Received: April 29, 2022. Revised: May 24 2022.

International Journal of
Intelligent Engineering & Systems

http://www.inass.org/

Enhancing Performance of Solar Photovoltaic Drip Irrigation System Through Binary Particle Swarm Optimization

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Abstract: This paper presents a multisector drip irrigation system (DIS) powered by solar photovoltaic (PV). A binary particle swarm optimization (BPSO) method possibly determines irrigation in multisector, depending on the power availability of the solar PV. The power from solar PV in this study was optimized through maximum power point tracking (MPPT) using an incremental conductance (INC) method. A prototype was built using a PV emulator in 10 controlled irrigation sectors. Three operating modes applied include control of all sectors with BPSO, partly sectors with a combination of linear programming, and all sectors with bypassed without BPSO. Simulations and tests showed very similar results, indicating that the BPSO method provides an optimal and accurate irrigation system with 0.7 psi of an average irrigation operating pressure (IOP) error, 4.01 % of water volume error, and 96.55 % of the uniformity coefficient of water volume.

Keywords: Drip irrigation system, Photovoltaic, Binary particle swarm optimization, Maximum power point tracking, And microcontroller.

1. Introduction

Drip irrigation system (DIS) is considered significant in improving energy and water use efficiency and crop quality [1-3]. The quality of irrigation depends on three main challenges: building an effective water allocation scheme for crops; determining how to optimize the integration of water allocation elements; and defining a complete distribution scenario [4, 5].

To increase the efficiency of water and energy use, irrigation areas are divided into several sectors, called multisector [6, 7]. It is necessary in solar photovoltaic drip irrigation systems (SPVDIS) to obtain smaller solar panel sizes. Scheduling and managing irrigation canals critically help optimize the utilization of water resources and agricultural productivity. With a suitable drip irrigation system controller, water and fertilizer can be supplied at accurate doses and places in the plant's root [8, 9]. SPVDIS with a direct pumping method but without storage facilities is cheaper due to no cost for storage investment and maintenance. However, the system's operation is more complex due to limited duration of using the energy from PV to obtain precise irrigation [6, 10, 11].

Several researchers have developed an irrigation optimization method for the SPVDIS type. Zavala [2] developed a simulation of the SPVDIS model that can synchronize energy availability with plant's water needs to produce an optimal system size. However, this system does not precisely control water supply to plants. López-Luque [12] developed a direct pumping SPVDIS simulation with a single sector and a non-compensated emitter. Synchronization between PV power and irrigation capacity is done using a variable speed drive (VSD), but it requires a larger PV to carry simultaneous irrigation. Reca [13] developed the SPVDIS by dividing the irrigation area into several sectors, adjusting the speed of several pumps with a VSD, and regulating the activation of

Received: April 29, 2022. Revised: May 24 2022.

the irrigation sector according to the PV power. Although the system produces efficient irrigation, it still requires complex calculations.

Most of the research on direct pumping SPVDIS with multisector irrigation focuses on optimizing irrigation capacity according to the output power of PV panels. It ignores the stability of irrigation operating pressure (IOP) which dramatically affects the accuracy of irrigation volume. The relationship between discharge and IOP at a non-pressure compensating emitter is not linear [14].

The SPVDIS in the current proposed system consists of a MPPT system that optimizes PV power extraction using the INC method and a multisector drip irrigation system through the BPSO method. This current study looked into the use of the BPSO method in a real-time basis to optimize irrigation capacity according to the PV power for efficient and accurate irrigation. In this study, the irrigation area was divided into many irrigation sectors to improve efficiency in producing a more precise capacity. Besides, multisector irrigation likely makes irrigation able to operate normally even though the PV output power is low. The system was built through simulation with MATLAB/SIMULINK and verified through hardware testing.

This paper is structured as follows: Section 2 describes our proposed system. The setup of the simulation and experiment settings is described in section 3. A detailed discussion of the simulation and experimental results are found in section 4. Section 5 presents the conclusions of this paper.

2. The proposed system

The proposed system aims to optimize the performance of SPVDIS using BPSO. SPVDIS in this study is drip irrigation powered by solar panels with a direct pumping type from groundwater reservoirs to the irrigation distribution network, divided into ten sectors. This system does not have an overhead water tank or battery for energy storage. In this study, the irrigation system is evaluated from the ability of the system to adjust irrigation capacity depending on irradiation or the availability of PV power, IOP stability, and the accuracy of the water volume produced. Fig. 1 shows a functional diagram on how the proposed SPVDIS works. The system consists of a PV panel, a MPPT system, a BLDC motor-driven centrifugal pump, a multisector irrigation distribution network, and an irrigation optimization control system.

The MPPT system uses a DC boost converter and the INC method to optimize the extraction of PV output power. Power from the boost converter is fed to a BLDC motor-driven water pump to push water from the groundwater tank to the multi-sector irrigation network. BPSO, as the proposed method, metaheuristically combines the capacity of all irrigation sectors according to the PV output power. This process would find a compatibility between PV power and irrigation capacity to stabilize IOP and produce precise water volume.

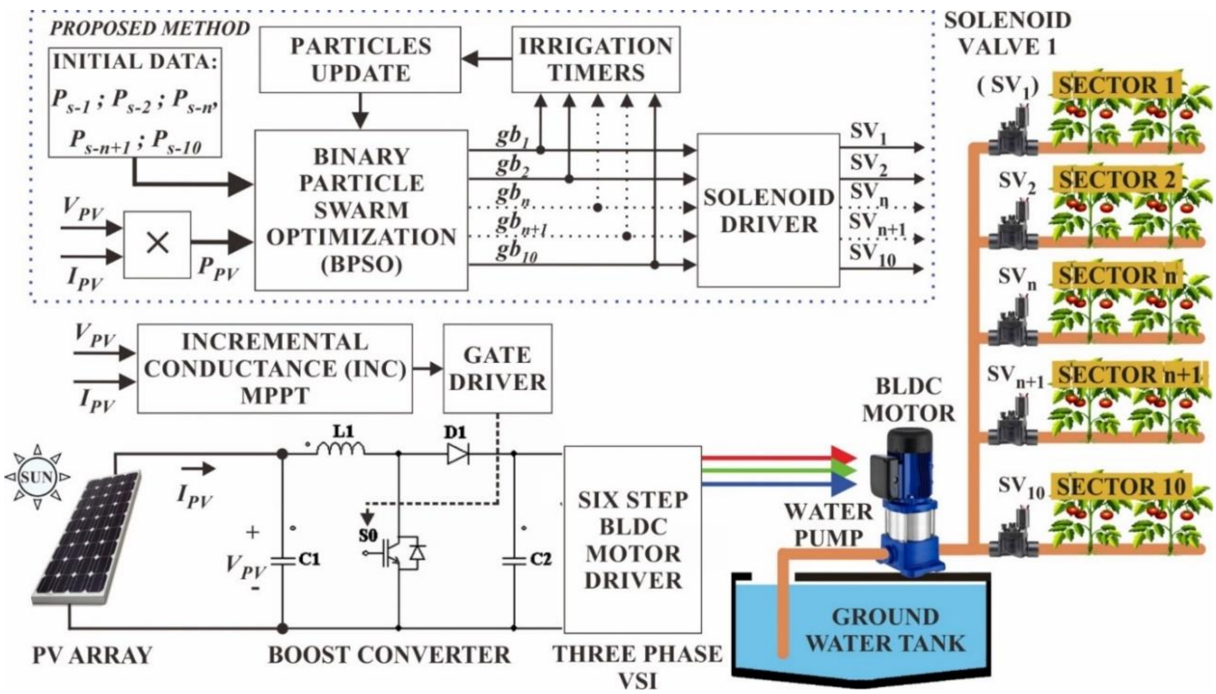

Figure. 1 The functional diagram of the proposed system

Received: April 29, 2022. Revised: May 24 2022.

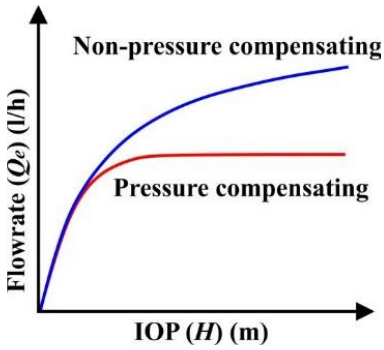

Figure. 2 Flowrate - IOP emitters

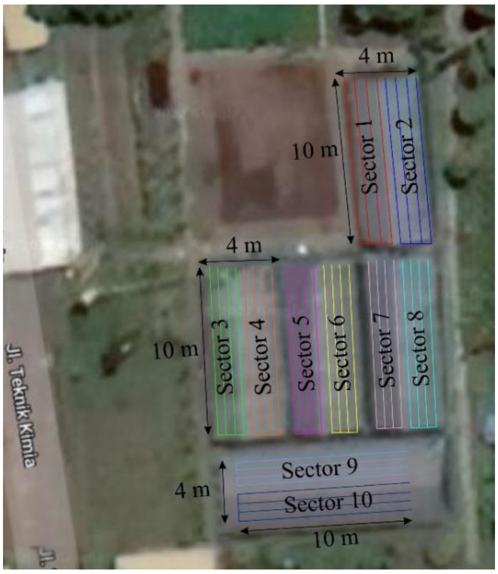

Figure. 3 The location of the SPVDIS installation in a vegetable garden at the institut teknologi sepuluh nopember (ITS), Surabaya, Indonesia

2.1 Drip irrigation network planning

Water contributes to the evapotranspiration process in plant growth. Reference evapotranspiration is generally calculated using the Penman-Monteith method [15], and an emitter from the irrigation network drips water periodically with a specific discharge to meet the plants' needs. The discharge is strongly influenced by the IOP (H in m) of the irrigation network. To identify a relationship between the flow rate of emitter and system operating pressure, the following Eq. (1) is used [14].

$$Q_e = K.H^x \tag{1}$$

In the formula, K refers to the emitter coefficient, and x is the emitter exponent. This study uses a non-pressure compensating emitter, the most widely used and much cheaper emitter. Fig. 2 displays a comparison of flow rate between non-pressure and pressure compensating emitters.

The proposed SPVDIS was installed in a vegetable garden in the institut teknologi sepuluh nopember (ITS), Surabaya, Indonesia. The garden is located at coordinates 7°17'6.072"S, 112°47'53.879"E is shown in Fig. 3. Within ten sectors, each has four laterals with a length of 10 m. The main crop irrigated is tomatoes. Table 1 shows specifications of the irrigation network in the vegetable garden.

Table 1. Specifications of irrigation distribution networ

Characteristics	Values
Type of crop	Tomato
Reference evapotranspiration, ET_o	8 mm/day
Crop coefficient, K_c	1.68
Emitter droplet rate, EDR	4 mm/h
Flow rate of emitters, Q_e	4 l/h
Number of emitters per sector	80
Watering time, T_i	3.36 hour
IOP	7 Psi

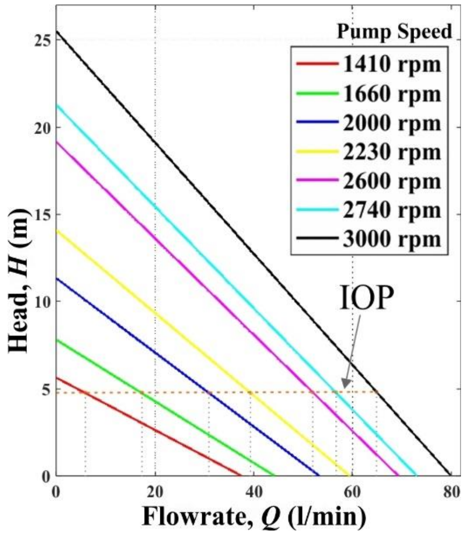

Figure. 4 Head-flow rates of a centrifugal pump

2.2 BLDC motor-driven centrifugal pump

Groundwater was pumped directly to the irrigation distribution network using a brushless DC motor-driven centrifugal water pump. Fig. 4 illustrates various discharge rates of the pump at different H-Q points based on its rotational speed, and the specifications of the BLDC motor are shown in Table 2. The hydraulic power of pump (HP_{water})

Table 2. BLDC motor parameters

Parameters	Values
Rated power	125 W
Rated speed	3,000 RPM
Rated voltage	24 V
Poles	4
Back EMF Constant	12 V/kRPM
Phase resistance	0.3 Ω
Phase inductance	0.00035 mH

Received: April 29, 2022. Revised: May 24 2022.

Table 3. Electrical specifications of the PV panels

Characteristics	Values
Maximum Power P_{mpp}	100W
Maximum Power Voltage V_{mpp}	18V
Maximum Power Current I_{mpp}	5.56A
Short-Circuit Current I_{SC}	6.00A
Open-Circuit Voltage V_{OC}	22.5V

is the amount of energy delivered to water in a unit of time. The motor's input power to the pump is referred to brake horsepower (BHP) calculated as Eq. (2) [16].

$$BHP = \frac{HP_{water}}{\eta_m \eta_p} \tag{2}$$

The equation shows η_m is the efficiency of the BLDC motor, and η_p is the efficiency of the water pump head. The proposed BLDC motor and centrifugal pump had the maximum efficiency in transferring power at 0.85 and 0.8, respectively. The efficiency value possibly changes according to the rotational speed of the motor or water pump. The amount of BHP power in each sector is referred to the hydraulic capacity of the sector (P_{S-i}).

2.3 PV panel system

The PV panel used in this study is a monocrystalline type with a capacity of 100 Wp on a fixed stand with an angle of 12 degrees to the north. Table 3 shows specifications of PV panels installed adjacent to the irrigation distribution network.

The PV output power was optimized using the MPPT technique with a boost type DC converter through the INC method is shown in Fig. 1. The inductor L1 value of the boost converter is 1.4 mH, capacitor C1 is 1.8 mF, and capacitor C2 is 1.8mF.

2.4 Use of BPSO in optimizing SPVDIS

The BPSO method adapts the particle swarm optimization (PSO) approach to solve binary versions of discrete or combinatorial optimization problems. BPSO was first introduced by Kennedy and Eberhart, and proved to be a simple, efficient, and successful global optimization method [17]. The proposed BPSO method has an algorithm input as the hydraulic irrigation capacity of each sector (P_{S-i}) and the current PV output power (P_{PV}). The output of this algorithm is a control signal to activate the solenoid valve in order to regulate irrigation capacity in each sector.

The optimization process works if the number of active irrigation sectors or the PV output power changes. According to a flow chart diagram in Fig. 5,

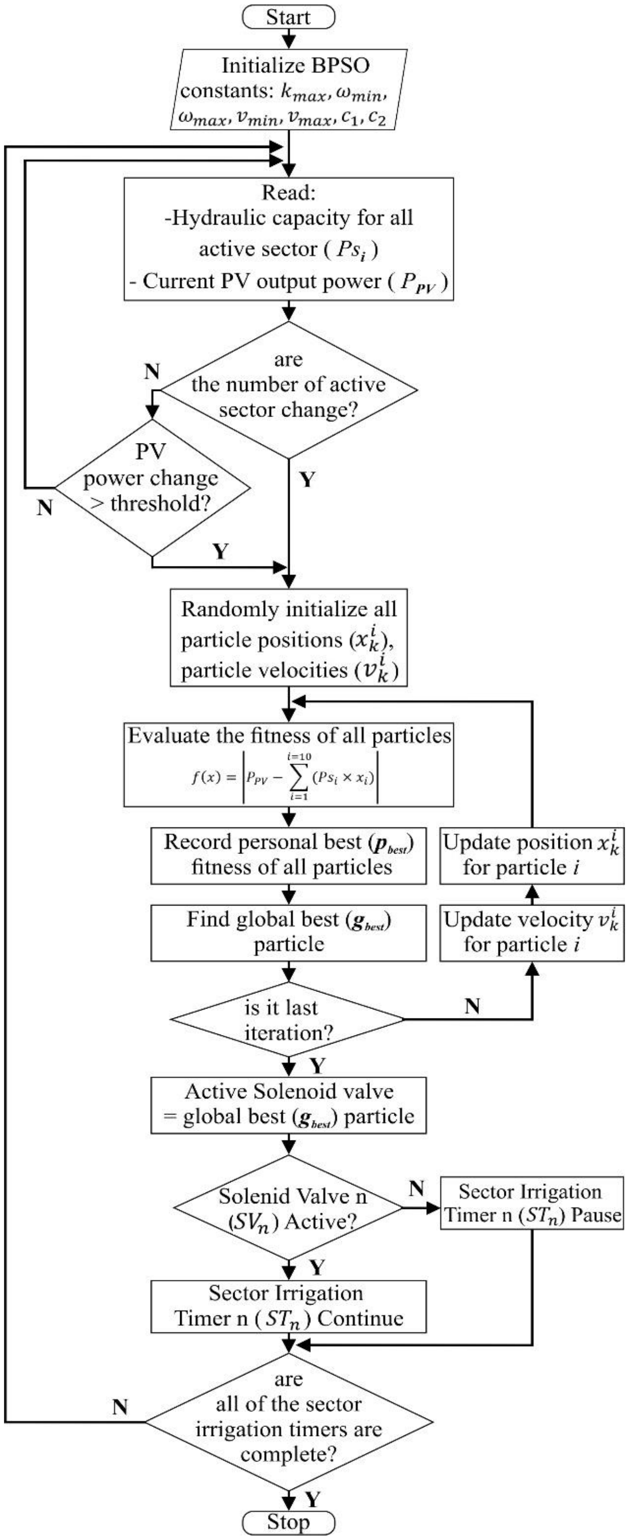

Figure. 5 Flow chart of the proposed BPSO method for SPVDIS management

the optimization process using the BPSO method starts from initializing the number of variables, population size, maximum inertia weight (w_{max}), minimum inertia weight (w_{min}), maximum velocity (v_{max}), minimum velocity (v_{min}), two acceleration factors, and a maximum number of iterations (k_{max}).

This study involved 10 variables equal to the number of irrigation sectors, population size is 50, w_{max} is 0.8, w_{min} is 0.5, v_{max} is 0.7, and v_{min} is 0.1. The learning rate includes the individual ability (c_1) and social influence (c_2) is 2, and the maximum iteration is set at 500 times.

The step after initialization is to read the P_{S-i} and the P_{PV}. The P_{S-i} value is stored as a constant variable in the program, and in this study is 4 Watts per sector. The value of the P_{PV} is a requirement of this BPSO optimization process. Suppose the PV power value changes by more than half of the P_{S-i}, and there is still an irrigation sector whose irrigation timer has not been reached, then the BPSO optimization process is carried out. If there is no BPSO optimization process, the solenoid valve output is the same as the previous output.

The BPSO process begins by randomly creating 50 initial populations. The kth iteration of each particle (i) is referred to x_k^i, and its velocity is referred to v_k^i. At the beginning of the iteration (k=1), the initial velocity of the particle moving towards the optimal point is assumed to be zero ($v_1^i = 0$). The next step is evaluating the value of the particle's objective function, the proximity of the combined results of the waterhorse power from the irrigation sector to the PV output power. It is calculated using Eq. (3).

$$f(x) = \left|P_{PV} - \sum_{i=1}^{i=10}(P_{S-i} \times x_i)\right| \tag{3}$$

After evaluating the objective functions, the next step is finding two critical parameters for each particle. These include the best coordinate value of particle in the kth iteration ($P_{best,i}$) which has the minimum objective function and the best value for all particles (G_{best}) which has minimum objective function among all the particles. Meanwhile, if the maximum iteration is not reached, the next step is continued by updating the velocity and position of the particle in the (k+1)th iteration using Eq. (4).

$$v_{k+1}^i = w.v_k^i + c_1 r_1\left[P_{best,\ i} - x_k^i\right] + c_1 r_1\left[G_{best,\ i} - x_k^i\right]; \quad i = 1,2,\ldots,10 \tag{4}$$

Here, w is the update inertial weight calculated according to the Eq. (5).

$$w = (w_{max} - w_{min})k/k_{max} \tag{5}$$

The value of the particle velocity is limited by the most maximum (v_{max}) and minimum (v_{min}) values. Through BPSO, the particle position only occurs at a binary value of 0 or 1. The updated particle position is calculated using the Eq. (6) [17-19].

$$x_{k+1}^i = \begin{cases} 1 & if\ rand(1) < \frac{1}{1+e^{v_{k+1}^i}} \\ 0 & \end{cases} \tag{6}$$

If the iteration has reached the maximum, the last G_{best} value is used as a control signal for the solenoid valve in the irrigation sectors.

3. Simulation and experimental setup

3.1 Simulation setup

The SPVDIS model in this study was simulated using MATLAB/Simulink. The system model is setup with the PV panel model, MPPT model, BLDC motor-driven centrifugal pump, multisector irrigation distribution network model, and irrigation controller through the BPSO method. The system model has a functional diagram is shown in Fig. 1.

The performance and characteristics of the proposed system are identified through simulation and experiment testing on several irradiation patterns. The pattern may be a natural irradiation and unit step. The natural pattern was obtained on August 16, 2021 from the daily solar irradiation pattern recorded by the data logger on the 16 kW rooftop PV System located at coordinates 7°16'52.4892"S, 112°47'50.838"E at the Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia. While the unit step pattern may indicate the transient response of the system.

3.2 Experimental setup

The proposed multisector SPVDIS was validated using a hardware, a laboratory-scale prototype which consists of three main parts: a computer system, an embedded system, and a drip irrigation emulator system. The functional diagram of the system prototype is shown in Fig. 6. The BPSO algorithm runs on the MATLAB/Simulink software in the computer system to generate data and control the equipment through the Arduino device driver, connected via serial communication with the I/O server in the embedded system. Through the I/O server, MATLAB/Simulink may obtain data from the PV power sensor, control the solenoid valve via its driver, and analyse and visualise it on the simulink scope. The embedded system contains the MPPT system, I/O server, and solenoid driver. The MPPT system is composed of a DC boost converter, a signal conditioning circuit, an LCD, and a microcontroller. While, the I/O Server is a microcontroller connected

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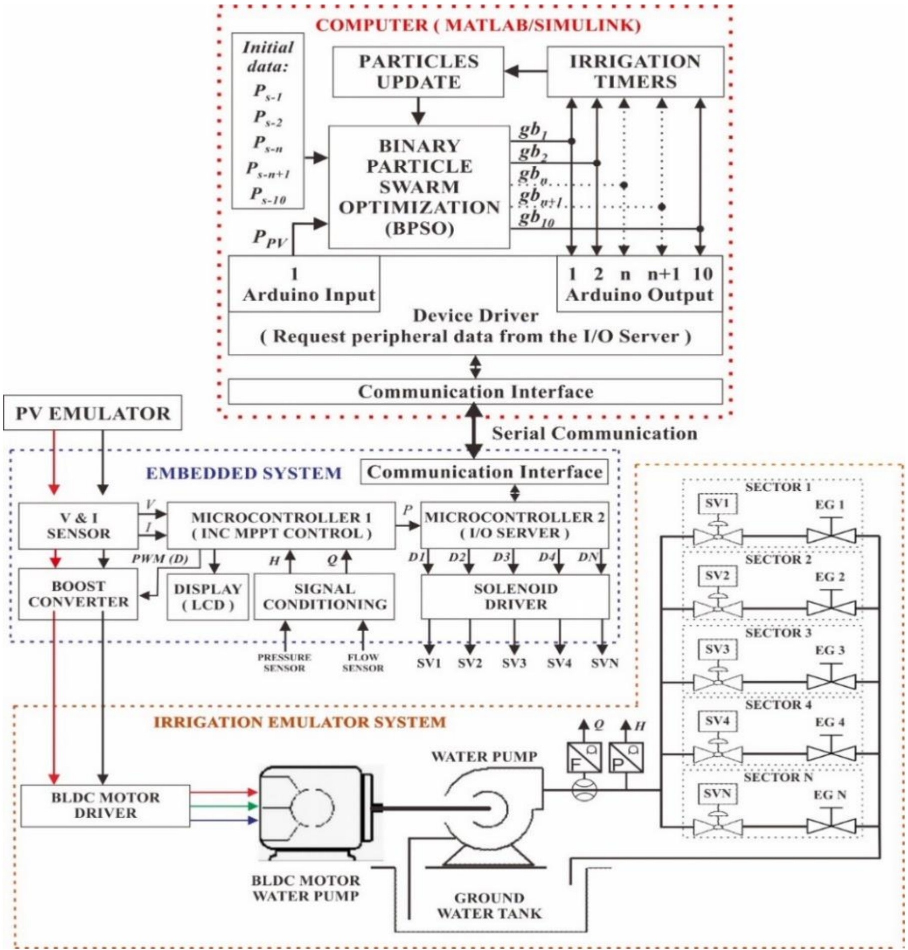
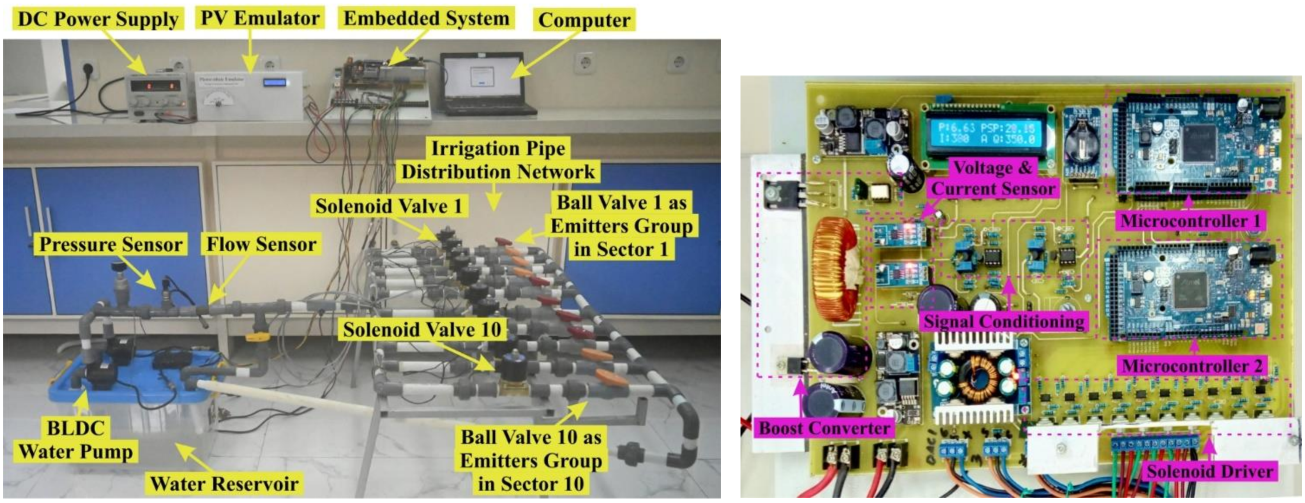


Figure. 6 Functional diagram of SPVDIS hardware connected in the loop with Matlab/Simulink



(a) (b)

Figure. 7 The prototype of the SPVDIS system used to validate the proposed method: (a) Photo of SPVDIS prototype and (b) An enlarged photo of the embedded system

to MATLAB/Simulink via a communication interface. Microcontroller 1 functions as an MPPT controller in the embedded system, and microcontroller 2 as an I/O server. Both microcontrollers have the exact specifications which are a 32-bit ARM core microcontroller with a clock speed of 84MHz.

In addition, the drip irrigation system emulator consists of a brushless DC motor-driven water pump system, a water reservoir and a multisector water distribution network controlled by a solenoid valve. The combined emitter in one sector is simulated with a ball valve. The SPVDIS prototype can be seen in Fig. 7 (a) along with the enlarged illustration of the embedded system in Fig. 7 (b).

The system works by activating the MPPT system to control the power supply from the PV panels and eventually maximize the output power. The output power is used to supply the BLDC motor-driven pump on the drip irrigation system emulator. Afterwards, the I/O server reads the PV power value from the MPP system or microcontroller 1. Then, the BPSO algorithm on the computer reads the PV power on the I/O server. If there is a power change of 2 watts and an unfinished irrigation timer value, the BPSO process will work. Once the G_{best} value is obtained to update the solenoid valve status, then the I/O server forwards the status data to the solenoid valve through the output pin of the microcontroller and the solenoid driver.

The PV panels in this system test are replaced with PV emulators. A PV emulator is a nonlinear power supply that can reproduce the current-voltage characteristics of photovoltaic panels [20, 21]. It is more accessible and scalable to test the MPPT approach using a PV emulator. The SPVDIS performance is known from recorded variable data, including PV output power, IOP, and the number of active sectors. The experimental test results are also compared with the simulation results with the same pattern.

4. Results and discussion

4.1 Simulation performance

The SPVDIS simulation took place in three operational modes: BPSO, combined, and bypass. The BPSO operating mode is the proposed system. The BPSO mode controls 10 valves to handle 10 irrigation sectors. The selection of the irrigated sector is based on the PV output power using the BPSO method. The combined operating mode controls 4 valves to handle 10 irrigation sectors. The combined operation to represent the optimization method used by several previous studies. The selection of the irrigated sector is based on the PV output power using a combination method with a linear program [2], [13]. Bypass mode controls 1 valve to handle 10 irrigation sectors. In this bypass mode, 10 irrigation sectors are directly connected in parallel. Bypass mode is a conventional SPVDIS method irrigating the whole area without contrasting the sectors [12].

All simulations were carried out using natural solar insulation for 3.36 hours is shown in Fig. 8. The MPPT systems on all three irrigation methods accurately track and achieve MPP, is shown in Fig. 9. The water pump wholly absorbs the PV output power. The BPSO works to optimize irrigation capacity by adjusting the number of active sectors according to the PV power is shown in Fig. 10. The number of irrigation sectors increases along with the increase in the PV power output. When some irrigation sectors have reached their irrigation duration of 3.36 hours, they have to be inactive despite the increasing PV power. It indicates that BPSO works and updates its particles well according to the enabled sectors. However, the combined method shows a cruder change than the BPSO method, leading to more

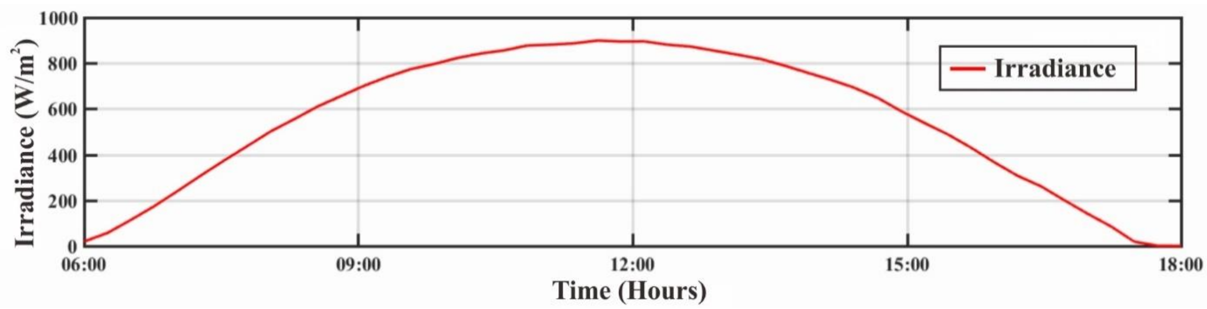


Figure. 8 Natural irradiation patterns on August 16, 2021

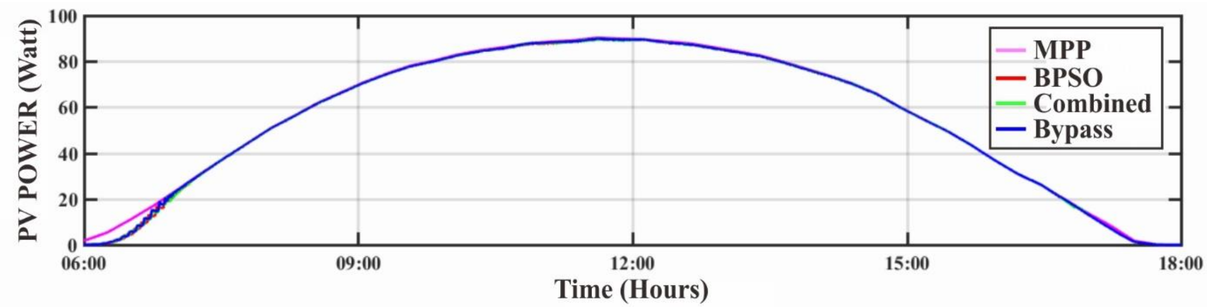


Figure. 9 Comparison of MPPT system responses on the irradiation pattern on August 16, 2021

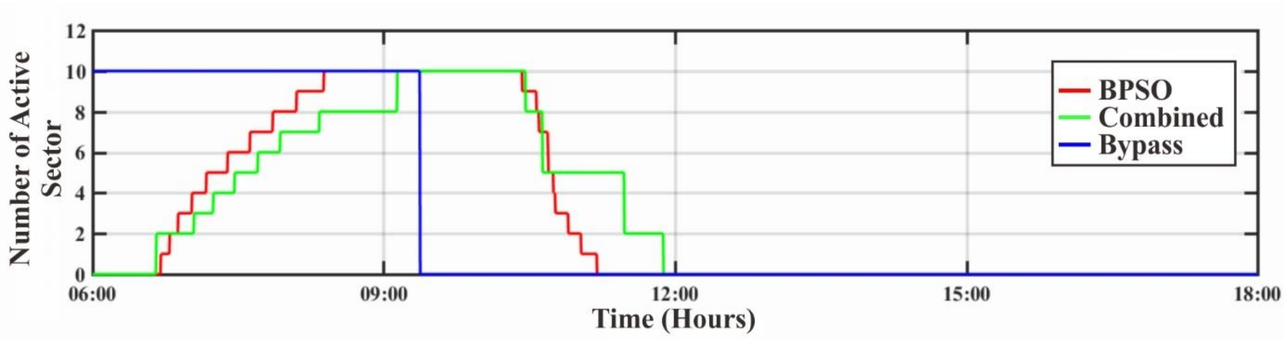


Figure. 10 Number of active sectors during irrigation process

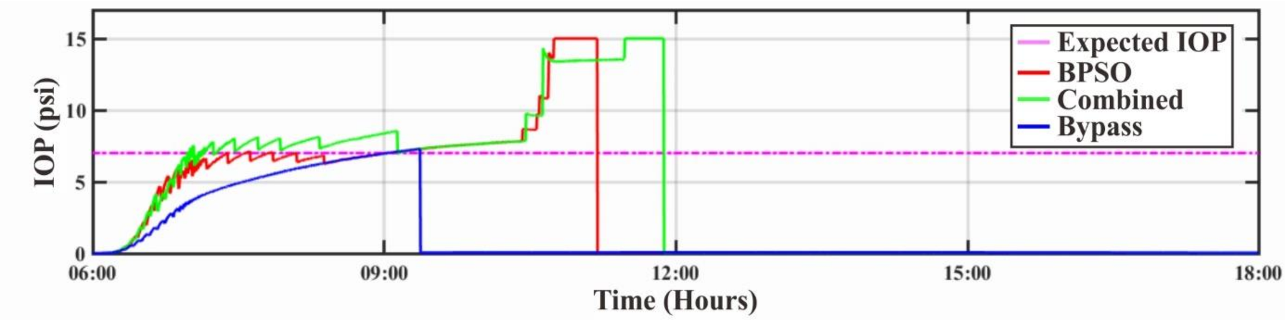


Figure. 11 Number of active sectors during irrigation process

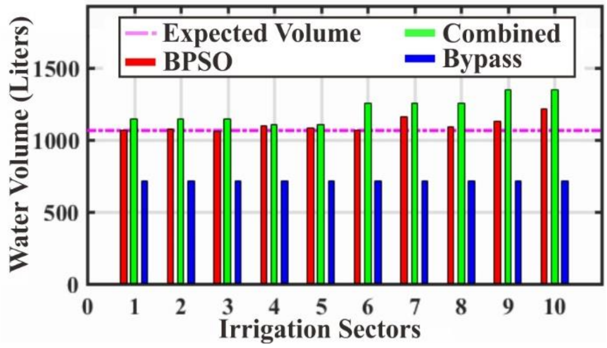


Figure. 12 Comparison of irrigation water volume with irradiation patterns on August 16th, 2021

significant IOP fluctuations is shown in Fig. 11. Meanwhile, all sectors are irrigated simultaneously in the bypass method. As a result, the IOP varies significantly according to the PV power. In other words, the BPSO method best produces the expected pressure among others. The combined method has more rough fluctuations, while the bypass method shows very low pressure. At the end of irrigation, the BPSO method and the combined have a drastic increase in pressure because the number of active sectors remains less as most have reached their duration. Then, a relief valve that connects the pump discharge to the reservoir will reduce the high pressure.

The success parameter of irrigation could be seen from the water volume produced from the irrigation process. Proper irrigation allows plants to get the right amount of water and save energy and water in a natural pattern. This study found out that the BPSO method produces the most proper volume among others. The combined method produces a much more volume than the dose, while the bypass method generates a significantly less volume than the dose, thus causing the plants to deprive of water. The uniformity of the volume results is calculated based on the Christiansen (CU) equation as in Eq. (7) [22].

Table 4. Comparison of irrigation methods from the natural irradiation pattern on August 16th, 2021

NO	Parameter	Method		
		BPSO	Combined	Bypass
1	Expected IOP (psi)	7.00	7.00	7.00
2	IOP average error (%)	29.38	39.04	74.78
3	Expected water volume (L)	1062.4	1062.4	1062.4
5	Average water volume error (%)	4.01	13.92	32.80
6	Coefficient of uniformity (CU) water volume (%)	95.55	93.17	100

$$CU = 100.\left[1 - \frac{\sum_{i=1}^{n} |V_i - \bar{V}|}{n.\bar{V}}\right], \% \tag{7}$$

In this formula, CU is referred to the Christiansen uniformity coefficient; V_i is water volume of sector i;

Received: April 29, 2022. Revised: May 24 2022.

$\bar{V}$ is the average irrigation volume; and n is the number of sectors. Based on the standards of the Christiansen equation, the value of uniformity can be divided into five rating categories: excellent at more than 90 %, good at 80 %-90 %, fair at 70 %-80 %, poor at 60 %-70 %, and unacceptable at less than 60 %.

Table 4 shows the comparison of the three methods according to the natural irradiation pattern. In conclusion, the BPSO method produces the most optimal and precise irrigation quality compared to others.

4.2 Experimental performance

The prototype's unit step pattern testing was carried out for 120 seconds with 60 seconds for the irrigation duration in each sector. Besides testing the prototype, this pattern is used to test the simulation model. The prototype's pattern test was carried out through a PV emulator. Fig. 14 shows the response of the MPPT system in the simulation and prototype. It was found that the system can track and control the PV output accurately according to the MPP value during the simulation. Moreover, the prototype response showed that the system can reach the MPP value with a small ripple at an average error of 1.58 watt because of noise in the power measurement resulting in less accurate MPP tracking.

However, the tracking results in the simulation and experiment showed similarities. Changes in the number of active sectors both in the simulation and prototype testing indicate that the BPSO method works well. The number of active sectors at the end of the irrigation duration decreases drastically due to the increasing number of finishing irrigation sectors. Fig. 15 displays the number of sectors that are active during the irrigation process. The simulation results in the same number of active sectors as the prototype testing responding to the PV output power. Meanwhile, changes in the active sectors happen earlier in the simulation than the prototype testing because the microcontroller sampling time and communication delay cause a time lag in the prototype testing.

Moreover, the IOP response both in the simulation and prototype testing almost produces the expected pressure. The planned IOP is 7 psi, but the average error is 0.49 psi in the simulation and 0.52 psi in the prototype testing. Fig. 16 presents the IOP response to the test pattern. At the end of the test, the IOP value increases dramatically because the duration of irrigation in all irrigation sectors has been reached.

4.3 Comparison of performance system

Table 5 shows how the proposed system works in comparison to previous irrigation systems. Some of the parameters compared are the MPPT method, type of pump, type of irrigation, IOP, and the suitability of water volume according to plant needs. Previous studies still leave shortcomings in the optimization method. Several parameters used in this current study are more comprehensive to those in previous research. It is rare for previous studies to discuss the success of the MPPT system in a multisector SPVDIS. The

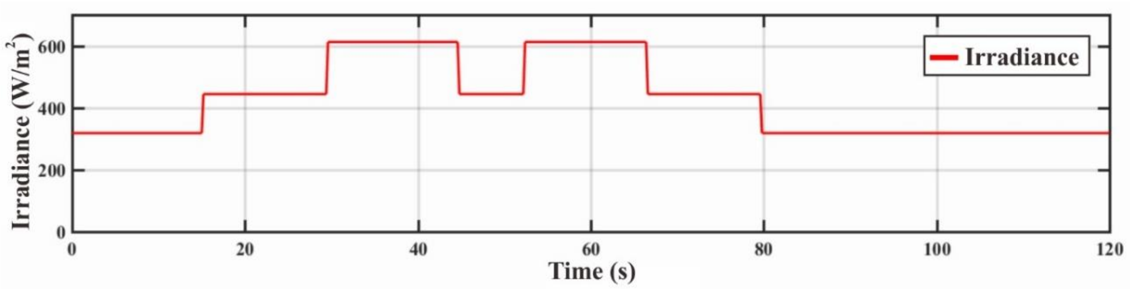


Figure. 13 Unit step irradiation pattern in the simulation and prototype testing (experiment)

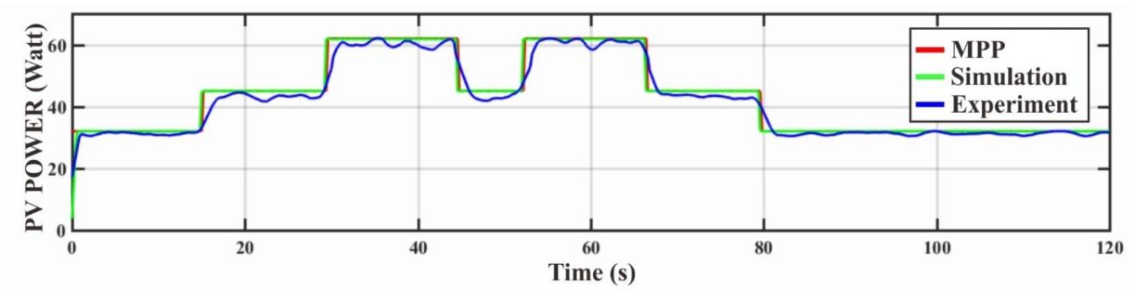


Figure. 14 Comparison of MPPT system response in the simulation and prototype testing (experiment)

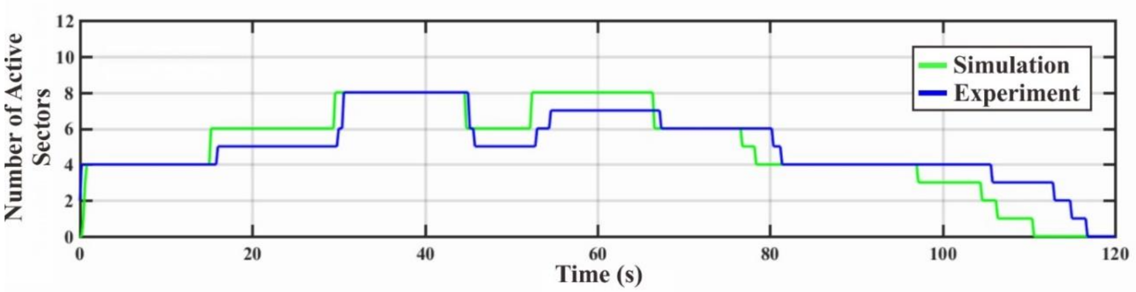


Figure. 15 Comparison of the number of active irrigation sectors during the irrigation process in the simulation and prototype testing (experiment)

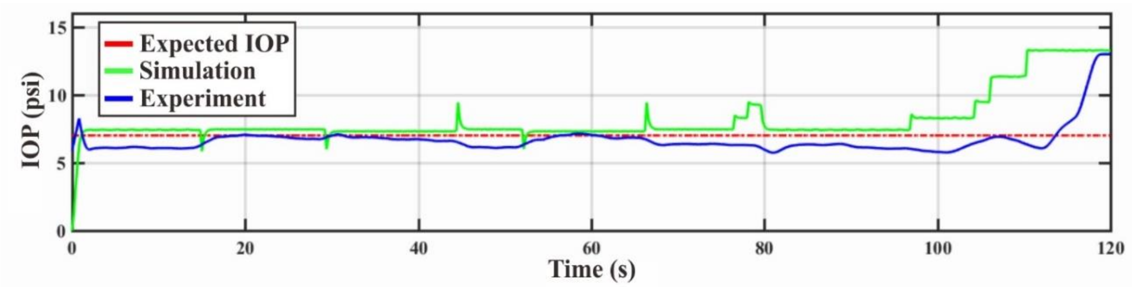


Figure. 16 Comparison of IOP response in the simulation and prototype testing (experiment)

Table 5. Comparison of MPPT and irrigation system performance

Performance	**MPPT Method**	**MPP Achievement**	**Minimum Irradiation**	**Motor-pump**	**Irrigation Type**	**IOP Response**	**Water Volume Needed by Crops**
Ref [2]	No	No description	Middle	Induction	Drip multisector (4)	Stable	Moderate error
Ref [12]	No	No description	High	Induction	Drip single sector (1)	Unstable	High error
Ref [13]	No	No description	Middle	Induction	Drip multisector (4)	Stable	Moderate error
Proposed	INC	Good	Low	BLDC	Drip multisector (10)	Stable	Low error

BLDC motor used in this study increases system efficiency better than an induction motor used in previous studies. This study also entails the lower minimum irradiation as the division of the irrigation sector is more than other methods. By using the BPSO method, the combination of multisector irrigation is much easier to achieve capacity according to PV power than other methods. The proposed irrigation control results in a more stable IOP which affects the accuracy of irrigation water volume according to crop needs. Finally, compared to other methods, the proposed method has a lower water volume error.

5. Conclusions

The use of BPSO has been proven to optimize a multisector SPVDIS after being tested through several irradiation patterns to determine its characteristics and performance. In comparison to other typical methods like combined and bypass methods, the MPPT and BPSO method has successfully resulted in optimal, efficient and accurate irrigation according to PV power output. The proposed SPVDIS simulation has an average IOP error of 29.38 %, a water volume error of 4.01 %, and a uniformity coefficient between sectors of 95.01 %.

The SPVDIS prototype test shows similar results to the simulation which had an average MPP error of 1.58 Watt and an average IOP error of 0.7 psi. The stability of the IOP makes the emitter discharge relatively constant which will produce the water volume according to the reference. The SPVDIS controlled by the BPSO method produces better performance than other methods.

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

In this research article author contribution are as follows: “Conceptualization and methodology, Suwito Suwito, and Mochamad Ashari; software, Suwito Suwito; validation, Suwito Suwito, Mochamad Ashari and Muhammad Rivai; formal analysis, Suwito Suwito, Mochamad Ashari and Muhammad Rivai; investigation, Suwito Suwito; resources, Suwito Suwito; data curation, Suwito Suwito; writing—original draft preparation, Suwito Suwito; writing—review and editing, Suwito Suwito, Mochamad Ashari, Muhammad Rivai, and M. Anis Mustaghfirin; visualization, Suwito Suwito; supervision, Mochamad Ashari, Muhammad Rivai, and M. Anis Mustaghfirin”.

Acknowledgments

The authors would like to thank the directorate of research and community service (DRPM) of Institut Teknologi Sepuluh Nopember Surabaya (ITS) and the Indonesian Ministry of Research and Technology/National Research and Innovation Agency for funding the research.

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