A high-performance control scheme for photovoltaic pumping system under sudden irradiance and load changes

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ABSTRACT

A low-cost photovoltaic (PV) pumping system based on three phase induction motor (IM) without the use of chemical energy storage elements is presented in this paper. The PV generator-side boost converter performs the maximum power point tracking (MPPT), while the IM−side two-level inverter regulates the net DC-link voltage and the developed electromagnetic torque by IM, which is coupled with a centrifugal pump. An improved variable step size perturb and observe (P&O) algorithm is proposed to reduce the steady-state PV power fluctuation, to accelerate the tracking operation under sudden irradiance changes, and to protect IM under load drops. The proposed algorithm is based on a current control approach of the boost converter with a model predictive current controller to select the optimal control action. Moreover, predictive torque and flux control (PTC) is used to control IM drive, due to its advantages such as faster torque response, lower torque ripple, and simplicity of implementation. Furthermore, a Takagi-Sugeno (T–S) type fuzzy logic controller (FLC) is developed in order to regulate the DC-link voltage, by producing the torque reference for PTC algorithm. In order to examine and assess the performance of the proposed control scheme for PV pumping system, a complete simulation model is developed using MATLAB/Simulink\textsuperscript{™} environment and confirmed through real-time hardware in the loop (HIL) system. The obtained results indicate the excellent performance of the proposed control scheme, which is much better than the conventional scheme based on conventional techniques (P&E algorithm and direct torque control (DTC)).

1. Introduction

In recent years, the photovoltaic (PV) power application in off-the-grid system is becoming more widespread, particularly in water pumping systems. These PV systems are employed widely in the fractional power range. In a continued effort to increase the efficiency, to decrease the cost and to improve the reliability performance of the PV pumping system, different configurations have been proposed in the literature (Achour et al., 2016; Antonello et al., 2017; Betka and Attali, 2010; Chergui and Bourahla, 2013; Elgendy et al., 2010; Elkholy and Fathy, 2016; Jain et al., 2015; Kumar and Bhim, 2016; Mohamed et al., 2017; Mohamed et al., 2014; Niapour et al., 2011; Periasamy et al., 2015; Rahrah et al., 2015; Singh et al., 2016; Vitorino et al., 2011). The PV pumping systems based on AC motors, particularly induction motors (IM) are often preferred because it makes them more reliable, economical, and no need to the permanent maintenance (Periasamy et al., 2015). The two typical configurations of a PV pumping systems using IM are single or dual stages (Periasamy et al., 2015). In dual stages, the first stage is a DC-DC boost converter, in general from the PV module to a DC link (usually as a capacitor). This converter is used for boosting the PV voltage array and maximizing the power; the second one is for conversion of the PV power into variable frequency power source. While, in the single stage, the DC-DC converter is not required, and a number of PV panels must be connected in a series arrangement. This method is impractical for fractional kilowatt rating (< 1 kW) PV system.

However, in such systems the generated PV energy must be properly regulated and maximized. Various control strategies have been suggested in the literature for tracking the maximum power point (MPPT) of PV array. Although these control strategies can achieve the same goals, such as high efficiency and fast speed under varying atmospheric (irradiance and temperature) conditions, their principles differ. The
most conventional MPPT techniques are known as Perturb and Observe (P&O) (Ahmed and Salam, 2015; de Brito et al., 2013; Femia et al., 2005; Femia et al., 2012) and incremental conductance (INC) (de Brito et al., 2013; Safari and Mekhilef, 2011; Tey and Mekhilef, 2014). Non-conventional MPPT techniques based on intelligent controller have been developed recently, such as fuzzy logic (Alajmi et al., 2011; Al Nabulsi and Dhahouadi, 2012; Bendib et al., 2015; Radjai et al., 2014; Salam et al., 2013), artificial neural network (Rizzo and Scelba, 2013; Salam et al., 2013), neuro-fuzzy (Syafaruddin et al., 2009), genetic algorithm (Shaiiek et al., 2013) and particle swarm optimization (Ishaque et al., 2012). Nevertheless, the flexibility and simplicity of the P&O, make it the most used in the commercial product (Femia et al., 2012). However, this control technique suffers from high frequency oscillations, large steady-state errors and poorer tracking of the MPP for sudden irradiance changes. In order to overcome these drawbacks, a closed loop performing the P&O is used to regulate the PV voltage in the case of the P&O voltage-based (VMPPT) (Elgendy et al., 2012; Harrag and Messalti, 2015; Piegari and Rizzo, 2010), or the PV current in the case of the P&O current-based (CMPPT) (Bianconi et al., 2013a, 2013b; Kollimalla and Mishra, 2014; Shadmand et al., 2014). According to the linear relationship between the PV current and irradiance, the CMPPT
becomes faster (Femia et al., 2012), but in sudden irradiance decrease, it might lead to the failure of the control. The instability problem of the CMPPT is discussed in detail in (Femia et al., 2012). This explains the few articles on CMPPT in the literature. In Bianconi et al., 2013a, 2013b, an appropriate voltage compensation loop is used to interface a sliding mode current-based controller with a P&O algorithm to ensure the right decision for the CMPPT operation, under sudden irradiance changes. An adaptive P&O method has been aimed to capture the optimal PV current by Kollimalla and Mishra (2014). The developed MPPT combines the fractional short-circuit current (FSCC) method with the conventional P&O algorithm based on a current perturbation as an alternative of voltage perturbation to speed-up the tracking performance. The algorithm applied the reference current of a proportional-integral (PI) controller that produces the signal controlling. A real-time application of a P&O algorithm that generates the reference current for the model predictive current controller has been suggested in Shadmand et al. (2014). Where the proposed controller uses the system model for calculating the future error for the next sampling time. Then, the switching state of the DC-DC converter that minimizes this error is chosen to apply in the upcoming sample time. However, the major issue in the battery-less PV pumping system with MPPT control is that the motor must absorb all the extracted power by the PV array even if there is no load demand (Mohamed et al., 2017). Therefore, the occurrence of load drops due to any reason might lead to increase the motor voltage, which can may damage the motor. In order to avoid this issue, Mohamed et al. (2017) designed a fuzzy MPPT for a battery-less PV system based on DC motor to maximize the PV power under sudden irradiance changes and to protect the motor under different load conditions. The designed method has been successfully implemented using a Cuck converter, and compared with conventional MPPT algorithms.

In addition, the electromechanical power conversion in the PV pumping system must be with minimum losses for different climatic conditions. Different control drives for IM are presented in the literature, the most effective control methods used in PV pumping systems are field-oriented control (FOC) (Vitorino et al., 2011) and direct torque control (DTC) (Achour et al., 2016; Chergui and Bourahla, 2013). The greatest drawbacks of these control strategies are the sensitivity to parameters change of IM, and torque ripples which lead to system power losses.

Nevertheless, during the last few years the model predictive control (MPC), especially finite control set model predictive has rapid expansion as of this technique simplicity that is very intuitive and easy to understand. Moreover, micro-electronics and microprocessor development has facilitated the implementation of this methodology (Rodriguez and Cortes, 2012; Rodriguez et al., 2013). The main idea of the MPC is to predict future changes in the process, by means of the
These predictions permit to select the optimal control action, to control electrical energy by using power converter (Rodriguez and Cortes, 2012; Rodriguez et al., 2013).

This work proposes an effective control scheme for a PV pumping system based on IM, where an improved P&O based-CMPPT is developed to generate a variable current step size in order to improve the performance of the conventional P&O, and increase the stability of the MPPT under abrupt irradiance changes. Moreover, the proposed algorithm supported by an extra condition to protect the IM under load drops. The MPPT control includes an MPC current controller, and the simplicity of implementation is nevertheless maintained. On the other hand, a Takagi-Sugeno (T-S) type fuzzy logic controller (FLC) is suggested to regulate and keep the DC-link voltage constant at the desired value regardless the operation conditions. The torque command produced by the FLC can be directly applied to the predictive torque and flux control (PTC) algorithm, which eliminates the use of speed control loop. By adopting the PTC algorithm for IM drive, a significant flux and torque ripples reduction are achieved, when compared with the conventional DTC. Numerical simulations and real-time hardware in the loop (HIL) implementations have been done to confirm the performance improvement of the proposed control scheme.

2. System description and modeling

The overall schematic of the PV pumping system under study is shown in Fig. 1. The PV modules convert the solar radiation into electrical energy, feeding an IM via a boost converter and a three phase two-level inverter. Therefore, the maximum of the PV generator power can be reasonably tracked by the boost converter, and fed to the IM through the inverter. The IM-side inverter regulates the DC-Link voltage and the power transfer between the DC-link and the utility IM. Finally, the mechanical energy is converted into hydraulic energy by the group IM-centrifugal pump.

3. Control scheme proposed

The complete control scheme based on the fuzzy logic and model predictive strategies for the proposed PV pumping water system is shown in Fig. 2. In the proposed system, regulation is needed for:

- MPPT during all climatic conditions to improve PV energy conversion efficiency.
- DC-link voltage to ensure proper operation for the inverter.
- Electromechanical power conversion for IM drive.

3.1. MPPT control

For the proposed MPPT control, an improved variable step size P&O based-CMPPT is used for extracting the optimum PV current. Therefore, an MPC current controller determines the optimal switching control for the boost converter in order to regulate the PV current, by controlling the average input current of the boost converter.

3.1.1. Variable step size P&O based-CMPPT

The P&O based-CMPPT is generally used with fixed current step size. This strategy works by perturbing the operation PV current, the perturbation effect is observed on the output power for deciding the direction of the next perturbation; if the present power is bigger than the previous, the perturbation remains in the same direction (the sign of the next perturbation is maintained), otherwise the direction is reversed. In this paper, an improved variable current step size algorithm is proposed for the P&O based-CMPPT method; its objective is to find a simple and effective way to improve tracking accuracy as well as...
tracking dynamics. The current control is chosen to speed-up the tracking performance and to follow the right direction of the MPP under irradiance changing; due to the linear relationship between PV current and irradiance levels. The derivative of the PV power to voltage \( \frac{dP_{PV}}{dV_{PV}} \), as shown in Fig. 3, is employed to determine the variable current step size, which is adopted to reduce the oscillation of the PV power in steady-state and accelerate the MPP tracking. The variable current step size is given as follows:

\[
I_{inc} = N \frac{dP_{PV}}{dV_{PV}}
\]

where the coefficient \( N \) is the scaling factor that is tuned by the design to adjust the current step size.

Fig. 4 illustrates the flowchart of the proposed algorithm. In order to ensure that the PV maximum power is provided during the sudden irradiance decrease, a simple loop is added to the main P&O based-CMPT scheme. When a sudden irradiance occurs, the proposed algorithm is quickly able to detect it using a simple if statement through the predetermined current \( I_{set} \) and voltage \( V_{set} \). Therefore, the modified algorithm is also required to reset the PV reference current for the upcoming MPPT period. Where, the stored value of \( I_{PV} \) is multiplied by a proportionality constant \( K_{opt} \), which is used in FSCC algorithm, to achieve an approximate value of the optimum operating current. Thus, the PV system is able to track the MPP smoothly under sudden irradiance decrease.

In addition, unlike conventional MPPTs, the modified algorithm is provided a simple and effective way to protect the IM under load drops. A predetermined value \( I_{min} \) which represents the stator current root mean square (rms) value at the rated speed without load, is stored to identify the existence of load drops. If the operation stator current rms \( I_s \) is smaller than the predetermined value, the PV reference current is set to zero in order to stop the PV power extraction; otherwise, the algorithm continues to track the MPP. Moreover, the proposed algorithm is supported by a numerical state machine to distinguish between the IM starting current and the load drop condition in the real-time implementation (Mohamed et al., 2017).

### 3.1.2. MPC current controller

The MPC is an advanced power converter control technique. The main idea of this control strategy is the prediction of the future behavior of the controlled variables. Then these predictions are used to generate the optimal control action. The boost converter is chosen to realize the MPPT. It is usually used in PV systems due to some of its important features, such as being simple, robust, and also it offers a continuous current at the input. The dynamic model of the boost converter can be expressed as follows (Femia et al., 2012):

![Fig. 7. FLC membership functions. (a-b) Inputs, (c) Output.](image)

![Fig. 8. (a) Current-voltage and (b) power-voltage characteristics of the PV array for different irradiance levels.](image)

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where \( I_L \) is the inductor current, \( V_{DC} \) the DC-link capacitor voltage, \( I_{inv} \) the inverter input current, \( L \) and \( C \) are the electrical parameters of the Boost converter, \( S \) the switching signal taking value from the discrete set \( S = \{0, 1\} \).

For discretization of the boost converter model Euler formula is used

\[
\frac{d}{dt}I_L = -(1-S) \frac{1}{L} V_{DC} + \frac{1}{L} V_{PV}
\]

\[
\frac{d}{dt}V_{DC} = (1-S) \frac{1}{C} I_L + \frac{1}{C} I_{inv}
\]

Therefore, the discrete equation of inductor current can be expressed as follows:

\[
I_L(k+1) = I_L(k) - (1-S) \frac{T_s}{L} V_{DC}(k) + \frac{T_s}{L} V_{PV}(k)
\]

where \( T_s \) is the sampling time used in the MPC algorithm.

The flowchart of the proposed MPC algorithm is presented in Fig. 5. From the actual inductor current, this algorithm predicts the value during the next sampling instant using Euler discretization method, the
measured inductor current, PV voltage and DC-link voltage. The prediction of inductor current $I_L(k+1)$ is obtained for both switch states, and the reference PV current $I_{PV}^*$ from MPPT algorithm. Finally, a cost function is minimized and the appropriate switching state is selected at every sampling time according to the following quantity:

$$g_{S_{a=0.1}} = |I_L(k+1) - I_{PV}^*|$$

(6)

3.2. Fuzzy logic DC-Link controller

Conventionally, a classical PI regulator is used to maintain a constant DC-link voltage at a reference value, and generates the torque reference regardless of operation conditions, for the two stages PV pumping system (Achour et al., 2016; Vitorino et al., 2011). However, the fuzzy logic control is characterized by simple structure, robustness, and independence of the process model on the contrary to the conventional control. Therefore, in order to optimize performance, a T-S-type FLC is developed to control the DC-link voltage. The block diagram of the proposed FLC is shown in Fig. 6. The error $e(k)$ and change of error $\Delta e(k)$ over a sampling period are considered as inputs of the FLC. The error is computed as the difference between the measured DC-link voltage $V_{DC}(k)$ and the desired reference $V_{DC}^*$.

Fig. 10. Simulation results of the PV pumping system with the proposed control scheme under sudden irradiance variations.
The error change is calculated as:

\[ \Delta e(k) = e(k) - e(k-1) \]  

where \( Z^{-1} \) represents the unit time delay.

The two inputs are fed into FLC unit for fuzzification after being adjusted by the normalization factors \( K_e \) and \( \Delta K_e \), where these factors are optimally selected by means of simulation and experiments.

Fig. 7(a-b) represents the proposed normalized input membership functions in terms of linguistic variables, NB (Negative Big) to PB (Positive Big). Triangular and trapezoidal membership functions are chosen in order to reduce the computational complexity. After fuzzification, the fuzzy inference is carried out by using a T-S method which requires the least computation effort compared to other fuzzy inference methods (Klir and Yuan, 1995). The fuzzy rules used in the proposed FLC can be represented in a symmetric form, as illustrated in Table 1.

Moreover, as presented in Fig. 7(c), the zero-order T-S model is
considered with seven fuzzy variables, i.e., NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big). In the last step, a center weighted average algorithm is used in the defuzzification to convert the output fuzzy subset torque changes \( \Delta T_s(k) \) into numerical value. The torque reference \( \tau_r \) is then produced as:

\[
\tau_r = K_T \Delta T_s(k)
\]

where \( K_T \) is the scaling factor for denormalization of the FLC output, which can be optimally selected through simulation and experiments.

### 3.3. Predictive torque control (PTC)

The MPC-based control for the IM is presented in Fig. 2. It is based on the computation of the required converter voltage vector to be applied during the next sampling time in order to minimize the flux and torque errors (Rodriguez et al., 2012; Uddin et al., 2015; Wang et al., 2015). The torque reference is calculated by an FLC; usually, the reference for the stator flux magnitude is set to a constant.

For the PTC operation, the estimation of stator and rotor flux is necessary. The stator flux \( \varphi_s \) can be calculated according to the dynamic IM model (Rodriguez et al., 2012; Uddin et al., 2015; Wang et al., 2015):

\[
\frac{d}{dt} \varphi_s = -\frac{L_s}{R_s} i_s + R_s \omega_r \varphi_s
\]

Also by using IM model, the rotor flux \( \varphi_r \) can be estimated by:

\[
\varphi_r = \frac{L_r}{L_m} \varphi_s - \left( \frac{L_m L_s}{L_m} + L_m \right) i_s
\]

Based on this estimation, the future behavior of the controlled variable is predicted for the next sampling time \( k + 1 \). For the stator flux vector prediction \( \varphi_s(k + 1) \), the same voltage vector equation used for its estimation is discretized by Euler formula:

\[
\varphi_s(k + 1) = \varphi_s(k) + \tau_i \omega_i(k) - \tau_r \omega_r(k) i_s(k)
\]

where \( \tau_i = L_m/L_r \) is the rotor coupling factor, \( \tau_r = L_r/R_r \) the rotor time constant, \( R_r = R_r + k_r^2 \) the equivalent resistance and \( \tau_r = \frac{L_r}{R_r} \frac{1}{1 - \frac{j \omega_r}{2 \tau_r}} \).

Finally, these predictions are evaluated by the following cost function:

\[
g_k = \| T_r^* - T_r(k + 1) \| + \Delta \| g_s^* \| - \| g_s(k + 1) \|
\]

where \( i \) denotes the index of the stator voltage vector used to calculate the predictions of the controlled variables. \( T_r^* \) is the torque reference,
and $||\phi||$ is the stator flux magnitude reference. The term $\lambda$ represents the weighting factor, which ponders the relative importance of the torque versus the flux control. If the same importance is considered, this factor would be computed as the ratio between the magnitudes of the nominal torque and stator flux $\lambda = \frac{T_{nom}}{||\phi_{nom}||}$ (Rodriguez et al., 2012). In conclusion, the voltage vector which minimizes the cost function will be applied to the inverter, during the next sampling period.

4. Results and discussion

4.1. Numerical simulations

Simulations using Matlab/Simulink™ environment are conducted to test the proposed strategies. The model created in Simulink takes into account the full control system, including the different elements models of the PV pumping system. The PV panel consists of four 120 Wp PV modules connected in a 2 (series) $\times$ 2 (parallel), with the current-voltage and power-voltage characteristics of the PV array illustrated in Fig. 8 (a) and (b). An IM of 0.37 KW is used to drive the pump. The PV pumping system parameters are listed in Appendix. Sampling times are 1 ms, 0.5 ms and 50 $\mu$s for the MPPT, the FLC and the MPC controllers (MPC current controller and PTC algorithm) respectively. The flux stator is kept constant at its rated value 0.71 Wb. The reference for the DC-link voltage is constant and equal to 450 V. For the conventional control scheme, a conventionally fixed step size P&O algorithm based on PI controller is used to track the MPP of the PV panel, and a conventional DTC technique is applied to control the IM drive. The same conditions for the conventional and proposed control schemes are considered, which makes a fair comparison possible.

4.1.1. Sudden irradiance change

An irradiance profile with various sudden irradiance change is

![Graphs showing hydraulic power, pump flow, PV voltage, current, power, and DC-link voltage waveforms for both conventional and proposed schemes under sudden load drop.](image-url)
Fig. 17. HIL responses of the PV voltage, current and power for (a) conventional and (b) proposed schemes under sudden irradiance variations.

Fig. 18. Zoom-in view of Fig. 16 during a step increase in the irradiance level (400 W/m²–600 W/m²).

Fig. 19. Zoom-in view of Fig. 16 during a step decrease in the irradiance level (1000 W/m²–400 W/m²).
applied for different control schemes, where the irradiance is 1000 W/m² at the beginning, after 1.5 s, is decreased suddenly to 400 W/m², and then increased abruptly to 600 W/m², after more than 1 s, it is again increased suddenly to 800 W/m². The temperature is considered constant (25 °C).

Figs. 9 and 10 present the simulated responses of the presented PV pumping system for the conventional and proposed control schemes, respectively. From top to bottom, the curves shown in Figs. 9 and 10 are: (a) the considered irradiance profile, (b) PV voltage, (c) PV and inductor currents, (d) PV power, (e) DC-link voltage with its reference, (f) IM speed, (g) electromagnetic and load torques, (h) stator flux amplitude.

Fig. 20. HIL responses of the DC-link voltage for (a) conventional and (b) proposed schemes under sudden irradiance variations.

Fig. 21. HIL responses of the speed, electromagnetic torque, stator flux amplitude and one-phase stator current for (a) conventional and (b) proposed schemes under sudden irradiance variations.
First of all, the results confirm the poor tracking of the conventional P&O under sudden irradiance changes with a significant PV power oscillation in steady-state. On the other hand, the proposed MPPT offers a high tracking performance with an instantaneous effect on the PV current, which is correctly achieved, under sudden irradiance variations, where the PV pumping system is pursuing the MPP permanently, as depicted in Fig. 11. Moreover, the proposed algorithm minimizes the frequency oscillation in the PV power. A comparative table regarding tracking speed, power oscillation in steady-state with the main values obtained in simulation for the two MPPT is presented in Table 2. The comparative results demonstrate the excellent performance of the proposed MPPT.

Moreover, the net DC-link voltage is regulated at its reference values by the proposed FLC for the conventional and proposed control schemes. As presented in Fig. 12, the DC-link voltage tracks the reference with good accuracy and stability, regardless the irradiance variations for the two control schemes, which proves the effectiveness of the proposed FLC. Moreover, the overshoots and settling times in the proposed scheme are less than those found in the conventional scheme, as summarized in Table 3.

On another side, the proposed control scheme using PTC proves a high dynamic and static performances for IM drive, contrary to conventional scheme (DTC). It is seen that the conventional scheme presents relatively large flux and torque ripples due to the harmonics in the stator currents, as illustrated in Fig. 13(a). Furthermore, the electromagnetic torque and stator flux of direct PTC drive IM are controlled directly and rapidly in the proposed scheme. It is found that the stator flux exhibits smooth response and lesser ripple, and as a consequence, good current waveforms, as presented in Fig. 13(b), which leads to good torque performance in steady-state (peak-to-peak torque ripple is always less than 0.2 N.m). A comparison summary in terms of current harmonics and torque ripple is presented in Fig. 14 for different irradiance levels.

Fig. 15 presents the hydraulic power and pump flow with the conventional and proposed schemes, for a hydraulic circuit with pumping head of 8.5 meters. It is clearly seen that the power conversion is more improved in terms of overshoot and speed response for the proposed scheme compared to the conventional one, which leads in improving the energy converted by the pump, as a consequence an increase of the pumped water quantity. Furthermore, Fig. 15 illustrates how the sudden irradiance decrease negatively effects (decreased to zero over a time period of 0.19 s) the hydraulic power and the pump flow with the conventional scheme. On another hand, it can be observed that the proposed scheme offers good performance in the case of sudden irradiance decrease.
For each sample time, the CPU obtains state variables from the real-time simulator through the communication channel. From these state variables, the CPU computes the optimal control actions and drives it to the real-time simulator. The control and system parameters used in the HIL implementation are the same as those used in the simulations. The HIL results are recorded using the 500 MHz Instek oscilloscope and ControlDesk interface. Both the conventional and proposed control schemes are tested and compared under sudden irradiance and load changes, as in the simulations.

4.1.2. Sudden load drop

To ensure that the proposed scheme is able to protect the IM under load drops. Both the conventional and proposed control schemes are examined for sudden loss of load. Fig. 16 shows the simulation results. At the beginning, the irradiance is 1000 W/m² and the PV pumping system is normally operating under reasonable load. Both of the MPPT algorithms ensure that the PV modules operate at the MPP. Then, a sudden load drop occurs at instant 1.5 s (no load operation). It is clearly seen that the PV modules remain at the MPP with the conventional scheme, which leads to increase the DC-link voltage and can damage the IM, as shown in Fig. 16(d). On the other hand, the proposed MPPT detected rapidly the load drop, and then kept on updating the PV reference current in order to protect the IM. As consequence, the PV current and power decrease to zero, the DC-link voltage keep stable and the PV voltage increase up to the open circuit voltage.

4.2. Real-time implementation

To prove correctness and effectiveness of the proposed control scheme, a real-time HIL system is carried out. HIL experiments take into account the communication problems and controller computational limitation. Consequently, the results obtained through these experiments are considered more practical. In this study, a dSPACE system has been used for HIL implementation. The HIL system consists, in general, of an independent control-processing unit (CPU) to build the control algorithms, a real-time simulator to simulate the plant model and a communication channel between the simulator and the CPU (Wilamowski and Irwin, 2011). For each sample time, the CPU obtains the state variables from the real-time simulator through the communication channel. From these state variables, the CPU computes the optimal control actions and drives it to the real-time simulator.

The control and system parameters used in the HIL implementation are the same as those used in the simulations. The HIL results are recorded using the 500 MHz Instek oscilloscope and ControlDesk interface. Both the conventional and proposed control schemes are tested and compared under sudden irradiance and load changes, as in the simulations.

Figs. 17, 18 and 19 compare the MPPT performance of the proposed scheme with the conventional one. As it is expected, the proposed MPPT is able to achieve MPPs faster and has good dynamics with insignificant steady-state oscillations under sudden irradiance changes, compared to the conventional P&O algorithm. On the other hand, by using the modified variable step size P&O algorithm, it tracks the MPP more accurately under step decrease in the irradiance from 1000 W/m² to 400 W/m², as presented in Fig. 19. As it is shown, the real-time HIL implementation of the proposed MPPT scheme confirms the simulation results.

Fig. 20 presents the HIL responses of the DC-link voltages when using the conventional and proposed schemes, where the DC-link voltage command is set to 450 V. It seen that the FLC in the proposed scheme tracks the desired voltage smoothly without steady-state error under sudden irradiance changes. While the conventional scheme has an overshoot and large settling time to arrive the desired voltage in comparison to the proposed scheme, when sudden irradiance variation occurs.

Fig. 21 shows the HIL responses of the speed, electromagnetic torque, stator flux amplitude and one-phase stator current for the conventional and proposed schemes. It is observed that the conventional DTC presents relatively large stator flux and torque ripples, also there are much current harmonics. In another side, the stator flux and torque ripples are much reduced in PTC algorithm. In addition, Fig. 21 demonstrates that small distortion of the stator current is achieved by using the proposed scheme.

The HIL responses of the hydraulic power and pump flow for the conventional and proposed schemes are shown in Fig. 22. The parameters of the hydraulic circuit are the same as in the simulations. These HIL results are similar to the simulation results shown in Fig. 15. In addition, there is a slight improvement in the pump flow with the proposed scheme. This improvement is clearly shown in the energy converted by the pump as well as the pumped water quantity for the long term. In this context, an irradiance profile over a time period of 10 min similar to the precedent one is considered. The pumped water quantity of conventional and proposed schemes at various pumping head are summarized in Fig. 23 for simulation and HIL tests. It can be seen that the proposed scheme presents the highest pumped water quantity at all pumping heads.

Fig. 24 shows the experimental results for sudden load drop with the proposed control scheme, where the results are similar to those in the simulation. The PV power waveform shows that the proposed algorithm stop tracking the MPP rapidly when a sudden load drop is occurred to protect the IM.

The whole system in the real-time HIL implementation demonstrates a satisfactory dynamic performance when the proposed scheme is used, which proves the effectiveness of the developed controllers and confirms the numerical simulation results obtained previously.

5. Conclusion

This paper has proposed a high-performance control scheme for battery-less PV pumping system based on IM, with an improved variable step size P&O current-based MPPT. The proposed CMPPT is employed with MPC current controller. The control scheme uses a PTC algorithm to control the IM drive, with a T-S type FLC to maintain the DC-link voltage constant at the desired reference value.

The performance of the proposed scheme has been found better than that of the conventional one (based on conventional P&O and DTC). Furthermore, as compared to the conventional scheme, simulations and HIL results indicated that the proposed scheme could offer better performance and good robustness to sudden irradiance and load variations. Moreover, the PTC algorithm exhibits a fast torque response, low flux and torque ripples with an effective control for the net DC-link voltage.

Consequently, the proposed scheme offers more pumped water quantity for PV pumping water systems under variable pumping heads.
Appendix

The parameters of the PV pumping system used in the simulation tests are listed in Table 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>Values (STC)</td>
</tr>
<tr>
<td>Open circuit voltage (V_{oc})</td>
<td>421.2 V</td>
</tr>
<tr>
<td>Optimum operating voltage (V_{mp})</td>
<td>33.7 V</td>
</tr>
<tr>
<td>Short circuit current (I_{sc})</td>
<td>3.87 A</td>
</tr>
<tr>
<td>Optimum operating current (I_{mp})</td>
<td>3.56 A</td>
</tr>
<tr>
<td>Maximum power (P_{mp})</td>
<td>120 W</td>
</tr>
<tr>
<td>Temperature coefficient of V_{oc}</td>
<td>−0.160 V/°C</td>
</tr>
<tr>
<td>Temperature coefficient of I_{sc}</td>
<td>0.065%/°C</td>
</tr>
<tr>
<td>Boost converter</td>
<td>Nominal values</td>
</tr>
<tr>
<td>Inductance (L)</td>
<td>10 mH</td>
</tr>
<tr>
<td>Capacitance (C)</td>
<td>1110 µF</td>
</tr>
<tr>
<td>Input capacitance (C_{in})</td>
<td>1110 µF</td>
</tr>
<tr>
<td>IM Nominal values</td>
<td>0.37 KW</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>76.1%</td>
</tr>
<tr>
<td>Stator resistance (R_{s})</td>
<td>20.2Ω</td>
</tr>
<tr>
<td>Rotor resistance (R_{r})</td>
<td>14.458Ω</td>
</tr>
<tr>
<td>Stator inductance (L_{s})</td>
<td>0.982 H</td>
</tr>
<tr>
<td>Rotor inductance (L_{r})</td>
<td>0.982 H</td>
</tr>
<tr>
<td>Magnetizing inductance (L_{m})</td>
<td>0.921 H</td>
</tr>
<tr>
<td>Inertia (I)</td>
<td>0.00095 kg m(^{2})</td>
</tr>
<tr>
<td>Viscous friction coefficient (F)</td>
<td>1 e−4 N m/(rad/s)</td>
</tr>
<tr>
<td>Number of pole pairs (P)</td>
<td>2</td>
</tr>
<tr>
<td>Centrifugal pump</td>
<td>Nominal values</td>
</tr>
<tr>
<td>Pumping flow (Q)</td>
<td>0.08–0.58 l/s</td>
</tr>
<tr>
<td>Pumping head</td>
<td>5–19.5 m</td>
</tr>
</tbody>
</table>

References


dromatic systems.