Novel control of standalone "Photovoltaic (PV) based Induction Motor Driven Water Pumping System" without battery

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Abstract: Water pumping system powered by PV without using battery bank is attracting by many scholars. Using of batteries can increase the overall system cost during the operation. A novel control algorithm must be incorporated to manage energy balance between load and generation since power produced from solar cells depends on solar irradiance. In order to lift the water from ground, a motor – pump set is used where power is fed by PV systems through proper converter. Generally induction motors are commonly using in water pumping systems. A direct torque control is applied on three phase induction motor in this paper. Three different configurations were discussed in this paper. In order to eliminate an extra converter for MPPT operation of the PV panels, the proposed method is forced the inverter to acts as a MPPT converter of the PV system. Various results are presented in this paper to validate the proposed method.

Keywords: PV system, water pumping, induction motor, DTC.

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1. Introduction

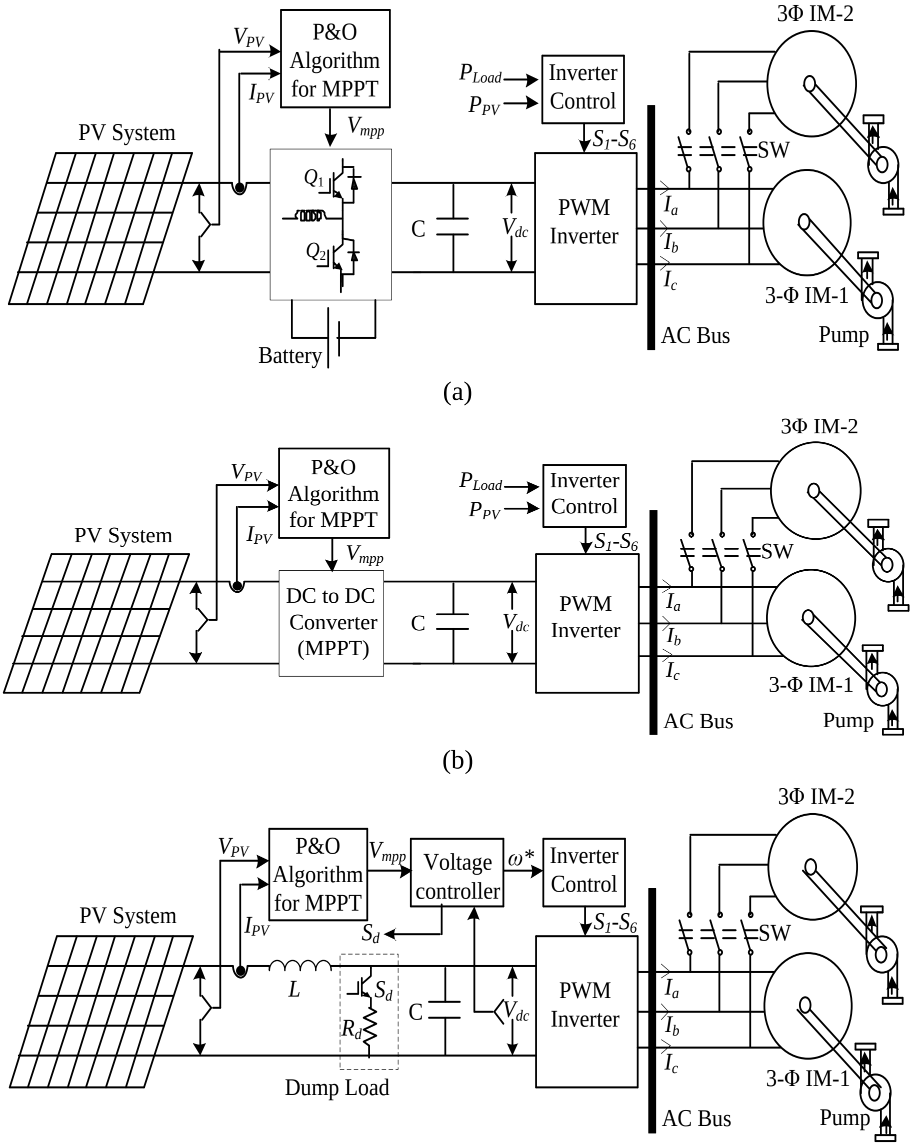
Water pumping systems are essential in society for drinking, agriculture, industrial, and personal usage. A pump is required to list the water from the underground. As a result, the pump must be powered by either an electric motor or a diesel generator. Diesel generators are typically environmentally dangerous since they exhaust carbon compounds into the atmosphere. However, power cannot be provided at all times and in all locations, especially in distant areas.. Under such circumstances, renewable energy sources can be a often solution to provide sufficient electricity to run motor as well as can be an eco-friendly to the nature. Photovoltaic (PV) panels can easily convert solar energy to electricity and also can be easily setup in many places. Further, among various motors the induction motor is very economical affordable by many formers. Hence, PV based water pumping system is developed in this paper.
The authors of [1] presented a PV-powered water pumping system with a dc motor operating the pump. However, among the many motors, the use of an induction motor (IM) for pumping applications is an appealing proposition due to the lack of a commutator and brushes, which allow dependable and maintenance-free operation [2-4]. Centrifugal pumps are the most often utilized kind of pump for PV-based pumping systems [1].

The maximum power point (MPP) on the power-voltage curve of a PV generator should be used.. As a result, the maximum power point tracking (MPPT) circuit is used to harvest the most power from the PV array [5-6]. The authors of suggest a water pumping system with battery storage and a dc-dc converter for MPPT in [5]. Although batteries give flexibility in operation and allow extra PV power to be stored, they raise the overall system cost by 10%-50% depending on the rating and type of batteries [7]. As a result, our goal is to create a PV-based pumping system that does not require batteries or a dc-dc converter (for MPPT).. Two methodologies are presented one is with battery storage {shown in Fig. 1(a)} and one is without storage {shown in Fig. 1(b) and (c)}. In case of without storage system, two control schemes are presented, one is based on power control {Fig. 1(b)} and another is based on voltage control {Fig. 1(c)}. In Fig. 1(c), inverter itself regulates the dc-link voltage at its reference value, hence no extra dc-dc converter required for MPPT. The schematic shown in Fig. 1(c) preferable over Fig. 1(a) and (b) for three reasons:

- System proposed in Fig. 1(c) do not require dc-dc converter for MPPT and inverter can be used for the same.
- System in Fig. 1(c) requires measure of dc-link voltage (V_{dc}), while in Fig. 1(a) and (b) requires measure of PV and load powers.
- System does not have any storage devices, so it is a cost effective system.

The MATLAB simulation results are presented to test the performance of proposed control scheme. Apart from simulation results, hardware-in-loop (HIL) results are presented in support of theory. The HIL is implemented with two units of real-time digital simulator (RTDS) manufactured by ‘OPAL-RT Technologies’. This has been carried out with an aim to develop a near realistic control scheme that can be used upfront by the industry.
MPPT stands for Maximum Power Point Tracker.

The use of solar PV cells is impeded by the fact that the power vs voltage curve in solar cells has a unique maximum power at a certain operating voltage (referred to as Vmpp). Figure 2(a) depicts the power vs. voltage characteristic curve. Power electronics interfaces will be able to deliver considerable benefits in solar panel processing power with quick response and autonomous control. Maximum power point trackers (MPPTs) are therefore used to continuously track the peak power and provide it to the load. MPPT is essentially a power electronic-based converter that regulates the dc-link voltage of PV equivalent to Vmpp, allowing the system to run at MPP [8-9]..



(c)

Fig. 1: PV based water pumping system, (a) with energy storage, (b) control based on power, (c) control based on voltage.

In case of power based control (Fig. 1(a) and (b)), the controller is based on comparison of PV power and load power (power at AC bus). The PV power may range from 0 to 100%. The maximum power generated by a PV system is determined by the dc-link voltage (Vmpp). As a result, in order to manage the dc-link voltage, the physical MPPT converter (i.e., dc-dc converter) is necessary. In the event of a battery storage system, a bidirectional converter manages the dc-link voltage and also serves as a solar MPPT. In the case of a voltage-based controller (Fig. 1(c)), the physical MPPT is not required because the inverter itself regulates the dc-link voltage corresponding to V_{mpp} which is generated by perturb and observe (P&O) algorithm. As a result, the inverter not only adjusts the AC bus voltage but also serves as an MPPT for PV. The P&O method is the most popular and widely used MPPT algorithm, as illustrated in Fig. 2 [10]. To determine the voltage at which the MPP is obtained, use the following equation [10]..

$$V_{mpp}(k)=V_{mpp}(k\text{-}1) + M\times\text{sign}(dp/dv) + V_{mpp}(k\text{-}1) \qquad (1)$$

where M is the steep voltage, k is the iteration, and dp/dv is the change in PV power as a function of PV voltage..

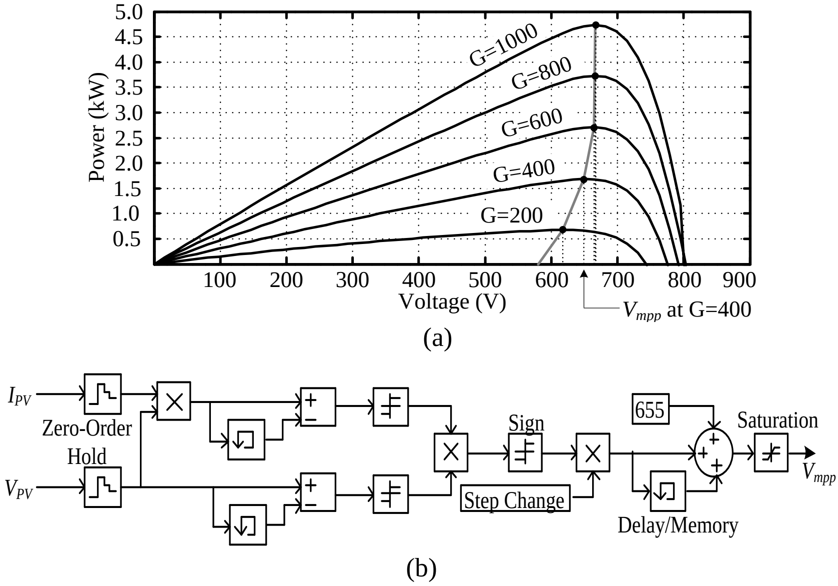


Fig. 2: (a) P-V curve, (b) P&O algorithm.

Regulation of Voltage at AC Bus

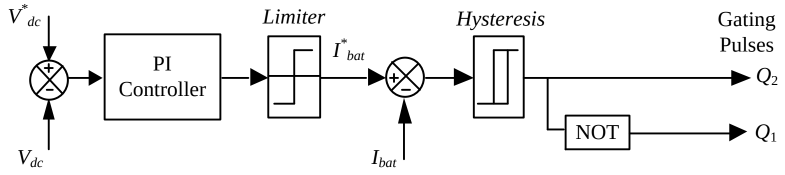
The authors presented a water pumping system based on IM drive scalar control in [11, 12]. The constraint of scalar control (v/f) is that voltage cannot rise over the rated value. For constant torque applications, frequency cannot be increased above the rated value due to this constraint. When applied to an IM, scalar control, such as the constant v/f technique, is very straightforward to design, but it produces a slow response due to the inherent coupling effect caused by torque and flux being functions of current and frequency. Furthermore, accurate position control is not attainable with scalar control since it needs immediate torque controlVector control, on the other hand, decouples the vectors of field current and armature flux, allowing them to be regulated individually to enable quick transient response [13]. The field component (Id) and torque component (Iq) of three-phase motor currents are separated. Under these conditions, the resultant torque may be represented as [14].

$$T_e = K I_d I_q \qquad (2)$$

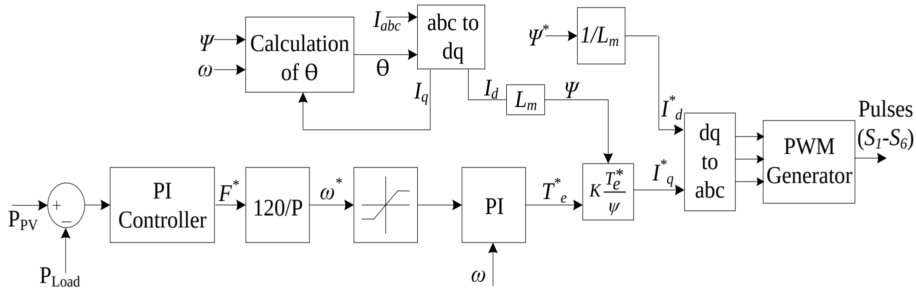
The control of battery connected system (Fig. 1(a)) can be implemented with the help of Fig. 3(a) and (b). Switches Q_1 and Q_2 of dc-dc converter (Fig. 3(a)) are used to control the voltage at dc-link and vector control is implemented to control a pulse width modulation (PWM) inverter (Fig. 3(b)). Therefore, the battery can be able to charge and discharge based on power difference between generation and load.

In water pumping system the motor torque depends on head and load torque is constant for constant head. As load torque becomes constant, the load power depends only on speed of the motor. So the power mismatch between load and generated power will reflect the change in speed. In the similar manner, when PV power is more/less than load requirement, dc-link voltage (V_{dc}) will increase/decrease. In order to regulate AC bus voltage (i.e, output of inverter where motor loads are connected), V_{dc} needs to be kept constant at its reference value (V_{mpp}). Hence, in the proposed control strategy, in order to keep dc-link voltage constant, the speed of IM is allowed to vary within permissible limits. The proposed control schemes without battery are presented in Fig. 3(b) and (c). Control scheme shown in Fig. 3(b) corresponds to power based control {Fig. 1(b)} while control scheme shown in Fig. 3(c) corresponds to voltage based control {Fig. 1(c)}. Since in Fig. 1(b) and (c), there is no energy storage device, power matching between generation and load demand is achieved on the cost of change in frequency of inverter by keeping the output voltage constant. Since, frequency of inverter is changing, speed of motor will also change. Hence for safe and reliable operation of motor, controller allows IM to run within permissible minimum and maximum speeds. Assuming head 25m and the maximum water discharge (Q) as 300 gal/min.,

In voltage based control, the reference frequency (F^*) is generated by PI-2 through change among V_{dc} & (V_{mpp} + V_{dcm}). By using the F^* and 120/P (P is number of poles of IM), the reference speed (ω^*) is estimated. In order to limit the speed under limit, a limiter is used after PI-2 controller as shown in Fig. 3(c). The limited speed signal will be treated as input signal of a vector control which produces pulses (S_1-S_6). F_{max} is the maximum allowable frequency. Under the scenario of PV power becomes more than induction motor power, then speed of induction motor and dc-link voltage both may rise beyond permissible limit. Hence to avoid this resistive type of dump load is connected so that it can consume surplus power from PV. Considering the protection of dc bus, the rise in dc-link voltage is allowable up to 5% of V_{mpp} and it is denoted by V_{dcm}. If generated power by PV is more than the IM load power, the controller can allow the speed of IM up to maximum limit (i.e, F_{max}). When $F^* \geq F_{max}$, V_{dcm} is added to V_{mpp}, which is now reference signal of dc-link voltage. The error signal (V_{mpp} + V_{dcm} - V_{dc}) is given to PI controller (PI-1) and output of PI-1 is responsible for generating PWM pulse to switch S_d which in turn controls the surplus power dissipated to dump load (R_d). Then the dc-link voltage can regulate by both the inverter and the dump load switch (S_d), so the dc-link voltage may rise up to permissible value (V_{mpp} + V_{dcm}).



(a)



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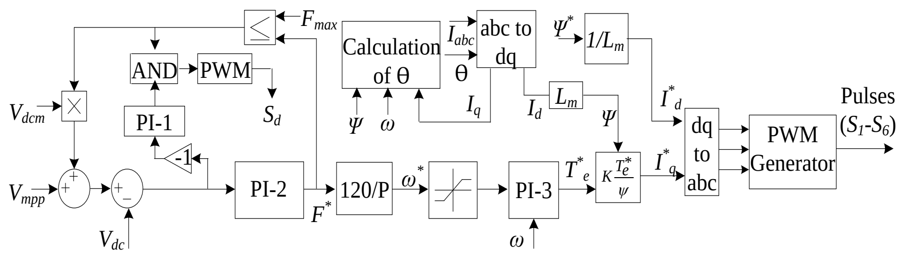

(c)

Fig. 3: Speed control of IM, a) controller for dc-link in battery connected system, b) power based control, c) voltage based control.

An energy management algorithm is required to maintain power balance among PV, load and dump load. A proper energy management helps in reducing power wasted in dump load under the scenario of PV power more than any of the induction motors power. The power rating of PV is considered less than that of total power rating of two induction motors, so that when both induction motors are running, power doesn't waste into dump load. In case only one IM is running and PV power becomes more than that of IM (which is running), controller will allow the IM to run up to its maximum possible speed. Once it reaches to its maximum speed and let's say still PV power is more than IM rating then according to energy management algorithm another IM should be switch ON so that power does not go to dump load. The energy management algorithm for proposed system is shown in Fig. 4 which is based on reference, maximum and minimum frequencies (F^*, F_{max} and F_{min}) which is function of speed of IM.

2. Simulation Outcomes

Matlab/Simulink is used to simulate the proposed PV-based water pumping system. In the Indian situation, 3-phase IM with capacity ratings ranging from 2 hp to 30 hp are often utilized for water pumping systems, depending on head and maximum water discharge [16]. In this study, two induction motors with ratings of 4 hp (2.942 kW) and 3hp (2.207 kW) are linked at an AC bus with a head of 25 m and a maximum water discharge of 300 gal/min. The PV array has a rating of 4.7 kW and is made up of 22 solar modules connected in series. Each module has an open circuit voltage of 36.90 V, a short circuit current of 8.01A, a voltage at maximum power (V_{mpp}) of 30.3V, and an i_{mpp} current of 7.10 [17]. The simulation findings are described using the case studies listed below.

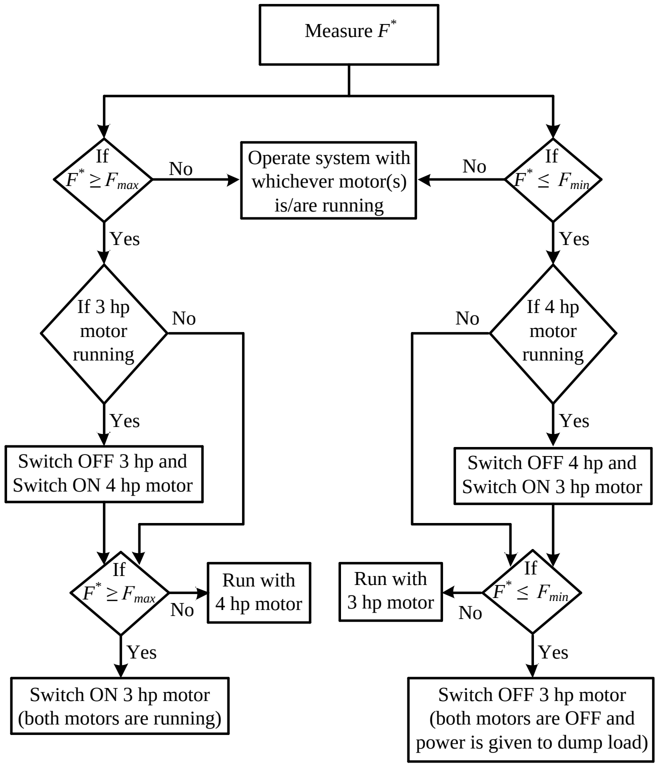

Fig. 4: Energy management algorithm

With battery storage

In the case of a battery storage system, the battery can charge from PV when the load demand is less than the PV power, and the battery can satisfy load demand when the PV power is less than the load demand. The charging and draining of a battery via a bidirectional dc-dc converter is controlled by adjusting the dc-link voltage, as shown in Fig. 5(a). Consider that the sun irradiation is at its peak (1000 W/m^2) for up to 3.0 seconds. Two induction motors are running, and after t=3.0 seconds, a 4 hp induction motor is unplugged from the AC bus. In this situation, after t=3.0 sec. lower rating IM (i.e., 3 hp) reaches to maximum permissible speed (1800 rpm). Once speed reaches to maximum limit, surplus power from PV goes to battery. The corresponding responses of dc-link voltage, battery power and speed of IM are shown in Fig. 5.

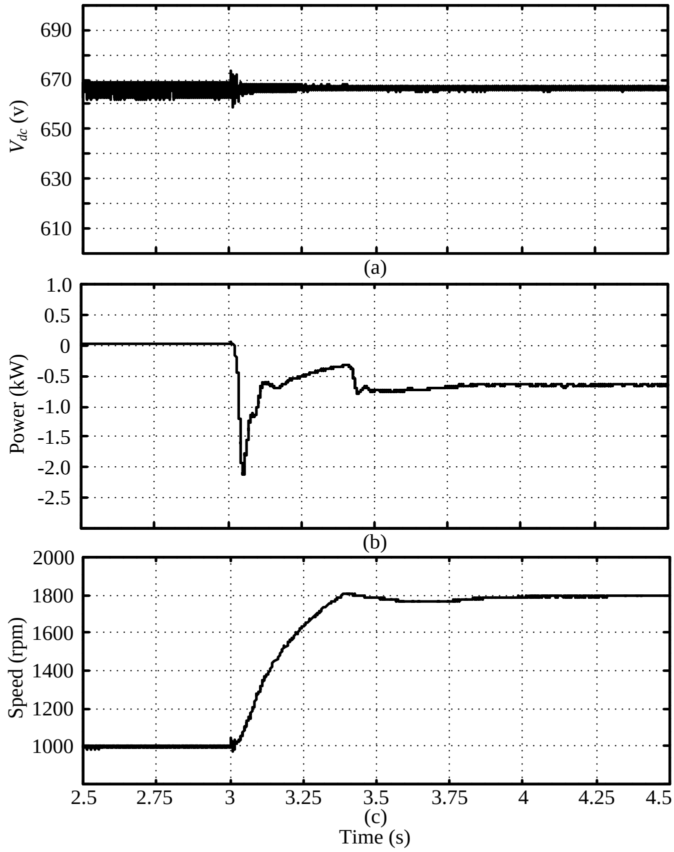

Fig. 5: Response of (a) V_{dc}, (b) battery power, (c) speed of IM

Proposed schemes without battery storage

Subjected to the change in solar irradiance from 970 W/m^2 to 800 W/m^2 at t=5.0 sec. the response of dc-link voltage and IM speed for both power based and voltage based (Fig. 1(b) and (c)) controllers are shown in Fig. 6. The responses of both controllers are almost same but in power based controller more sensors are required for measuring the load power and PV power. However, in voltage based controller, measure of only dc-link voltage is required. Therefore voltage based controller is recommended for PV based water pumping system.

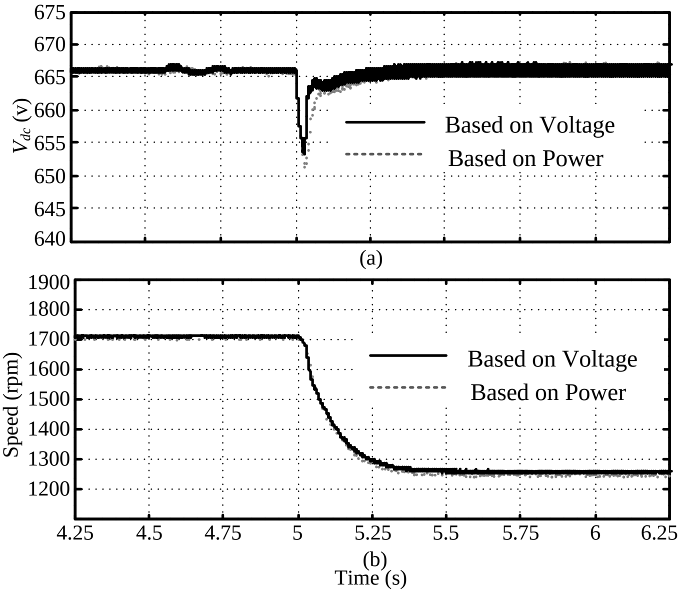

Fig. 6: Responses of (a) V_{dc}, (b) speed of IM

The performance of voltage based controller is tested considering following cases:

Case- A: Change in solar irradiance

Figure 7 depicts the reaction of V_{mpp} and PV power to changes in solar irradiation. The irradiance is lowered from 1000 to 700 W/m2 at t=4 sec (Fig. 7(a)). As illustrated in Fig. 7(b), the P&O controller tracks the voltage at maximum power point (V_{mpp}), which serves as the reference signal for the proposed voltage controller (Fig. 3(c)). The system now functions at $V_{dc} = V_{mpp}$, which indicates that the PV always generates maximum power, as illustrated in Fig. 7(c).

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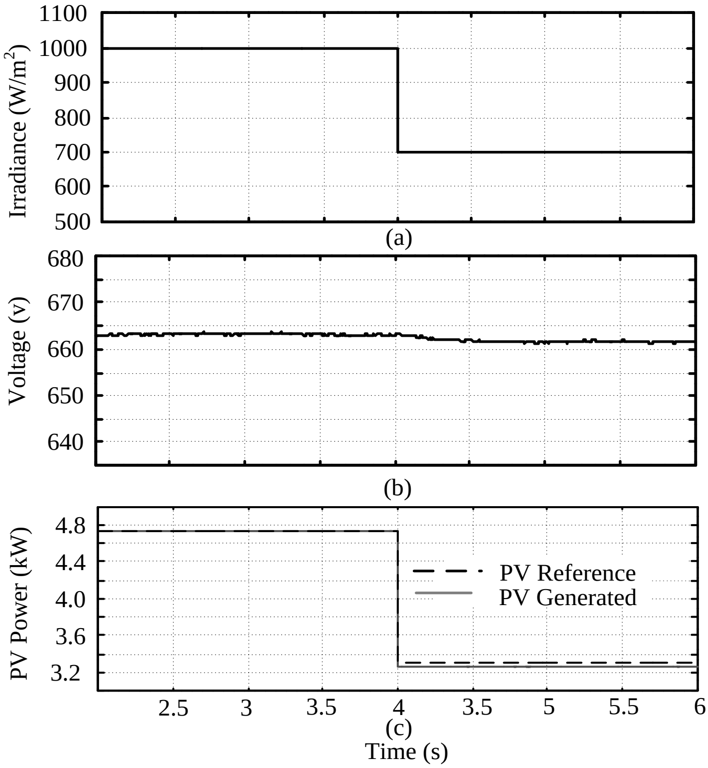

Fig. 7: (a) Solar irradiance, (b) V_{mpp} or V^*_{dc}, (c) PV Power

Figure 8 shows the response of dc-link voltage, corresponding speed of IM for change in irradiance from 1000 to 700 W/m^2 at t=4sec. and considering that one IM (4 hp) is running. From Fig. 8(a) it is seen that when irradiance is reduced at t=4 sec. V_{dc} reduces momentarily but settles at correspond V_{mpp} immediately. Since, solar irradiance is reduced, power from PV is reduced and hence to maintain the dc-link voltage constant frequency of inverter will reduce which in turn will reduce the speed of IM as shown in Fig. 8(b). Inspite of reduction in speed, the vector control maintains the flux constant as shown in Fig. 8(c). Since, flux remains constant the machine will not go into saturation.

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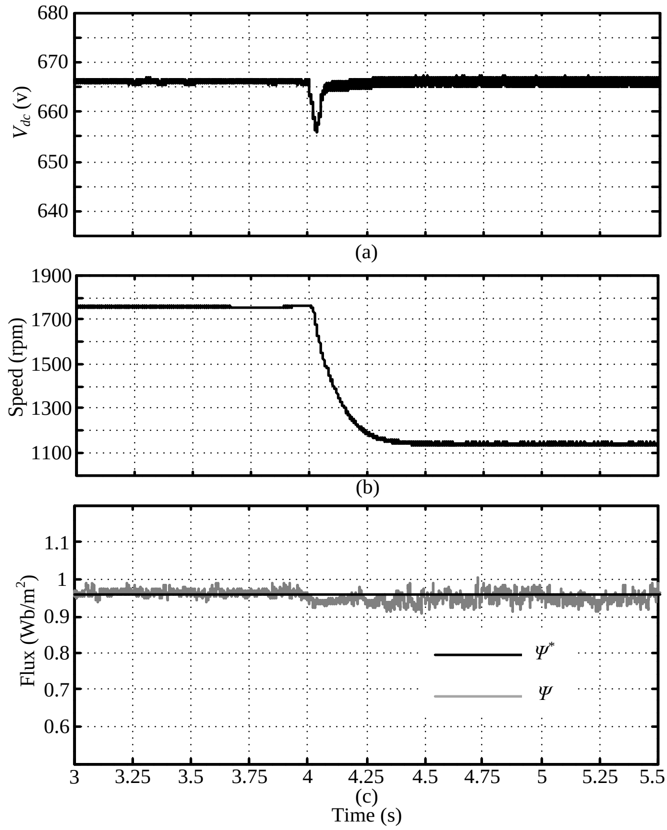

Fig. 8: (a) Dc-link voltage (V_{dc}), (b) speed of IM, (c) reference and actual flux of IM

Case- B: When PV power more than the load power

Consider profile of site Jharkhand in India [18] in which maximum irradiance (1000 W/m^2) occurred at 12 pm. In the simulation, assume that before 12 pm irradiance was 800 W/m^2 and 3 hp motor was running alone. When solar irradiance became 1000 W/m^2 at 12 pm, PV power became more than IM power and hence speed of IM increases up to permissible value as shown in Fig. 9(a). Since, power generated by PV is still more than the load power, V_{dc} will rise up to permissible maximum value (i.e, $V^*_{dc} + V_{dcm}$) as shown in Fig. 9(b) and dump load will act to consume the surplus power through switch S_d (Fig. 1(c)). Since, speed of IM as well as dc-link voltage reach to their maximum values and still PV power is more than load, operator has to switch ON another IM, so that power should not be wasted into dump load. After switching ON 4 hp motor, the load power (both motors are ON) becomes more than PV power, therefore speed of 3 hp IM will reduce as shown in Fig. 9(a). In this scenario, dump load will consume the power only during transition of switch ON of 4 hp motor from OFF position as shown in Fig. 9(c).

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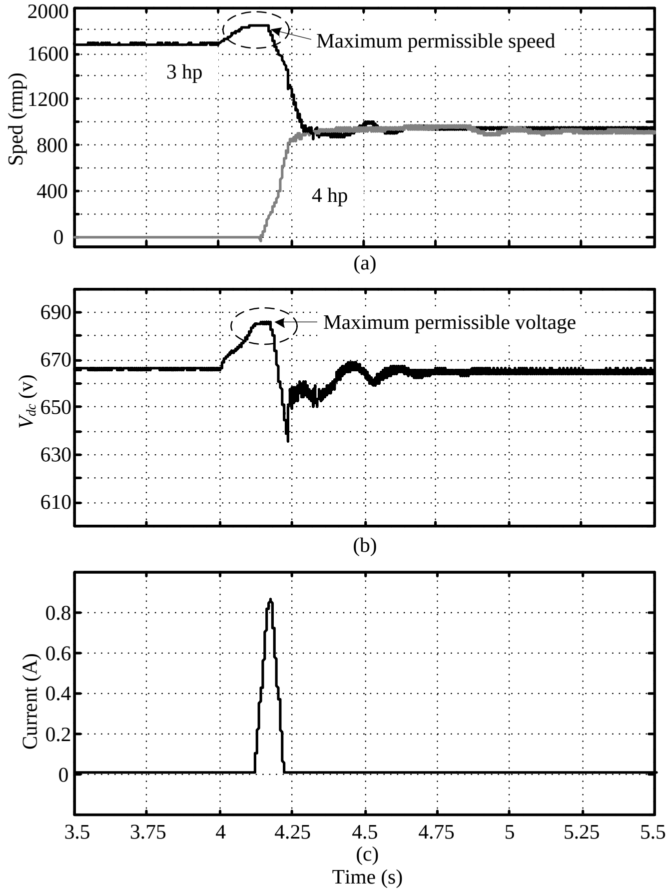

Fig. 9: Response of (a) speed of IMs, (b) V_{dc}, (c) dump load current

3. Conclusions

The control of a PV-based water pumping system based on induction motors (IM) without battery storage is given in this chapter. As a result, the suggested system is less expensive than a system with energy storage. The power balance between PV generation and load is achieved via unique inverter management by keeping the dc-link voltage constant at its reference value (V*dc) and adjusting the speed of the induction motor within allowed limits. Because of the proposed voltage-based inverter control, an additional dc-dc converter for MPPT is not required, and the inverter itself serves as the MPPT circuit.. The proposed integrated controller requires only measurements of dc-link voltage and load currents, no need to measure the PV and load powers. Different cases are discussed based upon change in solar irradiance and motor load. Through the simulation and HIL results it is concluded that performance of the controllers is satisfactory under conditions of change in irradiance and load.

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