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Design Considerations and Performance Improvement of a Photovoltaic Pumping System Based on a Synchronous Reluctance Motor

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***Abstract* – This paper presents the performance analysis of a photovoltaic (PV) energy source driving a Synchronous Reluctance (SyncRel) motor. The design considerations of the PV array, suitable for driving a centrifugal pump, are studied. Three design approaches are proposed at an average insolation of 0.5 kW/m^2. These approaches depend upon determining the system operating point firstly and then maintaining this point on the PV generator characteristics. Either starting current, maximum power point or pre-specified voltage regulation is taken into account in each design approach. It has been found that the minimum number of cells can be achieved using the second design approach. A simple control strategy is presented to improve the system performance based on the PV generator parameters estimated from the second design approach. The proposed control strategy has mainly three functions; ensuring a successful motor starting, maintaining the motor voltage within a permissible range and forcing the PV array to operate at the Maximum Power Point (MPP) as possible. A sample of simulation results is introduced using the SyncRel motor measured parameters and the estimated parameters of the PV array.**

***Index Terms* – Design considerations, photovoltaic pumping system, synchronous reluctance motor, maximum power point tracking (MPPT).**

I. NOMENCLATURE

A_p	Proportionality factor of the pump, N.m/rad/sec
B	Viscous friction coefficient, N.m/rad/sec
H	Total pumping head, m
I_{ds}, I_{qs}	Direct and quadrature axis stator current respectively, A
I_g	Current drawn from the array, A
J	Inertia of the system, Kg-m^2
L_{ds}, L_{qs}	Direct and quadrature axis stator inductance of SyncRel motor respectively, H
L_{md}, L_{mq}	Direct and quadrature axis magnetization inductance respectively, H
P	Number of pole pairs
p	Differential operator (d/dt)
P_o	Output power of the motor, W
Q	Flow rate, m^3/h
r_{dr}, r_{qr}	Direct and quadrature axis rotor resistance of SyncRel motor respectively, Ω
R_s	Stator resistance of SyncRel motor, Ω
T_e	Electromagnetic torque of the motor, N.m
T_o	Constant torque of the pump, N.m
V_{ds}, V_{qs}	Direct and quadrature component of stator voltage respectively, V
V_g	Terminal voltage of the array, V
V_m, V	Maximum and effective values of the motor input voltage respectively, V
δ	Load angle, rad
ω_r, ω_s	Motor and synchronous speed, rad/sec

II. INTRODUCTION

The photovoltaic (PV) pumping systems are receiving more attention in recent years especially in remote areas where connection to the grid is technically not possible or costly. In addition, PV pumps have recently received considerable attention due to major development in the field of solar cell material and technology. dc motors driven PV pumps are already used overall the world because they can be directly connected to the PV generator and an adjustable dc drive is easy to achieve [1, 2]. However, this system suffers from increased motor cost and maintenance problems due to the presence of commutator and brushes. Hence, pumping system based on brushless motors represents an attractive alternative due to its merits over dc motors [1, 3]. A synchronous reluctance motor fed by a photovoltaic generator represents a brushless scheme that should be studied in details.

The implementation of the PV energy sources for water pumping and irrigation applications based on dc motor [2, 5], an induction motor [1, 4] and permanent magnet (PM) synchronous motor [3] has found a considerable interest from researchers.

However, the photovoltaic pumping system based on a synchronous reluctance motor has not recorded any significant attention from researchers until to date.

The objective of this paper is to investigate the design considerations of the PV array, suitable for driving a centrifugal pump at an average insolation of 0.5 kW/m^2. In addition, the paper aims at suggesting suitable control strategies to improve the performance of the proposed system.

III. SYSTEM MODELING

Figure 1 shows the block diagram of the proposed system. The mathematical model of each part is given as follows:

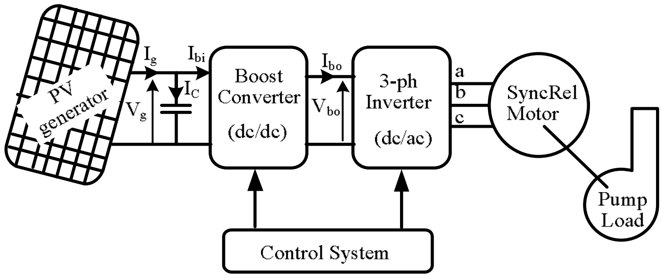

Fig. 1. Block diagram of the proposed system

A. PV Generator Model

The PV generator converts the solar insolation into electric dc power. It consists of an array of PV cell modules connected in series-parallel combinations to provide the desired dc voltage and current. The voltage-current (V_g-I_g) relation of the PV array is given by [5]:

$$V_g = (\frac{T_c N_s kA}{q}) \ln(\frac{I_{ph} - I_g + N_p I_s}{N_p I_s}) - (\frac{N_p}{N_s}) I_g r_s \quad (1)$$

where T_c is the cell temperature, I_{ph} is the photocurrent, I_s is the saturation current, K is the Boltzmann constant ($1.38*10^{-23}$ J/K), A is the solar cell ideal factor of the diode, r_s is the series cell resistance and q is the electron charge ($1.6*10^{-19}$ C).

The photocurrent which mainly depends upon the solar insolation and the cell temperature is described as [6]:

$$I_{ph} = (I_{sc} + k_i (T_c - T_{ref}))G \quad (2)$$

where I_{sc} is the cell short-circuit current at 25°C and the standard value of a solar insolation (1 kW/m^2), k_i is the temperature coefficient of the cell short-circuit current (A/°C), T_{ref} is the cell reference temperature and G is a solar insolation (kW/m^2).

The photocurrent which mainly depends upon the solar insolation and the cell temperature is described as [6]:

$$I_s = I_{rs} (\frac{T_c}{T_{ref}})^3 \exp(\frac{qE_G}{kA} (\frac{1}{T_{ref}} - \frac{1}{T_c})) \quad (3)$$

where I_{rs} is the cell reverse saturation current at the reference temperature and the solar radiation and E_G is the bang-gap energy of the semiconductor used in the cell.

B. Boost Converter Model

The dc-dc boost converter is inserted to adjust the dynamic equivalent impedance seen by the PV generator. An equivalent pure gain represents the converter model [7]. Therefore, the relation between the PV voltage (V_g) and the boost converter output voltage (i.e. the inverter input voltage, V_{bo}) can be written as [8]:

$$V_{bo} = \frac{1}{1-d} V_g \quad (4)$$

where d is the duty ratio of the boost converter.

For lossless converter, the relation between the boost converter input current (I_{bi}) and boost converter output current (i.e. the inverter input current, I_{bo}) is given by [8]:

$$I_{bi} = \frac{1}{1-d} I_{bo} \quad (5)$$

C. Inverter Model

The inverter is used to convert the dc voltage of the PV generator to a three-phase voltage with variable amplitude and variable frequency. A natural Pulse Width Modulation (PWM) switching technique is used to drive the inverter. The three-phase inverter voltages can be expressed as [9]:

$$\left.\begin{aligned} v_{an} &= \frac{1}{3}(2S_1 - S_2 - S_3)V_{bo} \\ v_{bn} &= \frac{1}{3}(-S_1 + 2S_2 - S_3)V_{bo} \\ v_{cn} &= \frac{1}{3}(-S_1 - S_2 + 2S_3)V_{bo} \end{aligned}\right\} \quad (6)$$

where v_{an},v_{bn} and v_{cn} are the outputs voltages of the inverter.

Furthermore, the photovoltaic current is given by:

$$I_g = I_c + \frac{S_1 i_a + S_2 i_b + S_3 i_c}{1-d} \quad (7)$$

where i_a, i_b and i_c are the SyncRel motor stator currents of the inverter and I_c is the capacitor current which is given by the following relation [9]:

$$I_C = C \frac{dv_g}{dt} \quad (8)$$

where C is the capacitance of the condenser which inserted between the PV generator and the power converters to smooth the output dc voltage and to reduce the equivalent impedance seen by the PV generator.

when a switch signal (S_1, S_2 or S_3) equals 1, it means that the corresponding upper switch is ON while the lower one is OFF and vice verse.

The effective value of the fundamental motor phase voltage is given by [8]:

$$V = \frac{MV_{bo}}{2\sqrt{2}} \quad (9)$$

where the modulation index M is the ratio between the reference sine wave and the triangular carrier wave.

C. Synchronous Reluctance Motor Model

The presented machine is a synchronous reluctance motor with an axially laminated rotor type [10]. The rotor is equipped with cage to provide a starting torque. The machine was represented in the qd- axis reference frame. The qd- axis reference frame is fixed in the rotor, which rotates at ω_r. The qd-axis voltage equations can be written in matrix form as:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + pL_{qs} & \omega_r PL_{ds} & pL_{mq} & \omega_r PL_{md} \\ -\omega_r PL_{qs} & R_s + pL_{ds} & -\omega_r PL_{mq} & pL_{md} \\ pL_{mq} & 0 & r_{qr} + pL_{qr} & 0 \\ 0 & pL_{md} & 0 & r_{dr} + pL_{dr} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (10)$$

The electromagnetic developed torque expression and the electromechanical equation can be written as:

$$T_e = \frac{3}{2} P(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (11)$$

$$T_e = Jp\dot{\omega}_r + B\dot{\omega}_r + T_L \quad (12)$$

The machine power angle δ can be calculated as:

$$\delta = \int (\omega_r - \omega_s) dt \quad (13)$$

The steady state qd-axis stator currents can be given by:

$$I_{qs} = (\frac{V}{D})[X_{ds} \sin(\delta) + R_s \cos(\delta)] \quad (14)$$

$$I_{ds} = (\frac{V}{D})[X_{qs} \cos(\delta) - R_s \sin(\delta)] \quad (15)$$

where $D = X_{ds} X_{qs} + R_s^2$ (16)

The qd- axis supply voltage can be expressed as a function of the machine power angle as:

$$V_{qs} = V_m \cos(\delta) \quad (17)$$

$$V_{ds} = -V_m \sin(\delta) \quad (18)$$

D. Centrifugal Pump Model

The hydraulic output power of the pump can be characterized by [11]:

$$P_p = 2.725QH \quad (19)$$

On the other hand, the load torque of the centrifugal pump is given by [5]:

$$T_L = T_o + A_p \omega_r^{1.8} \quad (20)$$

where T_o and A_p are constants.

IV. Design approaches

Three approaches are proposed in the design process for selecting the PV generator parameters at an average insolation of 0.5 kW/m^2. These approaches depend upon determination the steady state operating point of the system (V_g, I_g) firstly and then maintaining this point on the PV generator characteristics. In each approach, another criterion should be taken into account in order to complete the design process and obtain the final PV generator characteristics.

In the first approach, the selection of the PV generator parameters is based on the motor starting current in addition to the system operating point. In this approach, taking the motor starting current into account in the design process ensures the motor capability for starting with the rated conditions.

On the other hand, in the second approach, the steady state operating point (V_g, I_g) is assumed to be at the maximum output power point of the PV generator which equals to the required motor input power irrespective of the motor capability for starting with the rated conditions.

In the third approach, the PV open circuit voltage is taken into consideration in the design process in order to guarantee the level of this voltage in a permissible range. The selection of the PV generator parameters in this approach is based on assuming a voltage regulation of 20% at an average insolation of 0.5 kW/m^2.

V. Results and discussions

In order to investigate the validity of the proposed design approaches, a sample of simulation results is introduced. The given samples are obtained using the measured parameters of a synchronous reluctance motor rated at 470 W, 400 V and 4-poles. The parameters of the PV array are estimated depending upon the design approach. The proposed system parameters are given in the appendix section. Detailed parameters related to the used PV cell are given in [10].

The PV generator operating point has been obtained for the following assumptions:

- The motor runs at its rated output power of 470 W
- The motor efficiency is 0.83 so that the input motor power is 565 W.
- The PV generator output power equals the motor input power (assume lossless converters).
- The boost converter gain ($\frac{1}{1-d}$) equals 1
- The inverter gain ($\frac{M}{2\sqrt{2}}$) approximately equals 0.3.
- The motor is loaded by a suitable centrifugal pump which can be used in an irrigation system or other human needs.

According to the previous assumptions, it was found that, the PV generator operating point is V_g = 665.5 V and I_g = 0.85 A. A sample of the obtained simulated results corresponding to the proposed three approaches can be presented as follows:

A. The First Approach

According to the first approach, considering the motor starting current and the daily average solar insolation level (G) of 0.5 kW/m^2, the number of parallel strings (N_p) and the number of series cells (N_s) which gives this operating point (665.5 V, 0.85 A) are 9 and 1433 respectively so that total number of cells are 12897.

Fig. 2 shows the characteristics of the PV generator at different solar insolation levels corresponding to the first approach. Fig. 3 shows the run-up response of the SyncRel motor under rated conditions corresponding to the first approach at an insolation level of 50 %. It can be noted that the motor works synchronously with the rated conditions at this insolation level. In this approach, the no-load voltage is slightly higher than the rated value and the voltage regulation is less than 20 percent at an insolation level of 50 %. Detailed simulation results are presented in [10].

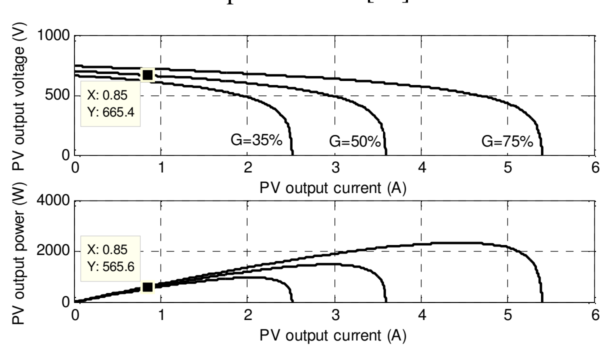

Fig. 2. Characteristics of the PV generator at different insolation level corresponding to the first approach

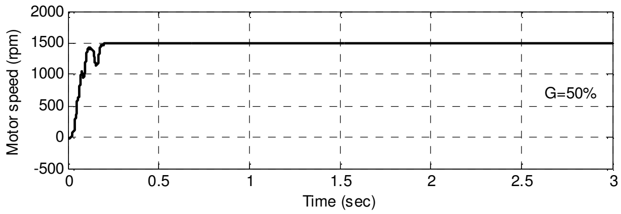

Fig. 3. Run-up response of a SyncRel motor under rated conditions corresponding to the first approach

B. The Second Approach

With respect to the second approach, the number of parallel strings (N_p) and the number of series cells (N_s) which gives this operating point (665.5 V, 0.85 A) are 3 and 1730 respectively so that the total number of cells are 5190. In this case, this operating point corresponds to the maximum output power of the PV generator.

Fig. 4 shows the characteristics of the PV generator corresponding to the second approach at different solar insolation levels. Fig. 5 shows the run-up response of the SyncRel motor under rated conditions corresponding to the second approach at insolation levels of 50 % and 75 %. It is clear that the motor cannot work synchronously with the rated conditions at an insolation level of 50%. In this case, the motor operates in asynchronous mode. However, this problem is solved at insolation levels higher than 50%. As shown in Fig. 5, the motor works synchronously with the rated conditions at an insolation level of 75%.

The voltage regulation in this approach is found to be higher than 20 percent at all insolation levels equal or higher than 0.5 kW/m^2.

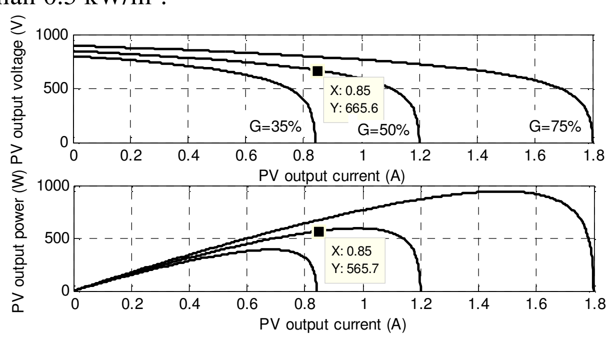

Fig. 4. Characteristics of the PV generator corresponding to the second approach at different insolation level

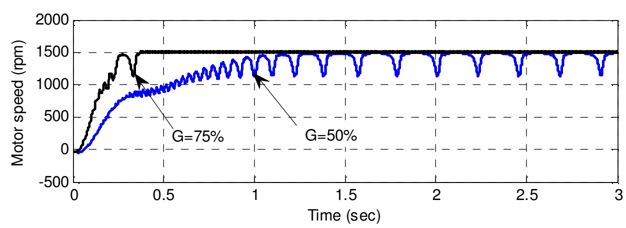

Fig. 5. Run-up response of a SyncRel motor under rated conditions corresponding to the second approach

C. The Third Approach

On the other hand, according to the third approach, considering the voltage regulation of 20% and the daily average solar insolation level (G) of 0.5 kW/m^2, the number of parallel strings (N_p) and the number of series cells (N_s) which gives this operating point (665.5 V, 0.85 A) are 6 and 1480 respectively so that the total number of cells are 8880.

The characteristics of the PV generator, corresponding to the third approach, at different solar insolation levels is shown in Fig. 6. Fig. 7 shows the run-up response of the SyncRel motor under rated conditions for N_p=6 and N_s=1480 at an insolation level of 50%. It is obvious that the motor works synchronously with the rated conditions at this insolation level.

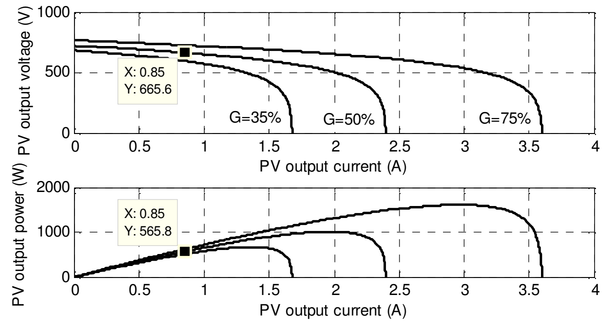

Fig. 6. Characteristics of the PV generator corresponding to the third approach at different insolation level

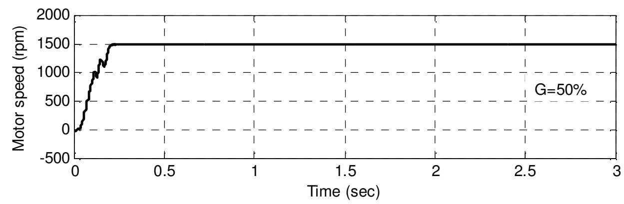

Fig. 7. Run-up response of a SyncRel motor under rated conditions corresponding to the third approach

VI. System Control

Based on the previous results of the three design approaches, it has been observed that the minimum number of cells can be achieved using the second approach. However, the motor cannot work synchronously at insolation level equal or less than 0.5 kW/m^2 and the voltage regulation is higher than 20 percent for all insolation levels equal or higher than 0.5 kW/m^2. In this work, the PV generator parameters are selected depending upon the second approach and all related problems will be studied and solved using the proposed control strategy.

The proposed control strategy performs the following functions:

- Ensuring successful motor starting
- Maintaining the motor voltage within a permissible range
- Forcing the PV array to operate at the Maximum Power Point (MPP) as possible

A. Ensuring successful motor starting

In general, the motor starting capability depends on the operating motor voltage and loading conditions. Moreover, the motor voltage depends on PV voltage for given values of insolation levels. Therefore, there is a critical insolation level for the system below which the SyncRel motor cannot work synchronously under the given pumping load. However, due to the presence of rotor cage, the motor can work asynchronously at insolation levels below the critical value.

To overcome the problem of starting, the ratio of the motor voltage to the motor frequency is kept constant. The motor frequency is controlled accordingly to the variation of its input voltage as follows [12].

$$\frac{V}{f} = \frac{MV_{bo}}{2\sqrt{2}f} = \text{constant} \quad (21)$$

B. Maintaining the motor voltage within a permissible range

With high insolation levels, the motor voltage increases. In the proposed control strategy, to keep motor voltage at its rated value, the modulation index (M) is varied.

C. Forcing the PV array to operate at the MPP as possible

Generally, when a PV array is directly coupled to a load, the operating point of the system depends upon characteristics of both the PV generator and the load. This operating point is seldom to be at the MPP of the PV array (i.e. the PV generator is not producing the maximum power). This mismatching between a PV module and a load requires further over-sizing of the PV array and thus increasing the overall system cost [13].

The peak power can be reached with the help of a dc-dc boost converter that acts as an interface between the load and the PV array. By changing the duty ratio of the boost converter, the load impedance as seen by the source is varied and matched at the point of the peak power with the source so as to transfer the maximum power. In the literature, several techniques of maximum power point tracking (MPPT) have been proposed, analyzed and implemented. However, Perturb and Observe (P and O) and Incremental Conductance (INC) algorithms are most widely used, especially for low-cost implementations. The perturb and observe MPPT technique is used in this work. The flow chart of perturb and observe MPPT algorithm is shown in [13].

For the proposed system, the critical insolation level (G_{cr}) below which the SyncRel motor cannot work synchronously under the given pumping load is found to be equal 55% (0.55 kW/m^2).

For all insolation levels less than 55%, the motor cannot reach synchronous speed when loaded by the given pump. A voltage per hertz (V/f) control method is suggested to be employed to deal with this situation.

For all insolation levels higher than 50%, the motor voltage is higher than its rated value. The modulation index (M) of the inverter is implemented to control the motor input voltage and maintain its level at the rated value. The modulation index (M) is controlled using a PI controller. A trial and error approach has been used to obtain the controller parameters k_p and k_i. An acceptable response is obtained using the following values k_p=0.54 and k_i=7.5.

On the other hand, at insolation levels less than 50%, the maximum output power of the PV array is less than the motor rated power. Therefore, the MPPT technique is required to maximize the PV usage. In order to achieve this target, the dc-dc boost converter is controlled via varying its duty ratio.

In the simulation process, the insolation level is firstly assumed to be equal 35 % for to 2 seconds; then it is increased to 75 %.

Figure 8 shows the run-up response of the SyncRel motor with and without control for the adopted insolation levels. It is obvious that the motor cannot work synchronously without control at insolation level of 35% because it is less than the critical value. However with the control strategy, the problem of starting is solved as shown in the figure. It can be noted that the motor operates at a synchronous speed of 1302 rpm which corresponds to a frequency approximately equals 43.5 Hz.

On the other hand, for insolation level of 75%, the motor can work synchronously without control as it is higher than the critical value.

The response of the PV output voltage and the motor RMS voltage at the same conditions is shown in figure 9. It can be deduced that, for insolation level of 35%, the motor voltage with control equals 173.6 V which ensures a constant voltage per hertz operation. Moreover, it can be noted that, for insolation level of 75%; the motor voltage without control is higher than the rated value. However, it can be observed that, aiding with the proposed control system; the problem is solved and the motor voltage can be maintained at its rated value.

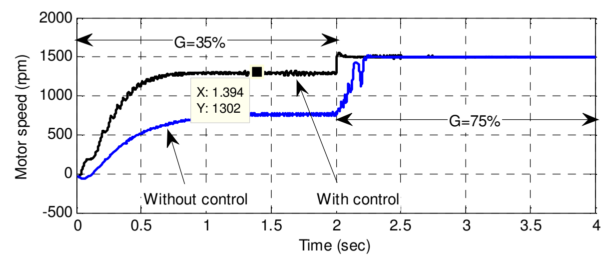

Fig. 8: Run-up response of the SyncRel motor with and without control for different insolation levels

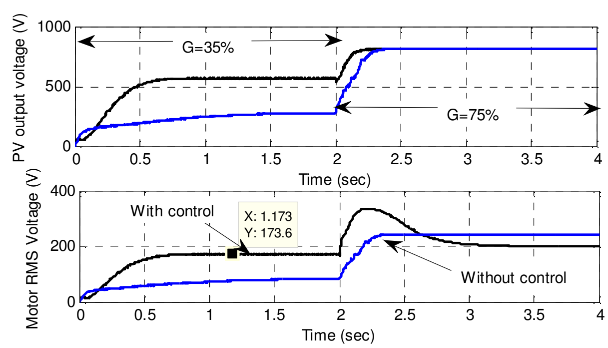

Fig. 9: Response of the PV output voltage and the motor RMS voltage with and without control for different insolation levels

Figure 10 shows the response of the PV output power for insolation levels of 35 % and 75%. At insolation level of 35%, without control, the PV output power is less than the maximum available power. However, it is clear from figure 10 that, using the MPPT control strategy, the steady-state PV output power is increased to be equal the corresponding maximum value. As a result of extracting the maximum power from the PV array, the PV voltage as will as the motor voltage are increased as shown in figure 9. At insolation level of 75%, it is noted that the steady-state PV output power is kept at the rated value so that MPPT is not required.

Moreover, figure 11 shows the response of the pump flow rate at a total pumping head of 10 m corresponding to the adopted insolation changes given. At insolation level of 35%, it can be noted that, due to using the MPPT control strategy, the pump flow rate is increased compared with uncontrolled system. On the other hand for insolation level of 75%, it can be observed that, the steady-state pump flow rate is constant with or without control as there is no control on the PV output power and the motor operates at the rated conditions.

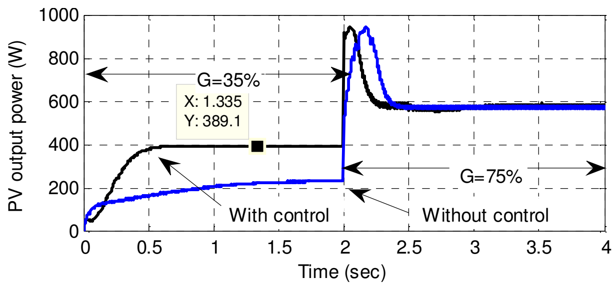

Fig. 10: Response of the PV output power with and without control for different insolation levels

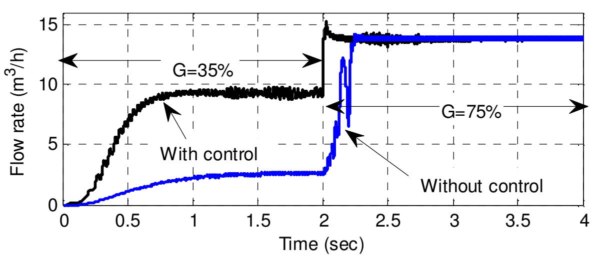

Fig. 11: Response of the pump flow rate with and without control for different insolation levels at H= 10 m

VII. CONCLUSIONS

This paper has investigated the design considerations of the photovoltaic energy source suitable for driving a centrifugal pump. Three approaches have been proposed in the design process, depending upon the operating point of the system. In these approaches, staring current, maximum power point or pre-specified voltage regulation has been taken into account.

On the other hand, it has been observed that the minimum number of cells can be achieved using the second approach. However, the motor cannot work synchronously at an average insolation level of 0.5 kW/m^2 and the voltage regulation is higher than 20 percent.

A simple control strategy has been proposed to improve the system performance based on the PV generator parameters estimated from the second approach. The proposed control strategy aims at ensuring a successful motor starting, the motor voltage to be within a permissible range and the PV array to operate at the maximum power point (MPP) as possible. The modulation index (M) of the inverter has been used to control the motor input voltage and maintain its level at the rated value. On the other hand, a voltage per hertz (V/f) control method has been suggested to ensure a successful motor stating. Moreover, the MPPT has been applied only at all insolation levels less than 50%. The obtained simulation results prove the effectiveness of the control strategy on the system performance. As a result, it has been observed that, using the MPPT control strategy, the pump flow rate has been increased compared with uncontrolled system.

VIII. APPENDIX

A. Parameters of the PV cell

V_{oc}=0.54 V, I_{sc} = 0.8 A, r_s = 0.05 Ω, C=220 μF

B. Parameters of SyncRel motor

P_o = 470 W, V_{rated} = 200 V, I_{rated} = 2 A
R_s=10 Ω, r_{qr}=19.29 Ω, r_{dr}=38.9 Ω
L_{qs} = 0.2228 H, L_{qr} = 0.0177, L_{mq} = 0.2043 H
L_{ds} = 0.6366 H, L_{dr} = 0.0745 H, L_{md} = 0.5621 H
B=0.000005 N.m/rad/sec, J=0.0015 Kg-m^2, P=2

C. Parameters of centrifugal pump

T_o =0.3 N.m, A_p=0.0003, η_p =80%

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