

COMPARISON OF TOTAL HARMONIC DISTORTION IN DIFFERENT LEVELS OF INVERTER

Mr.P.Thirumurugan¹, Ms.R.Preethi²

¹J.J. College of Engineering & Technology, Trichy, Tamil Nadu, India, 9791744325, thirum.tech16@gmail.com

²J.J. College of Engineering & Technology, Trichy, Tamil Nadu, India, 8344312743, prthi07@gmail.com

Abstract: In this paper the harmonic distortion rate for three phase neutral clamped multilevel inverter (NCI) for the grid connected solar system is presented for three level, five-level and six-level inverter. Solar system is controlled and maximum power is obtained by fuzzy based MPPT controller. The fuzzy MPPT is integrated with the inverter so that a DC–DC converter is not needed and the output shows accurate and fast response. Neutral clamped multilevel inverter is controlled by pulse width modulation technique called Sinusoidal Pulse Width Modulation (SPWM). The results are verified through MATLAB/SIMULINK software and the results are compared in terms of THD.

Key words: three phase three level, five-level and six-level inverter, NCI, THD, Solar system, MPPT, SPWM, MATLAB, fuzzy.

1. Introduction

Renewable energy is the energy which comes from natural resources such as sunlight, wind, rain, tides and geothermal heat. Recent years, due to big demand of electrical energy, extended research in electricity production from solar energy using Photovoltaic (PV) has been done. The two principal classifications of photovoltaic system are grid-connected or utility-interactive systems and stand-alone systems [1]. With the appropriate power conversion equipment, PV systems can produce alternating current (AC) compatible with any conventional appliances, and can operate in parallel with, and interconnected to, the utility grid. The PV system operates at its highest efficiency at the maximum power point. The maximum power operating point changes with insolation level and temperature [2].

In order to increase the efficiency, MPPT controllers are used. MPPT is the technique used to track the maximum power from the PV array.

Different tracking control strategies such as perturbation & observation, incremental conductance, parasitic capacitance, constant voltage, neural network and fuzzy logic control have been proposed to extract maximum power from the PV array. In this paper fuzzy control is used to track the maximum power from the PV array. Fuzzy Logic representations founded on fuzzy set theory try to capture the way humans represent and reason with real-world knowledge in the face of uncertainty. Design of fuzzy is easy and implemented and the output is fast and accurate [3]. The primary component in grid-connected PV systems is the inverter.

Multilevel inverters are suitable for high voltage and high power applications due to their ability to synthesize waveforms with better harmonic spectrum [4]. A multilevel inverter not only achieves high power ratings, but also enables the use of renewable energy sources. The attractive features of the multilevel inverters are staircase waveform quality, common mode voltage, input current, switching frequency. Among the different topologies like diode clamped multilevel inverter, flying capacitor multilevel inverter and cascaded inverter with different DC sources, Neutral Point Clamped (NPC) or Diode clamped multilevel inverter topology is used in this paper. The generalized multilevel topology can balance each voltage level by itself regardless of load characteristics, active or reactive power conversion and without any assistance from other circuits at any number of levels automatically.

A fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components. This is the most

popular method of controlling the output voltage and this method is termed as Pulse-Width Modulation (PWM) Control. Abundant modulation techniques have been introduced like Sinusoidal Pulse Width Modulation (SPWM), Space Vector Pulse Width Modulation (SVPWM) Selective Harmonic Elimination Pulse Width Modulation (SHE-PWM). Among all techniques Sinusoidal Pulse Width Modulation (SPWM) technique is used in this paper.

2. Solar Array

The power delivered by a solar system of one or more solar cells is dependent on the irradiance, temperature, and the current drawn from the cells. Solar arrays are built up with combined series/parallel combinations of solar cells. Series connections are responsible for increasing the voltage of the module whereas the parallel connection is responsible for increasing the current in the array [5]. A solar cell can be modeled by a current source and an inverted diode connected in parallel to it which is shown in fig.1. It has its own series and parallel resistance. Series resistance is due to hindrance in the path of flow of electrons and parallel resistance is due to the leakage current.

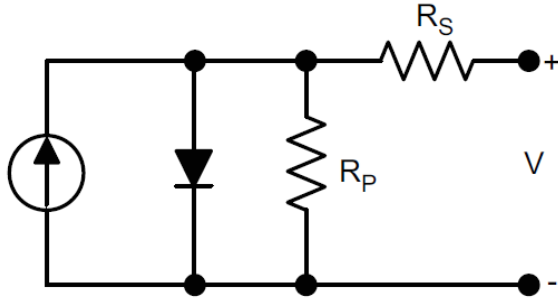


Fig.1 equivalent circuit of solar cell

In this PV array of KC200GT is used. KC200GT has following specifications: maximum power-200W; maximum power voltage-26.3V; maximum power current-7.61A. The PV cell output voltage is a function of the photocurrent that mainly determined by load current depending on the solar irradiation level during the operation [6]. Each solar cell is basically a p-n diode. As sunlight strikes a solar cell, the incident energy is converted directly into electrical energy without any mechanical

effort. Transmitted light is absorbed within the semiconductor by using its energy to excite free electrons from a low energy status to an unoccupied higher energy level. When a solar cell is illuminated, excess electron-hole pairs are generated by light throughout the material, hence the p-n junction is electrically shorted and current will flow.

$$V_c = \frac{AkT_c}{e} \ln \left(\frac{I_{ph} + I_0 - I_c}{I_0} \right) - R_s I_c \quad (1)$$

$$I_{ph} = [I_{scr} K_i (T - 298)] * \lambda / 1000 \quad (2)$$

where the symbols are defined as follows:

V_c : cell output voltage, V.

e : electron charge (1.602×10^{-19} C).

k : Boltzmann constant (1.38×10^{-23} J/ $^{\circ}$ K).

I_c : cell output current, A.

I_{ph} : photocurrent, function of irradiation level and junction temperature (5 A).

I_0 : reverse saturation current of diode (0.0002 A).

R_s : series resistance of cell (0.001 Ω).

T_c : reference cell operating temperature (20 $^{\circ}$ C).

I_{scr} is the PV module short-circuit current at 25 $^{\circ}$ C

K_i is the short circuit current temperature coefficient.

T is the module operating temperature in Kelvin.

λ is the PV module illumination (W/m 2) = 1000W/m 2

The curve fitting factor A is used to adjust the I-V characteristics of the cell obtained from (1) to the actual characteristics obtained by testing equation (1) gives the voltage of a single solar cell which is then multiplied by the number of the cells connected in series to calculate the full array voltage. The electrical system powered by solar arrays requires special design considerations due to varying nature of the solar power generated resulting from unpredictable and sudden changes in weather conditions which change the solar irradiation level as well as the cell.

3. MPPT controller

It is very difficult to operate the PV array on its maximum power point. Quick tracking under

changing conditions, small output power fluctuation, simplicity and low cost are the general requirements for an MPPT. This paper proposes a method to track maximum power point using FLC. FLC is suitable for nonlinear control [7]. FLC depend on shape of the membership function (μ^x) and the rule base, not on the complex mathematical model. Mamdani fuzzy logic model has been proposed to perform the MPPT, because this kind of controller is usually used in feedback control mode, because they are simple, present low sensibility to noise in the input.

Basically FLC has three parts namely: Fuzzification, Inference Engine and Defuzzification

Fuzzification

The fuzzification is the process of converting the crisp set into linguistic fuzzy sets using fuzzy membership function. The concept of linguistic variable was introduced to process the natural language. The membership function is a curvature that describes each point of membership value in the input space [8].

Variables are assigned as Negative Big ($-ve B$), Negative Medium ($-ve M$), Negative Small ($-ve S$), Zero, Positive Small ($+ve S$), Positive Medium ($+ve M$), and Positive Big ($+ve B$). The inputs of fuzzification are the error and change in error. The value of input error $E(k)$ and change in error $CE(k)$ are normalized by an input scaling factor. The input scaling factor has been designed such that input values are between -0.032 and 0.032. Membership function has many structures; among those triangular memberships function is used shown in fig.2 because for any particular input there is only one dominant fuzzy subset.

Fuzzy rule base is the basic function of fuzzification. A collection of rules referring to a particular system is known as fuzzy rule base. Fuzzy rule base for these seven linguistic variables is shown in table.1

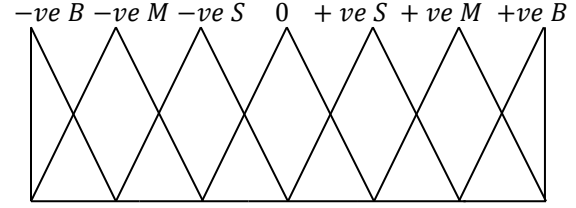


Fig.2 Input and output membership function for fuzzy

Table 1
Fuzzy Rule Base

$E(k)$	$CE(k)$						
$-ve B$	$-ve B$	$-ve M$	$-ve S$	Zero	$+ve S$	$+ve M$	$+ve B$
$-ve M$	$-ve B$	$-ve M$	$-ve S$	$-ve B$	$-ve M$	$-ve S$	zero
$-ve S$	$-ve B$	$-ve M$	$-ve S$	$-ve B$	$-ve M$	$-ve S$	zero
Zero	$-ve B$	$-ve M$	$-ve S$	Zero	$+ve S$	$+ve M$	$+ve B$
$+ve S$	$-ve B$	$-ve M$	$-ve S$	Zero	$+ve S$	$+ve M$	$+ve B$
$+ve M$	$-ve B$	$-ve M$	$-ve S$	Zero	$+ve S$	$+ve M$	$+ve B$
$+ve B$	$-ve B$	$-ve M$	$-ve S$	Zero	$+ve S$	$+ve M$	$+ve B$

Inference Engine

Fuzzy inference engine is an operating method that formulates a logical decision based on the fuzzy rule setting and transforms the fuzzy rule base into fuzzy linguistic output. Fuzzy linguistic descriptions are formal representations of systems made through fuzzy IF-THEN rules. They encode knowledge about a system in statements of the form: IF (a set of conditions) are satisfied THEN (a set of consequents) can be inferred. There are several methods for this such as Max-Min method, Max-Dot method. Inference engine is otherwise called as decision-making logic.

Defuzzification

The last step in the FLC process is the defuzzification. These will have a number of rules that transform a number of variables into a fuzzy result, that is, the result is described in terms of membership in fuzzy sets. Several methods are available for defuzzification such as centroid method, centre of sums, and mean of maxima. The Centre of Gravity (COG) defuzzification method is used [9]. Centre of gravity method is otherwise called as Centroid method, Centre of area method.

4. Multilevel inverter

Multilevel inverter is to synthesize a sinusoidal voltage from several levels of voltages. Levels of a multilevel inverter are designed according to the application. THD rate gets reduced when the levels are increased in a multilevel inverter. The switches are triggered by switching states [10].

Table 2 lists the output voltage level for one leg of the three phase six-level inverter which is shown in fig.3. State condition 1 means the switch is on, and 0 means the switch is off. The complementary pairs are (IGa1, IGa'1) and (IGa2, IGa'2), (IGa3, IGa'3), (IGa4, IGa'4), (IGa5, IGa'5). At any given time five switches are in ON state for each phase in three phase six level inverter.

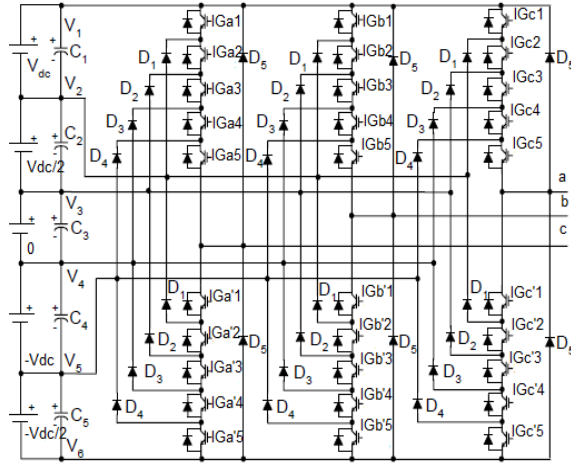


Fig.3 circuit diagram of three phase six-level inverter

The voltage across each capacitor is V_{dc} , and the voltage stress across each switching device is limited to V_{dc} through the clamping diodes [11]. The m-level NPC inverter has an m-level output phase voltage and a $2(m-1)$ level output line voltage. The number of diodes required for each phase would be $2(m-2)$. Five level diode clamped multilevel inverter is same as three level diode clamped inverter but differs in usage of number of switches, number of diodes, output voltage level.

Table 2

Switching states of three phase six level inverter for phase a

Switching state	1	2	3	4	5	1	2	3	4	5
$V_5 = 5V_d$	1	1	1	1	1	0	0	0	0	0
$V_4 = 4V_d$	0	1	1	1	1	1	0	0	0	0
$V_3 = 3V_d$	0	0	1	1	1	1	1	0	0	0
$V_2 = 2V_d$	0	0	0	1	1	1	1	1	0	0
$V_1 = V_{dc}$	0	0	0	0	1	1	1	1	1	0
$V_0 = 0$	0	0	0	0	0	1	1	1	1	1

5. Sinusoidal pulse width modulation (SPWM)

Sinusoidal Pulse Width Modulation (SPWM) refers to the generation of PWM outputs with sine wave as the modulating signal [12]. In this modulation method, the ON and OFF instants of PWM signals can be determined by comparing a reference signal with a high frequency triangular wave as shown in fig.7.

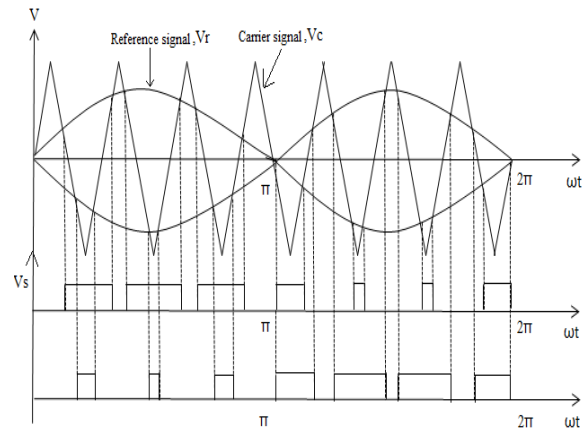


Fig.7 Principle of SPWM

For realizing SPWM, a high-frequency triangular carrier wave V_c is compared with a

sinusoidal reference wave V_r of the desired frequency. The intersection of V_c and V_r waves determines the switching instants and commutation of the modulated pulse. In fig.7 V_c is the peak value of triangular carrier wave and V_r that of the reference, or modulating signal. When triangular carrier wave has its peak coincident with zero of the reference sinusoid, there are $N = \frac{f_c}{2f}$ pulses per cycle. In case zero of the triangular wave coincides with zero of the reference sinusoid, there are $(N - 1)$ pulses per half cycle. The frequency of output voltage can be determined by the frequency of modulation wave. This technique improves distortion factor significantly compared to other ways of multi-phase modulation. It eliminates all harmonics less than or equal to $(2n-1)$, where 'n' is the number of pulses per half cycle of the sine wave.

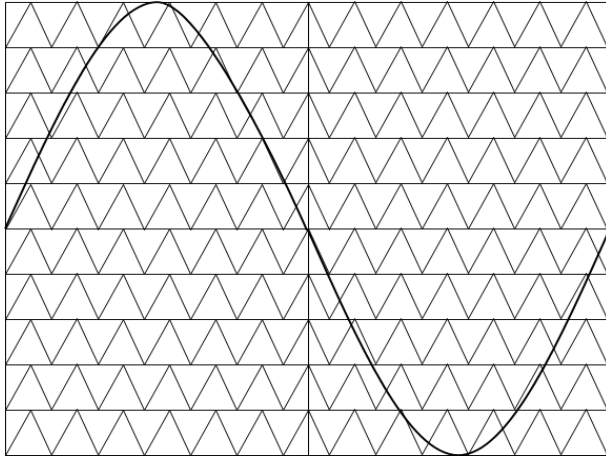


Fig.8 SPWM modulation for six level inverter

Fig 8 shows the SPWM modulation for six-level inverter. Sinusoidal signal amplitude determines the modulation factor [13]. Modulation factor is given by

$$M = \frac{A_m}{2A_c} \quad (3)$$

where A_m denotes the maximum value of reference voltage (V_{ref}) and A_c is peak to peak value of triangle wave (V_c).

To maintain the low total harmonic distortion, the modulation index should be maintained between 0 and 1. For three-level

inverter four triangular wave signals are compared with one reference signal. Pulse width of the pulses is varied according to the area of the two signals. As the number of switches increased in the multilevel inverter, the THD rate gets reduced.

THD

$$= \frac{\text{sum of the powers of all harmonic components}}{\text{Power of the fundamental frequency}}$$

$$THD = \frac{\sum_{i=2}^{\infty} P_i}{P_1} \quad (4)$$

6. Matlab simulation results

Simulation results show the harmonic rate of multilevel inverter when sinusoidal pulse width modulation is used. Multilevel inverter is connected to the solar system which is controlled by fuzzy logic control. Fig.9 shows the circuit diagram of the closed loop system.

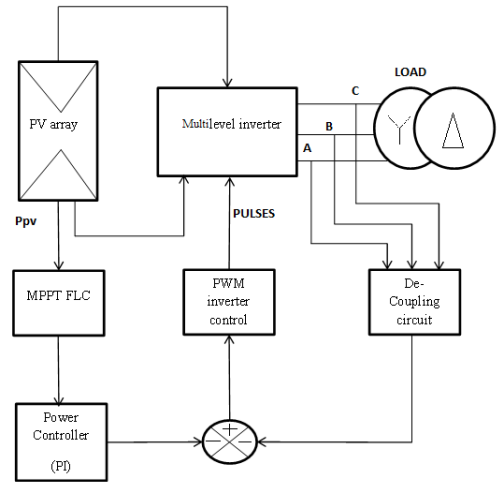


Fig.9 circuit diagram of the closed loop system

This is the closed loop system. Decoupling circuit and PI controller forms the feedback circuit. PV system is controlled by fuzzy based MPPT algorithm and inverter circuit is controlled by PWM control. A fuzzy rule for controlling PV system is shown in table.1.

Fig.10 shows the voltage graph for the six-level inverter. It has six-levels from the reference line and levels are varied according to the levels of the multilevel inverter used.

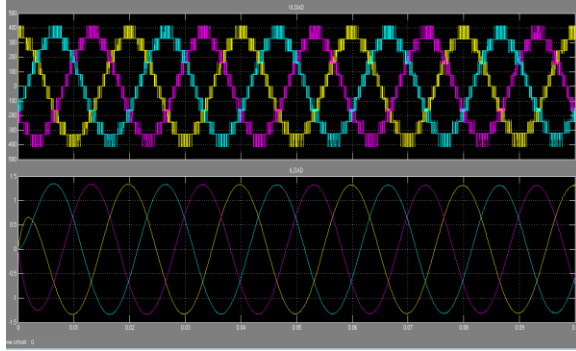


Fig.10 voltage and current waveform for six-level inverter circuit

Now we will discuss about the harmonic rate of the inverter circuit. Table 3 indicates the THD comparison table for three phase three level, five-level and six-level inverter for both open loop and closed loop.

Table.3 THD comparison

Sl.no	Number of levels	THD% for open loop	THD% for closed loop
1	3	35.13	32.14
2	5	16.32	15.35
3	6	17.10	15.16

First THD rate for open loop system is considered. Fig.11, 12 and 13 shows the THD rate for open loop of three phase three level, five-level and six-level inverter circuit.

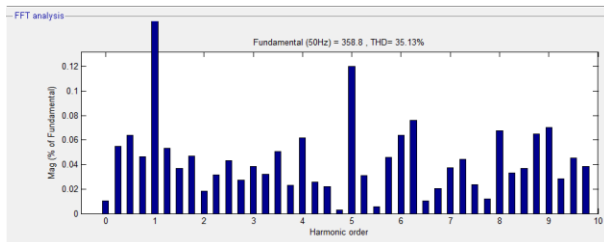


Fig. 11 THD rate of three phase three level inverter for open loop system

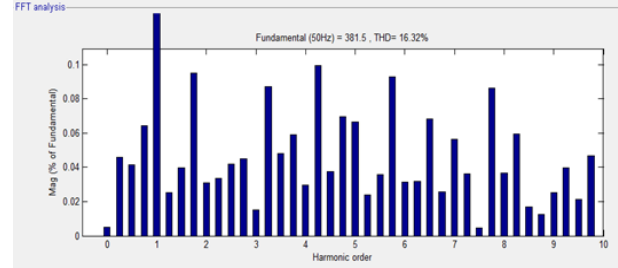


Fig.12 THD rate of three phase five-level inverter for open loop system

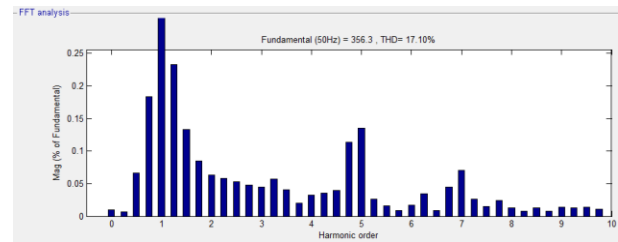


Fig.13 THD rate of three phase six-level inverter for open loop system

From figures 11, 12 and 13 it is evident that the THD rate is low for open loop of six-level inverter. THD rate is about 35.13%, 16.32% and 17.10% for three phase three level, five-level and six-level inverter respectively which are shown on figures 11, 12 and 13.

Now THD rate for closed loop system is considered. Fig.14, 15 and 16 shows the THD rate for closed loop of three phase three level, five-level and six-level inverter circuit.

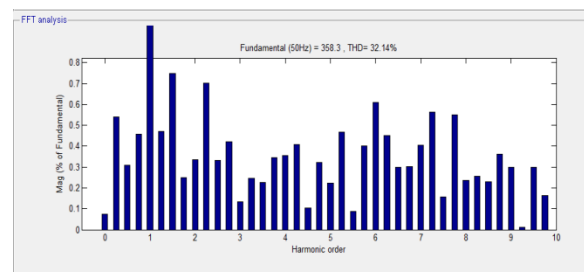


Fig.14 THD rate of three phase three level inverter for closed loop system

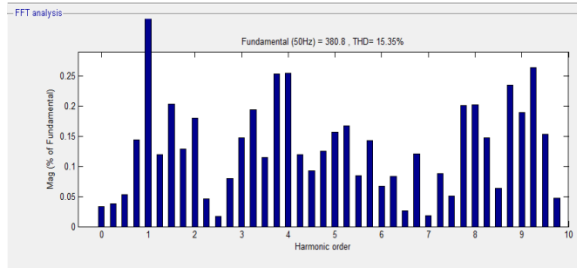


Fig.15 THD rate of three phase five level inverter for closed loop system

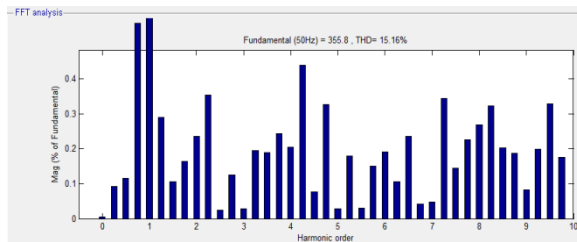


Fig.16 THD rate of three phase five-level inverter for closed loop system

From figures 14, 15 and 16 it is evident that the THD rate is low for open loop of six-level inverter. THD rate is about 32.14%, 15.35% and 15.16% for three phase three level, five-level and six-level inverter respectively which are shown on figures 14, 15 and 16.

7. Conclusion

Thus we conclude that the THD rate is low for high level inverter. Here, diode clamped multilevel inverter is used for inverter circuit. We know that the THD rate get reduces when multilevel inverter are used. Multilevel inverter is controlled by pulse width modulation technique called space vector pulse width modulation (SVPWM) technique. SVPWM technique is chosen because of its less switching stress and it gives high efficiency. SVPWM has numerous advantages compare to other techniques. And also fuzzy based MPPT works well to track maximum power from the photovoltaic system.

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Biography



P.Thirumurugan was born in Vandanmadu, Idukki district, Kerala, India in 1988. He got his B.E degree (Electronics and Instrumentation Engineering) in Bharath Niketan Engineering College, Anna University, Chennai, Tamil Nadu, India. In 2010, he was a GATE scorer and received his M.Tech (Control and Instrumentation Engineering) in Thiagarajar College of Engineering, Anna University, Chennai, Tamil Nadu, India. He got first class with Distinction in M.Tech. Now, he is working as Assistant Professor in J.J. college of Engineering and Technology, Trichy, Tamil Nadu, India. He published many papers in IEEE, various national and international conferences and a journal. His research interests include multilevel inverters.



R.Preethi was born in Ariyamangalam Village, Trichy, Tamil Nadu, India in 1989. She completed her B.E degree in J.J. College of Engineering and Technology, Anna University, Trichy, Tamil Nadu, India in the field of Electrical and Electronics Engineering. Now she is pursuing her M.E (Control and Instrumentation Engineering) in the same college, Anna University, Chennai, Tamil Nadu, India. She published papers in IEEE conference and a journal.