Operation and control of a 1-Φ induction machine fed from a typical transformer-less photovoltaic (PV) cells

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ABSTRACT

The work given in this paper illustrates how an adjustable speed 1-Φ induction machine's auxiliary winding is driven. Trina Solar's TSM-250PA05.08 array type model, which is made up of 1 series and 8 parallel-connected photovoltaic (PV) modules, feeds a single induction machine. PV system with perturb and observe (P&O) technique for maximum power point tracking (MPPT) tracking. The induction motor has been controlled using the field-oriented control (FOC) controlling approach. The outcomes of the 1-induction motor simulation were closely related to the parameters of insolation change. The outcomes are taken into account for the system's reaction FOC, which had been demonstrated in electromagnetic torque Te, main and auxiliary winding currents, and motor rotor speed.

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1. INTRODUCTION

As pollution is the most dangerous enemy for the earth's healthy environment, renewable energy has been used widely to overcome this danger [1], [2]. The significance of renewable energy is their types, such as solar, wind, geothermal and water energy, in employing it for generating electrical power, especially in remote areas, as solar energy is an inexhaustible supply of energy that may be utilized using the photovoltaic (PV) system [3], [4].

Solar energy can be utilized for different implementations such as water pumping, battery charging and grid network feeding [5]. The solar PV-based 1-Φ induction motor is widely utilized. Recently, the 1-Φ induction motor as one of the famous AC motors used in many applications such as refrigerators, vacuum cleaners and agricultural equipment [1]–[3]. The numerous uses of AC motors are mainly related to their simplicity in structure, outstanding reliability and low repair cost that is relatively less expensive [6], [7].

To harvest the maximum power from solar PV, the maximum power point tracking (MPPT) system using perturb and observe algorithm is influential and efficient [8], [9]. This paper studies the operation and control of a 1-Φ induction motor fed from typical transformer-less photovoltaic (PV) cells. The speed of a 1-Φ induction motor controlled by field-oriented control field-oriented control (FOC) technique.

2. THE PROPOSED SYSTEM DESIGN

The proposed system uses an H-bridge solar converter, as stated in Figure 1. The electrical energy is generated through PV cells. It does this by converting solar energy into electrical energy. The h-bridge converter the PV array's output voltage to preserve the DC link voltage, as stated in Figure 2. Drive of 1-Φ induction motor (the induction motor is driven by a rectifier, a braking chopper and an insulated gate bipolar transistor (IGBT) inverter) is applied to aid variable speed performance in achieving maximum power point tracking (MPPT). A single-phase induction motor (SPIM) drive is designed for a 1/4 HP, at voltage 110 V and frequency 60 Hz single phase AC motor with its main and auxiliary windings operation mode. A one-phase H-bridge converter feeds the SPIM. The converter utilizes the pulse width modulation (PWM)-control strategy. The speed control loop produces flux and torque references for the block controller by applying a proportional integral (PI) controller. Field-oriented control (FOC) controlling has been employed to control the induction motor.

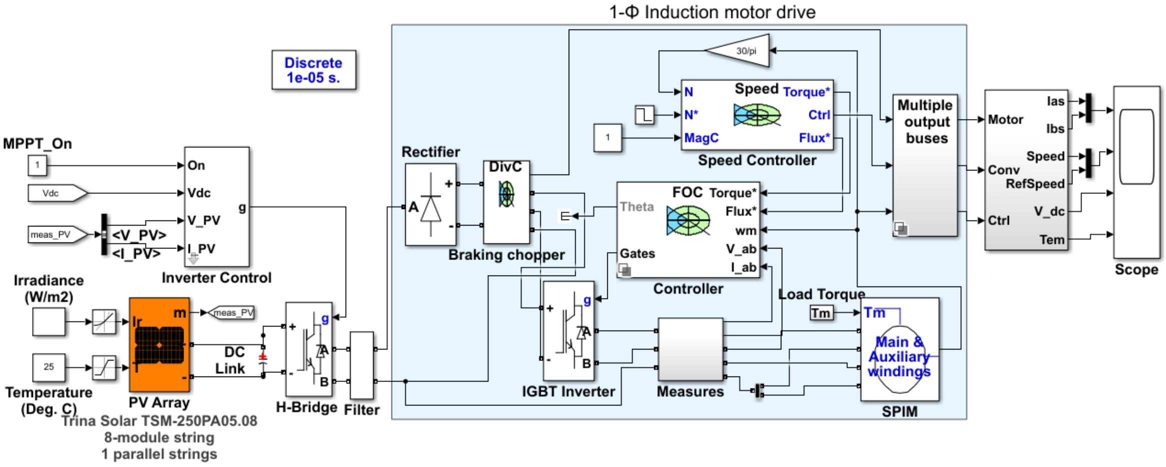


Figure 1. The proposed system designs

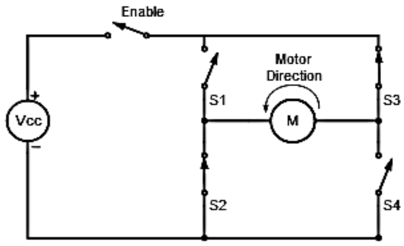


Figure 2. Full H-bridge schematic

2.1. PV array design characteristics

A PV cell's properties can be characterized as an electrical equivalent circuit, as illustrated in Figure 3. The most commonly used semiconductor dependent on building solar panels is silicon due to its high ability to control conductivity [10], [11]. Electricity is generated directly by converting solar energy to electricity from solar cells. These cells are formed in modules [6], [10]. Several PV modules, called an array, are often utilized to meet different energy demands [10], [12]. In this paper, Trina Solar TSM-250PA05.08 array model implements a PV array constructed from parallel-connected and series-connected PV modules. On the PV array block, two inputs allow for the supply of varying sun irradiance and temperature data, where (input Ir in W/m^2) and (input T in degrees Celsius) respectively. The PV array consists of one string of eight Trina Solar TSM-250PA05.08 modules connected in series. At 25° and an irradiance of 1000 W/m^2, the string can produce 3486 watt. To simulate parasitic capacitance between photovoltaic modules and ground, tiny capacitors (two capacitors linked at PV array terminals) are used.

A circuit stated in Figure 3 can be represented by the volt-ampere equation of a PV system stated by (1) [13], [14].

$$I = I_{ph} - I_D * \left(\frac{e(V+I*Rs)}{\left(N* \mathrm{kB}* \frac{\mathrm{T}}{\mathrm{q}}\right)} - 1 \right) - \frac{(V+I*Rs)}{R_{sh}}$$

$$I_{Ph} = Iph_0 * \frac{I_r}{Ir_0} \quad (1)$$

Where I_{ph}: solar-induced current, I_r: irradiance falling on the cell (light intensity), in W/m^2, I_{ph0}: solar-generated current measured for irradiance Ir_0, I_D: reverse diode's saturation current, Rs and R_{sh}: series and shunt resistance respectively in ohm, k_B: Boltzmann constant, T: the value of the device simulation temperature parameter, q: an electron's elementary charge, N: ideality factor, and V= solar cell ports' voltage. PV array parameters are illustrated in Table 1.

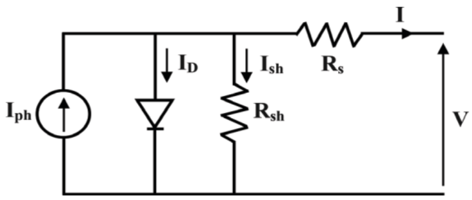


Figure 3. single PV cell

Table 1. PV array parameters

Parameter	Single module	Complete array module
Maximum power at MPP	249.86	3486
Voltage at MPP	31	434
Current at MPP	8.06	8.06
$V_{o.c}$ (V)	37.6	526.4
$I_{s.c}$ (A)	8.55	8.55
Light-generated current I_L (A)	-	8.5795
Shunt-connected resistance R_{sh} (Ω)	301.8149	301.8149
Series -connected resistance R_s (Ω)	0.247	1.976
No. of series modules	-	8
No. of parallel modules	-	1

2.2. Perturb and observe (P&O) technique of PV system

MPP tracker utilization in the PV array is to track the MPP at any alternative changes in irradiation and temperature at all times [15]. The corresponding flowchart for executing perturb and observe (P&O) technique is illustrated in Figure 4 [13], [16]. The P&O method periodically raises or lowers the panel voltage while contrasting the PV output power with that of the previous cycle. If the perturbation causes the module's power to increase or decrease, the subsequent perturbation occurs in the opposite direction. The size of the step and the interval between algorithm repetitions are the two factors for this strategy. As a result, the two variables opt for a trade-off for quicker tracking with greater accuracy [15], [17].

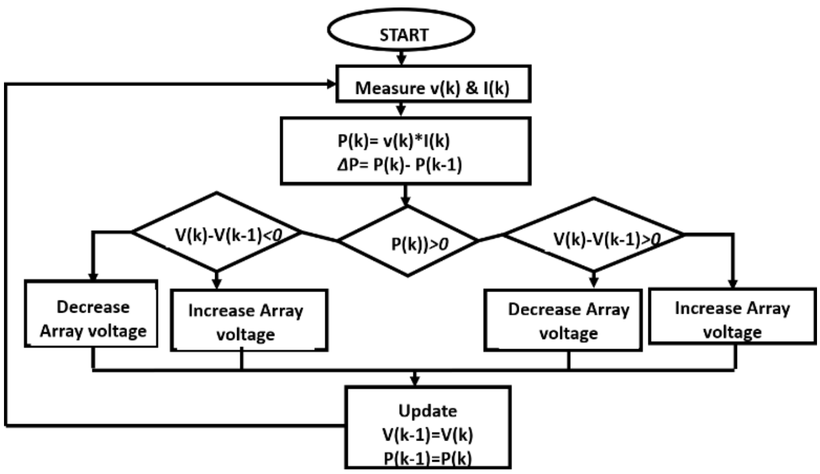


Figure 4. P&O method flow chart

2.3. 1-Φ induction motor

1-Φ induction motor is an asynchronous AC motor formed from a stator and rotor, representing the fixed and moveable parts in the motor, respectively. In the 1-Φ induction motor, AC voltage is utilized by the stator, which induces an electromagnetic field. Additionally, the induced field induces a current in the rotor, which causes the rotor to revolve as a result of the creation of a second field that attempts to synchronize with the stator field [18], [19]. The 1-Φ induction motor schematic is illustrated in Figure 5 [20], [21]. The induction motor has the ratings stated in Table 2.

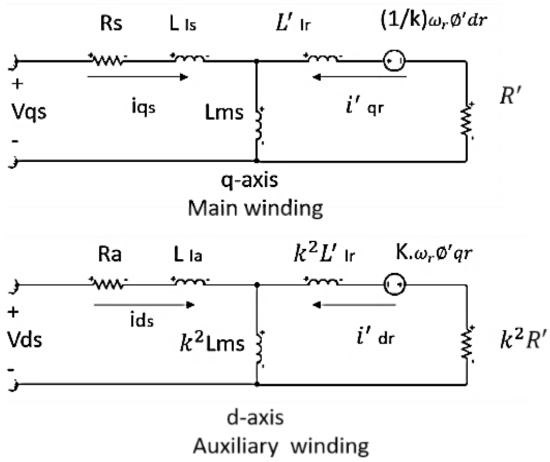


Figure 5. Equivalent circuit of unsymmetrical 1-Φ induction motor (stationary reference frame)

Table 2. Parameter of 1-Φ induction motor

Parameter	Value
Type of machine	Main and auxiliary winding
Rating	¼ hp
Voltage	110 volts
Frequency	60 Hz
Main winding resistance and inductance (stator)	2.02 Ω and 7.4 mH
Auxiliary winding resistance and inductance(stator)	7.14 Ω and 8.5 mH
Main winding resistance and inductance (rotor)	4.12 Ω and 5.6 mH
Initial speed (% synchronous speed)	0%

1-Φ induction motor drive included a 1-Φ induction motor, breaking chopper, inverter and rectifier. The gating pulses of the inverter are generated from the FOC controller, which its schematic has illustrated in Figure 6. Field-oriented control (FOC) is sophisticated control technology that tracks the speed of induction machine. FOC has been dependent on the requirements of high-performance speed and torque control responses to face the variation in online parameters. Utilizing of PI-controller in FOC causes overshoot and undershooting during the presence of load disturbance. For sinusoidally distributed stator windings, flux and torque are generated in alpha-beta frame [22]–[24]. A rotor flux position θ_s is the major part of FOC, that is determined as (2) [22].

$$\theta_s = \int \omega_S \, dt = \int \left(p \cdot \omega_m + \frac{iq}{Tid}\right) dt \tag{2}$$

Where *p*=machine pole pairs. The alpha-beta components are converted to the direct-quadrature ones by the rotational transformation [25].

$$[D] = \begin{bmatrix} cos\,\theta_s & sin\,\theta_s \\ sin\,\theta_s & cos\,\theta_s \end{bmatrix} \tag{3}$$

$$\left[i_d \; i_q\right]^T = [D]\left[\, i_\alpha \; i_\beta\right]^T \tag{4}$$

In FOC, 1-Φ induction motor under PI vector control has the following dynamic equations [22].

$$\frac{d}{dt}i_{sd} = -\frac{1}{\sigma\tau'_s}i_{sd} + \omega_s i_{sq} + \frac{1}{\sigma L_s \tau_r}\varphi_r + \frac{1}{\sigma L_s}v_{sd} \tag{5}$$

$$\frac{d}{dt}\varphi_r = -\frac{1}{\tau_r}\varphi_r + \frac{(1-\sigma)L_s}{\tau_r}i_{sd} \tag{6}$$

$$\frac{d}{dt}i_{sq} = -\frac{1}{\sigma\tau'_s}i_{sq} - \omega_s i_{sd} + \frac{P}{\sigma L_s}\omega_r\varphi_r + \frac{1}{\sigma L_s}v_{sq} \tag{7}$$

$$\frac{d}{dt}\omega_m = \frac{P}{J}\varphi_r i_{qs} - \frac{1}{J}T_L \tag{8}$$

Where $\varphi_r$is the direct-axis rotor flux linkage, ω_s is synchronous angular speed, $\tau_S' = L_S / R_{seq}$, $\sigma = 1 - M^2 / L_s L_R$, $R_{Seq} = M^2 / {L_s}^2$ and $\tau_r = L_r / R_r$ where, $\tau_r$is the rotor time constant.

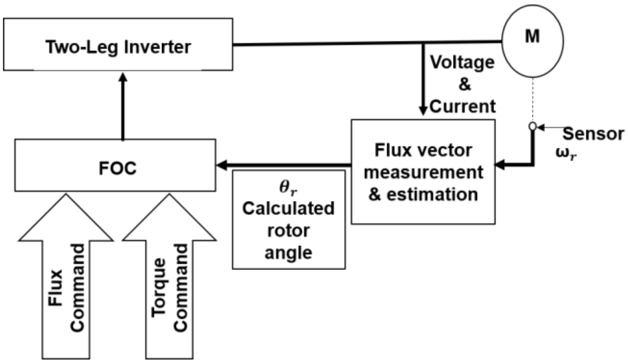


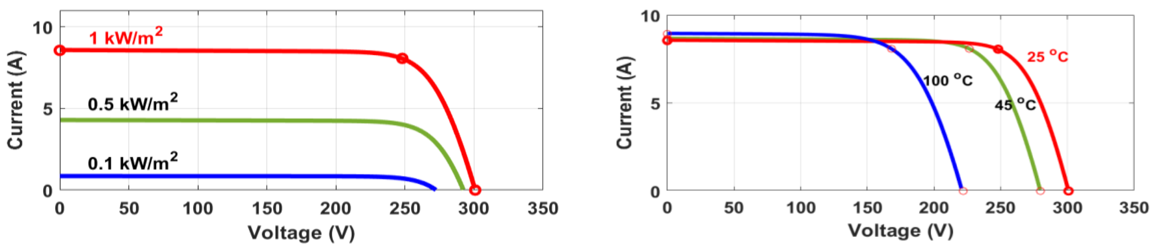
Figure 6. Diagram of FOC for 1-Φ induction motor

3. SIMULATION RESULTS AND DISCUSSION

The MATLAB program has evaluated the performance and characteristics of 1-Φ induction motor under several PV array conditions. The results have been taken according to the light intensity variation for three different temperature degrees. The results are taken under the response of utilization of FOC for the drive system by illustrating the motor's electromagnetic torque Te and speed.

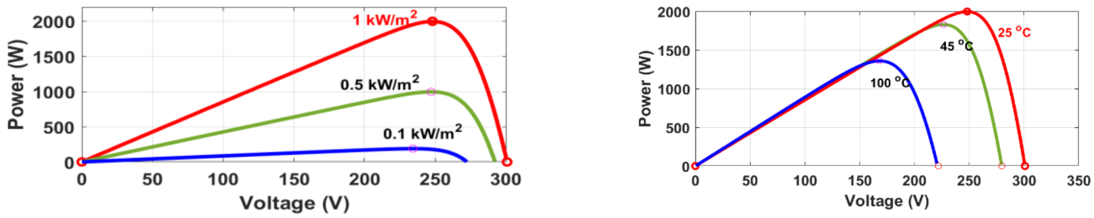
3.1. Simulation result of PV array

The V-I and V-P characteristics of Trina Solar TSM-250PA05.08 array type are demonstrated in Figures 7 and 8 respectively, for three levels. Both features are illustrated for the array at 1000 W/m^2 as demonstrated in Figures 7(a) and 8(a) respectively, and for 25^o with specified irradiation as demonstrated in Figures 7(b) and 8(b) respectively. The V-I, V-P characteristics of the PV array and absorbed irradiance by the PV array in (w/m^2), mean DC voltage in (v) and mean power in (w) generated by the PV array, are demonstrated in Figures 7, 8, and 9 respectively.



(a) (b)

Figure 7. V-I characteristics of Trina Solar TSM-250PA05.08 array type: (a) array @1000 W/m^2 and specified irradiation; and (b) array @25^o and specified irradiation



(a) (b)

Figure 8. V-P characteristics of TSM-250PA05.08 array type: (a) array @1000 W/m^2 and specified irradiation; and (b) array @25º and specified irradiation

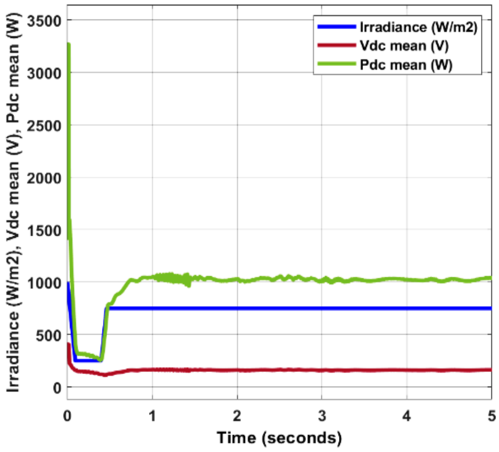
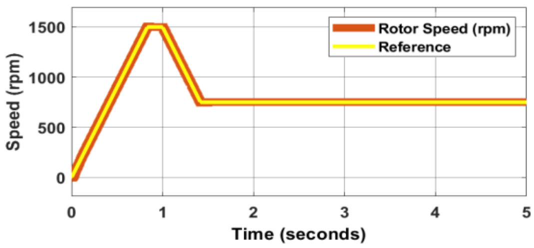


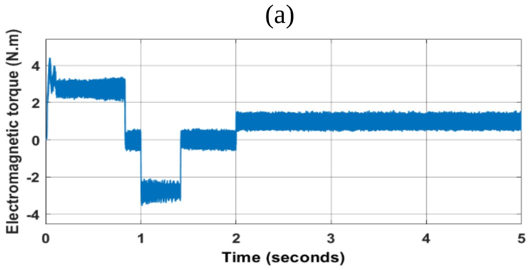
Figure 9. Absorbed irradiance by the PV array in (w/m^2), mean DC voltage in (v) and mean power in (w) generated by PV array

3.2. Simulation result of 1-Φ induction motor

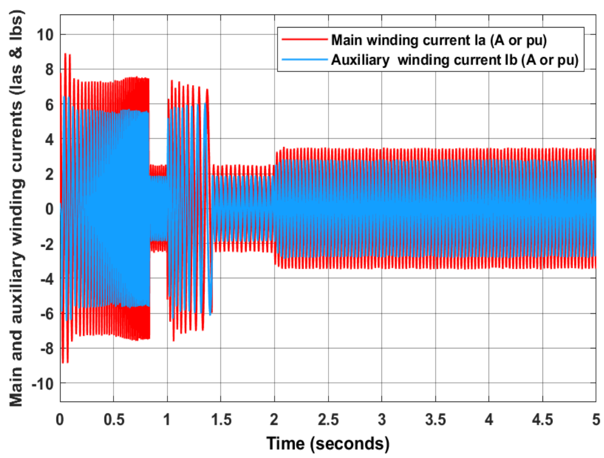
The results of 1-Φ induction motor simulated closely related to insolation change characteristics. The results are considered for the system's response FOC, which had been illustrated in electromagnetic torque Te, main and auxiliary winding currents and rotor speed of the motor. Figure 10(a) illustrates the rotor speed of the 1-Φ induction motor, tracking its reference value optimally. Figure 10(b) illustrates the main and auxiliary winding currents. Figure 10(c) illustrates the Te with a high settling time of 2 seconds.



(a)



(c)



(b)

Figure 10. 1-Φ induction motor simulation results (a) rotor speed, (b) main and auxiliary winding currents, and (c) electromagnetic torque Te

4. CONCLUSION

This paper proposes a 1-Φ induction motor that utilizes FOC fed from a Trina Solar TSM-250PA05.08 array type. The P&O technique had been depended on to track MPP in the PV array. The results show the behavior of the 1-Φ induction motor under step input change with a good response for rotor speed, Te and main and auxiliary winding currents. examines the operation and control of a one-induction motor that is powered by standard photovoltaic (PV) cells without a transformer. The field-oriented control FOC technique used to control the speed of a 1-Φ induction motor.

REFERENCES

[1] M. J. B. Kabeyi and O. A. Olanrewaju, "Sustainable energy transition for renewable and low carbon grid electricity generation and supply," *Frontiers in Energy Research*, vol. 9, Mar. 2022, doi: 10.3389/fenrg.2021.743114.

[2] M. J. Barasa Kabeyi and O. A. Olanrewaju, "Geothermal wellhead technology power plants in grid electricity generation: a review," *Energy Strategy Reviews*, vol. 39, p. 100735, Jan. 2022, doi: 10.1016/j.esr.2021.100735.

[3] V. Vongmanee, "The photovoltaic pumping system using a variable speed single phase induction motor drive controlled by field oriented principle," in *IEEE Asia-Pacific Conference on Circuits and Systems, Proceedings, APCCAS*, 2004, vol. 2, pp. 1185–1188, doi: 10.1109/apccas.2004.1413097.

[4] M. E. Ropp and S. Gonzalez, "Development of a MATLAB/Simulink model of a single-phase grid-connected photovoltaic system," *IEEE Transactions on Energy Conversion*, vol. 24, no. 1, pp. 195–202, Mar. 2009, doi: 10.1109/TEC.2008.2003206.

[5] S. Lekhchine, T. Bahi, I. Abadlia, and H. Bouzeria, "PV-battery energy storage system operating of asynchronous motor driven by using fuzzy sliding mode control," *International Journal of Hydrogen Energy*, vol. 42, no. 13, pp. 8756–8764, Mar. 2017, doi: 10.1016/j.ijhydene.2016.05.298.

[6] C.-E. Feraga and A. Bouldjedri, "Performance of a photovoltaic pumping system driven by a single phase induction motor connected to a photovoltaic generator," *Automatika*, vol. 57, no. 1, pp. 163–172, Jan. 2016, doi: 10.7305/automatika.2016.07.851.

[7] L. C. Kelley, E. Gilbertson, A. Sheikh, S. D. Eppinger, and S. Dubowsky, "On the feasibility of solar-powered irrigation," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 2669–2682, Dec. 2010, doi: 10.1016/j.rser.2010.07.061.

[8] M. Calavia, J. M. Perié, J. F. Sanz, and J. Sallán, "Comparison of MPPT strategies for solar modules," *Renewable Energy and Power Quality Journal*, vol. 1, no. 08, pp. 1440–1445, Apr. 2010, doi: 10.24084/repqj08.685.

[9] B. Singh, U. Sharma, and S. Kumar, "Standalone photovoltaic water pumping system using induction motor drive with reduced sensors," *IEEE Transactions on Industry Applications*, vol. 54, no. 4, pp. 3645–3655, Jul. 2018, doi: 10.1109/TIA.2018.2825285.

[10] A. K. Saini and A. K. Dubey, "Performance analysis of single phase induction motor with solar PV array for water pumping system," *International Journal of Engineering Research and*, vol. V6, no. 04, Apr. 2017, doi: 10.17577/IJERTV6IS040567.

[11] A. A. F. Husain, W. Z. W. Hasan, S. Shafie, M. N. Hamidon, and S. S. Pandey, "A review of transparent solar photovoltaic technologies," *Renewable and Sustainable Energy Reviews*, vol. 94, pp. 779–791, Oct. 2018, doi: 10.1016/j.rser.2018.06.031.

[12] A. S. Al-Ezzi and M. N. M. Ansari, "Photovoltaic solar cells: a review," *Applied System Innovation*, vol. 5, no. 4, p. 67, Jul. 2022, doi: 10.3390/asi5040067.

[13] D. Eddine Tourqui, A. Betka, A. Smaili, and T. Allaoui, "Improved performance of a photovoltaic panel by MPPT algorithms," *Recent Developments in Photovoltaic Materials and Devices*, Feb. 2019, doi: 10.5772/intechopen.79709.

[14] M. Y. Javed *et al.*, "A comprehensive review on a PV based system to harvest maximum power," *Electronics*, vol. 8, no. 12, p. 1480, Dec. 2019, doi: 10.3390/electronics8121480.

[15] A. Anurag, S. Bal, S. Sourav, and M. Nanda, "A review of maximum power-point tracking techniques for photovoltaic systems," *International Journal of Sustainable Energy*, vol. 35, no. 5, pp. 478–501, May 2016, doi: 10.1080/14786451.2014.918979.

[16] S. Bandri, Zulkarnaini, A. Syofian, and A. Effendi, "The application of perturb and observe algorithm to optimized of solar cell output," *Journal of Physics: Conference Series*, vol. 1185, p. 012012, Apr. 2019, doi: 10.1088/1742-6596/1185/1/012012.

[17] B. Subudhi and R. Pradhan, "A comparative study on maximum power point tracking techniques for photovoltaic power systems," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 1, pp. 89–98, Jan. 2013, doi: 10.1109/TSTE.2012.2202294.

[18] M. Jannati, T. Sutikno, N. R. N. Idris, and M. J. A. Aziz, "A novel method for rotor field-oriented control of single-phase induction motor," *International Journal of Electrical and Computer Engineering*, vol. 5, no. 2, pp. 205–212, Apr. 2015, doi: 10.11591/ijece.v5i2.pp205-212.

[19] M. Jannati *et al.*, "A review on variable speed control techniques for efficient control of single-phase induction motors: evolution, classification, comparison," *Renewable and Sustainable Energy Reviews*, vol. 75, pp. 1306–1319, Aug. 2017, doi: 10.1016/j.rser.2016.11.115.

[20] K. J. Lee, H. G. Kim, D. K. Lee, T. W. Chun, and E. C. Nho, "High performance drive of single-phase induction motor," in *IEEE International Symposium on Industrial Electronics*, 2001, vol. 2, pp. 983–988, doi: 10.1109/isie.2001.931608.

[21] M. I. Rahman and K. M. Salim, "Performance evaluation of single-phase induction motor controlled by variable frequency drive at non-ideal voltage conditions," *Australian Journal of Electrical and Electronics Engineering*, vol. 16, no. 2, pp. 65–73, Apr. 2019, doi: 10.1080/1448837X.2019.1600213.

[22] A. Hajary, S. G. Seifossadat, R. Kianinezhad, A. Saffarian, and S. S. Mortazavi, "An adaptive PI control design for multi-phase machines in healthy and faulty operations," *COMPEL - The international journal for computation and mathematics in electrical and electronic engineering*, vol. 38, no. 6, pp. 1986–2000, Oct. 2019, doi: 10.1108/COMPEL-12-2018-0552.

[23] N. Pham and K. Nguyen, "Sensorless control for high performance SPIM drives based on the improved rotor flux identifier using sliding mode," *International Journal of Intelligent Engineering and Systems*, vol. 12, no. 4, pp. 291–305, Aug. 2019, doi: 10.22266/ijies2019.0831.27.

[24] H. Ben Azza, N. Zaidi, M. Jemli, and M. Boussak, "Development and experimental evaluation of a sensorless speed control of SPIM using adaptive sliding mode-MRAS strategy," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 2, pp. 319–328, Jun. 2014, doi: 10.1109/JESTPE.2014.2299893.

[25] N. Pham, D. Nguyen, K. Nguyen, and N. Nguyen, "A novel neural network SC_MRAS based observer for high-performance SPIM drives," *International Journal of Intelligent Engineering and Systems*, vol. 11, no. 6, pp. 95–107, Dec. 2018, doi: 10.22266/ijies2018.1231.10.

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