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Design of Renewable Energy Powered Water Pumping System

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ABSTRACT

The paper shows the implementation of PV water pumping system management that utilizes motors without any battery storage. Proposed system offers an affordable operation compared to energy storage solutions. The control method uses a new inverter technique that maintains the dc-link voltage at its reference value (V*dc) while keeping the speed of the induction motor inside permitted ranges. Without the implementation of voltage-based inverter control there is no need for an additional MPPT dc-dc converter because the inverter operates as both MPPT controller and power converter at once. The operational concept of the integrated controller depends solely on the dc-link voltage measurement alongside load current measurements because power measurement is not essential. The analysis concentrates on different scenarios which involve solar irradiance variations and modifications in motor load. The controllers achieve satisfactory performance while irradiance and load conditions vary based on simulation and Hardware-In-Loop results.

Keywords: Renewable Energy; MPPT; HIL.

I. Introduction

Several countries exist with large deficits of power generation capabilities. A lack of electrical power functions as a primary obstacle for rural development throughout various nations. The lack of electricity affects three out of every ten rural residents in India [1]. Conventional power plants create severe environmental problems along with fossil-fuel exhaustion which concerns the global community. The rise in demand for renewable energy sources aims to resolve power shortages while reducing air contamination and fighting against greenhouse effects. Solar together with wind energy sources are experiencing increasing demand because of their growing popularity.

A majority of remote communities abroad require expensive power grid connections that are impractical therefore they depend on diesel generators as their primary power source. India operates numerous remote railway stations through use of DG [2]. The installation of an off-grid renewable energy system operated at a local scale emerges as an appropriate answer for such situations. Such systems function as remote area power supply (RAPS) systems. The 'Photovoltaic (PV)-Wind-DG' system located in Tirumala Tirupati; India [3] represents an example of a stand-alone hybrid generation system while 'PV-Diesel' hybrid system of 50kWh/day exists in Arbaminch town in the southern region of Ethiopia [4]. Typical off-grid (stand-alone) power systems contain energy sources, storage devices and their regulation standards. The renewable energy sources operating as stand-alone units must be positioned near the points of electrical consumption.

The International Energy Agency predicted in 2011 that solar power generators would supply most global electricity through the next fifty years to minimize harmful environmental greenhouse gas emissions [5]. Solar power installations worldwide reach 40,000 MW and solar power exists in the electrical grids of more than 100 different nations [5, 6]. PV systems have great potential in India because the country enjoys numerous sunny days throughout every year. The installation of solar-based systems in India focuses primarily on power regions without access to electricity or inconsistent power system areas. Solar plants in the country currently have an installed capacity of around 110 MW. The Jawaharlal Nehru National Solar Mission recently launched by the Indian government intends to establish off-grid solar applications at a capacity of 1,000 MW before 2017.

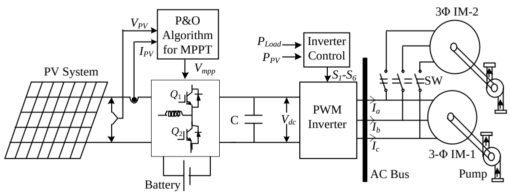
The water pumping system designed for irrigation ranks among the most popular PV installations because it has already reached more than 10,000 operational units worldwide [7]. The combination of PV-DG systems has become extensively popular for supplying telecommunication towers and providing emergency power backups in various settings including hospitals and industries. [8,9] Wind energy maintains its status as a renewable source of power since its development has expanded substantially during the previous years. The gross wind potential of India stands at 45 GW while the nation has installed wind power generation capacity of 19.8 GW as of January 2013 [10]. The extraction of maximum power from PV arrays requires operating the PV power generation system at its maximum power point (MPP) on P-V characteristics. The authors in [11] introduced a water pumping system which uses batteries in combination with dc-dc converters to operate maximum power point trackers (MPPT). The system's overall cost rises between 10% and 50% depending on battery capacity and type because battery storage creates operational benefits and PV surplus power storage capabilities [12]. The storage duration of batteries reaches approximately 3 to 4 years but their replacement expenses will be substantial. A PV water pumping system without energy storage reduces installation expenses as well as running expenses of the entire setup.

There are numerous sites throughout the world where DG operates as the primary electric power supplier. The PV system can operate together with DG to supply electricity to remote locations according to [13] and [14]. The integration of PV technology with DG systems leads to operation that is both sustainable and more dependable. The operating cost reduces because of fuel consumption diminishment. Solar irradiance together with wind velocity operate based on the current weather conditions which cause regular fluctuations. The output power production from solar and wind consistently varies according to their availability. Energy storage systems hold critical importance for stabilizing power balance between energy production and consumption in stand-alone power systems [15]. Among the available energy storage technologies i.e., super-capacitor and superconducting magnetic energy storage (SMES) and flywheel and battery; super-capacitor and SMES demonstrate rapid dynamic response abilities. Super-capacitors and SMES remain very expensive even though they are commercially available at limited power capacities [16].

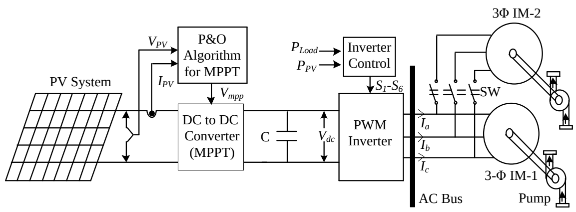
The paper introduces voltage-based inverter control for PV based water pumping systems that use IM motors without battery storage. Hence the proposed solution offers lower costs than systems which need energy storage. The proposed voltage-based inverter control system succeeds in preserving system power balance by utilizing no energy storage devices. The control system maintains dc-link voltage at V*dc reference while the IM speed stays within permissible boundaries to balance PV power against system load. The inverter functions as both the PV MPPT device and thus there is no need for separate MPPT dc-dc converter. The integrated controller system needs dc-link voltage and load current measurements as its only requirement without needing PV or load power measurements. The article supplements simulation results obtained from MATLAB to demonstrate the proposed theoretical framework.

II. Proposed System Modelling

The MATLAB simulation platform verifies the performance of the proposed control methodology through its output results. Additional to simulation findings the paper contains hardware-in-loop (HIL) results that validate the theoretical work. The HIL platform utilizes two units of RTDS equipment produced by 'OPAL-RT Technologies'. The tests were performed in order to create a near-industrial realistic control system that can directly benefit industry applications.



(a)



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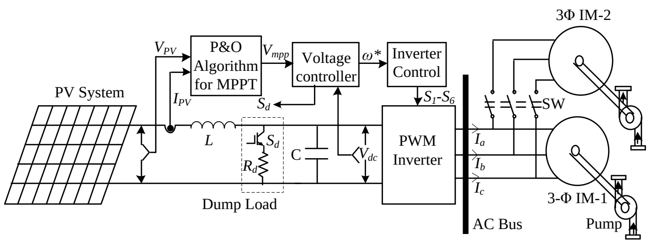


(c)

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

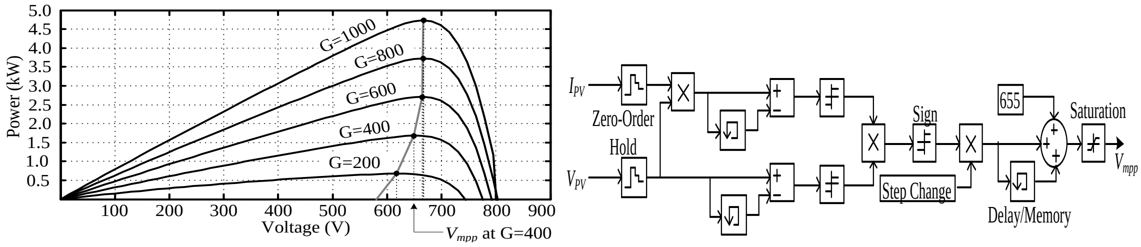
a. Maximum Power Point Tracker (MPPT)

A barrier to solar PV cell usage exists because the power vs voltage curve of solar cells produces maximum power at one specific operating voltage identified as Vmpp. The Fig. 2(a) displays the curve showing power against voltage. A power electronics interface offers important benefits which allow rapid processing of solar panel electricity with automatic control methods. The employment of maximum power point trackers (MPPTs) enables following peak power levels and delivering them continuously to the load systems. The power electronic converter of an MPPT governs the PV dc-link voltage to Vmpp level to maintain MPP operation.

The control system uses comparison between PV power and load power from the AC bus as shown in Fig. 1(a) and (b) under power-based control. The PV power ranges between complete zero output and its maximum level. The PV system's maximum power output depends on the selected value for dc-link voltage (i.e, Vmpp). A physical MPPT converter (dc-dc converter) must operate to control the dc-link voltage since its regulation requires the physical MPPT converter. An MPPT function exists within the bidirectional converter of battery storage systems which controls the dc-link voltage. For voltage-based controller (Fig. 1(c)) an actual MPPT device becomes unnecessary because the inverter controls the dc-link voltage at Vmpp levels through perturb and observe (P&O) algorithm operation. Within its duty, an inverter functions to manage AC bus voltage and performs maximum power point tracking for PV needs. P&O algorithm operates as the most preferred MPPT control procedure among its peers and represents the choice adopted by numerous systems as illustrated in Fig. 2. The algorithm provides the specific method to detect when Maximum Power Point is achieved.

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

Where, M is steep voltage and k is the iteration and dp/dv is change in PV power with respect to PV voltage.



a) (b)

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

b. Regulation of Voltage at AC Bus

The water pumping system described by the authors uses a drive control strategy that employs the scalar approach. The v/f scalar control method restricts voltage from exceeding its rated value. The rated frequency becomes the upper limit for constant torque operations. The implementation of scalar control through the constant v/f method on IMs ensures basic operation ease but produces delayed output because the inherently linked torque to flux dependence affects current and frequency relations. The inability to achieve accurate position control exists because scalar control lacks an immediate torque control capability. Through DTC field current vectors split from armature flux vectors the system gains independent control for rapid transient response. The Direct Torque Control (DTC) represents both the most popular and advanced version of DTC technology. Three phase motor currents provide two separate components including the field current (Id) and torque current (Iq). The resulting torque from these conditions stems from the following mathematical relation:

$$T_e= KI_dI_q \qquad (1)$$

Here, I_d is oriented in the direction of flux (Ψ) and I_q is established perpendicular to it. This means that when reference current of I_q (I^*_q) is controlled, it affects the actual I_q current only, but does not affect the flux. Similarly, when reference current of I_d (I^*_d) is controlled, it controls the flux only and does not affect the I^*_q component of current. In this thesis, since we are controlling I_q by keeping I_d as constant, the flux will remain constant for various operating conditions.

Fig. 3(a) and (b) may be used to implement the control of the battery-connected system (Fig. 1(a)). Switches Q1 and Q2 of the dc-dc converter control the DC-link voltage (Fig. 3(a)), while DTC controls the pulse width modulation (PWM) inverter (Fig. 3(b)). Thus, the battery may be charged if the PV power exceeds the load, and it can discharge to fulfil the load requirement if the PV power is less than the load.

The load torque in a water pumping system is constant for constant head, but the motor torque is dependent on head. The load power solely depends on the motor's speed after the load torque stabilises. As a result, the power imbalance between produced and load power will represent the speed variation. Similarly, DC-link voltage (Vdc) will rise or fall as PV power exceeds or falls short of load requirements. Vdc must be maintained at its reference value (Vmpp) in order to control AC bus voltage (i.e., the inverter's output where motor loads are attached).

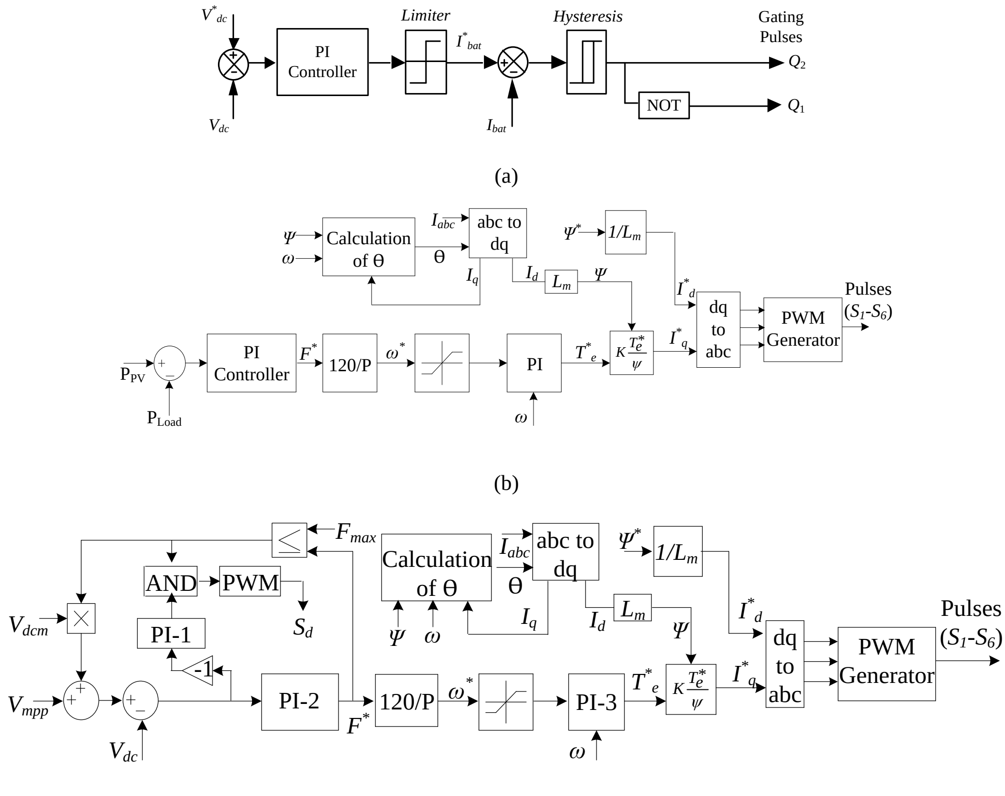
Therefore, the suggested control technique permits the IM speed to fluctuate within acceptable bounds to maintain a steady dc-link voltage. Fig. 3 (b) and (c) show the suggested battery-free control techniques. The power-based control {Fig. 1(b)} is represented by the control scheme in Fig. 3(b), and the voltage-based control {Fig. 1(c)} is represented by the control scheme in Fig. 2.3(c). Since there is no energy storage device in Figs. 1(b) and (c), power matching between generation and load demand is accomplished at the expense of an inverter frequency shift by maintaining a constant output voltage.

Since the inverter's frequency is fluctuating, the motor's speed will as well. Therefore, the controller permits IM to operate within the acceptable minimum and maximum speeds for the motor's safe and dependable functioning. The IM's minimum and maximum speeds are determined by assuming a head of 25 meters and a maximum water discharge (Q) of 300 gal/min.

The reference frequency (F*) in voltage-based control is produced by the proportional plus integral (PI-2) from the difference between Vdc and (Vmpp + Vdcm). The reference speed (ω*) is obtained by multiplying F* by 120/P, where P is the number of IM poles. As seen in Fig. 3(c), a limiter is attached after ω* produced by the PI-2 controller in order to restrict the speed between the lowest and maximum values. The input signal to DTC is the allowable speed (bounded by a limiter), and DTC produces the necessary pulses (S1–S6) for the inverter. The maximum permitted frequency that corresponds to the maximum speed is denoted by Fmax.

Both the induction motor's speed and the DC-link voltage may increase over the allowable limit if the PV power exceeds the induction motor's power. In order to prevent this, a resistive dump load is attached, allowing it to use excess PV power. The increase in dc-link voltage, represented by Vdcm, is permitted up to 5% of Vmpp while taking into account the protection of the dc bus.

The controller can permit IM speed up to the maximum limit (i.e., Fmax) if the power generated by PV exceeds the power of the IM load. The reference signal of the dc-link voltage is Vdcm, which is added to Vmpp when F* > Fmax. The PI controller (PI-1) receives the error signal (Vmpp + Vdcm - Vdc), and its output is in charge of producing a PWM pulse to switch Sd, which regulates the excess power wasted to dump load (Rd). Both the inverter and the dump load switch (Sd) may then control the dc-link voltage, allowing it to increase to an allowable level (Vmpp + Vdcm). The dump load design is given.



(c)

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

To keep PV, load, and dump load power balanced, an energy management algorithm is needed. In the case of PV electricity, effective energy management reduces power waste in dump loads more than any induction motor power. To prevent power waste into dump load when both induction motors are operating, the PV's power rating is regarded as lower than the combined power rating of the two induction motors.

The controller will let the IM to operate at its fastest speed if there is only one IM operating and the PV power exceeds that of the IM (which is operating). The energy management algorithm states that another IM should be turned on after it reaches its maximum speed and, let us say, the PV power is still more than the IM rating. This will prevent electricity from going to the dump load. Figure 4 illustrates the energy management algorithm for the suggested system, which is based on reference, maximum, and minimum frequencies (F*, Fmax, and Fmin) that vary with instant messaging speed.

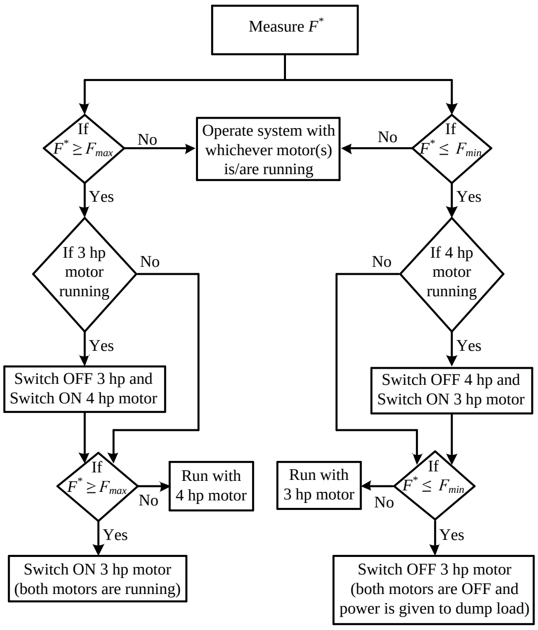


Fig. 4: Energy management algorithm

III. Simulation Results

MATLAB/Simulink is used to simulate the suggested PV-based water pumping system. Water pumping systems in India typically employ 3-phase IMs with capacity ratings ranging from 2 to 30 horsepower, depending on head and maximum water flow [36]. In this study considering head as 25 m and maximum water discharge as 300 gal/min, the two induction motors are connected at AC bus of rating 4 hp (2.942 kW) and 3hp (2.207 kW).

PV arrays consisting of 22 solar modules connected in series have a rating of 4.7 kW. The voltage at maximum power (Vmpp) is 30.3V, the current at maximum power (Impp) is 7.10, the open circuit voltage is 36.90 V, and the short circuit current is 8.01A for each module [37]. The following case studies are taken into consideration while discussing the simulation findings.

In a battery storage system, the battery may supply load demand when PV power is lower than load demand and charge from PV when load demand is lower than PV power. Fig. 3(a) illustrates how the bidirectional dc-dc converter organises battery charging and draining by regulating the dc-link voltage.

Assuming maximum solar irradiation (1000 W/m2), two induction motors run for 3.0 seconds, after which a 4-hp induction motor is unplugged from the AC bus. In this case, lower rated IM (i.e., 3 horsepower) achieves the maximum allowable speed (1800 rpm) after t=3.0 seconds. When the speed reaches its maximum, any excess PV power is transferred to the battery. Fig. 5 displays the matching responses of IM speed, battery power, and dc-link voltage.

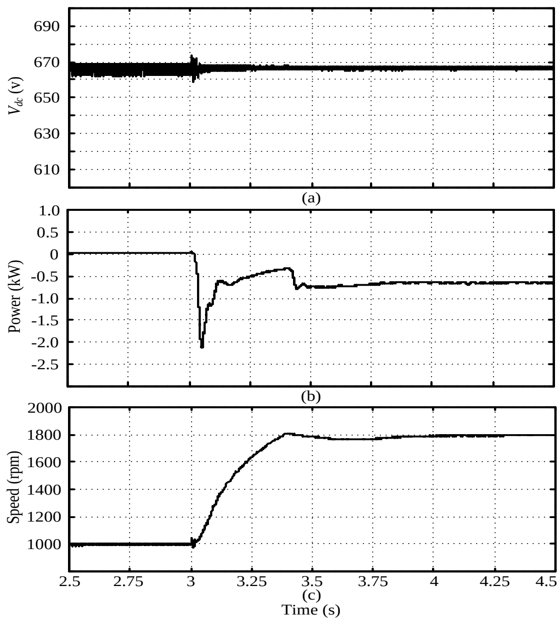


Fig. 5: Response of (a) V_{dc}, (b) battery power, (c) speed of IM

The dc-link voltage and IM speed response for both power-based and voltage-based (Fig. 1(b) and (c)) controllers are displayed in Fig. 6 when the sun irradiation changes from 970 W/m2 to 800 W/m2 at t=5.0 sec. Although the two controllers' responses are almost identical, a power-based controller needs additional sensors to measure PV and load power. However, just the dc-link voltage must be measured in a voltage-based controller. Consequently, for PV-based water pumping systems, a voltage-based controller is advised.

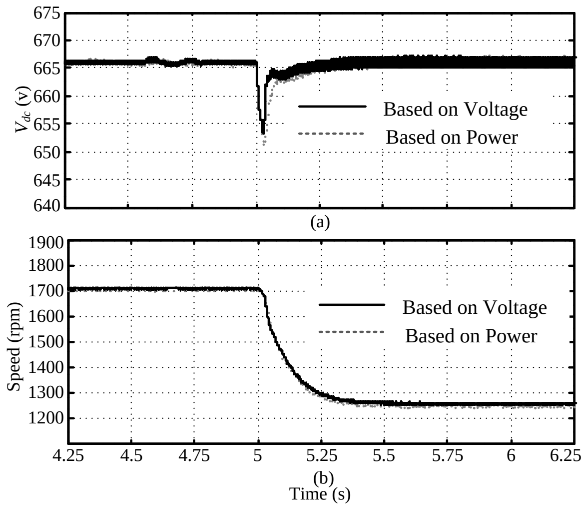


Fig. 6: Responses of (a) V_{dc}, (b) speed of IM

Case- A: Change in solar irradiance

Figure 7 illustrates how Vmpp and PV power react to variations in solar irradiation. Irradiance decreases from 1000 to 700 W/m2 at t=4 sec (Fig. 7(a)). The reference signal for the suggested voltage controller (Fig. 3(c)) is the voltage at maximum power point (Vmpp), which is tracked by the P&O controller in accordance with Fig. 7(b). As seen in Fig. 7(c), the system now runs at Vdc = Vmpp, meaning the PV always produces its maximum power.

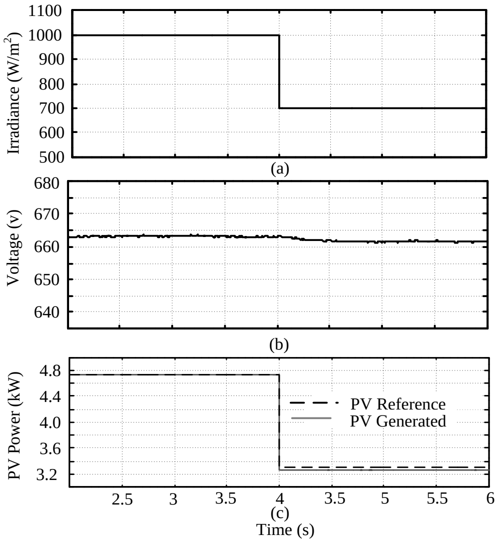


Fig. 7: (a) Solar irradiance, (b) V_{mpp}or V^*_{dc}, (c) PV Power

Considering that one IM (4 hp) is operating, Fig. 7 displays the response of the dc-link voltage and the associated speed of IM for a change in irradiance from 1000 to 700 W/m2 at t=4sec. As can be shown from Fig. 7(a), Vdc briefly decreases but instantly settles at the same Vmpp when irradiance is decreased at t=4 sec. When solar irradiance decreases, PV power decreases as well. As a result, the inverter's frequency must decrease to maintain a constant dc-link voltage, which lowers IM speed (Fig. 7(b)). As seen in Fig. 7(c), the DTC keeps the flux constant despite the speed decrease. Since, flux remains constant the machine will not go into saturation.

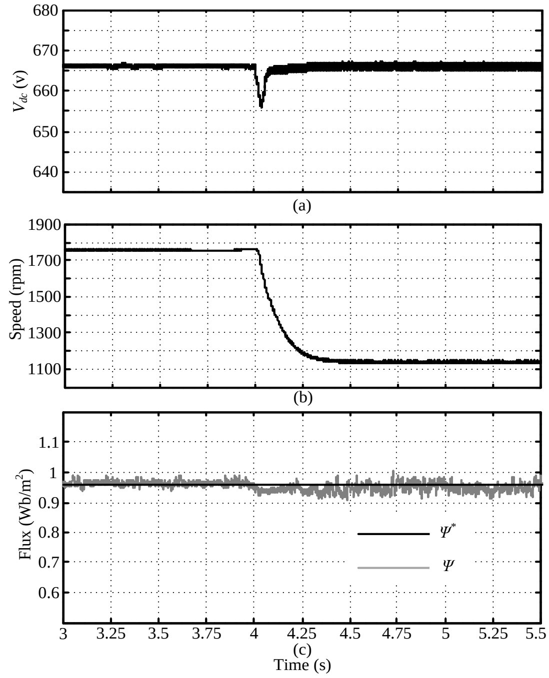
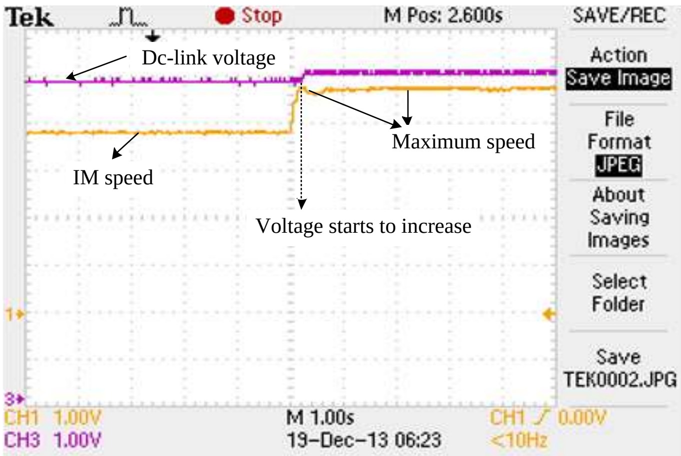


Fig. 8: (a) Dc-link voltage (V_{dc}), (b) speed of IM, (c) reference and actual flux of IM

HIL Results

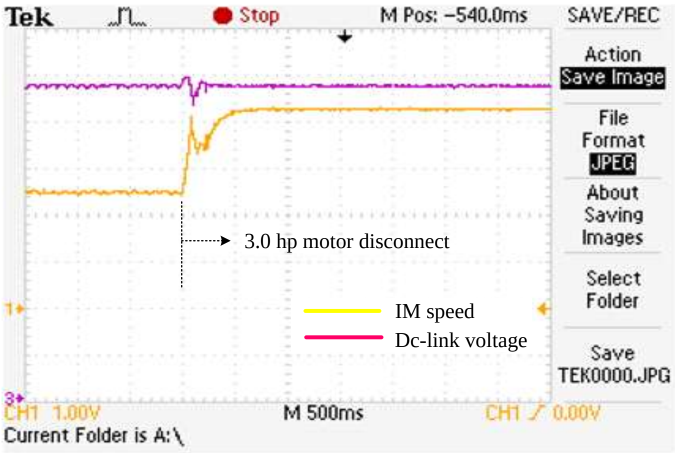
Assume that two instant messaging devices (i.e., 3.0 and 4.0 hp) are linked to the system. assuming a 3.0 horsepower motor is operating and that the irradiance rises from 800 to 1000 W/m2. The power produced by PV increases as a result of an increase in irradiance. As seen in Fig. 9, the motor's speed therefore rises to its allowable maximum, or 188.5 rad/s. However, still power provided by PV is higher than that of load; consequently, controller boosts dc-link voltage.

As the dc-link voltage rises, the PV's power output decreases, causing the motor's speed to stabilize at 188.5 rad/s (Fig. 9). Now imagine that the irradiance is 1000 W/m2 and both motors are operating. If the 3.0 hp motor is abruptly removed, the 4.0 hp motor's speed increases, as seen in Fig. 10 (yellow). Since the motor speed remains below the limit, the dc-link voltage is set to V_{mpp} (voltage at maximum power). Fig. 10 displays the corresponding dc voltage in pink.



(CH1, 1 V= 40 rad/s, CH3, 1 V=100 volts)

Fig. 9: Dc-link voltage and speed when irradiance increases from 800 to 1000 W/m^2



(CH1, 1 V= 40 rad/s, CH3, 1 V=100 volts)

Fig. 10: Dc-link voltage and speed when 3.0 hp motor is suddenly disconnected

V. Conclusions

This work presents the control of a PV-based water pumping system that uses induction motors (IM) without the need for battery storage. Therefore, compared to a system with energy storage, the suggested system offers a more affordable option. The power balance between PV generation and load is accomplished using innovative inverter control, which keeps the dc-link voltage steady at its reference value (V*dc) and regulates the induction motor's speed within allowable bounds. Due to proposed voltage-based inverter control, an extra dc-dc converter for MPPT is not required and inverter itself acts as MPPT circuit. PV and load power measurements are not necessary for the suggested integrated controller; just dc-link voltage and load current measurements are needed. Various scenarios are examined according to variations in motor load and solar irradiation. It is determined from the simulation and HIL findings that the controllers' performance is adequate when the load and irradiance vary.

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