in Figure 4.15.

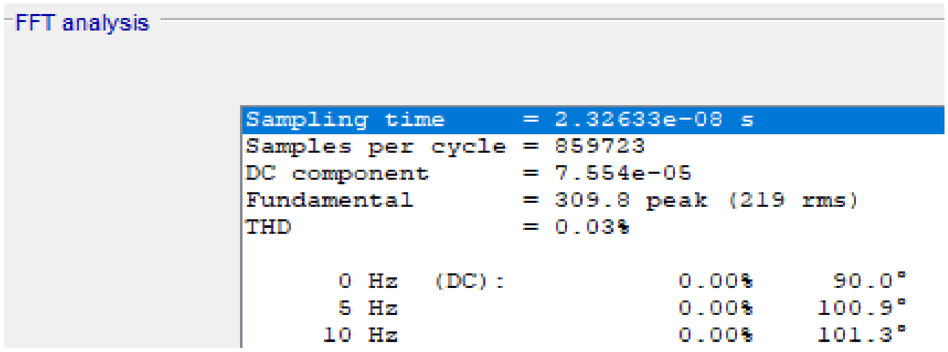

Figure 4.16 Supply voltage DC component for 2 backup battery-charging units; where DC component=0.0000755V; THD=total harmonic distortion; obtained from Simulink software.

The voltage DC value obtained by simulating 2 backup battery-charging unit was too small to affect the power quality on the distribution network.

The supply voltage DC component of 0.0008757V produced when 10 backup battery-charging units were operated, see Figure 4.17.

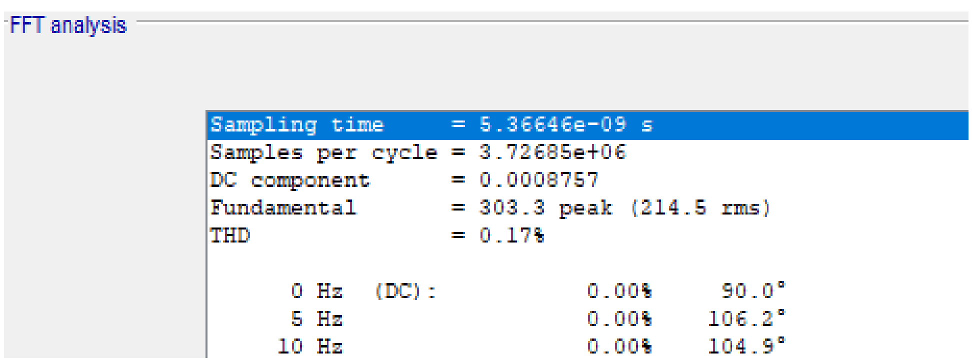

Figure 4.17 Supply voltage DC component for 10 backup battery-charging units; where DC component=0.0008757V; THD=total harmonic distortion; obtained from Simulink software.

The voltage DC value obtained by simulating 1 backup battery-charging unit was too small to affect the power quality on the distribution network.

Overall, the DC voltage component produced up to 10 backup battery-charging units were as shown in Table 4.5. The DC voltage produced was too small to affect distribution network.

4.3.3.2 Supply current DC component - simulation results

The current dc component generated by backup battery-charging units during voltage conversion traverses on the distribution network.

The current DC component produced by 1 backup battery-charging units was 0.00002763A as shown in Figure 4.18.

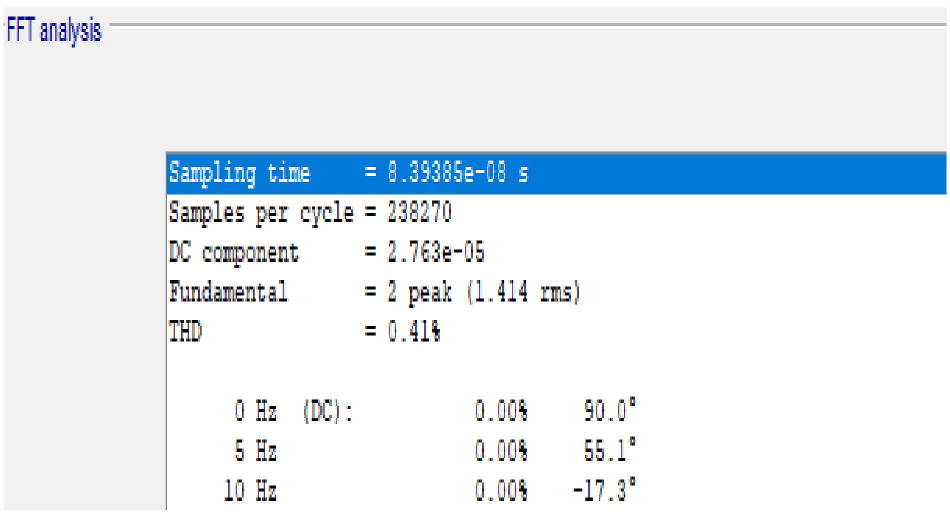

Figure 4.18: Current DC component for 1 backup battery-charging unit; where DC component=0.00002763A; Fundamental=2A (peak); THD=total harmonic distortion; obtained from Simulink software.

The magnitude of the current DC component produced by 1 backup battery-charging unit was too small. Therefore, it is safe to connect 1 backup battery-charging unit because it produces negligible amount of DC component to the distribution network.

Figure 4.19 shows the current DC component of 0.00004352A produced by operating 2 backup battery-charging units. The amount produced was too small, therefore it could not affect the distribution network.

Figure 4.19 below shows the DC component for 2 battery-charging units.

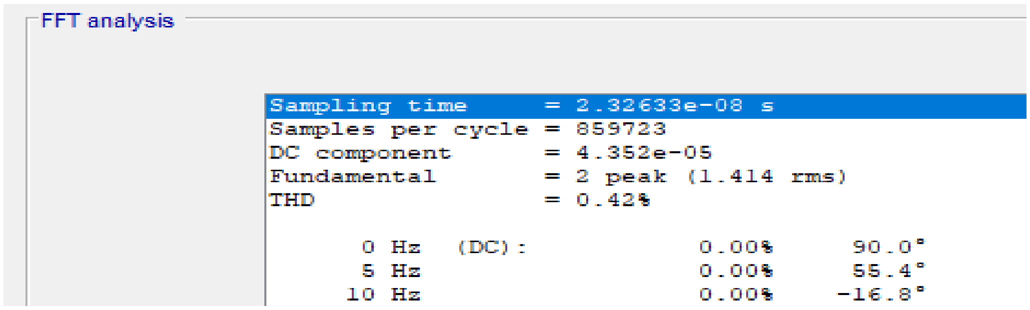

Figure 4.19: Current DC component for 2 backup battery-charging unit;

where DC component=0.00004352A; Fundamental=2A (peak); THD=total harmonic distortion; obtained from Simulink software.

Therefore, it was safe to connect 2 backup battery-charging units on the distribution network because they produce very small current.

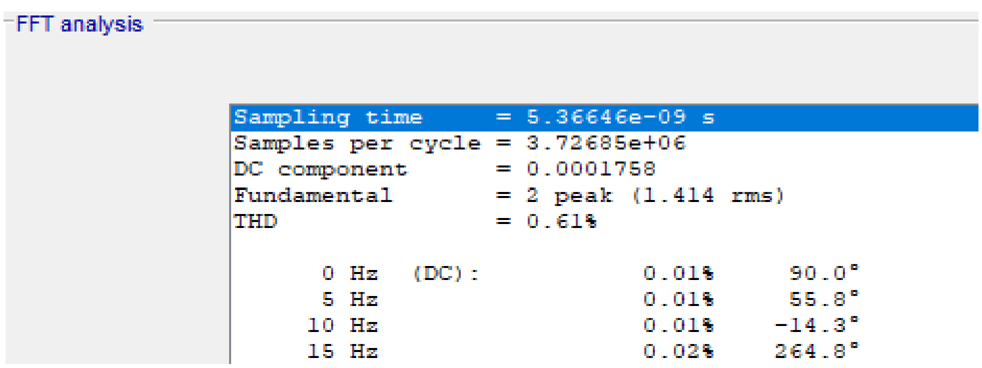

Figure 4.20 Current DC component for 10 backup battery-charging unit; where DC component=0.0001763A; Fundamental=2A (peak); THD=total harmonic distortion; obtained from Simulink software.

The current DC component produced by 10 backup battery-charging units was 0.0001763A. It is safe to connect 10 backup battery-charging units at the same time because they did not produce high voltage DC component that could affect the distribution network.

The current DC component obtained for up to 10 backup battery-charging units were all small, they did not affect the quality of current supplied to the distribution network.

The software used in this research work was unable to process more than 10 backup battery-charging units. To examine the amount of DC component produced by 11-50 backup battery-charging units extrapolation was conducted.

Simulation results for supply voltage and current DC components for up to 10 backup battery-charging units were tabulated as shown in Table 4.1 above.

Simulation results shown in Table 4.1 were used to draw graphs shown in Figure 4.21. The supply voltage DC component shows a stepper increase than supply current DC component. The graphs in Figure 4.21 reviewed that more voltage DC component were produced at a time than current DC component. Furthermore, the graphs show that the supply current DC component increases linearly, while supply voltage DC component does not increase linearly as the number of the backup battery-charging units increase

The equations in Figure 4.21 were generated by excel software. The equations fitted very well on the simulated DC components values for up 10 backup battery-charging units. The equations were used to calculate extrapolated values by simply replacing the number of backup battery-charging units being used.

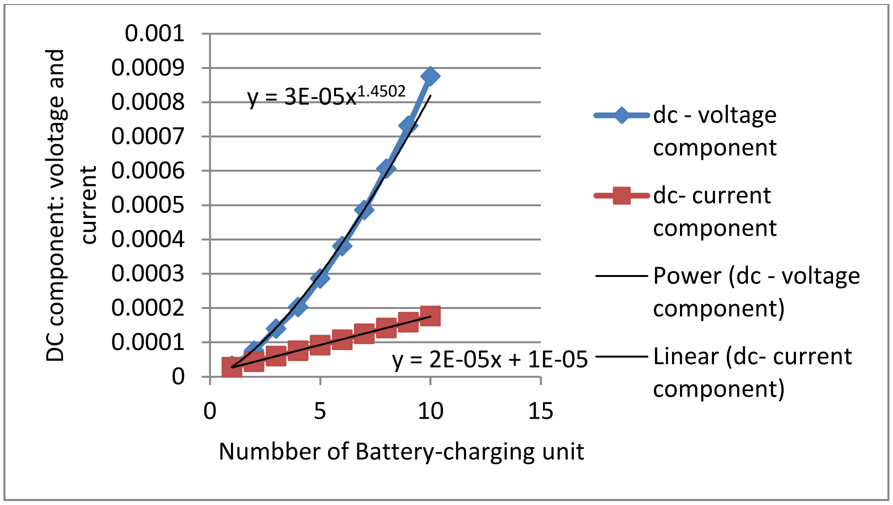

Figure 4.21: Graphs for simulated DC component against 1-10 backup battery-charging units with equations generated in excel.

y = 3E-05x^(1.4502)..12

In equation 12; where y= calculated voltage DC component; E= exponential value; x= a variable representing the number of backup battery-charging units.

y = 2E-05x + 1E-05...13

In equation 13; where y= calculated current DC component; x= a variable representing the number of backup battery-charging units; E=exponential.

4.3.3.3 Extrapolated values: Supply voltage and current DC component.

Table 4.2 shows the values of supply voltage and current DC component obtained by extrapolating 8 to 50 backup battery-charging units.

The supply voltage DC component of 0.0041614V was obtained by extrapolating 30 backup battery-charging units, while the supply current DC component obtained was 0.00051213A.

By extrapolating 50 backup battery-charging unit connections, the voltage DC component obtained was 0.0087291V, while current DC component obtained was 0.00084623A.

Figure 4.22 shows that backup battery-charging units produce more DC voltage component than DC current component during operation.

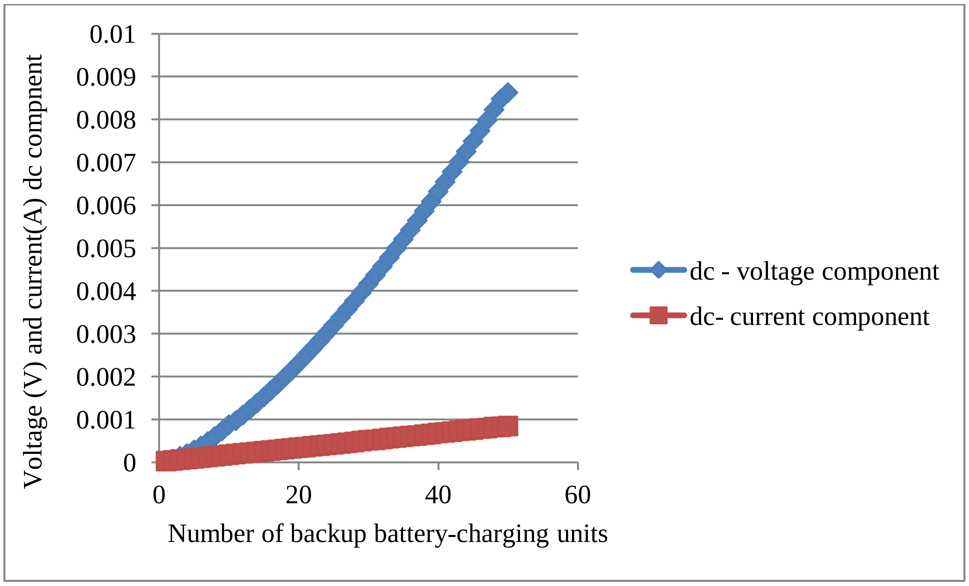

Figure 4.22: Supply voltage and current DC component graphs for 1-50 backup battery-charging units.

Figure 4.22 displays an extrapolated graphs for DC components. The DC components obtained by extrapolating up to 50 backup battery-charging units were too small to affect remote controlled devices or overload distribution network conductors.

DC components obtained by extrapolating up to 50 backup battery-charging units had no effect on the low voltage distribution network because they were too small. Therefore, DC components produced by this type of charging unit considered cannot harm the low voltage distribution network.

Conclusion

The total harmonic distortion, voltage drop and DC components produced by backup battery-charging units at the point of common coupling were assessed. The Simulink software was used assess the impact of the three performance parameters on the low voltage distribution network. Simulation and extrapolated results obtained were compared with results stipulated on IEEE 519 standards to draw conclusions on a particular performance parameter assessed. The results indicated that the voltage drop was the most influential parameter of the three because 39 battery-charging units produced maximum permissible drop10% . At the same number of battery-charging units, the THD and DC components produced were far below the maximum permissible values. Therefore, maximum number of battery-charging units to be used were guided by voltage drop produced.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Battery-charging units are considerably being used in residential application as power back-up in the face of power shortages. The study investigated the impact of battery charging by residential consumers on the low voltage distribution network using Simulink. The measurements were obtained at the point of common coupling by examining the supply voltage drop, total harmonic distortion (THD) and direct current (DC) component produced by backup battery-charging units.

Fourteen performance parameters were reviewed, of these, eight were found to be affected by backup battery-charging units. The 8 performance parameters affected by backup battery-charging units were the supply voltage, supply current, mains signaling interference, noise, voltage notches, direct current, harmonics, and voltage imbalance.

Three out of 8 performance parameters affected by backup battery-charging units were investigated in Simulink using a model. The performance parameters investigated were supply voltage drop, harmonics and direct current component.

By simulating up to 10 backup battery-charging units; the supply voltage drop obtained was found to range from 0.13 to 2.48%, supply voltage THD was found to range from 0.02 to 0.17%, supply current THD was found to range from 0.41 to 0.61%, DC voltage component was found to range from 0.0000318 to 0.0008757V and DC current component was found to range from 0.00002763 to 0.00017417A. Furthermore, by extrapolating 11 to 50 backup battery-charging units; the supply voltage drop was found to range from 2.74 to 12.93%, supply voltage THD was found to range from 0.18 to 0.83%, supply current THD was found to range from 0.63 to 3.65%, voltage DC component was found to range from 0.0009713 to 0.0087291V and current DC component was found to range from 0.00019423 to 0.00084623A were obtained.

The maximum number of backup battery-charging units required to produce maximum allowable supply voltage drop of 10% and the supply voltage and current THD of 5% were determined by extrapolation as being 39 for supply voltage drop, 57 for current THD and 300 for voltage THD. With 20 backup battery-charging units in operation distribution network suffers 5% voltage drop and current THD of 1.8%. That indicates acceptable distortions to the performance parameters under investigation. The voltage drop above 10% and the THD above 5% require mitigation to keep the values at the acceptable limit according to Institute of Electrical and Electronics Engineers (IEEE) 519 standard.

On the overall, the least number of backup battery-charging units found to violate the standard was considered as the maximum number of backup battery-charging units which can be connected simultaneously. Therefore, 39 backup battery-charging units was considered as the maximum number of backup battery-charging units to be connected on the low voltage distribution network where neither supply voltage drop nor THD limits would be violated.

5.2 Recommendations

Simulink was unable to process all the performance parameters affected by backup battery-charging units, due to software limitations. Further research work is required in which different investigation tools could be explored. That will enable to assess all the performance parameters affected by backup battery-charging units, especially those of which Simulink software was unable to assess.

In addition, a practical research would be required to get actual impact of charging of backup battery-charging on distribution network.

5.3 Research contribution

In general, there is specific number of backup battery-charging units to be connected on the low voltage distribution before a given standard specification is violated.

For the technology of convertor considered, the upper limit of the number of charging units on the PCC is 39, beyond which the power quality standards specification are violated.

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APPENDIXES

Appendix A: IEEE 519 standards, voltage and current harmonic distortion limits

IEEE voltage harmonic distortion limits

Bus voltage at PCC	Individual V_h , %	Voltage THD, %
V< 69kV	3.0	5.0
69k $\leqslant$ V $\leq$ 161kV	1.5	2.5
V$\geqslant$ 161kV	1.0	1.5

IEEE 519 current distortion limits

I_{sc} / I_L	I_h / I_L, %----general distribution systems (120V-69kV)					TDD %
	h <11	11≤ h< 17	17≤ h< 23	23 ≤ h < 35	h ≥ 35	
< 20	4.0	2.0	1.5	0.6	0.3	5
20 - 50	7.0	3.5	2.5	1.0	0.5	8
50-100	10	4.5	4.0	1.5	0.7	12
100-1000	12	5.5	5.0	2.0	1.0	15
> 1000	15	7.0	6.0	2.5	1.4	20
I_{sc} / I_L	I_h / I_L, %----general sub transmission systems (69-161kV)					TDD %
	h <11	11≤ h< 17	17≤ h< 23	23 ≤ h < 35	h ≥ 35	
I_{sc} / I_L	I_h / I_L, %----general transmission systems (>161kV)					TDD %
	h <11	11≤ h< 17	17≤ h< 23	23 ≤ h < 35	h ≥ 35	
< 50	2.0	1.0	0.75	0.3	0.15	2.5
≥ 50	3.0	1.5	1.15	0.45	0.22	3.75

Appendix B: Technical specifications and Characteristics for the of Backup battery-charging unit

Technical specifications of Sinetech backup battery charging unit

NO	DESCRIPTION	LIMIT
1	Input voltage	110/220V ac
2	Input frequency	47-63Hz
3	Output voltage	12V dc
4	Current	10A
5	Equalizer charge	14.4V±0.1V
6	Float charge	13.6V±0.1V
7	Efficiency	above 85% at full load

http://www.renobat.eu/en/communication/articles/1128-high-frequency-chargers-versus-conventional-chargers-all-you-need-to-know

Characteristics of a Sinetech backup battery charging unit

NO	DESCRIPTION
1	Charging process controlled by microprocessor
2	Possibility of rapid charging in less than an hour without the battery being damaged
3	High frequency and high efficiency design
4	A network voltage/ampere variation does not affect output voltage
5	It has display to see charging information and charts.
6	Temperature controlled equipment- stops charging when temperature is 70ºC±5ºC
7	Stops charging when the battery is fully charged
8	Charging current is varied according to the need of the battery
9	Can charge different type of batteries
10	Active power factor control
11	Low ripples
12	Does not overcharge the battery
13	Small design and light equipment
14	Expensive designs

https://www.adendorff.co.za/types-of-battery-chargers-applications/

Technical specification of conventional backup battery charging unit

NO	DESCRIPTION	LIMIT
1	Input voltage	110/220V ac
2	Input frequency	50-60Hz
3	Output voltage	12V dc
4	Current	10A
5	Poor efficiency	50-70% at full load

Characteristics of a conventional backup battery charging unit

NO	DESCRIPTION
1	Charging process is uncontrolled and it takes 10-12hrs
2	Large inrush current affects the life span of the battery
3	Low frequency and low efficiency design
4	A network voltage/ampere variation affect output voltage
5	It does not display charging information and charts.
6	Charging does not stop when temperature reaches 70ºC±5ºC
7	Does not stops charging when the battery is fully charged
8	Constant charging current/voltage regardless of the status of battery to be charged
9	Charges one type of battery
10	Low power factor that increases network harmonic
11	High ripples
12	Overcharges the battery if it is not disconnected after full charge
13	Large design and heavy equipment
14	Inexpensively designed and built
15	Utilizes step down transformer

https://www.adendorff.co.za/types-of-battery-chargers-applications/

http://www.renobat.eu/en/communication/articles/1128-high-frequency-chargers-versus-conventional-chargers-all-you-need-to-know

Appendix C: Questionnaire

Dear Buyantashi residents, Kitwe.

I Greenwell Malindi (0965631605) am conducting a survey on the usage of backup power sources in households during load shedding. In particular, the survey is meant to determine the usage of backup battery-charging units in households. You are cordially requested to answer the questions provided on the questionnaire. The questions mainly deal with load shedding embarked on by the utility company in residential communities. The information obtained would be used by relevant authorities to establish lasting solutions to load shedding.

Therefore, you are required to respond just by ticking in the box corresponding to the answer of your choice from the options provided on each question.

1) Do you experience load shedding in this community?

   Yes ☐

   No ☐

2) If your answer is yes, how low does it take?

   1-2 hours ☐

   3-5 hours ☐

   4-8 hours ☐

3) Do you have battery charger unit(s) in this house? If you do not have a battery charger unit(s) skip question 4 and 5.

   Yes ☐

   No ☐

4) What type of battery charger unit(s) do you have?

   ☐

Smart unit

Conventional unit ☐

Solar unit ☐

5) Where did you buy your battery charger unit(s)?

Kitwe Hardware limited ☐

Other shops ☐

6) What type of energy do you use for lighting, radio, TV, computers and other small loads when you experience load shedding?

Backup batteries ☐

Stationary engines ☐

Appendix D: Results of the questionnaire

Usage of backup power sources

NO	TYPE OF BACKUP POWER SOURCE USED	HOUSEHOLDS USING PARTICULAR TYPE OF BACKUP POWER SOURCE
1	Sinetech - Backup battery-charging unit	20
2	Conventional - Backup battery-charging unit	5
3	Solar unit	41
4	Stationary engine	8
5	Other	21
	Total	**95**

Appendix E: Curve fitting equations algorithms

(i) Excel generated exponential curve fitting equation

Microsoft excel generated non-linear curve-fitting equation 10 (shown on page 79) was computed from an exponential equation of the form y = Ae^{Bx}, where A and B are numerical values. In the case under consideration A = 0.3829 and B =0.0451. The curve-fitting algorithm for A and B are shown in equation 3 and 4 respectively below.

Below are the steps taken to generate curve-fitting algorithm for equation 10.

Step 1: y = Ae^{Bx}, where A and B are numerical values. In the case under consideration A = 0.3829 and B =0.0451.

Step 2: Take logarithms on both sides of equation y = Ae^{Bx} .

Iny = In[Ae^{Bx}]

= InA + Bx

The curve-fitting algorithms are then

$$InA = \frac{InYi\sum_{i=1}^{n} Xi^2 - \sum_{i=1}^{n} Xi \sum_{i=1}^{n} XiInYi}{n\sum_{i=1}^{n} Xi^2 - (\sum_{i=1}^{n} xi)^2} \quad \text{.........14}$$

$$B = \frac{n\sum_{i=1}^{n} XiInYi - \sum_{i=1}^{n} Xi \sum_{i=1}^{n} InYi}{n\sum_{i=1}^{n} Xi^2 - (\sum_{i=1}^{n} xi)^2} \quad \text{.........15}$$

where A = exp(a), B =b, Y_i = THDv values, X_i = THDi values, n = total number of entries considered.

Supply Voltage and current THD (this Table was compute A and B for exponential and linear equations)

No	X_i	X_i^2	Y_i	Zi	ln(Y_i)	X_i ln(Y_i)	XiZi
1	1	1	0.41	0.02	-0.8916	-0.8916	0.02
2	2	4	0.42	0.03	-0.8675	-1.7350	0.06
3	3	9	0.44	0.05	-0.8209	2.4630	0.15
4	4	16	0.45	0.06	-0.7985	-3.1940	0.24

5	5	25	0.47	0.08	-0.7550	-3.7750	0.4
6	6	36	0.50	0.1	-0.6931	-4.1589	0.6
7	7	49	0.52	0.11	-0.6539	-4.5775	0.77
8	8	64	0.55	0.13	-0.5978	-4.7827	1.04
9	9	81	0.58	0.15	-0.5447	-4.9025	1.35
10	10	100	0.61	0.17	-0.4943	-4.9430	1.7
Total	**55**	**385**	**4.95**	**0.9**	**-7.1175**	**-35.423**	**6.33**

In Table E1, Z_i = Simulations voltage THD values, X_i = Simulations THD values, n = total number of simulations.

The values of A and B were computed below as follows:

$$\text{InA} = \frac{InYi\sum_{i=1}^{n} Xi^2 - \sum_{i=1}^{n} Xi \sum_{i=1}^{n} XiInYi}{n\sum_{i=1}^{n} Xi^2 - \left(\sum_{i=1}^{n} xi\right)^2}$$

$$= \frac{-7.1175*385 - 55*-35.423}{10*385-(55)^2}$$

$$= \frac{-791.9725}{825}$$

InA = -0.95997

A =exp(-0.95997)

= **0.3829**

$$B = \frac{n\sum_{i=1}^{n} XiInYi - \sum_{i=1}^{n} Xi \sum_{i=1}^{n} InYi}{n\sum_{i=1}^{n} Xi^2 - \left(\sum_{i=1}^{n} xi\right)^2}$$

$$= \frac{10*-35.423-55*-7.1175}{10*385-(55)^2}$$

$$= \frac{37.2325}{825}$$

= **0.0451**

(ii) Excel generated linear curve fitting equation

Microsoft excel generated linear curve-fitting equation 11 (shown on page 79) was computed from a linear equation of the form y = Bx +A, where A and B are numerical values. In the case under consideration A = -0.002 and B =0.0167. The curve-fitting algorithm for A and B are shown in equation 10 and 11 respectively.

$$A = \frac{Zi\sum_{i=1}^{n} Xi^2 - \sum_{i=1}^{n} Xi \sum_{i=1}^{n} XiZi}{n\sum_{i=1}^{n} Xi^2 - \left(\sum_{i=1}^{n} Xi\right)^2} \quad \text{..........} 16$$

$$B = \frac{n\sum_{i=1}^{n} XiZi - \sum_{i=1}^{n} Xi \sum_{i=1}^{n} Zi}{n\sum_{i=1}^{n} Xi^2 - \left(\sum_{i=1}^{n} Xi\right)^2} \quad \text{..........} 17$$

The values of A and B are computed below as follows:

$$A = \frac{Zi\sum_{i=1}^{n} Xi^2 - \sum_{i=1}^{n} Xi \sum_{i=1}^{n} XiZi}{n\sum_{i=1}^{n} Xi^2 - \left(\sum_{i=1}^{n} Xi\right)^2}$$

$$= \frac{0.9*385 - 55*6.33}{10*385 - (55)^2}$$

$$= \frac{-1.65}{825}$$

= **-0.002**

$$B = \frac{n\sum_{i=1}^{n} XiYi - \sum_{i=1}^{n} Xi \sum_{i=1}^{n} Yi}{n\sum_{i=1}^{n} Xi^2 - \left(\sum_{i=1}^{n} xi\right)^2}$$

$$= \frac{10*6.33 - 55*0.9}{10*385 - (55)^2}$$

$$= \frac{13.8}{825}$$

= **0.0167**

Appendix F: Physical electrical installation for the backup battery-charging unit

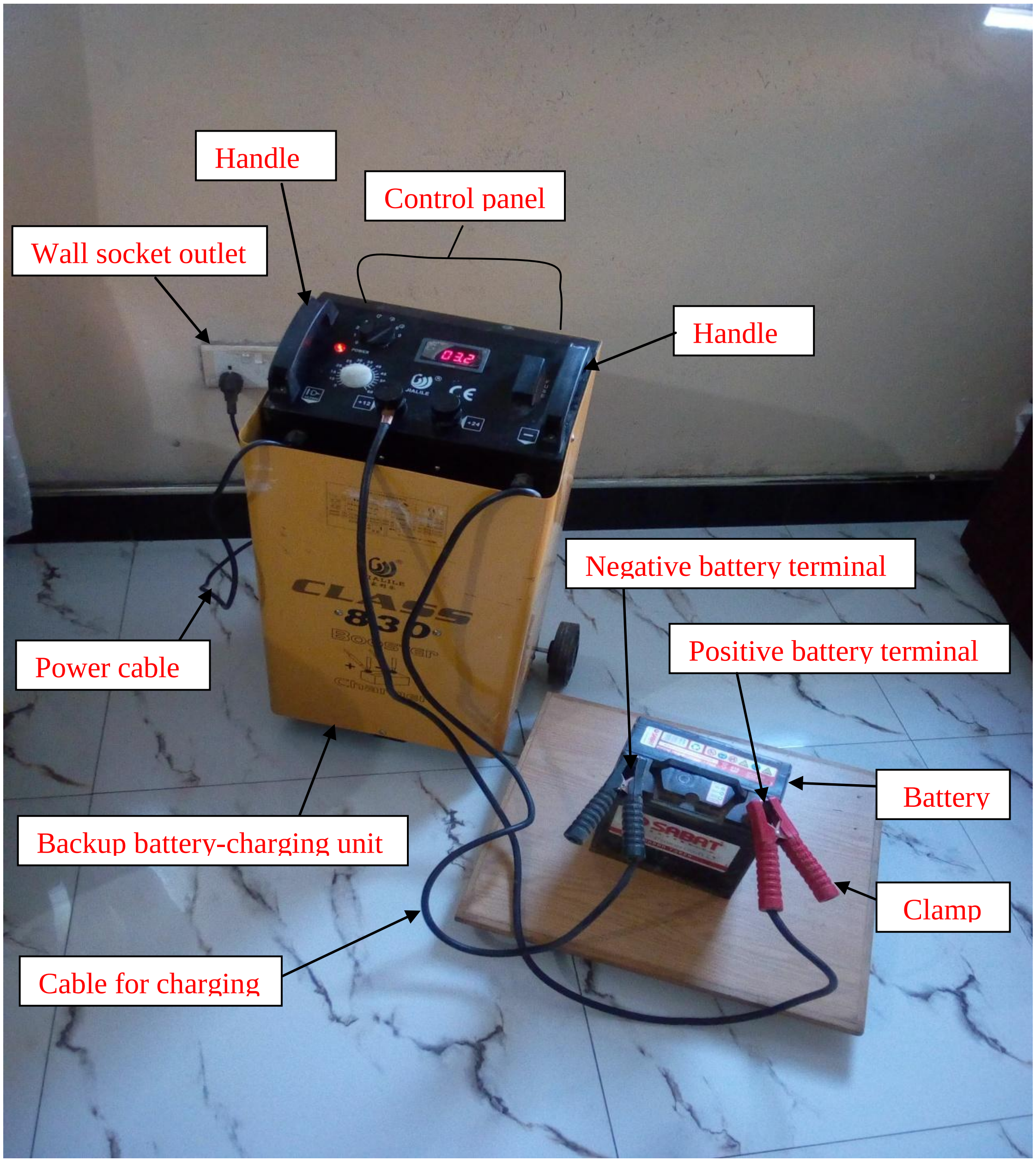

Figure F1: Backup battery-charging unit and battery being charged.

(Source: House N0.9 Mukuba Road, Buyantashi, Kitwe)

Appendix G: Experimental setups 1-3

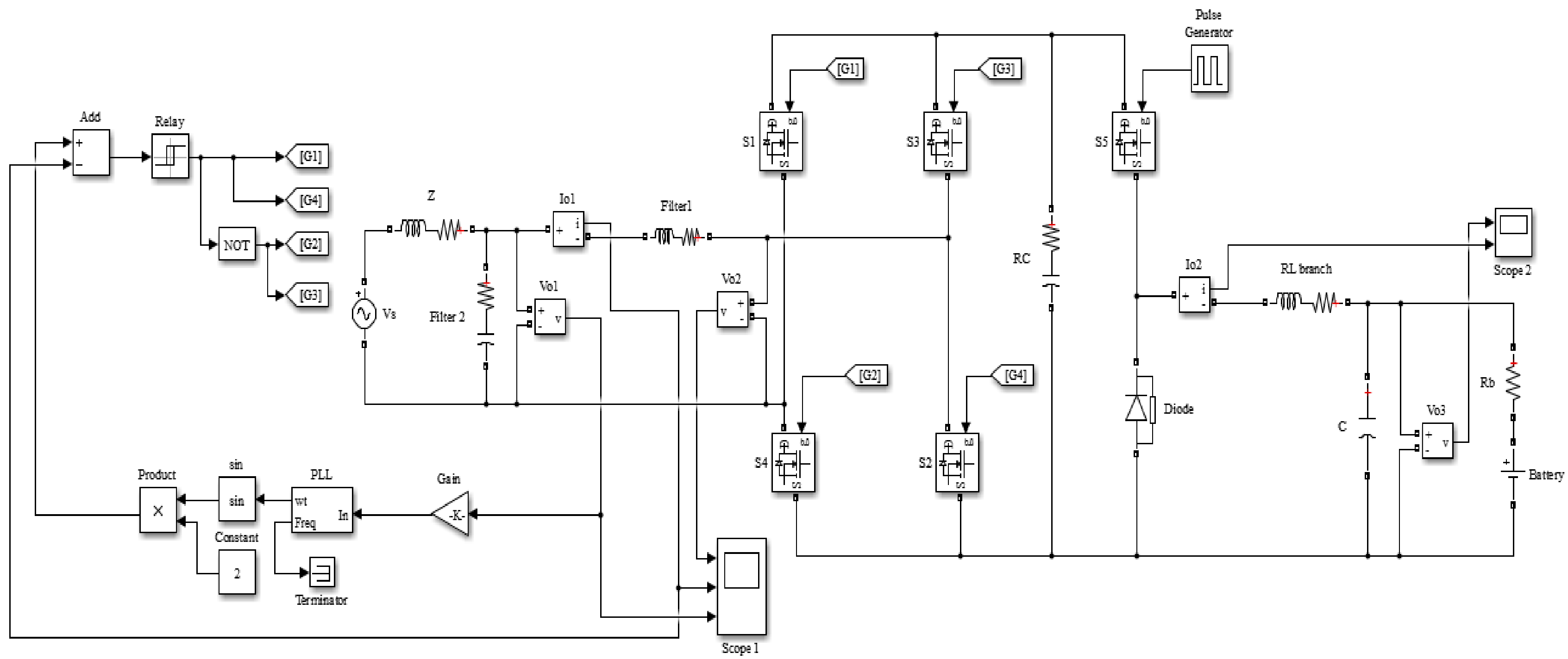

Figure G1: **1 Backup battery-charging unit experimental setup** ; where Vs=supply voltage; Z= line impendence; Io1, Io2=Ammeter; Vo1,Vo2,Vo3=Voltmeter; RC=resistor capacitor branch; RL=resistor inductor branch; C=capacitor; Rb=internal battery resistor; S1,S2,S3,S4,S5=Mosfet; PLL=phase locked loop; wt=angular velocity; Freq= frequency

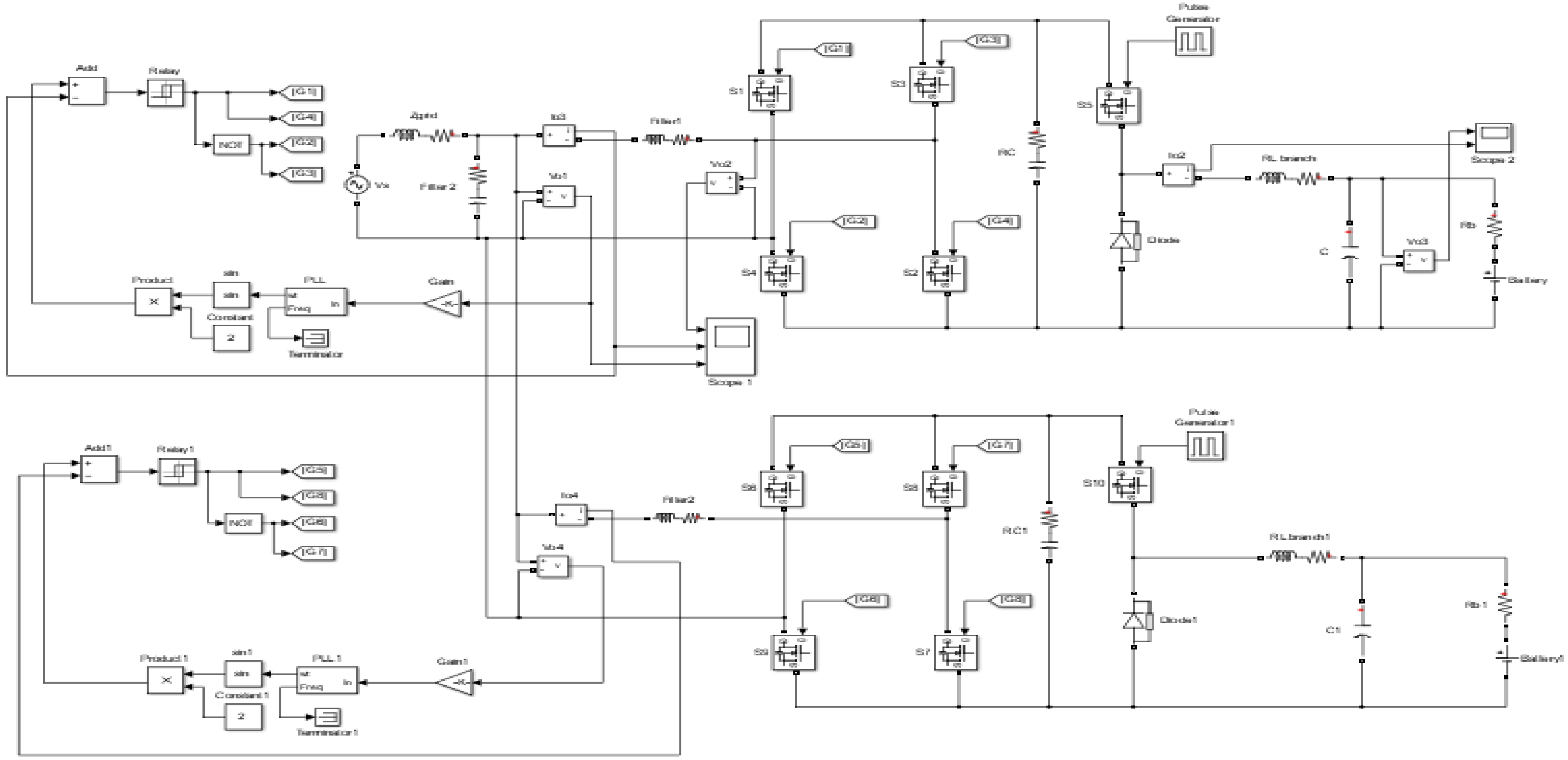

Figure G2: **2 Backup battery-charging units experimental setup** ; where Vs=supply voltage; Z= line impendence; Io1, Io2=Ammeter; Vo1,Vo2,Vo3=Voltmeter; RC=resistor capacitor branch; RL=resistor inductor branch; C=capacitor; Rb=internal battery resistor; S1,S2,S3,S4,S5=Mosfet; PLL=phase locked loop; wt=angular velocity; Freq= frequency

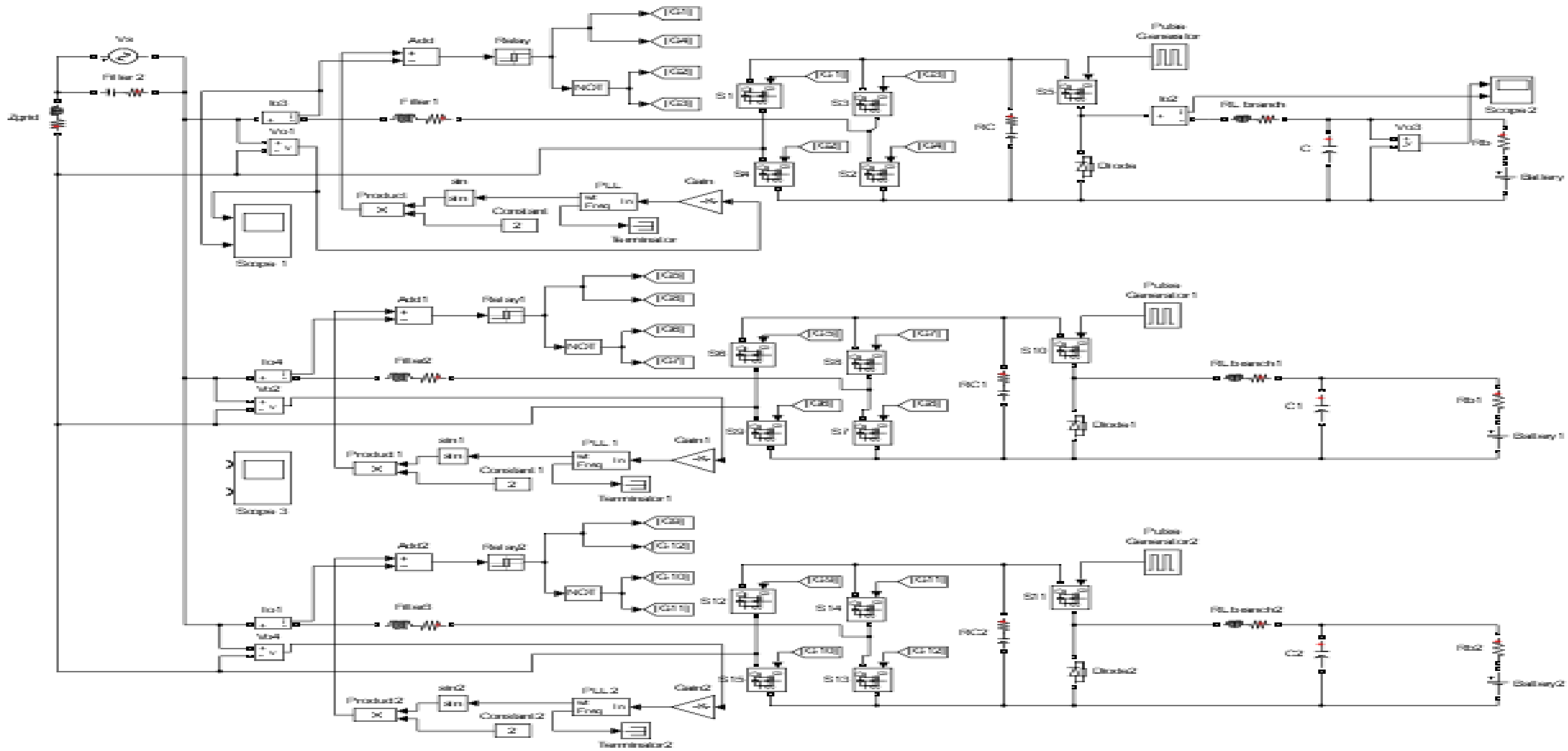

Figure G3: **3 Backup battery-charging units experimental setup** ; where Vs=supply voltage; Z= line impendence; Io1, Io2=Ammeter; Vo1,Vo2,Vo3=Voltmeter; RC=resistor capacitor branch; RL=resistor inductor branch; C=capacitor; Rb=internal battery resistor; S1,S2,S3,S4,S5=Mosfet; PLL=phase locked loop; wt=angular velocity; Freq= frequency