Predictive Switching Control for Multilevel Inverter using CNN-LSTM for Voltage Regulation

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Abstract*: *Now-a-days, model predictive control (MPC) is very commonly used for three phase inverters. But conventional MPC suffers computational complexities as well as unstable switching frequency issues. To address these issues related with conventional MPC model, this paper aims to use the benefits of deep learning model for predictive switching control. In this paper, CNN-LSTM network based predictive control is proposed for three phase inverters. Along with predictive control LC filter is cascaded to reduce the harmonics. The model is simulated using SIMULINK under fixed and dynamic load condition. The result shows decreased THD under different load conditions. Finally, the result is validated with existing models and achieves better performance.

***Keywords*: Multilevel Inverter, Predictive Control, Convolution Neural Network (CNN), Long Short-Term Memory (LSTM), Linear Load, Non-Linear Load, THD.**

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I. INTRODUCTION

The fast depletion of conventional sources of energy has resulted from the ever-increasing demand for electrical energy. Because of that, a lot of research has gone into renewable energy-based power generation. wind, and solar energy, in particular, are two of the most common alternative energy sources that are gaining popularity among power electronics producers. An inverter is a critical component of a renewable energy power generation system since it converts DC electricity to AC as needed by the grids [1]. However, the outputs of these inverters have a higher harmonic content, necessitating the installation of expensive and huge low pass passive filters before transferring the power to the distribution network [2][3]. As a result, for medium and high-power conversion systems, multilayer inverters (MLIs) have emerged as the most suitable substitute. In early 1975, MLI topology was initially established, and it has subsequently been modified in several ways [4][5]. Providing rural areas with access to electrical electricity is a critical prerequisite for impact on the implementation living conditions, and it is at the forefront of many developing nations' agendas. The most essential study areas in social structure are energy efficiency, electrical supply, and durability [6]. Efficient, regenerative, expense, trustworthy, and stable energy is a vital prerequisite for a nation's economic, societal, and technological growth. Renewable energy can be defined as life derived from an infinite supply of natural resources [7][8]. Natural light, water, wind, bioenergy, and geothermal energy are just a few examples of natural renewable energy resources. In contrast to other forms of energy, such as fossil fuels, which are limited and focused to certain geographic areas, the breadth and prospects for renewable energy resources are broad [9]. The intended output voltage is generated from several discrete DC source voltage levels in a cascade multilevel inverter, which can transform from fixed DC voltage to variable AC output voltage with static and dynamic frequency[10]. Some technological advancements for power quality enhancement and power stability enhancements are such as FACT devices, STATCOM, etc. As these devices are used with MLI for its voltage improvements. Along with these devices proper control strategies generates higher level of output voltage with limited switches uses [11][12].

Diode Clamped Multilevel Inverter (DCMLI), Flying Capacitor Multilevel Inverter (FCMLI), and Multi Module Cascaded Inverter (MMCI) are the three primary architectures of multilevel inverters. Several other designs for multilevel inverters with fewer thyristor elements and gate triggering circuits have been presented recently [13][14]. Various sorts of renewable energy sources may now be included into the micro-grid thanks to advancements in power electronic converters and elevated controllers [14][15]. To incorporate renewable energy, such as wind and solar power, in power grids, various converter topologies and control techniques have been developed [16]. Multilevel inverters (MLI) have subsequently been garnering and expanding attention in variable speed WT and PV systems because to the growing demands for medium and high-power applications. Multilevel converters allow the output voltage to rise without raising the switching device's voltage rating, allowing renewable energy systems to directly link to the grid voltage [17].The primary goal of MLIs is to synthesize higher levels of output voltage, which necessitates the use of additional switching semiconductors. Furthermore, it has a numerous advantage over traditional 3-level PWM converters, including high voltage capability without a stepping-up circuit, low harmonic content, low dv/dt stress on the switches, and a small filter size to generate the sinusoidal voltage in output. MLIs were divided into two types: single-phase and three-phase inverters. Cascaded H-bridge (CHBMLI), Neutral point clamped (NPC), and Flying capacitors are the three main types for single- and three-phases, respectively, depending on the strategic functions [18]. PV plants are connected which increases total harmonic distortion and introduces lower-level current harmonics [18][19]. THD of voltage and current harmonics of solar and wind power plants interconnecting to the public grid must be less than 5%, according to IEEE and IEC requirements. Multilevel converters enhance efficiency by lowering switching losses at high frequencies and utilizing modest output filters when compared to traditional two-level converters. Many semiconductor vendors provide detailed phase leg module data for a variety of multilevel converter topologies [20]. When compared to traditional two-level inverters, multilevel inverters offer numerous benefits. They achieve minimal harmonic content at their outputs without raising the inverter's switching frequency or lowering its output power. Furthermore, they provide a lower common-mode voltage, which reduces the load on the motor bearings greatly. Multilevel inverters with additional switches and DC voltage sources have a wider range of voltage levels at their output signals, resulting in higher output power [21].

The main disadvantages of multilayer inverters, as comparison to typical two-level inverters, are that they use more DC sources and have more intricate control algorithms [22]. Due to its high power, high voltage capacity, low switching losses, and low electromagnetic problems, multilevel power converters have been progressively prevalent. Conventional inverter drives are most typically utilised in industrial drives. They are made up of six power switches that switch using pulse width modulation (PWM). The output voltage and current waveform quality has worsened due to the use of such conventional converters [23].

II. Related Work

Bana et al. [1] discussed that MLI-based topologies have emerged as a strong contender for a number of major implementations in the power industry. Numerous MLI topologies have been established via research using fewer components as a result of the tremendous rise in power semiconductor techniques. New RS MLI topologies are still being developed for a variety of reasons, including lower costs, ideal compact, lower volume, lower wastage, and high efficiency. RS MLI topologies have recently been created for a variety of applications, including motor drives, renewable energy system integration, FACTs, power filtering, and so on. The objective of this research article was on RS MLI topologies that fall into three categories: symmetrical H-bridge based RS MLI, asymmetrical H-bridge based RS MLI, and modified RS MLI topologies.

Stonier et al. [9] used Proportional Integral (PI), Articial Neural Network (ANN), and Fuzzy Logic (FL) oriented controllers to explore the reduction level inverter. When the outcomes are considered, it is discovered that FLC produces better VR results when addressing fluctuations in the input solar PV. The commercial use of MLI by delivering a constant output voltage is explored, and the experimental findings demonstrates that the suggested approach is good. S. Boobalan and T.A. Ahmed et al. [11] presented a novel three-phaseMLI topology that uses a decreased number of phases. A variety of elements, including switches, dc power supply, and gate drivers. The suggested MLI can be used in a modular manner and for a variety of applications. The suggested MLI has the smallest average number of active elements per pole level when compared to current topologies. Moreover, because the number of working switches per pole is minimized in the suggested topology, it operates more efficiently. The expense of the dc supply is reduced using this topology. The designed MLI's better performance is confirmed by Matlab simulation and experimental implementation. Kaliamoorthy et al. [17] reported a unique single phase eleven inverter with minimized switching devices and separated DC sources, along with a sliding mode based MPPT algorithm. Simulations are run in MATLAB/Simulink, and a concept design for 2.4 KW has also been built. The FPGA board is used to construct the comprehensive control system. The simulation and experiment outcomes are precisely in line with each other. While comparing to a traditional cascaded H bridge inverter, the presented CHBMLI system has a lower number of isolated DC sources and switching components.

Sandhu et al. [20] developed and implemented a grid-connected hybrid alternative power 13-level modified CHBMLI topology model resources. It shows that the enhanced CHBMLI is capable of operating at high switching hz (frequencies). Harmonic distortion of the modified CHBMLI fell under the IEEE 519 THD factor limit of 5% due to the design's decrease in size. Switching losses, switches, and inverter costs may all be reduced thanks to the 13-level revised architecture. Switching losses, switches, and inverter costs may all be reduced thanks to the 13-level revised architecture. The system may be said to be employing an intelligent method that improves harmonic removal efficiency by combining the ANN technique with CHBMLI. When a sinusoidal stepped output waveform and greater inverter efficiency are sought in remote locations, it is advantageous.

Dhanasekaran [24] represented a discreet binary topology for cascaded multilevel Inverter, which has minimized number of thyristor switches. The recommended discreet binary design needs finite switches for synthesized output voltages. As a response, the suggested system's cost was decreased, and t he waveform of the output voltage has a very low total harmonic distortion profile and is more proficient.

The modeling and analysis of a thirteen-level modified Packed-U cell inverter were given by Fouda et al.[25]. The recommended inverter employs three DC and eight switches sources to reduce harmonics, and the triangular-carrier SPWM method at 2 kHz is used to efficiently regulate them. The output voltage and current waveforms were examined, revealing that the inverter is dependable and performs admirably. To reduce undesirable harmonics, an LCL low-pass filter is designed in the inverter's output. The suggested inverter has a low harmonic distortion, which results in great power quality and a small filter size. With the growing significance of renewable resources, DC-AC energy conversion is becoming an important area in power electronics. Conversion systems used in industry must acquire straight, pure, and efficient sinusoidal energy from these renewable energy resources. THD value is one of the indicators for this motive. 3-level CHB MLI is executed in by Colak et al. [26] with switching SPWM methodology. The main goal of this research is to find the simplest technique to generate signals. MATLAB/Simulink is used to create the DSP software. As a result, the developed and executed algorithm and MATLAB/Simulink codes are readily generated and downloaded to the processor. Only Simulink blocks can be used to create inverter-switching signals. Nguyen et al. [27] provided a model-based architecture and virtual prototyping study of a customizable multilevel inverter utilized to connect N dc voltage sources, such as solar panels, to the grid in this research. Virtual prototyping, loss modelling, and assessment may be beneficial in scenarios using multilevel inverters as grid-ties for different dc sources and in other architectures, in complement to the modular multilevel inverter investigated in this work. The findings show that individual and multiple inverter modules can breakdown in unique situations while keeping the grid-tie functional in terms of THD. Priyan and Ramani [28] created for a seven level FCMLI in this suggested technique. The newly created design will enhance system productivity and ensure voltage stability, allowing for more steady operation with fewer interruptions. The closed loop system controller can also be used to control a capacitor-clamped DC-DC boost converter, resulting in a constant output voltage of boost converter is acquired. Shimi et al. [29] presented the theory of functioning of a three-phase Maximum Power Point Tracking (MPPT) dependent solar powered 11 level cascade multilevel inverter. PV cells were modelled, and the dc supply for all of the H-bridges was provided by the PV cells. On the PV array that drives the multilevel inverter, the famous Maximum Power Point Tracking (MPPT) techniques Perturbation and Observation and Adaptive Control were employed. This work presents a predictive switching control of MLI for three phase renewable energy grid system using CNN-LSTM that reduces the THD by hybridizing it with LC filter to make the entire system more efficient. The objective is to get decreased THD and excellent performances for various loads. The suggested controller passes through two major stages: By proposing a neural network and using standard supervised learning, MPC can be used for offline training of data generation. After proper training of CNN-LSTM result in more accurate and successfully control. We compare the suggested CNN-LSTM-based technique to the traditional MPC in terms of performance under various operational situations.

III. System Description

The conceptual explanation of the converter examined in this article is presented in this part. The LC filter model is also presented in depth, and the forecasting controller uses it to forecast the voltage output for any specified input voltage vector.

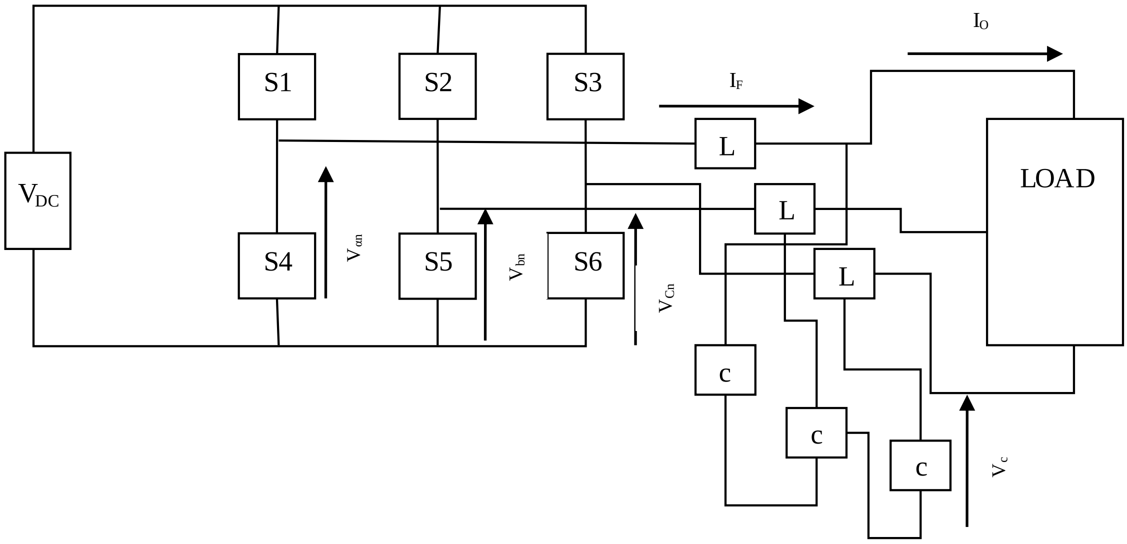

Fig. 1. Three Phase Inverter Control with LC filter for Renewable Energy Grid System

A. Clarke Transformation

The circuit design of proposed model is presented in Figure 1. In this system, the load condition is dynamic or undetermined, but the designs of the conversion and filtration are provided. Furthermore, in order to prevent short-circuit circumstances, the dual switches on every legs of the conversion work in a complimentary manner. The binary switches used in this work is represented as S_A, S_B, S_C. may be used to indicate the converter's switching states (Figure 2):

$$s_A = \begin{cases} 1, & if\ s_1\ is\ ON\ and\ s_4 is\ OFF \\ 0, & if\ s_1\ is\ OFF\ and\ s_4 is\ ON \end{cases}$$
$$s_B = \begin{cases} 1, & if\ s_2\ is\ ON\ and\ s_5 is\ OFF \\ 0, & if\ s_2\ is\ OFF\ and\ s_5 is\ ON \end{cases} \quad \text{(i)}$$
$$s_C = \begin{cases} 1, & if\ s_3\ is\ ON\ and\ s_6 is\ OFF \\ 0, & if\ s_3\ is\ OFF\ and\ s_6 is\ ON \end{cases}$$

The subsequent conversion can be used to describe these switching modes in vector illustration notation (i.e., in αβ reference frame):

$$s = \frac{2}{3}(s_A + a s_B + a^2 s_C) \equiv s_\alpha + j s_\beta, \qquad \text{(ii)}$$

$$\begin{bmatrix} s_\alpha \\ s_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \qquad \text{(iii)}$$

In which $a = e^{j(2\pi/3)}$. The condition of on/off od switches is ignored as perfect switches are considered in this simulation. The inverter's practicable output-voltage space vectors may be derived via

$$V_i = \frac{2}{3}(V_{An} + aV_{Bn} + a^2 V_{Cn}) \qquad \text{(iv)}$$

Wherein, V_{An} , V_{Bn}, V_{Cn} and are the inverter's phase-to-neutral, n voltages. V_i the voltage vector is mathematically represented as multiplication of V_{DC} and switching state S, which is shown in figure 2,:

$$V_i = V_{DC} s \qquad \text{(v)}$$

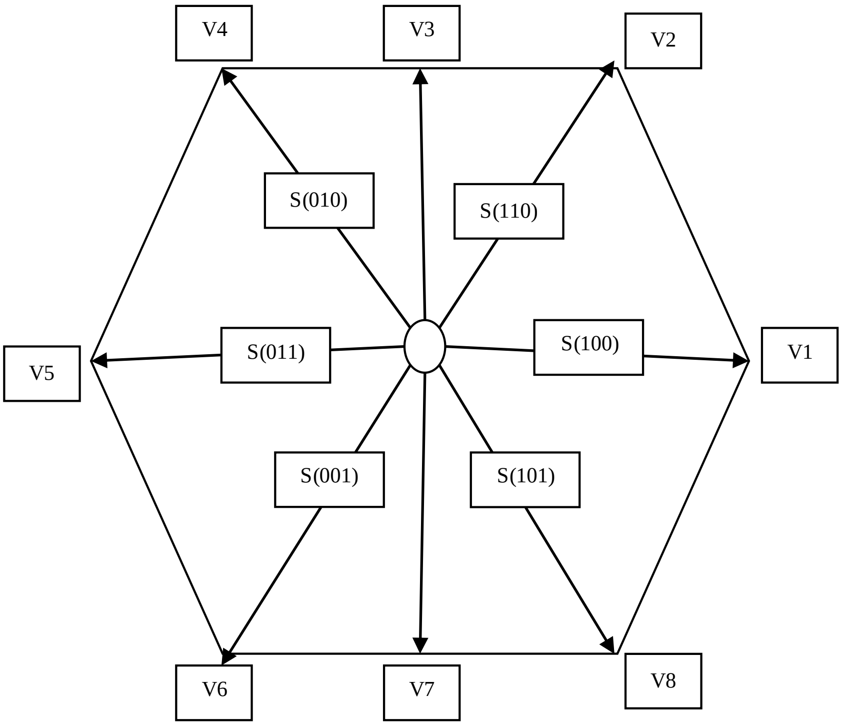

Fig. 2. Switching State Example

The diagram depicts the 8 switching modes and, as a result, the 8 voltage vectors created by the inverter using eqn (i) and eqn (iii), taking into account all conceivable pairings of the switching signals s_A, s_B, and s_C. The output current (I_o) is mathematically represented as:

$$I_F = \frac{2}{3}(I_{FA} + aI_{FB} + a^2 I_{FC}) \equiv I_{F\alpha} + j\, I_{F\beta} \qquad \text{(vi)}$$

$$V_C = \frac{2}{3}(V_{CA} + aV_{CB} + a^2 V_{CC}) \equiv V_{C\alpha} + j\, V_{C\beta} \qquad \text{(vii)}$$

$$I_O = \frac{2}{3}(I_{OA} + aI_{OB} + a^2 I_{OC}) \equiv I_{O\alpha} + j\, I_{O\beta} \qquad \text{(viii)}$$

B. LC Filter

The LC Filter model may be represented by two formulae: the first represents inductance movements, while the second represents capacitor dynamics. As an ongoing state-space system, this following equation may be represented as:

$$\frac{dx}{dt} = Ax + BV_I + B_Q I_O \qquad \text{(ix)}$$

$$\frac{d}{dt}\begin{bmatrix} I_F \\ V_C \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{l} \\ \frac{1}{c} & 0 \end{bmatrix}\begin{bmatrix} I_F \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{1}{l} \\ 0 \end{bmatrix} V_I + \begin{bmatrix} 0 \\ \frac{-1}{c} \end{bmatrix} I_O$$

Where, l= inductance

$_C$= capacitance.

According to eqn (iv), we can evaluate voltage vector(V_i) and according to eqn (vii), we evaluate terminal voltage V_c. Because of its dependency on an unpredictable load, the output current io is regarded as a disruption, although the value of V_{dc} is believed to be constant and predictable. Mathematically, the V_c equation is represented as:

$$V_C = [0 \quad 1]x \qquad \text{(x)}$$

The discrete-time state-space vector is mathematically represented as:

$$x(K+1) = A_Q x(K) + B_Q V_I(K) + B_{DQ} I_0(K) \qquad \text{(xi)}$$

$$\begin{bmatrix} I_F(K+1) \\ V_C(K+1) \end{bmatrix} = e^{At_s}\begin{bmatrix} I_F(K) \\ V_C(K) \end{bmatrix} + \int_0^{t_s} e^{A\tau} B d\tau V_I(K) + \int_0^{t_s} e^{A\tau} B d\tau I_O(K) \quad \text{(xii)}$$

The predictive controller (i.e., MPC) uses this model for forecasting V_C for all V_i. Then, in order to forecast the output voltage V_C utilizing (vii).

C. Proposed Predictive Controller Strategy

We consider that the inverters create just a finite range of potential switching modes and their related output-voltage vectors in the suggested control method, allowing us to address the prediction operator's optimisation issue online [1][25][30]. For every switching period, MPC uses the inverter's discrete-time model to predict future voltage behavior and its control. Following that, the best switching mode is selected based upon that minimizing of such a pre-defined cost function and sent straight towards the converter's switch at every sampling interval Ts, eliminating anything like a modulation step. The cost function is minimized as the error is minimized between predicted and reference voltage level. The cost function J, which describes the program's intended behaviour, is written in orthogonal coordinates as:

$$J = \left(Vca* - Vca(k+1)\right)^2 + \left(Vcb* - Vcb(k+1)\right)^2 \quad \text{(xiii)}$$

where v_{ca}* = real part of v_c* and v_{cb}* = imaginary parts of v_c* and v_{ca} = real part of $v_{c(k+1)}$ and v_{cb} = imaginary parts of $v_{c(k+1)}$. Figure 3 shows the MPC schematic diagram for a 3-phase inverter with output LC filter, having just one-step predictions horizon. The control function is declared, as S_A, S_B and S_C with input parameters as $v_{c(k)}$, $v_{c(k)*}$ with k sampling period.

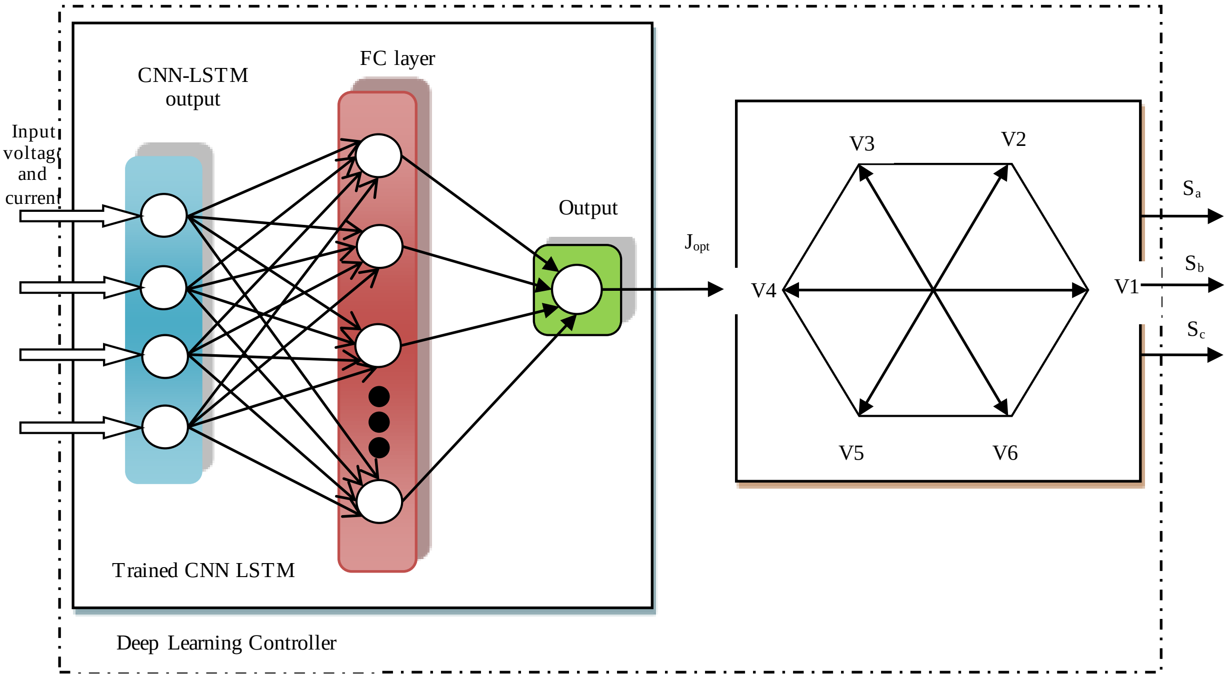

Fig. 3. MPC schematic diagram

The prediction of $v_{c(k+1)}$ at time instance k+1, the prediction algorithm predicts according to trained rules on several parameters such as V_i that is generated by inverters. For each voltage vector, the cost function would be used to calculate the error between V_{ref} and $v_{c(k+1)}$ at time instance k+1. Optimal value of cost function is evaluated as J_{opt} to obtain optimal voltage level. It's worth noting that J_{opt} is set to a relatively high number by default. Lastly, the optimal voltage vector's switching modes, S_a, S_b, and S_c, are produced and provided at the next sampled time (Fig 3).

IV. Results and Discussion

The proposed CNN-LSTM based control scheme and performance were compared to those of the suggested MPC by simulating the three-phase inverter system represented in Figure 4 with linear (i.e., resistive) and non-linear loads. The simulated system is configured with following parameters: reference voltage (Vref) = 200v, Cfilter = 40e-6F, Lfilter = 2.5e-3H, Vdc = 500v, and Load Resistance = 100. The steady-state behaviour of the CNN-LSTM -based controller with a load resistance of 100. As shown in figure 5,for the CNN-LSTM-based strategy, which has a THD of only 0.30 percent.

The result analysis shows that the output voltages (V_c) results in minimum power loss. As in conventional MLI's the output current (I_o) is proportional to V_c due to presence of linear load.

However, high-frequency harmonics are seen in the filtering current Io at the converter's output (figure 6), which are minimized by the LC filter, The recommended CNN-

LSTM-based management method's has remarkable dynamic features also the CNN-LSTM-based controller enables for a safe and simple transient response, demonstrating.

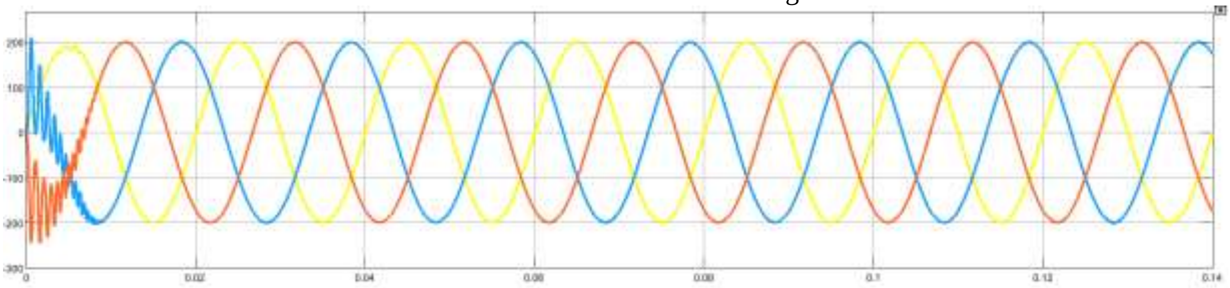

Fig. 4. Voltage Analysis under linear load

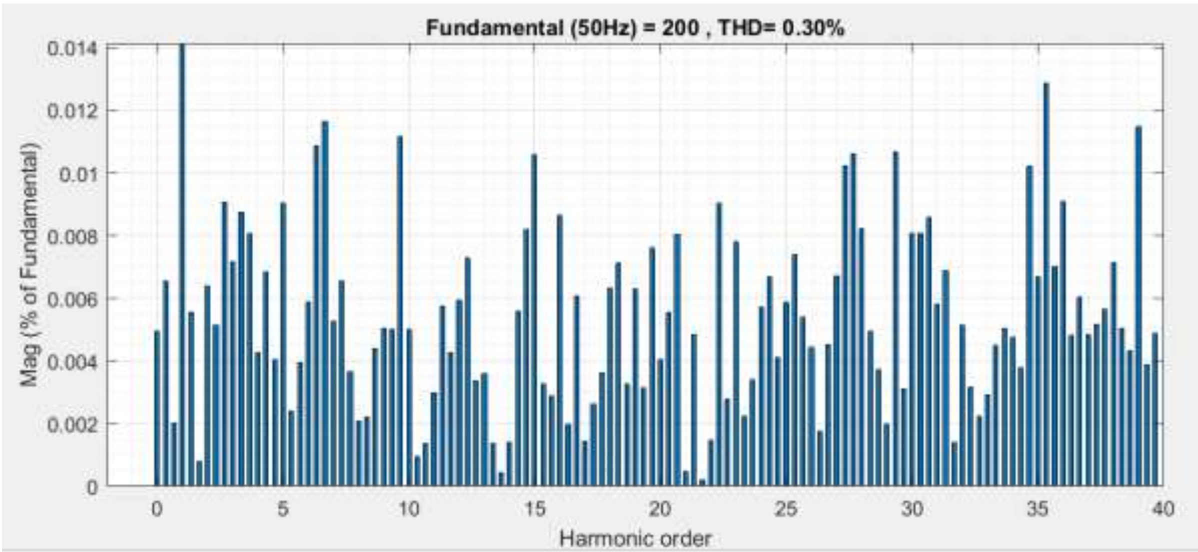

Fig. 5. Voltage THD under linear load

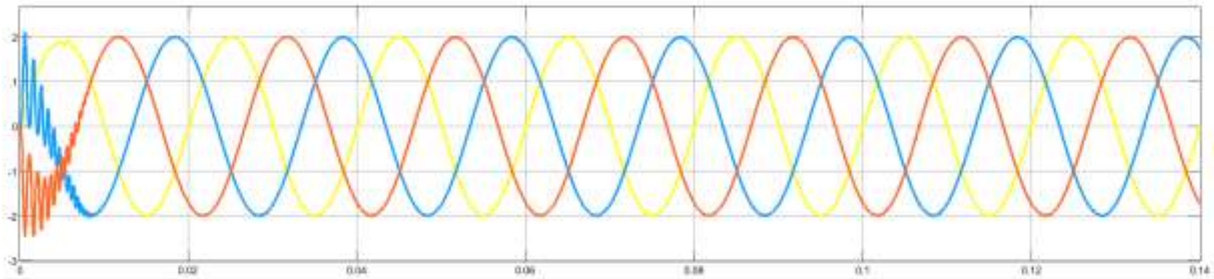

Fig. 6. Current under linear load

And from the other hand, using the CNN-LSTM-based controller, it is noted that reaching constant requires only around 5 ms for any workload. Additionally, with a THD of 2.05 percent, the output voltage amplitude of the CNN-LSTM-based method is considerably increased under non-linear load (Figure 7, Figure 8 and Figure 9). As previously stated, the suggested Network is trained off-line using a database that solely reflects distinct resistive load levels under different working circumstances including the parameters such as L-filter= 4.0e-3H, C-filter = 45e-6μF, Vdc = 520v, Vref = 250v; Load Resistance = 100; Load Capacitance = 500e-6. Furthermore, to prove the efficiency of the proposed model, the system is configured and evaluated with linear and non-linear loads. In fact, it is not unexpected that the presented CNN-LSTM-based controller outperforms MLI in both transient and steady-state responsiveness, even under previously unknown experimental parameters. This occurred due to two factors. In very first step, the deep learning (CNN-LSTM) model is trained with conventional SPWM controller and saved as trained model. Secondly, creating a sinusoidal waveform may be thought of as a repeated activity, and neural networks are very good at detecting and learning repetitive sequences of events.

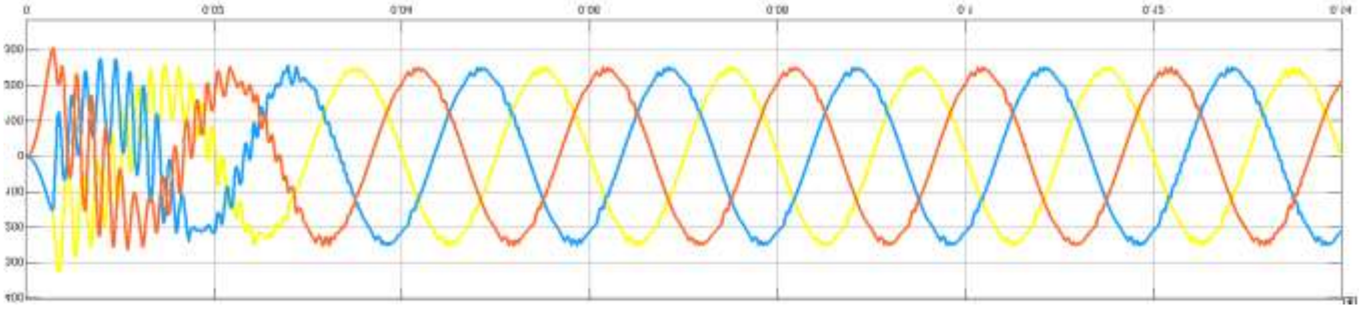

Fig. 7. Voltage Analysis under Non-Linear Load

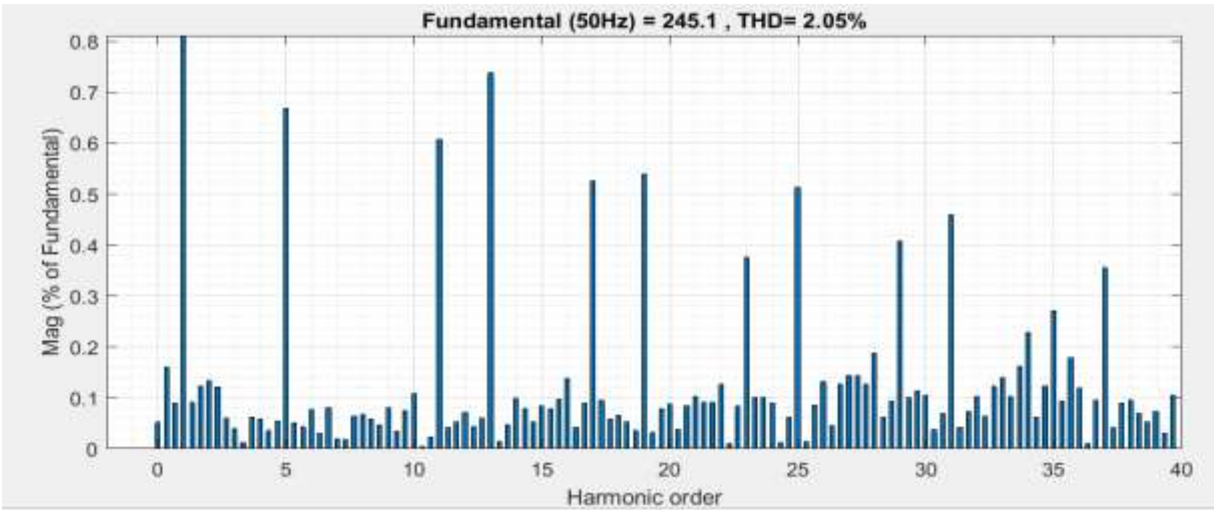

Fig. 8. Voltage THD under Non-Linear Load

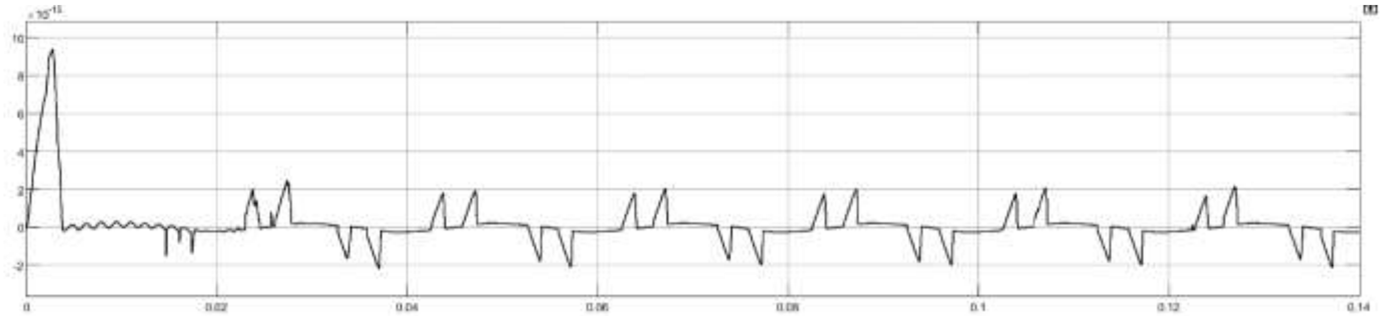

Fig. 9. Current output (one phase) under Non-Linear Load

We can see that all of the control techniques suggested in the research are model-based techniques in some form, requiring different processing or approximatively processes to implement its solutions in particular. MPC, the most frequently used method for three-phase inverter, depends upon resolving an optimization technique online, resulting in a high number of online computations. In other terms, at every time instant, the control signal of MPC is calculated by minimising a cost function online. In terms of giving a strong and rapid optimisation, convolutional neural networks (CNN_LSTM) have subsequently been utilised in conjunction with MPC. The use of neural network-based functions probabilistic models, which may be learned off-line to approximate the optimal control rule, is an alternate technique examined in this study.

Thus a method is recommended to prevent the disadvantages of MPC-based control approaches, even though it does not need a parametric representation to be managed. Therefore, the aim of this analysis is to regulate the three phase inverter with deep learning (CNN-LSTM) based predictive inverter control with regulated output by integrating LC filters. This hybrid approach results in lower harmonic distortion as a novelty with highly accurate inverter control using deep learning.

V. COMPARATIVE STATE OF ART

In this section, a state of art comparison is presented, table 1. Arikesh and Parvathy [7], presented a modular MLI that gives 1.89% of voltage THD. Taiea et al. [11] also presented modular MLI of THD 3.56% whereas Ali et al. [12]

Mamatha et al. [6], Dhanamjayulu et al. [23] presented cascaded transformer based MLI and achieved 3.08%, 3.58% and 4.12% of THD respectively. Similarly, Abarzadeh et al. [13] presented predictive MLI and achieved 4.38% of THD. As compared to these MLI techniques, this paper presented the deep learning based predictive MLI with LC filter that reduced the voltage of THD up to 0.30%. Below fig 10 represents the comparative state-of-art.

TABLE I. COMPARATIVE THD ANALYSIS

Ref	MLI	THD (in %)
Arikesh and Parvathy [7]	Modular MLI	1.89
Taiea et al. [11]	Modular MLI	3.56
Ali et al. [12]	Cascaded-Transformers MLI	3.08
Mamatha et al. [6]	Cascaded H-bridge MLI	3.58
Dhanamjayulu et al. [23]	Cascaded H-bridge MLI	4.12
Abarzadeh et al. [13]	Predictive MLI	4.38
Proposed	Deep-Learning Predictive MLI	0.30

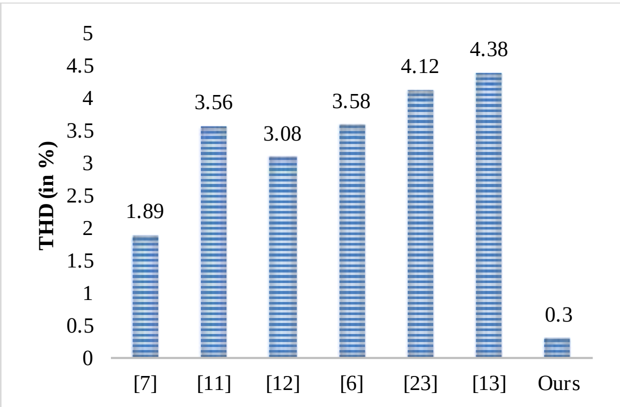

Fig. 10. THD Analysis of MLI Models

VI. CONCLUSION

In this paper, deep learning (CNN-LSTM) predictive control for multi-level inverter for renewable energy grid system is designed and implemented with LC filter for total harmonics reduction. The result was evaluated on linear and non-linear loads with proposed smart predictive control to generate three phase current and voltage within operational and controlled range. In terms of reduced THD, the proposed CNN-LSTM-based controller outperforms MPC, demonstrating the superior transient and steady-state efficiency of the indicated CNN-LSTM-based control method. THD is 0.30 percent for linear loads and 2.05 percent for nonlinear loads, according to the proposed approach.

REFERENCES

[1] P. R. Bana, K. P. Panda, R. T. Naayagi, P. Siano, and G. Panda, “Recently Developed Reduced Switch Multilevel Inverter for Renewable Energy Integration and Drives Application: Topologies, Comprehensive Analysis and Comparative Evaluation,” IEEE Access, vol. 7, pp. 54888–54909, 2019, doi: 10.1109/ACCESS.2019.2913447.

[2] B. Mahato, S. Majumdar, and K. C. Jana, “Single-phase Modified T-type–based multilevel inverter with reduced number of power electronic devices,” Int. Trans. Electr. Energy Syst., vol. 29, no. 11, p. e12097, Nov. 2019, doi: 10.1002/2050-7038.12097.

[3] S. Majhee, T. Roy, A. Chakraborty, and T. N. S. C. Sekhar, “Analysis and Development of A Novel Step-up 17 Level Switched Capacitor Multilevel Inverter For Renewable Energy Conversion System,” Proc. 2019 3rd IEEE Int. Conf. Electr. Comput. Commun. Technol. ICECCT 2019, Feb. 2019, doi: 10.1109/ICECCT.2019.8869420.

[4] C. M. N. Mukundan, P. Jayaprakash, U. Subramaniam, and D. J. Almakhles, “Binary hybrid multilevel inverter-based grid integrated solar energy conversion system with damped sogi control,” IEEE Access, vol. 8, pp. 37214–37228, 2020, doi: 10.1109/ACCESS.2020.2974773.

[5] E. Samadaei, M. Kaviani, and K. Bertilsson, “A 13-levels module (K-Type) with two DC sources for multilevel inverters,” IEEE Trans. Ind. Electron., vol. 66, no. 7, pp. 5186–5196, Jul. 2019, doi: 10.1109/TIE.2018.2868325.

[6] M. Sandhu and T. Thakur, “Modified Cascaded H-bridge Multilevel Inverter for Hybrid Renewable Energy Applications,” https://doi.org/10.1080/03772063.2020.1784802, pp. 1–13, 2020, doi: 10.1080/03772063.2020.1784802.

[7] A. Arikesh and A. K. Parvathy, “Modular multilevel inverter for renewable energy applications,” Int. J. Electr. Comput. Eng., vol. 10, no. 1, pp. 1–14, Feb. 2020, doi: 10.11591/IJECE.V10I1.PP1-14.

[8] V. Sangeetha, C. M. Nirmal Mukundan, P. Jayaprakash, and O. V. Asokan, “A new trinary source-based multilevel inverter for renewable applications,” 9th IEEE Int. Conf. Power Electron. Drives Energy Syst. PEDES 2020, Dec. 2020, doi: 10.1109/PEDES49360.2020.9379586.

[9] A. Stonier, S. Murugesan, R. Samikannu, S. K. Venkatachary, S. S. Kumar, and P. Arumugam, “Power quality improvement in solar fed cascaded multilevel inverter with output voltage regulation techniques,” IEEE Access, vol. 8, pp. 178360–178371, 2020, doi: 10.1109/ACCESS.2020.3027784.

[10] H. Abdoli, A. Khorsandi, B. Eskandari, and J. S. Moghani, “A New Reduced Switch Multilevel Inverter for PV Applications,” 2020 11th Power Electron. Drive Syst. Technol. Conf. PEDSTC 2020, Feb. 2020, doi: 10.1109/PEDSTC49159.2020.9088508.

[11] T. A. Ahmed, E. E. M. Mohamed, A. R. Youssef, A. A. Ibrahim, M. S. R. Saeed, and A. I. M. Ali, “Three phase modular multilevel inverter-based multi-terminal asymmetrical DC inputs for renewable energy applications,” Eng. Sci. Technol. an Int. J., vol. 23, no. 4, pp. 831–839, Aug. 2020, doi: 10.1016/J.JESTCH.2019.11.003.

[12] I. M. Ali, M. A. Sayed, and T. Takeshita, “New Cascaded-Transformers Multilevel Inverter for Renewable Distribution Systems,” ECCE 2020 - IEEE Energy Convers. Congr. Expo., pp. 3965–3971, Oct. 2020, doi: 10.1109/ECCE44975.2020.9236048.

[13] K. R. Sorto-Ventura, M. Abarzadeh, K. Al-Haddad, and L. A. Dessaint, “23-level single DC source hybrid PUC (H-PUC) converter topology with reduced number of components: Real-time implementation with model predictive control,” IEEE Open J. Ind. Electron. Soc., vol. 1, no. 1, pp. 127–137, 2020, doi: 10.1109/OJIES.2020.3007989.

[14] M. Vijeh, M. Rezanejad, E. Samadaei, and K. Bertilsson, “A General Review of Multilevel Inverters Based on Main Submodules: Structural Point of View,” IEEE Trans. Power Electron., vol. 34, no. 10, pp. 9479–9502, Oct. 2019, doi: 10.1109/TPEL.2018.2890649.

[15] Y. Yang et al., “Multiple-Voltage-Vector Model Predictive Control with Reduced Complexity for Multilevel Inverters,” IEEE Trans.

Transp. Electrif., vol. 6, no. 1, pp. 105–117, Mar. 2020, doi: 10.1109/TTE.2020.2973045.

[16] M. Aly and H. A. Ramadan, "Design and implementation of adaptive SVPWM algorithm for multilevel inverters in renewable energy applications," Sol. Energy, vol. 183, pp. 745–754, May 2019, doi: 10.1016/J.SOLENER.2019.03.069.

[17] M. Kaliamoorthy, V. Rajasekaran, and G. Praveenraj, "A novel single phase cascaded multilevel inverter for hybrid renewable energy sources," ICACCS 2015 - Proc. 2nd Int. Conf. Adv. Comput. Commun. Syst., Nov. 2015, doi: 10.1109/ICACCS.2015.7324097.

[18] M. M. Zaid and J. S. Ro, "Switch ladder modified h-bridge multilevel inverter with novel pulse width modulation technique," IEEE Access, vol. 7, pp. 102073–102086, 2019, doi: 10.1109/ACCESS.2019.2930720.

[19] M. M. Zaid and J. S. Ro, "Optimal design of a cascaded rectangular-type and circle-type multilevel inverters with a new switching technique," IET Power Electron., vol. 13, no. 13, pp. 2831–2846, Oct. 2020, doi: 10.1049/IET-PEL.2019.1389/CITE/REFWORKS.

[20] M. Sandhu and T. Thakur, "Harmonic Minimization in Modified Multilevel Inverter for Hybrid Renewable Energy Sources," 2018 6th Ed. Int. Conf. Wirel. Networks Embed. Syst. WECON 2018 - Proc., pp. 67–72, Nov. 2018, doi: 10.1109/WECON.2018.8782064.

[21] V. Anand and V. Singh, "Implementation of cascaded asymmetrical multilevel inverter for renewable energy integration," Int. J. Circuit Theory Appl., vol. 49, no. 6, pp. 1776–1794, Jun. 2021, doi: 10.1002/CTA.2944.

[22] Chappa, S. Gupta, L. K. Sahu, S. P. Gautam, and K. K. Gupta, "Symmetrical and Asymmetrical Reduced Device Multilevel Inverter Topology," IEEE J. Emerg. Sel. Top. Power Electron., vol. 9, no. 1, pp. 885–896, Feb. 2021, doi: 10.1109/JESTPE.2019.2955279.

[23] Dhanamjayulu, D. Prasad, S. Padmanaban, P. K. Maroti, J. B. Holm-Nielsen, and F. Blaabjerg, "Design and Implementation of Seventeen Level Inverter with Reduced Components," IEEE Access, vol. 9, pp. 16746–16760, 2021, doi: 10.1109/ACCESS.2021.3054001.

[24] S. Boobalan and R. Dhanasekaran, "Hybrid topology of asymmetric cascaded multilevel inverter with renewable energy sources," Proc. 2014 IEEE Int. Conf. Adv. Commun. Control Comput. Technol. ICACCCT 2014, pp. 1046–1051, Jan. 2015, doi: 10.1109/ICACCCT.2014.7019256.

[25] S. Fouda, M. S. Salem, A. Saeed, A. Shaker, and M. Abouelatta, "Thirteen-level modified packed u-cell multilevel inverter for renewable-energy applications," 2020 2nd Int. Conf. Smart Power Internet Energy Syst. SPIES 2020, pp. 431–435, Sep. 2020, doi: 10.1109/SPIES48661.2020.9243059.

[26] Colak, E. Kabalci, and G. Keven, "The effects of PR control in three-level single-phase multilevel inverter," 8th Int. Conf. Renew. Energy Res. Appl. ICRERA 2019, pp. 821–826, Nov. 2019, doi: 10.1109/ICRERA47325.2019.8996513.

[27] L. V. Nguyen, H. D. Tran, and T. T. Johnson, "Virtual prototyping for distributed control of a fault-tolerant modular multilevel inverter for photovoltaics," IEEE Trans. Energy Convers., vol. 29, no. 4, pp. 841–850, Dec. 2014, doi: 10.1109/TEC.2014.2362716.

[28] S. S. Priyan and K. Ramani, "Implementation of closed loop system for flying capacitor multilevel inverter with stand-alone Photovoltaic input," Proc. 2013 Int. Conf. Power, Energy Control. ICPEC 2013, pp. 281–286, 2013, doi: 10.1109/ICPEC.2013.6527666.

[29] S. L. Shimi, T. Thakur, J. Kumar, S. Chatterji, and D. Karanjkar, "MPPT based solar powered cascade multilevel inverter," 2013 Annu. Int. Conf. Emerg. Res. Areas, AICERA 2013 2013 Int. Conf. Microelectron. Commun. Renew. Energy, ICMiCR 2013 - Proc., 2013, doi: 10.1109/AICERA-ICMICR.2013.6576041.

[30] M. Humayun, M. M. Khan, A. Muhammad, J. Xu, and W. Zhang, "Evaluation of symmetric flying capacitor multilevel inverter for grid-connected application," Int. J. Electr. Power Energy Syst., vol. 115, p. 105430, Feb. 2020, doi: 10.1016/J.IJEPES.2019.105430.

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