

ORIGINAL RESEARCH

A coordinated control method for static PV model fed pump motor system under rapid irradiation drop

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Abstract

Photovoltaic (PV)-fed motor pump system employs an advanced system that eliminates the need for batteries to reduce maintenance and equipment costs during the day in desert areas. Real-time adjustment of the motor output speed stops the motor from drawing power from a storage capacitor in the DC link so that sensors and microcontrollers (MCU) do not lose power and restart. This paper proposes an extremum seeking control (ESC) to achieve high accuracy of the maximum power point tracking (MPPT) algorithm by improving the accuracy of current and voltage measurements. MPPT-based motor speed vector control rule is proposed. A field-oriented control (FOC) scheme and sensorless direct torque control (DTC) scheme are introduced for comparison. The control method and interior permanent magnet synchronous motor (IPMSM) are tested on the PV simulator and dynamometer experimental test-rig. The test results show that the sensorless DTC can regulate the motor speed and torque to the desired value without system power failure. In contrast, the speed fluctuation of FOC control is lower than sensorless DTC. However, the system tuning time of DTC is faster and easy to support the whole system operation. The main technical contribution of this study is to provide a coordinated control method to maintain the continuous operation of the entire system during the daytime.

1 | INTRODUCTION

Many countries have issued net-zero emission energy laws to meet future demands for energy services and industrial processes without net addition of CO₂ to the atmosphere [1]. From 2035 to 2060, over the 26 regions including the United States, European Union, and China, intend to achieve the carbon neutrality [2, 3]. The long-term goal of carbon neutrality is the same as Paris Agreement, which is to limit the rise in global average temperature to less than 2°C above pre-industrial levels, trying to determine it to 1.5°C [4]. Therefore, as one renewable energies, PV panels are often mentioned as a device that can convert solar energy into electricity. It is not only cited in the field of power generation and auxiliary power but also used as an independent power supply. According to Qazi [5] and Jurasz [6], the solar power in the share of global renewable electricity production is 1.9% in the year 2017. Simultaneously, this proportion recently has an upward trend as an independent power supply. Predictably, PV autonomous power systems will

be applied to more fields and will have great potential to reduce carbon neutrality.

To utilize PV power to drive many systems, people have thought of a lot of ways up. Without the grid connection of the PV system, one of the typical applications of PV energy utilization is a motor system driven by PV energy. Initially, people would straightly connect the PV to the motor, which is the most apparent program. Sashidhar et al. [7] realized that PV power is hard to control, and it caused research priorities to turn to the efficiency of PV power. Eventually, they applied the combination of MPPT control and motor control, that combined signal of both regulates the duty cycle of the inverter. And they designed a special pump and drive integrated motor as a special occasion application. Kashif et al. [8] and Murshid and Singh [9] proposed that a single-stage topology of PV motor system provides higher efficiency than a two-stage topology. But in general, the disadvantage of those systems without a converter is the decrease of the adjustable output range of the system, resulting in waste of power at the power supply end [10]. Tripathi

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et al. [10] compared the efficiency issues of single topology and two-stage topology, and concluded that the two-stage topology is generally more efficient than the single one. Meanwhile, this single-stage topology saves cost but simultaneously makes it difficult for them to establish effective control over the output voltage of the PV system. The applications of the designed system are also very limited, it can only be applied in environments with sufficient and stable irradiance.

In contrast, some people believe that PV motor systems can increase stability with a dual inverter structure. Jain et al. [11] proposed a neutral-based integrated MPPT control algorithm to improve the utilization of PV output power in the changing climate. In practice, the load torque is cubically related to the speed of the fan and pump. The water flow rate cannot change rapidly, so as the speed and torque. Therefore, water flow is an obstacle, method in [11] switches the load to match the environmental conditions. Ramulu et al. [12] investigated a three-level inverter to distribute the power of each PV panel for the system output. And both of them used dual inverters with induction motors as pump loads. The experimental results also show that the induction motor is not well utilized for the PV power, which further increases the waste of PV output. And the paper does not mention the problem of low voltage in the MCU system brought by the drop in irradiance. If the system voltage is lower than the minimum voltage required by the MCU, the system will stop completely or restart repeatedly.

In the single-stage topology, it has been considered how to apply the algorithm to keep the system running when the irradiance drops [13]. Antonello et al. [13] used the ESC algorithm to stabilize the MPPT signal and control the motor speed in combination with the speed signal of FOC. In this study, experiments were done in real PV arrays, although the experimental results show that the controller can regulate the output power well and the system run at MPP during the time irradiance changes. However, an array of four PV panels was used in the experiments to ensure that the system voltage was above the minimum voltage even during long periods of low irradiance. This ensures stable operation of the whole system, but increases the cost significantly. And the array of PV panels will need to take into account the matching of multiple MPP, but it is not mentioned in their paper.

Typically, the other conventional PV-fed motor system is combined with a battery to keep system operation in an acceptable voltage range even during rapidly dropping sunlight [14]. In a traditional setup, the converter output is directly connected with the power grid's battery or DC power supply [14, 15]. Although, the method of not entirely relying on PV supply ensures the stability and continuous operation of the whole system. But it also increases equipment cost and installation complexity. On the other hand, the life limit of the battery determines that the system needs regular maintenance, which significantly increases the labor cost. This system also has to work with the bidirectional buck-boost converter. Generally, batteries need about 35% cost of the whole system. The difficulty in choosing the specifications of batteries and PV meanwhile leads to a waste of energy. This method goes against the original intention of using PV power.

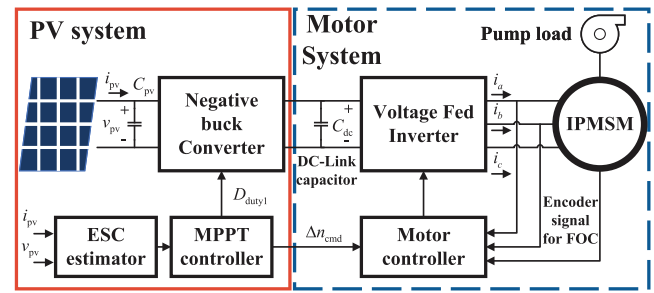


FIGURE 1 Diagram of an advanced PV-fed pump motor system

Various control strategies have been proposed for these actuators to complement the latest configurations of stand-alone two-stage topology PV systems. Chandra et al. [16] and Priyadarshi et al. [17] each use neural network and artificial neural network-fuzzy logic control at the converter control side to increase the efficiency of the MPPT. However, they spent on-chip resources in the MCU but only 2% of the control performance is improved. Even more, they picked mild irradiance and did not experiment in an environment where the irradiance varied greatly.

The maximum PV power available is variable due to varying sunlight and temperature levels during the day, especially in desert areas where the grid is unavailable. It means that the output of the motor system needs to be balanced with the output of the PV system. It requires a high-speed system dynamic response to reduce the output power to avoid system outages due to sudden irradiance drops. Thus, this paper introduced the advanced ESC of MPPT algorithm combined with motor speed and FOC, sensorless DTC scheme to get strong robustness and established an unattended independent operation PV-fed water pump system. And the system uses only one PV panel, so it avoids the power matching problem caused by multiple MPPs. The diagram of the unattended independent operation PV-fed water pump system is shown in Figure 1.

This paper investigates a control algorithm for the continuous operation of a photovoltaic pump motor system that is not connected to electricity in the presence of rapidly decreasing sunlight exposure. The pump motor runs at rated power when daytime irradiance is at its maximum and reduces output power when irradiance drops. Since the output torque of the pump load is proportional to the cube of the motor speed, the controller will vary the speed and so the power. The proposed system does not work properly on rainy days due to low irradiation. However, irrigation is not required on rainy days. The main contribution of this paper can be summarized as

- 1) Detailed control logic and design considerations for a two-stage topology of a pump motor system powered by only one PV panel are presented.
- 2) Derived the approximate output of the ESC in the paper to reduce the complexity of the MPPT algorithm to simplify the calculation of the motor command speed.

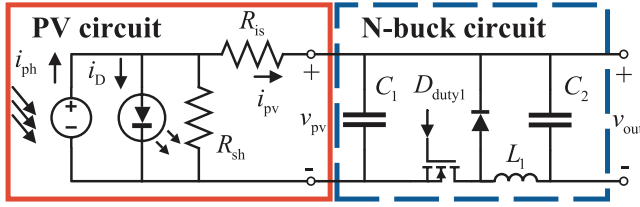


FIGURE 2 Equivalent circuit of PV and negative buck converter system

- 3) A control method without an energy storage device and motor position sensor is proposed for the problem of powering down and crashing when the irradiance drops suddenly to increase the operation time and reduce the cost.
- 4) The design principles highlighted in the paper can be extended to other types of loads such as fan load by adjusting the parameters.

This paper is focused on the coordination method between the ESC-based MPPT algorithm and the motor control algorithm, thereby keeping the entire system operating. The remainder of the paper is organized as follows. An equivalent circuit of PV, negative buck converter array and PMSM system will be presented in Section 2. The maximum adjustment time of the control system, circuit of the negative buck converter, ESC of MPPT control strategies and FOC and sensorless DTC method will be introduced in Section 3. Section 4 contains the FOC scheme and sensorless DTC scheme, followed by the discussion of the simulation results and the experimental results. Finally, the conclusion will be offered in Section 5.

2 | MODEL OF PV ARRAY AND PMSM SYSTEM

2.1 | Non-linear characteristics of PV array

An example equivalent circuit for PV solar module is shown in Figure 2, where i_{ph} is the photocurrent, i_D is a p-n junction current, i_{pv} and v_{pv} are a current and voltage of PV module. R_{sh} and R_{is} are an intrinsic shunt resistance and an internal series resistance of the cell. Considering the equivalent circuit for PV module in Figure 2, the output current of one PV cell and array can be calculated as follows

$$i_{pv} = i_{ph} - i_{sat} \left[\exp \left(\frac{q}{AKT_{mp}} v_{pv} \right) - 1 \right], \quad (1)$$

where i_{sat} is a diode saturation current, q is a electrical charge of electron ($1.6 \times 10^{-19} C$), A is a diode ideality factor (a number between 1 and 5), K is the Boltzmann's constant ($1.38 \times 10^{-23} J/K$), T_{mp} is a junction temperature. Also, i_{sat} is an inverse saturation current of PV cell which depends on PV panel

temperature and could be calculated by following equation

$$i_{sat} = i_0 \times \left(\frac{T_{mp}}{T_0} \right)^{\frac{3}{A}} \times \exp \left[\frac{qE_{gap}}{AK} \left(\frac{1}{T_0} - \frac{1}{T_{mp}} \right) \right], \quad (2)$$

where T_0 is a reference temperature of the cell, i_0 is an inverse saturation current of PV cell in T_0 and E_{gap} is the air-gap voltage of p-n junction in PV panel. According to (1), the output power of PV array P_{pv} could be determined as

$$\begin{aligned} P_{pv} &= i_{pv} v_{pv} \\ &= i_{ph} v_{pv} - i_{sat} v_{pv} \left[\exp \left(\frac{q}{nKT} v_{pv} \right) - 1 \right]. \end{aligned} \quad (3)$$

2.2 | Mathematical model of PMSM

In this section, the mathematical model of an Interior-PMSM will be given in two different reference frames, the dq rotor frame and the $\alpha\beta$ stationary reference frame. The dq frame corresponds to the synchronously rotating reference frame, and the d axis coincides with the N pole of the rotor. The $\alpha\beta$ frame is fixed to the stator winding and the α axis coincides with the u phase axis. In the dq rotor reference frame, the space vector form of the voltage equation is

$$\begin{aligned} v_d &= R_s i_d + \frac{d\psi_d}{dt} - \omega_r \psi_q \\ v_q &= R_s i_q + \frac{d\psi_q}{dt} + \omega_r \psi_d, \\ \psi_d &= L_s i_d + \psi_f \\ \psi_q &= L_s i_q \end{aligned} \quad (4)$$

where v_d , v_q , i_d , i_q , ψ_d and ψ_q are the dq components of the stator voltage, current and flux linkage, respectively. R_s and L_s are the stator resistance and inductance. ψ_f is the rotor flux linkage generated by the permanent magnets, $\omega_r = N_p \omega_m$ where N_p is the number of pole pairs and ω_m is the mechanical rotor speed.

In the $\alpha\beta$ stationary reference frame, the space vector form of the voltage equation is

$$\begin{aligned} v_\alpha &= R_s i_\alpha + \frac{d\psi_\alpha}{dt} - \omega_r \psi_f \sin \theta_r \\ v_\beta &= R_s i_\beta + \frac{d\psi_\beta}{dt} + \omega_r \psi_f \cos \theta_r, \\ \psi_\alpha &= L_s i_\alpha + \psi_f \sin \theta_r \\ \psi_\beta &= L_s i_\beta + \psi_f \cos \theta_r \end{aligned} \quad (5)$$

where v_α , v_β , i_α , i_β , ψ_α and ψ_β are the $\alpha\beta$ components of the stator voltage, current and flux linkage, respectively. θ_r is the rotor position angle.

3 | COORDINATED CONTROL METHOD OF MPPT SYSTEM AND MOTOR SYSTEM

This chapter starts by analyzing the system's maximum operation time and develops the control method for each part. In particular, a motor speed control vector rule is proposed to describe the balancing process of the power of MPPT system and motor system. It stops the motor from draining power from the storage capacitors in the DC link so that the sensors and MCU do not lose power.

3.1 | System maximum adjustment time

The structure of the unattended independent operation PV-fed water pump system is shown in Figure 1. In this system, the DC link capacitor specification C_{dc} is determined from the outset based on the area and heat dissipation of the printed circuit board (PCB). The value of DC link capacitor decides the maximum time of the entire system that can operate normally during the irradiation drop. The purpose of subsequent algorithms such as ESC-based MPPT and motor control aim to avoid using the power of DC link capacitor. Those control algorithms will be introduced in a subsequent chapter. Therefore, according to the capacitor energy storage equation and the output power equation of the synchronous motor, the maximum operation time t_{sys} can be calculated from

$$t_{sys} = \frac{E_c}{P_{out}} = \frac{\frac{1}{2}C_{dc}(\bar{v}_{dc}^2 - v_{min}^2)}{\frac{1}{9.55}T_e n_{out}}, \quad (6)$$

where E_c is total energy stored in the DC link capacitor, P_{out} is an output power of IPMSM. $\bar{v}_{dc}$ represents the average value of output voltage of the N-buck converter, equal to the input voltage of the inverter. v_{min} is the minimum inverter operation voltage decided by the specification of the MCU. T_e and n_{out} represent an output torque and rotating speed of IPMSM.

The premise for the system to complete one power adjustment is that the dynamic response time of the control method must be less than the t_{sys} . If the system response time exceeds this value, the MCU will no longer work properly. Furthermore, to extend the t_{sys} in terms of hardware, the auxiliary power supply in this system is designed to have a wide voltage range.

3.2 | Negative buck converter

For the problem of mismatch between the output voltage of the PV panel and the v_{dc} of the motor system, it is necessary to use the converter for voltage regulation. The estimated initial duty cycle D_{duty1}' of the negative buck converter can be obtained

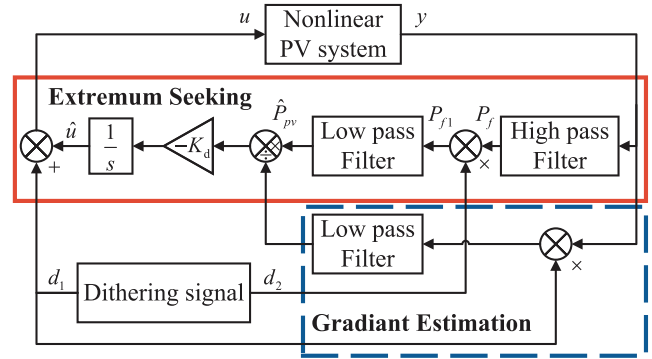


FIGURE 3 Block diagram of ESC method

from the following equation [17]

$$D_{duty1}' = \frac{v_{dc}}{v_{dc} + v_{mpp}}, \quad (7)$$

where v_{mpp} is the voltage value when the PV panel is at 25°C temperature and 1000 W/m² irradiance condition.

Since the gate source voltage v_{gs} must be greater than 15 V to fully conduct, if the N-type metal-oxide-semiconductor field-effect transistor (MOSFET) is placed on the bus side instead of the ground side, then the voltage value of v_g needs to be greater than v_g 15 V. A special driver chip needs to be used to fully conduct the MOSFET. For reasons of cost and the stability of the drive chips, negative buck converter can be used.

3.3 | ESC-based MPPT control strategy

One MPPT algorithm, ESC-based MPPT method can be used in order to increase system response time by maximizing the output power of photovoltaic panels under current irradiation conditions and reducing its output power fluctuations. The ESC method operates by periodically incrementing or decrementing the output terminal voltage of the PV panel and comparing the power obtained in the current cycle with the power of the previous process [18]. While the harsh climate, such as shading and heat distribution increases the measurement accuracy requirements for current and voltage sensors. To indicate that [19], predicted the voltage for the derivative breakpoints within small intervals.

The overview of the ESC scheme is shown in Figure 3. Lei et al. [19], Brunton et al. [20] and Moura and Chang [21] represented the ESC system for static nonlinear maps. Since the case study on PV systems involves a static plant model, the scope of this paper is limited to static plants. As it can be seen, ESC is an optimum operating point of a nonlinear system. In this method, it is supposed that the characteristics curve of the considered approach is concave. As a result, this method can be used for tracking MPP in the PV system. Considering a nonlinear characteristic curve for PV panel as following

equation

$$P_{pv} = f(u), \quad (8)$$

where P_{pv} is output power of panel and u is the input of panel which is a function of the signal u , $d_1 = \sin(\omega_d t)$ and $d_2 = a_0 \sin(\omega_d t)$ are both the dithering signal. a_0 represents the perturbation amplitude, ω_d is the dither frequency. Consequently, the output power can be obtained as follows

$$P_{pv} = y = f(u + a_0 \sin(\omega_d t)). \quad (9)$$

Now, Equation (6) could be approximated by Taylor's series around u , expanding in 3 terms

$$P_{pv} \approx f(u) + \frac{df(u)}{du} a_0 \sin(\omega_d t) + \frac{1}{4} \frac{d^2 f(u)}{du^2} a_0^2 \cos(2\omega_d t) - \frac{1}{4} \frac{d^2 f(u)}{du^2} a_0^2 \cos(2\omega_d t). \quad (10)$$

It could be seen that the output power is made of a part with a low frequency along with harmonics with frequencies equal to ω_d and $2\omega_d$. Then using a high pass filter, the output is obtained as follows

$$P_f \approx \frac{df(u)}{du} a_0 \sin(\omega_d t) - \frac{1}{4} \frac{d^2 f(u)}{du^2} a_0^2 \cos(2\omega_d t). \quad (11)$$

After P_f products $d_1 = \sin(\omega_d t)$, the output of ESC system is revealed as follows

$$\begin{aligned} P_{f1} &\approx \frac{df(u)}{du} a_0 \sin^2(\omega_d t) - \frac{1}{4} \frac{d^2 f(u)}{du^2} a_0^2 \cos(2\omega_d t) \sin(\omega_d t) \\ &= \frac{df(u)}{du} a_0 - \frac{df(u)}{du} a_0 \cos^2(\omega_d t) \\ &\quad - \frac{1}{4} \frac{d^2 f(u)}{du^2} a_0^2 \sin(\omega_d t) + \frac{1}{2} \frac{d^2 f(u)}{du^2} a_0^2 \sin^3(\omega_d t). \end{aligned} \quad (12)$$

Then this product results will pass through the low pass filter, it reveals the output of ESC system as follows

$$\hat{P}_{pv} \approx \frac{df(u)}{du} a_0. \quad (13)$$

To the negative buck converter in Figure 2, C_1 and C_{dc} are a PV output stabilization capacitor and DC link capacitor, L_1 is a charge and discharge inductance. v_{out} and D_{duty1} are a PV output voltage and a duty of PWM pulse in MOSFET. The basic relationships for the negative-buck converter and MPPT method are obtained as follows

$$v_{out} = D_{duty1} \times v_{pv} = (\hat{u} + a_0 \sin(\omega_d t)) v_{pv}, \quad (14)$$

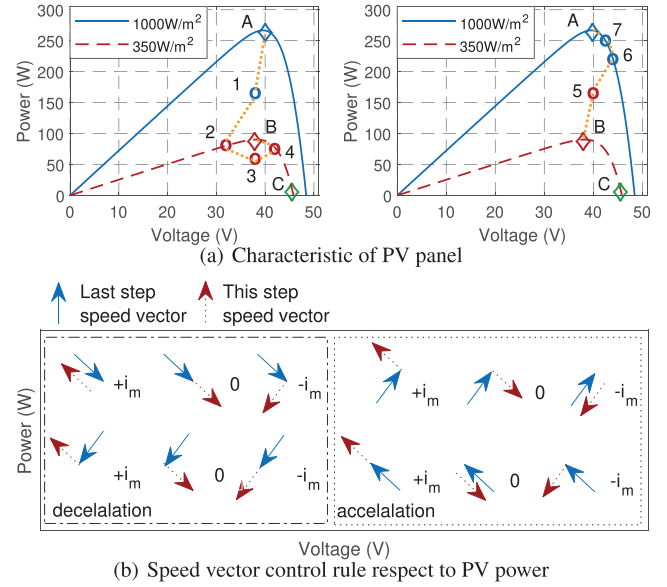


FIGURE 4 Characteristic of PV panel and speed acceleration and deceleration vector control rule respect to PV power. (a) Characteristic of PV panel, (b) Speed vector control rule respect to PV power

which we use for the following switched control law

$$\begin{cases} \hat{u} + a_0 \sin(\omega_d t) & dP_{pv}/dv_{out} \neq 0 \\ \begin{cases} \hat{u} + a \sin(\omega_d t) \\ \frac{da(t)}{dt} = -\rho a(t), \quad a(0) = a_0 \end{cases} & \text{otherwise} \end{cases}, \quad (15)$$

where a , a_t , a_0 are the changing perturbation amplitude, perturbation amplitude respect to the time t , original perturbation amplitude, respectively. ρ represents the decay parameter, and one would use the algorithm parameters to compute convergence speeds in practice.

3.4 | A motor speed control vector rule combined with MPPT

Figure 4a shows the P-V curves for varying irradiance using the equations mentioned earlier (1), (2), (3), and parameters. Moreover, we can obtain the assumed motion trajectory of the MPPT algorithm based on Equations (14) and (15). It is also shown in Figure 4a. The point A, B, C show the MPP of 1000 W/m² irradiation, MPP of 350 W/m² irradiation, the maximum output voltage of 350 W/m² irradiation, respectively.

The motor runs steadily when the converter system is initially at point A. Suppose the irradiance falls to 350 W/m² at this moment, and the ambient temperature does not change significantly. It means that the P-V characteristic has moved from the blue curve to the red one. The MPPT algorithm immediately reduces the D_{duty1} to find the new MPP, and the motor system needs to decelerate correspondingly. We can get point 1 as the next step in the interval of MPPT system after the

sampling period t_{s1} . The point 2, 3, 4 as the ordinal, the operation point finally moves to point B. Another case is the motor acceleration when the irradiation is recovered—assuming that the motor is also running steadily at this time on point B. The operation point moves to 5, 6 and 7 as ordered. In the end, point A is the MPP where the algorithm is found.

According to the MPPT motion trajectory and ESC algorithm obtained earlier, the subsequent motor speed control vector rule can be obtained. Considering the acceleration and deceleration command Δn_{cmd} according to Figure 4a yields the following relationships

$$\Delta n_{cmd} = \frac{\Delta P_{pv}}{P_m} n_{cmd},$$

$$\omega_{ref(k+1)} = \omega_{ref(k)} + \Delta n_{cmd} \frac{\pi}{30}, \quad (16)$$

$$P_m = P_c + P_{pv}, \quad (17)$$

where ΔP_{pv} is the difference between the current power of the PV array and the previous power. P_m , P_c , P_{pv} represents a current output power of IPMSM, a power gap obtained from the DC link capacitor, and a current PV array output. Parameters n_{cmd} weighs controller command speed. $\omega_{ref(k)}$, $\omega_{ref(k+1)}$ represent the motor reference angular velocity for this step and the next step. This angular speed will be communicated to the motor control DSP as the reference angular speed of the motor system. Equations (16) and (17) indicate that the motor speed will be stable when the power gap of PV and motor P_c tends toward zero.

Figure 4b shows the rule of speed vector expressed in Equations (16) and (17), where the i_m is the motor current. The controller compares the last step and this step of the irradiation trend and decides the direction of the speed vector. The trend of the arrows represents the power change of the motor control system. However, The units of x-y coordinates in Figure 4b are same as Figure 4a, and trajectory can also be mapped to Figure 4a. In general, whether the deceleration or acceleration (corresponding to the irradiation decrease or increase), increasing the i_m brings the operation point closer to the MPP of 1000 W/m² irradiation curve. Conversely, reducing the i_m brings it closer to the MPP of 350 W/m² irradiation curve. The operation point moves to the direction of point C when the i_m is not changed.

While practical execution time is longer than judgment time, it still means that when irradiation drops rapidly, the controller can reduce the command speed in the time between the few carrier waves.

3.5 | FOC and DTC algorithm

To obtain fast dynamic response, FOC and sensorless DTC schemes are considered here. The challenge of this control scheme design is from the variation of the converter output power. Namely, the difference between the converter output P_{out} and the motor output P_m on the DC link capacitor. As the input

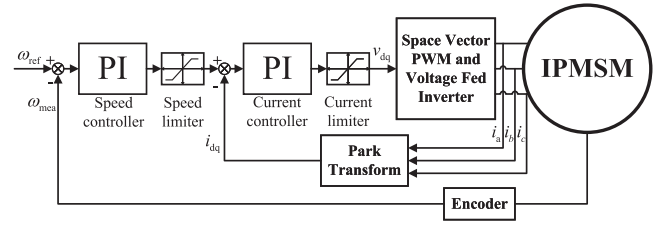


FIGURE 5 Conventional FOC block diagram

of inverter v_{dc} varies inconstantly, the response of the control scheme should be fast. For comparison purpose, two control methods have been considered.

3.5.1 | Conventional FOC system

The field oriented control is a linear strategy, which has been widely applied in the motor control methods [22]. Rotating the motor by controlling the dq axes voltage rotation. The basic principles of FOC is illustrated through the block diagram presented in Figure 5.

The PI coefficients in FOC have two parts: speed loop and current loop. Those coefficients can be obtained offline with the following equations from the Texas Instruments InstaSPIN-FOC guide [23]

$$K'_{pc} = B_0 L_s \frac{I_n}{V_n t_{s2}},$$

$$K'_{ic} = \frac{R_s}{L_s} t_{s2}, \quad (18)$$

where K'_{pc} , K'_{ic} are the 'series' topology of current loop coefficients. I_n , V_n are the stator rated current and voltage. B_0 is the value of the current loop bandwidth which is recommended to be 0.25 in Texas Instruments InstaSPIN-FOC guide [23].

$$K'_{ps} = \frac{K'_{is}}{c_1} \delta,$$

$$c_1 = \frac{3N_p \psi_r}{2J},$$

$$K'_{is} = \frac{K'_{pc}}{\delta^2 L_s}, \quad (19)$$

where K'_{ps} , K'_{is} are the 'series' topology of speed loop coefficients. The constant value c_1 can be obtained from ψ_r rotor flux linkage and inertia of the motor plus the load J . δ is the damping factor. According to the description of δ in the guide [23], the damping factor represents the tradeoff between system stability and system bandwidth in a single number. The guide provides the speed controller open loop magnitude and phase response as a function of different δ from 1 to 70. At the same time, it provides the close loop bandwidth and step response of speed

controller as a function of δ . The results show that value below 2 are usually unacceptable due to the large amount of overshoot. At the other end of the scale, values much above 30 usually do not work either because of the extremely long rise and settling times, as seen in the step response curves. δ should be chosen between the value from 2 to 30.

$$\begin{cases} K_{pc} = K'_{pc} \\ K_{ic} = K'_{ic} * K_{pc} \end{cases}, \quad (20)$$

$$\begin{cases} K_{ps} = K'_{ps} \\ K_{is} = K'_{is} * K_{ps} \end{cases}, \quad (21)$$

where K_{pc} , K_{ic} , K_{ps} , K_{is} are the current and speed loop PI coefficients using in experiments, respectively.

The space vector pulse width modulation (SVPWM) of the voltage fed inverter can be given by following equations in terms of v_d , v_q and v_{dc} as

$$\begin{cases} t_{as} = \frac{v_a}{v_{dc}} \frac{t_{s2}}{2} = \frac{t_{s2}}{3v_{dc}} (v_d \cos \theta_r - v_q \sin \theta_r) \\ t_{bs} = \frac{t_{s2}}{3v_{dc}} \left(v_d \cos \left(\theta_r - \frac{2}{3}\pi \right) - v_q \sin \left(\theta_r - \frac{2}{3}\pi \right) \right), \\ t_{cs} = \frac{t_{s2}}{3v_{dc}} \left(v_d \cos \left(\theta_r + \frac{2}{3}\pi \right) - v_q \sin \left(\theta_r + \frac{2}{3}\pi \right) \right) \end{cases} \quad (22)$$

$$t_{offset} = \frac{t_{s2}}{4} - \frac{t_{max}}{2} - \frac{3t_{min}}{2}, \quad (23)$$

where v_a , v_b , v_c represent the voltage of a, b, c phase winding, respectively. θ_r is the rotor angle obtain from encoder. t_{s2} represents the motor system carrier step time. t_{as} , t_{bs} , t_{cs} mean the equivalent a phase, b phase, c phase time for the load side. t_{offset} denotes the time shifting value for SVPWM generation. The maximum value and minimum value in the t_{as} , t_{bs} , t_{cs} represent the value of t_{max} , t_{min} , respectively. The MOSFET on time and off time t_{aon} and t_{aoff} in one carrier step can be calculated as follows

$$t_{aon} = \frac{t_{s2}}{2} - t_{as} - t_{offset}, \quad (24)$$

$$t_{aoff} = \frac{t_{s2}}{2} + t_{as} + t_{offset}. \quad (25)$$

3.5.2 | Sensorless DTC system

Direct torque control is a method for controlling the stator flux linkage to lead the rotor flux, rotating the motor. The conventional idea of DTC is applying a hysteresis controller for both flux and electromagnetic torque [24]. DTC has a rapidly dynamic response since there is an inner PI loop torque output. But also, DTC is no current loops. Hence the current is not regulated directly. In order to solve the influence of zero vector on flux linkage control and also to solve the abrupt change of current. The proposed sensorless DTC scheme with speed duty ratio regulation is presented in Figure 6.

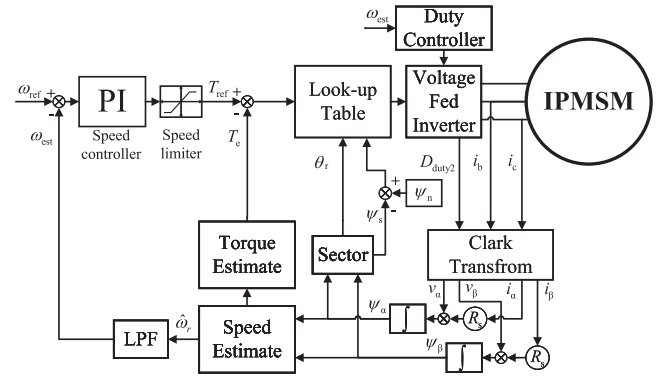


FIGURE 6 Sensorless DTC block diagram

The electromagnetic torque can be expressed as follows.

$$T_e = \frac{3}{2}N_p(\psi_\alpha i_\beta - \psi_\beta i_\alpha). \quad (26)$$

And the stator magnetic flux linkage and the reference value of flux linkage can be expressed by the discrete Euler integration method as

$$\psi_{s(k+1)} = \psi_{s k} + (v_{s k} - R_s i_{s k}) t_{s 2} = \psi'_{s k} + v_{s k} t_{s 2}, \quad (27)$$

$$\psi_n = \frac{E_n}{2\pi f_n}, \quad (28)$$

where $\psi_{s(k)}$, $\psi_{s(k+1)}$, $\psi_{s(k-1)}$, are this moment of stator flux linkage, the next motor system sampling period t_{s2} stator flux linkage, the last sampling period stator flux linkage, respectively. the ψ_n , E_n , f_n are the rated flux linkage, rated back-electromotive force and the frequency of the rated speed.

The pure integrator of ψ_s involves the drift of the flux linkage origin and the saturation problems. To solve the problems, the pure integrator is replaced by a low pass filter (LPF). The estimated stator flux by the LPF can be given as

$$\begin{aligned}\psi_{s(\ell+1)} &= \frac{2\tau - t_{s2}}{2\tau + t_{s2}} \psi_{s\ell} + \frac{t_{s2}}{2\tau + t_{s2}} (x_{(\ell)} + x_{(\ell+1)}) \\ x_{(\ell)} &= v_{s\ell} - R_{s\ell} i_{s\ell} \\ x_{(\ell+1)} &= v_{s(\ell+1)} - R_{s(\ell+1)} i_{s(\ell+1)}\end{aligned}\quad , \quad (29)$$

where $x_{(k)}$, $x_{(k+1)}$ represent this step input of LPF and the next step input of LPF, respectively. τ is the time constant.

The origin drift can be considered as an effect of the constant error in the short term. An error in resistance value changes the origin of the flux linkage which makes it away from the point (0, 0). After a few turns of the flux linkage, the motor will eventually out-of-step. Under the result of LPF, a constant error will be offset over the period of flux linkage one revolution as a circle. Eventually, the origin will return to the point (0, 0).

TABLE 1 PWM output switching table during forward acceleration or reverse deceleration

$\Delta\psi_s$	ΔT_e	Flux sector					
		1	2	3	4	5	6
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0

After the flux estimation, the equations of estimated rotor angular and estimated motor speed are obtained by the following

$$\begin{aligned}\psi_r &= \psi_s - L_s i_s \approx \psi_s \\ \hat{\theta}_r &= \arctan\left(\frac{\psi_{r\beta}}{\psi_{r\alpha}}\right),\end{aligned}\quad (30)$$

$$\hat{\omega}_r = \frac{d\psi_r}{dt} = \frac{(v_\beta - R_s i_\beta)\psi_\alpha - (v_\alpha - R_s i_\alpha)\psi_\beta}{\psi_\alpha^2 + \psi_\beta^2}, \quad (31)$$

where i_s , ψ_r , $\hat{\theta}_r$, $\hat{\omega}_r$ represent the stator current, rotor flux linkage, estimate rotor angular, estimate motor speed. The stator flux linkage is far greater than the result of the product i_s and ψ_r . Thus the rotor flux is approximate with stator flux. Since the estimated speed is disturbed by the flux integration time, the result fluctuates, and LPF is required.

In order to keep the fast system response time, the output speed duty ratio is used to replace the conventional hysteresis control. In conventional control, hysteresis is used to avoid the predicted rotor linkage exceeding the control trajectory too much, making the torque fluctuate. Thereby causing the entire system to fluctuate. Therefore, the speed duty ratio regulation is described as follows

$$D_{duty2} = \frac{\hat{\omega}_r}{\omega_n} + c_2, \quad (32)$$

where the D_{duty2} is the lookup table output duty, ω_n is the motor rated speed, and c_2 represents the minimum coefficient from 5% to 10%. Whether it is the hysteresis method [25] or the speed duty cycle method, their main significance among others is to avoid the zero vector in SVPWM from disturbing the flux linkage waveform and moving it away from the intended circular shape.

Considering the lookup table, the conventional DTC method with hysteresis comparator was proposed in [25]. The selection of suitable voltage vectors from the lookup table depends on the torque and stator flux linkage demand. In general, the rule is showed in a Tables 1 and 2.

Where the sector depends on the calculated rotor angle $\hat{\theta}_r$, the trend of $\Delta\psi_s$ and ΔT_e means the difference between the reference and estimated value of flux linkage and torque.

TABLE 2 PWM output switching table during forward deceleration or reverse acceleration

$\Delta\psi_s$	ΔT_e	Flux sector					
		1	2	3	4	5	6
0	1	V_5	V_6	V_1	V_2	V_3	V_4
	0	V_0	V_7	V_0	V_7	V_0	V_7
1	1	V_6	V_1	V_2	V_3	V_4	V_5
	0	V_7	V_0	V_7	V_0	V_7	V_0

TABLE 3 MPPT control board parameters

DC link capacitor C_{dc}	50 μ F
Number of DC link capacitor	10
N-buck converter average output voltage $\bar{v}_{dc}$	50 V
Microchip minimum operation voltage v_{min}	20 V
Working area of auxiliary power supply	20V ~ 60V

TABLE 4 IPMSM parameters

Number of pole pairs N_p	2
Rated speed	3000 r/min
Rated torque	0.3 N · m
Rated voltage V_n	48 V
Rated current I_n	5.85 A
Stator inductance L_s	0.4984 mH
Armature resistance R_s	0.4615 Ω
Phase back-electromotive force(EMF) E_n	14.03 V

4 | SIMULATION AND EXPERIMENTAL RESULTS

The specifications of MPPT control board are provided in Table 3. The IPMSM which was designed for high speed, low torque operation, its specifications are given in Table 4.

Now, the value of the maximum adjustment time $t_{ys} = 0.005571$ s is obtained from Equation (6) when the motor works on the rated range. The PI coefficients of FOC current and speed loop are also calculated as $K_{pc} = 0.1519$, $K_{ic} = 0.0925$, $K_{ps} = 0.2815$, $K_{pi} = 0.3225$. The stator rated flux linkage $\psi_n = 0.05$ Wb.

4.1 | Simulation

This simulation was built under the Simulink platform in order to prove the feasibility of this control method, when the drive operates in the 0.3 N · m torque at 3000 r/min. The simulation t_{s1} and t_{s2} are the PWM period and were set to 2×10^{-4} s and 1×10^{-4} s. The MPPT system and motor system sampling periods are selected cause the accuracy of the output trajectory.

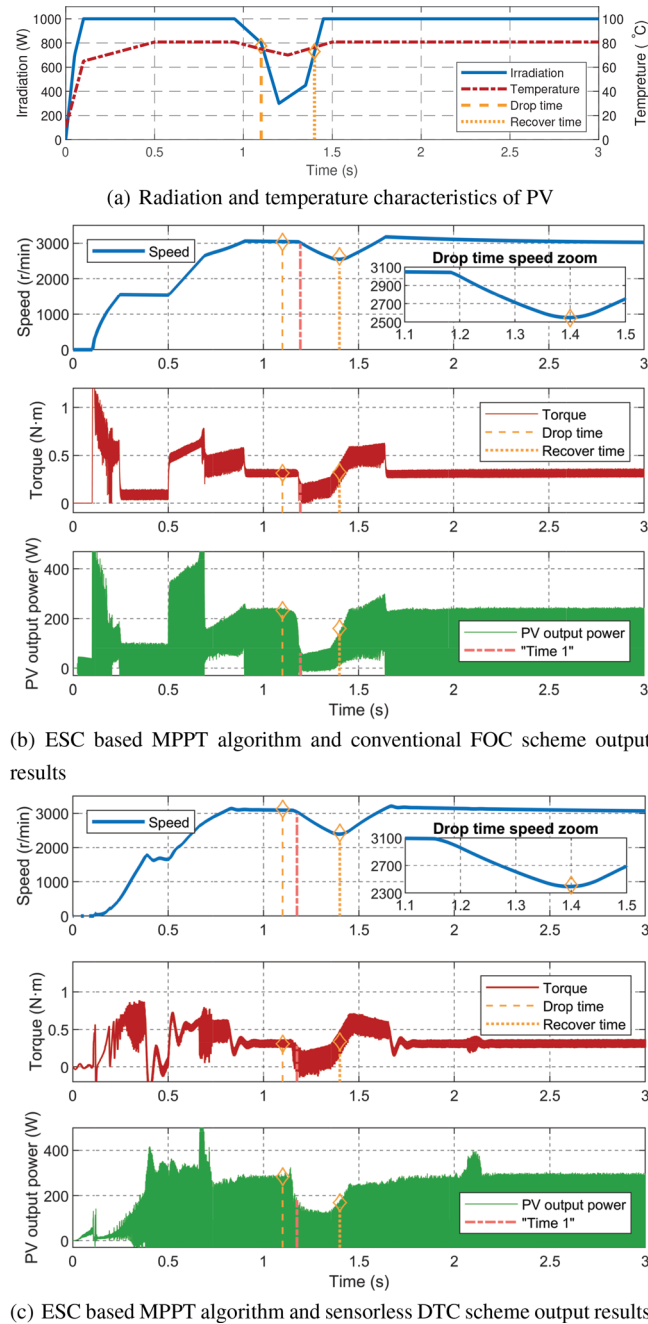


FIGURE 7 Radiation temperature characteristics and simulation results of system speed, torque and duty cycle. (a) Radiation and temperature characteristics of PV, (b) ESC based MPPT algorithm and conventional FOC scheme output results, (c) ESC based MPPT algorithm and sensorless DTC scheme output results

According to the calculation results, it represents that the entire simulation system has to be adjusted within in 4 carrier waves.

Figure 7a shows irradiation and temperature characteristics. The sunlight irradiation changes immediately during the time $t \in [1.25, 1.55]$ s around the environment such as deserts. Figure 7b,c shows the motor speed, torque and PV output power of FOC and sensorless DTC, respectively, when the sunlight irradiation dropped by 40% lower, then quickly recovered. Due to the drop and no electricity environment, the motor

speed can no longer maintain. Consequently, the torque amplitude decreased when the speed diminished. It is necessary to reduce the duty cycle to obtain the current MPP given that the changes in PV output characteristics are caused by the decrease in irradiance. For the speed of FOC scheme in Figure 7b, it reached 2560 r/min when it fell to the lowest point in the recovery time. By comparison, sensorless DTC in Figure 7c got to 2480 r/min in the recovery time of the lowest point. For torque response time, sensorless DTC is 0.019 s greater than FOC and the adjustment time 'Time 1'. It is evident that substituting the drop speed and drop output power into Equations (14) and (15), leads to the FOC $D_{duty1} = 0.956$ and DTC $D_{duty1} = 0.786$.

It follows from the simulation results shown in Figure 7 that the proposed control scheme is robust to irradiation and temperature drops in the short term. Practical experiments can be carried out to verify the feasibility of long-term continuous operation.

4.2 | Experimental results

The proposed scheme has been tested on the experimental test-rig, as shown in Figure 8. During the test, the IPMSM was loaded by a dynamometer in Figure 8d. The torque was measured by a high precision torque sensor, Model 8661 from Burster. The PV simulator ETS80X10.5C from the AMETEK was used to simulate the characteristics of PV panels and sunlight irradiation. Only one PV panel output was used in the experiment instead the PV array. The control board of MPPT system uses the microchip, type STM32F103CBT6 from STMicroelectronics is shown in Figure 8b. Using 48kHz as the MPPT system PWM frequency, $t_{d1} = 2.0833 \times 10^{-5}$ s. The motor control board uses the DSP in Figure 8c, type TMS320F28335PGFA from Texas Instruments which proceeded carrier interruption in 10 kHz. Means the motor system adjustment time $t_{d2} = 1 \times 10^{-4}$ s. According to Equation (6) and Table 3, the whole system must be adjusted within 56 carrier waves each time it meets irradiation drop during the experiment.

For comparison, different irradiation situations: cloudy day and heavy clouds day were operated. In Figure 9a and Figure 10a, as evident at first glance that the variation of irradiation and temperature in the cloudy day are more moderate than that in heavy clouds day. It can be known that the requirements for the entire system will be higher than it in heavy clouds day. It also requires for faster adjustment time.

The entire experiments were set to 265 s per time, adding a load of 0.15 N·m when the speed reaches 3000 r/min. As shown in Figure 9a and Figure 10a, the experiments both started at 35 s and ended at 300 s. In cloudy day, the irradiation started at 200 W/m² to 1000 W/m², ended at 800 W/m² and the temperature rose till 80°C. In heavy clouds day, the irradiation drop from 1200 W/m² to 300 W/m² within 10 s and the temperature drop from 80°C to 30°C at the time of 180 s inside the ellipse in Figure 10a. That temperature cycle simulates the course of an entire daytime. Also, in order to demonstrate the sensor and sensorless control scheme robustness, two controls were compared: FOC and sensorless DTC. In Figures 9b and 10b,

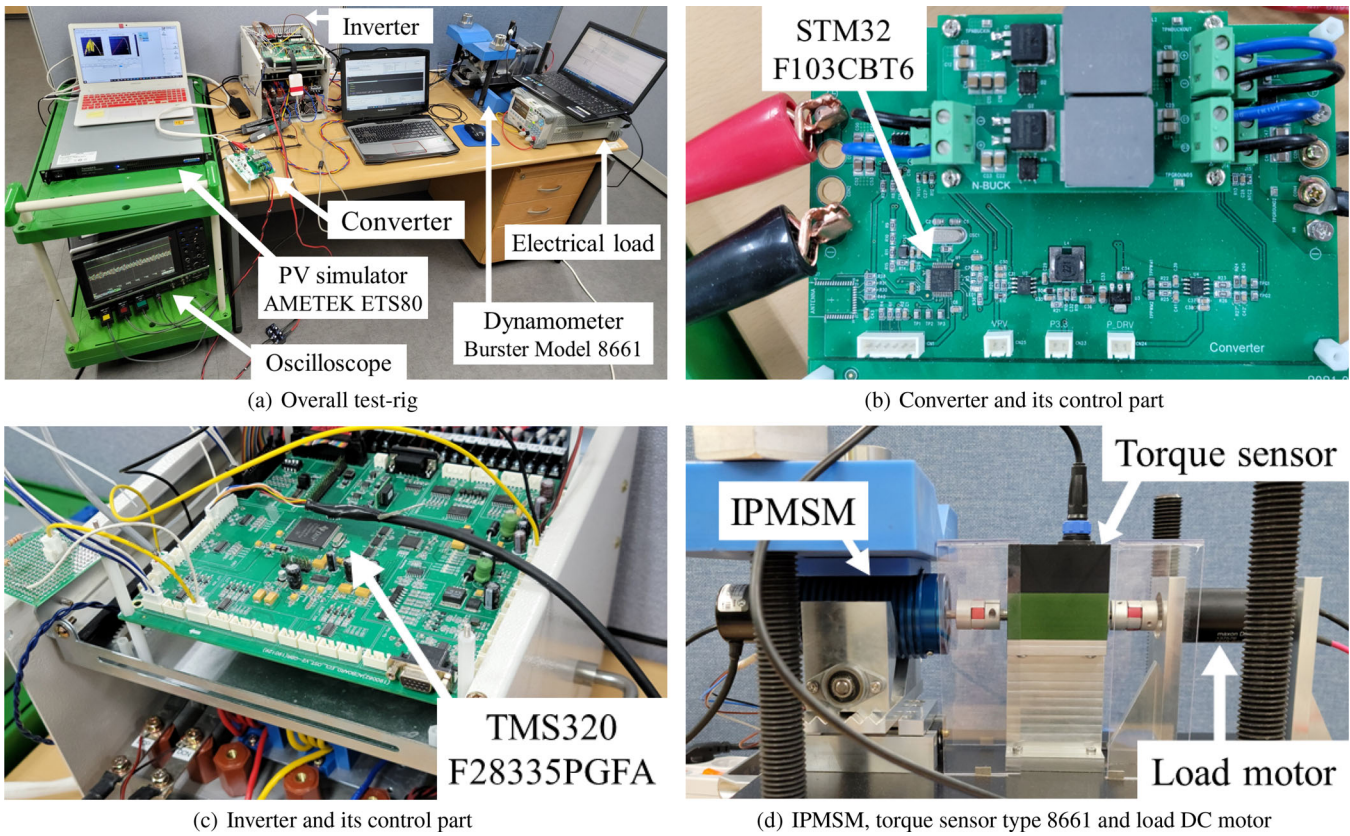


FIGURE 8 Experimental test-rig and its component. (a) Overall test-rig, (b) Converter and its control part, (c) Inverter and its control part, (d) IPMSM, torque sensor type 8661 and load DC motor

the MPP trajectories of cloudy day and heavy clouds day on each control method are demonstrated. And an open-loop FOC start method is operated since the DTC has a huge torque ripple at low speed region. Figures 9c,d and 10c,d shows the value of phase current i_a , i_b , i_c and v_{dc} within time 0.5 s, FOC and DTC scheme, respectively. Figures 9e,f and 10e,f shows the whole-time torque, speed, and output power of the FOC and DTC scheme, respectively.

The MPP trajectory in Figures 9b and 10b showed the MPP performance point respected the z-axis time. The colours range from dark blue to light yellow, and deep to shallow represents the time from small to large. As it could be seen, in order to balance the PV output and motor output, MPPT controller was adjusting the MPP according to irradiation, and the motor controller was also changing the output power. The points off-track in Figure 10b represent rapidly changing MPP, still less than the power required by the motor system. Therefore, the motor controller reduces its output power based on Equations (16) and (17). When the irradiation is restored conversely, it increases output power again, bringing MPP back to the original trajectory. Compared to heavy clouds day, the fluctuation of the curve for cloudy day is relatively small. Accordingly, the rotational motor speed and torque are also more stable.

Subsequently, Figure 9c,d shows the voltage regulation range of FOC was wider than that of DTC. Instead, the DTC had more current glitches and adjustment range. As a result, in the

MPPT scheme, the D_{duty1} noted the variation of the outer PI loop of FOC is larger than that of the DTC. Note that the value of stator flux linkage in DTC was real-time calculated from (14) and it is proportional to E_n . Similarly, the V_{abc} in the FOC had same relationship with E_n . However, the difference was that FOC has a precise speed value provided by the encoder which reduces the fluctuation of the system. Consequently, the DTC had greater fluctuation in the rotation speed. For Figure 10c,d, the voltage and current waveforms are jittered because they represent the time when the irradiance drops and fluctuate sharply by 0.5 s.

During the whole experiment in Figures 9e,f and 10e,f, neither FOC nor DTC had the phenomenon that the controller systems power failure by causing the adjustment time is greater than $t_{sys} = 0.005571$ s. Where the irradiance dropped to 300 W/m^2 at the time of 100 s, 130 s, 190 s in Figure 10 e,f, the FOC method changed the speed to 2450 r/min, 2350 r/min, 1102 r/min, respectively. The motor torque was maintained at around $0.15 \text{ N} \cdot \text{m}$. Under the effect of them, the motor output power reduced to 32 W, 30 W, 11 W. The DTC method adjusted the speed to 2250 r/min, 2193 r/min, 905 r/min, respectively. The torque had a huge ripple around $0.15 \text{ N} \cdot \text{m}$. The motor output power came to 26 W, 20 W, 9 W.

At the time of drop and recovery, the speed fluctuation of sensorless DTC was 8%, and the torque was within 5%. The FOC speed and torque fluctuations were relatively less than 2%.

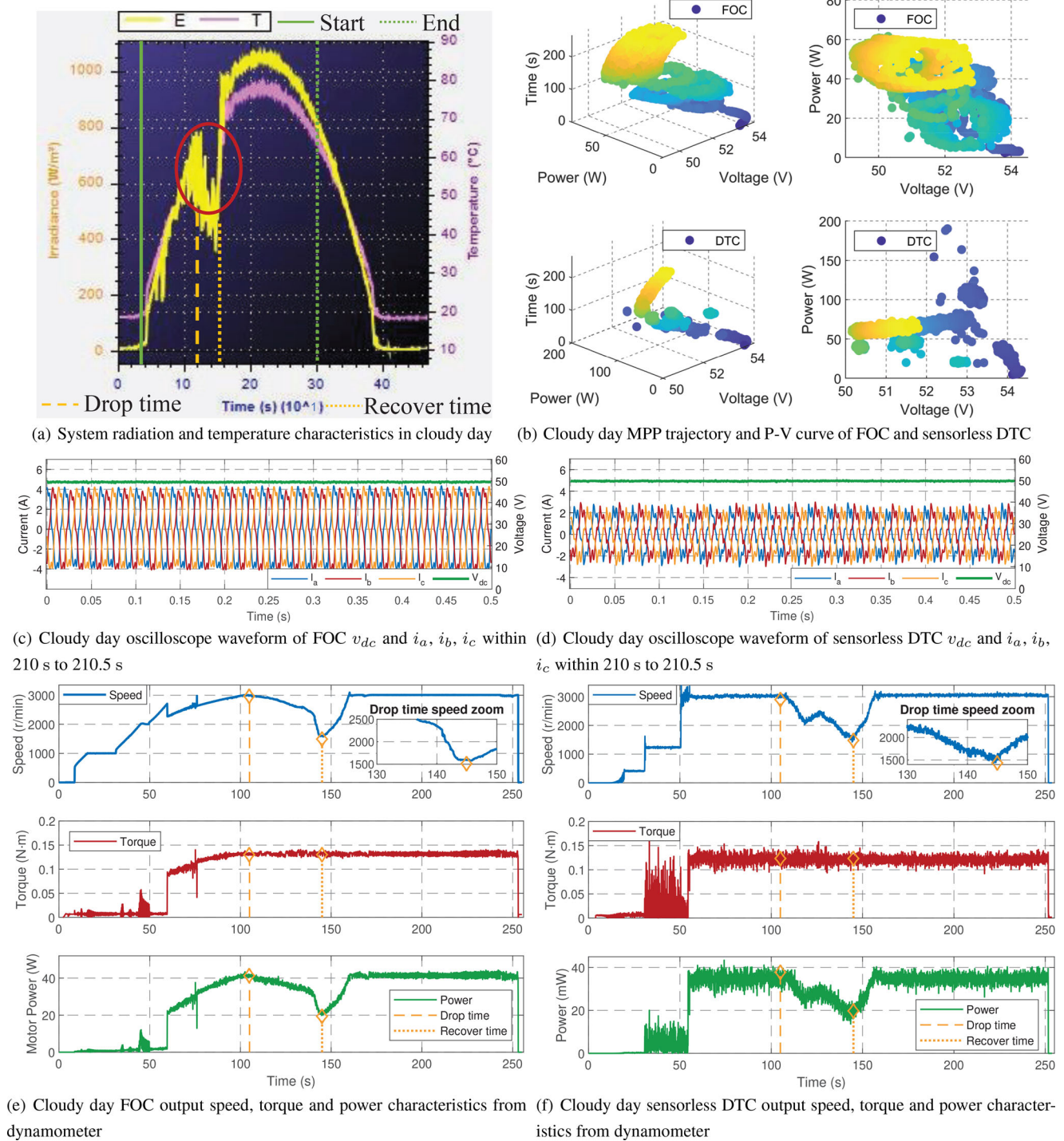
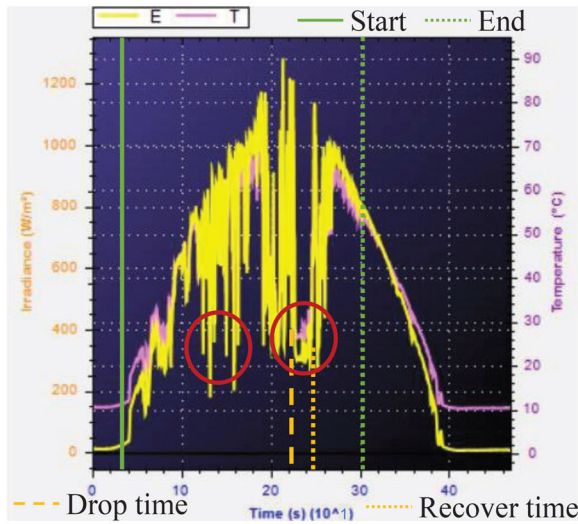


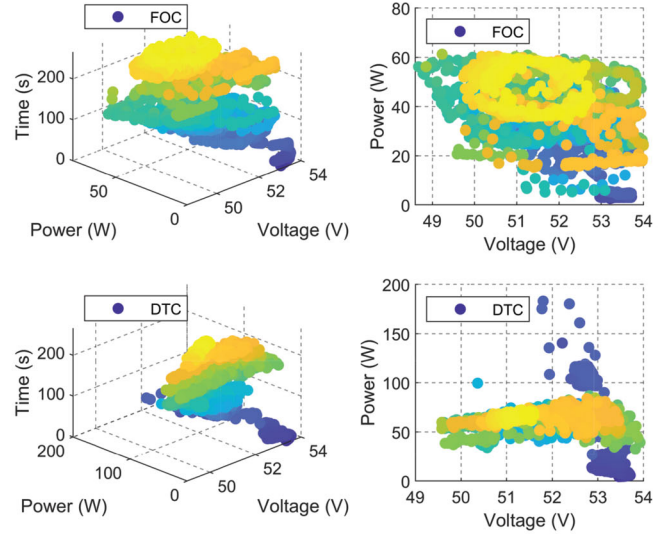
FIGURE 9 Output results of FOC and sensorless DTC speed, torque and power in cloudy day. (a) System radiation and temperature characteristics in cloudy day, (b) Cloudy day MPP trajectory and P-V curve of FOC and sensorless DTC, (c) Cloudy day oscilloscope waveform of FOC V_{dc} and i_a, i_b, i_c within 210 s to 210.5 s, (d) Cloudy day oscilloscope waveform of DTC V_{dc} and i_a, i_b, i_c within 210 s to 210.5 s, (e) Cloudy day FOC output speed, torque and power characteristics from dynamometer, (f) Cloudy day DTC output speed, torque and power characteristics from dynamometer

It must be noted that, DTC regulated the speed and torque at the drop time within 0.4 s. When the irradiance drops several times between time $t \in [100, 170]$ s, the speed of FOC and DTC both fluctuated in different magnitudes among 1% to 5%. However, a greater difference in the magnitudes range could be noticed.

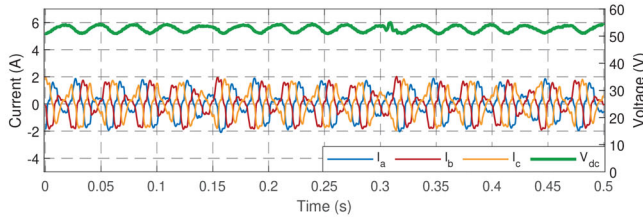
The experiment results in Figure 10 ef indicated that, in the absence of power electricity, a pump system fed only by PV can operate without power down under sunlight irradiation rapidly dropping. This experimental result verifies the feasibility and accuracy of the control method in this paper. An algorithms such as extended-Kalman filter and sliding mode control can



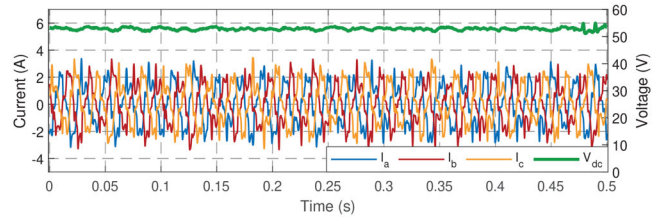
(a) System radiation and temperature characteristics in heavy clouds day



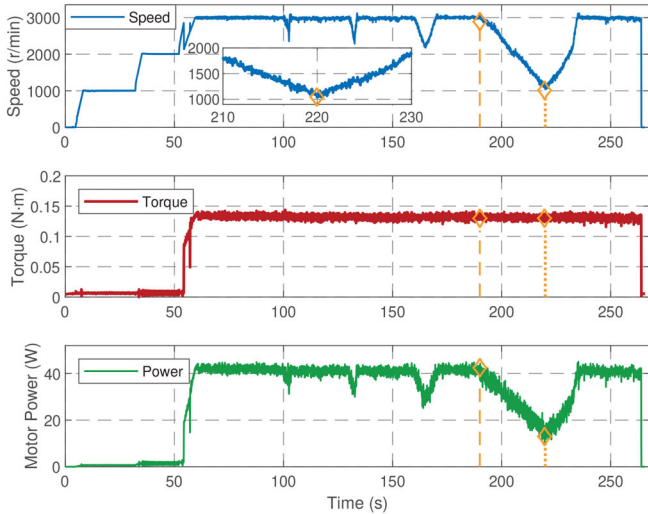
(b) MPP trajectory of FOC and sensorless DTC scheme



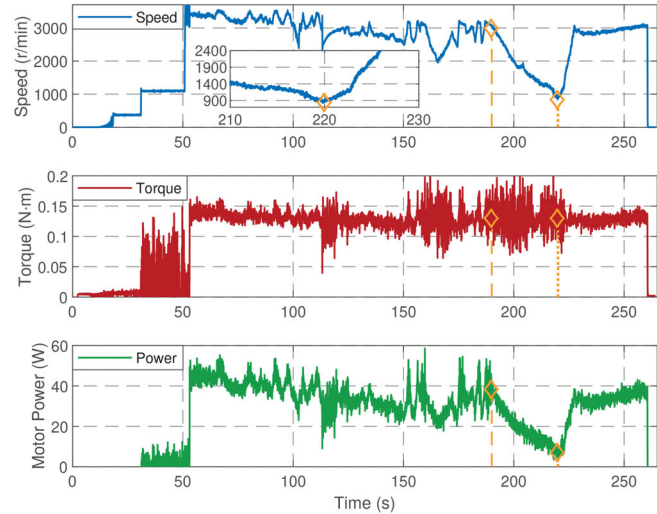
(c) Heavy clouds day oscilloscope waveform of FOC v_{dc} and i_a, i_b, i_c within 190 s to 190.5 s



(d) Heavy clouds day oscilloscope waveform of sensorless DTC v_{dc} and i_a, i_b, i_c within 190 s to 190.5 s



(e) Heavy clouds day FOC output speed, torque, power characteristics from dynamometer



(f) Heavy clouds day sensorless DTC output speed, torque, power characteristics from dynamometer

FIGURE 10 FOC and sensorless DTC output speed, torque, power results in heavy clouds day. (a) System radiation and temperature characteristics in heavy clouds day, (b) Heavy clouds day MPP trajectory and P-V curve of FOC and sensorless DTC, (c) Heavy clouds day oscilloscope waveform of FOC V_{dc} and i_a, i_b, i_c within 190 s to 190.5 s, (d) Heavy clouds day oscilloscope waveform of DTC V_{dc} and i_a, i_b, i_c within 190 s to 190.5 s, (e) Heavy clouds day FOC output speed, torque and power characteristics from dynamometer, (f) Heavy clouds day DTC output speed, torque and power characteristics from dynamometer

be used to achieve a smoother speed curve for the torque fluctuation problem considered in sensorless control. The proposed control method can also be used in similar loads such as fan only when we select different parameters. This will also be discussed in future research.

5 | CONCLUSION

This paper presents the design considerations of a two-stage topology of PV pump motor system. First, the maximum adjustment time of the overall system was obtained based on the

energy storage equation of the capacitor and the output equation of the synchronous motor. Then, the initial duty cycle of the negative buck converter was obtained based on the output characteristics of the PV. Next, the duty cycle output rule of the ESC-based MPPT algorithm was proposed. The relationship between the MPPT control algorithm and the command speed of the motor system were derived. Finally, for comparison purposes, two control schemes, FOC and sensorless DTC were introduced. And it applied to a test-rig feature with an IPMSM. The results indicated that proposed coordinated method can provide continuous balancing operation only by the one PV panel.

Tests have also revealed that extended kalman filter algorithms may further reduce speed fluctuations. This research provides insights into the future work of applications on different loads.

AUTHOR CONTRIBUTIONS

Jialiang Dai: Data curation, formal analysis, investigation, methodology, software, validation, visualization, writing - original draft. Jungho Ahn: Project administration, resources. Ju Lee: Conceptualization, supervision. Hyunwoo Kim: Writing - review and editing. Sunghong Won: Funding acquisition.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available on request from the authors. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

- Davis, S.J., Lewis, N.S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I.L., et al.: Net-zero emissions energy systems. *Science* 360(6396), eaas9793 (2018). <https://doi.org/10.1126/science.aas9793>
- Pye, S., Broad, O., Bataille, C., Brockway, P., Daly, H.E., Freeman, R., et al.: Modelling net-zero emissions energy systems requires a change in approach. *Climate Policy* 21(2), 222–231 (2021). <https://doi.org/10.1080/14693062.2020.1824891>
- Zhao, X., Ma, X., Chen, B., Shang, Y., Song M.: Challenges toward carbon neutrality in China: Strategies and countermeasures. *Res. Conser. Recycling* 176, 105959 (2022). <https://doi.org/10.1016/j.resconrec.2021.105959>
- Salvia, M., Reckien, D., Pietrapertosa, F., Eckersley, P., Spyridaki, N.A., Krook-Riekkola, A., et al.: Will climate mitigation ambitions lead to carbon neutrality? An analysis of the local-level plans of 327 cities in the EU. *Renew. Sustain. Energy Rev.* 135, 110253 (2021). <https://doi.org/10.1016/j.rser.2020.110253>
- Qazi, A., Hussain, F., Rahim, N.A.B.D., Hardaker, G., Alghazzawi, D., Shaban, K., et al.: Towards sustainable energy: a systematic review of renewable energy sources, technologies, and public opinions. *IEEE Access* 7, 63837–63851 (2019). <https://doi.org/10.1109/access.2019.2906402>
- Jurasz, J., Canales, F.A., Kies, A., Guezgouz, M., Beluco, A.: A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions. *Solar Energy* 195, 703–724 (2020). <https://doi.org/10.1016/j.solener.2019.11.087>
- Sashidhar, S., Reddy, V.G.P., Fernandes, B.G.: A single-stage sensorless control of a PV-based bore-well submersible BLDC motor. *IEEE J. Emerg. Sel. Topics Power Electron.* 7(2), 1173–1180 (2018). <https://doi.org/10.1109/JESTPE.2018.2810506>
- Kashif, M., Murshid, S., Singh, B.: Adaptive hybrid generalized integrator based SMO for solar PV array fed encoderless PMSM driven water pump. *IEEE Trans. Sustain. Energy* 12(3), 1651–1661 (2021). <https://doi.org/10.1109/TSTE.2021.3060912>
- Murshid, S., Singh, B.: Single stage autonomous solar water pumping system using PMSM drive. *IEEE Trans. Ind. Appl.* 56(4), 3985–3994 (2020). <https://doi.org/10.1109/TIA.2020.2988429>
- Tripathi, P.R., Thakura, P., Laxmi, V., Keshri, R.K.: Stand-alone PV water pumping system based on high-gain resonant inverter fed induction motor serving two-head for permanent water supply. *Int. J. Circuit Theory Appl.* 49(8), 2494–2514 (2021). <https://doi.org/10.1002/cta.2983>
- Jain, S., Karampuri, R., Somasekar, V.T.: An integrated control algorithm for a single-stage PV pumping system using an open-end winding induction motor. *IEEE Trans. Ind. Electron.* 63(2), 956–965 (2015). <https://doi.org/10.1109/TIE.2015.2480765>
- Ramulu, C., Sanjeevikumar, P., Karampuri, R., Jain, S., Ertas, A.h., Fedak, V.: A solar PV water pumping solution using a three-level cascaded inverter connected induction motor drive. *Eng. Sci. Technol.* 19(4), 1731–1741 (2016). <https://doi.org/10.1016/j.jestech.2016.08.019>
- Antonello, R., Carraro, M., Costabeber, A., et al.: Energy-efficient autonomous solar water-pumping system for permanent-magnet synchronous motors. *IEEE Trans. Ind. Electron.* 64(1), 43–51 (2016). <https://doi.org/10.1109/TIE.2016.2595480>
- Gherbi, A.D., Arab, A.H., Salhi, H.: Improvement and validation of PV motor-pump model for PV pumping system performance analysis. *Solar Energy* 144, 310–320 (2017). <https://doi.org/10.1016/j.solener.2016.12.042>
- Varma, R.K., Siavashi, E.M., Mohan, S., Vanderheide, A.T.: First in Canada, night and day field demonstration of a new photovoltaic solar-based flexible AC transmission system (FACTS) device PV-STATCOM for stabilizing critical induction motor. *IEEE Access* 7, 149479–149492 (2019). <https://doi.org/10.1109/ACCESS.2019.2935161>
- Chandra, S., Gaur, P., Pathak, D.: Radial basis function neural network based maximum power point tracking for photovoltaic brushless DC motor connected water pumping system. *Comput. Electr. Eng.* 86, 106730 (2020). <https://doi.org/10.1016/j.compeleceng.2020.106730>
- Priyadarshi, N., Padmanaban, S., Mihet-Popa, L., et al.: Maximum power point tracking for brushless DC motor-driven photovoltaic pumping systems using a hybrid ANFIS-FLOWER pollination optimization algorithm. *Energies* 11(5), 1067 (2018). <https://doi.org/10.3390/en11051067>
- De Brito, M.A.G., Galotto, L., Sampaio, L.P., e Melo, G.A., Canesin, C.A.: Evaluation of the main MPPT techniques for photovoltaic applications. *IEEE Trans. Ind. Electron.* 60(3), 1156–1167 (2012). <https://doi.org/10.1109/TIE.2012.2198036>
- Lei, P., Li, Y., Seem, J.E.: Sequential ESC-based global MPPT control for photovoltaic array with variable shading. *IEEE Trans. Sustainable Energy* 2(3), 348–358 (2011). <https://doi.org/10.1109/TSTE.2011.2141692>
- Brunton, S.L., Rowley, C.W., Kulkarni, S.R., Clarkson, C.: Maximum power point tracking for photovoltaic optimization using ripple-based extremum seeking control. *IEEE Trans. Power Electron.* 25(10), 2531–2540 (2010). <https://doi.org/10.1109/TPEL.2010.2049747>

21. Moura, S.J., Chang Y.A.,: Lyapunov-based switched extremum seeking for photovoltaic power maximization. *Control Eng. Pract.* 21(7), 971–980 (2013). <https://doi.org/10.1016/j.conengprac.2013.02.009>
22. Buja, G.S., Kazmierkowski, M.P.: Direct torque control of PWM inverter-fed AC motors-a survey. *IEEE Trans. Ind. Electron.* 51(4), 744–757 (2004). <https://doi.org/10.1109/TIE.2004.831717>
23. Texas Instruments: Chapter 11—Tuning regulators [Internet]. Texas Instruments, Texas (January 2013). [Updated 2021 October; cited 2022 March]. <https://www.ti.com/lit/pdf/spruh1>
24. Sun, T., Wang, J., Koc, M.: Virtual signal injection-based direct flux vector control of IPMSM drives. *IEEE Trans. Ind. Electron.* 63(8), 4773–4782 (2016). <https://doi.org/10.1109/TIE.2016.2548978>
25. Xia, C., Zhao, J., Yan, Y., Shi, T.: A novel direct torque control of matrix converter-fed PMSM drives using duty cycle control for torque ripple

reduction. *IEEE Trans. Ind. Electron.* 61(6), 2700–2713 (2013). <https://doi.org/10.1109/TIE.2013.2276039>

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