Minimizing THD in Railway's HOG using MLI in Hybrid Distributed Generation System

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Abstract – *This study describes a unique seven-level "reduced switch inverter" that have an LC filter aimed to minimize the amount of total harmonic distortion (THD). Traditional inverters often produce waveforms of output current and voltage significantly deviating from sinusoidal shapes mainly due to high THD percentages. Such waveforms are unsuitable for electric drives in coaches and renewable energy-based loads. To address this, a 7-level "reduced switch inverter" is proposed, where increasing levels in the output waveform bring it closer to a sinusoidal shape, limiting THD. This 7-level MLI is proposed consisting of five switches, Solar PV, a rectified power supply from HOG (Head-on Generation), and two batteries using phase disposition PWM (PDPWM). It significantly reduces THD, resulting in a near-sine wave-modulated output. Furthermore, several filters are employed to lower the THD even further. MATLAB software is used for waveform analysis and system model simulation.*

Keywords – Multilevel Inverter, Solar photovoltaic, Head-on generation (HOG), Total Harmonic Distortion.

1. INTRODUCTION

Presently there is a growing reliance on renewable energy sources, driven by the concerns due to depleting traditional fuels, environmental pollution, and global warming. In the context of Renewable Energy Systems (RES), inverters play a crucial role on the distribution side. However, these inverters must meet specific criteria related to power quality, ensuring output voltage as well as current close to sinusoidal with total harmonic distortion (THD) within permissible limits.

This paper describes a special type of inverter (MLI) that can produce a better sine wave by using various renewable energy sources like solar power, storage devices, and technologies using a special switching method (PDPWM). This results in less distortion in the power output.

Conventional inverters, tend to introduce harmonic that is challenging to minimize. To mitigate the harmonics from the system's output, the use of the filter circuit becomes necessary. In many applications, traditional LC filters prove effective in reducing THD. Additionally, contemporary practices involve various Pulse Width Modulation (PWM) techniques aimed at minimizing harmonics in the system.

A range of studies have explored the use of filters and different topologies to mitigate the total harmonic distortion (THD) in seven-level inverters. Research introduced a seven-level reduced switch inverter with an LC filter, achieving a nearly sinusoidal waveform. Two batteries, a multi-level inverter with fewer switches, a solar panel, a HOG, and the PWM technique have all been put into practice [1]. A study proposed a hybrid topology with a modified ladder modulation method, yielding an 18.38 THD for the 7-level inverter [2]. In [3], [4] author reported the work to decrease the number of electronic power switches in seven-level inverters. Study by [4] was reported using a 7-level inverter with only six switches. These studies collectively highlight the potential for improved topologies and filters to enhance the performance of 7-level inverters.

The utilization of renewable energy sources is expanding in the modern era. By decreasing energy transport losses, the utilization of renewable energy sources enhances local and regional developments, fosters community expansion, and increases the security of the local energy supply [5]. A study states that renewable microgrids are hybrid off-grid or on-grid systems that integrate backup batteries with renewable energy sources (hydropower, solar, wind, biomass, and hydrogen fuel cells) [6]. Solar and wind energy are the most popular clean energy sources because they do not pollute the environment, do not cost much to run, and are fairly simple to set up [7]. Switching to renewable energy is becoming more common around the world and has many benefits like saving money on energy bills, boosting the economy, and helping the environment [8].

The use of solar panels (solar photovoltaic) is being considered for different things. One idea in Indian railways is being explored that uses sunlight to purify water for batteries. This would save them the electricity they would normally use for this purpose [9]. In simpler terms, a study by researcher found that placing solar panels on train carriages can reduce the amount of diesel fuel they burn and the pollution they create [10]. In 2017, a researcher named Kilic investigated whether solar panels could be used to power lights inside subway cars (urban rail cars) [11]. This idea could potentially make these trains more energy-efficient. The author proposed a solar-powered, 25 kV AC traction supply brushless DC motor fan energy-saving solution for coaches. All these studies show that solar panels (solar photovoltaics) have great potential to make Indian railways greener and more efficient [12]. Imaging cars and trucks in India powered

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by the sun is another use of solar cell. A smart system that collects rooftop solar energy could dramatically reduce dependence on fossil fuels like gasoline and diesel. This would be a huge victory for the environment and would help fight climate change [13].

A researcher examined India's hopes by 2030 to have "net zero" carbon emissions and Indian Railway has worked hard to lower its fuel costs and carbon footprint. Among its primary decarbonization initiatives are the full electrification of the wide gauge railway network, energy conservation, and meeting energy demand with renewable energy or head-on generation [14]. Indian Railways has significantly improved train power supply with the HOG system, introduced in 2006. This system uses advanced IGBT technology instead of older GTO technology, resulting in smaller, more reliable, and energy-efficient trains due to reduced heat and power loss, eliminating the need for extra cooling. Harnessing power from an overhead catenary through a traction transformer, head-on generation (HOG) meets the hotel load requirement of a superfast Shatabdi express train; it is described by [15].

The organization of this paper is as follows:

Section 2 presents the various topologies of the proposed multilevel inverter overall used to get better-modulated waveforms.

Section 3 describes the HOG system of Indian Railways that supplies rectified power from the locomotive to the rest of the train.

Section 4 is about effect of harmonics on the system performance.

Section 5 details the configuration of the proposed multilevel inverter with 7-level five switches using PWM techniques, pulse generation circuit, etc. The whole work is performed in MATLAB.

Section 6 presents the comparative study of used MLI with and without filter circuits. The voltage waveforms and FFT analysis give more effective results having less THD comparing a filter circuit against the without filter circuit.

Section 7 summarizes the results and conclusion of this paper about this work which presents results with reduced carbon emission, global warming, and THD.

2. CONVENTIONAL CASCADED MULTILEVEL INVERTER TOPOLOGIES

A range of innovative topologies for conventional cascaded 7-level multilevel inverters have been proposed in recent years. The author of [16] provides a comprehensive review of these topologies, highlighting their reduced switch counts and low-voltage component configurations. An energy-efficient 7-level inverter topology with a high energy efficiency of around 97% was reported by [17]. The closest level is modulated flexibly to control it. A study [18] proposes a modified 7-level hybrid inverter that has fewer power switches to address the problems of voltage balancing and more components. In 2015, a study [19] explained how to use a single DC source to remove a particular harmonic from a 7-level cascaded multilevel inverter, creating an easy-to-use inverter output filter design. The conventional 7-level cascaded multilevel inverter topologies are advanced by the work presented in just mentioned references.

This paper presents a new topology for multilayer inverters (MLIs) that uses solar PV, three battery supplies, five power electronic switches, and a rectified power supply (HOG). The architecture that is used for this work suggested makes sure that there are as few transitions as possible within a set amount of time. It is observed that in this work, THD at the output falls as MLI values rise, and the modulated output waveform has a sine-like appearance.

3. HOG SYSTEM

The train gets the power supply from the locomotive through hotel load winding through a scheme known as HOG.

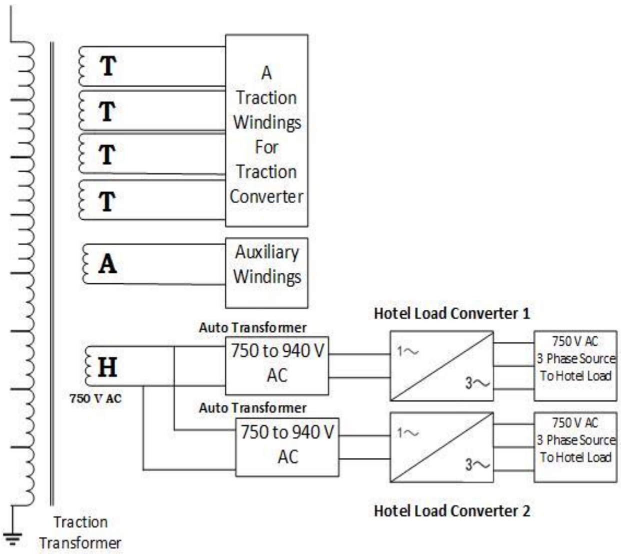

Fig. 1. Hotel Load winding in the HOG system in Railways.

After the power supply (normally 25 kV) from OHE through pantograph to the locomotive traction transformer, which is installed with extra winding (Approx 1000 kVA) known as hotel load winding. A single-phase 750 V voltage, rises and falls according to the OHE voltage variation and is sent to the converter. This converter provides a three-phase, 750V, 50Hz power supply at the hotel load output connector. Then the hotel load output feeds the power supply to all coaches including the pantry car. The schematic diagram is shown in Figure 1 and Figure 2 shows the MATLAB simulation modelling of the HOG.

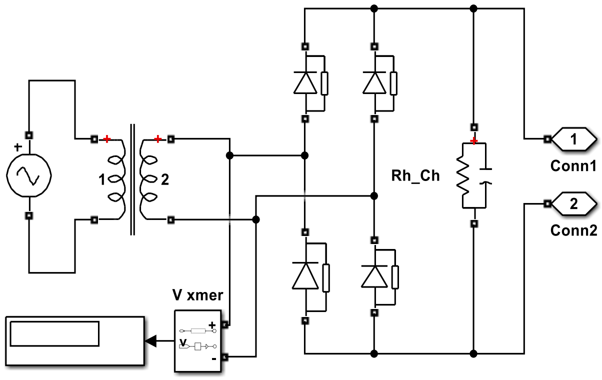

Fig. 2. MATLAB Simulink modeling of the HOG.

4. THE INFLUENCE OF HARMONICS ON SYSTEM PERFORMANCE

Harmonics have a significant impact on power system performance. The study of [20], [21] reported the detrimental effects of harmonics on equipment, including increased losses and decreased life expectancy in transformers. Further [22] emphasized these effects, detailing thermal overloading, disruption, and dielectric stressing as potential consequences. The author reported the adverse effects of harmonics on power quality and the use of active filtering techniques to mitigate these effects. These studies collectively underscore the need for effective management of harmonics to ensure optimal system performance [23].

Thus, from above and in general, it is observed that harmonics significantly affect system performance by causing voltage and current distortions. In electrical systems, harmonics result in increased total harmonic distortion (THD), leading to issues such as reduced power quality, overheating of equipment, and potential malfunctions. Harmonic oscillations can shorten the life of electronic devices and cause them to work less efficiently. Filters and other controls are used to reduce the ill-effects of harmonics.

5. PROPOSED CONFIGURATION OF 7-LEVEL AND FIVE SWITCHES MULTILEVEL INVERTER

Figure 1 gives the proposed consideration used in this work for multilevel inverter (MLI). This MLI work uses 5 switches to create 7 voltage levels. which is an improvement over previous designs that needed 6 switches [24]. The proposed design for a multilevel inverter (MLI) is much easier to build than previous ones. You only need a few parts: solar panels, a special power supply, three batteries, and five switches. The output waveform was improved since the multilevel inverter produced nearly sinusoidal output voltage waveforms; hence the total harmonic distortion was also low. The switching losses also become less. These parts work together to create a 7-level MLI.

The output voltage level is determined by the following:

$$V_n = 2 * S_n - 3 \qquad \text{- (1)}$$

Where, V_n = no. of output voltages
S_n = no. of switches

$$V_n = 2 * c_n - 1 \qquad \text{- (2)}$$

Where, c_n = no. of DC link capacitor

A seven-level output waveform can be produced with solar PV, a HOG rectified power supply, two batteries, and five switches, as shown in Figure 1. A load resistor (R) of 10 ohms is employed [25]. The circuit's switching operations are managed by the 'On' (✓) and 'Off' (✗) states as detailed in Table 1. This controlled switching mechanism produces an output voltage waveform with a maximum amplitude of +3 volts and a minimum of -3 volts. Table 1 provides the exact switching states for inverters with three phases, five switches, and seven levels.

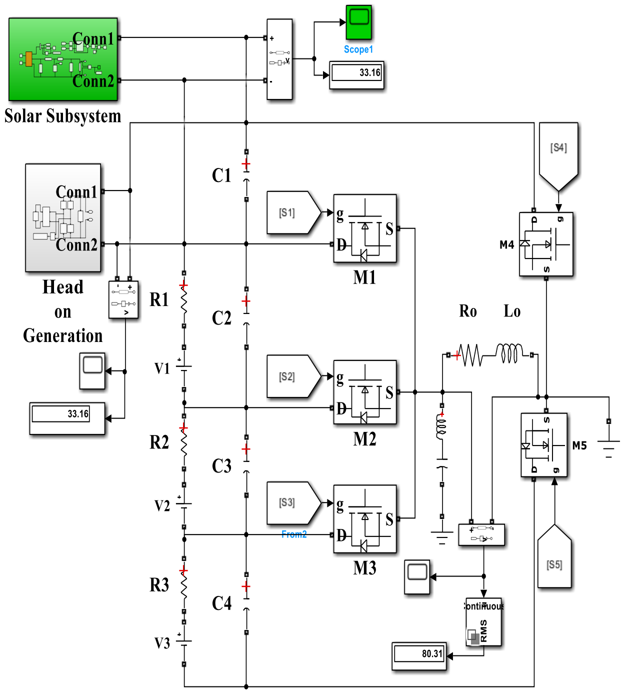

Fig. 3. MATLAB Simulink modeling MLI.

Table 1. Seven-level reduced switch topology switching pattern.

S. No.	S1	S2	S3	S4	S5	Output Voltage
1	✗	✗	✓	✗	✓	V
2	✗	✓	✗	✗	✓	2V
3	✓	✗	✗	✗	✓	3V
4	✗	✗	✗	✗	✗	0
5	✓	✗	✗	✓	✗	-V
6	✗	✓	✗	✓	✗	-2V
7	✗	✗	✓	✓	✗	-3V

5.1 PWM Techniques

The modulation method employed in this work is level shift modulation. The use of phase-shifted modulation is deemed unsuitable due to its tendency to generate higher harmonic contents. Four options available within the level shift modulation scheme are phase arrangement, phase opposition arrangement, alternating phase opposition arrangement, and inverted phase arrangement [26]. In this work, as shown in Figure 2, the phase array pulse width modulation (PDPWM) method is employed which uses carrier waves with sinusoidal modulating waves for a 7-level multilevel inverter (MLI).

5.2 Pulse Generation Circuit

Every carrier wave is compared to a sine wave to create a pulse. Following the generation of the pulses, matching switches accept them and produce an output voltage waveform with seven levels. The MATLAB Simulink model having circuit-producing activation sequence pulses is depicted in Figure 3, and the switch topology switching pattern is given in Table 1.

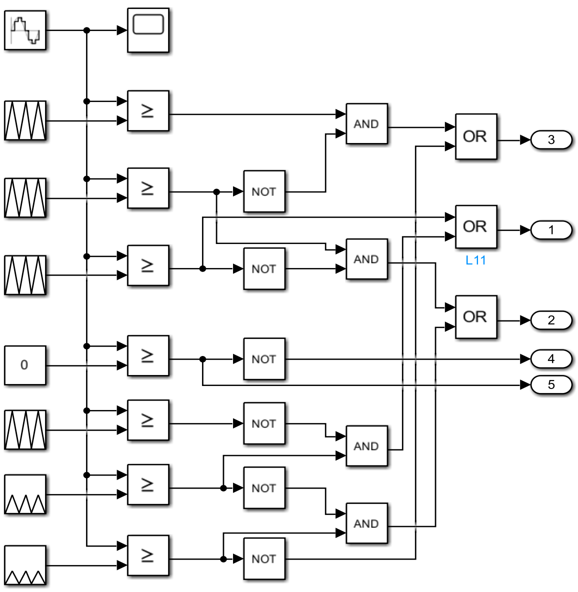

Fig. 4. Gate pulse generation Circuit for MLI switches.

To attain specific output levels, the activation pulses of every switch are set up as follows: Switch S1 requires an activation pulse for +3 V_{dc} and - V_{dc} output; switch S2 requires +2 V_{dc} and -2 V_{dc}; and switch S3 requires + V_{dc} and -3 V_{dc}. Switches S4 and S5 are active throughout the negative and positive half cycles, respectively. An m-level output waveform can be synthesized with (m-1) carrier waves [27]. The features of the pulse production circuit include the greatest triangular carrier's amplitude of 3 volts, the carrier wave's frequency of 2 KHz, the magnitude of the reference wave of 3 volts, and the frequency of the reference wave of 50 Hz.

6. SUGGESTED TOPOLOGY OF MLI WITH AND WITHOUT FILTER

The basic circuit in Figure 1 for generating a 7-level output voltage waveform with an RL load has lower total harmonic distortion (THD) than other current topologies [27]. To further lower the harmonic content and make the inverter appropriate for drive systems and renewable energy applications, several types of filters are used in conjunction with RL loads in the specified combinations. When an LC filter is connected to the inverter circuit's load, the total harmonic distortion (THD) of the output waveform decreases to a lower value. Figure 4 depicts output voltage waveforms for filter configurations. It is evident that an LC filter's output voltage waveform has a low THD and resembles a sine wave.

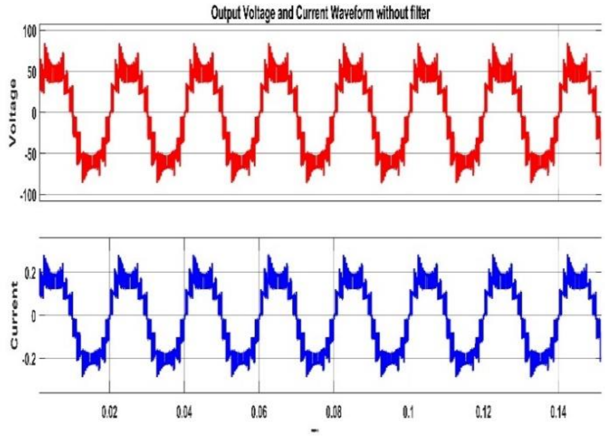

Fig. 5. Output voltage waveform without filter.

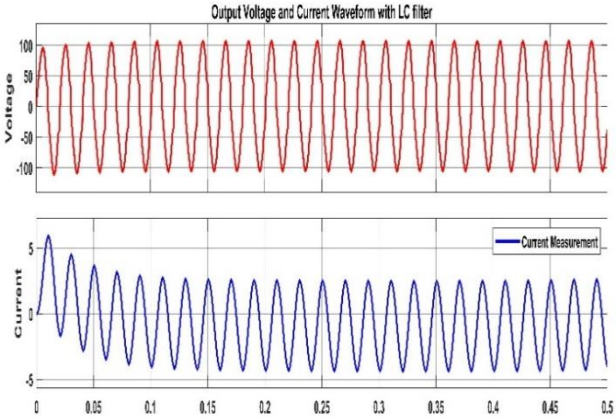

Fig. 6. Output voltage and Current waveform with filter.

Using FFT analysis, Figure 5 and 6 display the THD with and without filters. THD is observed to be lower at the output when the proposed MLI's output terminals are not connected to a filter circuit. The THD drops when the MLI circuit's output terminal is subjected to an LC-type filter circuit. It reaches its lowest value when the LC and MLI circuits are combined to suppress the harmonic contents. Therefore, by employing and altering the filter circuit and modulation index, appropriately, it is feasible to lower the harmonic content or percentage of THD in the suggested supply system below the allowed limits for voltage and current harmonics.

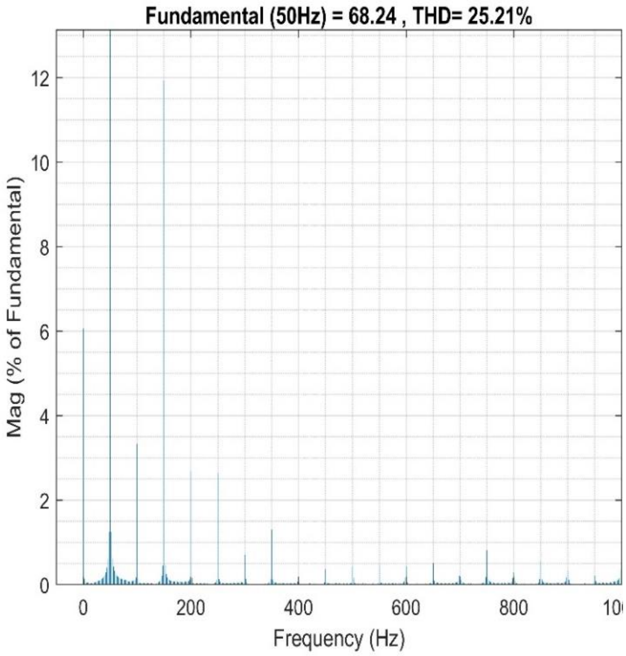

Fig. 7. FFT Analysis of MLI without filter circuit.

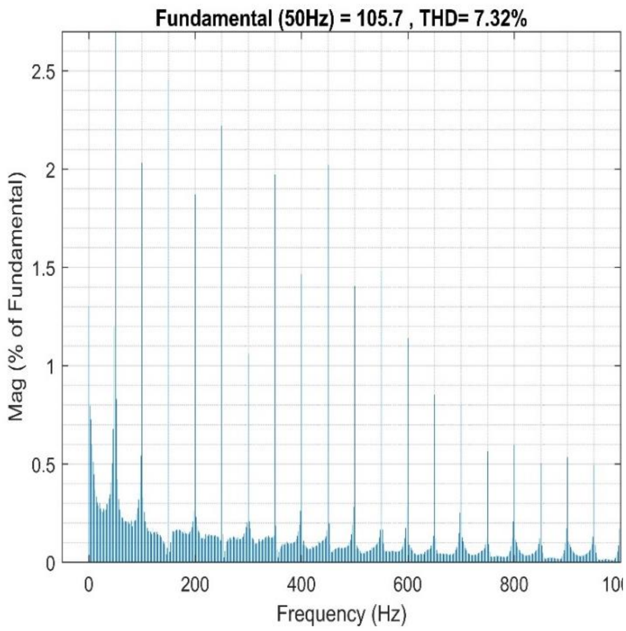

Fig. 8. FFT Analysis of MLI without filter circuit.

A comparison of the total harmonic distortion percentage with and without the LC filter employed with the used MLI. In this paper, the obtained output voltage is given in Table 2.

Table 2. Comparative study of total harmonic distortion % with & without filter.

Total Harmonic Distortion at the load voltage	
In the absence of an LC filter	In the presence of an LC filter
25.21	7.32

7. RESULT & CONCLUSION

The 7-level multilevel inverter architecture used in this work employs fine switches. India's efforts are on to have "net zero" carbon emissions by 2030, and IR has worked hard to lower its fuel costs and carbon footprint. The benefit of this research by using HOG in railways, observing calculation and measurement is reduced Co_2 emission, saving money, reducing global warming, and replacement of 2 EOG coaches with passenger coaches. So, the capacity of transportation will increase.

A MATLAB Simulink model of a seven-level inverter with five switches and solar PV, a rectified power supply from HOG, and two batteries, including filters, in comparison to earlier designs employing the same method, decreases distortion (THD) in the output voltage. To reduce the THD, a unique pulse width modulation (PDPWM) method utilizing filters is applied in this work. The THD is down to 7.32% by the used design with filters. Compared to other inverter designs, the used design is smaller, achieves a lower THD, utilizes fewer switches and thus becomes more effective and loses less energy. The THD can be further reduced in cases where a high-quality output is crucial by increasing the inverter's number of levels.

REFERENCES

[1] S. Naruka and D. K. Yadav, "An improved topology of reduced switch seven level inverter using filters for THD reduction," in *2016 IEEE 7th Power India International Conference (PIICON)*, IEEE, Nov. 2016, pp. 1–5. doi: 10.1109/POWERI.2016.8077159.

[2] V. Singh, S. Gupta, S. Pattnaik, and M. Tyagi, "A new hybrid topology for multilevel inverter for power quality improvement," in *2015 IEEE Power, Communication, and Information Technology Conference (PCITC)*, IEEE, Oct. 2015, pp. 628–634. doi: 10.1109/PCITC.2015.7438073.

[3] S. Umashankar, T. S. Sreedevi, V. G. Nithya, and D. Vijayakumar, "A New 7-Level Symmetric Multilevel Inverter with Minimum Number of Switches," *ISRN Electronics*, vol. 2013, pp. 1–8, Aug. 2013, doi: 10.1155/2013/476876.

[4] R. Singh and A. Kumar, "A New Seven Level Inverter Topology with Reduced Number of Power Electronic Switches," in *2018 2nd International Conference on Trends in Electronics and Informatics (ICOEI)*, IEEE, May 2018, pp. 1381–1384. doi: 10.1109/ICOEI.2018.8553762.

[5] C. V. Rădulescu, P. S. Angheluță, S. Burlacu, and A. Kant, "Aspects Regarding Renewable Sources in the European Union," *European Journal of Sustainable Development*, vol. 11, no. 3, p. 93, Oct. 2022, doi: 10.14207/ejsd.2022.v11n3p93.

[6] R. F. Dad and S. Saleem, "A Comparative Study of Various Optimization Techniques to Size a Hybrid Renewable Energy System," in *2022 24th International Multitopic Conference (INMIC)*, IEEE, Oct. 2022, pp. 1–5. doi: 10.1109/INMIC56986.2022.9972951.

[7] H. Shah, J. Chakravorty, and N. G. Chothani, “Protection challenges and mitigation techniques of power grid integrated to renewable energy sources: A review,” *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 45, no. 2, pp. 4195–4210, Jun. 2023, doi: 10.1080/15567036.2023.2203111.

[8] J. T. de F. Cavalcanti, J. G. de Lima, M. R. do Nascimento Melo, E. C. B. Monteiro, and G. M. Campos-Takaki, “Fossil fuels, nuclear energy and renewable energy,” in *A LOOK AT DEVELOPMENT*, Seven Editora, 2023. doi: 10.56238/alookdevelopv1-146.

[9] A. Ajay Mate, B. V P Katekar, and C. H. S Bhatkulkar, “Performance Investigation of Solar Still for Batteries of Railway Engine, Indian Railways, at Ajni Loco Shed, Nagpur.” [Online]. Available: https://ssrn.com/abstract=3101269

[10] M. Shravanth Vasisht, G. A. Vashista, J. Srinivasan, and S. K. Ramasesha, “Rail coaches with rooftop solar photovoltaic systems: A feasibility study,” *Energy*, vol. 118, pp. 684–691, Jan. 2017, doi: 10.1016/j.energy.2016.10.103.

[11] B. Kilic and E. Dursun, “Integration of innovative photovoltaic technology to the railway trains: A case study for Istanbul airport-M1 light metro line,” in *IEEE EUROCON 2017 -17th International Conference on Smart Technologies*, IEEE, Jul. 2017, pp. 336–340. doi: 10.1109/EUROCON.2017.8011131.

[12] N. H. Agarwal and B. B. Pimple, “Solar photovoltaic array based brushless DC motor for fans in Indian railways using maximum power point tracking algorithm,” in *2015 39th National Systems Conference (NSC)*, IEEE, Dec. 2015, pp. 1–6. doi: 10.1109/NATSYS.2015.7489122.

[13] M. K. Darshana, K. Karnataki, G. Shankar, and K. R. Sheela, “A practical implementation of energy harvesting, monitoring and analysis system for solar photo voltaic terrestrial vehicles in Indian scenarios: A case of pilot implementation in the Indian Railways,” in *2015 IEEE International WIE Conference on Electrical and Computer Engineering (WIECON-ECE)*, IEEE, Dec. 2015, pp. 542–545. doi: 10.1109/WIECON-ECE.2015.7443989.

[14] G. Marik and A. Dutta, “Low-Carbon Emission Initiative by Indian Railways—A Case Study,” *Climate and Energy*, vol. 39, no. 11, pp. 9–16, Jun. 2023, doi: 10.1002/gas.22348.

[15] G. S. Dhunna, “Novel approach of electrical hotel load feeding for trains,” in *2008 IEEE Canada Electric Power Conference*, IEEE, Oct. 2008, pp. 1–6. doi: 10.1109/EPC.2008.4763313.

[16] K. T. Maheswari, R. Bharanikumar, V. Arjun, R. Amrish, and M. Bhuvanesh, “A comprehensive review on cascaded H-bridge multilevel inverter for medium voltage high power applications,” *Mater Today Proc*, vol. 45, pp. 2666–2670, 2021, doi: 10.1016/j.matpr.2020.11.519.

[17] M. Setti, M. Ouassaid, and M. Cherkaoui, “New power efficient seven-level inverter topology controlled by flexible nearest level modulation,” in *2017 International Conference on Electrical and Information Technologies (ICEIT)*, IEEE, Nov. 2017, pp. 1–6. doi: 10.1109/EITech.2017.8255249.

[18] A. K. Yarlagadda, V. kumar Eate, Y. S. K. Babu, and A. Chakraborti, “A Modified Seven Level Cascaded H Bridge Inverter,” in *2018 5th IEEE Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON)*, IEEE, Nov. 2018, pp. 1–6. doi: 10.1109/UPCON.2018.8597096.

[19] H. Manafi, H. Ebrahimian, and M. Salimi, “7-level cascade multilevel inverter using a single DC source and minimum THD of Output Voltage,” in *2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST)*, IEEE, Sep. 2015, pp. 390–393. doi: 10.1109/SEDST.2015.7315240.

[20] C. Kocatepe *et al.*, “Harmonic Effects of Power System Loads: An Experimental Study,” in *Power Quality Issues*, InTech, 2013. doi: 10.5772/53108.

[21] D. M. Said and K. M. Nor, “Effects of harmonics on distribution transformers,” in *2008 Australasian Universities Power Engineering Conference*, 2008, pp. 1–5.

[22] V. E. Wagner *et al.*, “Effects of harmonics on equipment,” *IEEE Transactions on Power Delivery*, vol. 8, no. 2, pp. 672–680, Apr. 1993, doi: 10.1109/61.216874.

[23] S. Acharya, R. Ghosh, and T. Halder, “An adverse effect of the harmonics for the power quality issues,” in *2016 International Conference on Computational Techniques in Information and Communication Technologies (ICCTICT)*, IEEE, Mar. 2016, pp. 569–574. doi: 10.1109/ICCTICT.2016.7514644.

[24] G. Prakash, B. M, and U. S, “A New Multilevel Inverter with Reduced Number of Switches,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 5, no. 1, Jul. 2014, doi: 10.11591/ijpeds.v4i5.6089.

[25] Dheeraj Kumar Dhaked and D. Birla. "Microgrid Designing for Electrical Two-Wheeler Charging Station Supported by Solar PV and Fuel Cell" *Indian Journal of Science and Technology*, vol. 14, no. 30, pp. 2517-2525, 2021.

[26] Dheeraj Kumar Dhaked, Dinesh Birla “Modeling and control of a solar-thermal dish-Stirling coupled PMDC generator and battery-based DC microgrid in the framework of the ENERGY NEXUS” *Energy Nexus, Elsevier*, vol. 5, (2022): 100048. DOI: 10.1016/j.nexus.2022.100048.

[27] Dheeraj K. Dhaked, Y. Gopal, D. Birla, “Battery Charging Optimization of Solar Energy Based Telecom Sites in India” Engineering, Technology & Applied Science Research, Vol. 9, No. 6, 5041-5046, 2019.

APPENDIX

Parameter of MLI:
- Resistive Load: 1 Ω
- Inductive Load: 0.1 H
- R1, R2, R3: 1 Ω
- C1, C2, C3, C4: 5 e^{-6}
- V1, V2, V3: 37 volt

Pulse Generation Circuit Parameters:
- Reference wave magnitude: 3 volt
- Reference wave frequency: 50 Hz
- Higher triangular carrier amplitude: 3 volt
- Carrier wave frequency: 2 kHz

Filter Parameters:
- Inductor for LC filter: L = 9 e^{-10} H
- Capacitor for LC filter: C = 500 μF