A C O Standalone Photovoltaic Water Pumping System Using IMD with Reduced Sensors

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Abstract - A simple and efficient solar photovoltaic (PV) water pumping system utilizing an induction motor drive (IMD) is presented in this paper. This solar PV water pumping system comprises of two stages of power conversion. The first stage extracts the maximum power from a solar PV array by controlling the duty ratio of a DC-DC boost converter. The DC bus voltage is maintained by the controlling the motor speed. This regulation helps in reduction of motor losses because of reduction in motor currents at higher voltage for same power injection. To control the duty ratio, an Ant colony optimization (ACO) based maximum power point tracking (MPPT) control technique is used. A scalar controlled voltage source inverter (VSI) serves the purpose of operating an IMD. The stator frequency reference of IMD is generated by the proposed control scheme. The scalar control eliminates the requirement of speed sensor/encoder. Precisely, the need of motor current sensor is also eliminated. Moreover, the dynamics are improved by an additional speed feed forward term in the control scheme. The proposed control scheme makes the system inherently immune to the pump's constant variation.

***Index Terms*- Photovoltaic Cells, MPPT, Water Pumping, Scalar Control, Induction Motor Drives.**

I. INTRODUCTION

Solar photovoltaic (PV) energy converters earlier have been inefficient with the efficiency as low as 5-6 % and highly costly [3]. However, with increased technological research and advancements, the efficiency of PV array, at present, has reached 15-16%. Moreover, the prices have been reducing gradually. Today, PV energy conversion is viewed as one of the promising alternatives to fossil fuel based electricity generating systems, as there are no toxic emissions, no greenhouse gases emission, no fuel cost involvement, least maintenance cost, no water use etc. However, the technology is in developing phase and there are many challenges which need to be addressed such as, intermittency, high initial cost and low efficiency.

The solar water pumps [4]-[6] are gaining the popularity in rural areas, where the electricity is not available. Moreover, solar PV fed water pumps are the favored in remote areas for irrigation, water treatment plant, and agriculture purpose. Country like India, where 70% population depends upon agriculture, therefore, and irrigation is necessary for good yield. There is large number of water pumps in the world running with electricity or with non-renewable energy sources. The acquisitions of solar PV based water pumping systems [7] are more convenient as compared to diesel based water pumping systems in respect to the cost and pollution. In PV pumping (PVP) systems, an induction motor drive (IMD) shows good performance as compared to other commercial motors because of its rugged construction. The evolution is intended to develop productive, reliable, maintenance-free and cheap PV water pumping system [9]. However, new permanent magnet motors such as brushless DC motor and permanent magnet sine fed motors are used into pumping, but are still overshadowed by induction motor because of cost and availability constraints [10]. Moreover, the manufacturing of the induction motor is in matured stage giving an edge to its use in developing countries for solar water pumping application. With the emergence of outperforming solid state switches, high speed processors and efficient motor control algorithms, IMD based water pumping systems have taken a step ahead to conventional water pumping systems. Moreover, PV array fed IMD has performed ruggedly in the field of pumping system by utilizing a VSI (Voltage Source Inverter). The proposed work deals with a three-phase IMD for solar water pumping, which meets the requirement of life without electricity in remote locations.

The initial cost of solar power plant is high. Therefore, once the plant is installed, the focus is to obtain the peak power from the solar panels of the installed capacity. The developed water pumping system powered directly from PV array requires MPPT algorithms to operate under different irradiation levels and to extract the peak power from a solar PV array. Some of these, MPPT algorithms are recommended in [11]. A comparative study on different MPPT techniques is provided in [12]-[14]. From operational point of view, MPPT is a mandatory segment of a PV system. The substantial research is reported in past few years in the area of MPPT. In this paper, an ACO (Ant colony optimization) based technique is used to obtain the peak power from the solar PV array. Therefore, the proposed PV fed water pumping system produces peak torque even at low radiation. The ACO technique is based on the comparison of output conductance of solar PV array to the incremental conductance. As compared to solar PV grid interfaced systems [15], the major challenge in PV water pumping is timely control of active power.

This is due to the fact that the mechanical time constant of the motor pump system is much higher than that of aforementioned system. Under sudden fall in solar insulation, the PV array voltage tends to reduce drastically and consequently the level of flux in the motor falls rapidly. Once the flux has been fallen, the motor starts drawing higher current, which is limited by the short circuit current of the PV array in order to rebuild the flux. The operating point in the I vs V curves of PV array, shifts to current source region demonstrated by short circuit current and very low voltage. Due to insufficient power, the motor starts operating in an unstable zone of torque-speed characteristics near to a point where slip = 1. This particular condition is menacing for the motor health and once the motor enters this zone then there has to be a provision in the control, which can identify this condition and restart the motor from the standstill condition. The motor entering into such situations frequently, would reduce the overall duty of the pump, hence it's the responsibility of MPPT algorithm to take care of such events. To control the IMD tied VSI, a simple V/*f* (voltage/frequency) control approach is utilized in [15], [16]. The pumping system with a DC-DC converter and VSI is used for water pumping application in [17]-[19]. However, presented approach suffers from DC link voltage instability.

V/*f* approach is simple, easy to implement and cost effective. Dual inverters are used to supply power to centrifugal pump with SAZEPWM technique [20]. Apart from V/*f* control, DTC (Direct Torque Control) and vector control techniques are complicated and they require extra current sensors for implementation [21]. In V/*f* control, only PV array current, voltage, and DC bus voltage are sensed. The proposed system tracks the MPP point by altering the modulation frequency so that the IMD is able to extract the maximum power from the solar PV array at sustained torque for different solar insulation levels. The proposed system is able to supply more water as compared to a solar PV fed DC motor based water pump. By utilizing V/*f* control, the starting performance of the IMD is improved even if IMD is started with lower solar insulation. Therefore, water is permanently pumped from morning to till the evening.

The starting current of the induction motor connected to the fixed voltage AC mains is around 5 to 6 times of full load current. Therefore, to start the motor without any control, higher numbers of solar modules are required. Whereas, smooth starting of the induction motor is possible by using V/*f* control without drawing high starting current. This also improves the life of the motor. Moreover, the areas which are blessed with the electrical connectivity, may utilize the grid interfaced PVPs [22]. In Indian context, still many indoor villages and agricultural lands do not possess a privilege of having electrical network.

II. DESIGN OF PROPOSED SYSTEM

The system configuration for PV water pumping system is depicted in Fig. 1. It consists of a PV array followed by a boost converter. A VSI is used to provide pulse width modulated voltage input to the motor and pump assembly. The power from a PV array is regulated using an incremental conductance method to attain its maximum value with available radiation. The V/f control is used to give reference speed to IMD.

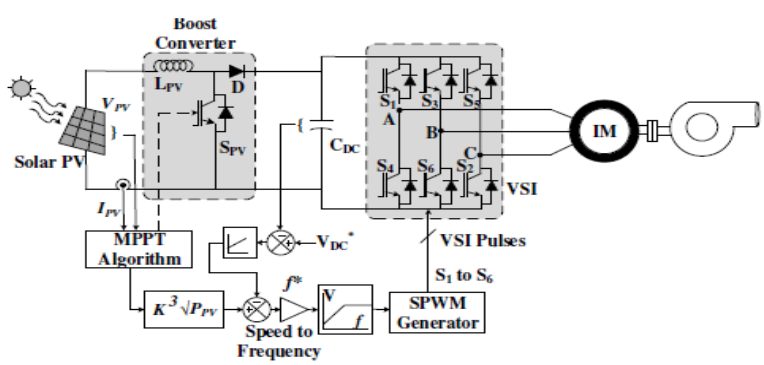

Figure 1. System architecture for the standalone solar water pumping system.

2.1. Design of Solar PV Array

An induction motor of a 2.2 kW is selected for proposed system. If losses of the motor and pump are neglected, the capacity of the PV array should be equivalent to the motor capacity. In this case, a PV array is selected as of 2.4 kW.

$$P_{mp} = \left(N_P \times I_{mp}\right) \times \left(N_s \times V_{mp}\right) = 2.4KW \quad (1)$$

Where, $P_{mp}$is the maximum power that can be drawn from panels at a given radiation, Vmp is the PV panel voltage at MPP and Imp is the current at MPP. Ns and Np are the number of modules connected in series and parallel, respectively. Considering an open circuit voltage of the panel to be near to a DC link voltage and power drawn from a panel to be 2.4 kW, number of modules in series and parallel are selected to be 11 and 1. The individual module and array specifications are provided in Table I.

TABLE I

SPECIFICATIONS OF THE SOLAR MODULE AND ARRAY

Module peak power of the single module	225 W
Module open circuit voltage (v_{oc})	41.79 V
Module short circuit current (i_{sc})	7.13 A
Module voltage at MPP (v_{mp})	33.9 V
Module current at MPP (i_{mp})	6.63 A
Array peak power (P_{mp})	2.4 kW
Array open circuit voltage (V_{oc})	459.69
Array short circuit current (I_{sc})	7.13 A
Array voltage at MPP (V_{mp})	372.9 V
Array current at MPP (I_{mp})	6.63 A

2.2. Selection of DC Link Voltage

The DC bus voltage of VSI is estimated from a relation as,

$$m \times \frac{V_{DC}}{2\sqrt{2}} = \frac{V_{L-L}}{\sqrt{3}} \quad (2)$$

Where, m is the modulation index and V_{L-L} is a line voltage across the motor terminals. Hence,

$$V_{DC} = \frac{2\sqrt{2}}{\sqrt{3}} \times 230 = 375V$$

Where modulation index is 1. The DC link voltage is chosen to 400 V.

2.3. Design of DC Link Capacitor

The DC link capacitor is supposed to provide sufficient energy at the time of transients such as fall in radiation and an increase in the load. Its value is calculated as [24]

$$\frac{1}{2}C_{DC}[V^{*2}{}_{DC} - V^{2}{}_{DC}] = 3\alpha VIt \quad (3)$$

$$\frac{1}{2}C_{DC}[400^2 - 375^2] = 3 \times 1.2 \times 133 \times 8.2 \times 0.005$$

$$C_{DC} = 2026\mu F$$

In above expression, V_{DC}^* refers to the set DC bus voltage while V_{DC1} is acceptable lower most voltage during transients. Moreover, α is an overloading factor and t is duration of transient.

2.4. Selection of DC-DC Boost Converter

The boost inductor duty cycle, D is given as [25],

$$D = \frac{V_{DC} - V_{mp}}{V_{DC}} = \frac{400 - 373}{400} = 0.0675 \quad (4)$$

$$L_m = \frac{372.9 \times 0.0677}{(0.2 \times 7.6 \times 10000)} = 1.875mH \quad (5)$$

Thus the inductance L value is selected as 3 mHz. Where, f_s is switching frequency, ΔI_1 is amount of ripple current.

2.5. Design of Pump

For a selected water pump, proportionality constant (K_{pump}) is given as,

$$K_{pump} = \frac{T_L}{{\omega_r}^2} \qquad (6)$$

Where, T_L is the load toque of water pump, which is equal to the torque offered by an induction motor under steady state operation and ω_r is the rotational speed of the rotor in rad/sec. Since the rated torque and rated speed of the induction motor are 14.69 N-m and 1430 rpm. Then proportionality constant (K_{pump}) is estimated using (6) as,

$$K_{pump} = \frac{14.69}{\left(2 * \pi * \frac{1430}{60}\right)^2} = 6.55 \times 10^{-4} \frac{N-m}{\left(\frac{rad}{s}\right)^2}$$

So proportionality constant is selected as $6.55 \times 10^{-4} \frac{N-m}{\left(\frac{rad}{s}\right)^2}$.

III. CONTROL SCHEME FOR PROPOSED SYSTEM

The proposed topology is a two stage power conversion system for a solar PV array fed water pumping. It embodies scalar control for IMD operation and an Ant colony optimization (ACO) method for maximum power extraction from the PV array. The simplicity and ease of implementation of scalar control overshadows precise but computation intensive control algorithms such as vector control and direct torque control. Moreover, in later mentioned algorithms, the sensor less operation is itself an exhaustive task. The voltage and current of PV array are sensed and fed to the INC algorithm. Based on the change in voltage, current and power, this algorithm decides the duty ratio of the boost converter. The boost converter output voltage is maintained to a constant value using a proportional - integral (PI) controller. Since the pump characteristics are centrifugal in nature, the power absorbed and the speed of the pump have direct relation as mentioned in (6). A speed feed forward term is calculated from the available PV power from which, the PI controller output is subtracted. This is helpful in reducing the burden on the PI controller and improving the dynamic performance of the system. V/*f* control algorithm generates the switching logic for VSI using sinusoidal pulse width modulation. If DC link voltage is higher than the reference value, the PI controller increases the reference speed given to V/f control and vice versa. The sum of two quantities gives a resultant speed reference f * for IMD, which is fed to V/f control algorithm. The DC link voltage error is estimated as,

$$V_{DCr} = V_{DC}^{*} - V_{DC} \qquad (7)$$

The output of the DC link voltage PI controller is as,

$$\omega_{DC(n)} = \omega_{DCr(n-1)} + K_P\{V_{DCr} - V_{DCr(n-1)}\} + K_i V_{DCr(n)} \qquad (8)$$

The speed term corresponding to PV power is as,

$$\omega_p = K \sqrt[3]{P_{PV}} \qquad (9)$$

Where, constant K is derived from pump's constant. The reference frequency of the IMD is as,

$$f^{*} = \frac{1}{2\pi}(\omega_r - \omega_{DCr}) \qquad (10)$$

Initially the boost converter pulses are kept off such that the system works as a single stage system and the speed is ramped up to a threshold speed. After threshold speed, the control of the boost converter is activated and the duty ratio is calculated from ACO algorithm. This is realized to avoid high current at starting since MPPT algorithm gives maximum power even at starting. Using ramp frequency start, the starting current of the motor is limited, which in case of direct online starting (DOL) at rated frequency is about 5-6 times the rated current. Moreover, it prevents the solar PV array to go into current source region at starting as the current drawn is very high in DOL starting.

3.1. Ant colony optimization

Ant colony system based PI-MPPT (ASPI-MPPT) Control is applied to the standalone PV system equipped with a switched mode DC-DC converter and connected to a battery load as configured in Fig. 4 to achieve maximum power transfer to the load. The switching frequency for the phase of practical implementation is chosen to be 100 KHz. The goal is to track the maximum power point on the PV power curve by forcing the PV panel to work at maximum power voltage on its I-V characteristics [1] even under severe varying insulation levels. The switching frequency chosen ensures stability of the practical implementation phase which will be our future work in this research point.

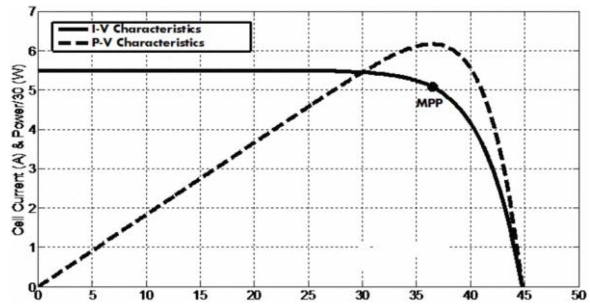

Figure 2 . I-V & P-V characteristics of the studied PV module

3.1.1 Closed loop control

At the point of maximum power on the PV power voltage curve, the change of power with respect to change of voltage is equal to zero ($\frac{dp}{dv} = 0$). In Fig. 5, the signal of dP/dV is chosen as the feedback variable that is compared with zero reference signals and the error signal is fed to an ant based PI controller that outputs a signal for the duty cycle of the DC - DC converter. The output of the controller that depends on the incremental conductance method is enhanced by the fractional open circuit voltage technique to reduce the settling or tracking time by giving an initial estimation for the operating voltage. Same ant colony optimization algorithm is used. The idea is to start the proposed algorithm with already known PI gains then enhance the dynamic response of the closed loop system according to the performance index via the steps of the algorithm. Finally, the algorithm will reach the optimal parameters of the PI-MPPT ensuring maximum power transfer from the standalone PV system

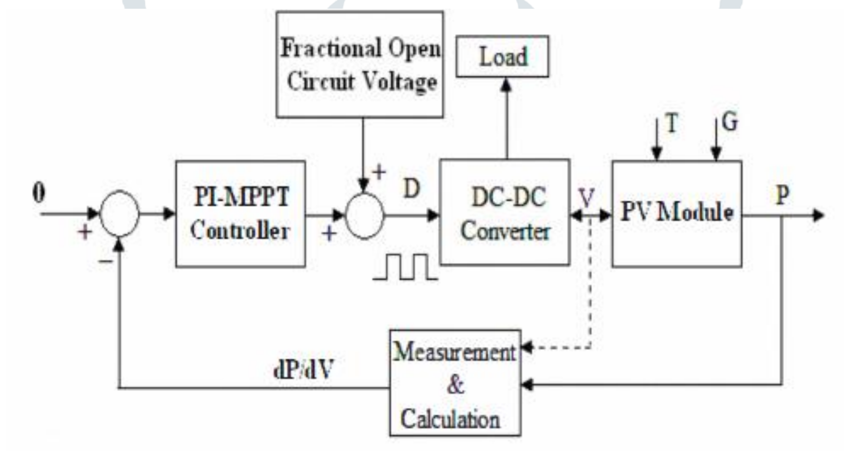

Figure 3. Closed loop control of ant colony system

3.2. Scalar (V/f) Control of Induction Motor

The scalar control of an induction motor is most common and simplest control so far. Usually induction motors are designed for 50 Hz input voltage. For the operation at lower speed, the voltage has to be reduced. The frequency control along with voltage magnitude control is also desired for constant flux operation. The voltage should be proportional to the frequency [2] such that flux magnitude is maintained constant as φ_s=V/ω. An IM is usually fed from a three phase PWM VSI. Only an input parameter is the reference speed. Neglecting the small slip speed, the speed of the motor is approximately equal to the reference speed. The speed reference is integrated to generate the θ, which is used to obtain three sinusoidal voltage references, which are compared with high frequency triangular wave to generate the switching pulses for VSI. The speed reference is estimated from the control scheme as mentioned in previous subsection.

$$\theta = \int \omega^* \, dt \tag{11}$$

Three phase reference voltages are,

$$V_a^* = m \times \sin(\theta) \tag{12}$$

$$V_b^* = m \times \sin(\theta - 120°) \tag{13}$$

$$V_b^* = m \times \sin(\theta - 240°) \tag{14}$$

Where, $m = k_f \omega^*$, m is modulation index.

IV. RESULT AND DISCUSSION

Performance of a double stage PV fed water pumping system is evaluated using the simulation package. The proposed system is designed, modeled and simulated in the MATLAB/Simulink environment. The step change in the solar radiation is also simulated in order to determine the satisfactory performance of the system under dynamic conditions.

4.1. Starting Performance of Proposed System

Fig. 4 exhibits various parameters of the proposed water pumping system at 500 W/m^2 radiations. The DC link of VSI is energized initially. Since the switching device of the boost converter is off, the voltage across the DC link of VSI is the open circuit voltage of PV array. It starts falling once the motor speed increases. The PV array current starts from zero and rises up to I_{mp}. The PV voltage reaches V_{mp} once a threshold frequency is passed and the control of the boost converter is activated for MPPT. At t = 8 s, the boost converter is activated and the system reaches corresponding MPP. The DC link voltage is settled at reference value because of action of PI controller. It is verified from the figure that the motor current never exceeds the rated current, which is by the virtue of soft start. This practice improves the lifespan of the motor.

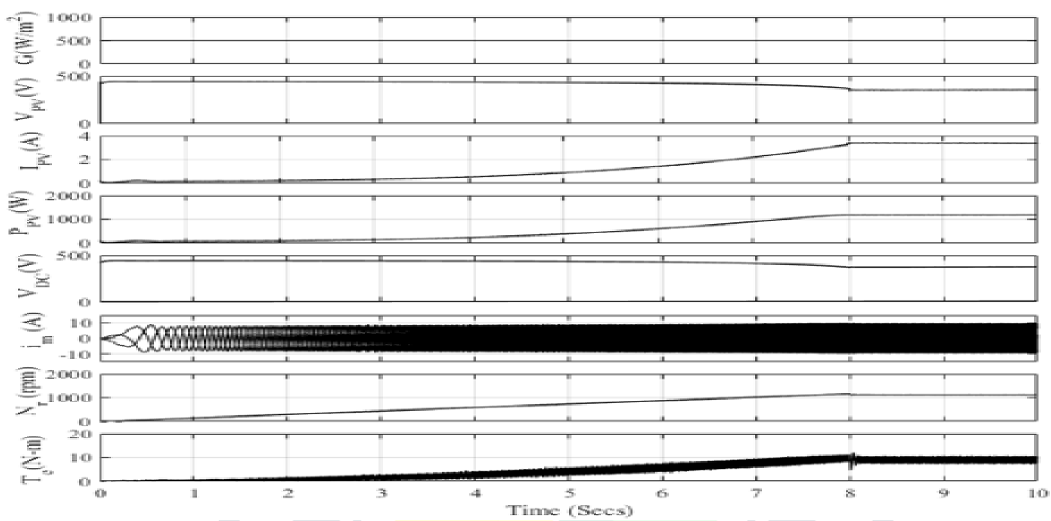

Figure 4 starting performance of proposed system

4.2. Steady State and Dynamic Performances of Proposed System

The behavior of the proposed standalone PV water pumping system is depicted in Fig. 5. This figure comprises simulation of varied solar insulation changes. From t = 1 s to 2 s, the solar insulation is constant at 800 W/m2. The PV indices are at the corresponding MPP. At t = 2 s, a slope decrement in the solar insulation is simulated to test the MPPT algorithm effectiveness. The PV voltage observes negligible change while the PV current varies proportional to the available insulation. Moreover, the DC bus voltage is also maintained at reference voltage of 400 V without any failure. The speed and torque of the motor are reduced with the reduction in PV power. This continues to happen till t = 4 s, from where the system experiences a slope increase in the solar insulation. Similar to the previous behavior, the PV current starts increasing proportional to the solar radiation, while there is not much change in the PV voltage. Consequently, the available power from a PV source ramps up along with the motor speed and the motor torque. From t = 6 s, the system operates in steady state at a solar radiation of 1000 W/m2. The system faces a step decrement in the solar insulation from 1000 W/m2 to 500 W/m2 at t = 7 s, owing to which the PV current reduces instantly. However, still the PV voltage does not face many transients. The DC bus voltage experiences slight transient change, however, it restores to a reference voltage quickly. It is noteworthy that, the DC bus voltage is maintained even at 50 % reduction in rated power. Similarly, a step increase in a solar insulation is observed at t = 9 s. As anticipated from previous behavior of the system, the DC bus voltage is maintained to a reference value while there is no significant change in the PV voltage. The motor speed and torque increase proportionally to balance a power from a source.

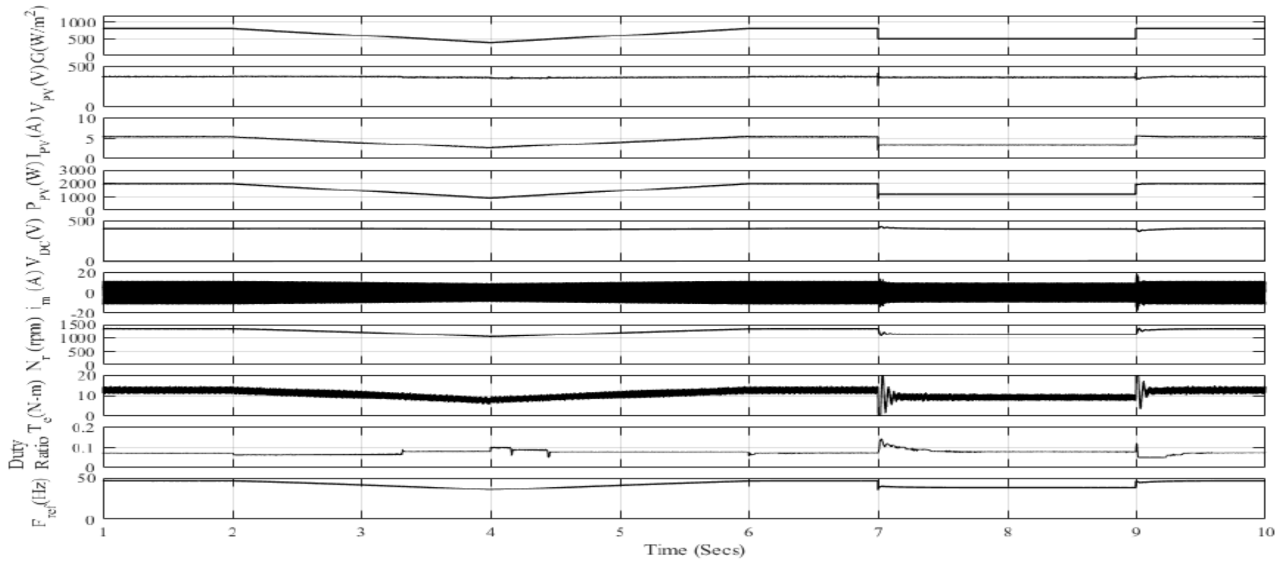

Figure 5 Steady state and transient behavior of proposed system

V. CONCLUSION

The standalone photovoltaic water pumping system with reduced sensor has been proposed. It utilizes only three sensors. The reference speed generation for V/f control scheme has been proposed based on the available power the regulating the active power at DC bus. The PWM frequency and pump affinity law have been used to control the speed of an induction motor drive. Its feasibility of operation has been verified through simulation and experimental validation. Various performance conditions such as starting, variation in radiation and steady state have been experimentally verified and found to be satisfactory. The main contribution of the proposed control scheme is that it is inherently, immune to the error in estimation of pumps constant. The system tracks the ant colony optimized MPPT with acceptable tolerance even at varying radiation. Incremental conductance and ant colony optimization MPPT technique exhibits same characteristics.

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