MITIGATION OF ELECTRICITY THEFT AT LOW VOLTAGE DISTRIBUTION END USING INDIRECT MATRIX CONVERTER

BY

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MEng/SEET/2018/8418

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FEDERAL UNIVERSITY OF TECHNOLOGY
MINNA,

JUNE, 2023

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A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL FEDERAL UNIVERSITY OF TECHNOLOGY MINNA, NIGERIA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF ENGINEERING (MENG) IN POWER SYSTEM ENGINEERING.

JUNE, 2023

DECLARATION

I hereby declare that this thesis titled **"Mitigation of Electricity Theft at Low Voltage Distribution End using Indirect Matrix Converter"** is a collection of my original research work and it has not been presented for any qualification anywhere. Information from other sources both published and unpublished have been duly acknowledged.

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CERTIFICATION

The thesis titled: **"Mitigation of Electricity Theft at Low Voltage Distribution End using Indirect Matrix Converter"** by: ABEL, Sunday Tope (**MEng/SEET/2018/8418**) meets the regulations governing the award of the degree of MEng of Federal University of Technology, Minna and it is approved for its contribution to scientific knowledge and literary presentation.

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ACKNOWLEDGEMENTS

I thank God, who has given me life and good health to complete this work. May His name be praised.

I want to convey my heartfelt gratitude to my supervisor in person of Engr. Prof. Tsado Jacob for his tremendous support and assistance in completing this work. The work would not have been perfected without his input, corrections, and directions.

I would also like to thank my co-supervisor in person of Engr. Dr. Tola Omokhafe James for providing me with technical support to perfect this work.

I thank the postgraduate coordinator of the department in the person of Engr. Dr. Tola Omokhafe James for his encouragement and patience towards me during this thesis work.

I also thank the internal examiner, in the person of Engr. Dr. James Ambafi for exercising due diligence to examine and make corrections on the work.

I appreciate the Head of Department Engr. Dr. Lanre Olatomiwa for his encouragement and counsel given to better this work in order to make the department proud.

I want to appreciate Engr. Dr. Michael David, Engr. Ndakara Isah and Mr. David Oluwatimilehin Bamikole for taking the time to read and point out corrections in this work.

I cannot also forget all our academic and non-academic staff of the school, who has supported me in all capacity to contribute to the work's success. All your efforts are duly acknowledged and recognised.

I also want to thank my wife Mrs. Adetutu Abel, and my children, Oluwatodunsin Sunday, Oluwatobi Sunday, and Oluwatamilore Sunday, for their encouragement towards the success of this work.

My heartfelt appreciation goes to all my classmates in the power system option during this master's program for their collective encouragement and support. Thank you.

ABSTRACT

Electricity is essential for the development of any nation. However, theft of electrical energy has been a major challenge on the distribution network, which makes the utility company lose much revenue. This illegal practice is majorly practised through meter bypassing and hookup connections. Various works have been presented to Mitigate Electricity Theft, such as techniques using Energy Meters, IoT, and Energy Theft detecting circuits. These various works; measure and detects before mitigating electricity theft. However, this study employs the method of Indirect Matrix Converter to reduce electricity theft at the Low Distribution Voltage End. An indirect Matrix converter is used because there is no need for a large, bulky dc link electrolytic capacitor that increases system complexity; an indirect matrix converter is utilised because it ensures compactness and reliability. The indirect matrix converter converts AC-to-AC (from 50Hz to 10Hz-20Hz) at the output terminal of the distribution transformer. Hence, any connection without using the proposed add-on device in the energy meter, which converts the frequency, would make the electricity unusable. This work is designed and simulated using Matlab. For the converter's design, a frequency of 10 Hz was used. The result shows that the best mitigation frequency is to produce a worst-case with a Total Harmonic Distortion of 10Hz, giving a total harmonic distortion (THD) of 204.99%. If implemented, this would drastically mitigate electricity theft along the low distribution voltage end using a matrix converter.

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LIST OF ABBREVIATION

AC	Alternating Current
CCU	Consumer Care Unit
CT	Current Transformer
DC	Direct Current
DMC	Direct Matrix Converter
DVD	Digital Video Disc
EPSRA	Electric Power Sector Reform Act
ETPS	Electricity Theft Prevention System
FFT	Fast Fourier Transform
FLC	Fuzzy Logic Controller
GENCOS	Generation Company of Nigeria
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IMC	Indirect Matrix Converter
IoT	Internet of Things
LCD	Liquid Crystal Display
LV	Low Voltage
MC	Matrix Converter
MCU	Microcontroller Unit
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MW	Mega Watt
NERC	National Electricity Regulatory Commission
NESI	Nigerian Electricity Supply Industry
NTL	Non-Technical Losses

PLC	Power Line Communication
PWM	Pulse Width Modulation
RMS	Root Mean Square
TCN	Transmission Company of Nigeria
THD	Total Harmonic Distortion
TL	Technical Losses

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

Electricity is crucial in many aspects of daily life to power electrical gadgets that facilitate human work or activity. Based on its usefulness, utility corporations are very concerned about the efficient and effective use of electricity globally. Electricity theft is how the cost of power for customers and utility businesses is negatively impacted (Arkorful, 2022; Mihret and Ojo, 2011; Saeed *et al.*, 2020). Electricity theft is the use of electricity from a utility company without a contract or valid obligation to alter its Measurement (Smith, 2004).

From a commercial standpoint, electricity theft causes financial losses for the utility. Some may contend that huge utilities that offer necessary services provide substandard service, overcharge, and make too much money regardless; as a result, a small amount of theft will not bankrupt the business or significantly impact its operations and profits. Others looking at the same situation would say that theft is a crime and should not be tolerated. To prevent power theft, particularly for the financial security of power utility companies, the International Utilities Revenue Protection Association was founded (Wabukala *et al.*, 2023).

The impacts of theft in the worst-case scenarios are crucial to the sustainability of the offered services. Utilities are forced to operate at a loss and raise electricity prices due to some systems' cumulative losses (including non-payment of bills) (Arkorful, 2022; Otuoze *et al.*, 2022; Wabukala *et al.*, 2023). The electricity utilities struggle to provide dependable service because they are trapped in a culture of inefficiency and corruption. Electricity theft accounts for 10–40% of the entire generation capacity in many developing nations. For example, power utilities in India lose much money due to the approximately 420 MW of electricity stolen yearly. Electricity thieves can be found in nearly every country, including the US. Whether it's performing illegal hookups or tampering with meters, over $200 billion in electricity is lost each year due to equipment failure or electricity thieves in the US alone (Olaoluwa, 2017). Electricity theft in Nigeria causes enormous financial losses that negatively affect the activities of Power Distribution companies (Obafemi *et al.*, 2021). Electricity theft significantly impacted the Nigerian Electricity Supply Industry's (NESI) debt profile in Nigeria. Electricity theft costs Nigerian distribution companies around 174 billion nairas per year, according to Business Day 2017.

Consequently, the financial viability of the electricity business is diminished, and new investment in the sector is decreased. This impacts the distribution company's ability to fulfil its financial commitments and advance its plans for network development and service quality enhancements. In addition, the liquidity issues brought on by energy theft also affect other segments of the power network, including consumers, generating companies (GENCOS), and transmission companies (TCN) (Obafemi *et al.*, 2021).

In Nigeria, electricity theft is not subject to the same harsh penalties as other offences. However, more severe measures have lately been established to deal with those who participate in unauthorised electrical hookups in Nigeria. The electric power sector reform act (EPSRA section 96(1)) created Nigeria Electricity Regulatory Commission (NERC) as a regulatory agency with the primary responsibility of developing policies to prevent electricity theft.

Furthermore, section 94 (3) of the electric power sector reform Act (EPSRA) states that "Anything contained in any other law, any person who willfully destroys, injures or removes equipment or apparatus of a license commits an offence and is liable on conviction to imprisonment for not less than five (5) years and not more than seven (7) years". In every power system, electricity theft can never be completely eliminated. The highly effective systems in Japan, Western Europe, and North America have made great efforts to employ the administrative and technology techniques required to decrease theft to tolerable levels (Obafemi *et al.*, 2021). The governance culture in which many of these systems function encourages organisational effectiveness and theft law enforcement. Although few will attempt to steal electricity, this does not always mean that customers of power companies love them. Diverse power system defence mechanisms exist against theft. Some businesses pay little attention to theft issues, hoping that it will disappear and not become a public problem. Other power systems give the top importance to preventing electricity theft. Learning about the theft issue is the first step in reducing electricity theft. However, despite the rules and laws in place, electricity theft remains a problem for Nigeria's power industry. Meter bypass and unauthorised hookups are Nigeria's two most typical types of power theft (Smith, 2004).

An illegal hookup connection is made by attaching a connecting wire, commonly called a service wire to distribution lines. This can have an impact on the distribution networks' supply quality. Additionally, this adds to the load on the distribution transformer and raises the unmetered users' bill charges. An unauthorised hookup connection on overhead distribution cables is seen in Figure 1.1. The illustration depicts a distribution line with four conductors, three of which stand in for the phases, and the fourth serves as a neutral. This type of connection is prohibited and causes substantial harm to the lines and overall distribution network. When there is wind, which disrupts the system, arcing occurs at the point of hooking. Additionally, it results in an overloaded distribution transformer. The utility company suffers huge revenue losses because the unregistered customer will not pay for their respective consumption (Hardianto and Akbar, 2021).

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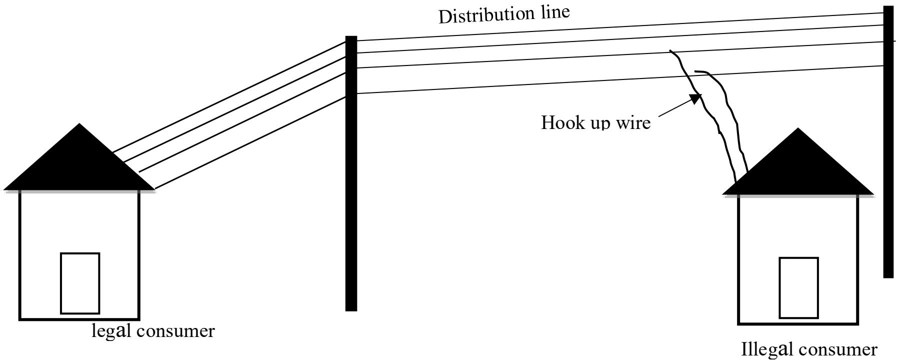


Figure 1.1: Illegal hook-up connection (Jaiswal and Ballal, 2020)

Meter bypass, which is a deliberate act of tapping electricity without the meter reading all the consumers' consumption and results in paying less for the total consumption by fiddling with the meter installation for the customers, is another way energy theft occurs along the distribution lines, as shown in Figure 1.2. These result in unpaid electricity bills, which lowers the utility providers' overall revenue (Blazakis *et al.*, 2020). Additionally, this causes the distribution transformer to be overloaded, which may harm the installed distribution transformer(Shokoya *et al.*, 2019).

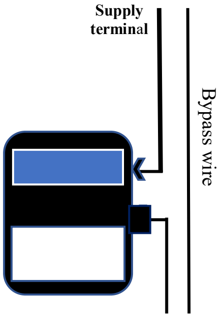


Figure 1.2: Meter bypass (Jaiswal *et al.*, 2020)

Several measures have been suggested and put into practice to lessen power theft. These tactics, however, have not helped to tackle the issue. Technical and non-technical mitigation strategies are the two types (Blazakis *et al.*, 2020; de Souza Savian *et al.*, 2021). While the technical strategy uses electrical circuit constructions to reduce electricity theft, the non-technical approach focuses on community policing and public awareness efforts. Nevertheless, the methods have significantly decreased electricity theft (Evwiekpaefe and Adamu, 2022).

In contrast, the indirect matrix converter is taken into account in this study because, in contrast to the direct matrix converter, it provides better voltage regulation and frequency regulation because of its simpler commutation strategy, which ensures compactness and reliability and does away with the need for a sizable dc link electrolytic capacitor that increases system complexity. In addition, direct matrix converters convert AC to AC power in a single step, unlike indirect matrix converters, which break the process into two stages—rectification and inversion. The rectifier step supplies a fictitious DC connection voltage with a variable average.

The switching pattern is produced including Venturini, space vector, and saw-tooth wave modulations. Nevertheless, a matrix converter requires precise Pulse Width Modulation (PWM) methods to manage the system autonomously. Furthermore, carried-based or duty ratio-based PWM methods are possible (Depuru *et al.*, 2011).

The motivation for this study stems from the fact that electricity theft brought on by pole taping and energy meter bypassing has posed a substantial challenge to the stabilisation of the power supply and has also resulted in a large loss of revenue for the Nigerian power industry.

This work proposes using indirect matrix converters to alter the frequency between the distribution network transformer and the consumer premises to decrease power theft. The frequency range of illegal clients is 10 Hz to 20 Hz, but the frequency range of legal customers is 50 Hz. Distribution at frequencies between 10Hz and 20Hz is much lower than the typical distribution frequency, which will undoubtedly cause a systemic disturbance. Electricity theft along the line can be reduced with the help of this disturbance. This proposed model aims to offer a practical strategy for preventing electricity theft brought on by hook-line and meter bypass activities. Outlawing activities like hook-lining and meter bypassing, it also prevents the distribution network from becoming overloaded and increases the lifespan of the electricity system. Throughout this study, this model will be thoroughly examined offering research foundations for those studying electrical power systems planning and economics. The use of this method will mitigate electricity theft.

1. 2 Statement of the Research Problem

In a deregulated power system, the task of acquiring electricity from the Transmission Company and reselling it to the consumers falls on distribution companies. This was anticipated to be accomplished using an energy meter. However, energy meters can no longer be used to gauge consumer consumption because consumers and distribution personnel are involved in electricity theft (Hashmi, 2015). The utility company's revenue generation, as a result, has been dismal. This makes it impossible for utility companies to purchase enough electricity to supply consumers (Jaiswal *et al.*, 2020). Although many efforts have been made to reduce electricity theft, it still exists(Jadeja, 2015). Thangalakshmi *et al.,* (2015) presented a power theft prevention system that senses and mitigates unregistered load tapping on the distribution network. It detects the illegal connection before enabling the mitigation of the illegal act. The detection before cutting off illegal consumers is a gap that this proposed work seeks to address. It focuses on addressing the identification and disconnection of legitimate consumers before mitigating electricity theft.

1.3 Aim and Objectives

This work aim to mitigate electricity theft at low distribution voltage end using an indirect Matrix Converter. The objectives are to:

i. Design a Matrix Converter at different frequencies.
ii. Develop a Matrix converter model
iii. Simulate the developed model in (ii) above using MATLAB (2021 version)
iv. Examine the effects of the frequencies on Resistive, Capacitive, and Inductive Load

1. 4 Scope of the Work

This work seeks to technically mitigate electricity theft at the low distribution voltage end. Any practice of electricity theft between the distribution transformer and the point of use by consumers is the extent of coverage by this work. The three-phase distribution line is considered in this work. The converter circuits are not standalone but add-on circuits to the existing transformers and board of the energy meter. The indirect matrix converter model will also be modelled. The model will be simulated using MATLAB (2021 version), and the effect of frequency variations on the distribution load will be studied. The prototype will be constructed and tested. The result of the construction will be compared with the simulated result.

1.5 Justification for the Study

Electricity theft along the distribution network has affected the revenue of utility companies and the quality of electrical power supply to consumers. Various technical attempt has been made to stop the practice of electricity theft along the distribution network, nonetheless the illegal practice is still taking place (Aminu, 2020). The previous work concentrated on detecting before mitigation, but this work will present a work whereby there is no need for detection before mitigation (Blazakis *et al.*, 2020). This work onthe mitigation process will be incorporated into the distribution signal even before distribution at the distribution transformer. This will mitigate electricity theft along the distribution network.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Historical Background on Electricity Theft and its Mitigations

The stealing of electrical energy is known as electricity theft. It was revealed in New York on March 27, 1886, that some dishonest people were illegally tapping into Edison's electricity (Dindar, 2022). The power plant's superintendent then intervened to stop this action by delivering a surge into the line to disable all unlawfully connected devices. The biggest problem the distribution company had ever faced was electricity theft. Electricity theft has taken the form of illegal direct connections, meter fraud or bypass, irregular invoicing, and unpaid bills (Dindar, 2022; Mohammad *et al.*, 2017).

In contrast to other types of crime, electricity theft rarely carries harsh penalties (Nizar *et al.*, 2008). Recently, more severe measures have been developed to handle persons involved in the illegal extraction of electrical energy in Nigeria. There are numerous ways to access electrical power unlawfully. Electricity can be unlawfully accessed through illegal direct connections, meter fraud or bypass, billing problems, and unpaid bills. Some types of electricity theft are linked to high hazards like electrocution and electrical fire incidence. Meter bypass takes place due to portioning the building's wiring design to avoid going through the meter. Similar to meter tampering, this is not easy to discover. By paying bribes to utility authorities, billing inconsistencies are signs of corruption within the utility company. Usually, the utility personnel taking the meter reading gets reimbursement for not reporting the facility's precise power usage. All socioeconomic classes regularly avoid paying their power utility bills. Since they can disconnect clients for outstanding bills, the utility company has great control over this. Disconnections frequently signal the beginning of another type of energy theft. Power theft is a significant issue that, if not controlled and mitigated, can impede the expansion and development of the distribution company's business (Smith, 2004).

2.2 Types of Electricity Theft

Numerous types of electrical power theft exist, such as energy meter bypass or illegal connection to a power line. According to Nizar *et al.*, (2008), 80 percent of global energy theft occurs in residential environments and 20% on commercial and industrial premises. Some of the various types of electrical theft are discussed as follows:

2.2.1 Direct hooking from line

The most frequent method of electricity theft is direct connection. Power theft from the electrical power line accounts for over 80 percent of all thefts worldwide. Here, customers are attached to a power line before the energy meter. It is possible to obtain this unmeasured energy consumption with or without switches as shown in Figure 1.1 (Li *et al.*, 2019).

2.2.2 Bypassing the energy meter

This form of energy theft involves connecting the energy meter's input and output terminals to end the energy meter from recording the amount of energy consumed by the consumer. (Li *et al.*, 2019).

2.2.3 Injecting foreign element into the energy meter

This method involves the manipulation of energy meters via a remotely installed circuit inside the meter, thereby slowing the meter reading at any time. Since the meter is always accurate unless the circuit is activated, this alteration can elude attempts at external scrutiny.

2.2.4 Physical obstruction

This entails manipulating a rotating electromechanical meter such that a foreign object is put inside the energy meter to slow down the disc from freely rotating, resulting in a slower revolving disc and lesser energy consumption. (Li *et al.*, 2019).

2.2.5 Electrostatic discharge (ESD) attack on the energy meter

This energy theft causes either latent harm or permanent damage to an electronic meter. Only sophisticated meters can reliably detect it (Dendouga, 2020).

2.3 Matrix Converter

A new form of direct power converter called a matrix converter controls the output voltage, amplitude, and frequency. Regardless of the load, it has an adjustable power factor to manage the input. Matrix converters can operate at high temperatures, improve reliability, manage input and output current and change voltage sine waves with a movable phase shift since they do not require bulky, prone-to-failure capacitors (Varajão and Araújo, 2021). These are regarded as a few benefits of this category of converters. One extra benefit above the ones just mentioned and over other converters is the ability to control output voltage, amplitude, and frequency. These benefits encourage the incorporation of this innovative topology in various industrial application fields. There are two types of matrix converters, namely: direct matrix converters and indirect matrix converters (Wheeler *et al.*, 2002).

2.3.1 Matrix converter structure

A matrix converter is an electronic device that can transform electrical power from one form to another (from AC to DC and DC to AC). Fundamentally, the matrix converter (MC) is made up of Nine (9) two-directional switches, (Varajão and Araújo, 2021; Wheeler *et al.,* 2002) as seen in Figure 2.1, the dots on the grid represent a direct connection between the output and input terminals. A three-phase voltage source supplies power to the converter's input side, and its output side is connected to an inductive load such as an induction motor and clippers (used for hair cut).

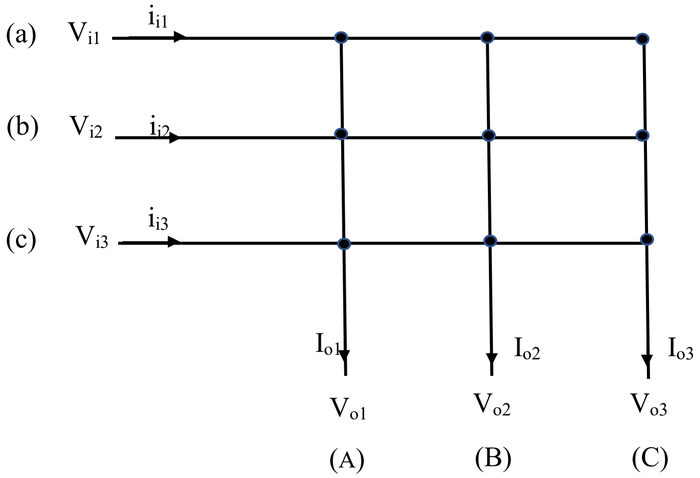


Figure 2.1: Basic scheme of matrix converter (Nizar *et al*., 2008)

V_{i1}, V_{i2}, and V_{i3} are the input voltages on the three-phase line, and I_{i1}, I_{i2}, and I_{i3} are input currents on the three-phase lines, respectively. These voltages and currents are the signals at the distribution transformer's output terminal, which is electrically linked to the converter's input terminal at the distribution point. V_{o1}, V_{o2}, V_{o3}, and I_{o1}, I_{o2}, and I_{o3} are the converter circuit output voltages and currents, respectively (Wheeler *et al.,* 2002). These output parameters become the distribution line parameters.

2.3.1 Direct matrix converter

Cyclo-converter was the first direct matrix AC-AC converter that could produce low-frequency AC output voltage waveforms from alternating higher-frequency parts of an AC source (Dendouga, 2020). This converter design, however, has a restricted output frequency range, a low input power factorand substantial distortion in both the input and output waveforms because of the inherently commutated device feature. As completely controlled power semiconductor devices advanced quickly, a force-commutated cyclo-converter, also known as a matrix converter, emerged as a potential method for converting direct AC to AC power. The matrix converter topology may produce varied output voltages with unconstrained frequency from an AC voltage supply by using the completely regulated bi-directional switches to connect the inputs directly to the outputs (Nizar *et al*., 2008).

The main justification for the popularity of Matrix Converter**s** (MC) Is that it offers a small-footprint alternative to a four-quadrant converter that delivers sinusoidal input and output without using passive components in the DC link. However, the lack of a DC connection has drawbacks in that input and output disturbances are not adequately filtered, and additional commutation methods are needed to prevent a bridge of the supply voltage (Christopher *et al.*, 2014).

Matrix converter has advantagesover traditional rectifier-inverter converter types. With fewer high-order harmonics and no subharmonics, the matrix converter creates sinusoidal input and output waveforms. It also uses fewer energy storage components, eliminating the need for massive and limited-lifetime energy-storing capacitors (Nizar *et al*., 2008).

However, the matrix converter also has significant drawbacks. Compared the ordinary indirect power frequency converters, power frequency conversion requires many components (Aryanezhad, 2019; Christopher Alwin *et al.*, 2014).

2.3.2 Indirect matrix converter (IMC)

An indirect Matrix Converter (IMC) is made up of the rectifier stage and an inverter stage (Ammar *et al.,* 2020) as shown in Figure 2.2. it offers the choice to reduce the number of switches in the line bridge to three if bi-directional power flow is unnecessary. Smooth variations in converter output voltage are produced by safe semiconductor device commutation.

The rectifier stage converts the incoming AC signal to a DC voltage (V_{dc}) at a frequency of 50Hz. The inverter stage converts the DC signal (V_{dc}) back to the AC signal at a varied frequency (Ammar *et al.*, 2020). The six switches *Sap, Sbp, Scp, San, Sbn, and Scn* are the rectifying switches, while the other six switches *SAp, SBp, SCp, SAn, SBn, and SCn* are the inverter switches.

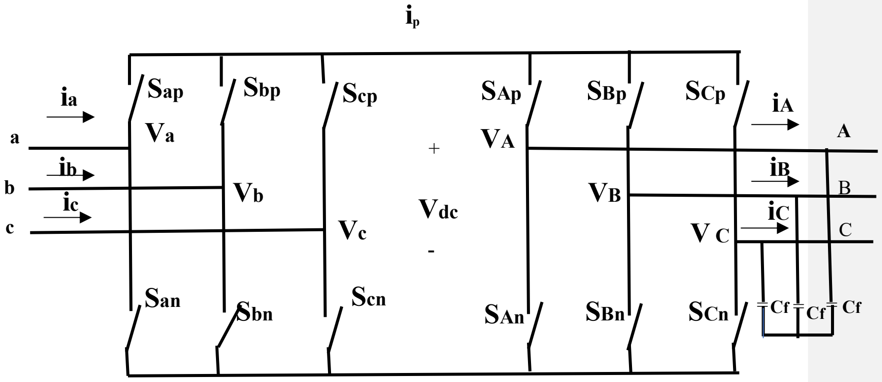


Figure 2.2: An Indirect Matrix Converter (Mihret and Ojo, 2011)

2.4 Types of Load across the Distribution Network

Inductive, capacitive, and resistive loads are the three primary types of loads connected in the distribution section. These loads use electricity in various ways when connected to an alternating current (AC) network. These loads are sometimes called "linear" and "nonlinear" loads.

2.4.1 Resistive loads

The load which consumes only active power is called a resistive load. Moreover, if you look at the voltage and current waveforms of such load, it could be found that the voltage & current are perfectly in phase. Resistive loads are loads that include a heating element. These loads include space warmers, toasters, pressing irons, incandescent lights, ovens, and coffee machines (Mihret and Ojo, 2011).

2.4.2 Inductive loads

The load which consumes only reactive power is called an inductive load.Moreover, if you look at the voltage and current waveforms of such load, it could be found that the voltage & current are out of phase by 90 degrees. These loads include fans, DVDs, vacuum cleaners, dishwashers, washing machines, compressors in refrigerators, and air conditioners. Compared to resistive loads and a purely inductive load, the current follows a sinusoidal waveform that reaches peaks after the voltage sine wave reaches peaks, but the maximum, minimum, and zero points are out of phase (Mihret and Ojo, 2011).

2.4.2.1 Effect of low frequency on inductive loads

Considering an electric motor as an example of an inductive load, a lower frequency than the rated frequency decreases the speed of the motor, the locked-rotor torque of the motor will increase, and the power factor will also increase. (Mihret and Ojo, 2011).

2.4.3 Capacitive loads

Current and voltage in capacitive loads behave similarly to an inductive load in that they are out of phase. Inductive and capacitive loads differ because the maximum current value is reached before the maximum voltage. However, when a load is inductive, the current waveform lags the voltage waveform instead of leading it (Depuru *et al.*, 2011).

Capacitive loads in electrical engineering are not constructed in a standalone manner. In the same way, air conditioners are labeled as inductive and lightbulbs as resistive, and no devices are designated capacitive. However, large networks can benefit from using capacitors to manage power consumption. They are frequently included in electrical substations to raise the network's overall "power factor." Capacitors can be fitted to counteract this depletion, but inductive loads raise the cost of a power system and decrease the amount of power that can be used (Depuru *et al.*, 2011).

2.4.3.1 Effect of low frequency on connected distribution load

At low frequencies, the connected loads will be affected in various ways. This effect on the three basic load typesis discussed in the sections below.

2.4.3.2 Effect on capacitive load

Capacitors are frequently used in electrical power systems, including transmission networks and commercial and industrial systems, as devices for power factor adjustment. Even though it is a fundamental part of a harmonic filter (in addition to the reactor), it is nevertheless susceptible to the negative effects of harmonics. High harmonic distortion levels in a power supply make capacitor banks susceptible to failure (Dangar and Joshi, 2015).

The low-frequency signal's introduction of harmonics has effects on capacitors, including increased heating, overloading, dielectric or voltage stress, and undesired losses. In addition, the presence of harmonics and capacitors in a system may result in harmonic resonance, a more severe power quality issue that can cause significant injury. As a result, these adverse consequences will reduce capacitor life.

A capacitor is intended to run at a maximum of 135% of its reactive power (kVAR) values, following IEEE 18-2002. In addition, a continuous RMS over voltage of 110%, a peak overvoltage of 120%, and an overcurrent of 180% of name plate rating must also be tolerated. The percentages mentioned above can guide establishing the maximum permissible harmonic levels even if the standard does not specify the limitations for individual harmonics (Dangar and Joshi, 2015).

The reactance of a capacitor bank is inversely proportional to the frequency, as shown in equation 2.1

$$Xc = \frac{1}{(2\pi fC)} \tag{2.1}$$

where:

Xc = Capacitive reactance

C = Capacitance

f = Frequency

The capacitor bank consequently behaves like a sink, drawing in unfiltered harmonic currents. This impact makes the capacitor units more susceptible to thermal and dielectric stresses, which leads to overload.

System resonance is a potential side effect of low-frequency electrical power distribution in an electrical power system. A harmonically rich environment has both types of harmonic resonance, which can be categorised as parallel or series resonance in a power system. While series resonance results in voltage magnification, parallel resonance increases current. If the amplitude of the offending frequency is large enough during resonant conditions, significant damage to capacitor banks will follow. In addition, there is a tendency that other electrical components of the system might suffer harm. Installing a power factor correction capacitor bank must therefore be preceded by a harmonic analysis to ensure resonance frequencies do not coincide with major harmonics present in the currents and voltages.

2.3 Related Works

Previous works done on the mitigation of energy theft are reviewed in this section. Mohammad and Dar, (2018) employed power signal encryption to stop "power robberies in distribution systems. "The distribution transformer's secondary sides employ power semiconductor switching systems to pass three phases (Red, Yellow, and Blue) and neutral through a semiconductor-based switching system. First, a microcontroller creates a bit sequence for switching purposes. Then, using RF transmitter-receiver synchronisation, the load circuit in a smart meter generates the same bit sequence. An encrypted power signal that cannot be used to power household appliances travels down the power line between the distribution transformer and the energy meter to prevent unauthorised power line tapping.

(Prachal, 2015), developed a circuit that prevented energy theft by disconnecting the electrical supply of consumers if there was any detection of energy theft along the distribution line so that the consumers would have to notify the electricity board to be reconnected to the main supply, thereby exposing and disconnecting illegal users. The circuit is cost-effective. It contains components such as optocouplers, relays and sensors.

Smith (2004) proposed two methods of preventing electricity theft such as technical/engineering methods and managerial methods. Under the technical method, he concentrated on meter tampering and suggested tamper-proof meters. The meter would be sealed so that it could be tampered with, while in the management method, an approach to inspection and monitoring was adopted, and in some instances, power system reorganisation occurred as well. Strong technological advancements combined with a proactive and clever anti-theft program may result in considerable improvements. Reducing electricity theft in the distribution system requires routine inspection and monitoring of power users.

(Depuru *et al.*, 2011), proposed an architectural work of a smart meter, external control station, unwanted signal generator and filter circuit. Energy conservation and efficient use are core objectives of the research. Data on a variety of characteristics relating to instantaneous power consumption were provided by smart meters. An external control station used data from the sending end of the distribution feeder to calculate non-technical losses (NTL) in the feeder. If a large volume of NTL is discovered, a harmonic generator is activated at that feeder to introduce an additional harmonic component for disabling the appliances from unlawful customers, thereby mitigating electricity theft along distribution lines.

(Hashmi and Priolkar, 2015) employed a conceptual technique to determine the area's general location and the estimated amount of energy theft that could occur there. Utilising power line communication, the two parties have access to real-time information. It transmits data across power lines using high-frequency carriers. The information being transferred has no impact on the AC power signal. A receiver filters information sent by a distant sender.

Additionally, electricity theft detection is employed with modern metering infrastructure with power line communication capacity through specialised sender and receiver. Following each other, Meter One and Meter Two exchange signals. Upon acknowledgement, meter two transmits it to the central station. If none of the electrical meters along the line are tapped, then the Power Line Communication (PLC) signal will not deteriorate; the filtered PLC signal is compared to a base signatureto determine the level of degradation. However, if there is a tap, the signal transmitted by meter one is tampered with at the hooking point. At the meter two receivers, the distorted signal is then picked up. It notified the central station of the signal corruption and identified it. Then, disconnection of supply can now be initiated, thereby cutting-out illegal tapping.
(Jaiswal *et al.*, 2020) proposed a real-time electricity theft detection method that used data on the energy usage of all authorised users and information from the transformer energy meter of outgoing distribution lines to prevent hookup behaviour using a fuzzy inference-based strategy that was deployed in Lab View to manage an electrical theft prevention system (ETPS). The anti-theft system for electricity generates an inappropriate voltage

for unlawful consumers, which interferes with the proper operation of their appliances. Consumer care unit (CCU) and electricity theft prevention system interlocking maintained normal supply voltage at the end of the legal consumers.

(Rengarajan and Loganathan, 2012) presented a current sensor to measure the current value on the side of the actual load. The current value is delivered to the node MCU via the Internet of Things (IoT) platform (microcontroller unit). The mode MCU was configured for a specific amount of current. If the current value is exceeded, power theft has occurred. There will be an LCD. With the occurrence of electricity theft, information is passed to the PC of the control room where Personnel can now be sent to locate the point of illegal tapping for disconnection.

(Mohammad *et al.*, 2017) introduced Encoding and decoding techniques for analogue signals. This technique prevented illegal electrical power theft on distribution lines. This method involved encoding the output of the distribution transformer before distributing it to the consumers. Then decoding also occurred at the customer end by incorporating a decoding circuit within the smart meter. Using encoded power signals that could not be utilised to power household appliances, the power line between the distribution transformer and the energy meter is safeguarded from unauthorised distribution line tapping.

In 2020, (Muthunagai and Rajkumar, 2020) deployed a microcontroller system and radio communication strategies together for detecting theft of power consumption to provide a reliable real-time electrical power monitoring system; it controls and samples alerts to the nearby substation. Receiving and transmitting portions comprised the entire detecting and controlling process, with the former deployed at the consumer end and the latter at the local electrical station. An ATMEGA644P microcontroller and GSM were used to develop the automobile system to transfer the data gathered from the sensors (current, voltage, and frequency) to the transmitting end. A computer at the local station, which was located at a distant location, displayed the monitored signal. Controlling operations were carried out to prevent electricity theft based on the information obtained.

(Ogu *et al.*, 2016) developed an embedded system that used Internet of Things technologies to thwart electricity theft. This system's networking and controller functions were handled by an Arduino Wi-Fi Shield 101 installed on top of an Arduino Mega 2560 board, while sensing and activation were handled by a passive infrared sensor and solid-state relay. This work was a feature of an "Internet of Things-based system," which could identify tampering and disconnect any unauthorised users. It notified the distribution business portal of the meter's GPS location.

(Majid, 2019) Used an online approach to perform theft detection and electricity pilferage prevention system (EPPS) to generate various voltage amplitude of unsuitable supply voltage for random time intervals to unregistered load depending on the voltage regulation of the power distribution network after which a consumer supervision unit (CSU) disconnect the detected illegality.

(Sridhar *et al.*, 2016) demonstrated a straight forward design for a single-phase power theft identification alarm system that used a real-time comparison technique to compare the current (I_1) at the incoming side of the energy meter with that of the load side (I_2). If there has been a power theft, the I_1 will be greater than I_2, and the system will immediately transmit a real-time signal to the electricity board through the internet. The load was remotely disconnected by electricity board staff when the notification was received on a smartphone.

(Christopher *et al.*, 2014) used Arduino-based power theft detection and protection system where an AC5712 series current sensor was introduced as the interfacing instrument between the power current and the Arduino. In addition, a power theft system relay was used as a switching gear to mitigate power theft on the power line. The Arduino-based power theft detection and prevention system controlsthe operations of all connected devices by detecting and preventing electrical power theft. This operation was performed through the communication channel, in which the server received messages when users bypassed the meter. It also provided billing activity in addition to the detection and protection of power theft.

Using fuzzy logic, (Rengarajan and Loganathan, 2012) built a system for preventing power theft and improving power quality. The error signal was used to pin point the power theft when comparing the total load that the distribution transformer supplied with the total load that the customer consumed. To increase quality and stop power theft, load (energy) and voltage are sent into the fuzzy logic controller as inputs, and the controller then changes the output voltage in accordance.

(Jaiswal *et al.*, 2020) proposed using an energy meter at the transformer output point and the legal consumer end to take readings. The data were reconciled to determine real-time illegal collections. However, the normal operation of their appliances was hampered by an electricity theft prevention system (ETPS) attached to produce an inappropriate voltage across unauthorised consumers. A consumer care unit (CCU) interlocked with the ETPS maintained the regular supply voltage at the legal consumers' end.

(Nagi *et al.*, 2008) used an online technique for detecting theft and an electricity theft prevention system (EPPS) to provide a varying voltage amplitude of an improper supply voltage for a random time to an illegally connected load dependent on the voltage regulation of the power distribution network. Afterwards, a consumer surveillance unit disconnected the observed unlawful (CSU).

(Akram *et al.*, 2021) used a novel Convolution Neural Network (CNN) with RUSBoost Manta-Ray Foraging Optimization (rus-MRFO) and RUSBoost Bird Swarm Algorithm (rus-BSA) models to mitigate electricity theft, which proved to be very innovative.

A power theft detection and protection system based on Arduino was used by (Mangat *et al.*, 2021) The device used to interface the electrical current and Arduinowas an AC5712 series current sensor. Switching equipment for a power theft system relay was used to reduce power theft on power lines. Arduino managed every action that every device took by identifying and stopping power theft. The server that received the message when users bypassed the meter was used to carry out this activity. Along with the detection and defence against power theft, it also offered billing activity.

To automatically detect electricity theft, the authors of (Alalem *et al.*, 2019) introduced a novel hybrid convolutional neural network-random forest (CNN-RF) model designed to learn the characteristics of different days and hours of the day from vast and changing smart meter data using convolution and downsampling. The backpropagation technique was used to update network parameters during the training phase, and a dropout layer was introduced to reduce the danger of overfitting. The random forest (RF) was then trained using the acquired features to determine whether the consumer stole electricity.

However, the indirect matrix converter was taken into consideration in this study because, unlike the direct matrix converter, it offered better voltage regulation and frequency regulation due to its simpler commutation strategy, which guaranteed compactness and reliability and eliminated the need for a large dc link electrolytic capacitor that increased system complexity (Oyama *et al.*, 1989). In contrast to indirect matrix converters, which divided the process into two stages—rectification and inversion—direct matrix converters converted AC to AC power in a single step. The rectifier stage provided an imaginary DC connection voltage with a fluctuating average.

Various ways exist to create the switching pattern, including Venturini, space vector, and saw-tooth wave modulations. Nevertheless,a matrix converter needs accurate Pulse Width Modulation (PWM) techniques to regulate the system independently. Furthermore, PWM schemes can be carried-based or duty ratio-based (Tola *et al.*, 2021).

(Soma, 2012) presented an encoding technique that simplifies the received customer energy consumption readings (patterns) and maps them into corresponding irregularities in consumption. The encoding technique preserves exclusivity in energy consumption patterns. Furthermore, the encoding technique saves significant CPU time in the PREVIEW iv real-time analysis and classification of customers, decreasing the memory required to store historical data. Then, this dissertation elucidates the operation of intelligent classification techniques on customer energy consumption data to classify genuine and illegal consumers. These classification models are applied to regular energy consumption and encoded data to compare corresponding classification accuracies and computational overhead. The limitation discovered with this technique is the need for High-Performance Computers (HPC) with a large storage space required to implement this technique.

In summary, most of the previous works reviewed on mitigating electricity theft first detect illegal connections, and sometimes the energy consumed illegally before action was initiated to disconnect the power supply or report the illegal connection as strategies to mitigate electricity theft. However, if implemented, this work mitigated electricity theft right from the distribution transformer and need not detect theft before mitigation and prevent energy loss.

CHAPTER THREE

3.0 MATERIALS AND METHODS

This chapter centred on the methodology employed in the design and development of an indirect matrix converter. Indirect matrix converter design, the model, simulation and construction of the prototype are discussed here.

3.1 Conversion at the Distribution Transformer Point

Various devices, such as cyclo-converters, matrix converters, and six-step converters can alter the frequency (Biswas, 2013). Conversely, the indirect matrix converter is taken into account because the matrix converter has received little to no attention. Furthermore, there will be a frequency between the distribution transformer and the consumer location in the range of 10 to 25 Hz. This can be accomplished by integrating an indirect matrix converter at the distribution end, which will step down the supply's frequency from 50Hz to a range of 10–25Hz.

This technique provides mitigation of electricity theft along the distribution line. The starting point of this technique is at the output of the distribution transformer, as shown in Figure 3.1.

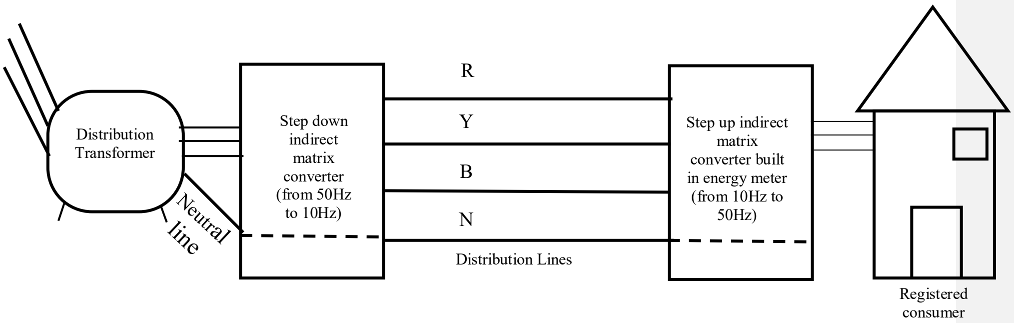


Figure 3.1: The Simplify Schematic of the proposed model

The matrix converter used is a frequency step-down indirect matrix converter. Three Phase output cables of the transformer are connected to the step-down indirect matrix converter as input. The matrix converter reduces the distribution frequency from 50Hz to a range of 10Hz. The output of the indirect matrix converter is a three-terminal cable. The neutral line of the distribution transformer is connected to the distribution lines, as shown in Figure 3.1. Each line carries voltage V_a, V_b, and V_c rated 230V and frequency 10-25Hz.The converter and distribution transformer are placed at the same site.

3.1.1 Step-down indirect matrix converter modelling

The voltage conversion splits into the rectifier and inverter stage with fictitious DC voltage and current links. A rectifier stage with six bidirectional switches coupled to a common emitter or common collector is part of the setup in Figure 3.2. Compared to other layouts, this one produces fewer switching and conduction losses; it has an intricate control system to manage the quantity of switches. As a result, various configurations are created to reduce the number of transistors needed, making it easier to monitor and manage the matrix converter.

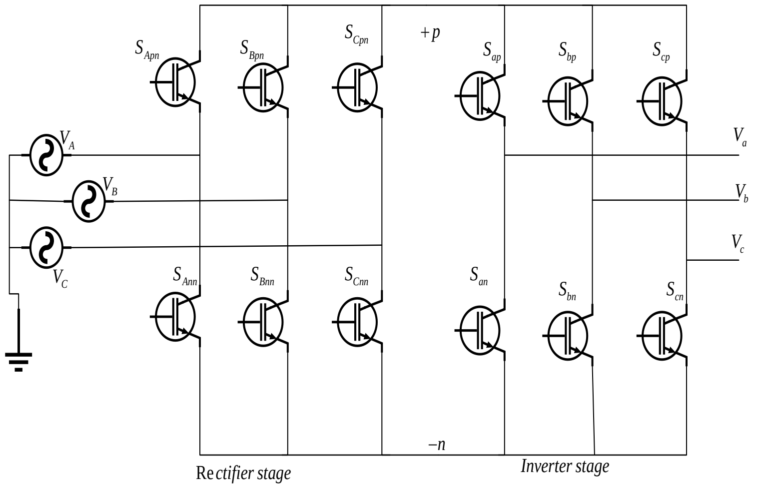


Figure 3.2: Indirect matrix converter

The voltages and currents (both input and output) are given by (3.1) and (3.2)

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.1}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \tag{3.2}$$

Where V_a, V_b, V_c are input voltages with an assumed value of 220V each in star connection, i_a, i_b, i_c: input currents, i_A, i_B, i_C: output currents and V_A, V_B, V_C: output voltages?

The voltage conversion splits into the rectifier and inverter stage described by the following expression as shown in (3.3) and (3.4)

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_{pA} & S_{nA} \\ S_{pB} & S_{nB} \\ S_{pC} & S_{nC} \end{bmatrix} \begin{bmatrix} S_{ap} & S_{bp} & S_{cp} \\ S_{an} & S_{bn} & S_{cn} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

(3.3)

$$V_{ABC} = S_{Inv} * S_{\text{Rect}} * V_{abc} \tag{3.4}$$

The rectifier and inverter comprise six switches. A parameter f_{ik} link between the input and output of each switch and given by (3.5).

$$\left.\begin{aligned} V_{ik} &= (1 - f_{ik})V_{ik}^* \\ I_{ik} &= f_{ik} I_{ik}^* \end{aligned}\right\} \tag{3.5}$$

where

$i \in \{a, b, c\}$, $k \in \{p, n\}$, V_{ik}^* is the supply voltage and I_{ik}^* is the output phase current

The switch is opened when $f_{ik}=0$ and closed if $f_{ik}=1$

The function of the switches must satisfy the following condition:

$f_{ip}+f_{in}=1$

Note that the phase voltages are given in (3.6)

$$\left.\begin{aligned} V_{ab} &= V_a - V_b \\ V_{bc} &= V_b - V_c \\ V_{ca} &= V_c - V_a \end{aligned}\right\} \tag{3.6}$$

However, equation 3.6 can be expressed to give (3.7)

$$\left.\begin{aligned} V_a &= \frac{1}{3}\left(V_{ab}-V_{ca}\right) \\ V_b &= \frac{1}{3}\left(V_{bc}-V_{ab}\right) \\ V_c &= \frac{1}{3}\left(V_{ca}-V_{bc}\right) \end{aligned}\right\} \tag{3.7}$$

Introducing the functions relating to (3.7), it gives (3.8)

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{pn} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} f_{ap} \\ f_{bp} \\ f_{cp} \end{bmatrix} \tag{3.8}$$

Substitute(3.8) into(3.7). it gives (3.9)

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{1}{3} V_{pn} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} f_{ap} \\ f_{bp} \\ f_{cp} \end{bmatrix} \tag{3.9}$$

The pulse width modulation (PWM) triangular-sinusoidal was used to compare the two signals. The first signal, a sine wave with the desired output frequency, is referred to as the reference wave and is far lower than the supply frequency. Therefore, the supply frequency of the sinusoid must be in phase with the frequency of the second signal, which is a triangular carrier.

This modulation strategy is based on two parameters, as shown in (3.10)

The modulation index is expressed as:

$$m = \frac{f_p}{f_r} \tag{3.10}$$

where= f_p is the frequency of the sine wave and f_r is the carrier wave frequency, and the tuning index is expressed as (3.11)

$$r = \frac{V_{m\_\max}}{V_p} \tag{3.11}$$

where$V_{m_\max}$ is the sine wave amplitude and V_p is the carrier maximum wave(3.12)

With $f_p(10 \quad 20)Hz$

$$\left. \begin{array}{l} f_{ap} = 1 \quad if \;\; V_m > V_p \quad and \quad V_m > 0 \\ f_{an} = 1 \quad if \;\; V_m < V_p \quad and \quad V_m < 0 \end{array} \right\} \tag{3.12}$$

The functions of the switches b and c are obtained by performing the same steps as performed on arm 'a' with shifts of the sine wave of $\frac{2\pi}{3}$ and $-\frac{2\pi}{3}$, respectively.

Any unauthorised client who tries to tap the transmission line will now have access to a supply with a frequency of 8–10Hz. Illegally connected appliances will suffer the worst possible harm.

3.1.2 Step-up indirect matrix converter modeling

The voltage conversion is divided into rectifier and inverter stages with a fictitious DC voltage link and DC link,as shown in Figure 3.1. the output and input voltages remain the same, as shown in (3.1). Likewise, the input and output currents remain the same, as shown in equation 3.2. the frequency output of the converter was what gives the indirect matrix its name, whether step-up or step-down indirect matrix converter. The modelling equation in (3.3) to (3.11) applies to the step-up indirect matrix converter, but the output sine wave frequency (f_p) is at 50Hz. This is because the amplitude of the sine wave $V_{m\_\max}$ is also 220 volts.

3.2 Cable Carrying Current at Distribution Network

The current-carrying conductors at the distribution network remain the same as the existing ones because the current and voltage ratings remain the same. The conductors must have an adequate spacing of about one foot (1ft) between one another, as shown in Figure 3.3, to avoid shunting along the overhead distribution network. The voltage along the line is 230V at 10-25Hz. The registered and metered customer will be connected at the point of use.

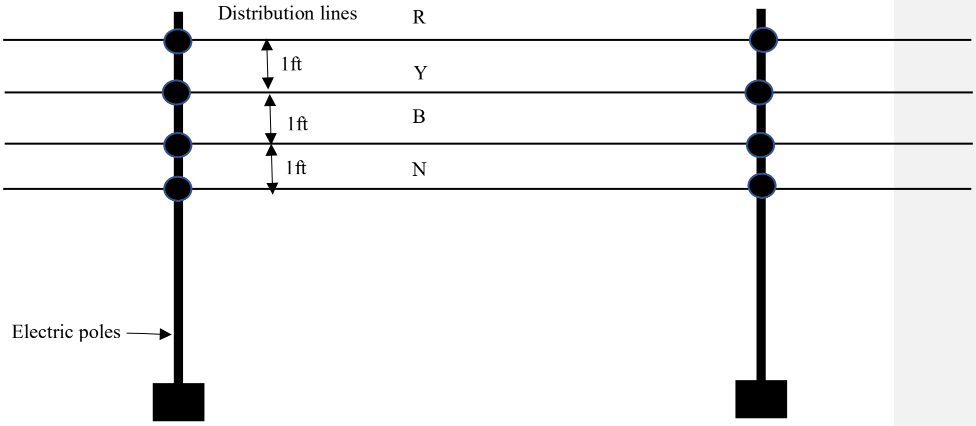


Figure 3.3: Overhead Distribution Line and their Spacing

3.3 Conversion at the Point of Use

This is the connection point where the metered customer is connected to the distribution network. In addition, a step-up indirect matrix converter is embedded in the energy meter. The matrix converter circuit comes before the measuring meter circuit to convert the signal frequency back to 50Hz before measuring the customer's consumption. The circuits are built in a permanently sealed casing to avoid illegal tampering with the energy meter. Any attempt to open the sealed casing will permanently damagethe energy meter.

If any illegal or unmetered customer connects to the distribution network either by hookup or energy meter bypass, an irritated power supply thatelectrical appliances cannot utilise will be received, thereby mitigating electricity theft.

3.4 Simulation Techniques

This mitigation technique was simulated using MATLAB (2021 version) Simulink. The indirect matrix converter was implemented in the simulation, as seen in Figure 3.1. The gates of the semiconductor switches were controlled systematically using a microcontroller. The AC-to-AC conversion was implemented at various sine wave frequencies of 10Hz, 15Hz and 20Hz. The result of this implementation was examined on a voltage amplitude (V_m) to time (sec) graph, as shown in chapter four of this work. In addition, the magnitude of disturbances at various harmonic orders was plotted to observe the total harmonic distortion (THD) at various frequencies.

3.5 The Construction of Prototype

The block diagram in Figure 3.4 shows how the prototype operates and is constructed. Figure 3.5 shows the circuit diagram of the system. A matrix converter (indirect) circuit is pictorially shown in plate 3.1. The CD4049 is a NAND gate component that generates the frequency to drive the CD4017 (an8-bit counter). 3-bitsout of the 8 are used for the counter functionwhile the 4th bit is connected to the reset pin. The three outputs pin of the CD4017 counter were connected to a pair of half-bridge transistor drives. The transistor is an MJE13003 transistor suitable to handle and drive high voltage pulse. The driver is of three pairs, making it to be a three-phase signal generator. The driving frequency can be varied by adjusting the variable resistor connected to the NAND gate to generate a pulse.

The transformer's output will be converted to DC with the help of the three-phase rectifier section, which will convert the AC to DC using power transistors. The signal drivers need 12 volts to power it from a step-down transformer (220 volts to 24 volts DC), and a voltage regulator regulates the voltage from 24 volts to 12 volts.

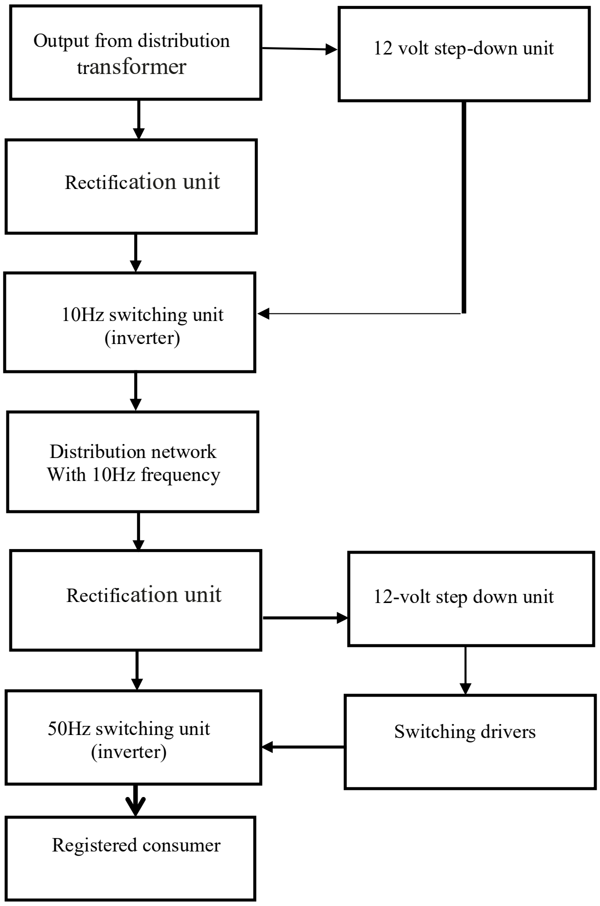


Figure 3.4: Block diagram for prototype construction

Circuit Diagram

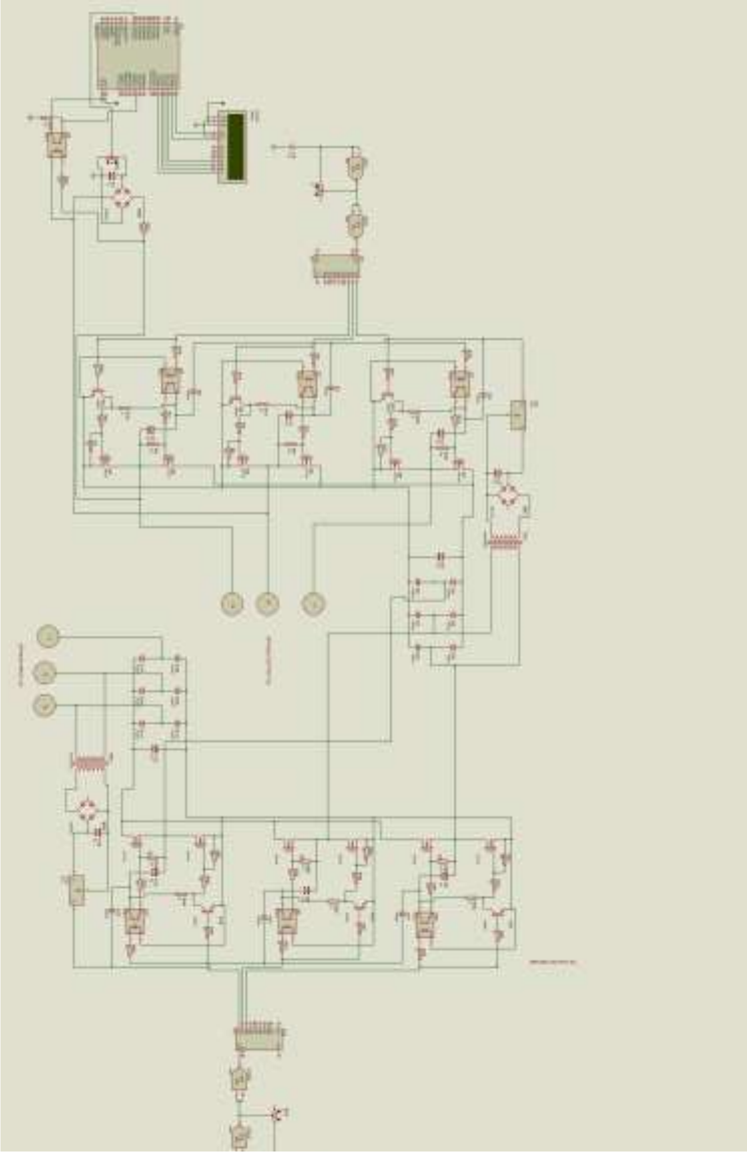
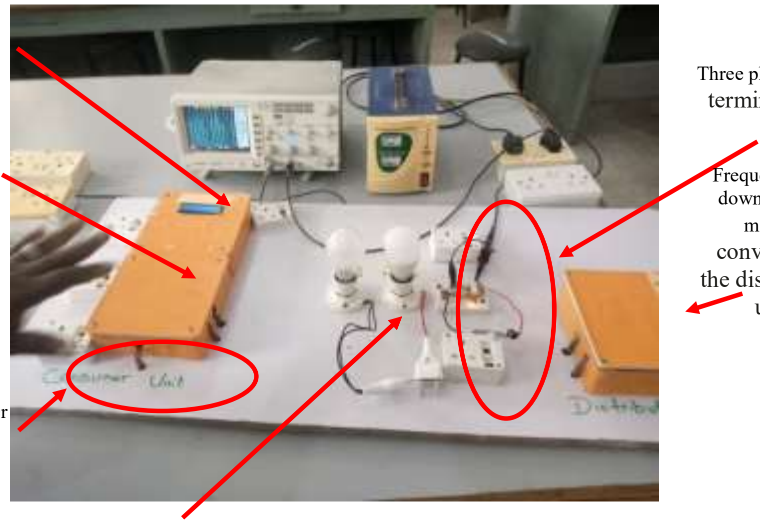


Figure 3.5: Circuit Diagram of the Entire System

The distribution transformer's output frequency (at 50Hz) was stepped down to 10Hz when the driver circuit drives the power transistor to switch at 10Hz. The output of the inverter unit was converted to ac signal at a 10Hz frequency. This signal was distributed to all connected customers, whether registered or unregistered.

At the consumer's point of use, the 10Hz signal was converted back to 50Hz at the registered consumer end. The conversion was achieved using the indirect step-up converter, where the rectifier unit first rectified the signal and then inverted the DC signal to AC at 50Hz by switching the power transistor at a 50Hz frequency. This indirect step-up matrix was built on the board of the energy meter at the consumer building.

Plate 3.1 shows the pictorial view of the entire matrix converter (indirect) arrangement.



Output Measuring unit

Frequency step up indirect matrix converter at the consumer side

Consumer side

Testing load

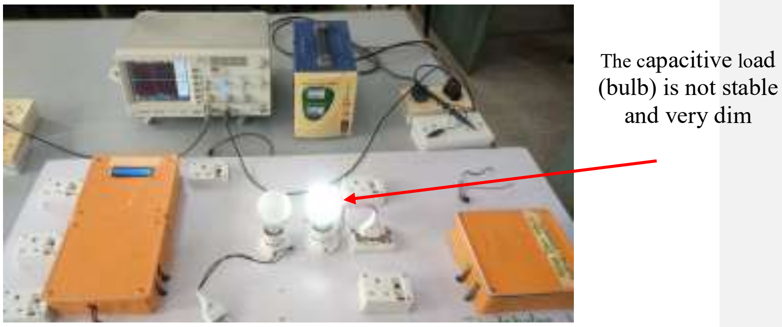
Three phase terminal

Frequency step down indirect matrix converter at the distribution unit

Plate 3.1: The Prototype

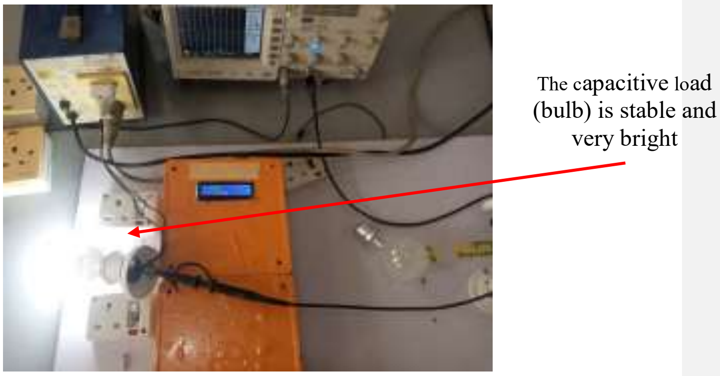
The output terminals of this circuit were distributed to the distribution network to make all connected load malfunction, thereby mitigating energy theft along the low-voltage end.

The 10-20Hz signal was connected to another step-up indirect matrix converter at the consumer end, which rectified the signal to make the signal useful again. Finally, the driver drove the power transistor at 50Hz to step it back to 50Hz for proper use by the connected load of a registered consumer. Plates 3.2, 3.3, 3.4, 3.5 and 3.6 showed the prototype when this technique was implemented with capacitive, resistive, and inductive loads.



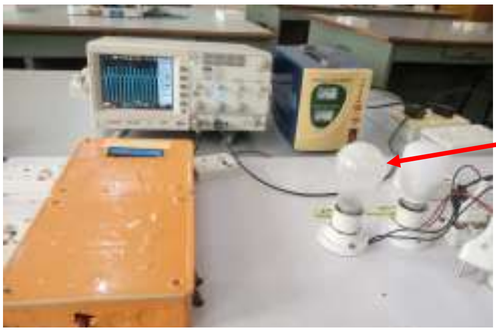
The capacitive load (bulb) is not stable and very dim

Plate 3.2: Experimental test showing capacitive load on 10Hz supply



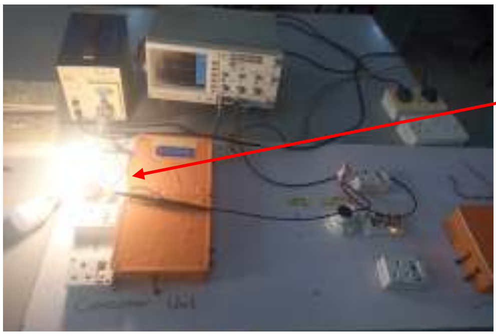
The capacitive load (bulb) is stable and very bright

Plate 3.3: Experimental test showing Capacitive load on 50Hz supply



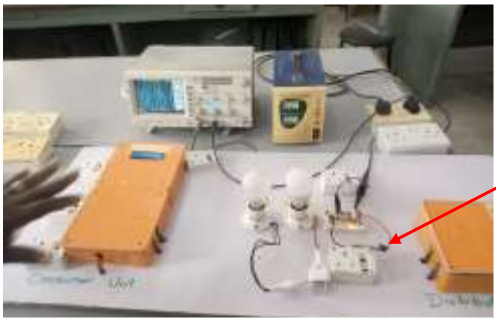
The resistive load
(bulb) is off

Plate 3.4: Experimental test showing Resistive load on 10Hz supply



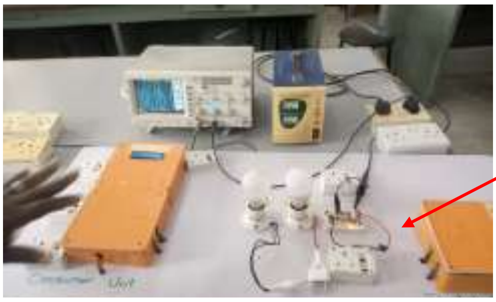
The resistive load
(bulb) is very bright
and stable

Plate 3.5: Experimental test showing Resistive load on 50Hz supply



The inductive load
is humming

Plate 3.6: Experimental test showing Inductive load on 10Hz supply



The inductiveload
Was operating well

Plate 3.7: Experimental test showing Inductive load on 50Hz supply

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

Figures 4.1, 4.3 and 4.5 show the converter's output voltage at 20 Hz, 15 Hz, and 10 Hz, respectively. Figures 4.2, 4.4 and 4.6 show the Fast Fourier transform of the output voltage at 20Hz, 15Hz and 10Hz, respectively, and the three-phase output voltage of the step-up converter with 10Hz to 50Hz. Plates 4.1 to 4.3 show the experimented result waveform on an oscilloscope for resistive load at 10Hz, inductive load at 10Hz and capacitive load at 10Hz, respectively.

4.1 Results of simulation at 10Hz to 20Hz Frequencies

The output voltage signals at 20Hz, 15Hz and 10Hz was observed to be distorted and contained unbearable harmonics.

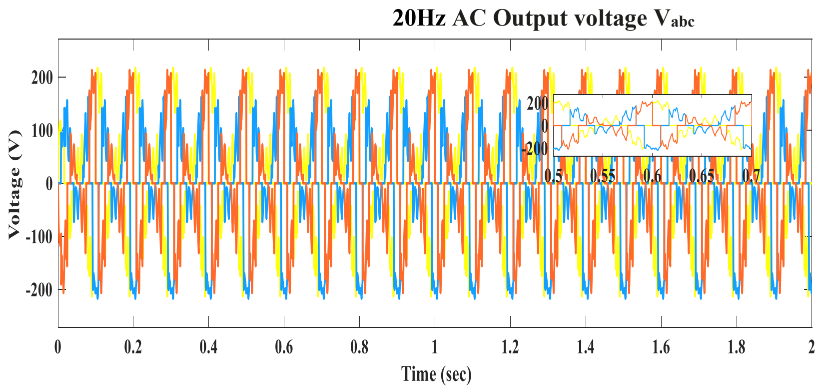


Figure 4.1: AC output voltage at 20 Hz

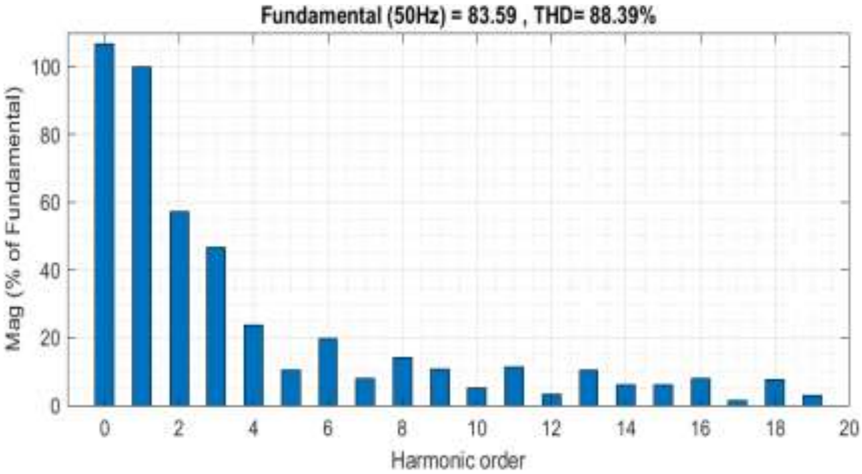

Fundamental (50Hz) = 83.59 , THD= 88.39%

Figure 4.2: FFT plot of the output voltage at 20 Hz

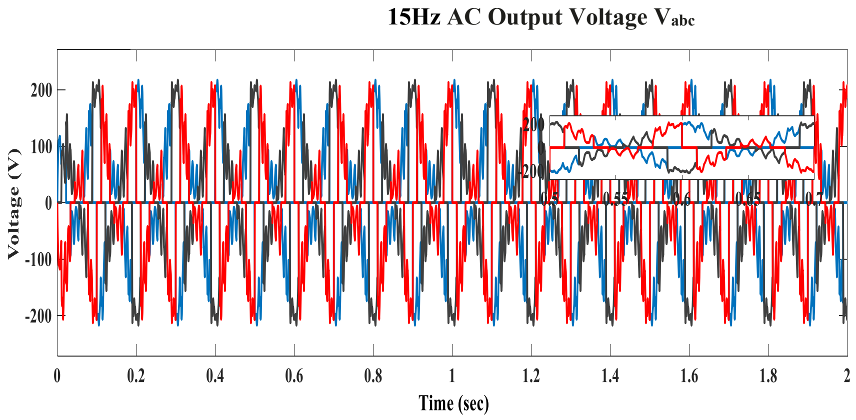

15Hz AC Output Voltage V_{abc}

Figure 4.3: AC output voltage at 15 Hz

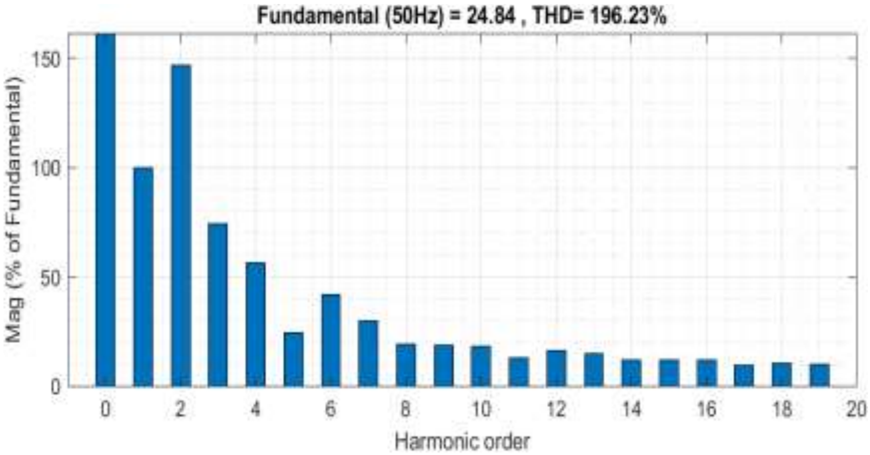


Figure 4.4: FFT plot of the output voltage at 15 Hz

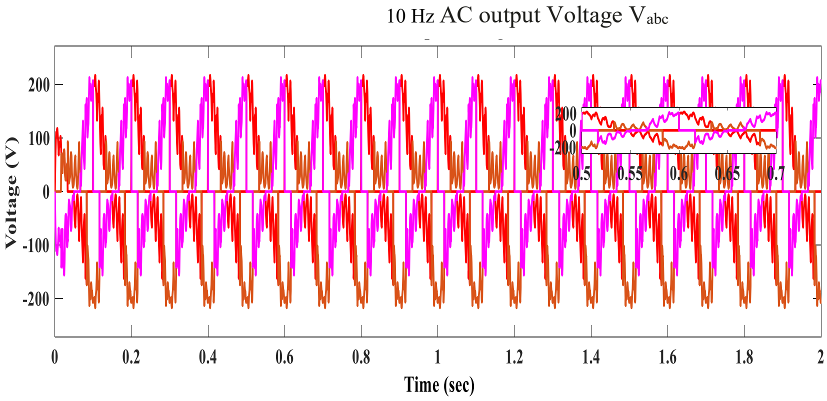


Figure 4.5: AC output voltage at 10 Hz

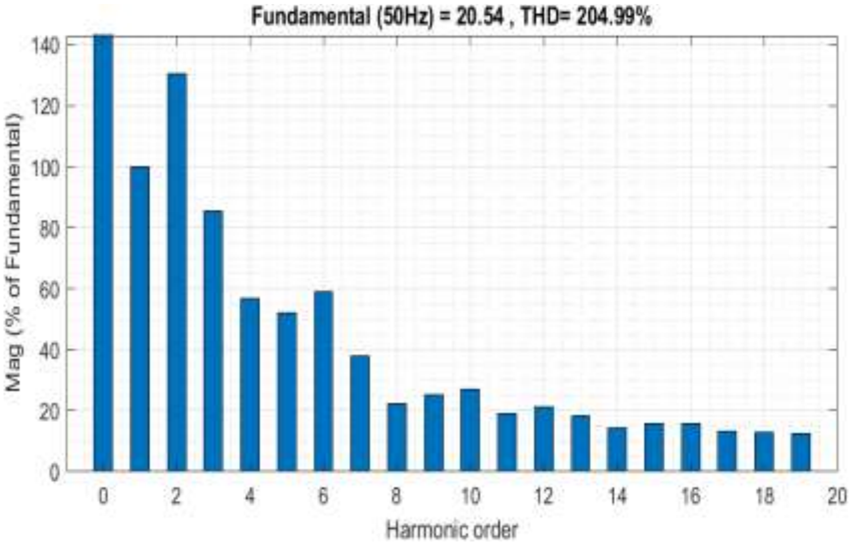


Figure 4.6: FFT plot of the output voltage at 10 Hz

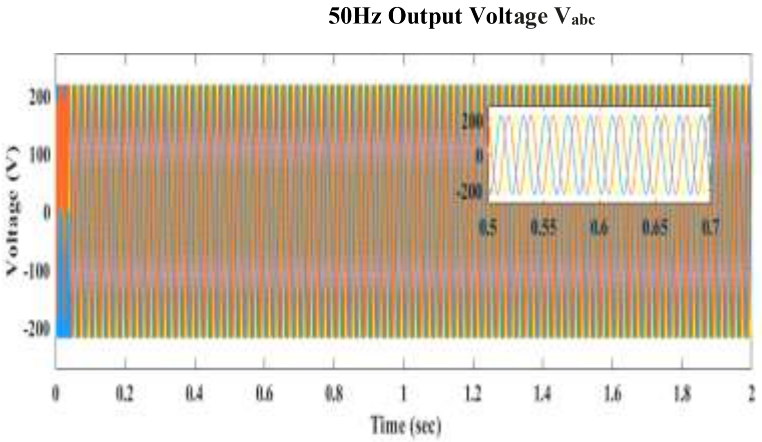


Figure 4.7: Three-phase output voltage of the step-up converter with (10 Hz to 50 Hz)

Plate 4.1 shows the waveform on the oscilloscope for testing with a resistive load at 10 Hz.

Plate 4.1: Experimental result Waveform on oscilloscope for resistive load at 10Hz

Plate 4.2 shows the waveform on the oscilloscope for testing with an inductive load at 10 Hz.

Plate 4.2: Experimental result Waveform on oscilloscope for Inductive load at 10 Hz

Plate 4.3 shows the waveform on the oscilloscope for testing with a capacitve load at 10Hz.

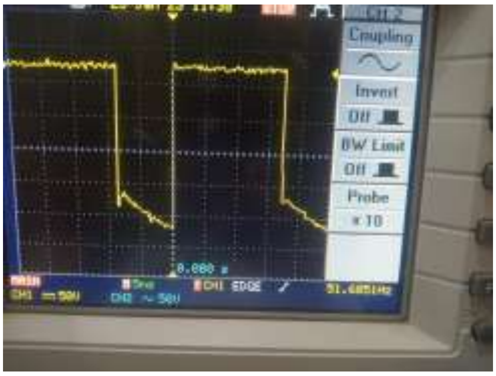


Plate 4.3: Experimental result Waveform on oscilloscope for Capacitive load at 10 Hz

4.2 Result Discussion

Figure 4.1 and Figure 4.2 show the AC output voltage waveform and the Fast Fourier Transform (FFT) at 20Hz. Figure 4.1 shows the nature of the distributed waveform, and the signal obtained was distorted. The total harmonic distortion of the voltage signal was 88.39% which was high enough to increase the current RMS value in the electrical system and deteriorate the supply voltage quality. The signal can stress any connected appliances and potentially damage the connected electrical appliances. The signal could also disrupt the normal operation of connected electrical devices and increase operating costs. It could also cause a heating effect, thereby increasing the appliance's temperature, which could, in turn, reduce the connected device's life span. It also harmed connected sensors leading to inaccurate measurements. When the signal at these frequencies was used to power telecommunication devices, it brought telecommunication interference resulting in noise. Power distributed at 20Hz would discourage electricity theft along the distribution line, either by direct hookup or meter bypass. If any illegal connection takes place along the line, it could cause great harm to any electrical device.

An energy meter with a step-up indirect matrix converter must be acquired for a registered consumer to utilise the distributed power. The step-up indirect matrix converter will increase the frequency to 50Hz, which is the required standard.

This result also showed that implementingan electricity theft detection system or human operator to monitor illegal connections on the distribution network will not be required because the distributed voltage was at a relatively low frequency from the distribution transformer output. This reduced costs and increased revenue generated by utility companies.

From the result, it could also be seen that voltage across the lines remained the same despite the harmonic distortion. This depicted that there was no voltage loss.

Figures 4.3 and 4.4 depict the AC output voltage waveform and the Fast Fourier Transform (FFT) at 15Hz. Figure 4.3 result shows the nature of the waveform that was also distributed, and a distorted signal was obtained. The total harmonic distortion of the voltage signal was 196.23% which was high enough to increase the current RMS value in the electrical system and deteriorate the supply voltage quality. The signal could stress any connected appliances and potentially damage the connected electrical appliances. The signal could also disrupt the normal operation of connected electrical devices and increase operating costs. It could also cause a heating effect, thereby increasing the appliance's temperature; this could, inturn, reduce the life span of the connected device. It also harmed connected sensors leading to inaccurate measurements. When the signal at these frequencies was used to power telecommunication devices, it brought telecommunication interference resulting in noise. Power distributed at 15Hz would discourage electricity theft along the distribution line, either by direct hookup or meter bypass. If any illegal connection takes place along the line, it could cause great harm to any electrical device. An energy meter with a step-up indirect matrix converter must be acquired for a registered consumer to utilise the distributed power. The step-up indirect matrix converter would increase the frequency to 50Hz, which was the required standard.

This result also showed that implementing an electricity theft detection system or human operator to monitor illegal connections on the distribution network will not be required because the distributed voltage was at a relatively low frequency from the distribution transformer output. This reduced costs and increased revenue generated by utility companies.

From the result, it can also be seen that voltage across the lines remained the same despite the harmonic distortion. This depicts that there was no voltage loss.

Figures 4.5 and4.6 show the AC output voltage waveform and the fast Fourier transform (FFT) at 10Hz. Figure 4.5 shows the nature of the waveform that was also distributed. This signal was the most distorted among the three samples that were tested. The total harmonic distortion of the voltage signal was 204.99% which was high enough to increase the current rms value in the electrical system and deteriorate the supply voltage quality. This signal could stress any connected appliances and potentially damage the connected electrical appliances. The signal could also disrupt the normal operation of connected electrical devices and increase operating costs. It could also cause a heating effect, thereby increasing the appliance's temperature; this could, in turn, reduce the connected device's life span. It also harmed connected sensors leading to inaccurate measurements. When the signal at these frequencies was used to power telecommunication devices, it brought telecommunication interference resulting in noise. Power distributed at 10Hz will discourage electricity theft along the distribution line, either by direct hookup or meter bypass. However, if any illegal connection occurs along the line, it could cause great harm to any electrical device.

An energy meter with a step-up indirect matrix converter must be acquired for a registered consumer to utilise the distributed power. The step-up indirect matrix converter would increase the frequency to 50Hz, the required standard. This result also showed that implementing an electricity theft detection system or human operator to monitor illegal connections on the distribution network would not be required because the distributed voltage was at a relatively low frequency from the distribution transformer output. This reduced costs and increased revenue generated by utility companies. From the result, it could also be seen that voltage across the lines remained the same despite the harmonic distortion. This depicts that there was no voltage loss.

The three results above showed clearly that distribution at the frequency of 10Hz was most suitable for the mitigation techniques in this work. It had the highest total harmonic distortion (THD) among the three sampled frequencies, as seen in Table 4.1

Table 4.1: Frequencies and its THD (simulation result)

Distribution frequency	Total Harmonic Distortion (THD)	Suitability for mitigation
20Hz	88.39%	suitable
15Hz	196.23%	More suitable
10Hz	204.99%	Most suitable

The physical interpretation of Table 4.1 showed 204.99 THD at 10Hz, which is high enough to increase the I_{rms}value in the distribution network and liable to damage any connected electrical appliance. So when power is distributed at 10Hz, it will discourage electricity theft along the distribution line by direct hookup or meter bypass. However, any illegal connection that will take place along the line could result in damage to the connected appliances.

From the Table, it can be concluded that the distribution frequencies (F_d) are inversely proportional to the total harmonic distortion (THD) as shown in (4.1)

$$F_d \ \alpha \ \frac{1}{THD} \qquad (4.1)$$

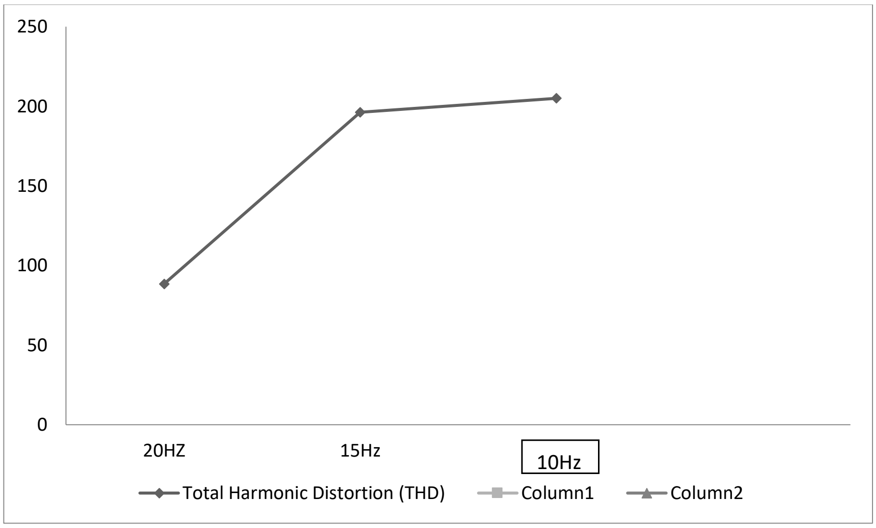


Figure 4.8: Total Harmonic Distortion at various frequencies

Figure 4.8 shows total harmonic distortion (THD) against various frequencies. This graph shows that at 10Hz, the highest harmonic distortion was achieved, making it the best frequency choice for the mitigation techniques.

Asseen in Figures 4.2, 4.4, and 4.6, the plot of Fast Fourier Transform (FFT) of the voltage signals, when tapped by unlawful consumers, gives a poorly induced emf, significant noise and complex harmonics. Figure 4.6 showed that the worst-case scenario had a Total Harmonic Distortion (THD) of 204.99%. In appliances and equipment used by unregistered customers, harmonics induced noisy operation, harmonic losses, torque pulsationsand heat generation. Appliances can occasionally be burned, as tested and seen on the prototype in section 4.2.1 and Table 4.2. Figure 4.7 shows the output of the step-up converter with the energy meter in a closed seal. This displayed a pure sinusoidal signal sufficient to excite the appliances of the metered consumers.

4.2 Result from Testing Prototype

The test and result of the prototype are carried out in two ways; By physical observation of the connected load and Oscilloscope testing.

4.2.1 Test Result of prototype carried out through physical observation

A motor was chosen as an example of an inductive load contained in many electrical appliances. When connected to the distribution line, the motor runs slowly and finally stops rotating with a humming sound as the frequency is varied downward (from 20Hz to 10Hz). The humming sound is repelling to any consumer at that lower frequency. However, when the motor was connected after the step-up indirect matrix converter, the motor rotated properly without the humming sound.

Afterwards, the lead bulb was connected as a capacitive load before and after the step-up indirect matrix converter. The lead bulb became dim and dim as the frequency was tuned lower from 20Hz to 10Hz, and at 10Hz, it blinked and became irritating to users' eyes.

When a filament bulb was used as a resistive load, connected before and after the step-up indirect matrix converter, it was observed that the brightness also dimmed to the eyes as the frequency varied from 20Hz to 10Hz. At 10Hz, the intensity was very low, and the heating effect was slow. Table 4.2 shows the test result of the constructed prototype.

The experimental result for the resistive, capacitive and inductive load was shown in Figures 4.9, 4.10, and 4.11; the results were discussed and tabulated in Table 4.2.

Table 4.2:Test Result of the Construction (Prototype)

Frequency(Hz)	Effect on Resistive Load	Effect on Capacitive Load	Effect on Inductive
20	i. The heating effect is slow ii. The brightness of the Filament element is low	i. Charging of capacitor is low ii. The capacitive bulb is dim in brightness	i. Motor rotation slows down ii. Little humming effect
15	i. The heating effect is slower. ii. The brightness of the Filament element is lower	i. Charging of capacitor is lower **ii.** The capacitive bulb is dimmer in brightness	i. Motor rotates slower ii. Humming effect increase
10	i. Heating effect isthe slowest. ii. The brightness of the Filament element is the lowest	i. Charging of capacitor is the lowest ii. The capacitive bulb is dimmest in brightness	i. Motor stop rotating ii. The humming effect is the loudest
50	i. The heating effect is effective. ii. The brightness of the Filament element is the lowest	i. Charging of capacitor is normal ii. The capacitive bulb is stable	i. The motor rotates well and normal ii. The humming effect is absent

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This work revealed that some developing nations, such as Nigeria, lose revenue through electricity theft and gave an overview of various mitigating efforts presented by some authors. Analysis was done between the transformer's output and the consumer premises at the low-voltage distribution end. It was demonstrated that energy theft could not be eradicated but reduced through technical approaches like an indirect matrix converter. In this work, because there was no need for a large, bulky dc link electrolytic capacitor that increased system complexity, an indirect matrix converter was utilised because it ensured compactness and reliability. A 50 Hz to 10 Hz step-downwas used to develop and simulate the suggested system using the MATLAB Simulink software (2021 version). Another step-down system at 50Hz to 15Hz was also simulated. The third step-down system is at 50Hz to 20Hz,which was also simulated; the simulation results were graphically presented as Fast Fourier Transform and voltage waveforms. The results revealed that the step-down system at 50Hz to 10Hz produced the best mitigation effect with a total harmonic distortion (THD) of 204.99%. The prototype was constructed, and the effect of stepping down the frequency from 50Hz to 10Hz, 50Hz to 15Hz and 50Hz to 10Hz was observed. Although the proposed model could not identify energy theft committed via meter bypass and direct connection, it could discourage unregistered consumers who will become irritated if insufficient excitation exists to power their equipment.

This technique is relevant to conventional techniquesbecause it does not require an energy theft detection scheme before mitigating illegal practices on the electrical network. The mitigation process started from the transformer's output to all branches in the distribution network. This power was also made un-useful to unregistered consumers, thereby discouraging theft than other conventional techniques.

5.2 Recommendations

Based on the outcome of this research work, Utility companies should consider implementing this indirect matrix converter as an add-on device to the existing distribution network installations at low voltage end to improve revenue.

Utility companies should reduce distribution line workers since their services are changed from monitoring theft to maintenance work along the network to reduce expenses and increase revenue.

5.3 Contribution to Knowledge

This thesis has contributed knowledge to the field of research by using Indirect Matrix converter to successfully model and simulate using MATLAB (2021 version)/SIMULINK environment. And an indirect matrix converter was used to step–down the frequency of the distribution signal from 50Hz to 10Hz. Moreover, it produced a worst-case scenario of Total Harmonic Distortion (THD) of 204.99% that demotivated unregistered consumers. State the implecation of the results obtained.

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