Research Article

Power Quality Improvement in a Solar PV Assisted Microgrid Using Upgraded ANN-Based Controller

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This paper proposes the design of a controller using the artificial neural network (ANN) for a solar photovoltaic (PV)-fed cascaded multilevel inverter (CMLI) to enhance the power quality. The objective of this presented ANN controller is to obtain a maximum output voltage with no filter components. This paper also investigates and eliminates the voltage harmonics that occurred in a solar-fed cascaded 3-stage inverter using various techniques such as pulse width modulation (PWM), digital logic control (DLC), fuzzy logic controller (FLC), and ANN, and the results are compared. Based on the results, the proposed ANN-based controller efficiently reduces harmonics and improves the power quality. This is achieved by solving the harmonic equations and thereby changing the switching angles of each semiconductor to a minimum value. The ANN is trained by a dataset consisting of varying input voltage and switching angles. The simulation was performed using MATLAB/Simulink for different types of controllers like PWM, DLC, FLC, and ANN for the 3-stage inverter. The simulated results are compared with the results obtained from a 3 kWp photovoltaic plant connected to the CMLI. Finally, on the basis of performance analysis, it was confirmed that the ANN-based controller effectively eliminates harmonics and improves the power quality.

1. Introduction

Many developing countries mainly focus on harvesting solar photovoltaic energy. Nowadays, the burning of fossil fuels causes much destruction to the environment, so they are turning towards renewable energy like wind, solar, tidal, biogas, etc. Even then, nonrenewable energy sources are used for solving the load demands of industries and buildings. It requires great effort and infrastructure to meet the demand. Solar power is mainly focused on overcoming these alternative sources, such as nonrenewable energy. This is because solar panels are installed elsewhere where solar radiation is absorbed. Sometimes, wind turbines require a large space, and the production cost is higher than solar power. The solar panels are easy to install on the rooftops, which is a suitable option for the industry to connect its existing grid to the solar.

This type of development (or) upgradation is analyzed with the development of rural areas. The economy of rural areas depends on small-scale industries, and their production is depleted with the existing grid. This makes the government focus on developing microgrids or smart grids. Here, microgrids play a major role in distributing the power within the grid when there is a power demand [1].

Such grid-tie microgrid infrastructure is reliable with the microgrid (MG) consortium [2]. A microgrid (MG) has multiple load systems and an island form where the utility grid is powered [3]. The microgrid (MG) is installed at different load demand areas such as municipalities, ports, military bases, and industrial facilities.

The microgrid is tied to the solar photovoltaic cell either in series or parallel to meet the load demand. The scheme consists of the inverter for converting the DC voltage to AC voltage; the latter is stored in the battery. Under fully charged conditions, the excess power is shared with the demand areas. Solar photovoltaic cells, or otherwise solar cells, convert irradiation to electrical energy by the process of the PV effect [4], which consists of both physical and
chemical phenomena. Photoelectricity is governed by voltage, current, and resistance. PV systems are employed for applications such as lighting street lights, commercial buildings, UPS charging, rural lights, and lighting. The solar-electric power system supports an independent grid against power failures. On the other hand, PV solar systems are economical, especially in hilly and remote areas when the conventional grid power supply is too expensive to reach the required range. A wide range of the literature reviews available on the investigation of such globalized infrastructure is discussed to understand how different power quality issues are compromised.

Padmanaban et al. proposed a system with an 11-level H-bridge inverter [5]. Here, a hybrid ANN-governed Newton–Raphson (ANN-NR) method was used for minimizing the harmonics in the system. The harmonics were extracted by various switching angles with selective harmonics elimination (SHE). SHE and PWM were combined as a unified algorithm to train the ANN to optimize the system. The ANN-optimized system was trained with switching angles and was used to estimate the generated firing angle. In this system, the THD was compared with SHE-PWM of 9 levels and 11 levels, and the value is greater than the IEEE standard for a 9 level at 11.56% and 9.10% for an 11-level.

Das et al. proposed a distributed controller-based technique for emulating the harmonic voltage source using virtual impedance [6]. The virtual impedance reduced the voltage distortion in the system. Here, two voltage source inverters (VSIs) were used with a virtual impedance that reduced the congestion in the communication networks. Compared with the existing system, just two bits per harmonic frequency are conveyed among each inverter. Along with compensation, the stability of the inverter with virtual impedance was investigated, and the THD values were found to be above the standard. The THD value of each inverter without compensation is Inverter 1–7.66% and Inverter 2–7.42%. After the virtual impedance compensation, the THDs were Inverter 1–6.40% and Inverter 2–6.16%, respectively.

Padmanaban et al. mitigated lower-order harmonic contents in a cascaded H-bridge inverter for a PV using a hybrid ANN with the Newton–Raphson method used in [7]. The harmonics were extracted by switching angles using the selective harmonics elimination PWM technique. Here, the ANN was trained to generate the switching angles with an initial guess using NR. The proposed SHEPWM, along with (ANN-NR) gets a value THD of 9.1% for an 11-level inverter.

Stonier et al. discussed the harmonics removal in the solar-fed cascaded multilevel inverter, which comprises 15 levels [8]. Here, the 3 kWp solar panel is fed by a 15-level multilevel inverter intended to enhance power quality problems in the microgrid. The voltage regulation and frequency at the output of the inverter are maintained to meet grid requirements. Therefore, different controllers’ techniques are used to compare the reduction of harmonics, like proportional-Integral (PI), FLC, and ANN. In this work, the FLC was proven better with the THD value of 5.49%.

1.1. Multilevel Inverter. In a microgrid, the inverter plays a major role in converting DC to AC. There are different types of inverters available they are VSI and current source inverter (CSI).

The main focus of the microgrid is the multilevel inverter, which is a voltage source inverter mainly used for industrial applications such as control of driver systems, AC power supplies, and static VAR compensators. The multilevel inverter has the major advantage of reducing the harmonics in the output voltage without changing the frequency of the inverter output power. The output waveform of the voltage will be composed of levels in the multilevel. As the number of levels increases, the THD value will become zero. The voltage level has been limited to the achievable level because it causes the unbalance voltage problem, clamping of voltage, and packaging constraints. Various types of multilevel inverters are available, like a diode-clamped multilevel inverter, a CMLI, and a flying capacitor multilevel inverter.

1.2. Cascaded Multilevel Inverter. In this research, a CMLI was proposed, which requires a separate DC source (SDCS). A multilevel inverter will be synthesized for achieving the needed voltage from the independent DC source voltage, and it could be acquired from the solar cells, batteries, and fuel cells. This has been popular recently in speed drive applications and AC power supplies [9]. A single-phase m-level inverter, as shown in Figure 1, has the configuration of a multilevel inverter with SDCS.

1.3. Comparison between Multilevel Inverters. A comparison of three different types of multilevel inverters was illustrated in Table 1. This comparison is carried out for an inverter of seven-level output using three stages.

1.4. Total Harmonics Distortion (THD). A total harmonic distortion (THD) is caused by the power electronics components present in equipment such as inverters, converters, and rectifiers switching devices used to turn ON and OFF of the switch [10, 11]. In this operation, the output voltage and current produce harmonics. It can also affect the operation of other equipment connected to the system. The heating of the induction motor has led to the harmonic current. If the control and regulation of the voltage are not properly performed, then this will affect the distribution side. If the source output waveform under discussion is voltage, then the THD is called voltage harmonic distortion [12–15]. The fundamental harmonics have calculated the total harmonic distortion with the input voltage and frequency, where the (1) of voltage harmonics is given as follows:

\[
\text{THD}_V = \sqrt{\sum_{n=2}^{m_{	ext{CO}}} V_n^2},
\]  

where THD is the total harmonic distortion, V is the voltage, and n is the harmonic order.
2. System Design and Methodology

The proposed model of the conventional multilevel inverter is different from the developed multilevel inverter with switching inverters. In this regard, diverse switching methods are used, like multiple carrier PWM, bipolar and unipolar PWM techniques, and so on, which are all utilized nowadays [16]. The standard technique is not much suggested for the asymmetrical type multilevel inverter, and it is due to the switching devices, as high voltage cells will be operated at a higher switching frequency over the period of the interval [17]. Since the input source from the solar PV system is asymmetrical, the ANN technique could replace the standard switching angles, and additionally, the switches of semiconductors are reduced.

The total level for the standard inverter is given in (2).

\[ m = 2ns + 1, \]  

(2)

where \( m \) is the number of output voltage levels and \( ns \) is the stages of individual inverters.

The total count of switches needed to achieve the \( m \) level is presented in (3).

\[ L = 2(m - 1), \]  

(3)

where \( L \) is the count of semiconductor switches needed to construct the multilevel inverter circuits. The 15-level inverter needs 7 inverter phases and 28 semiconductor switches.

Similarly, a 15-level inverter needs 3 inverter phases and 12 semiconductor switches for the proposed system.

For all three types of multilevel inverter equations above, two will be the same. Additionally, the count of clamping diodes needed in the multilevel inverter and the (4) and (5) do not require the cascaded H-bridge ML inverter.

\[ d = (m - 1) \times (m - 2), \]  

(4)

\[ c = \frac{(m - 1) \times (m - 2)}{2}. \]  

(5)

The developed model will require the following (6) to reduce the count of switches and increase the levels.

\[ m = 2^{ns+1} - 1. \]  

(6)

The proposed system block diagram, as shown in Figure 2, represents the details of how a 3 kWp solar power plant is connected to the cascaded multilevel inverter and connected to the AC induction motor load [18]. Here, the cascaded multilevel inverter and the firing angles to the switches are given by the ANN.

3. Formulation of ANN Algorithm

The SHE-PWM technique eliminates some particular harmonics in the voltage outputs. Eliminating the lower-order harmonics was significant in power electronics-based
applications [19]. In the SHE-PWM technique, the firing angles are computed by the required fundamental sine output voltages, and simultaneously, the harmonics have been removed [20–22]. The equation of output voltage for a 3-level CMLI is presented in (7).

\[ V_{\text{out}}(at) = \sum_{n=1,3,5}^{\infty} \left( \frac{4}{n m} \right) V_{PV1} \cos(na1) + V_{PV2} \cos(na2) + (V_{PV3} \cos(na3))\sin(nat), \]  

(7)

where the \( V_{\text{out}} \) is the output voltage of the inverter, \( n \) is the order of the harmonics, \( V_{PV1} \) to \( V_{PV3} \) are the input sources from the solar PV to each inverter stage, and \( a1 \) to \( a3 \) are the firing angles to each inverter switch.

When the CMLI is connected to a renewable source of energy like a solar panel or fuel cells, the voltage of the output will vary because of the change in temperatures, irradiance, and other elements considered. In the CMLI-based solar PV system, the input of the CMLI was the DC voltage of a conventional PV module ranging from 15 V to 21.2 V, and based on the energy stored in the battery, the output voltage would change due to the state of charge of the battery [23]. The variation in voltage that occurs in the inverter stage would cause unregulated fundamentals with a high magnitude of lower-order harmonics. The DC-DC converter must regulate the voltage at each stage to prevent this process. This will increase the complexity of the circuit, and it requires a separate control algorithm for each converter.

This paper deals with determining the switching angles for solar-fed CMLI for cancelling the lower-order harmonics using the ANN. At first, the PTC Mathcad Prime 8.0 software was utilized for obtaining diverse datasets for a diverse set of input voltages by solving the harmonics elimination equation. The acquired dataset has been utilized for training the ANN. The trained model produces the suitable angles for switching to the inverter on the basis of the input voltage. Here the ANN was utilized for generating the angles for switching to the MLI. The dataset acquired for the ANN training is determined by deriving the harmonic elimination equation as presented in (8) to (10).

\[ V_1 \cos(a1) + V_2 \cos(a2) + V_3 \cos(a3) = \left( \frac{\pi \times V_{\text{fund}}}{4V_{\text{dc}}} \right), \]  

(8)

\[ V_1 \cos(3a1) + V_2 \cos(3a2) + V_3 \cos(3a3) = 0, \]  

(9)

\[ V_1 \cos(5a1) + V_2 \cos(5a2) + V_3 \cos(5a3) = 0. \]  

(10)

For the inverter with 3-levels, the equation presented above is derived. The guess values produced for deriving the above conditions in PTC Mathcad Prime 8.0 were \( a1 = 50.25^\circ, a2 = 65.5^\circ, \) and \( a3 = 80.75^\circ \). By the above equation, the 2000 datasets have been acquired just as for the related input voltage \( V \) from solar panels, and a necessary set of angles is given for switching the MLI.

The ANN is trained to predict the angles of switching to control MLI based on the change in voltage caused by the solar. The major benefit of the ANN method is that it can auto-tune the applications with no explicit control functions. The architecture of ANN is shown in Figure 3, and Table 2 shows the dataset of the ANN sample given.

3.1. Conventional PWM Controller. The conventional PWM techniques are used to calculate the firing angle according to the frequency of the system. The PWM is the older technique used to give an individual firing pulse to each IGBT; if it is a 15-level MLI with 28 switches, the PWM pulse also must be given to each separately and its compilation used for the circuit to assemble each type of equipment.

3.2. Digital Logic Controller for MLI. The digital logic controller (DLC), in which the binary mode of operation is implemented for solar-fed CMLI [24]. The power circuit comprises of 3-level stages that will be used in the conventional type inverter; it could acquire a maximum count of the levels of the MLI with a minimized count of switches by creating the appropriate firing angle sequences. The PWM technique has not been regularly used; instead, a detailed look-up table was given for the modulation controller. The truth table for the switches is given in the Table 3. Were In 1, In 2, and In 3 are the input DLC signals, and \( V_o \) is the output angle for the particular binary value.

3.3. Fuzzy Logic Controller. A fuzzy logic controller is unlike Boolean algebra. The main characteristic of FLC is that values can be stated as either 0 (OFF) or 1 (ON) [25]. The Boolean logic function can allow two or more variables among the false or true statements. FLC supports obtaining fixed convolutions from imprecise, vague, and ambiguous data. Figure 4 shows the structure of FLC used to perform voltage reference in a solar PV-fed CMLI. Here, the output voltage was obtained from the output of the 3-level inverter and was then correlated with the reference voltages, and it was to occur that the required voltage was to be obtained by the MLI to meet the grid requirement.
The error signal $e = V_{\text{ref}} - V_o$ and the change rate in error $\frac{dv}{dt}$ serve as input features for FLC. The signal line $C_s$ was the commanding signal acquired by the FLC and was then correlated with $V_{\text{ref}}$ to generate the modulating signal needed for the PWM to the semiconductor switches of the CMLI.

Where $e$ is the error signal, $V_{\text{ref}}$ is the reference voltage, $V_o$ is the output voltage, and $C_s$ is the commanding signal.

3.4. Process Flow Chart for System Design. The flow chart shown in Figure 5 with the overall methodology using different kinds of controllers and the harmonic values that occur. This flow chart shows the improvement in power quality according to the different controller techniques used in a solar PV-fed 3-stage inverter.

### Table 2: Sample ANN dataset for training.

<table>
<thead>
<tr>
<th>Input voltage (V)</th>
<th>Switching angle ($\alpha$ in rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41.5, 42.5, 43.5</td>
<td>[0.112, 0.198, 0.432]</td>
</tr>
<tr>
<td>42.4, 52.6, 52.7</td>
<td>0.117, 0.196, 0.427</td>
</tr>
<tr>
<td>44.4, 52.6, 52.7</td>
<td>0.136, 0.19, 0.444</td>
</tr>
</tbody>
</table>

### Table 3: Truth table for triggering switches.

<table>
<thead>
<tr>
<th>0° to 90°</th>
<th>90° to 180°</th>
<th>180° to 270°</th>
<th>270° to 360°</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_O$</td>
<td>$V_O$</td>
<td>$V_O$</td>
<td>$V_O$</td>
</tr>
<tr>
<td>In 3</td>
<td>In 2</td>
<td>In 1</td>
<td>In 3</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>48</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>96</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>144</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>192</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>240</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>240</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>288</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>336</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>336</td>
</tr>
</tbody>
</table>

4. Simulation Results and Discussion

The overall simulation block diagram is shown in Figure 6. It consists of a 3-stage cascaded multilevel inverter fed by three individual solar PV sources. These solar cells with different voltage levels have been tested using the MATLAB/Simulink model. The simulation block shows the input voltage has been sensed using the voltmeter and is fed to ANN using a multiplexer (MUX). The feedback closed-loop control of the ANN output is fed to the demultiplexer (DEMUX) unit to 3-level inverters. The output voltage 15-level has been achieved in a 3-stage CMLI, as shown in Figure 7.

The simulation is carried out with different types of controllers for the same 3-stage CMLI with a 15-level output voltage. The control strategy used for testing the CMLI is to reduce the harmonics using different controllers like the
PWM technique, digital logic controller, fuzzy logic controller, and ANN. A fast Fourier transform (FFT) analysis for different types of controllers is performed, and the THD reduction is shown. The Figure 8 shows the FFT analysis using the PWM controller technique. From the observation using the PWM technique, the THD occurred is not according to the IEEE standard. So, the other conventional method cannot be used for power quality improvement.

Next, the controller was changed to a digital logic controller. Here, the pulse signal is given to the switches based on the digital signals 0 and 1. By simulating using a DLC-based controller for CMLI, the output voltage has been in the range of 15-level, but the harmonics do not meet the IEEE standard. Figure 9 shows the FFT analysis of the DL-based controller for MLI.

Next, for better voltage and the reduction of harmonics, the fuzzy logic controller has been used to drive the CMLI. In this, the same 3-level inverter is fed with the reference voltage, and the output is 15-level is achieved. But the THD value does not meet the standard of the power system. Figure 10 shows the FFT analysis for a fuzzy logic controller that has been carried out and shows the THD value.

An ANN-based controller is tested with the same 3-level CMLI. The output voltage has been at 15-level, and the THD has met the standards as shown in Figure 11. Here, the
Figure 6: MATLAB Simulink of a 3-stage cascaded multilevel inverter with an ANN controller.

Figure 7: The 15-level output voltage of CMLI with ANN.

Figure 8: FFT analysis for PWM controller-based CMLI.
ANN-based controller for switching angles is better than other conventional methods. Table 4 shows the comparison with the IEEE international standards followed. The comparison of the different types of controllers with the THD value is shown in the graph in Figure 12.

5. Experimental Setup and its Results

The experimental hardware setup of a 3-level CMLI is shown in Figure 13. The multilevel inverter is fed by the solar photovoltaic system with three input voltages. Each inverter
voltage is 48V, 96V, and 144V. The voltage can be varied according to the partial shading condition of the PV.

The hardware consists of 3 multilevel inverters with an FPGA pulse generator kit connected, and the input voltage has been sensed by the voltage sensor used to feed the FPGA. Here, two types of loads are connected at the output of the multilevel inverter. One is the motor load, and another is the lamp load connected in series. The AC induction motor load specification is given in Table 5.

The output voltage level has been recorded in the power quality analyser, and Figure 14 shows the 15-level output achieved by the 3-stage cascaded multilevel inverter. Figure 15 shows the output voltage, current, power, and the THD value of the proposed system.

**Table 4: Comparison table of THD with the IEEE international standard with ANN and other controllers.**

<table>
<thead>
<tr>
<th>International standard</th>
<th>THD %</th>
<th>PWM (%)</th>
<th>DL (%)</th>
<th>FLC (%)</th>
<th>ANN (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 519-2014</td>
<td>Less than 5%</td>
<td>10.79</td>
<td>6.79</td>
<td>5.49</td>
<td>4.52</td>
</tr>
</tbody>
</table>

![Graph showing comparison of THD with other controllers.](image-url)

**Figure 12: Overall comparison of THD with other controllers.**

![Microgrid with a 3-stage CMLI.](image-url)

**Figure 13: Microgrid with a 3-stage CMLI.**
Table 5: Specification of a single-phase AC induction motor.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>230 V</td>
</tr>
<tr>
<td>Current</td>
<td>4.2 A</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Speed</td>
<td>1425 rpm</td>
</tr>
<tr>
<td>Horsepower</td>
<td>0.5 hp</td>
</tr>
</tbody>
</table>

Figure 14: The 15-level output waveform of a 3-stage CMLI.

Figure 15: Power quality analyzer value of THD.
6. Conclusion

A 3-stage, 15-level, solar-fed CMLI for the reduction of harmonics has been developed and proposed for the enhancement of power quality. Here, different controller methodologies like PWM, DLC, FLC, and ANN are used to compare whether the proposed technique is better. The proposed ANN technique is given with the varying input voltage, and the firing angle has been produced with different voltage levels for training to produce the datasets. The datasets are collected and trained by the ANN network. The dataset has been collected using the equation of the harmonic. Thus, the ANN gives a better result and a fast response time for the change in output voltage concerning 15-level output. The THD value obtained by the proposed method is less than the IEEE standard.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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