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Design and Simulation of ANN Controlled LLC Resonant Converter with Switched Capacitor MLI

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ABSTRACT*:* This project presents the design and simulation of an Artificial Neural Network (ANN) controlled LLC resonant converter integrated with a switched-capacitor based 13-level multilevel inverter (MLI). The proposed system follows a two-stage power conversion architecture. In the first stage, a high-frequency LLC resonant DC–DC converter is employed to achieve voltage boosting and tight voltage regulation under varying load and reference conditions. An ANN-based voltage mode control strategy is implemented to enhance dynamic performance, reduce settling time, and improve efficiency compared to a conventional PI controller. In the second stage, the regulated DC output is converted into AC using a switched-capacitor multilevel inverter topology capable of producing 13 voltage levels with a reduced number of power switches and inherent self-voltage balancing of capacitors, eliminating the need for auxiliary balancing circuits.

The complete system is model-led and simulated in MATLAB/Simulink for power ratings of 1 kW and 2 kW under different power factor conditions. Key performance parameters such as voltage regulation, dynamic response, output power, efficiency, and total harmonic distortion (THD) are evaluated. Simulation results demonstrate that the ANN-controlled LLC converter significantly outperforms the PI-controlled counterpart in terms of faster transient response, higher efficiency, and improved power delivery. The proposed configuration is well suited for renewable energy systems, DC microgrids, and high-quality AC power applications.

I. INTRODUCTION

The rapid growth of renewable energy systems, electric vehicles, and distributed generation has increased the demand for high-efficiency, high-power-density, and intelligent power electronic converters. Modern power conversion systems are expected to provide high voltage gain, excellent power quality, reduced component count, and fast dynamic response while maintaining high efficiency. Conventional two-level inverters and hard-switched DC–DC converters face challenges such as high switching losses, large electromagnetic interference (EMI), and poor harmonic performance at higher power levels.

Multilevel inverters (MLIs) and resonant DC–DC converters have emerged as promising solutions to address these issues. Among resonant converters, the LLC resonant converter is widely preferred due to its inherent soft-switching capability, wide operating range, and high efficiency. Similarly, switched-capacitor based MLIs offer voltage boosting capability, reduced device stress, and transformer-less operation. When combined with intelligent control techniques such as Artificial Neural Networks (ANNs), these converters can achieve superior dynamic and steady-state performance.

This project integrates an ANN-controlled LLC resonant converter with a switched-capacitor based 13-level multilevel inverter to realize a compact, efficient, and high-performance power conversion system.
The motivation behind this work is driven by the limitations of conventional power conversion systems and controllers. Traditional PI controllers require accurate mathematical modelling and often exhibit degraded performance under nonlinear operating conditions. In contrast, ANN controllers can learn system behaviour and provide faster and more robust control without precise system modelling.

Conventional DC–DC converters and multilevel inverters suffer from high switching losses, poor dynamic response, increased component count, and complex control strategies. PI-controlled converters show limited performance under nonlinear load conditions and reference voltage variations. Moreover, traditional MLI topologies require multiple DC sources, bulky transformers, or complex.

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II. LITERATURE SURVEY

Extensive research has been carried out in the areas of multiport converters, LLC resonant converters, multilevel inverters, and intelligent control techniques. The key contributions relevant to this project are summarized below:
[1] **Sato et al.** proposed a non-isolated multi-port DC–DC converter integrating PWM and phase-shift control, highlighting reduced component count and bidirectional power flow
[2] **Zhang et al.** introduced a three-port LLC resonant DC–DC converter suitable for renewable energy and energy storage applications, demonstrating soft-switching operation
[3] **Zeng et al.** developed a four-port DC–DC converter for hybrid wind–solar systems with effective power management and DC-link voltage regulation
[4] **Prabhakaran and Agarwal** presented a four-port DC–DC converter for bipolar DC microgrids with reduced components and high efficiency
[5] **Bana et al.** evaluated power quality performance of reduced-switch multilevel inverters, emphasizing lower standing voltage and improved harmonic performance
[6] **Panda et al.** proposed optimized selective harmonic elimination techniques for symmetric and asymmetric MLIs
[7] **Jahan et al.** introduced a switched-capacitor based single-source cascaded H-bridge inverter with voltage boosting capability
[8] **Panda et al.** developed a single-source switched-capacitor MLI for photovoltaic applications with quadruple voltage boost
[9] **Lee et al.** proposed an improved switched-capacitor integrated MLI with reduced voltage stress across switches
[10] **Roy and Sadhu** presented a step-up switched-capacitor multilevel inverter with reduced components and high boosting capability
[11] **Lin et al.** introduced a symmetrical step-up MLI using crisscross capacitor units with self-voltage balancing
[12] **Lee et al.** proposed novel active neutral-point-clamped inverters with enhanced voltage boosting capability
[13] **Panda et al.** developed a self-balanced high-gain switched-capacitor MLI using a single DC source
[14] **Panda et al.** proposed a reduced device count hybrid switched-capacitor 13-level inverter with triple voltage boost
[15] Several studies have demonstrated that ANN-based controllers outperform conventional PI controllers in nonlinear power electronic systems by offering faster response and better robustness.from the literature, it is evident that combining LLC resonant converters, switched-capacitor MLIs, and ANN-based control can lead to a high-performance and efficient power conversion system.

However, limited work has been reported on the integrated implementation of ANN-controlled LLC converters with high-level switched-capacitor MLIs, which forms the core contribution of this project.

III. DATASET DESCRIPTION

The dataset employed for the development, training, validation, and testing of the Artificial Neural Network (ANN) controller was generated using the detailed MATLAB/Simulink model of the proposed ANN-controlled LLC resonant DC–DC converter integrated with a switched-capacitor based multilevel inverter, ensuring that the data accurately represents the dynamic and steady-state behavior of the actual system. Since the proposed power conversion system is intended for photovoltaic-based renewable energy applications, the dataset was created by simulating realistic operating conditions such as wide variations in solar irradiation levels ranging from 100 W/m² to 1000 W/m², corresponding changes in PV array output voltage, different load power ratings of 1 kW and 2 kW, and varying load power factor conditions from 0.7 to unity.

These variations introduce nonlinearities, disturbances, and parameter uncertainties into the system, which are essential for effective ANN training. For each operating condition, the LLC converter response was observed over time to capture both transient phenomena, such as sudden load changes and irradiation fluctuations, and steady-state characteristics, such as voltage ripple and regulation accuracy. The input variables of the dataset consist of the output voltage error, defined as the difference between the reference DC-link voltage and the measured output voltage of the LLC converter, and the change in voltage error between consecutive sampling intervals, which together provide sufficient information about system deviation, dynamic trend, and disturbance impact.

These inputs enable the ANN to learn the nonlinear mapping between voltage deviation and the optimal control action required for regulation. The corresponding output parameter of the dataset is the control signal in the form of switching frequency or duty ratio applied to the LLC resonant converter, which directly influences the converter output voltage.
Prior to training, all dataset samples were normalized to a suitable range to avoid numerical dominance of any single parameter and to improve convergence speed during learning. The dataset was structured to include a balanced mix of

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operating scenarios, covering low, medium, and high irradiation levels, light and heavy load conditions, and different power factor values, thereby enhancing the generalization capability of the ANN. Supervised learning was adopted, and the dataset was divided into training, validation, and testing subsets, where the training dataset was used to update ANN weights using the Levenberg–Marquardt backpropagation algorithm, the validation dataset was used to monitor learning performance and prevent overfitting, and the testing dataset was used to evaluate controller robustness under unseen operating conditions. This comprehensive dataset enables the ANN controller to accurately predict the required control signal under nonlinear and time-varying conditions, resulting in faster transient response, reduced settling time, improved voltage regulation, and higher overall efficiency compared to the conventional PI-controlled system.

IV. METHODOLOGY

The methodology adopted in this project involves the systematic design, modelling, control, and simulation of an ANN-controlled LLC resonant DC–DC converter integrated with a switched-capacitor based 13-level multilevel inverter using MATLAB/Simulink. The proposed system follows a two-stage power conversion structure, where the first stage performs DC–DC voltage boosting and regulation, and the second stage converts the regulated DC voltage into a high-quality AC output. Initially, a photovoltaic (PV) source is modelled to represent a practical renewable energy input with variable voltage characteristics due to changes in irradiation and temperature. This low-voltage DC input is supplied to the LLC resonant converter, which is designed to operate with soft-switching characteristics to reduce switching losses and improve efficiency.

The LLC resonant components are selected based on the required power ratings of 1 kW and 2 kW and a switching frequency of 50 kHz to ensure stable operation over a wide range of load conditions. To achieve effective voltage regulation, an Artificial Neural Network (ANN) based voltage-mode controller is developed, where the ANN is trained using simulation data obtained under different operating conditions.

The ANN inputs include the output voltage error and change in error, while the output represents the control signal in the form of switching frequency or duty ratio. The ANN is trained using the Levenberg–Marquardt backpropagation algorithm and then integrated into the Simulink model for real-time control of the LLC converter.

The regulated DC output is stored in a DC-link capacitor and fed to a switched-capacitor based multilevel inverter, which is designed to generate 13 voltage levels using a reduced number of switches and capacitors. The inverter operates based on predefined switching sequences that provide voltage boosting and inherent self-balancing of capacitor voltages without the need for auxiliary balancing circuits or multiple DC sources.

The inverter output is connected to an RL load with varying power factor conditions to evaluate system performance under realistic operating scenarios. The complete system is simulated in MATLAB/Simulink, and key performance parameters such as output voltage regulation, transient response, output power, efficiency, and total harmonic distortion (THD) are analyzed.

Finally, the performance of the ANN-controlled system is compared with that of a conventional PI-controlled system to demonstrate the effectiveness of the proposed methodology in achieving improved dynamic response, higher efficiency, and superior power quality.

methodology adopted for the design, modeling, control, and simulation of the proposed ANN-controlled LLC resonant converter integrated with a switched-capacitor based 13-level multilevel inverter. The methodology is systematically organized starting from the overall system block diagram, followed by detailed modeling of each subsystem including the photovoltaic (PV) source, LLC resonant DC–DC converter, multilevel inverter, and the ANN-based controller. The entire system is modeled and validated using MATLAB/Simulink.

The below is image that is drawn for the purpose for better understanding and better understandably for the view and also make better for visualization so that one can understand the image well also helps him to understand the working of this project by which it makes help to understand visually better rather than only theory so the below figure depicts the working of the project

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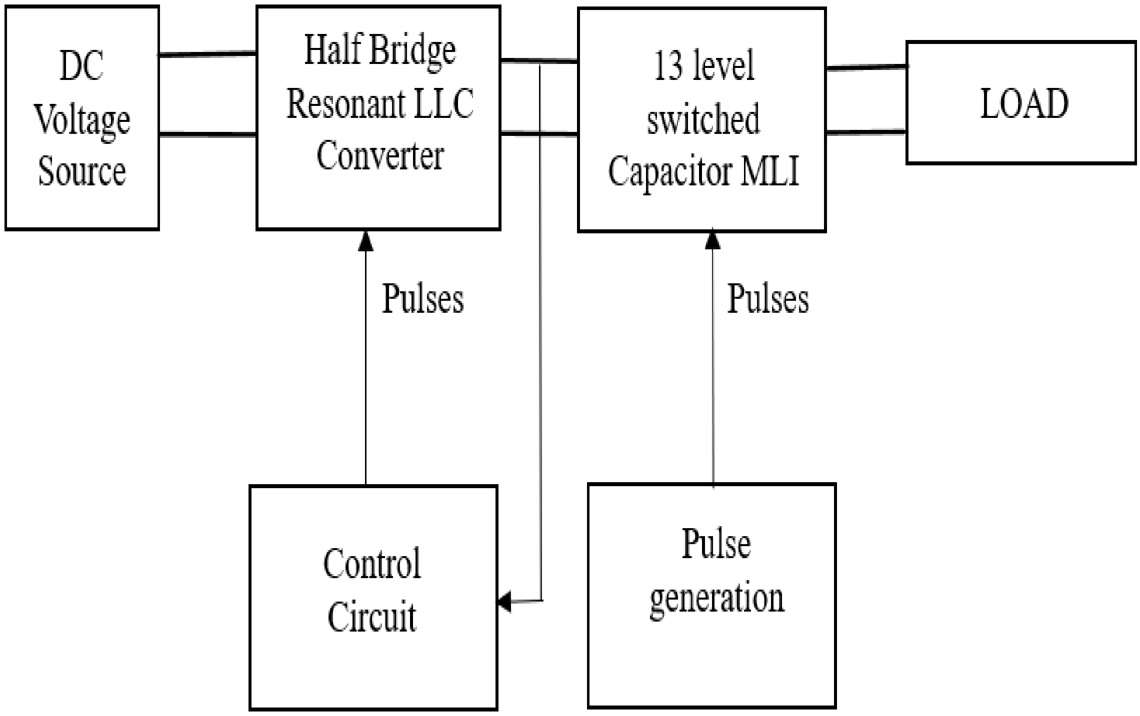

The block diagram of the proposed system consists of the following major functional blocks:
• Photovoltaic (PV) source / DC input source
• ANN-controlled LLC resonant DC–DC converter
• DC-link capacitor
• Switched-capacitor based 13-level multilevel inverter
• AC load (RL load with varying power factor)

The power flow in the proposed system is unidirectional, starting from the DC source and ending at the AC load. The block diagram represents a two-stage power conversion architecture where the first stage performs DC–DC voltage regulation and boosting, and the second stage performs DC–AC conversion with improved power quality
.

The PV source supplies a low-voltage DC power which is fed to the LLC resonant converter. Due to the inherent variability of PV voltage and load conditions, an intelligent control strategy is required to regulate the output voltage. An ANN-based voltage mode controller is employed to generate the appropriate control signal for the LLC converter switches.

The LLC resonant converter boosts and regulates the input voltage to the desired DC-link voltage while ensuring soft-switching operation (ZVS and ZCS), thereby reducing switching losses and improving efficiency. The regulated DC output is then supplied to the switched-capacitor based multilevel inverter.

The multilevel inverter converts the regulated DC voltage into a high-quality AC voltage with 13 discrete voltage levels. The switched-capacitor configuration provides inherent voltage boosting and self-balancing of capacitor voltages without requiring additional balancing circuits or isolated DC sources. Finally, the inverter feeds the AC power to the RL load operating at different power factors.

The primary side stage of LLC resonant converter can be built as a full-bridge or half-bridge type and the output stage can be implemented as a full-bridge or centre tapped rectifier configuration with capacitive output filter. The following figure shows the half-bridge implementation of the LLC resonant converter with full-bridge output rectifier, where Lm

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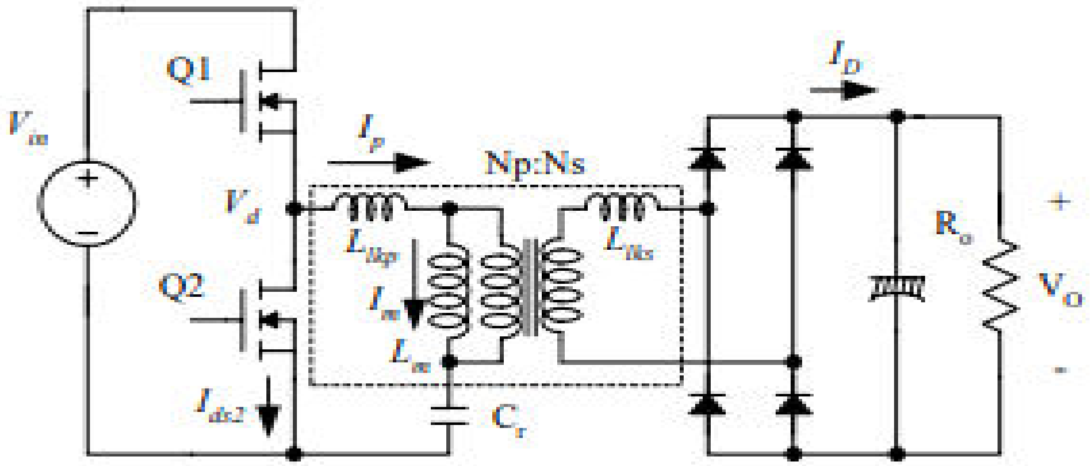
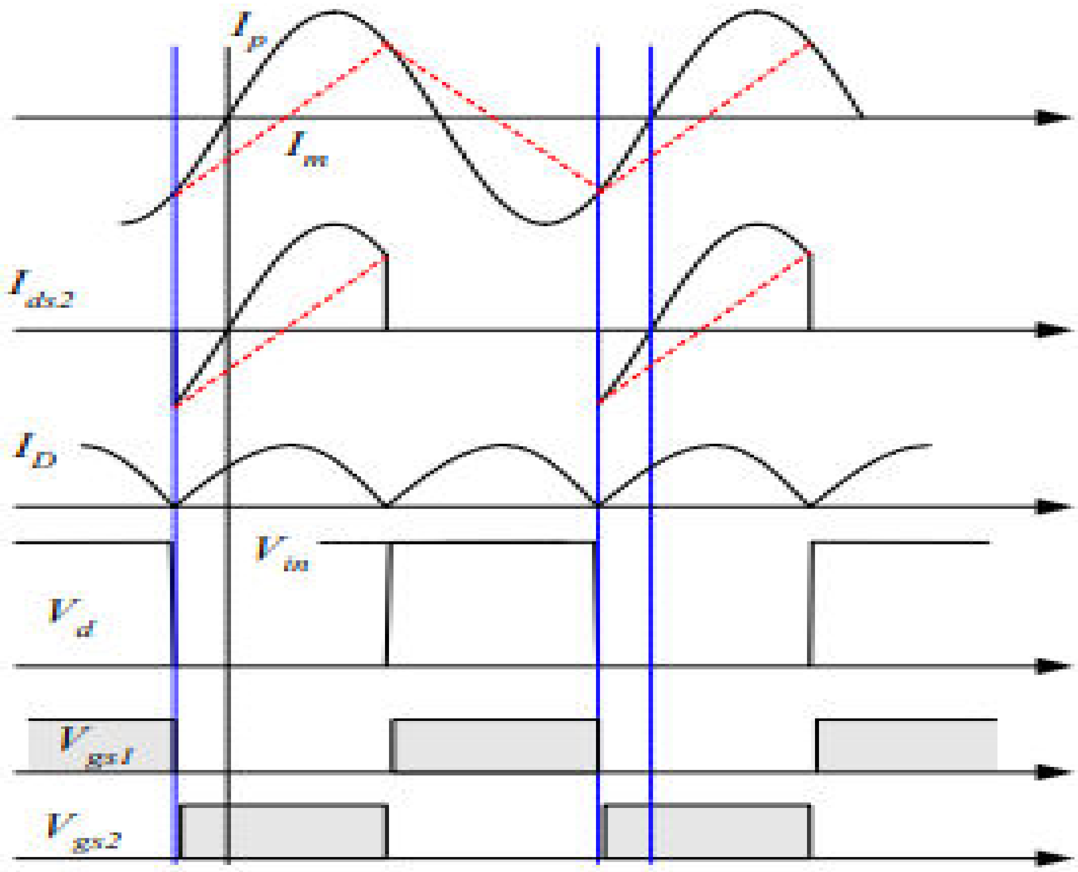
is the magnetizing inductance and Llkp and Llks are the leakage inductances in the primary and secondary, respectively.



Operation of the LLC resonant converter is similar to that of the conventional LC series resonant converter. The only difference is that the value of the magnetizing inductance is relatively small. Thus, the resonance between Lm+Llkp and Cr affect the converter operation. Since the magnetizing inductor is relatively small, there exists considerable magnetizing current (Im) as shown below.



The half-bridge totem pole composed of Q1 and Q2 applies a square wave voltage (Vd) to the resonant network. Since the resonant network has the effect of filtering the higher harmonic voltages, essentially, a sinusoidal current appears in the resonant network.

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The filtering action of the resonant network allows us to use the classical fundamental approximation to obtain the voltage gain of the resonant converter, which assumes that only the fundamental component of the square-wave voltage input to the resonant network contributes to the power transfer to the output.

The current is lagging the voltage applied to the resonant network (that is, the fundamental component of the square wave applied by the half-bridge totem pole), which enables the MOSFETs to be turned.

V. RESULTS AND DISCUSSION

The simulation results obtained for the proposed ANN-controlled LLC resonant converter integrated with a switched-capacitor based 13-level multilevel inverter demonstrate significant improvement in system performance when compared to the conventional PI-controlled approach. The complete system was simulated in MATLAB/Simulink for power ratings of 1 kW and 2 kW under different operating conditions, including variations in solar irradiation and load power factor. The output voltage waveform of the LLC resonant converter shows effective voltage regulation with minimal ripple, confirming stable operation under both steady-state and transient conditions. When the ANN controller is employed, the output voltage reaches the reference value faster with reduced overshoot and shorter settling time compared to the PI controller, highlighting the adaptive and nonlinear learning capability of the ANN. The soft-switching nature of the LLC converter ensures reduced switching losses, which directly contributes to improved efficiency. The switched-capacitor based multilevel inverter successfully generates a 13-level stepped output voltage waveform consisting of six positive levels, six negative levels, and a zero level, closely approximating a sinusoidal waveform. This increased number of voltage levels results in lower harmonic content and improved output power quality. FFT analysis confirms that the total harmonic distortion (THD) of the inverter output voltage is significantly reduced compared to conventional two-level inverters, thereby eliminating the need for bulky output filters. At a power rating of 1 kW, the proposed system achieves an efficiency of approximately 92%, while at 2 kW, the efficiency improves further to about 94.48%, indicating better utilization of power components at higher loads. The ANN-controlled system maintains stable DC-link voltage even under reduced irradiation levels, whereas the PI-controlled system exhibits noticeable voltage drop and degraded performance under similar conditions. The comparative analysis clearly shows that the ANN controller provides superior voltage regulation, higher output power, improved efficiency, and enhanced robustness against load and irradiation variations. Overall, the simulation results validate the effectiveness of the proposed ANN-controlled LLC resonant converter with switched-capacitor multilevel inverter for renewable energy applications, DC microgrids, and high-quality AC power generation

VI. LIMITATIONS AND FUTURE

Despite the promising performance of the proposed ANN-controlled LLC resonant converter integrated with a switched-capacitor based multilevel inverter, certain limitations exist in the present work. The entire study is validated only through MATLAB/Simulink simulation, and practical non-idealities such as semiconductor device losses, thermal effects, switching delays, sensor noise, and electromagnetic interference are not fully accounted for.

The ANN controller is trained offline using simulated data, which may limit its adaptability to unforeseen real-time operating conditions or parameter variations beyond the trained dataset. Additionally, the computational complexity of the ANN controller is higher compared to a conventional PI controller, which may pose challenges for implementation on low-cost digital controllers. The proposed system is also limited to single-phase operation and fixed power ratings of 1 kW and 2 kW, and scalability to higher power levels or three-phase systems has not been explored. Furthermore, the absence of a Maximum Power Point Tracking (MPPT) algorithm restricts optimal power extraction from the photovoltaic source under rapidly changing environmental conditions.

The future scope of this work includes several potential extensions to enhance system practicality and performance. Hardware implementation of the proposed topology using DSP or FPGA platforms can be carried out to validate the simulation results experimentally. The ANN controller can be implemented in real time with online learning capability to improve adaptability under varying system parameters and operating environments. Integration of advanced MPPT techniques can further improve energy extraction efficiency from the PV source.

The proposed topology can be extended to higher power ratings and three-phase configurations to suit industrial and grid-connected applications. Further optimization of the ANN architecture and training process can reduce computational burden while maintaining control accuracy. In addition, advanced modulation techniques and fault-tolerant strategies can be incorporated to improve system reliability, making the proposed system suitable for practical renewable energy systems, DC microgrids, and high-performance power electronic applications.

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VII.CONCLUSION

In this project, an Artificial Neural Network (ANN) controlled LLC resonant DC–DC converter integrated with a switched-capacitor based 13-level multilevel inverter has been successfully designed, modelled, and simulated using MATLAB/Simulink to meet the requirements of modern renewable energy and intelligent power conversion systems. The proposed two-stage architecture effectively combines the advantages of soft-switching DC–DC conversion and multilevel DC–AC inversion, resulting in improved voltage regulation, high efficiency, and enhanced output power quality.

The LLC resonant converter ensures efficient voltage boosting and tight DC-link regulation while operating under zero-voltage and zero-current switching conditions, thereby reducing switching losses and electromagnetic interference. The ANN-based voltage mode controller demonstrates superior performance compared to the conventional PI controller by providing faster transient response, reduced overshoot, shorter settling time, and improved robustness under varying load and irradiation conditions.

The switched-capacitor based 13-level multilevel inverter successfully produces a near-sinusoidal output voltage with low total harmonic distortion (THD) and inherent capacitor voltage balancing, eliminating the need for auxiliary balancing circuits and multiple isolated DC sources.

Simulation results obtained for power ratings of 1 kW and 2 kW confirm high system efficiency, with the ANN-controlled system achieving better performance than the PI-controlled counterpart across different operating conditions. These results validate the suitability of the proposed system for photovoltaic applications, DC microgrids, and high-performance power electronic systems requiring efficient and intelligent control.

The scope of the proposed work can be further extended in several directions to enhance its practical applicability and performance. Hardware implementation of the proposed topology can be carried out to experimentally validate the simulation results under real-world operating conditions.

Real-time implementation of the ANN controller using digital signal processors (DSP) or field-programmable gate arrays (FPGA) can be explored to assess computational efficiency and real-time performance. Integration of Maximum Power Point Tracking (MPPT) algorithms can improve energy extraction from the photovoltaic source under dynamic environmental conditions.

The system can be extended to higher power levels and three-phase configurations for industrial and grid-connected applications. Further optimization of the ANN architecture using advanced deep learning techniques can reduce computational complexity while improving control accuracy.Additionally, performance evaluation under grid-connected operation, including power quality analysis and fault-ride-through capability, can be investigated to enhance system reliability and grid compliance.

Despite the encouraging results obtained from simulation studies, certain limitations remain in the present work, which open avenues for future research and development. The scope of the proposed system can be extended by implementing the complete topology in hardware to experimentally validate the simulation results and analyze the impact of practical non-idealities such as device losses, thermal effects, sensor inaccuracies, and electromagnetic interference.

Real-time implementation of the ANN controller using digital signal processors (DSP) or field-programmable gate arrays (FPGA) can be explored to assess computational feasibility, execution speed, and real-time control performance. Integration of advanced Maximum Power Point Tracking (MPPT) algorithms can further enhance energy extraction efficiency from the photovoltaic source under rapidly changing environmental conditions.

The proposed system can also be extended to higher power ratings and three-phase configurations to meet industrial and grid-connected application requirements. Furthermore, optimization of the ANN architecture using advanced deep learning techniques can improve learning efficiency, reduce computational burden, and enhance controller adaptability.

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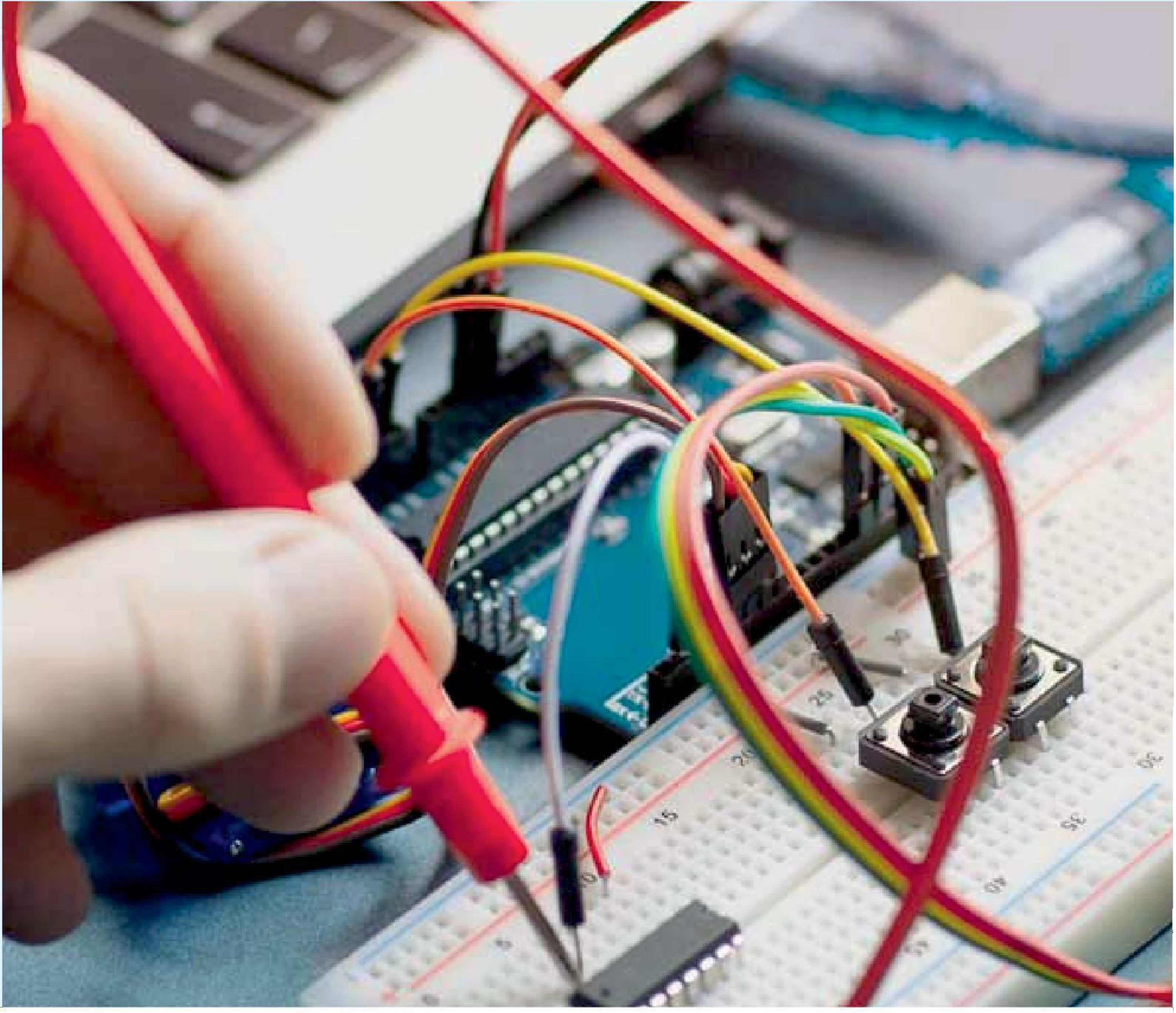

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