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ORIGINAL ARTICLE

A Performance Improvement of the Fuzzy Controller-Based Multi-Level Inverter-Fed Three-Phase Induction Motor with Enhanced Time and Speed of Response

S. Chandrasekaran[1] · **S. Durairaj**[2] · **S. Padmavathi**[3]

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Abstract
Right now, research in the power sector has generally limited itself to issues, for example, the nature of power and its improvement, with much research, focused on the two. Power network operations are constrained by non-direct electronic electronics that disrupt power systems. Power system issues harmonics, ripples, electromagnetic induction (EMI), voltage sags, voltage swells, and regulation, harmonics, the speed of response of the system, and the time response of the system. The tasks of the existing system depend on the working of the fractional-order proportional-integral (FOPID) controller, which comprises a photovoltaic panel, buck–boost converter, seven-level multi-level inverter, three-phase induction motor, and FOPID controller. The proposed framework comprises a fuzzy logic controller (FLC); PV-fed seven-level multi-level inverter and buck–boost converter, with a three-phase induction motor giving the heap. The simulation model worked for both the current and proposed frameworks is by MATLAB Simulink, and the outcomes for both are analyzed and recorded. The examination shows that the proposed framework has a quicker speed of reaction, time reaction, and lower THD esteem than the current framework.

Keywords Fractional order PID · MLI · Harmonic · Fuzzy logic controller (FLC) · Total harmonics distortion (THD) · PV panel

1 Introduction

Today, electric power systems assume a key job in the industry. The power sector is, nevertheless, overflowing with issues that sway the nature of intensity. Such issues are welcomed by the utilization of intensity electronic (or non-linear) electronics in the system. Issues with power quality have to do with harmonics, ripples, swells, EMI, speed of reaction, and timely reaction. Of these, harmonics and the speed of reaction of the framework are basic. A few controllers have been utilized lately to determine issues with the nature of intensity, and incorporate the proportional (P), proportional integral (PI), proportional integral derivative (PID), integral order PID (IOPID), fractional order PID (FOPID), and fuzzy logic controller (FLC).

The current framework involves a photovoltaic panel, buck–boost converter, multi-level inverter, three-phase induction motor, and FOPID controller. The proposed framework comprises a photovoltaic panel, buck–boost converter, multi-level inverter, three-phase induction motor, and fuzzy logic controller (rather than a FOPID controller),

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✉ S. Chandrasekaran
samuchandru1@gmail.com

S. Durairaj
durairaj_eee@yahoo.com

S. Padmavathi
spmcse@tce.edu

1 Arasu Engineering College, Chennai Main Road, Kumbakonam, Thanjavur, Tamilnadu 612501, India

2 Dhanalakshmi Srinivasan Engineering College, Thuraiyur Road, Perambalur, Tamilnadu 621212, India

3 Thiagarajar College of Engineering, Madurai, Tamilnadu 625015, India

photovoltaic panel, buck–boost converter, multi-level inverter, and three-phase induction motor.

The previous framework works on the 200 Vdc supply voltage produced from the PV panel. For the investigation, an aggravation voltage of 08 Vdc is finally applied to the framework to consider the manual unsettling influence. The buck–boost converter helps the information from 208 to 408 Vdc, and the seven-level multilevel inverter is utilized close by. The detriment of the PID controller is settling time is minimal high and high consistent steady-state [1] and it is decreased in this article.

The FOPID controller, generally utilized in the power sector, controls the working of the current framework. The controller is utilized with a Photovoltaic panel took care of multilevel inverter and works capably with present-day inserted programming. Predominantly utilized for mechanical applications, the controller controls the non-linear boost converter and applies the frequency domain analysis and control design methods [2]. The proposed framework portrayed in this article utilizes a fuzzy logic controller. Fuzzy controllers work dependent on fuzzification and defuzzification measures. The speed of reaction of the fuzzy logic controller is quicker than that of the current controller. The wind generation, solar generation, and load demand are demonstrated with the assistance of the FOPID controller [3]. The controller is accustomed to extracting the maximum power from the wind turbine, controlling power, load frequency deviation, and dealing with the supply and demand [4]. The rigid robotic manipulator is planned with the FOPID controller [5].

The seven-level multilevel inverter utilized believer 408 Vdc to 408 Vac. The MLI had its roots in a three-level inverter yet has since been stretched out to incorporate seven, and then some, levels. Multilevel inverters are of three sorts: the diode-clamped inverter (DCMLI), flying capacitor MLI (FCMLI), and cascaded MLI. The cascaded H-bridge MLI produces a more precise output than old-style inverters and, further, takes out the requirement for a boosting phase on the input side and a power transformer on the output side [6].

The serious issue in measure ventures is control of liquid level in the capacity tank, substance mixing, and response vessels [7]. The FOPID controller is utilized for the pH balance measure in the sugar stick juice measure [8].

In this article, the three-phase enlistment motor that goes about as a heap runs for 408 Vac. The speed of the motor is given as a contribution to the controller. From that point, an order given by the controller to the lift converter places the framework in a shut circle activity. The reaction of the FOPID controller is contrasted and that of the fuzzy logic controller and the outcome is confirmed in the reproduction circuit with a three-phase induction motor.

The primary contribution of the paper can be summed up as follows: (1) The speed of reaction of the framework is broke down. (2) The current harmonics are decreased in the proposed framework. (3) The time-domain parameter, for example, rise time, peak time, and settling time are investigated and confirmed for both existing and proposed systems. (4) The THD estimations of the fuzzy controller has diminished. (5) The steady-state error in the current and proposed controller is noted and broke down. The trouble of this paper is the guideline of the power output in the photovoltaic board and the synchronization of framework output with the utility network.

The remainder of the article is arranged as follows. Segment 2 examines the buck–boost converter activity and Sect. 3 the standards and activity of the cascaded multilevel inverter. Segment 4 portrays the reaction of the FOPID controller and its conduct, and Sect. 5 the development and utilization of the proposed framework with the fuzzy logic controller with a convenient reaction. Segment 6 breaks down harmonics decrease, while Sect. 7 confirms the recreation results. Segment 8 looks at the output parameters and closes the paper.

1.1 Specifications of the Systems

Table 1 presents the specifications of the existing and proposed systems.

Table 1 System specifications

S. No	Buck–boost converter	Inverter	Three-phase induction motor	FOPID	FLC
1	R = 0.001 Ohms	R = Ohms	Voltage = 460 V	Elliptic filter order = 5	Input and output ranges are [–0.4 0 0.4] and [–0.8 0 0.8]
2	L = $2e^{-3}$H	MOSFET R = 0.001 Ohms	N = 1750 Rpm	PID Kp = 0.9; Ki = 9; Kd = 0.0009	Input and output current variable ranges are [0 1] and [0 2]
3	C = $50e^{-6}$F	L = $1e^{-6}$ h	Hp = 5	VCO output amplitude = 50 V	–

1.2 The Sizing of the Photovoltaic Panel

Photovoltaic module sizing is designed and calculated based on parameters such as the electrical load, as well as specifications for the inverter, battery size, PV panel array, and controller [9]. The solar panel is constructed with a series–parallel connection of solar cells and it produces electricity due to the quantum mechanical process is called as "Photovoltaic effect" [10]. The Eqs. (1) and (2) represents the panel numbers calculation.

The watt-hours per day calculated are multiplied by 1.3 (loss in the system), and the number of panels is calculated by the

$$\text{Number of panels} = \text{total watt} - \text{hours/the rated power output of the panel} \tag{1}$$

$$\text{Total output} = \text{ total output delivered by the solar PV system/daily peak sun hours} \tag{2}$$

decrease the voltage of the PV system depending on the load requirements[15].

In a three-phase motor winding, the three winding wound and placed by 120^0 apart. So all the three phases a, b, c are displaced by 120^0. The phase-to-neutral voltage can be obtained from

$$Van = V_m \sin(\omega t) \tag{3}$$

Van—the phase to neutral voltage of phase 'a'. Phase 'a' is displaced by 0° degrees.

$$Vbn = V_m \sin\left(\omega t - \frac{2\pi}{3}\right) \tag{4}$$

Van—the phase to neutral voltage of phase 'b'. Phase 'b' is displaced by 120° degrees.

$$Vcn = V_m \sin\left(\omega t + \frac{2\pi}{3}\right) \tag{5}$$

Vcn—The phase to neutral voltage of phase 'c'. Phase 'c' is displaced by 240° degrees.

$$Vab = Van - Vbn = \sqrt{3} V_m \sin\left(\omega t - \frac{\pi}{6}\right) \tag{6}$$

Vab represents the line-line voltage between the phase 'a' and 'b'. The line voltage Vab is calculated from the phase voltage Van and Vbn.

$$Vbc = Vbn - Vcn = \sqrt{3} V_m \sin\left(\omega t - \frac{\pi}{2}\right) \tag{7}$$

Vbc represents the line-line voltage between the phase 'b' and 'c'. The line voltage Vbc is calculated from the phase voltage Vbn and Vcn (Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 show the proposed system, the cascadded Multilevel

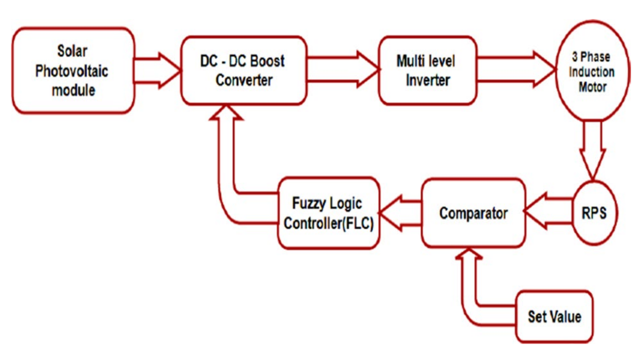

Fig. 1 The proposed system

2 Buck–Boost Converter

The boost converter that acts as a switch consists of a 200 Vdc source with a disturbance voltage of 8 V. The snubber capacitor is used as a filter in the source circuit, while the MOSFET acts as a switch. The MOSFET with its 360° operations offers the most advantages.

Two MOSFETs are used in the converter circuit: one is in parallel and the other in series with the source. Circuit parameters such as resistance R = 0.001 ohms, capacitance $C = 50e^{-6}$ and inductance $L = 2e^{-3}$ are used, and the feedback or flyback diode is connected through anti-parallel sources. The boost controller is used in the renewable energy generation system [11].

The diode comprises of inner resistance R = 0.001ohms and forward voltage Vf = 0.8 V. Input or flyback diodes have snubber resistance and snubber capacitance to encourage powerful tasks. Converters are planned and produced in various proportions, for example, 1:2, 1:4, and 1:8. In this article, both the current and proposed frameworks have a lift converter of a 1:2 proportion. The boost topology isn't appropriate for a series association because in arrangement the current are equivalent so this topology could work sufficiently in the parallel association [12].

The input 208 Vdc is boosted to 416 Vdc. Attributable to its boot-up activity; this converter is known as a DC–DC or buck–boost converter. The output voltage of the converter is having a reverse extremity than the input voltage thus it is otherwise called the Inverting converter [13]. The DC–DC converter is associated with a large portion of the areas which incorporate vehicle, space, flight, broadcast communications, medication, and sustainable power source [14]. The buck–boost converter increase or

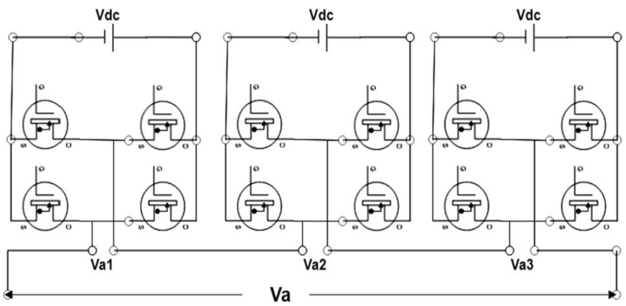

Fig. 2 The cascaded multi-level inverter

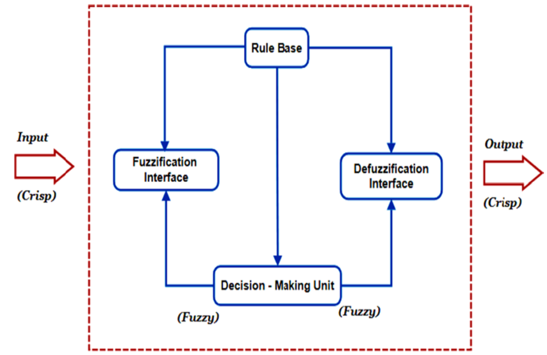

Fig. 5 The design of the fuzzy logic controller

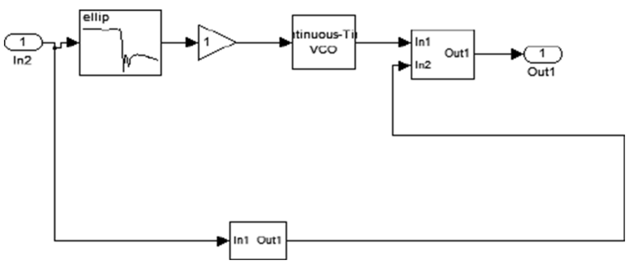

Fig. 3 The FOPID controller

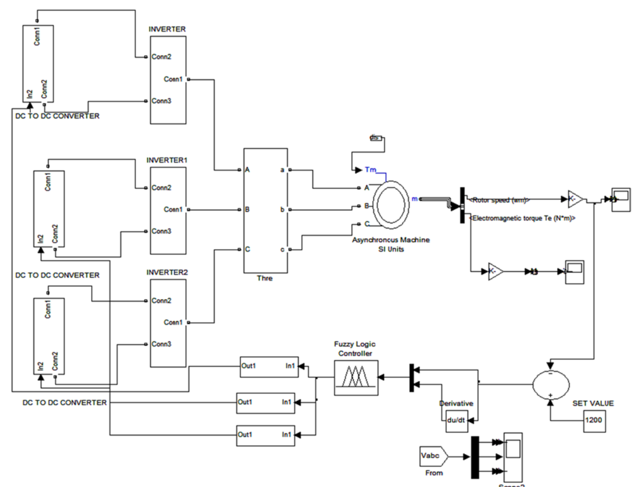

Fig. 6 The fuzzy logic controller model

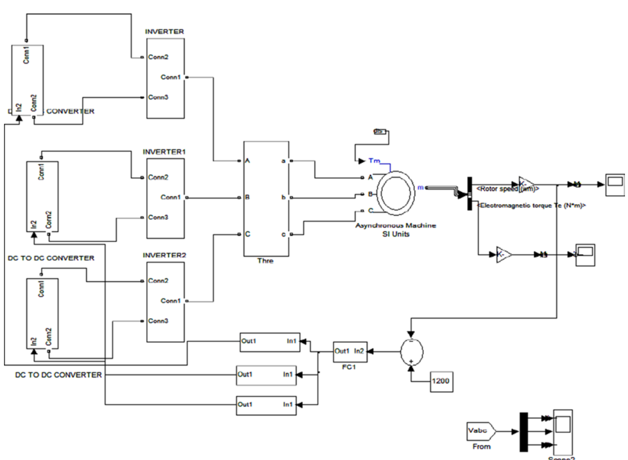

Fig. 4 The closed-loop with the FOPID controller

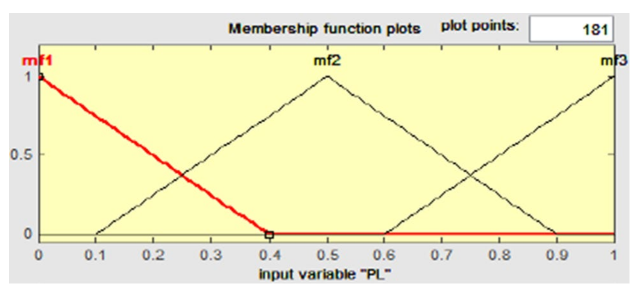

Fig. 7 The plot for the input variable, PL

Inverter, the FOPID controller, the closed loop with FOPID controller, the design of the Fuzzy Logic Controller, the Fuzzy Logic Controller model, the plot for the input variable PL, the plot for the input variable PM, the plot for the output variable PH, and comparision of current harmonics and THD).

Equation (3)–(7) represents the phase sequence analysis of the converter circuit.

3 Cascaded Multi-Level Inverter

In the proposed framework, seven-level inverters are utilized with IGBT switches. The different modulation techniques utilized in the inverter incorporate random pulse width modulation, single PWM, the sinusoidal PWM, and space vector PWM [16]. The inverter circuit involves eight

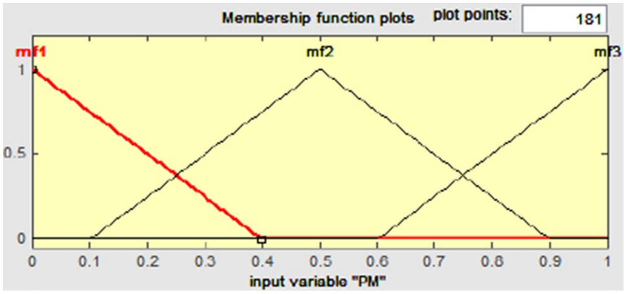

Fig. 8 The plot for the input variable, PM

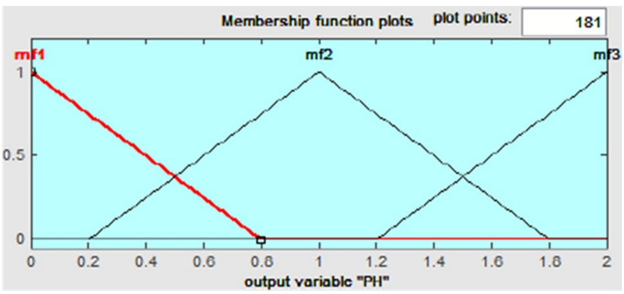

Fig. 9 The plot for the output variable, PH

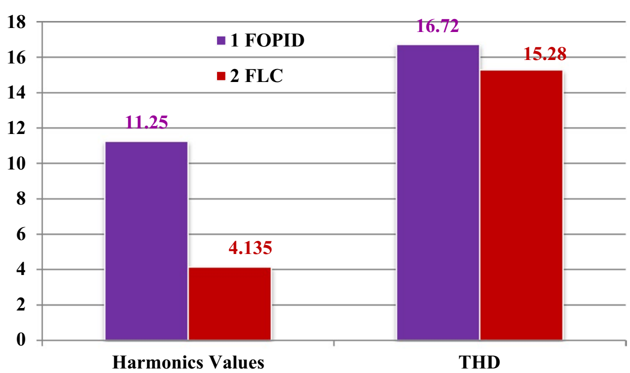

Fig. 10 Comparison of current harmonics and THD

MOSFET switches (M1, M2, M3, M4, M5, M6, M7, and M8), with each phase comprising of two switches.

This circuit is intended for a three-phase supply, and the working of the apparent multitude of switches depends on the activity of the pulse generator. The two possible schemes for gating electronics incorporate the 180-degree and 120-degree conduction method of activity [17]. The multilevel inverter kills the lower order harmonics from output voltage [6].

MOSFET parameters include diode resistance, diode inductance, snubber resistance, and snubber capacitance. PV based multilevel inverter is having low voltage stress, low harmonics distortion, low electromagnetic interference (EMI), and reduced current rating [18]. The multilevel inverter can be controlled using different modulation techniques according to switching frequency [15]. The levels of the inverter are directly proportional to the quality of the output (sine wave) [19].

This system uses a seven-level inverter circuit with the FOPID and fuzzy logic controllers. The seven-step waveform is produced as the output of the inverter. The inverter reduces the stress on the switching devices involved.

3.1 Feedback Circuit

The speed reference from the motor is taken as a feedback signal from the three-phase induction motor. The input differs dependent on the gain of the output. The gain of speed reference is gain = 4/Pi, and for the electromagnetic torque, it is gain = 825/Pi. The output of the input framework is associated with the comparator circuit.

The comparator contrasts the deliberate speed esteem and a set worth, and the distinction between the set worth and feedback esteem is balanced by the controller. The controller controls the input signal given to the converter to manage the output of the inverter. The fuzzy logic controller and the inverter consolidate to go about as an intelligent controller fit for taking care of a wide range of issues without a numerical model of the system [16].

4 The Response of the FOPID Controller

The current framework utilizes the fractional-order proportional integral derivative controller (FOPID), which works on fractional order calculus (FOC) standards. The FOPID controller has applications in such territories as designing, power systems, power electronics, control theory, and signal processing. The tuning of the fuzzy FOPID controller has endeavored with GA [20]. FOPID controllers are utilized in the pumped storage unit regulatory application [21].

4.1 Fractional Order Calculus (FOC)

Fractional order calculus is the most successful and best tool to analyze a timely response to dynamic conditions. Fractional calculus originates from control systems and allows derivatives and integrals of real numbers [22]. The fractional-order differentiator can be denoted by a general fundamental operator.

$$ {}_aDt^q = \begin{cases} \dfrac{d^x}{dt^x} \\ \displaystyle\int_a^1 (dt)^{-\alpha} \end{cases} \quad \mathrm{Re}\,\alpha > 0 || \alpha = 0 || \alpha < 0 \tag{8} $$

The Eq. (8) represents the real order generalization for fractional-order calculus and α range is $\alpha > 0||\alpha = 0||\alpha < 0$.

Where the upper output limit is 280 RPM, the lower output limit is 280 Rpm, and the sample time is $50e^{-6}$. The fractional calculus is the best tool for describing complex quantum field dynamic systems, dissipation, and long-range phenomenon [23].FOPID controllers are operate based on proportional, integral, and derivative parameters (Kp, Ki, and Kd) [23].

4.2 The FOPID Controller

The FOPID controller is structured utilizing the accompanying parameters and values. It comprises an elliptic channel, gain, voltage control oscillators, and PID blocks. The elliptic channel is simple. The fragmentary qualities applied to the simple channel are the channel request = 5, passband edge recurrence = 50 Hz, and passband ripple = 2, with 40 as the stopband weakening. The time reaction in this controller is quicker than in others. The FOPID controller is a complex process and diminishes overshoot and settling time [24]. The FOPID controller accomplishes the minimum steady-state error and improved dynamic behavior [25].

The voltage-controlled oscillator (VCO) decides the amplitude of a signal. The PID blocks have all the gain values. The output of the controller controls the input given to the DC–DC converter. Rise time, peak time, settling time and steady-state error are reduced and efficiency improved. The FOPID controller is used in wind turbine generators, electro-hydraulic systems, twin-rotor systems, tilt control of rail vehicles, industrial electric drives, and precision positioning systems. Pneumatic pressure control systems are modeled and designed using the integral order PID controller [26].

The FOPID controller is used to design twin-rotor systems, Industrial electrical drive, and precision positioning systems [2]. In the automation sector to boost the performance of the PID controller, the fractional-order PID (FOPID) controller is used for the past decades [27].

5 The Response of the Proposed Fuzzy Logic Controller

The fuzzy logic controller is a competent technology that improves the speed of response of the system. FLCs operate based on a set of fuzzy rules, member functions, linguistic variables, and control algorithms. The control rule base is played as a key role in designing an efficient fuzzy logic controller [28]. The fuzzy logic controller is used for controlling both the DC–DC converter and the DC–AC converter [29].

5.1 The Fuzzy Logic Controller Process

Fuzzy logic controllers are mostly used for nonlinear analyses and non-linear loads. The response of the system is connected directly to the fuzzy logic controller, which has a crisp set and a fuzzy set of data. The fuzzification and processes are carried out based on fuzzy rules and member functions. The rule-based fuzzy controller tracks and extracts maximum power under an appropriate isolation level [30]. The proposed controller is designed under the Mamdani FIS type.

The fuzzy adaptive control schemes are constructed for handling the non-linear system control problem [31]. Fuzzy controllers are used to saving the communication and computation resources in multi-agent systems applications such as natural networks and biological communities [32].

The fuzzy logic system consists of two inputs and one output. The input parameter range is [−0.4 0 0.4] and the output [−0.8 0 0.8]. The type of member function of the system is trimf. The input current variable range is [0 1] and output current variable [0 2].

The input signal is nonfuzzy (crisp) values which must be fuzzified to be used as an input signal to the fuzzy controller [30]. The fuzzy logic controller is the simplest controller among the various intelligent controller and it is robust and less sensitive to source and load [16]. The fuzzy logic controller can save more energy consumed by the induction motor during the starting time and when it works less than the full load [33].

5.2 Fuzzy Rules Table

Fuzzy rules are listed, based on system parameters. The input variables are PL and PM, and the output variable is PH.

5.3 Membership Functions

The proposed system comprises two input member functions and one output member function.

5.4 Real-Time Applications of the Fuzzy Logic Controller

Fuzzy logic has utilized in a variety of uses, including facial pattern recognition, climate control systems, clothes washers, vacuum cleaners, new product prizing or project risk assessment models, medical diagnosis and treatment plans, stock exchanging, just as in the accompanying frameworks: antiskid braking, transmissions, subway control, power optimization, and climate determining [34]. The fuzzy logic controller is utilized to control the speed of the train[35].

The fuzzy logic controller is used for examining the unsure factor in communication among the operators, for example, noise, quantization, packet loss, and delay [36]. The missing measurement in the switched system, for example, sensors systems, electronic circuits, and PC controlled systems are dissected by the fuzzy logic frameworks [37]. The significance of the dissipative framework is that the measure of energy put away ought not to surpass the measure of energy provided by the outside environment and energy dissemination is constrained by the fuzzy logic framework [38].

6 Harmonics Reduction

Harmonics are a significant issue in the power area. This paper examines multilevel inverter-took care of three-phase induction motor, with the investigation being done for the FOPID and fuzzy logic controllers. Of the apparent multitude of harmonics, the third and ninth impact the output current of the inverter the most. The 9th harmonics are checked and decreased. At the point when the inverter level expands, the estimations of the harmonics lessen correspondingly [39]. The multilevel inverter is the most appropriate decision for diminishing THD esteems [40]. The sufficiency of the odd-order harmonics is determined by utilizing THD (total harmonics contortion) [17].

The ninth harmonics finally named triplen harmonics, are viewed as the most exceedingly terrible high-frequency harmonics. The third and ninth harmonics act comparatively and face similar issues. The extent and THD estimations of the FOPID controller are as per the following: major greatness (50 Hz) = 11.25 and THD = 16.72%. The size and THD estimations of the fuzzy logic controller are as per the following, with fundamental magnitude (50 Hz) = 4.135 and THD = 15.28%, displaying decreased THD esteems which thusly brought about expanded execution.

6.1 Equations for THD Calculation

- If the measurement data is in power,

$$THD\,(\%) = 100 * \sqrt{P2 + P3 + P4 + \ldots + PnP1} \quad (9)$$

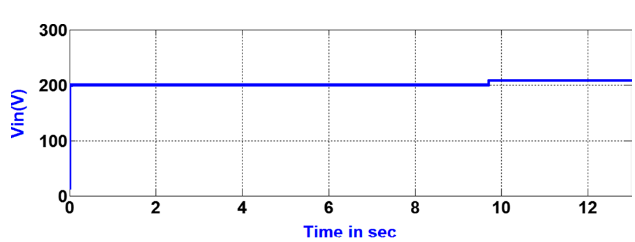

Fig. 11 Input voltage

where P1, P2, P3, P4, and Pn is Power in watts.

- If the measurement data is in volts,

$$THD\,(\%\,) = 100 * \sqrt{V22 + V32 +} V42 + \ldots + Vn2V1 \quad (10)$$

where V1, V22, V32, V42, and Vn is the RMS voltage.

$$\mathrm{THD} = \sqrt{\frac{\Sigma_{n=3,5,7,\ldots} V_n^{\ 2}}{V_1^{\ 2}}} \quad (11)$$

where THD represents total harmonics distortion. The Eqs. (9)–(11) is used for THD calculation.

6.2 A Comparison of Harmonics Parameters and THD Values

In this article, the current harmonics of the existing and proposed controller are compared. The current harmonics value of the proposed controller (FLC) is very low when compared with the existing controller (FOPID). So the reduced harmonics and total harmonics distortion (THD) values are achieved by the proposed fuzzy controller.

7 Simulation Results

7.1 The Closed-Loop with the FOPID Controller

Figures 11, 12, 13, 14, and 15 show the input voltage, converter voltage, motor speed, inverter output, and harmonic profile of the fractional order PID controller.

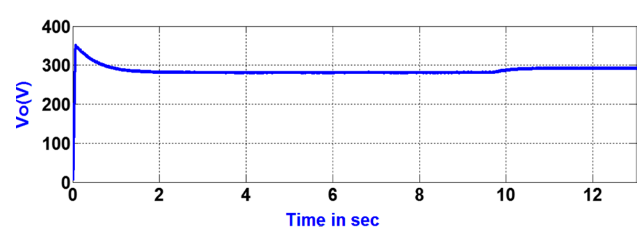

Fig. 12 Buck–boost converter voltage

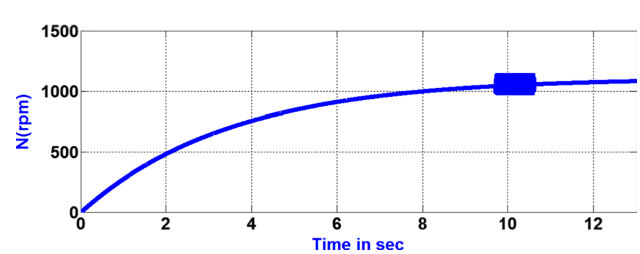

Fig. 13 Motor speed

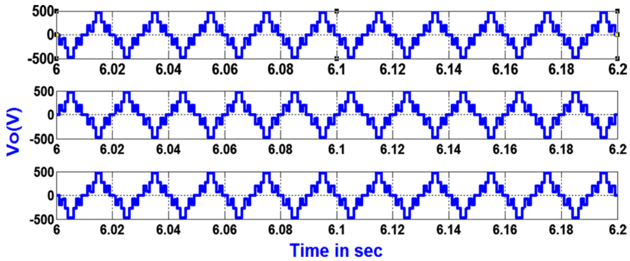

Fig. 14 Output voltage of the inverter

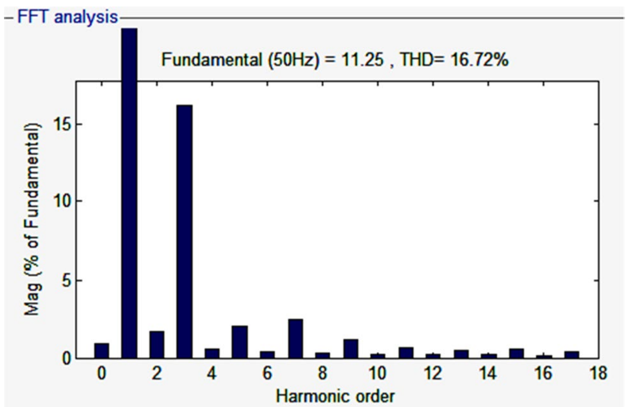

Fig. 15 Output current and THD of the FOPID controller (frequency = 11.25, THD = 16.72%)

7.2 The Closed-Loop with the Fuzzy Logic Controller

The time reaction of the FOPID controller is contrasted with that of the fuzzy logic controller. The information voltage and aggravation voltage of the current and proposed frameworks are equivalent to the two controllers. The adequacy of a fuzzy controller relies on the estimations of parameters, for example, input–output member functions (MFs), fuzzy principles, input and output scaling factor, and input and output derivatives and integrative parameters [41]. The fractional-order fuzzy controller is utilized as a genetic-based optimization search algorithm [42]. The converter maximizes the output voltage to the maximum value, which is

$$Va = Vdc + V_m \sin \omega t \tag{12}$$

In Eq. (12) the supply voltage is added with Vdc and Va represents the voltage of Phase ‘a’.

$$Vb = Vdc - V_m \sin \omega t \tag{13}$$

In Eq. (13) represents the supply voltage is subtracted from the Vdc and Vb represents the voltage of Phase ‘b’.

The voltage across the load is

Table 2 Fuzzy rules table

e/Δe	PL	PM	PH
PL	PH	PM	PL
PM	PL	Z	PH
PH	Z	PM	PH

Table 3 A comparison of the current harmonics and THD

S. No	Controller	Harmonics values	THD
1	FOPID	11.25	16.72
2	FLC	4.135	15.28

$$Vo = Va - Vb = 2V_m \sin \omega t \tag{14}$$

In Eq. (14), Vo represents the output voltage of the converter.

Several parameters decide the efficiency of the fuzzy logic controller but in this article proposed controller (fuzzy) is designed to achieve better speed (lowest steady-state error) and time (lowest rise time, peak time, and settling time) response when compared with the existing FOPID controller. Because this proposed controller is designed with suitable rules, best aggregation, and implication method (Tables 2, 3 and 4 show the fuzzy rules table, comparision of the current harmonics and THD, and comparision of time-domain parameters).

8 A Comparison of Output Parameters

The speed response of the FOPID controller-based inverter is compared with that of the fuzzy logic controller. The time response of the latter shows a marked improvement, maximizing the overall efficiency of the system. Based on the output the time taken by the fuzzy controller is less than the existing system (Figs. 16, 17, 18, 19, 20, 21 show the input voltage, Buck-Boost converter’s output voltage, motor speed, inverter’s voltage profile, output current and THD of the Fuzzy Logic Controller (frequency = 4.135, THD = 15.28%), and comparision of the time-domain parameters).

9 Conclusion and Future Work

This article has examined the speed of reaction and harmonics investigation of the photovoltaic-based seven-level inverter circuit with a three-phase induction motor. In this present article’s speed of reaction, time-domain parameters, for example, rise time, peak time, and settling time, and

Table 4 A comparison of time-domain parameters

Controller	Rise time (s)	Peak time (s)	Settling time (s)	Steady-state error (RPM)	ISE	Frequency
FOPID	9.7	9.9	10.6	5.8	58	11.25
FLC	6	0	9.8	1.3	25	4.135

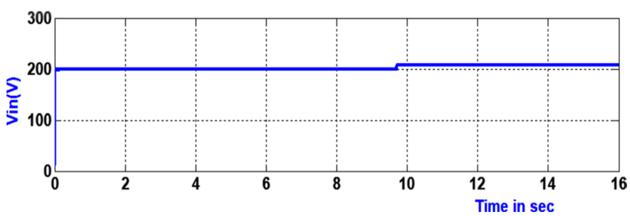

Fig. 16 Input voltage

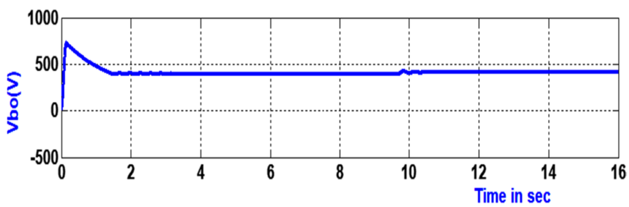

Fig. 17 Buck–boost converter output voltage

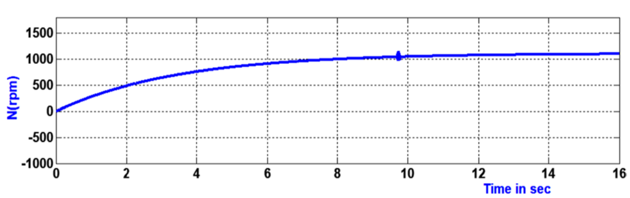

Fig. 18 Motor speed

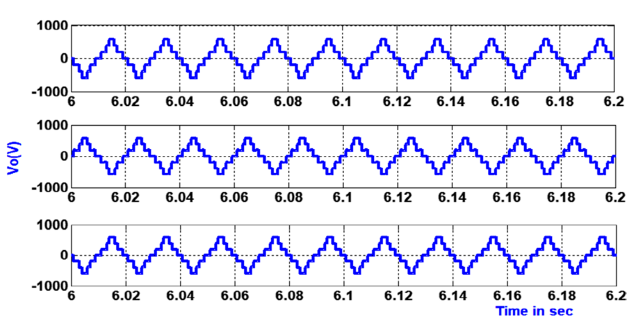

Fig. 19 Inverter voltage profile

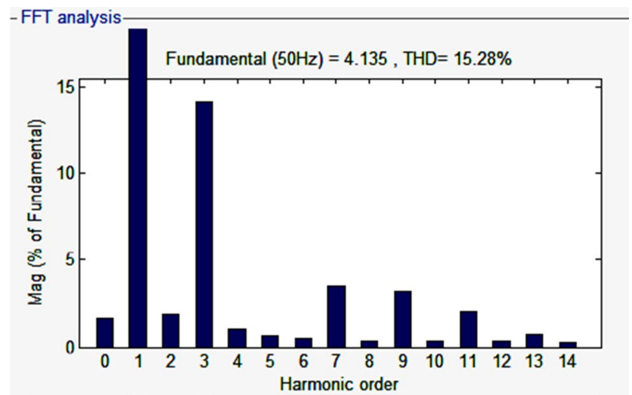

Fig. 20 Output current and THD of the fuzzy logic controller (frequency = 4.135, THD = 15.28%)

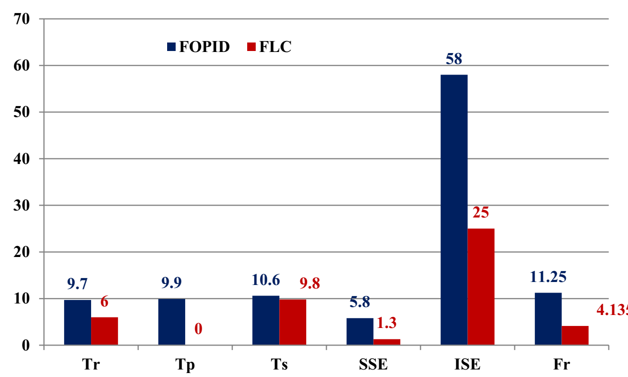

Fig. 21 A comparison of time-domain parameters

THD esteems are investigated and noted. The output of the motor is estimated and confirmed with both the FOPID and fuzzy logic controllers. The investigation and results show that the fuzzy logic controller delivered the most effective and qualified output with the least mistakes. The output of the multilevel inverter with its three-phase induction motor was confirmed and the nature of the sine wave improved. Subsequently, the seven multilevel inverter-based fuzzy logic controllers (FLC) delivered a considerably more effective output than the FOPID controller.

References

1. Babu MVG, Naik DRS (2017) Comparative analysis of P-I, I-P, PID and fuzzy controllers for speed control of DC motor. Int Res J Eng Technol 04(10):5
2. Tepljakov A, Alagoz BB, Yeroglu C, Gonzalez E, HosseinNia H, Petlenkov E (2018) FOPID controllers and their industrial applications: a survey of recent results. In: IFAC conference on advances in proportional-integral-derivative control, Ghent, Belgium, 9–11 May 2018. International Federation of Automatic Control
3. Pan I, Das S (2016) Fractional-order fuzzy control of hybrid power system with renewable generation using chaotic PSO. ISA Trans 62:19–29. https://doi.org/10.1016/j.isatra.2015.03.003
4. Mahto T, Mukherjee V (2017) Fractional-order fuzzy PID controller for wind energy-based hybrid power system using quasi-resistanceal harmony search algorithm. IET Gener Transm Distrib 11(13):3299–3309. https://doi.org/10.1049/iet-gtd.2016.1975
5. Sharma R, Rana KPS, Kumar V (2014) Performance analysis of fractional-order fuzzy PID controllers applied to a robotic manipulator. Expert Syst Appl 41(9):4274–4289. https://doi.org/10.1016/j.eswa.2013.12.030
6. Ahmed M, Sheir A, Orabi M (2017) Real-time solution and implementation of selective harmonic elimination of seven-level multilevel inverter. IEEE J Emerg Sel Topics Power Electron 5(4):1700–1709. https://doi.org/10.1109/JESTPE.2017.2746760
7. Jegatheesh A, AgeesKumar C (2020) Novel fuzzy fractional order PID controller for non-linear interacting coupled spherical tank system for level process. Microprocess Microsyst 72:102948. https://doi.org/10.1016/j.micpro.2019.102948
8. Reza M, Nemati A (2011) On fractional-order PID design. In: Michalowski T (ed) Applications of MATLAB in science and motorering. InTech, London
9. Salam MA, Aziz A, Alwaeli AHA, Kazem HA (2013) Optimal sizing of photovoltaic systems using HOMER for Sohar, Oman. Int J Renew Energy Res 3:8
10. Kumari P, Keshari RK, Banerjee DS (2017) Design and implementation of photovoltaic module using a multilevel inverter and boost converter. Int Res J Eng Technol 04(11):5
11. Rosas-Caro JC, Ramirez JM, Peng FZ, Valderrabano A (2010) A DC–DC multilevel boost converter. IET Power Electr 3(1):129. https://doi.org/10.1049/iet-pel.2008.0253
12. Hafez AAA (2015) Multi-level cascaded DC/DC converters for PV applications. Alex Mot J 54(4):1135–1146. https://doi.org/10.1016/j.aej.2015.09.004
13. Dave B (2013) Design & simulation of buck–boost converter modulation technique for solar application. J Inform Knowl Res Electr Eng 02(02):336
14. Doubabi H, Salhi I, Chennani M, Essounbouli N (2019) Voltage control of DC–DC three-level boost converter using TS fuzzy PI controller. In: 2019 6th international conference on control, decision and information technologies (CoDIT), Paris, France, pp 1266–1271. doi: https://doi.org/10.1109/CoDIT.2019.8820554.
15. EL-Hosainy A, Azazi HZ, Hamed HA (2017) A two-stage buck-boost multilevel inverter for photovoltaic power generation. In: Proceedings of 4th international conference on energy engineering, Faculty of Energy Engineering, Aswan University, Aswan, Egypt, 26–28 December 2017
16. Zheng X, Zaman H, Wu X, Ali H, Khan S (2017) Direct fuzzy logic controller for voltage control of standalone three-phase inverter. In: 2017 international electrical motorering congress (iEECON), Pattaya, Thailand, pp 1–4. doi:https://doi.org/10.1109/IEECON.2017.8075779.
17. Rajpriya G, Ravi S, Zaidi AMA (2013) Design and development of MATLAB Simulink based Selective Harmonic Elimination technique for three-phase voltage source inverter. In: 2013 international conference on advanced computing and communication systems, Coimbatore, India, pp 1–5. doi:https://doi.org/10.1109/ICACCS.2013.6938734.
18. Ge X et al (2019) A single-phase buck–boost three-level neutral-point-clamped inverter with two input sources for the grid-tied photovoltaic power generation. Math Probl Mot 2019:1–15. https://doi.org/10.1155/2019/3238159
19. Kumar LA, Jayashree LS, Manimegalai R (eds) (2020) In: Proceedings of international conference on artificial intelligence, smart grid and smart city applications: AISGSC 2019. Springer, Cham
20. Das S, Pan I, Das S, Gupta A (2012) A novel fractional-order fuzzy PID controller and its optimal time-domain tuning based on integral performance indices. Mot Appl Artif Intell 25(2):430–442. https://doi.org/10.1016/j.engappai.2011.10.004
21. Wu X, Xu Y, Liu J, Lv C, Zhou J, Zhang Q (2019) Characteristics analysis and fuzzy fractional-order PID parameter optimization for primary frequency modulation of a pumped storage unit based on a multi-objective gravitational search algorithm. Energies 13(1):137. https://doi.org/10.3390/en13010137
22. Sandhya A, Sandhya R, Prameela M (2016) An overview of fractional order PID controllers and its industrial applications. Int J Innov Mot Technol 6(4):13
23. Mohamed DMJ, Khashan MA (2014) Comparison between PID and FOPID controllers based on particle swarm optimization, p 9
24. Karthikeyan R, Pasam S, Sudheer S, Teja V, Tripathi S (2014) Fuzzy fractional order PID based parallel cascade control system. In: Thampi SM, Abraham A, Pal SK, Rodriguez JMC (eds) Recent advances in intelligent informatics. Advances in intelligent systems and computing, vol 235. Springer, Cham, pp 293–302. https://doi.org/10.1007/978-3-319-01778-5_30
25. Ghany MAA, Bahgat ME, Refaey WM, Sharaf S (2020) Type-2 fuzzy self-tuning of modified fractional-order PID based on Takagi–Sugeno method. J Electr Syst Inf Technol 7(1):2. https://doi.org/10.1186/s43067-019-0009-9
26. Kanagaraj N, Al-Dhaifalla M, Nisar KS (2017) Design of intelligent fuzzy fractional-order pid controller for pressure control application. In: 2017 international conference on intelligent computing, instrumentation and control technologies (ICICICT), Kannur, India, 6–7 July 2017, pp 525–530
27. Dhandayuthapani S, Mohanapriya R, Sharmeela C, Kanimozhi E (2018) FOPID controlled shunt active filter in IEEE nine bus system with improved dynamic time response. In: 2018 international conference on power, energy, control and transmission systems (ICPECTS), Chennai, pp 358–361. doi:https://doi.org/10.1109/ICPECTS.2018.8521561.
28. Mohan V, Chhabra H, Rani A, Singh V (2019) An expert 2DOF fractional order fuzzy PID controller for nonlinear systems. Neural Comput Appl 31(8):4253–4270. https://doi.org/10.1007/s00521-017-3330-z
29. Mutlag AH, Shareef H, Mohamed A, Hannan MA, Abd Ali J (2014) An improved fuzzy logic controller design for PV inverters utilizing differential search optimization. Int J Photoenergy 2014:1–14. https://doi.org/10.1155/2014/469313
30. Hilloowala RM, Sharaf AM (1992) A rule-based fuzzy logic controller for a PWM inverter in photo-voltaic energy conversion scheme. In: Conference record of the 1992 IEEE industry applications society annual meeting, Houston, TX, USA, pp 762–769. doi: 10.1109/IAS.1992.244319.
31. Zhu Z, Pan Y, Zhou Q, Lu C (2020) Event-triggered adaptive fuzzy control for stochastic nonlinear systems with unmeasured states and unknown backlash-like hysteresis. IEEE Trans Fuzzy Syst. https://doi.org/10.1109/TFUZZ.2020.2973950

32. Liang H, Guo X, Pan Y, Huang T (2020) Event-triggered fuzzy bipartite tracking control for network systems based on distributed reduced-order observers (revised manuscript of TFS-2019-1049). IEEE Trans Fuzzy Syst. https://doi.org/10.1109/TFUZZ.2020.2982618
33. Menghal PM, Laxmi AJ (2016) Fuzzy based real-time control of induction motor drive. Procedia Comput Sci 85:228–235. https://doi.org/10.1016/j.procs.2016.05.219
34. Singh H et al (2013) Real-life applications of fuzzy logic. Adv Fuzzy Syst 2013:1–3. https://doi.org/10.1155/2013/581879
35. Neema DD (2011) Speed control of induction motor using fuzzy rule base. Int J Comput Appl 33:9
36. Liang H, Zhang L, Sun Y, Huang T (2019) Containment control of semi-markovian multiagent systems with switching topologies. IEEE Trans Syst Man Cybern Syst. https://doi.org/10.1109/TSMC.2019.2946248
37. Zhang M, Shen C, Wu Z-G, Zhang D (2020) Dissipative filtering for switched fuzzy systems with missing measurements. IEEE Trans Cybern 50(5):1931–1940. https://doi.org/10.1109/TCYB.2019.2908430
38. Zhang M, Shi P, Shen C, Wu Z-G (2019) Static output feedback control of switched nonlinear systems with actuator faults. IEEE Trans Fuzzy Syst. https://doi.org/10.1109/TFUZZ.2019.2917177
39. Sahoo SK, Bhattacharya T (2018) Phase-shifted carrier-based synchronized sinusoidal PWM techniques for a cascaded H-bridge multilevel inverter. IEEE Trans Power Electron 33(1):513–524. https://doi.org/10.1109/TPEL.2017.2669084
40. Venkatesan M, Rajeswari R, Devarajan N (2015) A fuzzy logic based three phase inverter with single DC source for grid connected PV system employing three phase transformer. Int J Renew Energy Res 5:739–745
41. Zamani A-A, Tavakoli S, Etedali S, Sadeghi J (2018) Online tuning of fractional order fuzzy PID controller in smart seismic isolated structures. Bull Earthq Eng 16(7):3153–3170. https://doi.org/10.1007/s10518-017-0294-4
42. Zaheeruddin Z, Singh K (2020) Intelligent frequency control in microgrid: fractional-order fuzzy PID controller. IFS 39(1):195–212. https://doi.org/10.3233/JIFS-190963

S. Chandrasekaran is a Ph.D., Research Scholar at Anna University, Chennai. He has received a Diploma in Computer Technology at Muthiah Polytechnic College, Chidambaram, Tamilnadu in 2002. He has received an undergraduate in the Department of Electrical and Electronics Engineering at Arasu Engineering College, Kumbakonam, Thanjavur, Tamilnadu in 2006, and a Master's Degree in the Department of Power Electronics and Drives at Periyar Maniammai University, Vallam, Thanjavur, Tamilnadu in 2013. He has 14 years of teaching experience. He is a life member of ISTE. His areas of research interests include Power Quality, Controller, and Renewable Energy.

S. Durairaj received the Post-Doctoral Fellowship degree at Queen's University Belfast, Northern Ireland, the United Kingdom in 2008. He has received a Doctoral degree at Madurai Kamaraj University, Madurai in 2006. He has received the Master of Engineering degree in Power System Engineering at Thiagarajar College of Engineering, Madurai Kamaraj University in 1999. He has received an undergraduate degree in Electrical and Electronics Engineering at Thiagarajar College of Engineering, Madurai in 1994. He has been working as a professor in the Department of Electrical and Electronics Engineering at Dhanalakshmi Srinivasan Engineering College, Perambalur, Tamilnadu. He has more than 24 years of teaching experience. He has published more than 90 research articles in reputed journals and international conferences. He has received BOYSCAST FELLOWSHIP from DST, Govt. of India for the year 2006–2007 for Post-Doctoral Research at Queen's University, Belfast, United Kingdom in the area of Renewable Energy Sources and Young Scientist Fellowship (YSF) for the year 2002 from Tamilnadu State Council for Science and Technology (TNSCST) and awarded Rs. 10,000/- with a Certificate of Excellence and undergone training in Asea Brown Boveri (ABB), Bangalore in the area of Power System Automation. His areas of research interests include Electrical Engineering, Power Quality, and Reactive Power Management.

S. Padmavathi received a Doctoral degree in Computer Science and Engineering at Anna University, Chennai in 2011. She has received the Master of Engineering degree in Computer Science and Engineering at Arulmigu Kalasalingam College of Engineering, Srivilliputhur, Virudunagar, Tamilnadu in 2002. She has received an undergraduate degree in Electrical and Electronics Engineering at Thiagarajar College of Engineering, Madurai in 1999. She has been working as a professor in the Department of Information Technology at Thiagarajar College of Engineering, Madurai. She has more than 21 years of teaching experience. She has published more than 90 research articles in reputed journals and international conferences. She is a member of IEEE and ISTE. She has received Rs. 6,52,556/- as a grant for sponsored research from the All India Council for Technical Education. Her areas of research interests include Free Space and Adaptive Optics, Scheduling Algorithms, and Parallel Computing.