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PV Supplied Single Stage MPPT Inverter for Induction Motor Actuated Ventilation Systems

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[1]***Abstract*—Ventilation and refrigeration is indispensable process for human life. Particularly, it has vital importance in desert climate conditions and rural areas, where the grid power may not be available. Although the cost is still higher than traditional energy resources, renewable energy may be the right choice for these applications. In this paper, a DSP based variable speed drive for induction motors to actuate a ventilation system supplied photovoltaic arrays is proposed. The maximum power point of the photovoltaic arrays is tracked by proposed variable speed drive. A variable stepped incremental conductance and constant voltage methods are combined to obtain fast tracking algorithm which generates voltage and frequency references for three phase three level inverter. Also the switching frequency of the inverter is kept constant to improve the quality of current waveform at low power levels. Experimental results show that, the proposed system has fast reaction and is suitable for rapidly changing irradiation level. Since the additional converter requirement is eliminated by using single stage inverter, the total system efficiency is increased.**

***Index Terms*—PV, ventilation, V/f, single stage inverter, MPPT.**

I. INTRODUCTION

The interest in renewable energy sources is increasing day after day parallel with the world energy demand. Since, solar energy is common nearly all around the world; it is one of the most promising renewable energy sources in the world. The world installed solar energy capacity was 22928.9 MW in 2009, and it is 46.9 % higher than previous year [1], [2]. Since the unit cost of energy generated from these sources is more expensive than traditional sources, energy efficiency has been in the focus of attention of researchers. Today, efficiencies of the commercial available photovoltaic (PV) modules are between 12 % and 19 %. The performance of the PV module is related with various factors such as temperature, exposure to sunlight, properties of sunlight, dirt, dust and etc. [3]. PV modules generate a specific power for a constant temperature and irradiation level. The variations in irradiation and temperature levels change the obtainable maximum power (MP) level. So, level of load power should be arranged according to the PV panel power versus voltage (P-V) curve to provide maximum benefit from investment. This can be realized through a maximum power point tracking (MPPT) algorithm [4], [5].

Since, variations in energy supply and load power demand match during a day, PV supplied electrical power is suitable for ventilation and air conditioning applications [6]. On the other hand, PV can be used for both cooling and heating of the buildings. Namely, standard roof tiles can be many degrees warmer than the ambient of outside air. A positive pressure mechanical ventilation system can be designed both for ventilating and preheating the house via a small fan. However, an auxiliary electric source requirement is disadvantage of this system. PV module can be used to supply the fan to overcome this drawback [7].

Unlike most of the loads used in the daily life, a PV panel produces DC voltage which has some disadvantages in use. These are the mechanical effects of a brush and the collector such as electrical arc, lower efficiency of the DC motors, and higher cost of the DC system equipment such as fuse, chiller, fan etc. So, PV power should be converted to AC by static inverters. Additionally, almost 70 % of the whole electric energy generated is used by the electric motors in industrialized countries. Furthermore, over than 60 % of whole electric energy transformed to mechanical energy is used up by induction motor driven pumps and fans. Therefore, energy saving and efficiency are important in these kind of applications [8], [9]. Nevertheless, flow and pressure of these systems are often regulated by mechanical devices, such as throttle valves and similar. The mechanical control decreases the efficiency and increases the pressure in pipes and valves as well as increasing electrical losses. Despite the fact that, the most extended method of electrical control is still based only on the soft starting without any speed control after the starting, these disadvantages can be removed by controlling the motor speed [9], [10].

Different speed control methods such as scalar control, vector control, direct torque control and etc. have already been proposed for induction motors [11], [12]. The scalar control method called as V/f control is very common in both open and closed loop controlled industrial applications. In these applications, inverter switching frequency usually varies with speed of drives and the associated error bands, and also it is quite low as compared to the sampling frequency of system. But the variable switching frequency makes very complicate designing of inverter output filter

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[13].

PV supplied motor drive applications have been proposed in past studies. In most of these studies, MPPT process is carried out by additional DC/DC converter [14], [15]. Since the DC/DC and DC/AC power conversion schemes are used, these systems are called two-stage inverters. The DC/DC converter performs MPPT and inverter converts DC generated by PV to AC. While using two-stage inverter simplifies the control, it decreases the total efficiency of the system and increases the cost. PV systems' cost can be minimized by decreasing the number of power conversion stages and the number of components involved in each stage. In these systems DC/AC conversion and MPPT processes are performed by same converters, meanwhile this causes an increase in complexity. Furthermore single-stage inverters are 4 %–10 % more efficient than the two stage configurations [16].

In this study, a DSP based variable speed drive for PV supplied induction motor is proposed to generate the mechanical energy for ventilation, refrigeration and aspiration applications. Operation point of the induction motor is determined by the MPPT algorithm according to PV array parameters to obtain maximum efficiency. Combination of variable stepped incremental conductance (IC) method and constant voltage (CV) method is used as MPPT algorithm. In addition, the switching frequency is kept constant for all frequency values of output voltage, so same effects obtained for all operation region and current waveform distortions are prevented at low frequencies. Experimental results showed that the proposed MPPT algorithm has fast starting response of the CV method, and stability and accuracy of the IC method. Also variable step operation capability of IC method decreases the oscillations at steady state. Since the system is designed as single stage inverter, the total system efficiency of the driver has been increased and measured as 94.7 %.

II. V/F CONTROL OF INDUCTION MOTOR

Three phase squirrel cage induction motors are low cost, high efficient, robust, reliable and low maintenance required motors and they are widely used in industrial application with these advantages [11], [12], [17]. Nevertheless, speed variation with load level and lack of variable speed operation capability are the main drawbacks of these motors [12]. The state equations which are expressed as non-linear differential equations in the synchronous reference frame are given below for a symmetrical squirrel cage induction motor [18]

$$\dot{X} = F\left(X, U\right), \tag{1}$$

where:

$$\frac{d\mu}{dt} = -\frac{f}{J}\mu_r + \frac{3}{2}p\frac{M}{J}i_{md}i_{qs} - \frac{3}{2}p\frac{M}{J}i_{mq}i_{ds} - \frac{1}{J}T_L, \tag{2}$$

$$\frac{di_{md}}{dt} = -\frac{r_r}{L_r}i_{md} + \left(\mu_s - \mu_r\right)i_{mq} + \frac{r_r M}{L_r^2}i_{ds}, \tag{3}$$

$$\frac{di_{mq}}{dt} = -\frac{r_r}{L_r}i_{mq} - \left(\mu_s - \mu_r\right)i_{md} + \frac{r_r M}{L_r^2}i_{qs}, \tag{4}$$

where:

$$\dot{X} = \begin{bmatrix} \mu_r & i_{md} & i_{mq} \end{bmatrix}^T, \tag{5}$$

$$U = \begin{bmatrix} i_{ds} & i_{qs} & \mu_s \end{bmatrix}^T. \tag{6}$$

where μ_r and μ_s are rotor and synchronous speeds respectively; p is the pole number of the induction motor; M is mutual inductance and J is moment of inertia; i_{md} and i_{mq} are rotor d–q-magnetizing currents; T_L is load torque; r_r is equivalent rotor resistance; L_r is rotor inductance. When a linear optimal control is applied, a linearization of the above motor model is expressed in state space as a determinist linear system:

$$\dot{X} = AX + BU, \tag{7}$$

$$A = \left.\frac{\partial F}{\partial X}\right|_{X_d}, \tag{8}$$

$$B = \left.\frac{\partial F}{\partial X}\right|_{U_d}. \tag{9}$$

where X_d and U_d are the desired state and control variables. If the rotor magnetizing current i_{mq} is properly tuned to zero, the field orientation with the rotor flux may be ideal. Then, (10)–(12) are obtained under steady state [18]:

$$i_{md}^d = \frac{M}{L_r}i_{ds}^d, \tag{10}$$

$$\mu_s^d = \frac{r_r M}{L_r^2}\frac{i_{qs}^d}{i_{md}^d}, \tag{11}$$

$$T^d = \frac{3}{2}pMi_{dm}^d i_{qs}^d. \tag{12}$$

If the stator power loses are neglected, torque (T) by using stator supply voltage and flux for steady state are given below [17]:

$$T = \frac{3}{2}.\frac{P}{2}.\left|\frac{\overline{v_s}}{\text{®} f}\right|^2 . \frac{R_r/S}{\left(R_r + R_r/S\right)^2 + \left(X_{ls} + X_{lr}\right)^2}, \tag{13}$$

$$\left|\bar{\text{ª}}_S\right| \approx \frac{1}{2\text{®}}.\frac{\left|\overline{v_S}\right|}{f}. \tag{14}$$

It is seen that, the torque and the magnitude of the stator flux of the induction motor are directly related with the ratio between the stator voltage and frequency (V/f). In industrial applications, induction motors are used with different type of loads such as constant torque, constant power and variable torque. Speed, power and torque variations of these loads are given in Fig. 1.

The V/f control is a low cost and simple method to control the speed of the induction motor in wide speed ranges. In this method, torque response is related with the electrical time constant of the motor and tuning requirement of the control parameters is removed. It can be said that, V/f control is effective solution for simple variable speed applications like fans, pumps [15], [16], [19].

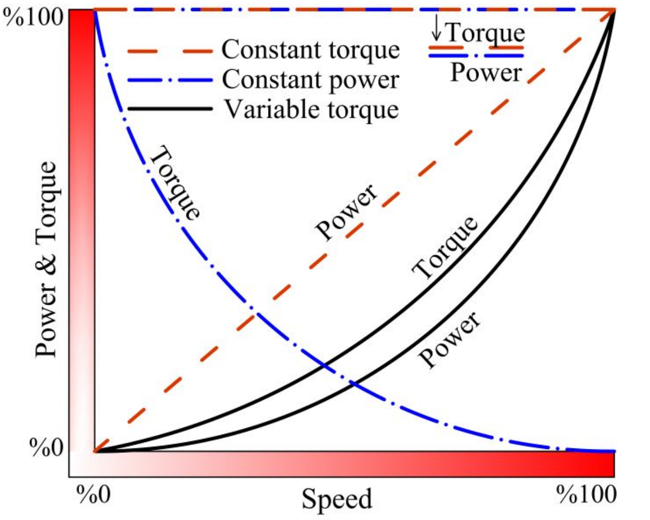


Fig. 1. Types of the load.

The centrifugal fans and pumps are variable torque loads and they have great energy saving potential. The Affinity Laws describes the relationship between the speed and other fan or pump variables. It also governs these loads. According to law 1, change in flow proportional to change in speed; the change in head (pressure) proportional to the change in speed squared; the change in power proportional to the change in speed cubed as given in (15)–(17):

$$\frac{Q1}{Q2} = \frac{N1}{N2}, \tag{15}$$

$$\frac{H1}{H2} = \left(\frac{N1}{N2}\right)^2, \tag{16}$$

$$\frac{P1}{P2} = \left(\frac{N1}{N2}\right)^3. \tag{17}$$

where Q is volumetric flow, H is head (pressure), P is power and N is speed (rpm). According to (15)–(17), if the flow is controlled by reducing the speed of the fan or pump, a relatively small speed change will result in a large reduction in power consumption. The power consumption of a fan or pump system is related with the flow control method as given in Fig. 2. By replacing dampers, which are used to regulate the flow of fans, with variable frequency drive (VFD) for induction motor, more efficient operation can be obtained for same flow. A novel control algorithm for VFDs reduces the input power of an induction motor used to drive a variable torque load, as fan or pump. In addition, noise and vibration of the fan are also decreased with speed.

In V/f control, value of the V/f ratio affects the system performance and related with type of the system. The regulation law for the pump and fan units can be written as in (18)

$$\frac{V}{f^{1+\frac{k}{2}}} = constant, \tag{18}$$

where k is the factor depending on the kind of mechanical characteristic of the pump, and generally determined as k=2…4. Big values of k correspond to characteristics of the pump with higher static pressure component.

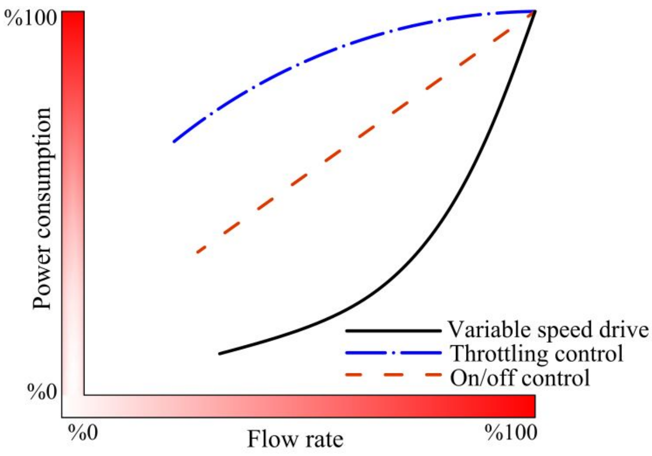


Fig. 2. Power consumptions of the systems according to control techniques.

III. NPC INVERTERS

Multi-level inverters that introduced by Nabae have some advantages such as reduced filter requirement at the same switching frequency; reduced voltage and/or current harmonics, and reduced electromagnetic interference (EMI) [7]. Recent progress in microprocessor technologies make easier of controlling multi-level inverters. They have been started to be used commonly especially in high power applications. However, these inverters are required more components such as power semiconductor switches, capacitors, gate drivers etc. and their circuit structures are more complex [3], [5], [6], [8]. In addition, multi-level inverters have an advantage of achieving high voltage and high power levels.

There are different types of multi-level inverters such as the neutral point clamped (NPC) inverter, the cascaded H-bridge (CHB) inverter and the flying capacitor (FC) inverter [3], [8]. These topologies have different advantages and disadvantages such as difficulty of balancing of two capacitors' voltages in NPC inverter, bigger capacitor requirement and increased size of FC topology, isolated voltage requirement of CHB. In addition, isolated DC voltage source requirements can be removed by using NPC inverters. In last decade, switch modules for a leg of the NPC inverter have become commercial available and this makes easier design and implementation of NPC inverter. The general diagram of the NPC inverter is shown in Fig. 3.

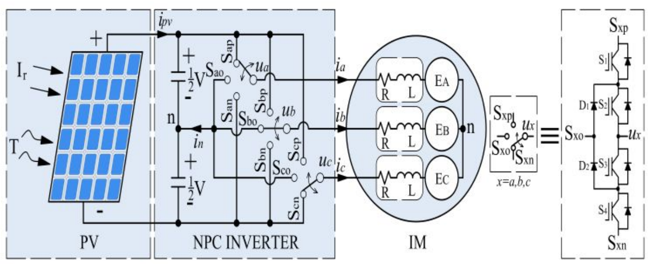


Fig. 3. Equivalent circuit of PV supplied NPC IM driver.

The switches operate with only half of the DC bus voltage for all positions (P, O and N) in NPC inverter [10].

Variation of the output voltage value of inverter one leg with respect to switch position is given in Table I.

TABLE I. OUTPUT VOLTAGES OF INVERTER ONE LEG ACCORDING TO SWITCHES STATUS.

Switch Position	S1	S2	S3	S4	Output voltage
P (Positive)	1	1	0	0	1/2V
O (Medium)	0	1	1	0	0
N (Negative)	0	0	1	1	-1/2V

IV. MPPT METHODS

There is a nonlinear relationship between PV output power level and a variety of factors such as temperature, solar irradiation, properties of sunlight, dirt, dust and etc. These factors affect the PV cell performance [3], [20]. The equivalent circuit of the PV is shown in Fig. 4.

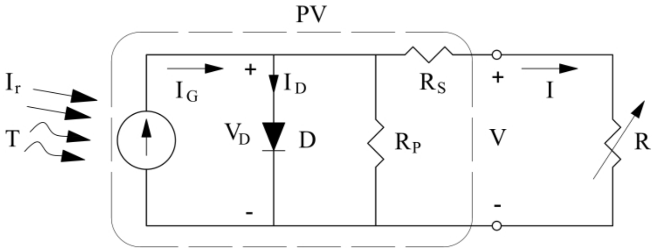


Fig. 4. The equivalent circuit of PV.

According to this equivalent model, (19)–(22) can be written for output voltage of PV, V_c, by neglecting I_d and I_p currents [21]:

$$V(I,T,I_r)=\frac{V_{oc}(T,I_r).\ln\left(2-\left(\frac{I}{I_{sc}(T,I_r)}\right)^{N(T,I_r)}\right)-\left(R_S(T,I_r).\left(I-I_{sc}(T,I_r)\right)\right)}{\left(1+\frac{R_S(T,I_r).I_{sc}(T,I_r)}{V_{oc}(T,I_r)}\right)\times\ln(2)}, \quad (19)$$

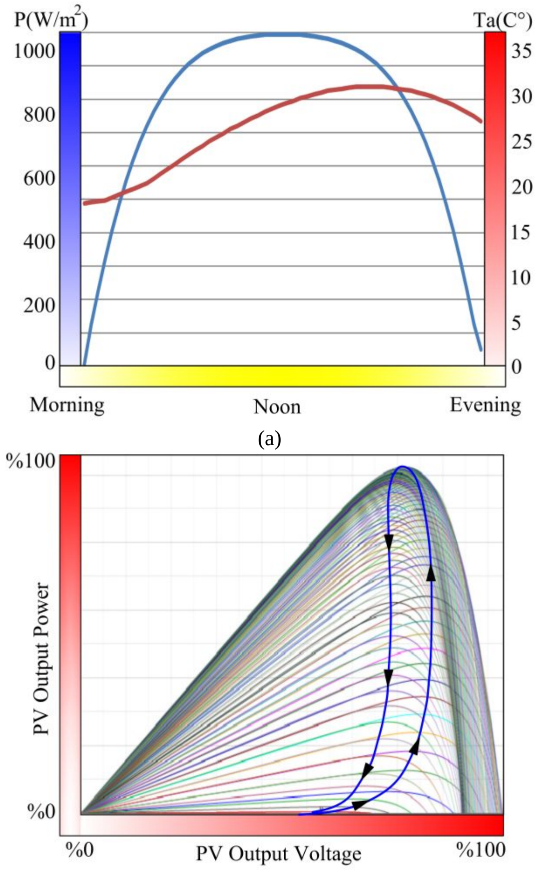
$$R_s(T,I_r)=\frac{V_{oc}(T,I_r)-V_{mp}(T,I_r)}{I_{mp}(T,I_r)}, \quad (20)$$

$$N(T,I_r)=\frac{ln\left(2-2^{\propto(T,I_r)}\right)}{ln\left(\frac{I_{mp}(T,I_r)}{I_{sc}(T,I_r)}\right)}, \quad (21)$$

$$\propto(T,I_r)=\frac{V_{mp}(T,I_r).\left(1+\frac{R_s(T,I_r).I_{sc}(T,I_r)}{V_{oc}(T,I_r)}\right)+R_s(T,I_r).\left(I_{mp}(T,I_r)-I_{sc}(T,I_r)\right)}{V_{oc}(T,I_r)}. \quad (22)$$

Exporting maximum obtainable energy to the load and obtaining maximum efficiency can only be provided via MPPT methods. The MPPT method is used to control power converter operation point according to the load and the PV system properties. Daily variation of irradiation level and temperature measured from 2-axis plane; obtained P-V curves and MP curve which is composed of maximum power points (MPPs) of these P-V curves are seen in Fig. 5. The power converter should track this MP curve which varies during the daytime to obtain maximum efficiency [22].

MPPT methods can be categorized as online (direct or true seeking) and offline (indirect or quasi seeking) methods [23], [24]. The main factor in this classification relates to the true MPPT operation. The offline methods use PV current, voltage, irradiation, temperature etc. values and some mathematical equations or pre-prepared tables for evaluating the power converter control signal to determine the appropriate operating point of the PV system. Constant current (CC), Constant Voltage (CV), Pilot Cell (PC) and Look-up Table (LUT) are examples of the offline methods. Although, offline methods have fast response time, they are affected from environmental conditions and aging of the PV modules. Furthermore, they find approximate MPP and they are effective for only specified panel.



(a)

Fig. 5. Irradiation and ambient temperature levels (a); MPPT curve (b).

On the other hand, online methods check the PV system if it is operating at its MPP or not all the time. The Perturb & Observe (P&O) method and the IC method are the most common online methods. The IC method checks the variation of output power according to PV voltage (dP/dV) and defines the point of dP/dV = 0 as MPP point. If dP/dV < 0, this means operating point is on left side of the P-V curve, and if dP/dV > 0, operating point is on right side of the P-V curve, and next control signal of the power converter is determined according to this value. Unlike offline methods, online methods find the real MPP; thus environmental effects and panel dependency are removed.

V. PROPOSED SYSTEM

In this study, three phase variable speed drive for PV supplied induction motor actuated ventilation, refrigeration and aspiration applications is proposed. The principle scheme of the proposed system is depicted in Fig. 6. MAGNA-POWER TDS, III, 600-8 Photovoltaic Power Profile Emulator (PPPE) which can operate as PV modules is used as DC voltage source. As seen from Fig. 7, the PPPE interface program is used to define the commercial available PV module SHARP NA-901WP by using I_{mp}, V_{mp}, V_{oc}, I_{sc}, T_n, T_{op}, I_{rn}, I_{rop}, temperature and irradiation coefficients values which are given in datasheet. The electrical characteristics of a module at 25 °C, 8 serial connected PV modules at 25 °C and 8 serial connected PV modules at 39 °C are given in Table II. The total power of the PV system is 656.12 W.

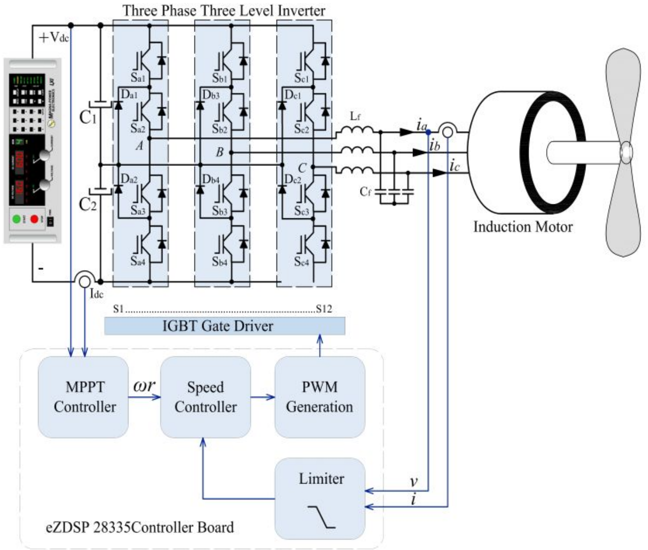


Fig. 6. Proposed system.

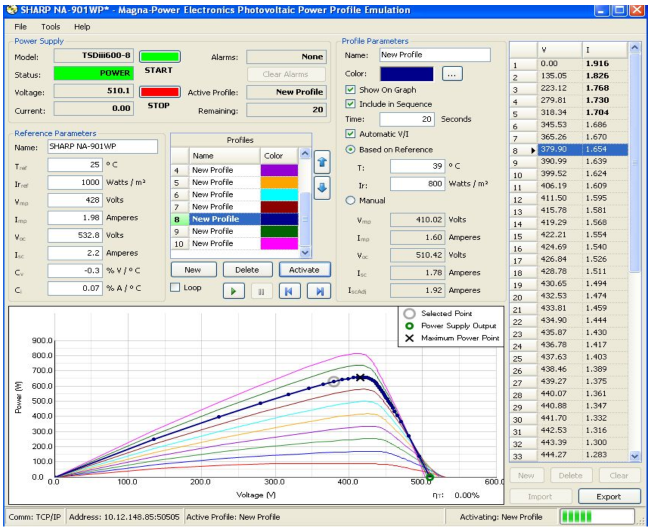


Fig. 7. Interface program of the PPPE.

TABLE II. THE ELECTRICAL CHARACTERISTICS OF THE PV MODULE.

Number of PV	T (C)	I_{rref} (W/m²)	V_{mp} (V)	I_{mp} (A)	V_{oc} (V)	I_{sc} (A)	P (W)
1	25	1000	53.5	1.98	66.6	2.20	105.9
8	25	1000	428	1.98	532.8	2.20	847.4
8	39	800	410.08	1.6	510.42	1.78	656.1

In this study, combination of IC and CV method is used as MPPT algorithm. This algorithm determines the speed reference according to PV operation point to obtain maximum energy conversion efficiency. The V/f control method which is commonly used in variable speed induction motor applications for both open and closed-loop controller is used as speed controller. In this study, V/f regulation law, given in (18) is used and *k* is determined as 2. Since speed response accuracy is not main concern, generally open-loop speed control is used in heating, ventilation and air conditioning (HVAC), fan or blower applications. In this case, slip of the motor neglected and actual speed of the motor is found by assumption that the motor will roughly follow its synchronous speed.

Also, in PV supplied HVAC applications, desired motor speed is determined by MPPT algorithm to obtain MP that the PV modules can generate. In other words, in the PV supplied HVAC applications main concern is tracking the MPP of the PV system not speed reference. So, an open-loop speed controller is used in this application. The V/f speed controller determines the voltage and frequency values for PWM generator according to the speed reference.

In Fig. 8, the flowchart of the proposed MPPT algorithm is depicted. Initially, CV method which is one of the off-line methods is used to achieve a faster start up time. When the PV voltage reduces to MPP voltage (0.80 of V_{OC}), a variable stepped IC method is operated. Consequently, the fast start up response of the CV method with reduced oscillation and fast tracking speed of IC method are integrated by the proposed MPPT algorithm. The step size of the IC method is changed depending on absolute value of dP/dV to improve the performance of the proposed method which is controlled via eZDSP 28335 controller board.

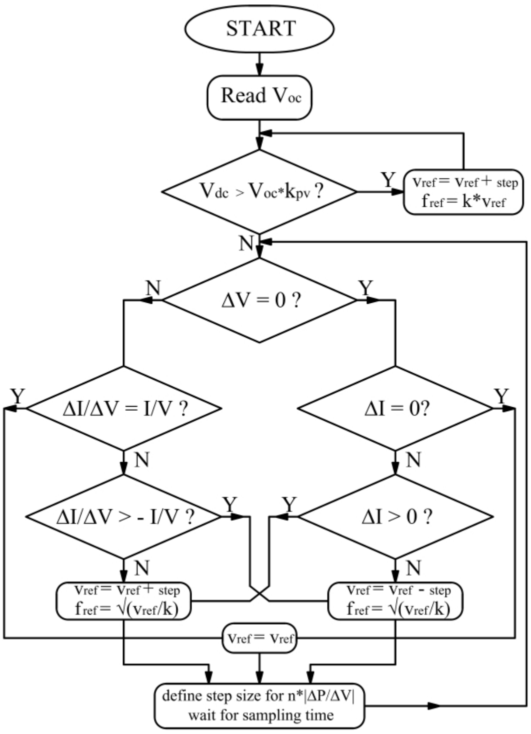


Fig. 8. Flowchart of the proposed MPPT algorithm.

VI. EXPERIMENTAL RESULTS

The experimental setup of the proposed system is shown in Fig. 9. The test rig of system covers Magna Power PPPE, eZDSP28335 controller board, voltage source inverter and backward curved centrifugal fan. The parameters of the induction motor used to actuate the fan are given in Table III. The PPPE is programmed to emulate 8 series connected SHARP NA-901WP PV modules. Also the system was tested with different irradiation temperature levels.

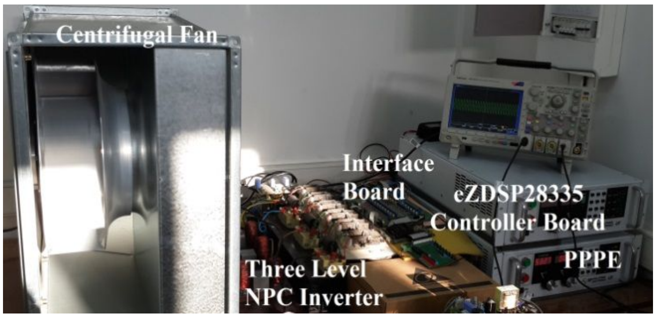


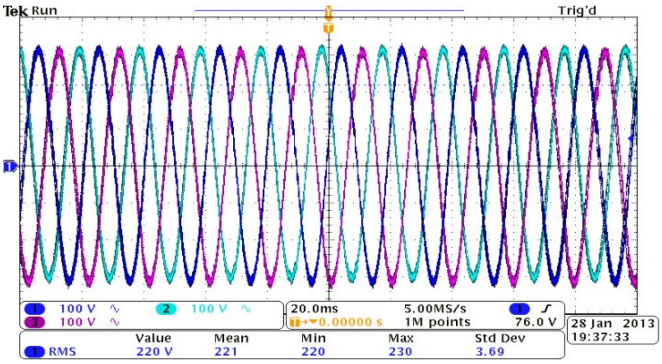
Fig. 9. Experimental setup.

The line voltages and currents of the induction motor are plotted in Fig. 10. Since, the switching frequency of the inverter is kept constant, the line voltages and currents are in sinusoidal waveform and their harmonic components are reduced even under low speed conditions.

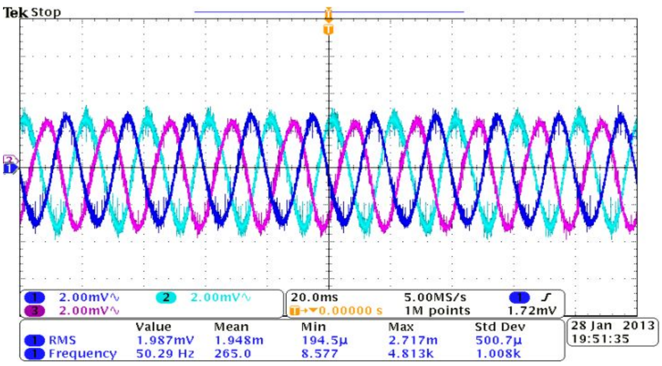
TABLE III. PARAMETERS OF INDUCTION MOTOR.

Parameter	**P (W)**	**U_{LL} (V)**	**n (rpm)**	**f (Hz)**
Value	550	220	1415	50

The startup of the induction motor is shown in Fig. 11. Initially, the reference speed is defined by CV method and the V/f speed controller provides soft starting and the inrush current of the motor is limited. After start-up, the IC method determines the reference speed according to operation point of the PV system. The speed controller determines the required voltage level and the frequency according to reference speed, and then controls the PWM generator. The proposed system tracks the MPP of the PV system and it has fast response. In addition efficiency of the drive system is measured as 94.7 %.



(a)



(b)

Fig. 10. Three phase line voltages of induction motor (a); Three phase motor currents (b).

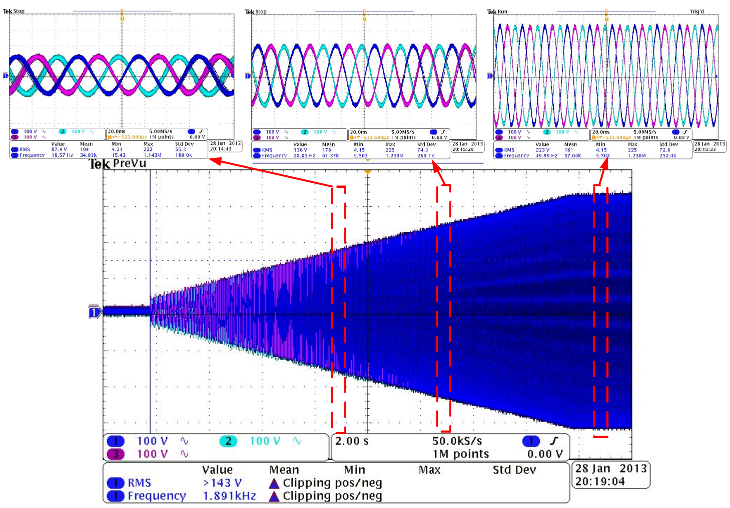


Fig. 11. Variable speed operation of proposed system.

VII. CONCLUSIONS

In this study, a three phase induction motor driver supplied from PV is proposed to generate the mechanical energy for applications such as ventilation, refrigeration and aspiration. The proposed drive is capable of online MPPT of the PV panel without any additional converter. Combination of CV and variable stepped IC method is used as the MPPT algorithm. The step size of the IC method is varied according to absolute value of dP/dV. So fast starting response of the constant voltage, and stability and accuracy of the IC method are integrated. The MPPT algorithm generates speed reference and V/f speed controller controls the inverter output voltage and frequency. Since, the switching frequency is kept constant for all operation conditions; the quality of the output voltage waveform is improved especially at low speed. Both variable speed drive and MPPT functions are carried out by the three-level voltage source inverter. The efficiency of the proposed drive is measured as 94.7 %. Since single-stage operation is obtained, efficiency of the inverter is improved.

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