Electricity Theft Mitigation at Low Voltage Distribution End Using Indirect Matrix Converter

*Sunday T. Abel, Jacob Tsado, and Omokhafe J. Tola
Department of Electrical and Electronic Engineering, Federal University of Technology, Minna, Nigeria
olupitione@gmail.com | {tsadojacob | omokhafe}@futminna.edu.ng

Received: 23-JUL-2023; Reviewed: 26-AUG-2023; Accepted: 06-SEP -2023
http://doi.org/10.46792/fuoyejet.v8i3.1074

ORIGINAL RESEARCH

Abstract- This paper presents the design and implementation of an indirect matrix converter for electricity theft mitigation at low voltage distribution network. The power distribution network saddle with the responsivity of delivering electricity to consumers are been face with electricity theft through meter bypassing and hook up connections, causing significant financial inflow problem to the utility company, particularly in a developing country. A step-down indirect matrix converter was designed and simulated with a frequency range of (10 – 20Hz) at the converter's output. The analysis of the results favors the use of 10Hz being the worst-case scenario to mitigate electricity with a total harmonic distortion (THD) of 204.99%. With different resistive and inductive loads, the effectiveness of the real-world system was investigated and the effects of lowering the frequency from 50Hz to 10Hz were observed and in particular make the electricity unusable. The proposed system is intended to be connected at the output of the distribution transformer to convert the power frequency to 10Hz and the other unit incorporated to the meter at the consumer end to convert their power frequency to 50Hz to make it usable. This system prevents unregistered clients from using the electricity, substantially lowering electricity theft and boosting the utility company's bottom line. In comparison to previous studies, the key advantage of matrix converters is that they do not require a DC-Link capacitor, making them more reliable and suitable for installation at the customer's premises.

Keywords- Electricity theft, Indirect matrix converter, Meter bypassing, THD, unregister consumer.

1 INTRODUCTION

In developing countries, and Nigeria in particular, one of the prevalent ways of electricity theft is the illegal tapping (hooking) on distribution lines (Shokoya & Raji, 2019). The term "illegal tapings" refers to the direct rigging of the distribution line, which is accomplished by installing a line to a nearby position to evade the electrical energy meter. As a result, the energy meter records a lower reading of consumption without accurately accounting for the precise amount of energy utilized by consumers. Furthermore, the distribution companies suffered significant financial losses, this discourages upcoming investments in the power industry.

Every year, a considerable amount of energy is stolen, and the costs are routinely transferred to legal customers, directly or indirectly, in the form disproportionate increase in tariff rates. The sustainability of the services provided by utility companies depends on how theft may affect them in the worst-case circumstances. Some systems' cumulative losses, including non-payment of bills (Otuoze et al., 2019; Arkorful, 2022; Wabukala et al., 2023), cause utilities to run at ~~a~~ loss. It is estimated that between 10-40% of power generation is lost due to electricity theft in many developing countries. Due to the approximately 420 MW of electricity that is stolen each year, for instance, power providers in India suffer significant financial losses. Almost every country has electricity theft challenges. In US alone, about $200 billion worth of electricity is misused yearly due to equipment catastrophes or electricity theft (Olaoluwa, 2017).

*Corresponding Author

Section B- ELECTRICAL/COMPUTER ENGINEERING & RELATED SCIENCES
Can be cited as:
Abel S.T., Tsado J., and Tola O.J. (2023), Electricity Theft Mitigation at Low Voltage Distribution End Using Indirect Matrix Converter, FUOYE Journal of Engineering and Technology (FUOYE**JET**), **8(3), 314-318.**
http://doi.org/10.46792/fuoyejet.v8i3.1074

The operations of utility companies are severely impacted by the enormous financial losses caused by energy theft in Nigeria (Obafemi et al., 2022). At the same time, energy theft significantly impacted the debt profile of the Nigerian energy Supply Industry (NESI). Several measures have been suggested and some practical steps taken to minimize electricity theft. However, this efforts has not significantly helped to tackle the issue (Prachal Jadeja, 2015), (Ali et al., 2023). Technical and non-technical mitigation strategies are the two types (Blazakis et al., 2020). 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.

Energy meters can no longer visibly be utilized to estimate customer electricity usage because consumers and utility staff are also involve in the process of in electricity theft (Hashmi & Priolkar, 2015). As a result, the power distribution companies suffered low revenue collection. According to (Jaiswal & Ballal, 2020), this makes it impossible for utility companies to buy enough electricity to supply consumers. In (Thangalakshmi *et al.*, 2015), the authors 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 proposed study seeks to address the detection before cutting off illegal consumers. It focuses on addressing the identification and disconnection of legitimate consumers before mitigating electricity theft. Also in (Okelola et al., 2019), the study proposed a triggering point detection (JTPD) scheme with a view to achieving a more accurate PQ event detection in a voltage waveform.

© 2023 The Author(s). Published by Faculty of Engineering, Federal University Oye-Ekiti.
This is an open access article under the CC BY NC license. (https://creativecommons.org/licenses/by-nc/4.0/)

A power electronic AC-to-AC converter without a capacitor or inductor for DC storage is known as a matrix converter (MC). With this modification, converter size is reduced, converter dependability is increased, and four-quadrant operation is provided(Lei et al., 2022; Praženica et al., 2023; Rmili et al., 2023). Because of these distinguishing characteristics, MCs have been employed in a variety of applications, including AC motors, marine propulsion systems, the aerospace sector, and renewable energy systems (Gong et al., 2023).

The matrix converter is one of the most intriguing families of AC-AC converters. The matrix converter serves as the primary power source and is composed of a number of bidirectional switches. It is known as an all-silicon solution because it directly links a three-phase power supply to a three-phase demand without utilizing a DC link or other high-energy components. The converter's primary features include (i) simple and compact power circuits, (ii) the ability to generate load voltage with any amplitude and frequency, (iii) sinusoidal input and output currents, (iv) operating with a unity power factor, and (v) the ability to regenerate. The huge interest in this topology is a result of these desirable qualities (Aminu, 2020) (Tawfiq et al., 2022).

2 Proposed System

The proposed system is presented in Figure 1 using a schematic design, and the suggested indirect matrix converter's equivalent circuit is shown in Figure 2.

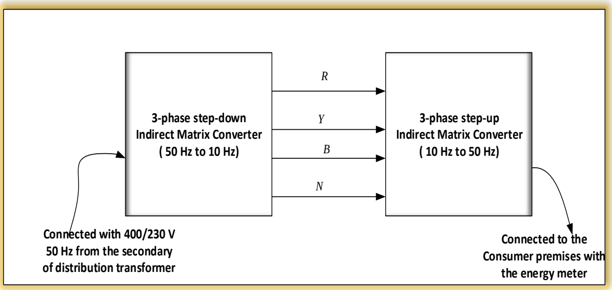

Fig. 1: Schematic Diagram of the Proposed System

The system is designed for frequencies range of 10Hz to 25Hz, and it consists of an indirect matrix converter that will step down the supply frequency from 50Hz to 10Hz at the distribution transformer end and step-up the frequency from 10Hz to 50Hz at the consumer end before the energy meter.

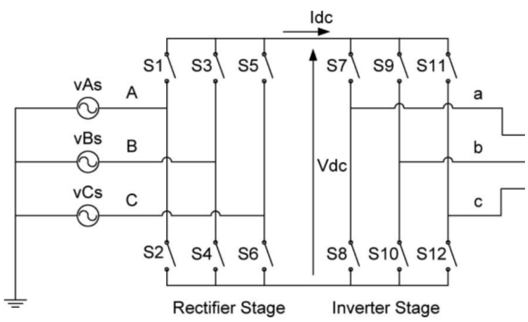

Fig. 2: Equivalent Circuit of Proposed Indirect Matrix Converter

To ensure the intended outcome is achieved, the indirect matrix converter in Figure 2 uses unidirectional switches, a rectifier stage, and an inverter stage without input and output filters. The supply voltage-dependent switch frequency is kept consistent with the rectifier. The inverter side employs a PWM control technique, whereas the switching frequency is as low as 10Hz. The frequency for the output voltage can be regulated by altering the fundamental modulation signal's frequency. Moreover, as there is no requirement for a DC link capacitor, the converter starts up without any current overshoot (Abel et al., 2022). The following input, output, and currents are provided in (1):

$$\begin{bmatrix} V_{As} \\ V_{Bs} \\ V_{Cs} \end{bmatrix} = \begin{bmatrix} S_{Asa} S_{Asb} S_{Asc} & \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \\ S_{Bsa} S_{Bsb} S_{Bsc} & \\ S_{Csa} S_{Csb} S_{Csc} & \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} S_{Aa} S_{Ba} S_{Ca} \\ S_{Ab} S_{Bb} S_{Cb} \\ S_{Ac} S_{Bc} S_{Cc} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad (2)$$

Where V_{As}, V_{Bs}, V_{Cs} input voltages, i_a, i_b, i_c: input currents, i_A, i_B, i_C: output currents and V_a, V_b, V_c. The voltage conversion is split into rectifier and inverter stages described by the expression:

$$\begin{bmatrix} V_{As} \\ V_{Bs} \\ V_{Cs} \end{bmatrix} = \begin{bmatrix} S_{p1} S_{n1} \\ S_{p2} S_{n2} \\ S_{p3} S_{n3} \end{bmatrix} \begin{bmatrix} S_{1p} S_{2p} S_{3p} \\ S_{1n} S_{2n} S_{3n} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (3)$$

$$V_{ABC} = S_{Inv} * S_{Re\,ct} * V_{abc} \quad (4)$$

There are six switches in both the rectifier and the inverter. A functional connection between each switch's input and output. The expression for current and voltage is written as

$$\begin{cases} V_{ik} = (1 - f_{ik}) V_{ik}^* \\ I_{ik} = f_{ik} I_{ik}^* \end{cases} \quad (5)$$

where

$i \in \{a, b, c\}$, $k \in \{p, n\}$ and V_{ik}^* represent the input voltage I_{ik}^* represent output phase of the load current.

For $f_{ik} = 0$ switch is open and if $f_{ik} = 1$ is closed. The following condition must satisfy as a function of the switches:

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

Note that

$$\begin{cases} V_{ab} = V_a - V_b \\ V_{bc} = V_b - V_c \\ V_{ca} = V_c - V_a \end{cases} \quad (6)$$

Rewrite (5) as

$$\begin{cases} V_a = \frac{1}{3}(V_{ab} - V_{ca}) \\ V_b = \frac{1}{3}(V_{bc} - V_{ab}) \\ V_c = \frac{1}{3}(V_{ca} - V_{bc}) \end{cases} \quad (7)$$

Presenting the functions relating to each connection as

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{pn} \begin{bmatrix} 1 - 1 & & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} f_{ap} \\ f_{bp} \\ f_{cp} \end{bmatrix} \quad (8)$$

Substitute (8) in (7) gives equation 9.

© 2023 The Author(s). Published by Faculty of Engineering, Federal University Oye-Ekiti.
This is an open access article under the CC BY NC license. (https://creativecommons.org/licenses/by-nc/4.0/)
http://doi.org/10.46792/fuoyejet.v8i3.1074 engineering.fuoye.edu.ng/journal

$$\begin{bmatrix} V_a \\ V_b \\ V_{ca} \end{bmatrix} = \frac{1}{3} V_{pn} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} f_{ap} \\ f_{bp} \\ f_{cp} \end{bmatrix} \quad (9)$$

PWM triangular-sinusoidal is a command that can be used to compare two signals. The first signal is the reference wave, which is significantly lower than the supply frequency. It is a sine wave with the desired output frequency. The sinusoid's supply frequency must coincide with the frequency of the triangle carrier in the second signal. The two parameters in (10) form the basics of this control strategy. The modulation index is written as:

$$m = \frac{f_p}{f_r} \quad (10)$$

where f_r and f_p are the carrier and sine wave frequency, respectively and also, the tuning index is written as

$$r = \frac{V_{m\_max}}{V_p} \quad (11)$$

V_{m_max} represent the amplitude of the sine wave and V_p is the carrier maximum wave

For $f_p(10-20)Hz$

$$\begin{cases} f_{ap} = 1 \quad if\ V_m > V_p \quad and\ V_m > 0 \\ f_{an} = 1 \quad if\ V_m < V_p \quad and\ V_m < 0 \end{cases} \quad (12)$$

The functions of the switches of the other two arms, b and c, are obtained by performing the same steps as for arm 'a' with shifts of the sine wave of $\frac{2\pi}{3}$ and $-\frac{2\pi}{3}$. Three-phase controlled rectifier and inverter stages are components of the proposed indirect matrix converter. The rectifier and the inverter need six unidirectional switches, and the rectifier produces a sinusoidal input current while preserving a positive DC link voltage. The inverter output, however, continues to provide a sinusoidal voltage with a changed frequency magnitude.

3 Validated Through Experiment

A single-phase prototype was used to validate the analysis and simulation in this section and for testing purposes. Figure 3 depicts the implementation's test setup. LMG5200, an integrated power (Si) device, was used to implement the switches. A driver is fitted onto a half-bridge. The goal of choosing this device was to lower the size of the converter while increasing power density. The proposed converter uses a switching frequency of 10Hz.

4 Results and Discussion

Figures 4, 5, and 6 illustrate, respectively, the output voltage of the step-down converter at 20Hz, 15Hz, and 10Hz. These voltage signals can be observed to produce poor induced emf, substantial noise, and complex harmonics when illegal users tap them.

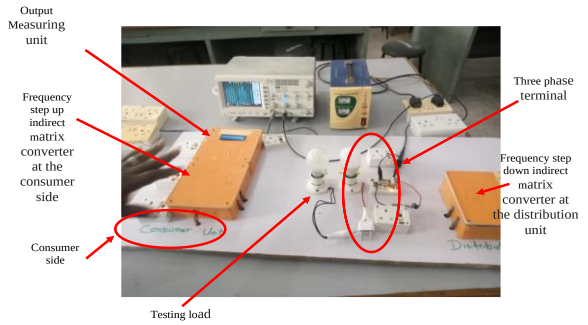

Fig. 3: Test setup for the implementation of the system

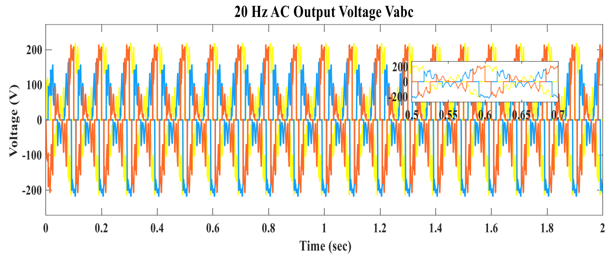

Fig. 4: The plot of the output voltage at 20 Hz

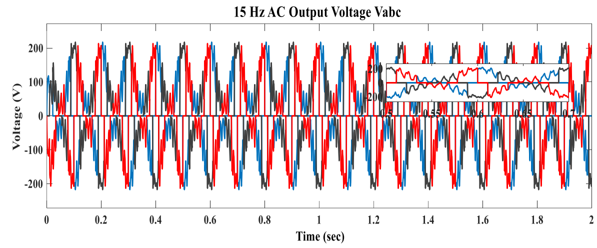

Fig. 5: The plot of the output voltage at 15 Hz

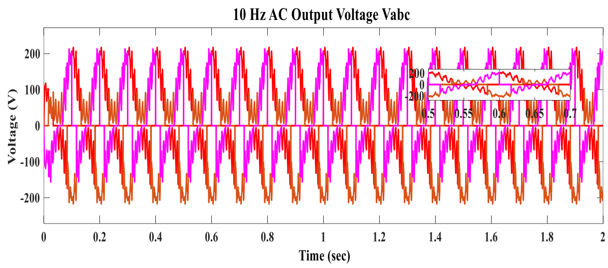

Fig. 6: The plot of the output voltage at 10 Hz

Figures 7, 8, and 9 of the voltage signals show the corresponding Fast Fourier Transform (FFT). It is clear from Figure 8 that the worst-case scenario has a Total Harmonic Distortion (THD) of 204.99 per cent. Harmonics cause noisy operation, harmonic losses, torque pulsations, and heat generation in appliances and equipment used by unlicensed users. Figure 1 depicts the schematic diagram for the step-up converter design with (10Hz to 50Hz) frequency range.

© 2023 The Author(s). Published by Faculty of Engineering, Federal University Oye-Ekiti.
This is an open access article under the CC BY NC license. (https://creativecommons.org/licenses/by-nc/4.0/)

http://doi.org/10.46792/fuoyejet.v8i3.1074 engineering.fuoye.edu.ng/journal

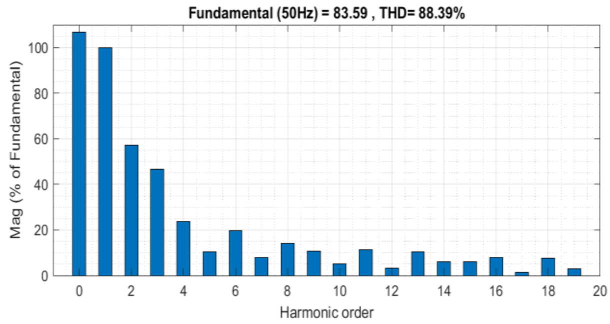

Fig. 7: Output voltage THD plot at 20 Hz

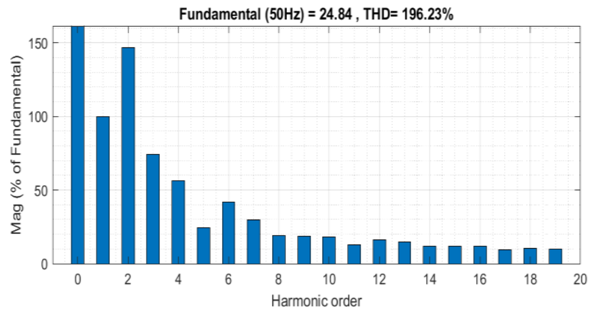

Fig. 8: Output voltage THD plot at 15 Hz

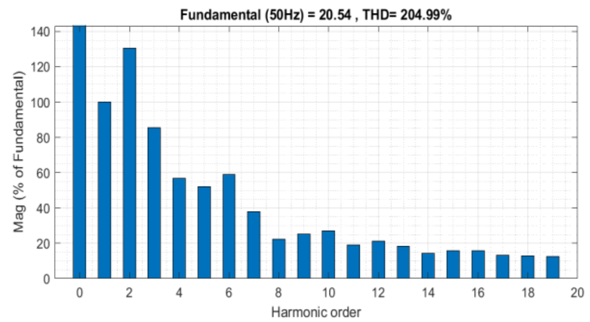

Fig. 9: Output Voltage THD plot at 10 Hz

Figure 10 shows the indirect matrix converter's output voltage. This clearly showed a sinusoidal signal that was pure and strong enough to activate the appliances of the metered consumers. Both resistive and inductive output loads are used. The output waveforms were analyzed using a six-channel power analyzer. Figure 11 shows the measured results. As observed, the converter's output voltage is sinusoidal, as anticipated. With a large percentage of THD at frequencies between 10Hz and 15Hz, the output frequency can be altered regardless of the input frequency.

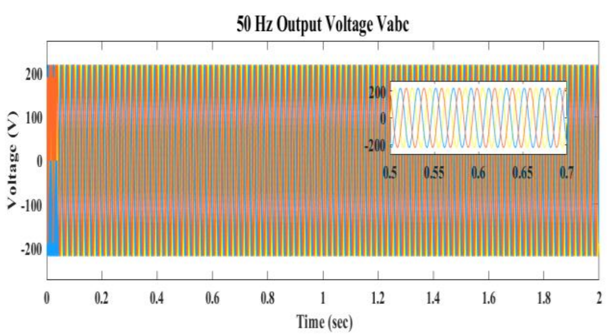

Fig. 10: Three-phase output voltage of the step-up converter with (10 Hz to 50 Hz)

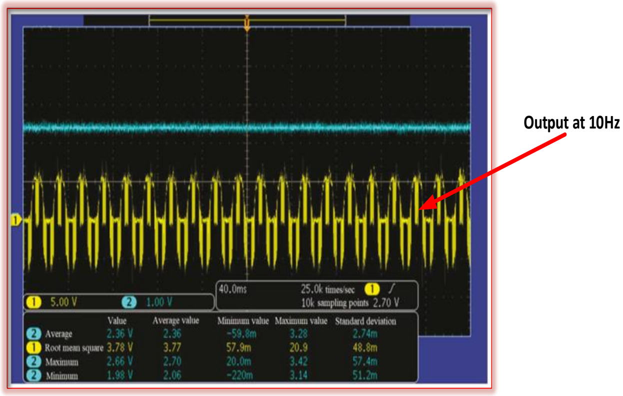

Fig. 11: The waveform for testing with a resistive load at 10 Hz.

5 Conclusion

In this study, an indirect matrix converter strategy for reducing electricity theft was developed, and its practical use was confirmed. The design and simulation of a step-down indirect matrix converter resulted in an output frequency range of (10–20Hz). However, with a THD of 204.99%, 10Hz was selected as the worst-case scenario for mitigating electricity theft. The effectiveness of the real-world system was examined in conjunction with various resistive and inductive loads, and the impact of dropping the frequency from 50Hz to 10Hz was seen. The proposed methodology may not be able to detect energy theft performed through meter bypass and direct connection. However, it may deter unregistered consumers who may feel upset if their equipment cannot receive enough excitation. In comparison to previous studies, the key advantage of matrix converters is that they don't require a DC-Link capacitor, making them more reliable and suitable for installation at the customer's premises.

References

Abel, S., Tsado, J., & Tola, O. J. (2022). Mitigation of Electricity Theft at Low Distribution Voltage End Using Matrix Converter. *Proceedings of the 5th International Conference on Information Technology for Education and Development: Changing the Narratives Through Building a Secure Society with Disruptive Technologies, ITED 2022*, 1–5. https://doi.org/10.1109/ITED56637.2022.10051599

Ali, S., Yongzhi, M., & Ali, W. (2023). Prevention and Detection of Electricity Theft of Distribution Network. *Sustainability*, *15*(6), 4868. https://doi.org/10.3390/su15064868

Aminu, M. A. (2020). 5-Hz Distribution System for Mitigation of Energy Theft by Residential Consumers. *Frontiers in Energy Research*, *7*(January). https://doi.org/10.3389/fenrg.2019.00153

Blazakis, K. V., Kapetanakis, T. N., & Stavrakakis, G. S. (2020). Effective electricity theft detection in power distribution grids using an adaptive neuro fuzzy inference system. *Energies*, *13*(12). https://doi.org/10.3390/en13123110

Gong, Z., Dai, P., Li, J., Su, D., & Su, X. (2023). Topology and Modulation for a New Indirect Matrix Converter to Reduce the Common-Mode Voltage. *IEEE Transactions on Industrial Electronics*, *70*(7), 6518–6529. https://doi.org/10.1109/TIE.2022.3203745

Hashmi, M. U., & Priolkar, J. G. (2015). Anti-theft energy metering for smart electrical distribution system. *2015 International Conference on Industrial Instrumentation and Control, ICIC 2015*, 1424–1428. https://doi.org/10.1109/IIC.2015.7150972

Jaiswal, S., & Ballal, M. S. (2020). Fuzzy Inference Based Electricity Theft Prevention System to Restrict Direct Tapping Over Distribution Line. *Journal of Electrical Engineering and*

© 2023 The Author(s). Published by Faculty of Engineering, Federal University Oye-Ekiti.
This is an open access article under the CC BY NC license. (https://creativecommons.org/licenses/by-nc/4.0/)

Technology, *15*(3), 1095–1106. https://doi.org/10.1007/s42835-020-00408-7

Lei, J., Huang, X., Wheeler, P., Xia, Y., Zhao, J., & Chen, W. (2022). Matrix Converter Based on Trapezoidal Current Injection. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, *2*(Mc). https://doi.org/10.1109/JESTPE.2022.3216862

Obafemi, M. O., Oluwole, E. A., Omoniyi, T. E., Meduna, P. ., & Alaye, A. S. (2022). Prevalence of electricity theft among households in Lagos State, Nigeria. *Nigerian Journal of Technology*, *40*(5), 872–881. https://doi.org/10.4314/njt.v40i5.13

Okelola, M. O., Amoo, A. L., & Soremekun, R. K. (2019). Power Quality Events Segmentation in a Voltage Waveform using Joint Triggering Point Detection Scheme. *FUOYE Journal of Engineering and Technology*, *4*(1), 8–12. https://doi.org/10.46792/fuoyejet.v4i1.262

Olaoluwa, O. (2017). Electricity theft and power quality in Nigeria. *International Journal of Engineering Research*, *6*(6), 1180–1184. https://www.academia.edu/download/60803763/electricity-theft-and-power-quality-in-nigeria-IJERTV6IS06049220191005-121020-khqmdl.pdf

Otuoze, A. O., Mustafa, M. W., Sofimieari, I. E., Dobi, A. M., Sule, A. H., Abioye, A. E., & Saeed, M. S. (2019). Electricity theft detection framework based on universal prediction algorithm. *Indonesian Journal of Electrical Engineering and Computer Science*, *15*(2), 758–768. https://doi.org/10.11591/ijeecs.v15.i2.pp758-768

Prachal Jadeja. (2015). Detection and Instantaneous Prevention of Power Theft\n. *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, *10*(1), 01–03. https://doi.org/10.9790/1676-10120103

Praženica, M., Resutík, P., & Kaščák, S. (2023). Practical Implementation of the Indirect Control to the Direct 3 × 5 Matrix Converter Using DSP and Low-Cost FPGA. *Sensors (Basel, Switzerland)*, *23*(7). https://doi.org/10.3390/s23073581

Rmili, L., Ktata, S., Yefrni, K., Rahmani, S., & Al-Haddad, K. (2023). *Overview of Matrix Converter: Topologies and Modulation*. *February*, 465–470. https://doi.org/10.1109/sta56120.2022.10018982

Shokoya N. O., & Raji A. K. (2019). Electricity theft mitigation in the Nigerian power sector. *International Journal of Engineering & Technology*, *8*(4), 467. https://doi.org/10.14419/ijet.v8i4.29391

Tawfiq, K. B., Ibrahim, M. N., & Sergeant, P. (2022). Power Loss Analysis of a Five-Phase Drive System Using a Synchronous Reluctance Motor and an Indirect Matrix Converter with Reduced Switching Losses. *Machines*, *10*(9). https://doi.org/10.3390/machines10090738

Thangalakshmi, S., Sangeetha bharath, G., & Muthu, S. (2015). Power Theft Prevention in Distribution System Using Smart Devices. *International Journal of Applied Engineering Research - IJAER*, *10*(42), 30841–30845. http://www.ripublication.comijaer.htm

Vincent Ekow Arkorful. (2022). Unravelling electricity theft whistleblowing antecedents using the theory of planned behavior and norm activation model. *Energy Policy*, *160*(112680). https://doi.org/10.1016/j.enpol.2021.112680

Wabukala, B. M., Mukisa, N., Watundu, S., Bergland, O., Rudaheranwa, N., & Adaramola, M. S. (2023). Impact of household electricity theft and unaffordability on electricity security: A case of Uganda. *Energy Policy*, *173*(December 2022). https://doi.org/10.1016/j.enpol.2022.113411

© 2023 The Author(s). Published by Faculty of Engineering, Federal University Oye-Ekiti.
This is an open access article under the CC BY NC license. (https://creativecommons.org/licenses/by-nc/4.0/)