

Sustainable Power Solutions for LHB Coaches: Integrating Solar PV and MLI-Based Harmonic Mitigation in a Hybrid Distributed Generation System for Railway HOGs

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Abstract—The demand for reliable, sustainable, and environmentally friendly transportation is need of time, and developments are underway for transportation purposes. The use of DG (diesel generator) sets and fuels increase the emission of carbon dioxide and GHG (greenhouse gases) in transportation. Thus, causing pollution and global warming, could result in drastic climate appears to have changed, extinction of living things, soaring of ocean floor, and leading natural disaster. Non - conventional power sources like solar power, wind spin energy, geothermal energy etc. are rising congruent power resources in current time at place of conventional energy sources. This article has proposed a Solar PV, a unique seven-level “reduced switch inverter” that have an LC filter aimed to minimize the amount of total harmonic distortion (THD) and storage-based system for power solutions of LHB (Linke Hoffman Bosch, Germany) coaches used in railway transportation. The study has shown, the area available a top train coaches is more than the required power during sunlight hours). 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). The total calculation was made according to observing a standard running route, the number of coaches, and DG Set. The cost of diesel is 90.70 INR/lit. in the proposed study there will be an annual saving of 2,57,75,942 INR. corresponding to 2,84,189 lit. diesel/ train in a year with implementing those arrangements. The establishment cost of this

system would be recovered approx. within 5 months as calculated. Hence, the system significantly reduces THD, resulting in a near-sine wave-modulated output implemented is a better solution for transportation which is reliable, sustainable, and eco-friendly too.

Index Terms—Multi-level inverter (MLI), LHB Coaches, Railway, Solar photovoltaic, Global horizontal irradiation.

I. INTRODUCTION

Indian Railways forms the backbone of transportation in India, facilitating the movement of both passengers and freight across the vast expanse of the country. It operates one of the world's largest railway networks, handling a massive volume of traffic daily. Passenger transportation ranges from suburban commuter trains to long-distance express services, connecting diverse regions and social strata.[1] Simultaneously, the railway plays a critical role in freight transportation, carrying essential commodities like coal, iron ore, and agricultural products, contributing significantly to the nation's economy [2]. Railway transportation plays a critical role in Indonesia's economic development by serving as a catalyst for local growth and complementing existing transportation infrastructure [3]. The ongoing modernization efforts, including electrification, the introduction of high-speed trains like the Vande Bharat Express, and the development of dedicated freight corridors, aim to enhance efficiency and capacity, ensuring that railways continue to be a vital artery for India's growth [4]. The paper discusses the significant advancements in India's railway transport system, particularly highlighting the completion of the Unigauge program, which transitioned the railway network to a single gauge of

1676 mm, resulting in 95.7% of the network being wide-gauge by 2022. This development facilitates the creation of a modern unified railway transport system and enhances its integration with other transport modes [5].

The evolution of trains in India reflects a journey from early steam-powered locomotives to modern, high-speed electric units. Initially, in the mid-19th century, steam locomotives dominated, laying the foundation for India's vast railway network [6]. As technology progressed, the 20th century saw the introduction of electric trains, beginning with suburban services in Mumbai. Subsequently, diesel locomotives also became a very common form of locomotive. Over time, there has been a shift towards electrification, driven by efficiency and environmental concerns [7]. Alongside this, there has been a steady progression in passenger train types, from basic passenger trains, to mail and express trains, and then to faster trains like the Rajdhani and Shatabdi Expresses [8]. More recently, India has witnessed the development of semi-high-speed trains like the Vande Bharat Express, and the widespread growth of metro rail systems in urban areas, addressing the increasing demand for rapid transit. Additionally, luxury trains like the Maharaja's Express cater to high end tourism. In parallel, freight trains have also evolved, with specialized wagons and powerful locomotives designed to transport diverse commodities [9].

Electric Multiple Units (EMUs) are integral to the modern Indian Railways, serving a variety of transportation needs. Primarily, they form the backbone of suburban rail networks in densely populated cities like Mumbai, Chennai, and Kolkata, facilitating the daily commute of millions [10]. Beyond urban centers, Mainline Electric Multiple Units (MEMUs) are increasingly deployed for short to medium-distance intercity travel, replacing traditional locomotive-hauled trains with more efficient and faster services [11]. Furthermore, the introduction of modern EMUs like the Vande Bharat Express signifies a shift towards higher-speed, enhanced-comfort intercity travel. This widespread adoption of EMUs underscores their importance in improving the efficiency, speed, and overall passenger experience within the Indian railway system [12]. Electric Multiple Units (EMUs) receive their power from overhead catenary lines or a third rail system, which is then distributed throughout the train to power the

traction motors and various auxiliary systems. The pantograph, mounted on the roof of the leading coaches, collects the high-voltage electricity and feeds it into the train's electrical system [13]. Electric Multiple Units (EMUs) receive their power from overhead catenary lines or a third rail system, which is then distributed throughout the train to power the traction motors and various auxiliary systems. The pantograph, mounted on the roof of the leading coaches, collects the high-voltage electricity and feeds it into the train's electrical system [14]. This power is then managed and converted by onboard equipment, including transformers and rectifiers, to the appropriate voltage and current required for the traction motors, which propel the train. Additionally, a separate low-voltage distribution system supplies power to the coaches' lighting, air conditioning, and other passenger amenities [15]. In Electric Multiple Unit (EMU) trains, battery chargers play a crucial role in maintaining the functionality of essential onboard systems, even when the train is not drawing power from the overhead catenary or third rail. These chargers ensure that the train's auxiliary battery banks remain adequately charged, which in turn power critical systems such as lighting, air conditioning, door operation, communication systems, and emergency equipment [16]. In cases where regenerative braking is employed, some of the energy recovered can also be used to supplement the battery charging process. This ensures that even during periods of power disruption or when the train is stationary, vital systems continue to operate reliably [17].

Cascaded H-Bridge Multilevel Inverters (CHB-MLIs) have gained popularity in power electronics due to their modular structure and ability to produce high-quality voltage waveforms [18]. HB-MLIs are particularly suitable for integrating renewable energy sources, as they can operate with separate DC sources for each H-bridge [19]. Multilevel inverter topologies offer improved performance, higher power quality, and fewer switching losses, but require a reduced number of switches for optimal system complexity [20]. Never multilevel inverter topologies can reduce power semiconductor device count, gate driver, and isolated DC sources, offering advantage in medium and high-power applications [21]. In [22] highlights multilevel inverter topologies reduce the number of elements and power switches, making them suitable for renewable energy sources and reducing power loss.

Study of [23] binds the benefits of reduced switch multilevel inverter topologies over the comparative method to consider the component ratings.

II. CONVENTIONAL CASCADED MULTILEVEL INVERTER TOPOLOGIES

Conventional cascaded H-bridge (CHB) multilevel inverters represent a widely utilized topology in power electronics, primarily due to their modular structure and ability to synthesize high-quality voltage waveforms. These inverters are built by connecting multiple H-bridge units in series, with each unit powered by a separate DC source. This configuration allows for the generation of stepped output voltage waveforms, where the number of levels increases with the addition of H-bridge units, leading to a reduction in harmonic distortion. While offering advantages like simplified manufacturing and suitability for renewable energy applications, a key consideration is the requirement for separate DC sources, which can limit their application in certain scenarios. Nevertheless, their relative simplicity in control and effective waveform synthesis has solidified their role in various high-power applications.

Conventional cascaded multilevel inverter used in proposed study is found beneficial due to the following reasons

- Modular structure, which simplifies manufacturing and maintenance.
- Requires fewer components compared to other MLI topologies for the same number of voltage levels.
- Suitable for applications with separate DC sources, such as photovoltaic systems.
- Relatively simple control.

This paper presents a new topology for multilayer inverters (MLIs) that uses solar PV, three battery supplies, five power electronic switches, and railway battery charger output. 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.

III. THE INFLUENCE OF HARMONICS ON SYSTEM PERFORMANCE

Harmonics, unwanted multiples of the fundamental frequency, significantly impact system performance

across various electrical and electronic applications. Their presence introduces distortion into voltage and current waveforms, leading to a cascade of detrimental effects. Increased harmonic content elevates the root-mean-square (RMS) value of currents, resulting in higher power losses and potential overheating of equipment such as transformers, motors, and cables. This can drastically reduce the lifespan and efficiency of these components. Moreover, harmonics can interfere with the proper operation of sensitive electronic devices, causing malfunctions and communication errors. Power quality issues, such as voltage fluctuations and resonance, become more prevalent, potentially destabilizing the entire system. In industrial settings, harmonics can disrupt the operation of variable-speed drives and other automation equipment, leading to production downtime and financial losses. Therefore, controlling, and mitigating harmonics is crucial for ensuring reliable and efficient system performance.

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.

IV. DETAILS OF TRAIN

Concerning daylight hours, the year's longest day is 13 hours 49 minutes while the shortest is 10 hours 10 minutes. The shortest day is 3 hours 38 minutes shorter than the longest one. A median of 2856 hrs of daylight per year (out of a potential 4383), or 7:49 per day [22]. So, it is observed that the train is running to Sunshine for 8 hours during a single trip. This is a good opportunity to utilize the roof-top area to generate energy through solar PV. This is beneficial over, using an EOG (End on generation) system with fossil fuel or diesel. Hence, this study can extract more power from solar instead of diesel generation. The Route of the considered train is shown in Fig. 1, and its load description with fuel consumption details and discussed in Table 1.

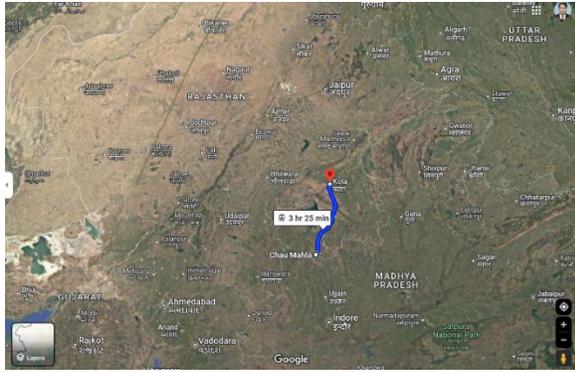


Fig. 1. Route Map of the Train Considered in Study.

Table 1. Details of the LHB train considered

Name of the Train	Kota ↔ Chaumahla (CMU)
	Chaumahla-Kota MEMU (61624-61623)
Rake Composition	
1 Basic unit (BU) contains	4 bogies (1 DMC (Driving Motor Car) + 3 TC (Trailer Coach))
Rake Composition (4 Basic Units)	4 x 4 = 16 Coaches/ bogies
Duration of 1 Trip	7 hours 20 min
The total sunshine period during the trip	7 hours
Total Required Power[24]	
Lighting	7 kW
Air Conditioning	30 kW
Passenger information system	5 kW
Automatic doors and miscellaneous	5 kW
Total	47 kW

The route map of the train is given in Fig. 1 which is running between the Kota and Nizamuddin stations of Indian railways. More details for the route and train are presented in Table 1.

V. ROOFTOP AREA CALCULATION OF LHB COACH FOR SOLAR PV MOUNTING

The typical ICF coaches are 1.7 meters shorter than the LHB coaches., is useful to mount more solar PV modules on the roof-top [25]. The roof-top layout and calculation of the LHB coach along with the area available for placing the solar PV modules are shown in Fig. 2, 3, and Table 2 respectively.

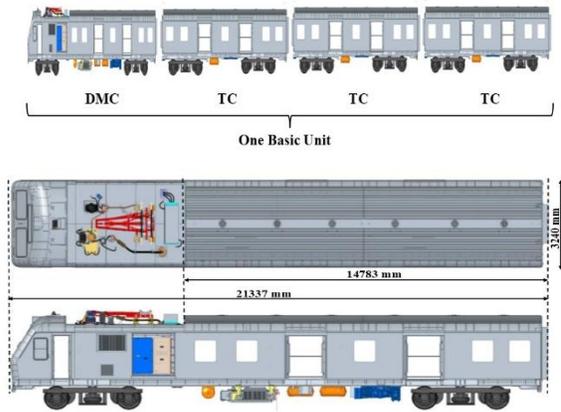


Fig. 2. Layout DMC Coach.



Fig. 3. Layout of TC coach.

Table 2. Roof-top area available for the mountain of solar PV modules on an EMU rake.

Gross rooftop area available on 1 Basic unit	276.52 m ²
The area is engaged on DMC by pantograph and electric equipment's	21.73 m ²
Net rooftop area available on 1 Basic unit (BU)	254.79 m ²
Net rooftop area available on rake 4 BU (80%)	≈ 820 m ²

VI. SOLAR POWER POTENTIAL PER M²

The panel used for consideration and details are presented in Table 3.

A. Details of Solar (PV) used

Table 3. Features of solar panel considered [26]

Specification	Details
Brand (Model)	Waaree (WFLW-520)
Output Power	520 W
Required Space	2.67 m ²
Max. peak Voltage	41.90 V

Panel Technology	Mono PERC flexible
Fill factor	80%
Single Panel Cost of Kw	19,000 INR

Table 4. Power potential of solar PV system on a single LHB coach.

Potential solar energy in a 2.67 m ² area	520W
Total potential solar energy in the available space on the roof-top	159.70 kW
Net solar power potential observes system efficiency to be 80% and the shaded region as 15%	127.76 kW

VII. ANNUAL REDUCTION IN CO2

The train considered is assumed to make up to 365 trips in the year because it runs daily. The arrangement can get the benefits mentioned in the next Table 5 along with a large reduction in (CO2) emissions. The carbon composition of the fuel determines how much (CO2) is created after it has burned. When a fuel is burned, its carbon (C) and hydrogen (H) contents primarily govern how much energy is released. When oxygen (O) and carbon (C) mix during combustion, heat is created. Diesel weighs 835 grams per liter and contains 86.2% carbon. This carbon requires 1920 grams of oxygen to burn, producing (CO2). $720+1920 = 2640$ grams (2.64kg) of carbon-ignited diesel is the result.[23]

Table 5. Annual reduction in CO2.

The maximum number of trips in a year	365
The volume of diesel that can be annually consumed by the EOG system of train	$365 \times 778.6 = 2,84,189$ lit.
Annual reduction in the CO2 emitted by a train, taking the amount of CO2 emitted per liter of diesel burnt as 2.64 kg and factor of combustion as 0.99	$2,84,189 \times 2.64 = 755942.74$ kg (756 tons)

VIII. IMPACT OF THIS SCHEME

The train considered requires 170 kWh power but considering some variation time so 200 kW PV system will be installed on the rooftop of a train rake. The cost per kW solar PV installation is around 40,000 INR/kW. The total cost of mounting solar PV will be returned in 5 months by this scheme.

Table 6. Savings and Return of Investment (ROI) of the considered system.

The total cost of mounting Solar PV on the Roof-top of a train	$19,000 \times 60 = 11,40,000$ INR
Daily saving by using Solar power per day	5813.08 INR
Return on investment (ROI)	$11,40,000/5813 = 196$ days (Around 7 Months)

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

The suggested consideration used in this work for the multilayer inverter (MLI) is shown in Fig 4. Five switches are used in this MLI work to produce seven different voltage levels. This is better than earlier versions that required six switches [24]. Compared to earlier designs, the suggested multilayer inverter (MLI) design is substantially simpler to construct. Only five switches, three batteries, a specific power supply, and solar panels are required. Since the multilayer inverter generated output voltage waveforms that were almost sinusoidal, the output waveform was enhanced; as a result, the overall harmonic distortion was likewise minimal. Additionally, the switching losses decrease. Together, these components form a seven-level MLI.

The output voltage level is determined by the following:

$$V_n = 2 * S_n - 3$$

Where, V_n = no. of output voltages

$$S_n = \text{no. of switches}$$

$$V_n = 2 * c_n - 1$$

Where, c_n = no. of DC link capacitor

A seven-level output voltage waveform is synthesized utilizing a photovoltaic (PV) source, a half-cycle operational gate (HOG) rectified power supply, two independent battery storage units, and a switching network comprising five semiconductor devices, as illustrated in Fig 4. A resistive load (R) of 10 ohms is implemented for characterization purposes [25]. The operational states of the switching devices, defined as 'On' (✓) and 'Off' (X), are governed by a switching logic detailed in Table 7. This controlled switching scheme generates a stepped

output voltage waveform with a peak positive amplitude of +3 volts and a peak negative amplitude of -3 volts. Table 7 enumerates the specific switching states for a three-phase inverter configuration employing five switches to achieve seven distinct voltage levels.

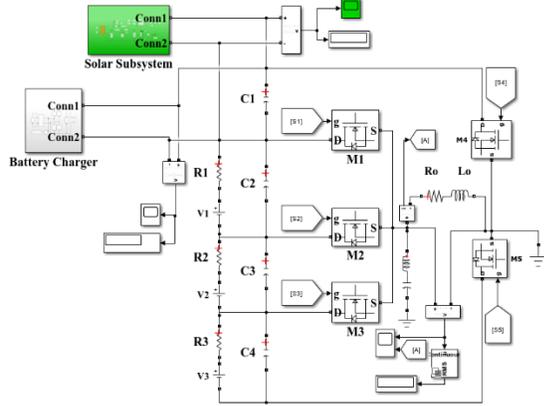


Fig. 4. MATLAB Simulink modeling MLI.

Table 7. Seven-level reduced switch topology switching pattern.

S . N o.	S 1	S 2	S 3	S 4	S 5	O/P Volt.
1	X	X	✓	X	✓	V
2	X	✓	X	X	✓	2V
3	✓	X	X	X	✓	3V
4	X	X	X	X	X	0
5	✓	X	X	✓	X	-V
6	X	✓	X	✓	X	-2V
7	X	X	✓	✓	X	-3V

A. PWM Techniques

Level shift modulation is the modulation technique used in this piece. Because phase-shifted modulation tends to produce higher harmonic contents, its application is considered inappropriate. Phase arrangement, phase opposition arrangement, alternating phase opposition arrangement, and inverted phase arrangement are the four possibilities that are accessible under the level shift modulation system [26]. The phase array pulse width modulation (PDPWM) technique, which combines carrier waves

with sinusoidal modulating waves for a 7-level multilevel inverter (MLI), is used in this work, as illustrated in Fig 5.

B. Pulse Generation Circuit

To generate a pulse, each carrier wave is contrasted with a sine wave. Matching switches receive the pulses after they are generated and provide a seven-level output voltage waveform. Fig 5 shows the MATLAB Simulink model with circuits that generate activation sequence pulses, and Table 7 shows the switch topology switching pattern.

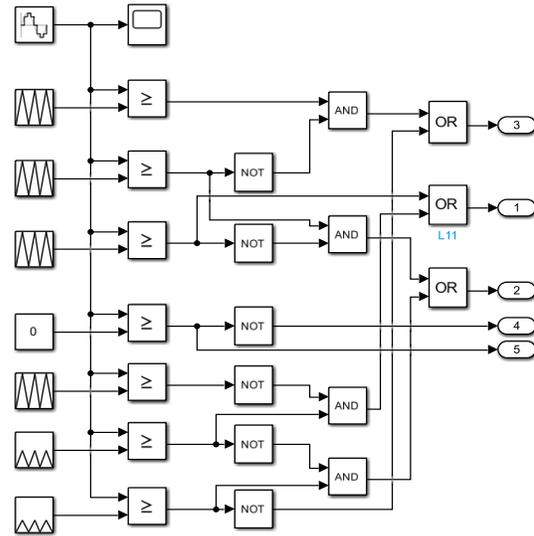


Fig. 5. Gate pulse generation Circuit for MLI switches.

Each switch's activation pulses are configured as follows to achieve output levels: An activation pulse is needed for the +3 Vdc and -Vdc output of switch S1, +2 Vdc and -2 Vdc for switch S2, and +Vdc and -3 Vdc for switch S3. During the positive and negative half cycles, respectively, switches S4 and S5 remain in an active state. (m-1) carrier waves can be used to create an m-level output waveform [27]. The pulse generating circuit's characteristics include the maximum triangular carrier's amplitude of 3 volts, the carrier wave's frequency of 2 KHz, the reference wave's magnitude of 3 volts, and the reference wave's frequency of 50 Hz.

X. RESULT

Compared to other current topologies, the basic circuit shown in Fig 4 for producing a 7-level output voltage waveform with an RL load has a lower total harmonic distortion (THD) [27]. Several filter types are

employed in conjunction with RL loads in the designated combinations to further reduce the harmonic content and make the inverter suitable for drive systems and renewable energy applications.

The output waveform's total harmonic distortion (THD) drops to a lower value when an LC filter is attached to the load of the inverter circuit. Waveforms of output voltage for various filter setups are shown in Fig 6. The output voltage waveform of an LC filter clearly exhibits a low THD and resembles a sine wave.

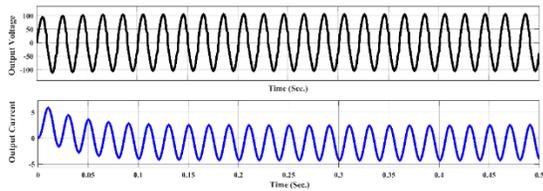


Fig. 6. waveforms of output voltage and currents

Using FFT analysis, Fig 7 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.

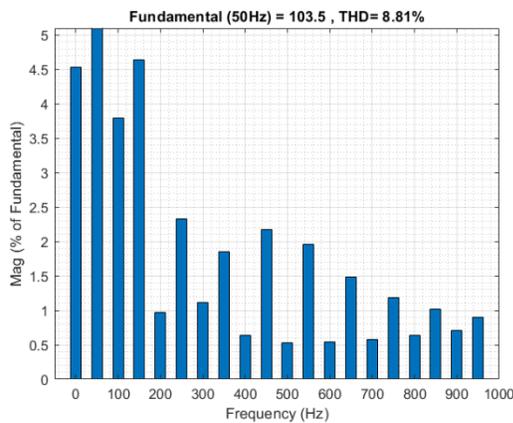


Fig. 7. FFT analysis of MLI

The total harmonic distortion percentage with the LC filter employed with the used MLI is 8.81 %.

XI. 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 Co2 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.

REFERENCE

[1] V. Chakraborty and S. Dutta, "Indian railway infrastructure systems: global comparison, challenges and opportunities," *Proceedings of the Institution of Civil Engineers: Smart Infrastructure and Construction*, vol. 175, no. 3, pp. 127–140, Jul. 2022, doi: 10.1680/JSMIC.22.00014/ASSET/IMAGES/SMALL/JSMIC175-0127-F15.GIF.

[2] Dr. Sanket Kasturiwala, Prajwal S Thakare, Samir A Pihul, Kalyani S Parate, Sakshi Sakharkar, and Yash Khare, "Accident Prevention of BOXN Wagon Train," *Int J Sci Res Sci Eng Technol*, vol. 11, no. 5, pp. 265–270, Oct. 2024, doi: 10.32628/IJSRSET24115122.

[3] R. S. Rivaldi, "Strengthening the National Logistics Network: PT Kereta Api Indonesia's Impact

in East Java Province,” *Asian Journal of Logistics Management*, vol. 3, no. 1, pp. 37–43, May 2024, doi: 10.14710/ajlm.2024.22795.

[4] P. Lahoti and D. S. Wason, “Why Railways aren’t Privatised in India,” *International Journal of Social Science and Economic Research*, vol. 09, no. 08, pp. 2713–2728, 2024, doi: 10.46609/IJSSER.2024.v09i08.010.

[5] V. B. Zakharov and E. Komarov, “Railways of India. Time to update and upgrade,” *BRICS Transport*, vol. 2, no. 3, pp. 1–12, Oct. 2023, doi: 10.46684/2023.3.3.

[6] R. Subramanian, “Evolution and Diffusion of ICTs in the Indian Railways: A Historical Analysis,” *Journal of International Technology and Information Management*, vol. 31, no. 2, pp. 84–109, Jan. 2022, doi: 10.58729/1941-6679.1498.

[7] D. Sehgal, “Review Paper on Locomotives in Trains,” *Int J Res Appl Sci Eng Technol*, vol. 9, no. 10, pp. 207–209, Oct. 2021, doi: 10.22214/ijraset.2021.38212.

[8] V. B. Zakharov and E. Komarov, “The development of passenger carriage design and passenger service on the railways of India: The end of the 19th – the first half of the 20th century,” *BRICS Transport*, vol. 3, no. 4, Dec. 2024, doi: 10.46684/2024.4.3.

[9] M. Rudenko, “DIGITAL TRANSFORMATION OF PASSENGER RAIL TRANSPORT: EVALUATION OF THE EFFECTIVENESS OF INSTALLING DIGITAL SCREENS AND IMPLEMENTING INTERACTIVE INFORMATION SYSTEMS ON TRAINS,” *ECONOMIC BULLETIN OF THE DNIPROVSK STATE TECHNICAL UNIVERSITY*, no. 1(8), pp. 110–122, Jun. 2024, doi: 10.31319/2709-2879.2024iss1(8).306486pp110-122.

[10] B. P. Donohue, “Review of Passenger Railroad EMU and MU Rolling Stock in the US and Canada – Part I, New York State Region,” in *2024 Joint Rail Conference*, American Society of Mechanical Engineers, May 2024. doi: 10.1115/JRC2024-122275.

[11] H. Chaudhary *et al.*, “Design and Development of a Small Scale EMU Model with Motorman Cabin Emulation,” in *2023 5th Biennial International Conference on Nascent Technologies in Engineering (ICNTE)*, IEEE, Jan. 2023, pp. 1–6. doi: 10.1109/ICNTE56631.2023.10146617.

[12] L. Liu and Z. Zhong, “High-Speed Railway Electric Multiple Unit,” in *Introduction to High-Speed Railway*, Singapore: Springer Nature Singapore, 2024, pp. 145–197. doi: 10.1007/978-981-99-6423-9_4.

[13] F.-G. Paul *et al.*, “Power-Hardware-in-the-Loop Emulation of the Low-Frequency Oscillation Phenomenon in AC Railway Networks,” *IEEE Access*, vol. 10, pp. 87374–87386, 2022, doi: 10.1109/ACCESS.2022.3198945.

[14] G. Wu *et al.*, “Pantograph–catenary electrical contact system of high-speed railways: recent progress, challenges, and outlooks,” *Railway Engineering Science*, vol. 30, no. 4, pp. 437–467, Dec. 2022, doi: 10.1007/s40534-022-00281-2.

[15] M. Davoodi, H. Jafari Kaleybar, M. Brenna, and D. Zaninelli, “Energy Management Systems for Smart Electric Railway Networks: A Methodological Review,” *Sustainability*, vol. 15, no. 16, p. 12204, Aug. 2023, doi: 10.3390/su151612204.

[16] M. Saeed *et al.*, “Onboard Energy Storage Systems for Railway: Present and Trends,” *IEEE Open Journal of Industry Applications*, vol. 4, pp. 238–259, 2023, doi: 10.1109/OJIA.2023.3293059.

[17] C. Shu, Y. Cao, T. Sun, T. Zhang, and X. Wang, “Energy recovery in automotive systems: A review of regenerative braking, flywheel, thermoelectric, rankin cycle and electric turbo compound,” *Applied and Computational Engineering*, vol. 85, no. 1, pp. 44–60, Jul. 2024, doi: 10.54254/2755-2721/85/20240623.

[18] Dr. S. Venkateshwarlu, N. Koushik, V. Ravi Prasad, and Ch. Sai Karthik, “Comparative Analysis of 5-Level and 7-Level Single-Phase Cascaded H-bridge Multilevel Inverters,” *CVR Journal of Science and Technology*, vol. 26, no. 1, pp. 54–61, Jun. 2024, doi: 10.32377/cvrjst2609.

[19] S. R. Hameed and T. H. AL-Mhana, "Cascaded H-Bridge Multilevel Inverter: Review of Topologies and Pulse Width Modulation," *Tikrit Journal of Engineering Sciences*, vol. 31, no. 1, pp. 138–151, Feb. 2024, doi: 10.25130/tjes.31.1.12.

[20] A. Balal, S. Dinkhah, F. Shahabi, M. Herrera, and Y. L. Chuang, "A Review on Multilevel Inverter Topologies," *Emerging Science Journal*, vol. 6, no. 1, pp. 185–200, Feb. 2022, doi: 10.28991/ESJ-2022-06-01-014.

[21] P. Omer, J. Kumar, and B. S. Surjan, "A Review on Reduced Switch Count Multilevel Inverter Topologies," *IEEE Access*, vol. 8, pp. 22281–22302, 2020, doi: 10.1109/ACCESS.2020.2969551.

[22] M. Sarebanzadeh, M. A. Hosseinzadeh, C. Garcia, E. Babaei, S. Islam, and J. Rodriguez, "Reduced Switch Multilevel Inverter Topologies for Renewable Energy Sources," *IEEE Access*, vol. 9, pp. 120580–120595, 2021, doi: 10.1109/ACCESS.2021.3105832.

[23] A. Salem, H. Van Khang, K. G. Robbersmyr, M. Norambuena, and J. Rodriguez, "Voltage Source Multilevel Inverters With Reduced Device Count: Topological Review and Novel Comparative Factors," *IEEE Trans Power Electron*, vol. 36, no. 3, pp. 2720–2747, Mar. 2021, doi: 10.1109/TPEL.2020.3011908.

[24] V. Vishab, P. Fred, and A. Bindu, "Article Title: Simulation of Electrification of Railway Lines using Microgrids Simulation of Electrification of Railway Lines using Microgrids," *IJATEM*.

[25] "3 PHASE MEMU BOOK 12.04.2022-unlocked".

[26] "WFLW-520." [Online]. Available: www.waaree.com