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https://doi.org/10.5109/4843121

出版情報：Evergreen. 9 (3), pp.893-902, 2022-09. 九州大学グリーンテクノロジー研究教育センター
バージョン：

A Comparative Study of Photovoltaic Water Pumping System-Driving Conventional AC Single-phase and Three-phase Motor Submersible Pumps

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(Received May 31, 2022; Revised August 24, 2022; accepted September 16, 2022).

Abstract: The water is very important to human lives. The best and most appropriate way to have an adequate supply of water is to use solar energy to drive pumps instead of using fossil energy. This research was conducted as a comparative study of a conventional submersible AC motor–pump driven by a photovoltaic system using two types of AC motor which are single-phase and three-phase submersible water pumps. The performance of the system was measured according to the standard test procedure in IEC 62253: 2011 while the depth of the well was simulated by an adjustable pump discharge pressure and a pump installed in a predetermined location of 40 meters. The results showed that the three-phase pump supplied more water and has a good response as indicated by a low irradiance of approximately 75 Watt/m^2 in the morning, around 06.15 AM which runs the pump motor effectively while the one-phase pump required a higher irradiance of 750 Watt/m^2 at around 10.30 A.M. Moreover, the PVWPS system with the three-phase pump also had higher efficiency and PR values with 0.64 and 0.40598 respectively than the system with the single-phase with 0.48 and 0.21388.

Keywords: *Photovoltaic, Water Pumping, Submersible Pump, AC Motor Single-phase, AC Motor Three-phase, PVWPS*

1. Introduction

The water needed in the household and for irrigation is very important throughout the world, especially in districts with a lack of water and an electricity grid. The data from Pusat Sumber Daya Air Tanah, Badan Geologi Kementerian ESDM showed that Indonesia has several districts being faced with this problem because it is majorly an agrarian country with high dependence on agriculture. The country often has the challenges of water during the dry season and this normally leads to crop failure with further effects on the economy. Based on data from BPS, in 2021, rice harvested area has decreased by around 2.30 percent compared to 2020. This resulted in rice production in 2021 falling by 0.45 percent compared to production in 2020. The decline in harvested area and rice production was due to damaged land, one of which is caused by drought[1)].

Several efforts have been made to solve this problem such as the installation of submersible pumps in deep wells and an example of this is the pump placed in a deep well in the district area of Sudan in 1995 and powered through a diesel engine with the objective of supplying water for household and agricultural needs [2)].

Several problems have, however, been associated with the use of diesel and gasoline engines in driving submersible pumps and these include (i) the non-renewable nature of fossil fuels and the need for its supply from another region, (ii) production of carbon emission considered to be environmentally unfriendly, and (iii) high cost of operation [3)]. This means there is a need for an environmentally friendly and sustainable technology to provide water to irrigate farms and satisfy household needs and an example of this is the photovoltaic water pumping system (PVWPS) technology.

Several studies have been conducted on the application of PVWPS as a more optimal and efficient system to replace diesel or gasoline pumping systems and its performance is commonly evaluated based on the solar irradiance of the specific area studied [2]. Moreover, the long-term performance evaluation of the PVWPS as well as the model for its optimization have been created based on techno-economy to ensure the system supplies water effectively during its lifetime to meet household or irrigation needs [4-6]. This is necessary due to the high cost associated with the initial investment in developing PVWPS and this means there is a need to ensure efficiency, optimization, and adequate maintenance every time [7].

The application of small to medium-scale PVWPS to pump water in remote areas is a good choice in countries with optimal solar irradiation [8]. Abdolzadeh et. al. showed that it is possible to improve the efficiency of the system by installing water spray on the PV panels to reduce their temperature, increase the electricity they produced, and enhance the system efficiency by approximately 12.5% compared to the system without water spray [7]. Meanwhile, there is a need to ascertain the models to simulate flow rate using solar radiation for different PV array heads and configurations, the size to ensure pump supply during the pumping period, the energy required by the pump as well as other loads when a battery is used, and volume of water required for irrigation during the process of designing a PV water pumping system in order to have an initial estimate of the head and the suitable PV configuration [6), 8), 9]. The process of selecting the appropriate pump for the PVWPS system has also been studied by Almeida et.al., [10] while P. Caton analyzed the application of solar trackers for photovoltaic systems which led to an increase in system efficiency by approximately 17.6% greater than non-tracking horizontal arrays [11].

Indonesia is one of the developing countries where energy supply is an essential factor for overall development [12]. The scarcity of fossil energy sources and climate change issues has built the commitment to develop and utilize new and renewable energy (NRE) through clean energy transition programs to achieve net zero emissions [13),14]. The Indonesian government plans to gradually phase out coal-fired power generation starting in 2030 to reach net zero carbon emissions by 2060 or earlier[15]. The target for the contribution of NRE to the energy mix is 24,8 % by 2030 [16]. Currently, NRE capacity is still far from the target where Indonesia should add at least 3 GW per year for the next four years [17]. Many efforts have been made to promote renewable energy utilization, particularly in solar energy by deploying PV technology in urban and rural areas, such as PV-diesel-battery hybrid systems, converting diesel-based power plants to PV-battery storage systems, solar street lighting, PV rooftop, solar home system, solar cold storage, and others.

Indonesia is a tropical area with high solar intensity, and this is the reason the use of solar energy to pump water, especially in dry areas without grid electricity, is considered suitable by Rejekiningrum, et. al. [18]. The study installed a PVWPS in Gunungkidul Regency and the system was observed to have pumped for approximately 7.59 hours/day with the ability to irrigate an area of 2,333 m^2. Another system installed in Imogiri district, Bantul regency operated for 5.42 hours/day and irrigated an area of 3,630 m^2. Moreover, Setiawan et. al. used a PVWPS with a PV power of 3200 Wp to supply energy for two submersible pumps with a flow rate of around 0.4 – 0.9 l/s to satisfy water needs in Gunung Kidul and conduct field practice for students [19]. It was, however, discovered by Susanto et. al. [20] that 51% of the aspects in IEC 62253: 2011 standard parameters required in PVWPS installations in Indonesia have not been fulfilled by installers or users, thereby, leading to a reduction in efficiency and even failure of the system. This means there is a need for standardization and operation-maintenance manuals to reduce problems in this system in the future.

The main difference in the application of AC motor submersible water pump with grid electricity or diesel generator compared to PV generator is in the frequency of the AC electricity supply to meet the demand of the pump when the PV is not connected to a storage system or battery. This is due to the fact that the frequency in the PV generator fluctuates significantly according to solar irradiance while grid or diesel generators have constant frequency [10].

To support the Government of Indonesia in achieving net zero carbon emissions by 2060 or earlier, with a target for the contribution of NRE to the energy mix of 24.8% by 2030, therefore, this present study was conducted to compare AC motors of single-phase and three-phase submersible pumps powered with PV generators according to the standard testing at IEC 62253: 2011 [21]. This is necessary to provide an overview of the characteristics of these two types of pumps when applied using photovoltaic to fulfill water needs, especially in areas with water shortages and located far from the electricity grid, for installers, users, and government as regulators. The review of past studies showed that lesser attention has been placed on the discussion of the experimental difference between PVWPS using single-phase and three-phase AC motor submersible water pumps powered with PV generators.

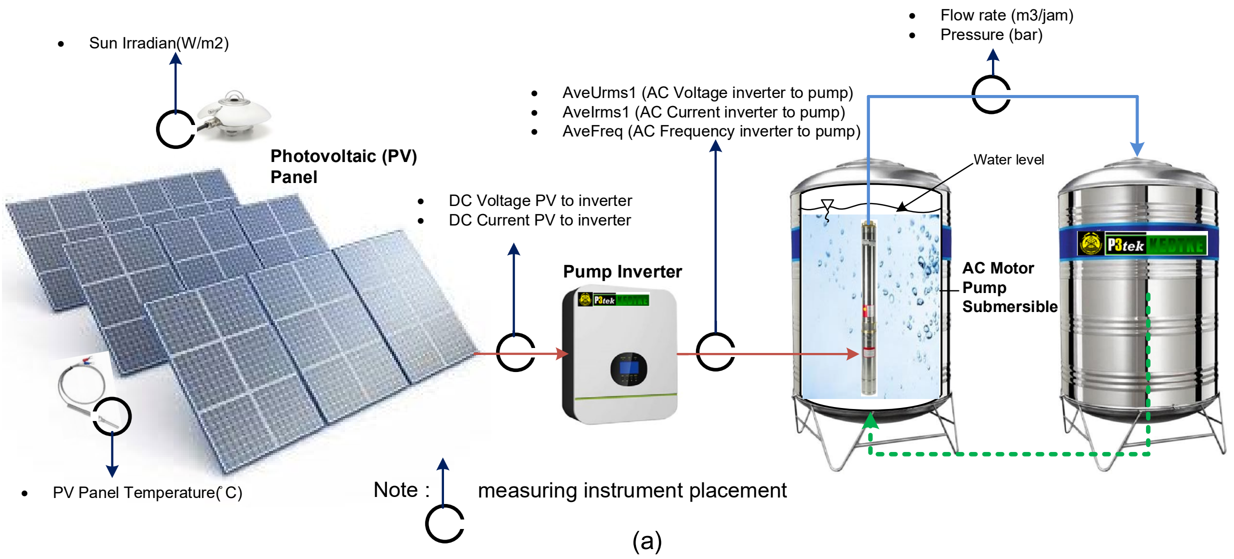
2. Materials and method

2.1. Photovoltaic Water Pumping System (PVWPS)

The main components of the PVWPS system used in this study include the Photo Voltage (PV) array, AC motor submersible water pump, and inverter. It is important to note that the system is without storage or battery such that the PV array is connected directly to a frequency converter (inverter) which is also connected directly to the AC motor submersible water pump. The advantage of this system is that it is cheaper because there is no need to buy a battery but the disadvantage is that it cannot be used when there is no sun irradiation during cloudy weather or at night. The schematic diagram of the system is presented in Fig. 1(a) with some protection devices placed between the PV array and inverter such as the fuse DC, miniature circuit breaker (MCB) DC, and surge protective device (DC) as well as between the inverter and AC motor such as the MCB AC, and SPD AC. Moreover, all the devices used were connected to grounding protection.

The specifications of the PV array system include the nominal maximum power (Pmax) of 375 Watts, optimum operating voltage (Vpm) of 39.77 Volts, optimum operating current (Ipm) of 9.44 Amperes, open-circuit voltage (Voc) of 48.45 Volts, short circuit current (Isc) of 9.98 Amperes, maximum system voltage (Vmax) 1500 Volts, and maximum series fuse rating of 16 Amperes. Moreover, two types of inverters were used and these include the single-phase and three-phase such that the single-phase inverter needs 380 Volt DC minimum input voltage from the PV array to produce 220 Volt AC while the three-phase inverter needs 560 Volt DC minimum input from the PV array to produce 380 Volt AC. It is important to note that 8 pcs of PV arrays connected in a series configuration were required in a single-phase inverter while 14 pcs connected in a series configuration were needed in a three-phase inverter as indicated in Fig. 1 (b).

The pump used also has two types which include the single-phase AC motor and a three-phase AC motor connected to a single-phase and three-phase inverter, respectively. An induction AC motor with a cooling oil bath system was used due to its availability and the existence of dealers for the motor submersible pump spread all over Indonesia. This means the consideration of this study also covers the situation when the user has a motor AC submersible pump or requires information on the best type to use in installing a new PVWPS system.



(a)

No	Variation	Specification of PV Panel	Spesification of Pump Inverter	Spesification of Submersible Motor and Pump
1	System 1 phase	- 375 Wp - 40.8 V - 8.8 A - 8 pcs of quantity	- 2.2 kW - Accumulated voltage of connected panel should be close to 330 V with 220 V output voltage - Max output current 14 A	-1 Hp/0.75 kW - 220 V - 50 Hz
2	System 3 phase	- 375 Wp - 40.8 V - 8.8 A - 14 pcs of quantity	- 7.5 kW - Accumulated voltage of connected panel should be close to 560 V with 380 V output voltage - Max output current 15 A	- 3.5 Hp/2.6 kW - 380 V - 50 Hz

(b)

Fig. 1. (a) Photovoltaic pump system testing and schematic placement of measuring instruments, and (b) Specification of the main component

2.2. Experimental design

The test bench of PVWPS used in this study is presented in Fig. 2 and observed to be installed in the Research and Development Center for Electricity, New, Renewable Energy and Energy Conservation Technology (P3tek KEBTKE), Ministry of Energy and Mineral Resources (KESDM), Bogor, Indonesia. The schematic diagram of the measurement is presented in Fig. 1(a) while the sensors applied are listed in Table 1.

All the measurement devices were calibrated, verified, and compared with another calibrated device before they were applied in the experiment. Moreover, the pressure value in the pump submersible outlet interpreted as the head was determined by setting the main valve in the simulation well through the operation of the submersible water pump on the grid according to the electricity input needed. The main valve was adjusted up to the moment the pressure or head reached the characteristic curve of the pump, thereby, leading to a value of 4.5 bar for the submersible pumps tested in this study.

The PVWPS system was tested in November 2021 during the rainy season starting from 04.30 am before sunrise to approximately 07.30 pm at the end of sunset. The parameters stated in Fig. 1(a) were recorded in the datalogger in real-time. It is important to note that some devices such as pyranometers and power quality analyzers have a built-in data logger while some that did not have such as a flowmeter, thermocouple, DC voltage and current, and pressure used Grapthec GL 7000 datalogger.

Fig. 2. Photovoltaic pump system testing test section on-site.

Table 1. The variables and sensor measurement devices used in this study

No	Variable	Sensors or measurement device	Type and Brand	Accuracy
1	PV Temperature	Thermocouple	Autonics PT 100	± 0.5% ^{0}C
2	Solar radiation	Pyranometer	Meteon Kipp & Zonen	< 0.5% over full temperature range
3	Flow	Water flow meter and pulse meter	Water flow sensor YF-DN40 and Autonics MP5W	5 - 150L/min ±3%
4	AC Current AC Voltage AC Frequency	AC Power Quality Analyzer (PAQ)	Hioki 3197	Voltage Accuracy ±0.3% rdg. ±0.2%f.s; Current Accuracy ±0.3% rdg. ±0.2%f.s. + Clamp sensor accuracy; Frequency Accuracy ±0.01 Hz ±1 dgt. (when input is at least 10% of range)
5	DC Voltage	DC voltage transmitter	DC Voltage Transducer CE-VZ01-33MSI-0.5/500 Volt	± 0.5 % DC Voltage
6	DC Current	DC current transmitter	DC Current Transducer CE-1Z04-33ES3-1.0/30 A	± 0.5 % DC Current
7	Pressure	Pressure Transmitter	WIKA A10 0 – 10 bar/ 4 – 20 mA	Non-linearity 0.25 % or 0.5 %

2.3. *Performance of PVWPS system*

The performance of the PVWPS system was evaluated based on different solar radiation conditions according to the irradiance value when tested in the laboratory. It was agreed during the test that all the components used passed the FAT (Factory Acceptance Test) and are relevant to existing standards.

According to the IEC 62253:2011 standard, the efficiency of the PVWPS was determined using the following equation:

$$\eta = \frac{H\ x\ Q\ x\ g}{I\ x\ V} \quad (1)$$

Where g is the earth gravitation = 9,81 m/s^2; H [m] is the static + dynamic water head, Q [l/s] is the flow rate of pumped water, V [Volt] is the input of the converter DC voltage, and I [A] is the DC measured from PV arrays to a frequency-converter (inverter). Moreover, one of the parameters in the WPS PV system is the performance ratio (PR) [22-24] which was adjudged by Khalid et al. as an important and crucial parameter to monitor PV system performance [25]. It is defined as the ratio between the energy produced and the energy input as indicated in the following equation:

$$P_r = \frac{Y_f\ (Final\ Yield)}{Y_r\ (Reference\ Yield)} \quad (2)$$

Where Y_f is the ratio between the final energy generated from the pumping per unit time (kWh) and the incoming energy from the PV panel (DC) while Y_r is the ratio between solar energy entering the PVWPS system (kWh/m^2) and standard irradiance (1 kWh/m^2) according to the standard test condition (STC). These are further represented as follows:

$$Y_f = \frac{Final\ energy\ output\ (kWh)}{Nominal\ DC\ power\ (kW)} \quad (3)$$

$$Y_r = \frac{Total\ in{-}plane\ irradiance\ (kWh/m^2)}{PV\ reference\ irradiance\ (kW/m^2)} \quad (4)$$

3. Results and Discussion

3.1. *Real-time radiation intensity and influence on all measurement systems*

The real-time data measured for the three-phase AC motor submersible water pump

for a full day is presented in Fig. 3. It was discovered in Fig. 3 (a), that the solar irradiance value is fluctuating significantly due to the cloudy condition of the weather during the test, and this affected the quantity of electricity produced from the PV panels to the inverter, especially the DC electric current generated. Moreover, the output of the inverter has a similar trend with the solar irradiance as indicated in Fig 3 (b) and this means the electricity supply to the three-phase AC motor submersible water pump is also influenced by the solar irradiance as presented in Figs 3 (c) and (d). The pump was observed to start rotating at a low irradiant which was approximately 75 Watt/m^2 at 06.15 AM and continued rotating when the value was exceeded but stopped by 04.00 PM.

A similar phenomenon was found in Fig. 4 for the PVWPS system with a single-phase AC motor submersible water pump. The solar irradiant conditions also have a significant effect on the water supplied but a slight difference was observed when compared to the three-phase pump because it was only able to rotate when the solar irradiance was around 750 W/m^2 at 10.30 am and stopped at 440 W/m^2.

The frequency of the inverter for both PVWPS systems was set at the same value of 10 Hz and this means the output frequency below the value will not produce electricity to the pump as indicated in the two graphs in Figs. 3 and 4 where the inverter failed to produce electricity and tended to fluctuate until it reached 10 Hz.

3.2. *The effect of the capacitor on Single-phase AC motor submersible water pump*

One of the reasons the single-phase is different from the three-phase AC motor submersible water pump is due to the capacitor installed as shown in Fig. 5. It was discovered from Fig. 7 that the inverter was only able to supply electricity to the pump motor when the AC power output frequency reached 50 Hz. A capacitor is an electronic device that stores energy and is normally used in single-phase induction motors to ensure the motors start early considering their inability to ignite independently. The function of the capacitor itself is to increase the coupling or initial starting torque, reduce the initial starting current of the motor, and sharpen the phase difference shift between the main and auxiliary windings to close to 90º. The existence of an auxiliary winding and a capacitor means that there is a phase difference between the two, this is where there is a magnetic flux and the resultant force that differs forward or backward depending on the magnitude of the resultant force itself and generally the resultant force occurs in a clockwise direction so that the motor can rotate to the right. After the motor rotates 75% of the nominal rotation, the centrifugal switch works to disconnect the auxiliary winding circuit and the capacitor and the motor works only with the main winding. It is important to note that most submersible pumps use a dual start/run capacitor which performs both functions. Moreover, the capacitor normally used in a water pump motor is usually perfectly cylindrical and the one installed in the AC single phase submersible pump motor designed in this study is presented in Fig. 5.

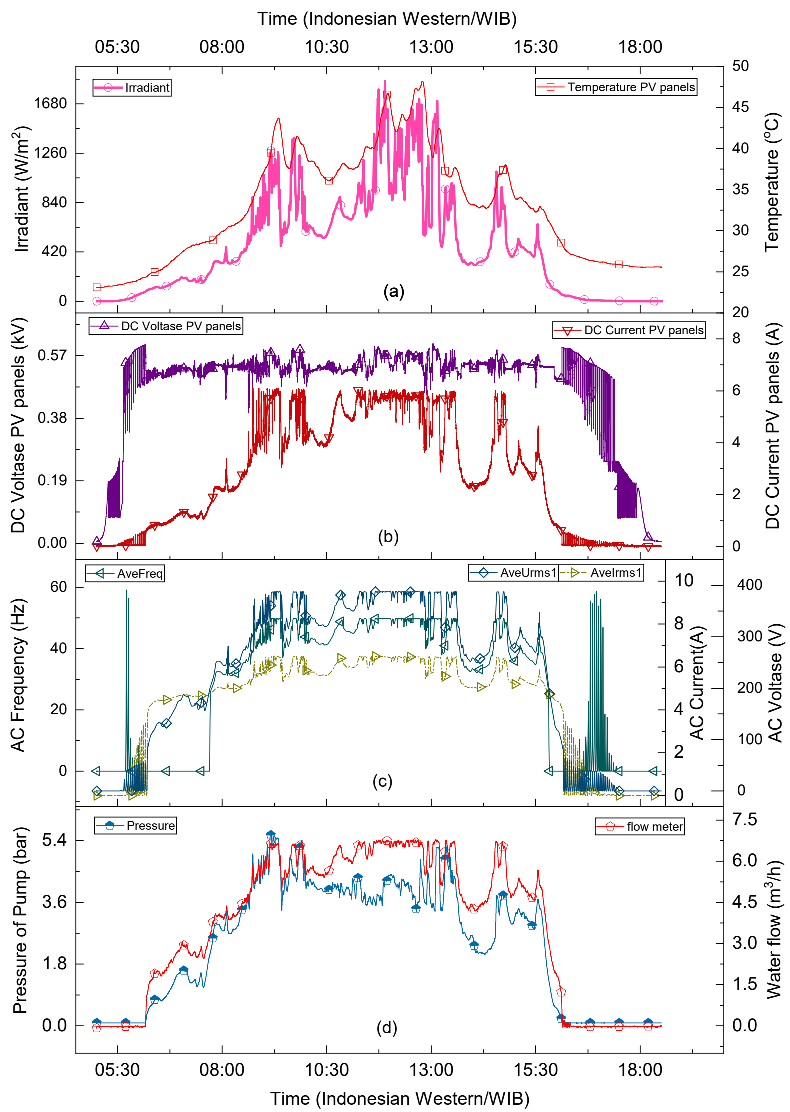


Fig. 3. Real-time measurement on the three-phase AC motor submersible water pump.

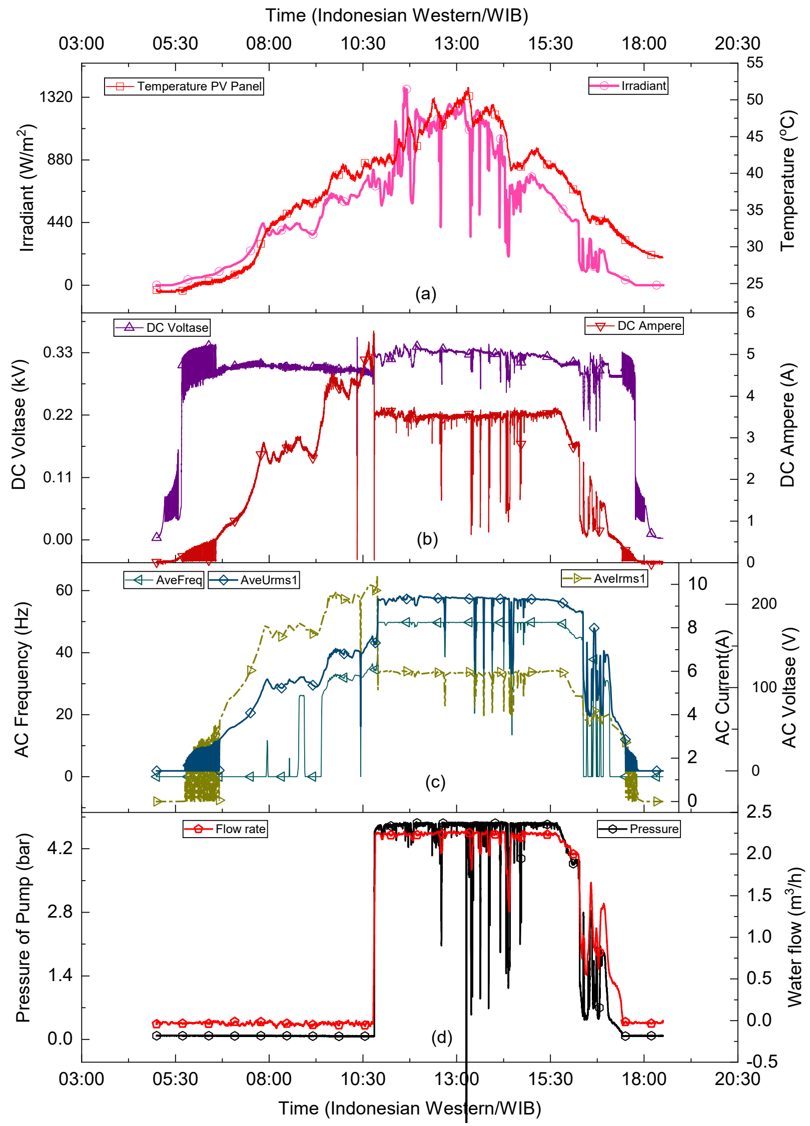


Fig. 4. Real-time measurement on the single-phase AC motor submersible water pump.

Fig. 5. The capacitor used in single-phase AC motor submersible water pump

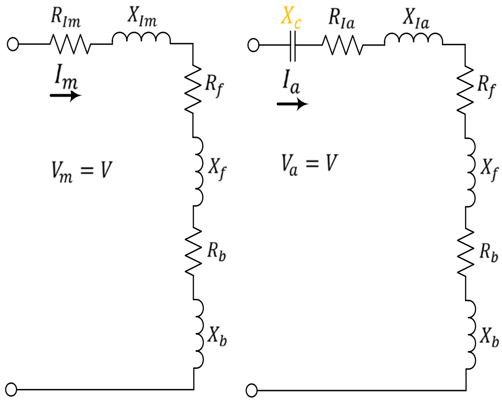


Fig. 6. The equivalent configuration in induction motor capacitor at starting

Capacitors in electric power systems normally generate reactive power (X_c) to improve voltage and power factors. A capacitor connected in series to the auxiliary coil (starting) of a single-phase induction motor is intended to obtain a phase difference between the main winding/coil current (running) and a larger starting/auxiliary coil current to produce sufficient torque to drive the cage rotor at the starting time. Meanwhile, the reactive power of the capacitor is usually affected by the capacitance value of a capacitor (C) and the AC frequency (Hz) of the inverter, according to the following equation:

$$X_c = \frac{1}{\omega_c} = \frac{1}{2xfxC} \quad (5)$$

The starting torque of a single-phase induction motor is highly dependent on the reactive power of the capacitor as indicated in the equivalent circuit when the motor starts in Fig. 6. This means the value of Ia which is the starting current in a single-phase induction motor is very high in Equation (5) and also influenced by the frequency value of the AC entering the capacitor such that a lesser current is supplied to the motor when the frequency is below the nominal input of the capacitor. This is clarified in Fig. 6 where the current coming out of the capacitor in (c) is low when the frequency in (a) has not reached 50 Hz while the voltage produced in (b) was observed to be increasing with the frequency value.

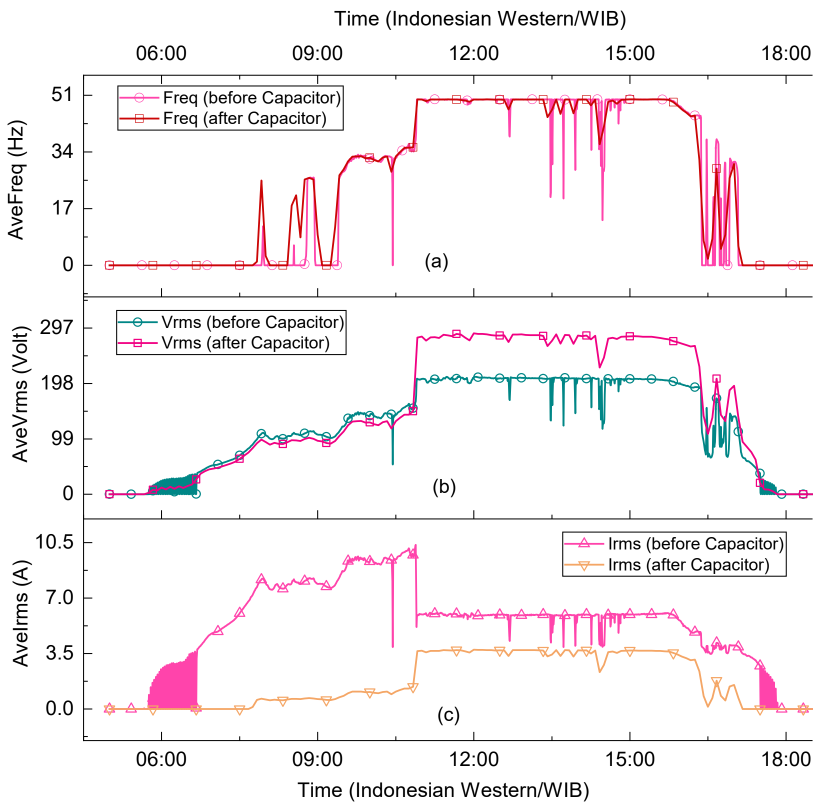


Fig. 7. The effect capacitor in 1 phase AC motor submersible water pump system.

3.3. *The Performance of photovoltaic pumping system*

The efficiency of the PVWPS system calculated using Equation (1) is presented in Fig. 8 (a) and it was discovered that the system with a three-phase AC motor submersible water pump has the highest efficiency of 0.64 while the lowest was 0.3. The values were, however, observed to be fluctuating in line with the solar irradiant value such that the highest efficiency was recorded at low irradiant values which were in the morning and evening for the three-phase pump. These results are in line with the findings of Benghanem et al. [9] but different efficiency of the PVWPS system with a single-phase AC motor submersible water pump, where the value was recorded when the system is producing current at a solar irradiance condition of 750 W/m^2 by 10.30 AM. It is important to note that the highest efficiency value for this type of pump was found to be 0.48 while the lowest was 0.275.

The PR value calculated using Equations (2), (3), and (4) are presented in Fig. 8 (b) and it was discovered that the PVWPS system with a three-phase AC motor submersible water pump has a higher value because the single-phase started running when the solar irradiance value was at the minimum frequency required for the capacitor to transmit current to the motor.

From the tests carried out for the two pump specifications used, the three-phase submersible pump can pump about 49 kilo liters of water/day with the amount of solar radiation energy used is 748.312 kW/m^2 at the time of the test. As for the submersible pump with a single-phase motor, it can pump about 12 kilo liters of water/day with solar energy used of 807.13 kW/m^2 at the time of the test

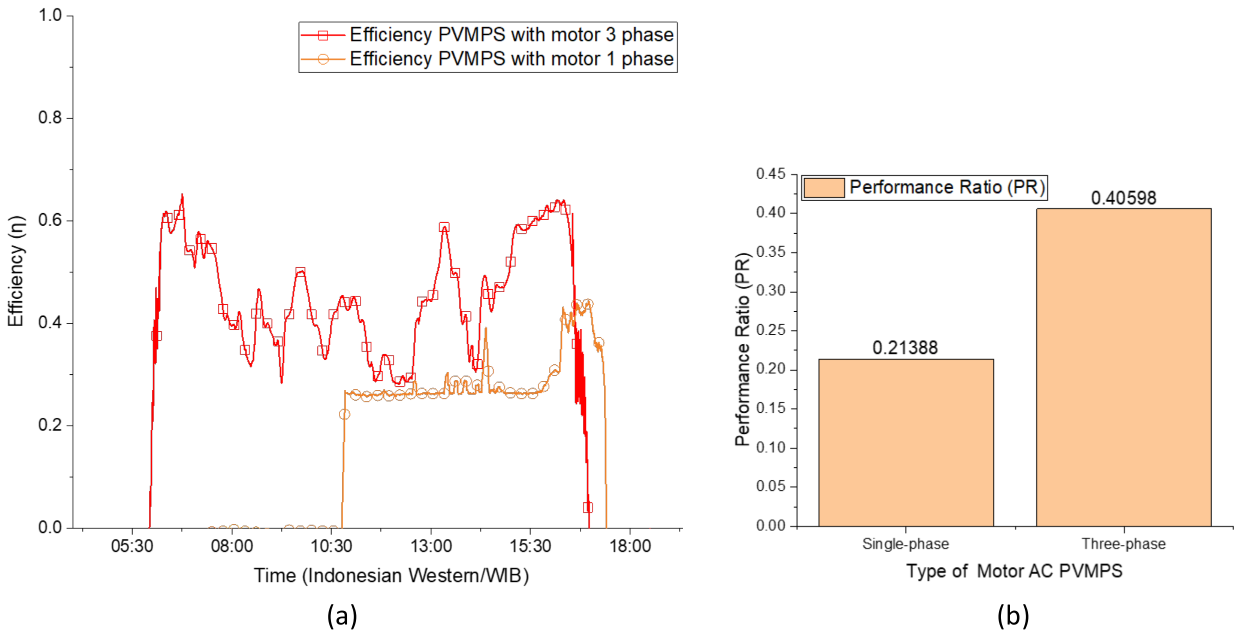


Fig. 8. (a) The efficiency of the PVWPS system, and (b) The performance ratio of the PVWPS system.

4. Conclusion

From the results of this study, the observed three-phase pump began to rotate and flowed water at low radiation, which was around 75 Watt/m^2 (occurred at 06.15 A.M.) and continued to rotate as the solar radiation value increased. The maximum rotation of the three-phase pump occurs when the irradian value is around 800 Watt/m^2, then the pump starts to stop rotating when the irradian value approaches 75 Watt/m^2. The experiment also showed that the PVWPS system with a three-phase pump has higher efficiency and PR values at 0.63 and 0.40589 than the system with a single-phase pump at 0.48 and 0.21388, when solar irradiance is around 868 W/m^2 and 750 W/m^2, respectively. It was also discovered that the system with a three-phase pump can work at any irradiance input as long as the solar irradiation is capable of producing more than 10 Hz frequency at the AC while the system with a single-phase pump started working at 750 W/m^2 solar irradiance and stops at 440 W/m^2. This is because the pump with a single-phase motor uses a circuit with an additional capacitor and this requires the frequency value of the AC generated by the inverter from the PV panel to be close to 50 Hz to allow the system to provide sufficient initial current for the pump to start. This means the photovoltaic pump system with a good response to the irradiance increase the efficiency and PH value, thereby, leading to the pumping of more water with solar irradiation.

Declaration of competing interest

This manuscript has been approved and an agreement with submission to The Electricity Journal was made.

Furthermore, there are no conflicts of interest to declare. The manuscript has not been published elsewhere and is not under consideration by another journal.

Acknowledgement

The authors are grateful to Head of P3tek KEBTKE, Adjar Hadiyono, M.Eng., Guntur Tri Setiadanu, M.Eng., Nina Supriatna Konintat, M.Eng., Saiful Nasution, M.Eng., Iyung, M.Eng., Suprapto, Janu Marwoto, and Bambang, for supporting the study.

Credit authorship contribution statement

Yohanes Gunawan: Supervision, Conceptualization, Methodology, Investigation, Visualization, Writing – original draft. **Slamet Kasbi:** Methodology, Writing – review & editing, Validation. **Khalif Ahadi:** Investigation, Visualization, Writing – review & editing, Validation. **Vetri Nurliyanti:** Writing – review & editing. **Novan Akhiriyanto:** Writing – review & editing. **Sujono:** Writing – review & editing. **Muhammad Nabil Makarim Rizkillah:** Visualization, Data curation. **Muhammad Rizal Fadilah Permana:** Investigation, Visualization, Data curation.

References

1) I. N. (Badan P. S. Khasanah and K. (Badan P. S. Astuti, “LUAS PANEN DAN PRODUKSI PADI DI INDONESIA 2021,” *Badan Pus. Stat.*, 2022.
2) A. Z. T. Ali A. Hamza, “Performance of Submersible PV Solar Pumping Systems Under Conditions in The Sudan,” *Water*, vol. 6, no. 5, pp. 491–495, 1995.
3) A. Allouhi *et al.*, “PV water pumping systems for domestic uses in remote areas: Sizing process, simulation and economic evaluation,” *Renew. Energy*, vol. 132, pp. 798–812, 2019, doi: 10.1016/j.renene.2018.08.019.
4) M. Benghanem, K. O. Daffallah, and A. Almohammedi, “Estimation of daily flow rate of photovoltaic water pumping systems using solar radiation data,” *Results Phys.*, vol. 8, pp. 949–954, 2018, doi: 10.1016/j.rinp.2018.01.022.
5) I. Odeh, Y. G. Yohanis, and B. Norton, “Influence of pumping head, insolation and PV array size on PV water pumping system performance,” *Sol. Energy*, vol. 80, no. 1, pp. 51–64, 2006, doi: 10.1016/j.solener.2005.07.009.
6) I. Yahyaoui, G. Tina, M. Chaabene, and F. Tadeo, “Design and Evaluation of a Renewable Water Pumping System,” *IFAC-PapersOnLine*, vol. 48, no. 30, pp. 462–467, 2015, doi: 10.1016/j.ifacol.2015.12.422.
7) M. Abdolzadeh and M. Ameri, “Improving the effectiveness of a photovoltaic water pumping system by spraying water over the front of photovoltaic cells,” *Renew. Energy*, vol. 34, no. 1, pp. 91–96, 2009, doi: 10.1016/j.renene.2008.03.024.
8) B. G. Belgacem, “Performance of submersible PV water pumping systems in Tunisia,” *Energy Sustain. Dev.*, vol. 16, no. 4, pp. 415–420, 2012, doi: 10.1016/j.esd.2012.10.003.
9) M. Benghanem, K. O. Daffallah, A. A. Joraid, S. N. Alamri, and A. Jaber, “Performances of solar water pumping system using helical pump for a deep well: A case study for Madinah, Saudi Arabia,” *Energy Convers. Manag.*, vol. 65, pp. 50–56, 2013, doi: 10.1016/j.enconman.2012.08.013.
10) R. H. Almeida, J. R. Ledesma, I. B. Carrêlo, L. Narvarte, G. Ferrara, and L. Antipodi, “A new pump selection method for large-power PV irrigation systems at a variable frequency,” *Energy Convers. Manag.*, vol. 174, no. August, pp. 874–885, 2018, doi: 10.1016/j.enconman.2018.08.071.
11) P. Caton, “Design of rural photovoltaic water pumping systems and the potential of manual array tracking for a West-African village,” *Sol. Energy*, vol. 103, pp. 288–302, 2014, doi: 10.1016/j.solener.2014.02.024.
12) R. Nugroho, J. Hanafi, K. Shobatake, Y.-Y. Chun, K. Tahara, and W. W. Purwanto, “Life cycle inventories and life cycle assessment for an electricity grid network: case study of the Jamali grid, Indonesia,” *Int. J. Life Cycle Assess.*, pp. 1081–1091, 2022, doi: 10.1007/s11367-022-02082-5.
13) K. Samarasinghe and P. D. C. Wijayatunga, “Techno-economic feasibility and environmental sustainability of waste-to-energy in a circular economy: Sri Lanka case study,” *Energy Sustain. Dev.*, vol. 68, pp. 308–317, 2022, doi: 10.1016/j.esd.2022.04.005.
14) N. Reyseliani, A. Hidayatno, and W. W. Purwanto, “Implication of the Paris agreement target on Indonesia electricity sector transition to 2050 using TIMES model,” *Energy Policy*, vol. 169, no. April 2021, p. 113184, 2022, doi: 10.1016/j.enpol.2022.113184.
15) “Kementerian ESDM RI - Media Center - News Archives - Speaking at COP26, Energy Minister Gives Indonesia’s Commitment to Net Zero Emission.” https://www.esdm.go.id/en/media-center/news-archives/speaking-at-cop26-energy-minister-gives-indonesias-commitment-to-net-zero-emission (accessed Sep. 28, 2022).
16) P. P. Persero, “Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) PT PLN (Persero) 2021-2030,” 2021.
17) “Indonesia Energy Transition Outlook,” 2021.
18) P. Rejekiningrum and Y. Apriyana, “Design and implementation of solar pump irrigation systems for the optimization of irrigation and increase of productivity,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 622, no. 1, 2021, doi: 10.1088/1755-1315/622/1/012046.
19) A. A. Setiawan, D. H. Purwanto, D. S. Pamuji, and N.

Huda, "Development of a solar water pumping system in karsts rural area tepus, gunungkidul through student community services," *Energy Procedia*, vol. 47, no. V, pp. 7–14, 2014, doi: 10.1016/j.egypro.2014.01.190.

20) H. F. dan M. A. Danar A. Susanto, Utari Ayuningtyas, "Evaluasi Instalasi Pompa Air Tenaga Surya Di Indonesia dengan Menggunakan Standar IEC 62253-2011," *J. Stand.*, vol. 20, no. 2, pp. 85–94, 2018.
21) IEC 62253, "Photovoltaic pumping systems – Design qualification and performance measurements." 2011.
22) R. H. Almeida *et al.*, "Development and test of solutions to enlarge the power of PV irrigation and application to a 140 kW PV-diesel representative case," *Energies*, vol. 11, no. 12, Dec. 2018, doi: 10.3390/EN11123538.
23) N. H. Reich, B. Mueller, A. Armbruster, W. G. J. H. M. Van Sark, K. Kiefer, and C. Reise, "Performance ratio revisited: is PR > 90% realistic?," *Prog. Photovoltaics Res. Appl.*, vol. 20, no. 6, pp. 717–726, Sep. 2012, doi: 10.1002/PIP.1219.
24) B. Zhao, Y. Ren, D. Gao, and L. Xu, "Performance ratio prediction of photovoltaic pumping system based on grey clustering and second curvelet neural network," *Energy*, vol. 171, pp. 360–371, 2019, doi: https://doi.org/10.1016/j.energy.2019.01.028.
25) A. M. Khalid, I. Mitra, W. Warmuth, and V. Schacht, "Performance ratio – Crucial parameter for grid connected PV plants," *Renew. Sustain. Energy Rev.*, vol. 65, pp. 1139–1158, 2016, doi: 10.1016/j.rser.2016.07.066.