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Adaptive Neuro-Fuzzy Model for Grid-Connected Photovoltaic System

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Abstract This paper proposed an adaptive neuro-fuzzy inference system (ANFIS) model to multilevel inverter for grid-connected photovoltaic (PV) system. The purpose of the proposed controller is to avoid the requirement of any optimal PWM (pulse width-modulated) switching-angle generator and proportional–integral controller. The proposed method strictly prevents the variations present in the output voltage of the cascaded H-bridge multilevel inverter. Here, the ANFIS models have the inputs which are the grid voltage and the difference voltage, and the output target is the control voltage. By means of these parameters, the ANFIS makes the rules and can be tuned perfectly. During the testing time, the ANFIS provides the control voltage according to the different inputs. Then, the ANFIS-based algorithm for multilevel inverter for grid-connected PV system is implemented in the MATLAB/simulink platform, and the effectiveness of the proposed control technique is analyzed by comparing the model's performances with the neural network, fuzzy logic control, etc.

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Keywords PV · Cascaded multilevel inverter · Grid voltage · Control voltage · ANFIS

1 Introduction

In the last decade, for most of the countries, the environmental crisis and the economic evolutions have forced them to deeply explore the technologies in respect of renewable energy resources, which possess significant advantages [1] like efficiency, authenticity, easy implementation, being economic in cost, causing minimal impact on environment, and also ability to operate microgrid systems and to provide facile connectivity to the electric grid [2]. The most scrutinized technologies are hydro-, photovoltaic (PV)-, and wind-energy conversions to generate electric power. Among these technologies, photovoltaic system affords the most standardized and environmentally affable technology [3]. It is the most suitable alternative system for producing electricity and also for being used in remote applications [4, 5].

Solar energy is converted into electrical energy by means of photovoltaic arrays [6]. The merits of PV arrays are that they generate pollution-free, inexhaustible, and low-cost energy and also require less maintenance . For these conversions, PV systems need power converters, to be positioned between photovoltaic arrays and the grid [7], because PV arrays are operated at maximum power point (MPPT) [8, 9] in order to infuse alternating current into the grid. There are two types of power connectors [10, 11]: (i) DC/DC power converter and (ii) DC/AC power converter. DC/DC power converter is used to operate the PV arrays at the peak power point, and DC/AC power converter is used to join the PV system to the grid [12]. A few advantages of these two converters are less distortion,

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shrinking switching frequency, diminishing dv/dt stress, and so on [13, 14]. By this technique, fewer multilevel topologies are implemented to operate PV systems [15].

The three fundamental characteristics of multilevel inverter (MLI) topologies are the Neutral-point-clamped and flying-capacitor MLIs, and cascaded H-bridge MLI (CHB-MLI). Of these MLI topologies, flying-capacitor MLIs needs single dc source, which is a major disadvantage. However, it becomes popular in case of photovoltaic systems. Because solar cells needs individual generators for gathered [16]. Among these, CHB-MLI is having more features than others, with the additional advantages of there being no need for dc/dc booster, and no decline in power drops due to sun fading; consequently, its efficiency will be increased, thereby assuring more reliability [17]. However, the significant obstacle in multilevel converter is the complication related to control and the pulse-width modulation (PWM) [18, 19]. Also the implementation of conventional space-vector PWM-based current regulator is difficult [20].

This paper proposed an adaptive neuro-fuzzy inference (ANFIS) model to multilevel inverter (MLI) for the grid-connected photovoltaic (PV) system. The intention of the proposed controller is avoiding the use of any optimal PWM switching-angle generator and proportional–integral controller. In this technique, it hinders the fluctuation in the output voltage of the cascaded H-bridge multilevel inverter (CHB-MLI). The input voltages are the grid voltage and the difference voltage, and the output voltage is control voltage. According to this, ANFIS be in control and tuned accurately. According to various inputs, the ANFIS generates the control voltage at the time of testing. The output voltage equivalent gate pulses are used for handling the insulated gate Bi-polar switches (IGBTs) of multilevel inverter. The remainder of the paper is organized as follows: the recent research works are reviewed briefly in Sect. 2; a brief explanation of the proposed work is elucidated in Sect. 3; the proposed controlling technique is described in Sect. 4; Simulation results and the related discussions are given in Sect. 5; and Sect. 6 concludes the paper.

2 Recent Research Works: A Brief Review

In the literature, so many applications are accessible, corresponding to multilevel inverter with photovoltaic applications. A few of them are analyzed. Carlo Cecati et al. [21] have examined the converter for photovoltaic (PV) system, which includes two stages: a dc/dc booster and a pulse width-modulated (PWM) inverter. They project a single-phase H-bridge multilevel converter for PV systems controlled by an integrated fuzzy logic controller (FLC)/modulator. The uniqueness of the projected system is that it utilizes a fully FLC and utilizes a H-bridge power-sharing algorithm. The essential signal processing was auctioned by a resulting in a fully integrated System-on-Chip controller, mixed-mode field-programmable gate array. The common architecture of the system and its execution in an extreme manner were obtainable and examined.

Seyezhai et al. [22] have proposed a multilevel inverter (MLI). This is an advanced topology-based high voltage DC–AC conversion. For fuel cell function, silicon carbide (SiC) switches are used in a hybrid multilevel inverter, and also they aim on a double-orientation modulation technique. Stair the carrier waveform the projected waveform performs two reference waveforms and a solitary inverted sine wave. However, in the output voltage, spectral quality and switching losses were in contrast with the conventional dual carrier waveform. The execution of the inverter obtained from the theory and simulation have been explored.

Chandralekha et al. [23] have presented the escalation in a wind turbine-driven induction generator (IG) subsystem, joint power system with solar cell subsystem, and diesel generator set. Solar cells would produce the power only in day time, whereas the power generated by the turbine-driven IG varies according to the different velocities of wind. Constant power supply is assured by the subsystem operated in tandem and with battery backup. For the people living in remote areas such as villages and hill tops where power supply may not be available, the amalgamation, however, affords a constant power supply. For generating a constant voltage-and-frequency a.c. power supply for functions and business applications, the power electronic scheme is proposed which engages a choice of power source inverter.

Vijayalakshmi et al. [24] have presented regarding the system based on a high conversion ratio hybrid DC–DC converter-fed single-phase low-harmonic distortion, nine-level photovoltaic (PV) inverter topology for PV power-conditioning systems with a pulse width-modulated (PWM) control scheme. In microcontroller, PIC16C7F88, a digital PI control algorithm is implemented in it. Before utilizing it to ac for grid-connection applications to convert the energy sources to a higher-voltage dc, a power-conditioning system (PCS) is necessary for low-voltage dc sources. The endeavor of this venture is to introduce and confer the main aspects of novel topologies that deal with design problems.

Three-phase cascaded H-bridge converter is the architect for stand-alone photovoltaic (PV) systems. It is presented by Raghu et al. [25]. Several H-bridge cells are coupled in series, and each one is linked to a string of PV modules in the multilevel topology. The adopted control

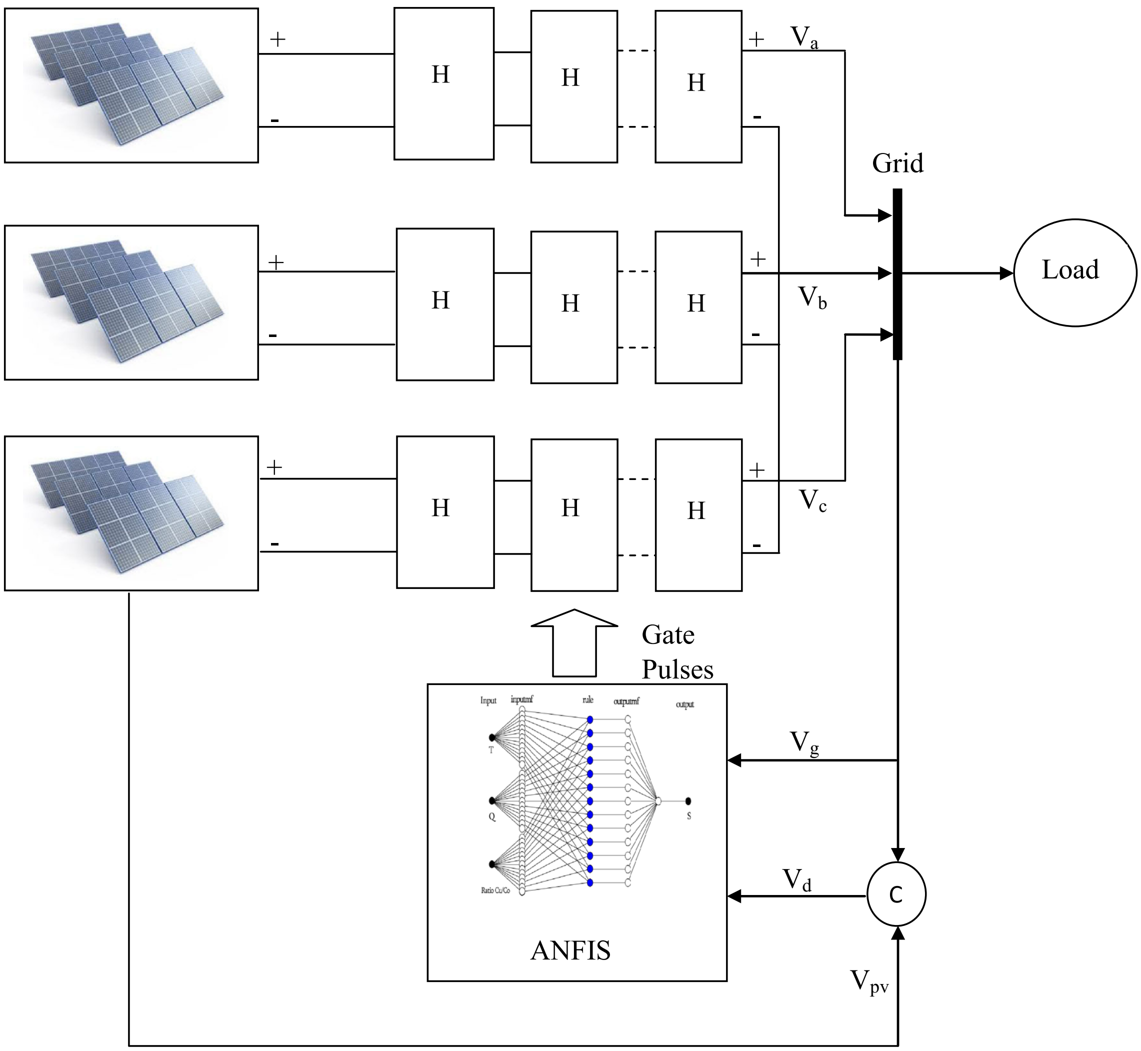

Fig. 1 Structure of the proposed control technique

system allows for the self-governing control of each dc-link voltage, implementing, in this way, the tracking of the most power points for each string of PV panels in addition to low-ripple sinusoidal-current waveforms that are obtained with unity power factor. Other advantages are its ability to perform at lower switching frequency or lower current ripple in contrast to standard two-level topologies. For distinct performing conditions, simulation and experimental results were analyzed. A control method for three-phase multilevel cascaded H-bridge inverter for photovoltaic (PV) system was presented by Valan Rajkumar et al. [26]. The maximum power point tracking (MPPT) has the ability to extract the peak power from the PV array allied to each DC link voltage level. Besides, this algorithm was carried out by perturbation and observation method (P&O). The alterations of modulation index and phase angles were amalgamated onto field-programmable gate array (FPGA) by means of hardware description language (VHDL).

The optimization of switching angle of an adaptive H-bridge single-phase, seven-level inverter for stand-alone photovoltaic (PV) system was presented by Krismadinata et al. [27]. The inverter embraces a conventional H- bridge inverter and two bidirectional switches, and it could produce a seven-level output voltage level, namely +Vdc, +2/3Vdc, +1/3Vdc, 0, −1/3Vdc, −2/3Vdc, and −Vdc. To enhance the output waveform better, optimized harmonic elimination stepped waveform (OHESW) method was performed. Based on OHESW, Newton–Raphson method was employed to solve the transcendental equations, which creates all feasible elucidations with any random primary presumptions.

The multilevel inverter is widely used as the most modular and environmentally friendly technologies which are reviewed from the recent research works. The multilevel inverter topology plays an important role in rectifying the switching losses, the voltage stress, the total harmonic distortion (THD), and the high switching frequency in solar

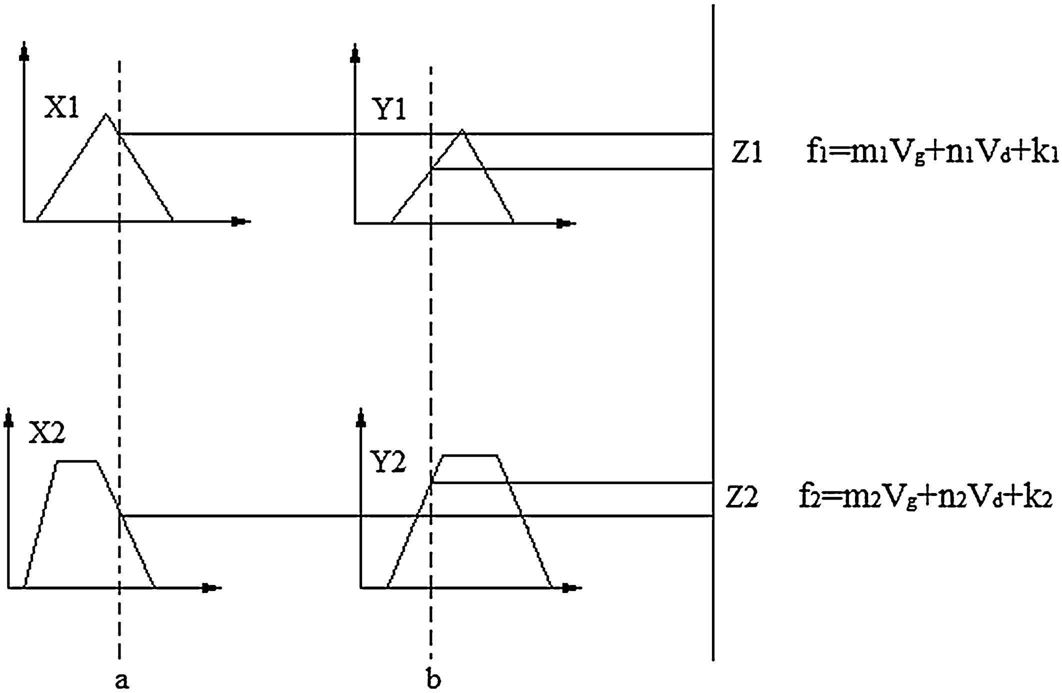

Fig. 2 First-order Takagi–Sugeno fuzzy reasoning

power generation system. Different multilevel inverter topologies are used in solar power generation (PV). The topology is varied due to the output variation and THD of inverter; also, designing of the topology is a complex task. By different essential topologies like single-phase, cascaded H-bridge multilevel inverter, diode-clamped multilevel inverter, and single-phase five-level inverter, the problems are overcome. For the unknown load and parameter variations, the above existing models depend on the precise topology of the system, and the topologies cannot be adaptive. Therefore, an effective control technique is needed for the multilevel inverter, which is explained in the following section.

3 Proposed Control Technique Using Multilevel Inverter for PV Applications

In solar power generation system, the multilevel inverter topology plays an important role in rectifying the switching losses, the voltage stress, the total harmonic distortion (THD), and the high switching frequency. In solar power generation (PV), different multilevel inverter topologies are used. Because the multilevel inverter has better working performance compared to the conventional Pulse Width Modulation (PWM) inverters, it provides even voltage sharing, both statically and dynamically, and reduces the size and volume due to the elimination of the bulky coupling transformers or inductors. However, the topology is varied due to the output variation and THD of inverter. The designing of the topology is a complex task since the topologies cannot be adaptive for the unknown load and parameter variations. Therefore, it needs an efficient control structure to overcome the mentioned drawbacks. The required control system is explained in Fig. 1, and the detailed explanation about the control structure is described below.

The above structure explains the proposed control structure, which contains PV panels connected to each H-bridge of the multilevel inverter. The three-phase multilevel inverter output (V_a, V_b, and V_c) is fed to the grid, i.e., known as grid voltage (V_g). The grid voltage variation is determined from the comparator, which evaluates the difference between the PV voltage (V_{pv}) and the grid voltage (V_g). The difference voltage (V_d) and the grid voltage (V_g)

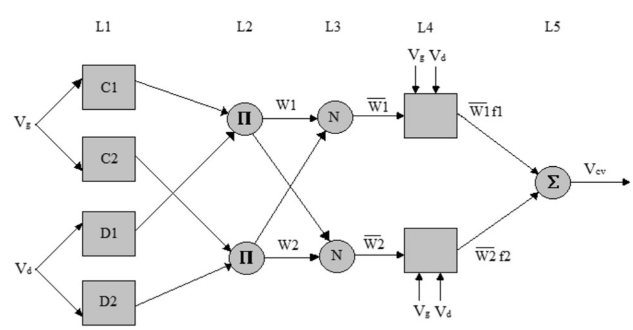

Fig. 3 Structure of the ANFIS

are used as the input parameters of the ANFIS. The output of the ANFIS structure is the control voltage (V_{cn}); it is converted into the corresponding gate pulses to operate the multilevel inverter. The detailed explanations about the presented PV panel, multilevel inverter, and the proposed control technique are given in the following section.

4 Control Voltage Generation Using ANFIS

ANFIS is a hybrid software computing model, i.e., combination of neuro-fuzzy and neural network, which contains high-level reasoning capability and low-level computational power [28]. The ANFIS constructs a fuzzy interference rules depending on the input and the output target. The fuzzy interference mechanism is tuned by the neural network learning mechanism. In general, the ANFIS has a layered structure, which is described in Fig. 3. It consists of five different layers such as input layer, fuzzification layer, Product layer, Normalization layer, and Defuzzification layer [29]. The nodes are represented as both adaptive and fixed nodes, i.e., the square nodes are adaptive nodes, and the circle nodes are fixed nodes. Here, the ANFIS inputs may be the grid voltage V_g and the difference voltage V_d, and the output target is the control voltage V_{cv}. By using these parameters, the ANFIS has been constructing the rules and can be tuned perfectly. The inputs of the ANFIS are the grid voltage (V_g) and the difference voltage (V_d), which is described later. For first-order Takagi–Sugeno interference system with two fuzzy a common rule set is described in Eqs. (1) and (2). *Rule 1* If V_g is C_1 and THD is D_1, then

$$f_1 = m_1 V_g + n_1 V_d + k_1. \quad (1)$$

Rule 2 If V_g is C_2 and THD is D_2, then

$$f_2 = m_2 V_g + n_2 V_d + k_2, \quad (2)$$

where, m_1, m_2, n_1, n_2, k_1, and k_2 are the linear parameters; C_1, C_2, D_1, and D_2 are the nonlinear parameters. Figure 2 shows the fuzzy reasoning of the ANFIS.

Activation levels of the fuzzy rules are calculated using $W = X_i(a) \cdot Y_i(b)$, where the logical operator "and" may be modeled by a continuous *t*-norm, and in this case, it is expressed as a product. The individual output of each rule is obtained as a linear combination between parameters of the antecedents of each rule as given in Eq. (3) [30]:

$$f_1 = m_1 V_g + n_1 V_d + k_1 \quad i = 1, 2\ldots \quad (3)$$

The output of the model f is obtained by multiplying the standardized activation degrees of the rules by the individual output of each rule, which is expressed in Eq. (4).

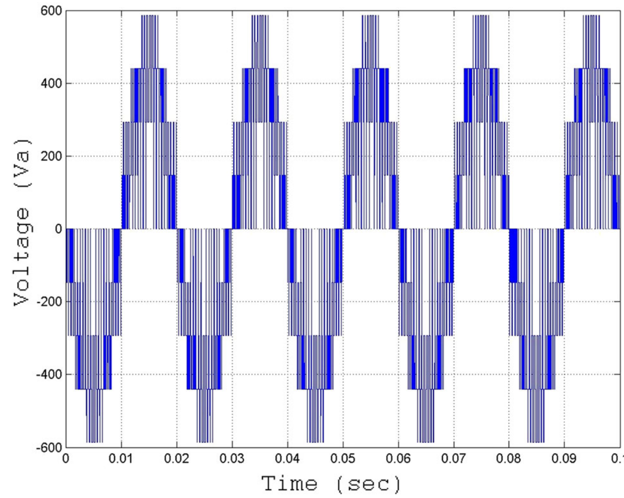

Fig. 4 Multilevel inverter output voltage of a-phase

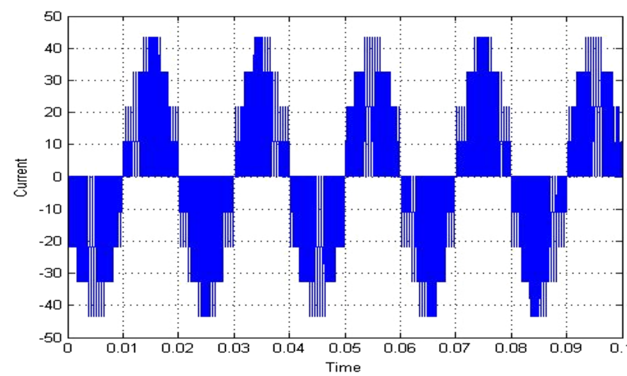

Fig. 5 Multilevel inverter output current of a-phase

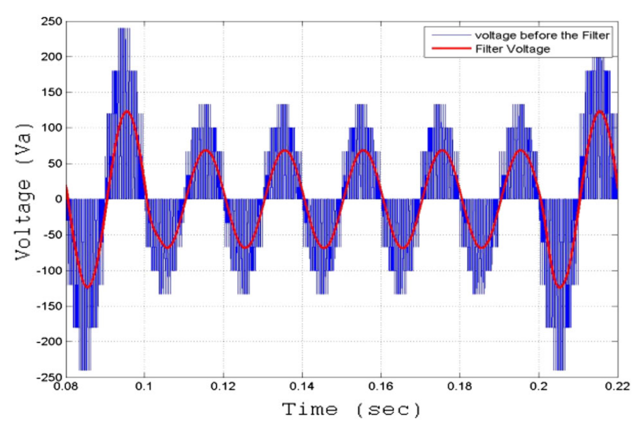

Fig. 6 Output voltages before and after filter

$$f = \frac{\sum \overline{W_i} f_i}{\sum W_i}, \quad i = 1, 2\ldots, \quad (4)$$

where W_i is the normalized value, which is the sum of W_1 and W_2. The ANFIS layer structure is described in Fig. 3, and the corresponding description is given below.

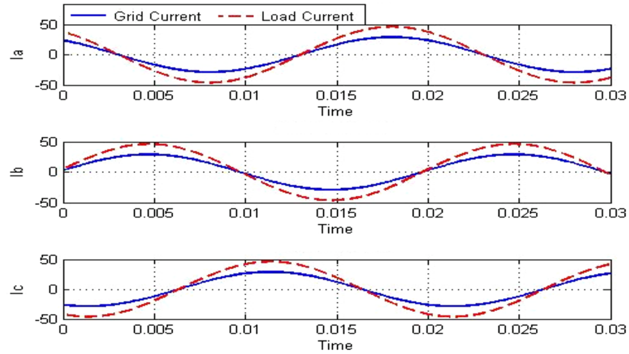

Fig. 7 Multilevel inverter with RC load

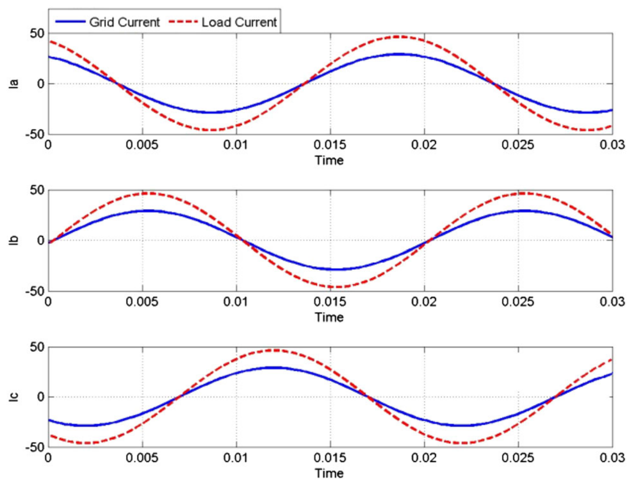

Fig. 8 Multilevel inverter with RL load

4.1 Fuzzification Layer

In this mode, each input layer represents an input variable, and it is transmitted into fuzzification layer. The grid voltage (V_g) and the difference voltage (V_d) of nodes are C_1, C_2, D_1, and D_2, in which C_1, C_2, D_1, and D_2 are the linguistic labels of fuzzy theory for dividing the membership functions. The outputs of the fuzzy layer are given by Eqs. (5) and (6):

$$R_{L1,i} = \mu C_i(V_g) \quad i = 1,2 \tag{5}$$

$$R_{L1,j} = \mu D_j(V_d), \quad j = 1,2, \tag{6}$$

where $R_{L1,i}$ and $R_{L1,j}$ are the outputs of the fuzzy layer; and $\mu C_i(V_g)$ and $\mu D_j(V_d)$ are the membership functions of the fuzzy layer.

4.2 Product Layer

This layer performs logical "and" or product of the input membership functions, which is labeled as π. The product layer output is the input weight function of the next node. The outputs of this layer are described by Eqs. (7) and (8).

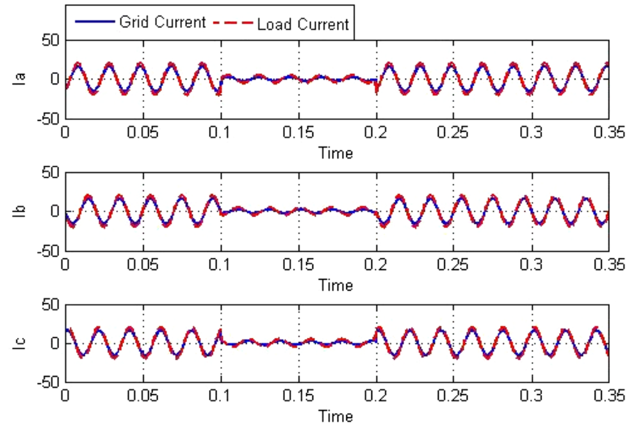

Fig. 9 Variations of the active and reactive power required by the load

$$W_1 = R_{L2,i} = \mu C_i(V_g) \cdot \mu D_i(V_d), \quad i = 1,2, \tag{7}$$

$$W_2 = R_{L2,j} = \mu C_j(V_g) \cdot \mu D_j(V_d), \quad j = 1,\ 2, \tag{8}$$

where W_1 and W_2 are the outputs of the product layer.

4.3 Normalization Layer

The normalized layer is the third layer, in which each node is fixed—the one that represents the IF part of a fuzzy rule. It is used to normalize the input weights, which can perform the fuzzy "and" operation. This layer is labeled as N, and the output of this layer is given by Eqs. (9) and (10).

$$\overline{W_1} = R_{L3,i} = \frac{W_i}{W_1 + W_2}, \quad i = 1,\ 2, \tag{9}$$

$$\overline{W_2} = R_{L3,j} = \frac{W_j}{W_1 + W_2}, \quad j = 1,\ 2, \tag{10}$$

where $\overline{W_1}$ and $\overline{W_2}$ are the outputs of the normalized layer.

4.4 Defuzzification Layer

This layer performs an adaptive function, which gives output membership function based on predetermined fuzzy rules. The outputs of this layer are given in Eqs. (11) and (12).

$$\overline{W_1} f_i = R_{L4,i} = \frac{W_i}{W_1 + W_2}\left[m_1 V_g + n_1 V_d + k_1\right] \tag{11}$$

$$\overline{W_2} f_j = R_{L4,j} = \frac{W_j}{W_1 + W_2}\left[m_2 V_g + n_2 V_d + k_2\right], \tag{12}$$

where $\overline{Z_1} f_i$ and $\overline{Z_2} f_i$ are the outputs of the defuzzy layer.

4.5 Total Output Layer

The output layer represents the THEN part of the fuzzy rule. The total of the input signals can be calculated, which is labeled as Σ. The total output of the layer is given in Eq. (13).

$$f = R_{L5,i} = \sum \overline{W}_i f_i = \frac{\sum \overline{W}_i f_i}{\sum W_i}, \tag{13}$$

where f is the total output, and once the ANFIS is training finished, it is ready to give the control voltage (V_{cn}) to reduce the output variation and THD of the multilevel inverter. Once the process is over, the ANFIS is ready to give the control voltage for the various input grid voltage and difference voltage. Then the proposed control technique is implemented in the MATLAB/simulink platform, and the effectiveness is tested by comparing with other techniques. The brief description about the proposed method's implementation and the relevant discussion is provided in Sect. 5.

5 Results and Discussions

The proposed method is implemented in MATLAB/simulink 7.10.0 (R2012a) platform, 4 GB RAM, and Intel(R) core(TM) i5. Here, the multilevel inverter output voltages of the three phases, grid voltage, filter voltage; DC voltage from the PV panel; and the output voltages before and after filter were analyzed. Also with that here the effects of RL and RC loads in the inverter current in each phase, and the variations of active and reactive powers, inverter voltage, and current required by the load and the voltage sag were analyzed. By means of the analysis of the THD of the voltages and currents with normal, Neural, Fuzzy and ANFIS methods, it was proven that the proposed method is more effective compared with the previous method. The analysis of the results is discussed later.

The multilevel inverter normal output voltage of the phases a was represented in the Fig. 4. Similarly the multilevel inverter phase current for normal time is explained in Fig. 5. These results show that the required seven-level inverter is working without any fault. The variations of output voltage before and after filter in a-phase are shown, Fig. 6. However, both before and after filter, the voltage magnitudes get reduced during the same time period (i.e., 0.1–0.2 s) when the DC voltage gets reduced. The proposed system shows better performance in terms of the output voltage, and there is even a variation in the input DC voltage.

Different loads were considered in order to evaluate the performance of the ANFIS, and in particular, the series RC and RL loads were considered, Figs. 7 and 8 show that, whatever be the load (leading or lagging), the output current

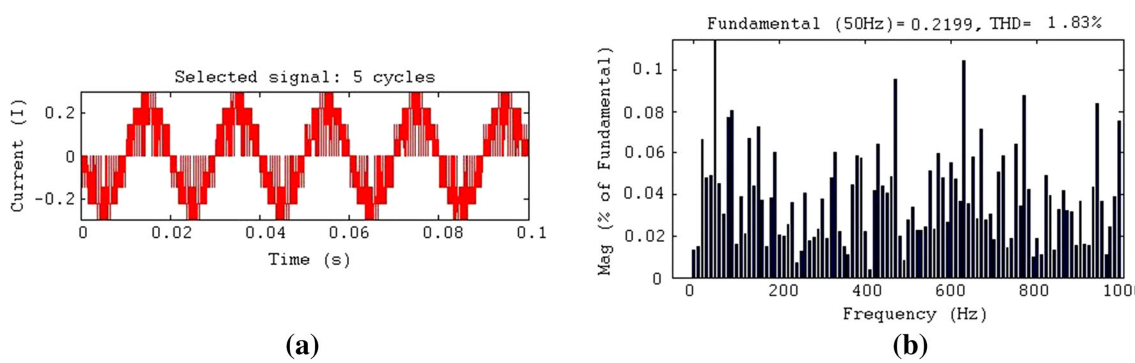

Fig. 10 THD analysis of output current with ANFIS method. **a** Selected five cycles of voltage, **b** THD

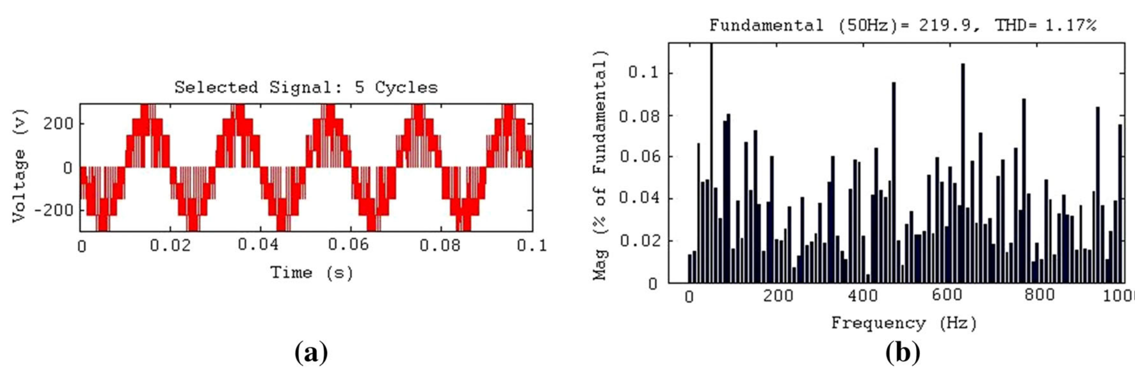

Fig. 11 THD analysis of output voltage with ANFIS method. **a** Selected five cycles of voltage, **b** THD

Table 1 Comparison of THDs for simulation

Percentage THD of the MLI				
Method	Normal [31]	Neural network [32]	Fuzzy [33]	ANFIS
Voltage THD (%)	2.7	5.29	1.48	1.17

Table 2 Efficiency comparison

Efficiency			
Normal	Neural network	Fuzzy	ANFIS
90.9 %	91.6 %	92.3 %	93.7 %

follows its reference. It can be noticed that the inverter current was synchronized with the grid voltage (Fig. 9).

Results shown in Figs. 10 and 11 revealed the THD analysis of the inverter voltage and current in the proposed method (i.e., ANFIS). The voltage and current percentages of THDs of the multilevel inverter in different methods are presented in Table 1. The effectivenesses of the harmonic elimination process have been determined by the THD analysis of the multilevel inverter for the models without the controller, neural network, fuzzy, and the proposed ANFIS. During the THD analysis process, five cycles of multilevel inverter voltage have been selected for each control technique. From the THD analysis, the amount of THD present in the multilevel inverter output voltage without controller is determined as 2.7 %. In the proposed method, the high THD affects the multilevel inverter output voltage presenting with distortions, and this reduced the power quality. By means of the Neural network control technique, in the multilevel inverter, the THD in the output voltage is determined as 5.29 % and by using the fuzzy control technique, the THD in the output voltage as 1.48 %. The amount of THD present in the output voltage is much reduced by means of the proposed ANFIS controller. THD present in the multilevel inverter output voltage with ANFIS controller is determined as 1.17 %. Similarly, the proposed method's efficiency is compared with the above-mentioned techniques, and the comparison is shown in the Table 2. In this paper, the multilevel inverter output voltages and the corresponding efficiencies for normal method, NN technique, fuzzy. and proposed method are analyzed. The comparison results prove the effectiveness of the proposed control technique.

6 Conclusion

This paper has proposed an adaptive neuro-fuzzy (ANFIS) model for multilevel inverter for grid-connected photovoltaic (PV) system, and it is simulated in the MATLAB platform, with the enhanced knowledge rules based on the proposed ANFIS-generated switching angles for the appropriate voltage variations. The performances of the proposed method were compared with the multilevel inverter THDs in the output voltages obtained with normal conventional method, neural network method, and Fuzzy method. The simulation results reveal that the proposed ANFIS controller outperforms the other previous techniques. It is also seen that the proposed method has smaller THD under various load conditions. The comparison results show that the proposed method is a technique with the well-advanced features and with less harmonics and better efficiency, which is more efficient than the other techniques.

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