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Application of Fuzzy control to Maximum Power Point Tracking of H5 Transformerless Inverter Used in Grid Connected PV Systems

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Abstract

An efficient PV system tied to the utility grid via an H5 transformer-less inverter is present in this paper. Moreover, Fuzzy controller is adapted to the Maximum Power Point Tracking (MPPT) of the PV panel. This condition gives high efficiency and extracts the maximum power from the PV system. To improve the utilization factor of the system and ensure MPPT operation, a boost converter is inserted between the PV and the conventional H5 transformer-less inverter. The performance of the proposed system with the fuzzy controller is tested at step changes in the insolation. Matlab simulations show that the proposed system perfectly tracks the MPPT condition. Also, it has high efficiency low earth leakage current.

Keywords: transformer-less inverter, PV, H5, Fuzzy control, MPPT.

1. INTRODUCTION

Due to its cleanness, availability, and sustainability photovoltaic energy is regarded as one of the most attractive renewable energy sources. The costs of the PV generation systems drops with time [1]. Therefore, widespread PV systems and installations are increasing worldwide. The energy generation systems utilizing PV arrays may classified into stand-alone systems or grid tied systems. Stand-alone system stands for a generation system that supplies isolated loads. It is popular in rural regions. However, grid tied stands for a generation system that is connected to grid. Recently, grid tied systems becomes very popular. Traditionally, grid tied PV systems are connected to the utility grid through power transformers [2]. These transformers have the advantages of galvanic isolation that is important for safety and protection. Also, it provides voltage level matching between the PV system converter and the grid [3]. On the other side, integrating these transformers with the PV power generation system increases the size, weight, power losses, and cost of the PV energy generation system.

Nowadays, a new topology for the grid tied PV energy generation system becomes widespread. This topology is named transformer-less energy generation system. In that system the power transformer is replaced by a transformerless inverter. Nevers less, removing the power transformer provides a path for a leakage current to follow through the PV parasitic capacitances and earth [4-9]. This leakage current produces serious noise and safety problems. Some world standard associations produce standard regulations for the leakage current levels that generated by PV grid tied systems [10].

Traditionally, half-bridge inverter is proposed by [11], however, its big problem is the low voltage gain. Also, full-bridge inverter is proposed derived using unipolar Sinusoidal Pulse Width Modulation (SPWM) [12]. However, the common mode voltage changes at switching frequency resulting to high leakage current. Recently, many attempts for the transformer-less inverter topology and modulation have been proposed to reduce the leakage current problem [13-19]. The famous developed topologies in the literature are H5 topology, H6 topology, and Highly Efficient and Reliable Inverter Concept (HERIC) topology. Among these transformer-less inverters, H5 topology has the least number of transistors, lowest cost, and the simplest configuration compared to the others. In this paper, an H5 transformer-less inverter is employed between the PV panel and the grid to minimize the leakage current to standard level. Also, an MPPT unit is used to continuously extract maximum power from the PV panel. Several MPPT methods are introduced in literatures such as; Incremental Conductance (IC) method, Perturb and Observe (P&O) method, Fuzzy Logic method, Artificial Neural Network method , etc. [20-29]. On the other hand, a boost converter is added as a matching impedance between the PV panel and the H5 transformer-less inverter. The maximum power point tracker is achieved by controlling the boost inductor current at a constant value corresponding to the value of the maximum power. To improve the system performance a boost converter is integrated between the photovoltaic panel and the H5 inverter. Traditionally, the boost converter is controlled by the help of PID controllers. Consequently, these controllers do not give the satisfactory response with systems that incorporating varying reference values [30]. Adaptive PI controller is employed to enhance the system response. Fuzzy is a common and simple algorithm to implement adaptive PI controllers. Appling fuzzy algorithm to adjust the PI controller parameters, a Fuzzy PI (FPI) controller is generated that gives a suitable system response [31- 33]. A voltage controller is adapted to control the input voltage of the H5 inverter at a suitable value related to the grid voltage. This controller generates the reference current for the H5 inverter. The synchronizations required with the grid voltage is done using phase locked loop techniques.

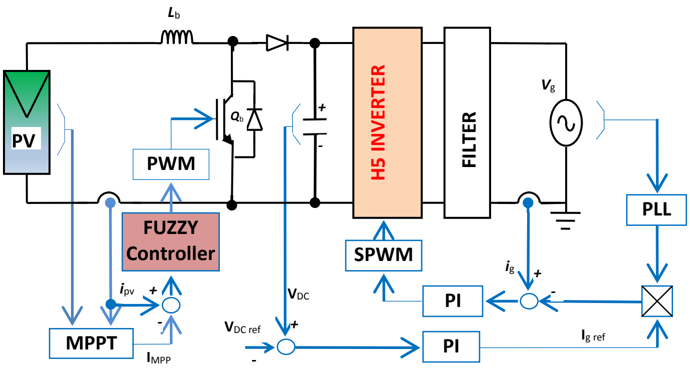

Fig. 1: Proposed PV transformer-less grid tied system

2. PROPOSED SYSTEM DESCRIPTION AND MODELLING

The proposed system is a PV power generation unit supplies electrical power to the utility grid via a transformer-less inverter, as shown in Fig.(1). A boost converter is cascaded to the photovoltaic panel to match the PV panel voltage and improve the system performance. A transformer-less inverter of type H5 is used to interface the boost converter to the grid. Its main function is to generate AC voltage that is synchronized and has the same voltage level as the grid utility. Also, a grid filter usually used to prevent high frequency harmonics from grid terminals. The proposed system model is described in the following paragraphs.

2.1 PV panel model

The PV array is formed of four parallel modules to supply the panel rated current. Each module includes 720 series cells and to give nearly 300V which is suitable voltage for the boost converter to achieve the required dc link voltage. The model of a PV cell is shown in Fig. 2 is composed of current source with parallel ideal diode, series and parallel resistances. Normally, the parallel resistance is large enough to be neglected. The equations of the model is well known in the literature [34].

$$I = I_{ph} - I_o\left(e^{\frac{V+IR_s}{v_T}} - 1\right) - \frac{V+IR_s}{R_p} \qquad (1)$$

Where; (I , V) are the PV terminal current and voltage; R_s is the series resistance; R_p is the parallel resistance; (I_{ph} , I_o) are the short circuit current and the saturation current; v_T is the thermal voltage.

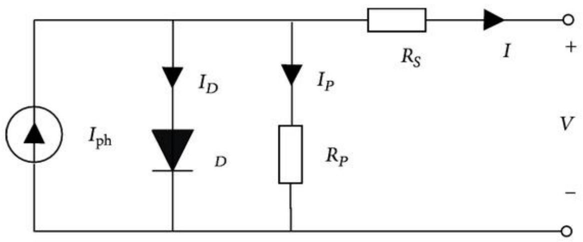

Fig. 2: Model of the PV cell.

2.2 Boost converter model

A unidirectional boost converter is utilized to interface the PV to the H5 inverter for the purpose of impedance matching. The voltage and current relations of the input and output terminals, of the boost converter shown in Fig.(3), are given by [35]:

$$V_d = V/(1-d) \quad , \; I_d = (1-d)I \qquad (2)$$

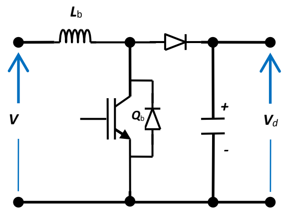

Fig. 3: The boost circuit diagram.

Where; d is the duty cycle ratio of the boost converter, (V, I) are the PV output voltage and current, (V_d, I_d) are the DC bus voltage and current.

The inductor current of the boost converter is the PV panel terminal current. Usually, the boost input current is continuous using simple design constrains. Hence, continuous energy extraction from the PV can be achieved. On the other hand, this energy can be controlled to be at the MPPT conditions of the PV. This condition is adapted by controlling the boost input current.

2.3 H5 transormerless inverter model

Adding an extra fifth transistor to the traditional H-bridge inverter, H5 inverter is formed. Hence, it has the lowest number of power transistors among the famous transformer-less inverters. The topological circuit diagram of H5 inverter is shown in Fig. 4. The function of the added fifth transistor is to isolate the PV from the grid during the inverter zero state. Hence, the earth leakage current path is disconnected causing its rms value to be reduced. An AC grid filter is used to suppress the inverter harmonics and ensure good quality of supplied energy.

The H5 inverter principles of operation are:

- ✓ The gate signal of transistor (Q1) is square wave synchronized with the grid voltage. However, the gate signal of transistor (Q3) is square wave opposite to Q1 but.
- ✓ The gate signal of transistor (Q5) is a Sinusoidal Pulse width Modulation SPWM of fundamental frequency equal to the grid frequency. However, the carier frequency is high to minimize the harmonics.
- ✓ The gate signal of transistor (Q4) is the same as Q5 at the positive half cycle but off in the negative half cycle.
- ✓ The gate signal of transistor (Q2) is the same as Q5 at the negative half cycle but off in the positive half cycle.

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The modes of operation of the H5 inverter are as follows:

i. Positive state of inverter output voltage. This mode occurs during the positive half cycle where the transistores Q5, Q1 and Q4 are turned on. This mode is known as the active mode.

ii. Zero state of inverter output voltage in the positive half cycle. During this mode, the PV array is disconnected from the grid. The transistor Q1 and the antiparallel diode of transistor Q3 conducts together. This mode is known as freewheeling mode.

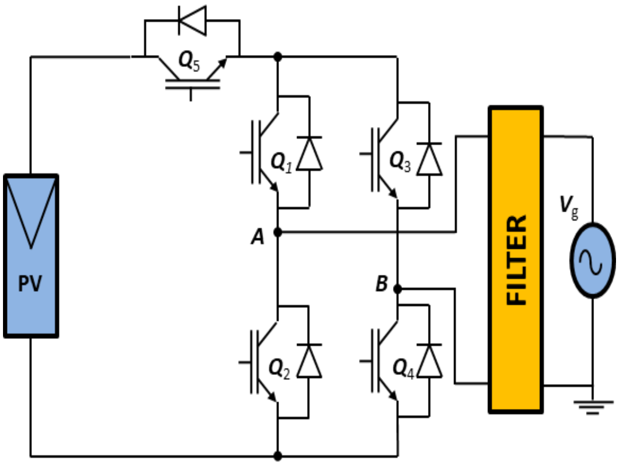

Fig. 4: Circuit topology of H5 inverter.

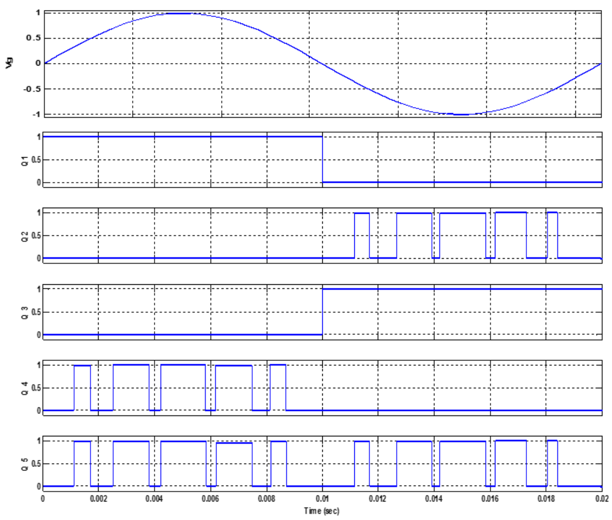

Fig. 5: Gate signals of H5 inverter transistors

iii. Negative state of inverter output voltage. This mode occurs during the negative half cycle where the transistors Q5, Q3 and Q2 are turned on. This mode is known as the active mode

iv. Zero state of inverter output voltage in the negative half cycle. During this mode, the PV array is disconnected from the grid. The transistor Q3 and the antiparallel diode of transistor Q1 conducts together. This mode is known as freewheeling mode.

The gate control signals of the H5 inverter transistors, for one complete cycle of the grid, is shown in Fig. 5.

3. Utilization factor of the PV panel

At a certain insolation level, the ratio of the actual PV power to the MPPT power of the PV panel is called the Utilization factor (K_u). The maximum value of the utilization factor of the PV panel, connected to H5 transformer-less inverter, has been calculated to be as low as 50% [36]. This means that only half value of MPPT power is taken from the PV panel. The origin of this problem is the discontinuous nature of the power extracted from the PV.

To alleviate this problem and increase the value of (K_u), a boost converter is inserted between the PV terminals and the H5 inverter as proposed in Fig. 1. It is well known that the boost converter input current can be controlled simply to be continuous. Hence, the PV discontinuous power can be removed and the extracted power becomes continuous. If the reference value of the current controller is adjusted at the MPPT current, then the PV panel will give its maximum power. Consequently, the factor (K_u) becomes close to unity.

Maximum Power Point Tracking (MPPT)

The extracted power of the PV panel is a function of many factors the insolation level, ambient temperature, PV current, and terminal voltage. For a given temperature and insolation level, the PV output power is typically related to its terminal voltage by the curve shown in Fig. 6. At a certain terminal voltage or loading conditions, maximum power can be extracted from the PV. Hence, MPPT conditions can be achieved by the help of the boost converter. It acts as a matching impedance for PV panel and load. The boost converter input impedance is controlled by varying its duty cycle ratio. A control unit named MPPT is adapted to derive the duty cycle achieving the MPPT conditions. Many MPPT techniques are used in the literature, but, the incremental conductance technique is usually used for the conventional systems. However, the proposed system implements a Fuzzy current controller to achieve the MPPT conditions. The Fuzzy controller maintains the boost input current at the value of the MPPT conditions of the PV-panel.

An off-line MPPT method is used to memories the MPPT conditions of the PV for a given temperature and insolation level. The reference current for the Fuzzy current controller is generated according to the measured temperature and insolation level.

Proposed System Controllers

The proposed system controllers, shown in Fig. 1, is divided into the following parts:

- **DC bus voltage controller**

This controller maintain the output voltage of the boost converter at a constant value that is suitable to meet the voltage level of the utility grid. The controller as proposed has a reference set point of nearly 450 V. The controller is a PI controller as the set point is constant. This comes from the fact that PI controllers give reasonable response with constant set values. The feedback signal is the actual DC bus voltage. The controller will generate the reference grid current. Consequently, the DC bus controller forms the outer loop for the grid current loop. Hence, for stability issues, the DC bus loop should be slower than the grid current loop [36].

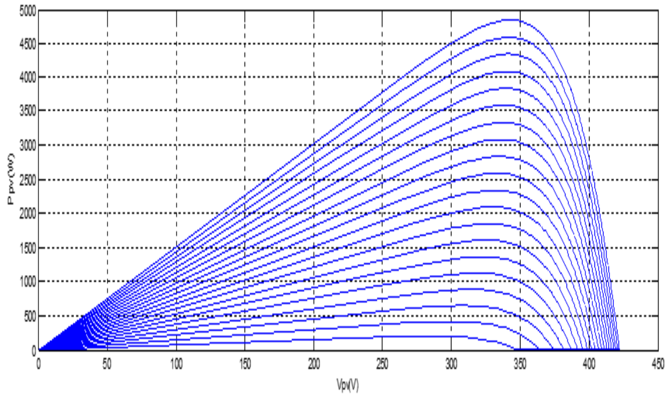

Fig.6: The PV panel characteristics curves.

- **H5 inverter controller**

The proposed H5 inverter controller is a current controlled voltage source inverter. The reference grid current is multiplied by the grid voltage synchronization signal producing the modulating signal for the SPWM unit. The grid voltage synchronization signal is generated using PLL circuit. The SPWM unit generates the control signals of the five transistors with the help of the operation principles discussed before.

- **Boost converter controller**

It is proposed a FPID controller to control the boost converter inductor current so as to track the PV MPPT condition. The input to the FPID is the PV actual current which is compared to the reference current as shown in Fig. 1. It is mainly an PID controller, however, its parameters (K_p, K_d, and K_i) are tuned using fuzzy algorithm. The classical PI controller relations are []:

$$d = K_p e - K_i \int edt \qquad (3)$$

$$e = i_{pv} - I_{ref} \qquad (4)$$

Where; d is the controller signal, the duty ratio of the boost converter transistor that represents the reference to the PWM modulator; e is the current error. The details of the Fuzzy controller is discussed in the following paragraph.

Fuzzy Controller Design

Firstly, the error and its change (e and Δe) are fuzzified using fuzzy partition with seven terms. These terms have linguistic values NB: negative big, NM: negative medium, NS: negative small, ZE: zero, PS: positive small, PM: positive medium, and PB: positive big. A triangular membership function is assigned to each linguistic value as shown in Fig. 7.

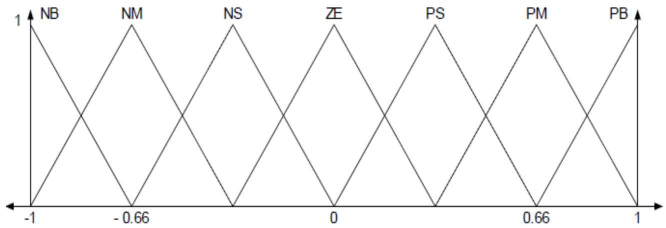

Fig. 7: The membership functions for e and Δe

Assuming that δK_p and δK_d are the change in the proportional and derivative gains that adapt the proportional and derivative parameters of PID controller, as follows:

$$K_p = A_p \delta K_p, \quad K_d = A_d \delta K_d \qquad (5)$$

Where; (A_p, A_d) are adaptation factors for proportional and derivative gains respectively.

The linguistic values for δK_p and δK_d are assumed to be either small or big and assigned the Gaussian membership functions.

The integral gain is determined with reference to the proportional and derivative parameters, i.e.,

$$K_i = K_p^2/(\alpha K_d) \qquad (14)$$

The linguistic values for α are assumed to be either S (small), MS (medium small), M (medium) or B (big). These fuzzy sets are represented in singleton membership functions. The second stage, namely defuzzification, is determined using set of fuzzy rules as in the following:

If $e_n(i)$ is F_{1j} and $\Delta e_n(i)$ is F_{2j}, then δK_p is H_{1j}, δK_d is H_2, and α is H_3.

Where; $e_n(i)$: is the i^{th} observation for normalized error.

$e_n(i)$: is the i^{th} observation for normalized first difference in error.

F_{1j}: is the fuzzy set for input (1) and j^{th} rule.

H_{1j} :is fuzzy set for output (1) and j^{th} rule.

j : is equal to 1,2,3,…,R and R is the number of rules.

The fuzzy tuning rules are shown in Table [1].

Table 1: Fuzzy tuning rules for δK_p, δK_d, and α.

	tuning rules of ΔK_p	$\Delta e_n(i)$						
		NB	NM	NS	ZE	PS	PM	PB
$e_n(i)$	NB	B	B	B	B	B	S	B
	NM	B	B	B	B	S	B	B
	NS	B	B	B	B	B	B	B
	ZE	B	B	B	B	B	B	B
	PS	B	B	S	B	B	B	B
	PM	B	B	S	B	B	B	B
	PB	B	S	B	B	B	B	B
	tuning rules of ΔK_d							
	NB	B	B	B	B	B	B	S
	NM	B	B	B	B	B	B	S
	NS	B	B	B	B	B	S	S
	ZE	S	S	S	B	S	S	S
	PS	S	S	B	B	B	B	B
	PM	S	B	B	B	B	B	B
	PB	S	B	B	B	B	B	B
	tuning rules of α							
	NB	S	S	S	S	S	S	S
	NM	MS	MS	S	S	S	MS	MS
	NS	M	MS	MS	S	MS	MS	M
	ZE	B	M	MS	MS	MS	M	B
	PS	M	MS	MS	S	MS	MS	B
	PM	MS	MS	S	S	S	MS	MS
	PB	S	S	S	S	S	S	S

SIMULATION RESULTS

The proposed PV grid connected H5 inverter, which is controlled by fuzzy logic and shown in Fig. 1., is simulated by Matlab program. The parameters and data of the system are listed in Table 2.

Table 2: System Parameters.

Parameter	Value
PV SC current	16.35A
PV OC voltage	422 V
C_f	2nF
L_f	1.8 mH
Grid voltage	230V, 50Hz
DC link capacitor	2000μF

Figure 8 presents the inverter output voltage (after and before filtering), grid current, and earth leakage current at full insolation. The inverter output voltage has a SPWM shape. However, after filtering, it has a sinusoidal shape synchronized with the grid voltage. Also, it is clear that the grid current is in phase with the grid voltage indicating unity power factor operation. The earth leakage current instantaneous value is shown to be small. Figure 9 shows the rms values of the leakage current with the insolation changes. The peak value of the earth leakage current satisfies the permissible limits given by [10]. Figure 10 shows the proposed system efficiency variations with the insolation level. The efficiency decreases as insolation level decreases and reaches 77% at 10% insolation level. The figure presents the Total Harmonic Distortion (THD). The THD increases as the insolation level drops.

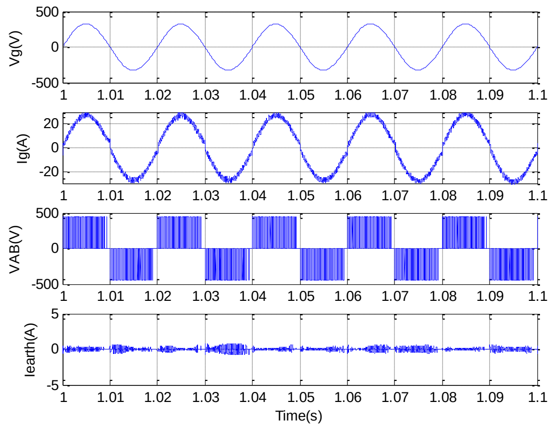

Fig. 8: Inverter output voltage, grid current, pre-filtering voltage, and earth leakage current

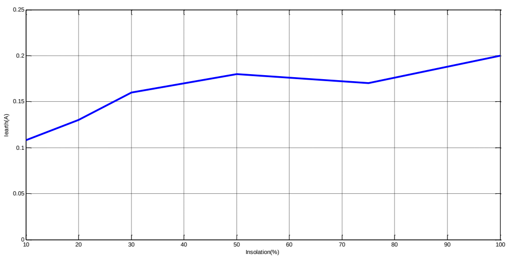

Fig. 9: Leakage current (rms) versus PV array power

The output power step response at different insolation levels is shown in Fig. 11. Simulations are carried out with insolation levels of 100%, 75%, 50%, 30%, 20%, and 10% according to Californian standards. Also, the MPPT power changes are indicated in the figure. It is seen that the output power tracks the MPPT level with small ripples. These ripples are built in ripples related to the instantaneous AC power. The FPID controller response is shown in Fig. 12. The PV current tracks perfectly the reference MPPT current as shown in the figure, due to small settling time and overshoot less response. The harmonic spectrum of the grid voltage is shown in Fig. 13. It indicate the low value of the THD of the proposed system at different insolation levels.

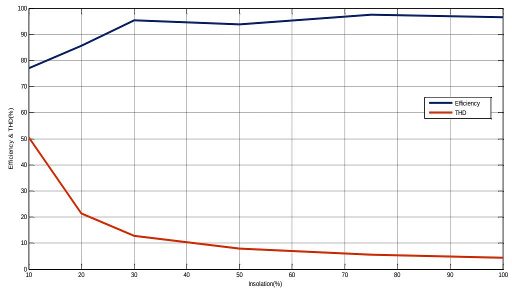

Fig. 10: Efficiency and THD of the proposed system versus PV array power

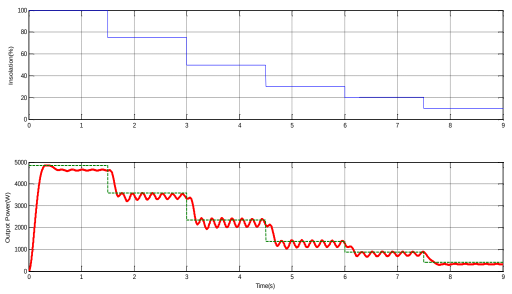

Fig. 11: Steps changes in the insolation, corresponding output power, and the MPPT power of the PV array

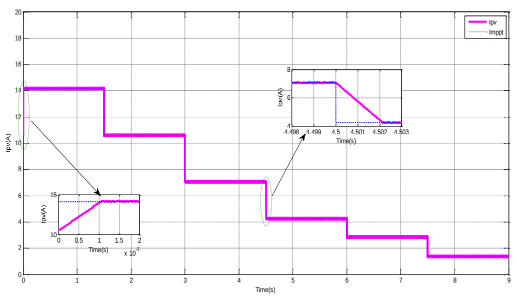

Fig. 12: PV current response with step in insolation

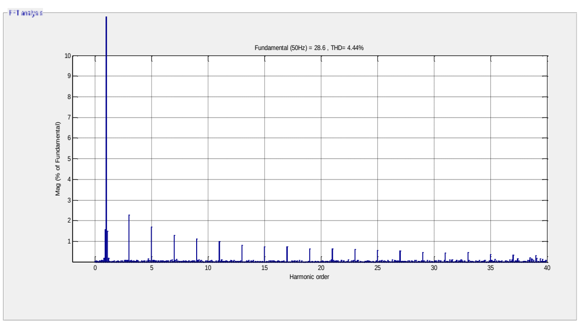

Fig. 16: The harmonic spectrum of the proposed at 100% insolation.

CONCLUSION

PV grid connected system incorporating an H5 transformer-less inverter and boost converter is introduced. The PV current utilizes an FPID current controller to achieve the MPPT operation. The dc link voltage is controlled using traditional PI controller. Simulation results show that the proposed system has quick response and good tracking for MPPT conditions. It also has excellent efficiency, low leakage current, and low THD.

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