ISSN 2229-5518

A Study on the Selection and Design of Ventilation Fans Powered by Photovoltaic System

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Abstract—This paper presents ventilation fan driven by induction motor powered by photovoltaic system. The proposed system is devoted for using the PV as an energy source for electrical motors. The investigations, shows that the performance of the fan is stable when it operates at its designed operating point. However, the deviation from such point, especially with high velocities, leads to instable operation and noise production. Consequently, the fan performance is affected and this leads to inefficient operation. The proposed system consists of PV system as an energy source, battery storage system for feeding electrical motors in addition to cooling fan load.

Index Terms— Ventilation Fans, Electrical Motors, Photovoltaic (PV) Systems.

1. Introduction

Recently 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 sun-light, properties of sun-light, 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. 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].

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 [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 multilevel inverters.

The DC/DC converter performs MPPT and inverter converts DC generated by PV to AC. While using multilevel 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 paper, a variable speed drive for PV supplied induction motor is used to generate the mechanical energy for ventilation, refrigeration and aspiration applications. Operating point of the induction motor is determined by the MPPT algorithm according to PV array parameters to obtain maximum efficiency.

2. The PVDC Power Supply

Figure 1 shows the PVDC, it consists of a PV module BP485 [15] type, MPPT control, high frequency transformer (HFT) and a battery charger system. The dc source of the main inverter unit is generated from the PV module as shown in figure 1. It consists of PV module which is the main unregulated dc source, dc-dc converter accompany with maximum power point tracking control required for catching the maximum available power from the PV module. To catch the maximum power from the PV module, the conventional perturb and observe (P&O) control method [16] – [17] has been adopted in this work. 2.3 kW PV module composed of string of about 30 units of BP485 connected in series has been chosen with nominal values for single unit is given in table I.

Figure (2) shows the (HFT) transform [8] which is a step down with 2/1 turn ratios which are suitable for this specific application and MLI. The main task of this HFT is to generate the dc source of the auxiliary inverter units from the main transformer unit dc source. By this method, an inherit voltage balancing between the main and auxiliary inverter units is obtained which is very important. This balancing will result in simplifying the control system.

Figure 2 shows the MATLAB/SIMULINK photovoltaic performances, current, voltage and power.

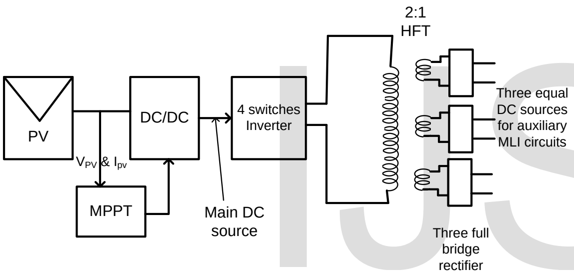

Figure 1 the PVDC power supply

Table I. PV module BP485 specifications

Rated Power (P_{max})	85W
Voltage at P_{max} (V_{mp})	17.4V
Current at P_{max} (I_{mp})	4.9A
Short circuit current (I_{sc})	5.48A
Open circuit voltage (V_{oc})	22V

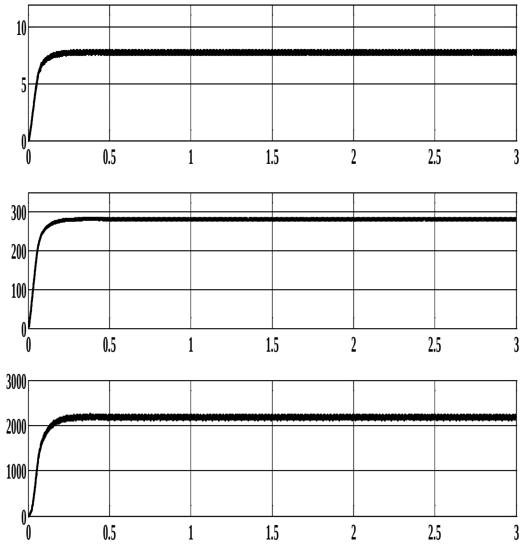

Figure 2 PV current, voltage and power

3. The Hybrid MLI Power Circuit

Figure 3 shows the general three phase configuration of the hybrid multilevel inverter topology with lower power component elements for 4 levels [7]. This inverter is composed of single unit of main stage, 3 units of auxiliary stages, '12' switches and '4' isolated dc voltage sources. The auxiliary stages are connected in series with the main stage. The main stage is a conventional two-level three-phase six switch inverter. Each auxiliary cell consists of two switches and single dc input voltage. The basic auxiliary cell of the proposed inverter includes two switches are always operating in a complementary mode and single input dc voltage to generate two levels output voltage waveform 0 and its input dc source. Therefore the auxiliary cell gives $V_o = 0$, when the switch S_1 is ON and it gives its input voltage when S_1 is OFF. To avoid short circuit condition, it should be kept in mind that both of the switches (S_1 and S_2) never be switched on at a time.

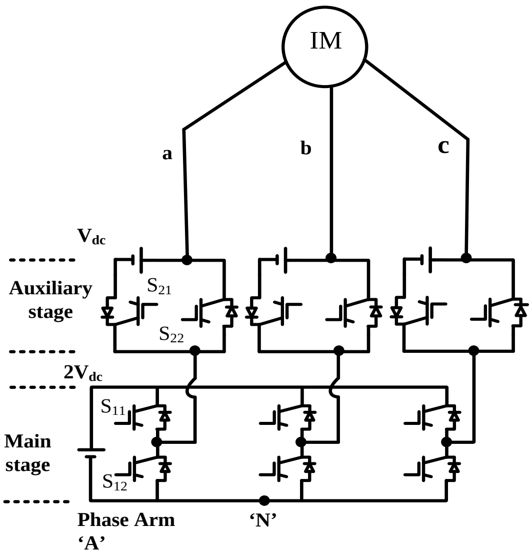

Figure 3 Four level line-to-line hybrid MLI

ISSN 2229-5518
Using three auxiliary cells with the main cell results in generating 4 levels output pole voltage and 7 levels for the line-to-line-voltage. It can be noted that the main cell dc source is 2 V_{dc} and the auxiliary cell dc source is V_{dc}, respectively, therefore V_{aN} has 4 states (0, V_{dc}, $2V_{dc}$, $3V_{dc}$). The load line-to-line voltages can be calculated as follows

$$v_{ab} = v_{aN} - v_{bN} \quad (1)$$

Therefore the load line-to-line voltages can have ($3V_{dc}$, $2V_{dc}$, $1V_{dc}$, 0, $-1V_{dc}$, $-2V_{dc}$, $-3V_{dc}$). And the load phase voltages V_{an}, V_{bn} and V_{cn} can be calculated as in (2)

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} v_{aN} \\ v_{bN} \\ v_{cN} \end{bmatrix} \quad (2)$$

Table II summarizes the output voltage levels for 4 levels using only single auxiliary cell with the main cell. The space vector as described in [7] will be employed which is the convenient modulation control to DTC.

TABLE II
Switching States of phase V_{aN}

MLI Pole voltage	Switches of arm 'A'					
v_{aN}	Sa11	Sa12	Sa21	Sa22	Sa31	Sa32
$0V_{dc}$	0	1	0	1	0	1
$1V_{dc}$	0	1	0	1	1	0
$2V_{dc}$	0	1	1	0	0	1
$3V_{dc}$	0	1	1	0	1	0

4. V/F Control of Induction Motor

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. 4. 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].

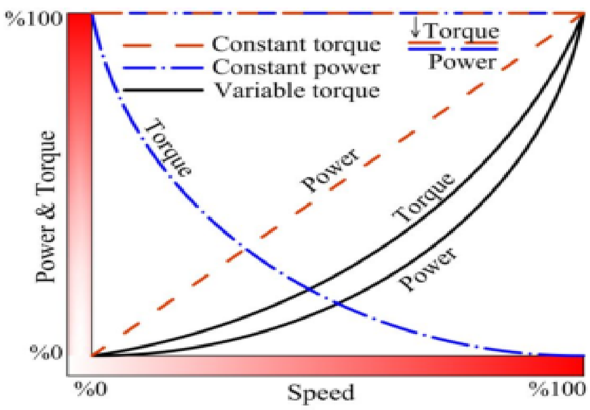

Fig. 4 Types of the load

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. The 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 (3)–(5):

$$Q_1/Q_2 = N_1/N_2 \quad (3)$$

$$H_1/H_2 = (N_1/N_2)^2 \quad (4)$$

$$P_1/P_2 = (N_1/N_2)^3 \quad (5)$$

where Q is volumetric flow, H is head (pressure), P is power and N is speed (rpm). According to (3)–(5), 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. 5.

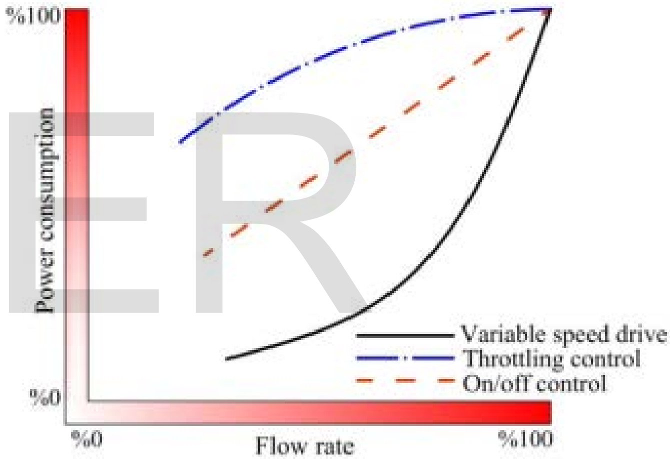

Fig. 5. Power consumptions of the systems according to control techniques.

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.

5. The Complete System

In this paper, three phase variable speed drive for PV Supplied induction motor actuated ventilation fans, refrigeration and aspiration applications is applied. The principle scheme of the used system is depicted in Fig. 6. MAGNA-POWER BP485 Photovoltaic Power Profile Emulator (PPPE) which can operate as PV module is used as DC voltage source.

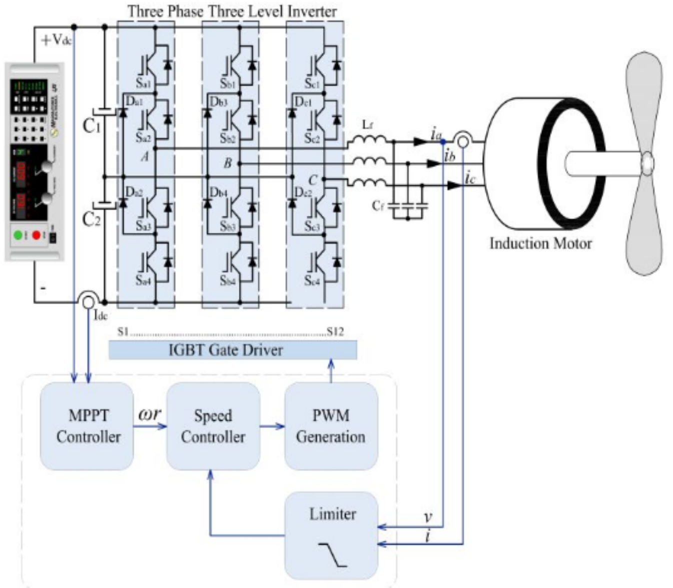

Fig. 6 The complete system

6. Determination of Switching Times of Inverter Switches

Generally, every switching state creates specific three-phase voltages v_{aN}, v_{bN} and v_{cN} with respect to the neutral of the dc bus voltage, which can be defined by the equation (6):

$$v_{aN} = k_a V_{dc}$$
$$v_{bN} = k_b V_{dc} \qquad (6)$$
$$v_{cN} = k_c V_{dc}$$

Where k_a, k_b and $k_c \in [0, 1, 2, 3, \ldots, +(2^k - 1)]$ and switching states of inverter line-to-line voltages v_{ab}, v_{bc} and v_{ca} can be calculated by equation (7).

$$v_{ab} = (k_a - k_b)\, V_{dc} = k_{ab} V_{dc}$$
$$v_{bc} = (k_b - k_c)\, V_{dc} = k_{bc} V_{dc} \qquad (7)$$
$$v_{ca} = (k_c - k_a)\, V_{dc} = k_{ca} V_{dc}$$

Equation (7) can be expressed in a matrix form as follows

$$V_{l-l(k_{ab}, k_{bc}, k_{ca})} = [v_{ab} \quad v_{bc} \quad v_{ca}]^T = \qquad (8)$$
$$= V_{dc} \quad [(k_a - k_b) \quad (k_b - k_c) \quad (k_c - k_a)]^T$$

Where k_{bc}, k_{bc} and $k_{ca} \in [-(2^k - 1), \ldots, -3, -2, -1, 0, 1, 2, 3, \ldots\ldots, (2^k - 1)]$. The vector form of the line-to-line reference voltage vector in steady state is the inverter line-to-line reference voltage vector demanded by the control algorithm in equation (5) is ampled at the low rate of switching frequency f_s. The sampling interval $T_s = \frac{1}{f_s}$ extends over three subcycles t_1, t_2 and t_3. V^*_{REF} is an arbitrary complex quantity and it cannot be generated by the inverter. Therefore it is approximated by the available voltage space vectors given by equation (8), where during each modulation subcycle a switching sequence is generated. Consequently the inverter pole voltages v_{an}, v_{bn} and v_{cn} can be evaluated as well as switches states. Looking to equation (6), it can be noted that k_a has a direct relationship with the inverter pole voltage and therefore the lookup table II is used to generate switches pulses for this MLI. The detailed analyses is provided in [7].

7. Simulation Results

In this paper for case study, 3HP, 220V, 50 Hz, 3-phase induction motor used for drive fan load. Induction motor parameters are given in table III.

The required speed is 1500 rpm and fan load torque is 12 N.m to which drive has to track. V/F control of induction motor is simulated for the sample time of 2e-6 second. Simulation time is 5 second. A step change with two case studies has been done in speed and in torque individually.
The simulation results are done at rotor speed 1500 rpm and load torque changed from no load to full load torque at time instant t= 3 sec. In this configuration, main objective is to design controller for hybrid multilevel inverter fed IM drive ventilation fan powered by PV system. Required signal for this controller is obtained from the speed controller.

Table III induction motor parameters

Stator resistance (Ohms)	0.435
Stator inductance (Henry)	2.0e-3
Rotor resistance (Ohms)	0.816
Rotor inductance (Henry)	2.0e-3
Mutual inductance (Henry)	69.31e-3
Inertia	0.089
Friction Factor	0
Pairs of poles	2

Figure 7 shows the d-q stator flux in the stationary reference frame. Figures 8 and 9 show the IM speed and torque profiles due to this specific loading condition. They give the conventional and well-know profiles, the torque tracks its reference with a very good performance. On the other hand, the speed builds up with a good performance.

Figure 10 and 11 show the hybrid MLI performances, they show the line-to-line voltages and the IM currents, respectively. The dc voltages of isolated batteries for the inverter have been chosen 150V and 300V, therefore their dc sum is 450 V. As mentioned before the load line-to-line voltages has ($3V_{dc}$, $2V_{dc}$, $1V_{dc}$, 0, $-1V_{dc}$, $-2V_{dc}$, $-3V_{dc}$). Figure 9 shows the motor currents which are very almost sinusoidal due to the high quality of the hybrid MLI output voltage and the natural low-pass load filter of the motor.

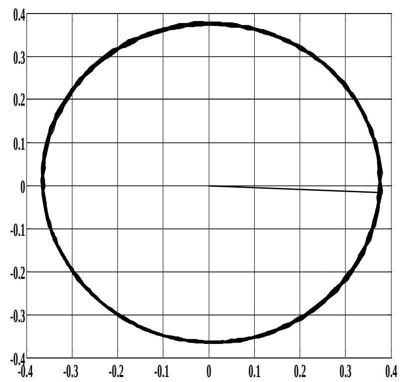

Figure 7 d-q plot Stator flux

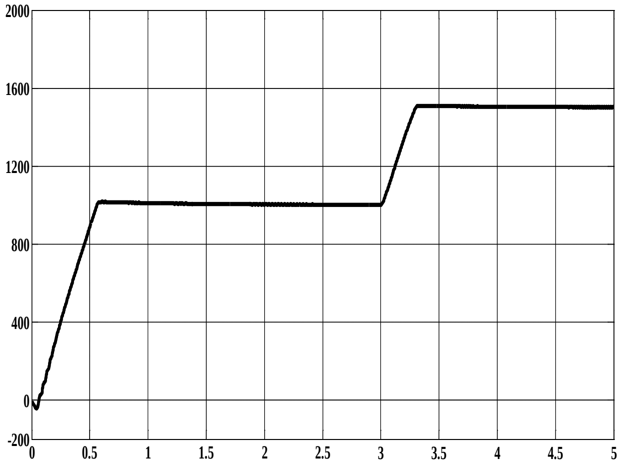

Figure 8 Motor speed

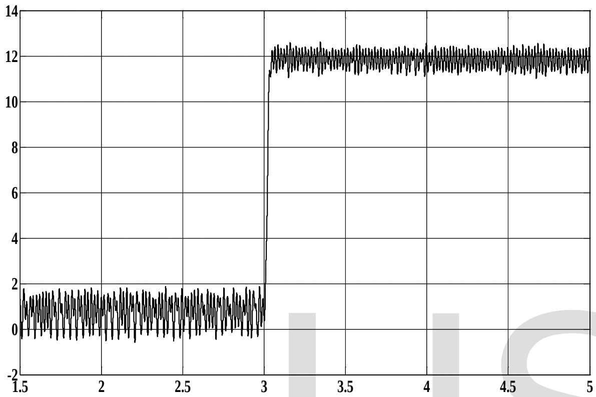

Figure 9 Motor Torque response

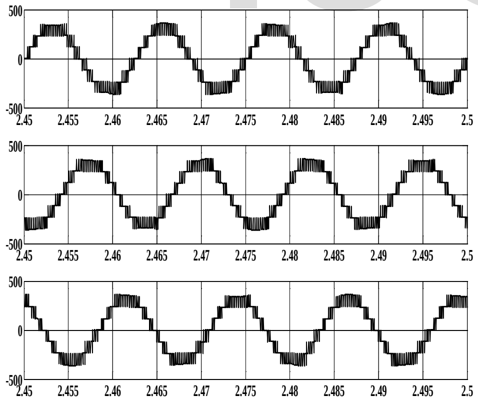

Figure 10 line-to-line inverter output voltages

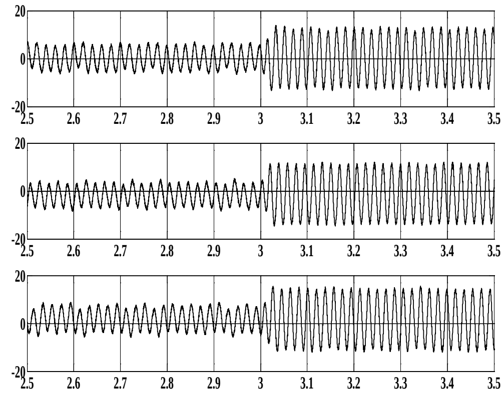

Figure 11. Stator currents

8. 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 drive is capable of online MPPT of the PV panel without any additional converter. 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 Multi-level voltage source inverter.

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