

# Whale Optimization for MPPT of Single Stage Grid Integrated PV Plant with $H_{\infty}$ and TSK-Fuzzy Controllers

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**Abstract:** Numerous techniques for maximum power point tracking (MPPT) are extensively employed to extract the utmost energy from Photovoltaic (PV) panels. The P&O method is a highly effective technique among those who perturb and observe. Nevertheless, in the presence of partial shading conditions, it becomes imperative to employ an optimization algorithm that can accurately pinpoint the global maximum location (GML) amidst the numerous local maximum locations. The Whale-inspired algorithm is a renowned optimization method for efficiently identifying GML in comparison to numerous other optimization algorithms. An inverter is required to interfacing between PV and grid in single stage grid connected system as it will also work as a MPPT device by controlling voltage corresponding to GML. In this situation, the utilization of a whale-inspired optimization technique can enhance energy harvesting through an appropriate inverter controller. The combination of TS-Fuzzy and  $H_{\infty}$  controllers through hybridization can lead to rapid response times and increased system stability. Hence, this paper introduces a new controller designed for the inverter to function effectively in a single-stage grid-connected PV system. The proposed controller can also provide the grid with high-quality power. This work showcases comprehensive findings derived from Hardware-in-the-Loop (HIL) testing conducted using OPAL-RT technologies.

**Keywords:** Photovoltaic, Whale Optimization Algorithm, TS-Fuzzy,  $H_{\infty}$  controllers, Partial Shading, HIL.

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## 1. INTRODUCTION

The global interest in generating power from renewable energy systems (RES) is progressively growing. Among the numerous RES accessible on the planet, solar is a more fascinating energy that is widely accessible in many locations. Because photovoltaic (PV) arrays can be quickly convert solar irradiation into electric power, solar energy generation can provide viable solutions to meet electrical load demand in many regions [1-2]. Grid-connected PV units are routinely installed in various areas across the world, including apartments, institutions, solar plants, and so on. Because of the nonlinear voltage - power characteristics of the panels, a MPPT circuit controlled by an efficient controller should be necessary to extract more power from them. To function as an MPPT circuit for PV unit, a DC-DC circuit is required [2]. PV generation in the mid and low power ranges is often linked to utility networks. As a result, these systems may be linked as single stage grid connected plant without the need for an additional DC-DC circuit to provide a cost effective model. The photovoltaic unit is connected directly to the inverter, while the recommended controller manages the voltage on the DC link to match its desired signal. The MPPT algorithm achieves the reference DC link voltage to maximize PV system usage. As a result, the inverter functions as an MPPT device for the PV unit. This architecture can minimize overall system size and expense, although separate MPPT converters can give a superior option in cases of high power production. As a result, a single stage grid-integrated module may be a viable option for medium and low power generating units.

The Perturb and Observe (P&O) technique stands out as the most effective MPPT mechanism due to its ability to identify the voltage that corresponds to the optimal power position in conditions of consistent irradiances [3-5]. However, in the event of a large number of PV modules, there is no assurance of equal irradiance on all PV modules. A Partial Shading Condition (PSC) occurs when PV panels receive non-uniform irradiation. The PSC is a frequent occurrence that may be caused by trees, shadows, clouds, birds, and dust, among other things. By stacking several modules in series and parallel, this work constructed a 1.0MW single stage grid-connected PV unit. As a result, there is a significant likelihood of PSCs occurring often. The standard P&O technique is unable to locate the global maximum location (GML) due to the presence of multiple local maximum points [2]. Hence, traditional approaches will be ineffective in extracting the utmost energy from PV panels and result in the PV system operating at a local maximum point. In order to overcome this problem, an optimization approach is used to discover the GML. An optimization method inspired by whale is used in this research to determine the GML under PSCs. At the same time, in order to function normally, the WOP is combined with the P&O algorithm. As a result, the hybrid WOP-P&O can efficiently determine the region where the most energy may be gathered under all conditions. The controller receives the reference voltage signal and proceeds to adjust the voltage at the DC link. Nevertheless, as there is no energy storage device in this configuration, the produced power needs to be transmitted to the utility grid through a controllable inverter. Furthermore, the reactive power compensation method is also included on the proposed control technique of the inverter. In this study, the H infinite ( $H_{\infty}$ ) controller methods are created to provide gating signals to an inverter for a quick and steady response. The research paper is structured to achieve the following goals:

- Establishment of 1.0MW grid integrated single stage PV plant.
- Implementing a hybrid P&O-WOA technique for a PV model can help determine the optimal voltage location for maximizing energy harvest under varying irradiances, whether uniform or non-uniform.

- To compensate demanded reactive power at load bus, an effective control method of the inverter is proposed.
- Design hybrid TS-Fuzzy and  $H_{\infty}$  controllers for inverter to achieve best performance.
- Setup of Hardware-in-Loop by arranging two OPAL-RT modules in back to back connection for presenting various responses.

The paper is segmented into the following sections. Section 2 contains system descriptions. Section 3 clearly demonstrates the hybrid WOA-P&O. Section 4 presents an examination of the suggested control approach based on the hybridization of TS-Fuzzy and  $H_{\infty}$  controllers. Section-5 examines the HIL-based findings in various instances. Section 6 discusses the conclusion.

## 2. System Descriptions and Ratings

Figure 1 depicts a single stage grid-connected PV unit which consisting of suggested control mechanism, PV system, utility grid etc. PV panels are arranged in the combination of parallel and series to form a 1.0MW plant. A direct current link connects the PV plant to the inverter. Between the utility grid and the inverter, a three-phase LCR filter is incorporated. The 1- $\emptyset$  & 3- $\emptyset$  loads are linked at a Point of Common Coupling (PCC) that possesses many loads including reactive, nonlinear, linear, unbalanced loads etc. The presence of several PV modules in a system increases the likelihood of PSCs. Table-1 lists the characteristics of a single module in the detailed PV unit depicted in Fig. 2. Every PV string consists of two parallel PV arrays, each of which consists of 16PV modules linked in series. As a result, each PV string can generate a maximum of 9.6kW. In this study, 105 strings are analyzed in parallel to build a 1MW PV system. As a result, the odds of PSCs will greater, and the list of PSC patterns addressed in this work is shown in Table-2. Figure 3(a) depicts the power vs. voltage nonlinear characteristics of a PV string. The relevance of optimization approaches in finding the optimal solution during PSCs is illustrated in Fig. 3(a). The TS-Fuzzy controllers are also added to achieve quick and precise output of the suggested approach when the load changes.

The integrated WOA-P&O approach is illustrated in Fig. 3(b) of PCS-1. There are several local maximum (LM) peaks, and the suggested method must locate a global maximum (GM) among them. In Fig. 3(b), a uniform irradiance of 805.5W/m<sup>2</sup> capable of delivering the same power as the PV string under PSC-1 is also presented for clarity. The traditional P&O method can determine the voltage when  $dp/dv \cong 0$ . To locate point P2 (GM) from four potential maximum points through conventional P&O method, the combined WOA-P&O approach can aid in tracing P2 as illustrated in Figure 3(b). A voltage signal will be generated to represent the GM point and then transmitted to the DC voltage controller. The  $H_{\infty}$  controller is able to act for injecting produced current into the grid by controlling both the input (voltage at dc-link) & output voltages of the inverter.

Many researchers have lately conducted similar study, and the most important of them are included below. The researchers in [2-4] employed GA to detect the GM for functioning as the MPPT of the PV modules within the PV system. The authors of [5-9] use the PSO approach to determine the MPPT position of a PV system. A small number of authors from [10-13] employed the GWO mechanism to identify the optimal position of the highest power point during PSCs in a PV system. However, in many ways, the Modified Invasive Weed Optimization (MIWO) approach outperforms GA, PSO, and GWO, as developed by the authors in [14] for PV system MPPT under PSCs. The authors of [15] suggest the Flying Squirrel Search Optimization (SSO) on PV system for MPPT principle. The authors of [16] implement a novel Spline-based MPPT algorithm for PV systems that works under

both non-uniform & uniform irradianations. Nevertheless, the WOA method has attracted the attention of numerous researchers because of its quick and effective tracking approach in comparison to the aforementioned current mechanisms [17-18]. The combination of the WOA and P&O can provide a rapid method for determining the voltage equivalent to GML in PV systems with PSC.As a result, the hybrid WOA-P&O approach is used in this research to improve tracking responsiveness. Furthermore, a few writers from the aforementioned literature review used PI, Fuzzy, and ANN-based controller approaches when constructing the system's controller. Because of easy and simple implementation process, conventional controllers such as Hysteresis current, PI, model predictive controller, and proportional plus resonant methods is the most common [19-24]. Due to the lack of resilience and limits in the preceding controllers, the  $H_{\infty}$  controller is capable to outperform many other controllers [25] under various system conditions.

**Table-1: Parameters of a PV unit.**

| S.No | Parameters of Modules         | Values |
|------|-------------------------------|--------|
| 1    | Voltage/module(open circuit). | 48.51V |
| 2    | Current when Short circuited. | 8.15A  |
| 3    | Vmpp                          | 39.61V |
| 4    | MPP Current.                  | 7.67A  |
| 5    | Module Maximum power.         | 302.0W |
| 6    | No. Of modules in a array.    | 16     |

**Table-2: 3 Patterns of PSCs.**

| Pattern       | Insulation of 32 panels in String-1 W/m <sup>2</sup> .   |
|---------------|--|
| <b>PSC-1.</b> | <b>Array-1:</b> Module 1-5: 1000, Module: 6-10: 940, Module: 11-13: 810, Module: 14-16: 705.<br><b>Array-2:</b> Module 1-5: 1000, Module: 6-8: 900, Module: 9-13: 750, Module: 14-16: 720. |
| <b>PSC-2.</b> | <b>Array-1:</b> Module 1-4: 800, Module: 5-9: 940, Modules: 10-13: 605, Module: 14-16: 560.<br><b>Array-2:</b> Module 1-5: 905, Module: 4-7: 920, Module: 8-14: 720, Module: 15-16: 470.   |
| <b>PSC-3.</b> | <b>Array-1:</b> Module 1: 810, Module: 2-5: 700, Module: 6-11: 550, Module: 12-16: 300.<br><b>Array-2:</b> Module 1: 790, Module: 2-5: 720, Module: 6-11: 560, Module: 12-16: 304.         |

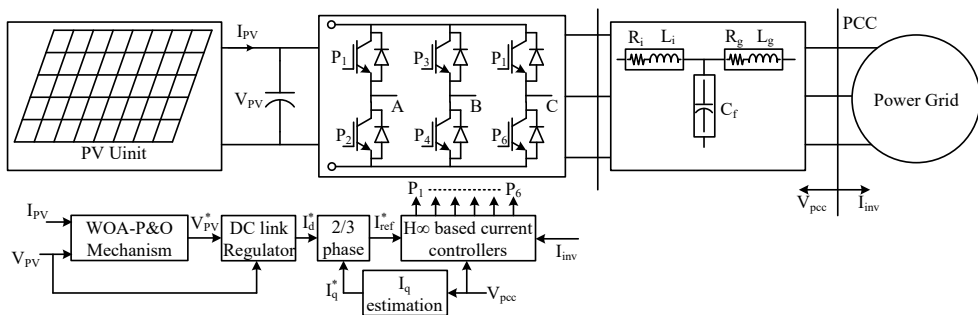


Fig. 1: Single stage grid-integrated PV unit.

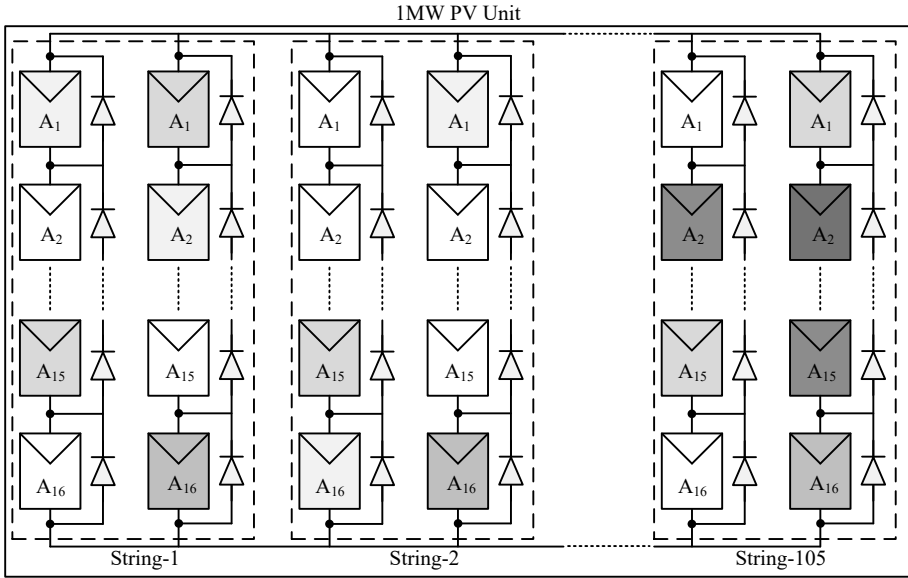


Fig.2: 1MW PV unit created by combining numerous PV modules.

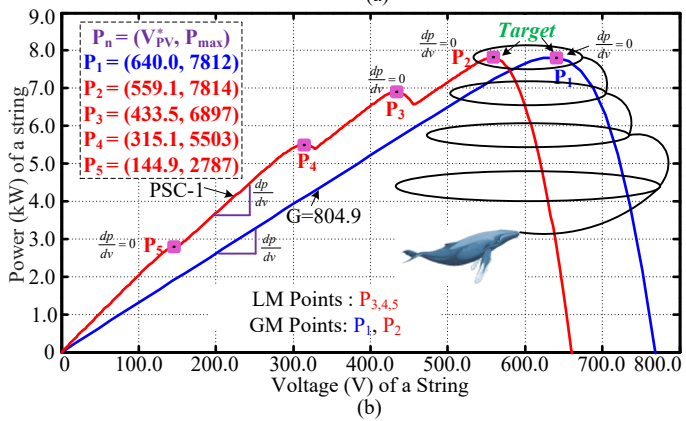
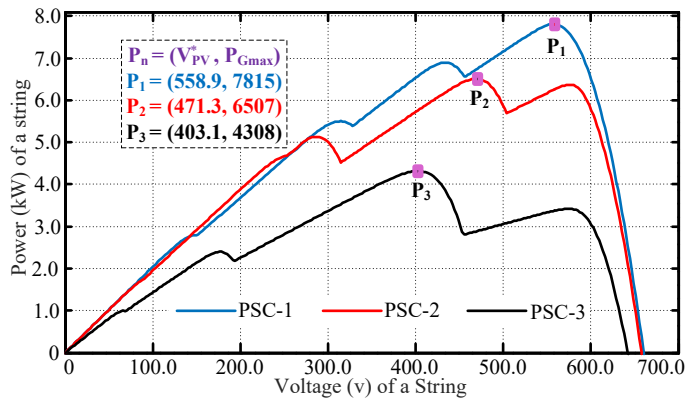


Fig. 3: (a) PSCs Table-2 condition, and (b) WOA-P&O approach P-V curves.

### 3. Hybrid WOA-P&O Mechanism

The conventional P&O technique adjusts the voltage of the PV to ensure that the PV unit's maximum power point is situated under consistent irradiation. This may be accomplished mathematically by utilizing eq.(1).

$$V_{mpp}(i) = \Delta V \times \text{sign} \left( \frac{dP_{pv}}{dV_{pv}} \right) + V_{mpp}(i-1) \quad (1)$$

Here  $V_{mpp}$  denotes the voltage at which the unit can output the most power, the iteration value represented by 'i', and 'V' is the tiny step change that can be disrupted throughout the process of determining  $V_{mpp}$ .

The next voltage move perturbation is dependent on the sign of the change in power with regard to the change in voltage of PV during the P&O algorithm process, and this is the key disadvantage in identifying the GM moment when PSCs happened. Once P&O method hits any of the LM-points during PSCs, the  $V_{mpp}$  will remain at that position, even if it cannot be changed due to sign. As a result, the standard P&O method will fail to acquire the correct voltage signal corresponding point of GM. This issue may be overcome by incorporating WOA to move quickly to the correct position of the GM point.

The WOA is a meta-heuristics-based optimization technique for solving nonlinear optimization problems with multiple objective functions. Lewis and Mirjalili presented this method for optimizing numerical problems in 2016, as the name implies. Among all species of whales, humpback whales have the finest strategy for hunting for food. It also has a unique hunting technique called the bubble-net feeding approach. Because their brains included spindle cells, they are undeniably clever. Foraging is performed by the production of specific bubbles in the shape of a route of spiral. WOA's full step-by-step procedure is outlined below.

**Step-1:** WOA optimization method is one of the finest strategies for identifying GM points on PV modules that does not require any sophisticated mathematical derivations. As previously stated, the Humpback whales hunt utilizing a bubble net approach around the circular course of the targeted group of fishes. This entire procedure may be deduced using the simple equations provided below.

$$\vec{D} = \left| \vec{C} \cdot \vec{V}^*(t) - \vec{V}(t) \right| \quad (2)$$

$$\vec{V}(t+1) = \vec{V}^*(t) - \vec{A} \cdot \vec{D} \quad (3)$$

The coefficient vectors, where 't' specifies the current iteration,  $\vec{A}$  and  $\vec{C}$  are utilized for prescribed directions for whale motions. The terms  $V$  and  $\vec{V}$  are vectors that are used to set the location of the optimal solution, which is commonly referred to as  $V_{mpp}$  in the PV system's MPPT approach..

**Step-2:** in previously stated, the vector position denotes the ideal point of the voltage signal(s) where the PV-unit may demonstrate its highest usage, i.e.,  $V_{mpp}$ . As an example, humpback whales in the process of implementing a WOA method may easily move around the prey within a diminishing circle. This form is similar to a long spiral and is denoted by the following mathematical expressions:

$$\vec{D}' = \vec{V}^*(t) - \vec{V}(t) \quad (4)$$

$$\vec{V}(t+1) = \begin{cases} \vec{V}^*(t) - \vec{A} \cdot \vec{D} & \text{if } p < 0.5 \\ \vec{D}' \cdot e^{bl} \cdot \cos(2\pi l) + \vec{V}^*(t) & \text{if } p \geq 0.5 \end{cases} \quad (5)$$

$$\vec{D} = \left| \vec{C} \bullet \vec{V}_{rand} - \vec{V} \right| \tag{6}$$

$$\vec{V}(t+1) = \vec{V}_{rand} - \vec{A} \bullet \vec{D} \tag{7}$$

**Step-3:** Once the proposed approach has determined the best search agent, the algorithm will attempt to update other search agents' locations and directions towards the superior agent. Furthermore, this procedure will be repeated until the global best location is identified in all local positions ( $V_{best}$  in the case of a PV panel during PSC). This procedure is broken into two steps: 'spiral updating position' and 'shrinking encircling'.

*Shrinking procedure:* This technique can assist whales in reaching their objective by shortening the distance between their current position and the target. Mathematically, this strategy may be accomplished by reducing the current value of the vector, as stated by the formulas below:

$$\vec{A} = 2\vec{d} \bullet \vec{r} - \vec{d} \tag{8}$$

$$\vec{C} = 2 \bullet \vec{r} \tag{9}$$

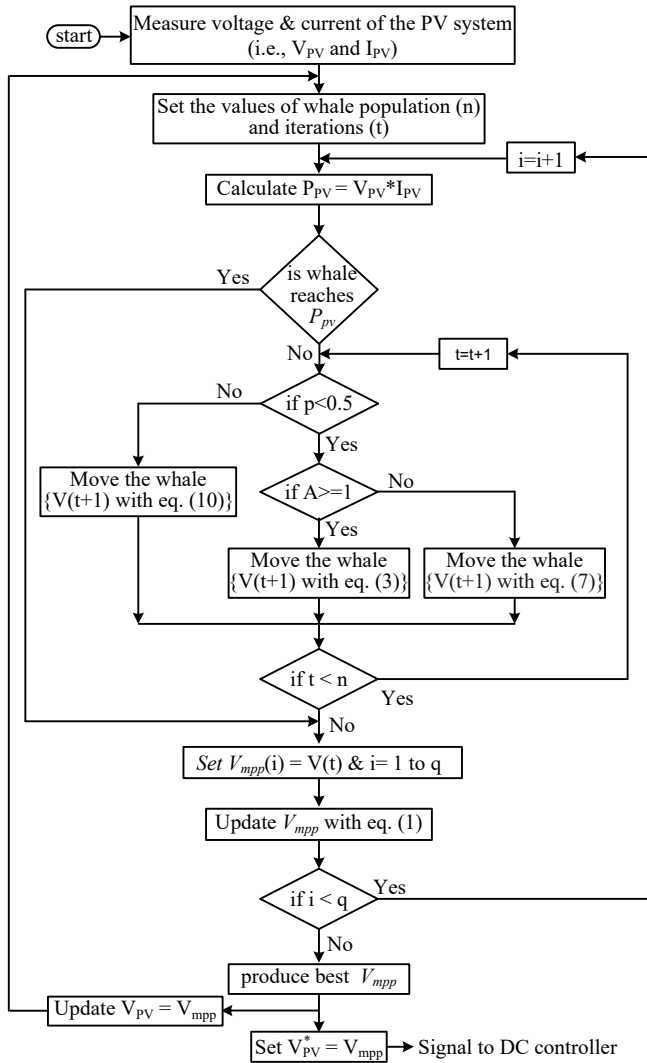


Fig. 4: Flowchart of the WOA-P&O approach.

*Spiral position updating: In this procedure, the movement and direction of whale(s) may be updated by estimating the distance between the whale(s) and the location of the prey/target. This is essentially described by the mathematical expression below..*

$$\vec{V}(t+1) = \vec{V}^*(t) + \vec{D}' \bullet e^{bl} \bullet \cos(2\pi l) \quad (10)$$

Once the algorithm has determined the position corresponding to the GM point for the current PSC, it will be updated the voltage signal by eq.(1) for the further step. For clarity, the flowchart of proposed WOA-P&O mechanism is illustrated in Fig. 4. The produced voltage signal will be considered as the DC link controller's reference voltage signal ( $V^*PV$ ). By creating a reference current signal for the inverter controller, this control unit can regulate the voltage of the PV at the maximum utilizing point. Because the filter is employed in between the grid and inverter, the effect due to the capacitance, resistance, & inductance, should be considered in the control of the inverter for achieving a stable operation.

#### 4. $H^\infty$ and TS-Fuzzy based Proposed Control Method

An effective inverter control method is necessary to inject current into the AC grid based on the available power of PV unit, which fluctuates continually. As a result,  $H^\infty$  controller is built in this work for PV system integration to the utility grid via the inverter. This study also considers a 3-phase LCL filter.  $R_i$  and  $L_i$  are represented by the resistance and inductance of the filter. Grid side is represented by  $R_g$  and  $L_g$ , whereas shunt capacitance is represented by  $C_f$ . The following approach [25] can be used to try a rudimentary design for a  $H^\infty$  controller.

From Fig. 1, the current Laplace transformation is:

$$I_{inv}(s) = G_{inv}(s)V_{inv}(s) - G_g(s)V_g(s)$$

$G_{inv}(s)$  and  $G_g(s)$  are the parameters of the transfer-function, which is composed of  $R_i$ ,  $R_g$ ,  $L_i$ ,  $L_g$ , and  $C_f$ .

The resonant frequency of the LC filter could impact the system's responsiveness, so it is recommended that the pass band of the desired controller be lower than the resonant frequency.

$$\text{Resonant frequency} = \frac{1}{2\pi} \sqrt{\frac{(L_i + L_g)}{L_i L_g C_f}}$$

Furthermore, the controller should be built to cope with grid values ranging from stiff to extremely weak, and the associated linearized transfer function may be described by

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} = \frac{1}{R_T + sL_T} \begin{bmatrix} -s\omega_L & \omega_R \\ s\omega_L & -\omega_R \end{bmatrix}$$

Where,  $L_T = L_g + \frac{1}{2}[L_{gh} + L_{gl}]$ ;  $\omega_L = \frac{1}{2}[L_{gh} - L_{gl}]$  and  $\omega_R = \frac{1}{2}[R_{gh} - R_{gl}]$  ,

$R_T = R_g + \frac{1}{2}[R_{gh} + R_{gl}]$ ; Here, grid impedance is incorporated and its high and low

values are denoted by  $L_{gh}$  and  $L_{gl}$ : high and low grid inductance values, respectively. Similarly,  $R_{gh}$  and  $R_{gl}$  are high and low grid resistance values, respectively.

Control is suggested in three segments: DC link control with TS-Fuzzy controllers, reactive power compensation, and H controllers. The DC link control is intended to transfer the

highest amount of active power. As a result, the reference current of the direct axis component is formed by comparing PV voltage with reference voltage obtained by the proposed WOA-P&O mechanism via the PI controller. Similarly, the component on the quadrature axis is obtained by controlling the RMS voltage at the PCC, which can serve to compensate for the reactive power operated at the PCC. Further these signals will be sent into the  $H_\infty$  current controller.

Because of its capacity to self-tune, a TS-Fuzzy controller can outperform traditional PI controllers in systems with fast variation [14]. The operational loads of a distribution system change at random. As a result, the suggested control strategy with developed TS-Fuzzy controllers performs well under all scenarios. Below is a thorough implementation of the TS-Fuzzy controller..

$$\mu_P(x_j) = \begin{cases} 0, & x_j < g_1 \\ \frac{x_j + g_1}{2g_1}, & -g_1 \leq x_j \leq g_1 \text{ and} \\ 1, & x_j > g_1 \end{cases} \quad (11)$$

$$\mu_N(x_j) = \begin{cases} 1, & x_j < g_1 \\ \frac{-x_j + g_1}{2g_1}, & -g_1 \leq x_j \leq g_1 \\ 0, & x_j > g_1 \end{cases}$$

$$\mu_P(\dot{x}_j) = \begin{cases} 0, & \dot{x}_j < g_2 \\ \frac{\dot{x}_j + g_2}{2L_2}, & -g_2 \leq \dot{x}_j \leq g_2 \text{ and} \\ 1, & \dot{x}_j > g_2 \end{cases} \quad (12)$$

$$\mu_N(\dot{x}_j) = \begin{cases} 1, & \dot{x}_j < g_2 \\ \frac{-\dot{x}_j + g_2}{2g_2}, & -g_2 \leq \dot{x}_j \leq g_2 \\ 0, & \dot{x}_j > g_2 \end{cases}$$

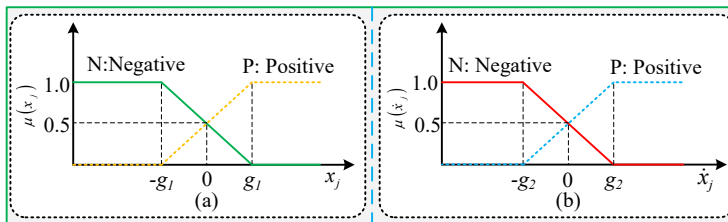


Fig.5: Membership function of TS-Fuzzy controller.

Figure 5 depicts the TS-Fuzzy controller model diagram. Table-3 has a set of four rules. Functions Z1-4 in Table-3 are utilized to calculate the output of the TS-Fuzzy controller. The sample moment is referred to as 'K,' and the constants a1-5, a2, a3, and a4 are modified by a tuning procedure that varies from one controller to the next. Figure 6 depicts the whole



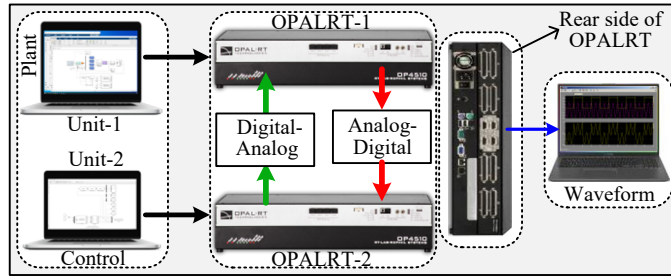


Fig. 7(a): HIL setup for results.

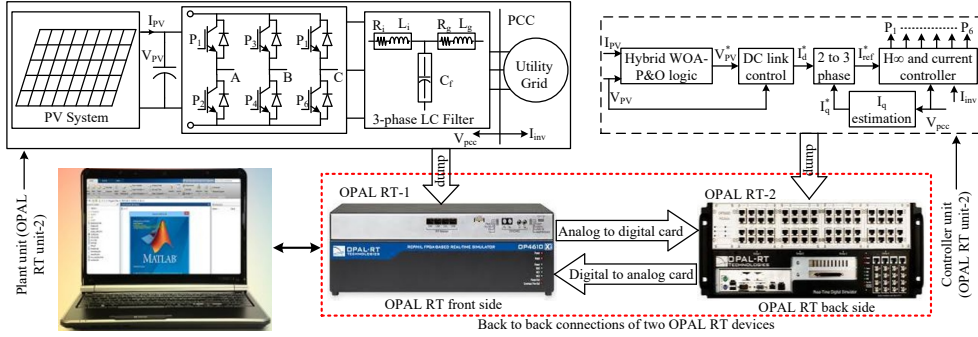


Fig. 7(b): The proposed method's HIL technique.

Case-I: performance with WOA-P&O under PSCs.

The suggested hybrid method has been tried for a variety of PSCs. The list in Table-2 is for one string, & the same pattern is used to produce the findings in this part for all 105 strings for better demonstration. When PSCs occur, the suggested technique responds promptly to locate the place where greatest energy may be harvested. The tracking behaviour for the specified PSC is presented in Fig. 8(i), and it was discovered that the suggested hybrid - P&O-WOA method tracks the GML in very little time under all situations. By comparing the suggested technique to the GA, PSO, & GWO methods, respective MPP of a PV system is displayed in Fig. 8(ii). When compared to previous algorithms, the suggested technique produces more electricity. However, presenting in the form of efficiency can provide more insight, therefore comparisons for efficiency are shown in Fig. 8(iii).

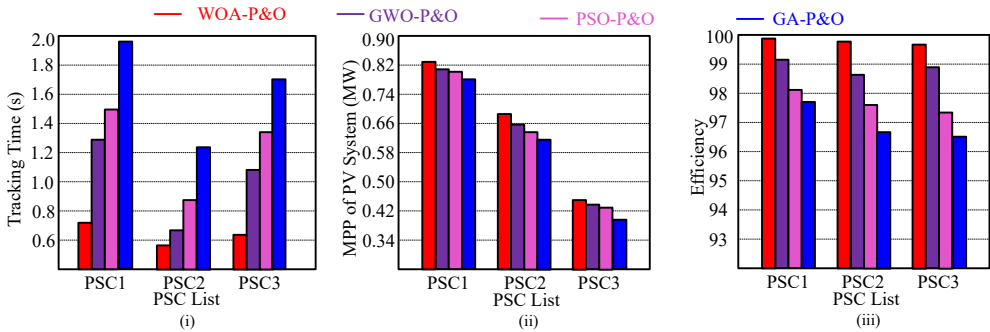
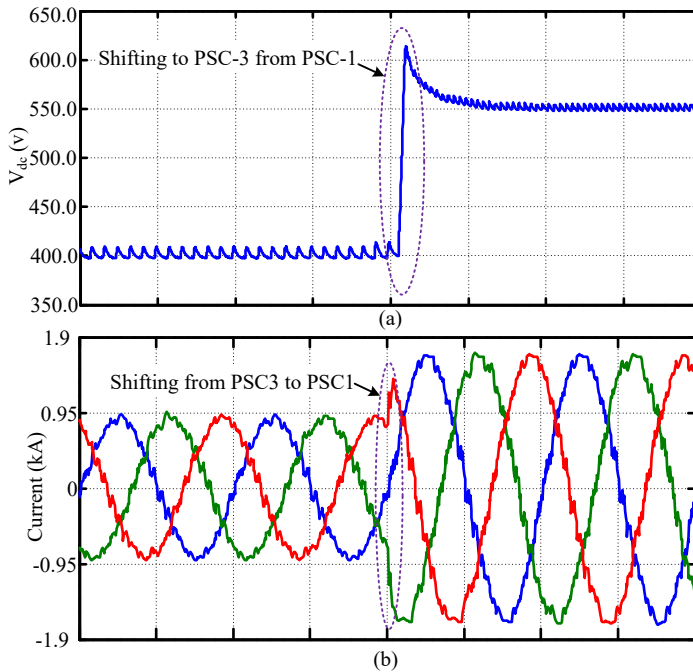


Fig. 8: PSC responses with {WOA, GA, PSO, & GWO}+P&O.

### Case-II: Proposed Controller Performances

The suggested controller is tested with PSCs changed from PSC-3 to PSC-1, this is one of the worst case of modification in partial shading impact. The shifting in PSC at  $t=2.5\text{sec}$ , when WOA-P&O must follow the voltage at DC link with respect to their reference signals, was considered. HIL is used to get the response of the DC link voltage and related inverter currents, as illustrated in Fig. 9. Fig. 9(a) shows a clear image of the changing DC link voltage during the transition from PSC-3 to PSC-1, and the smooth response is accomplished using the suggested controller. However, because PSC-1 has higher power than PSC-3, inverter currents should rise during the PSC switch from PSC-3 to PSC-1. Figure 9(b) depicts the corresponding inverter currents. Inverter currents did not alter much as a result of the H and TS-Fuzzy controllers. The inverter currents exhibit a seamless response thanks to the minimal ripples in the H controller, distinguishing it from other controllers. However, during the large shift in DC link voltage, the RMS voltage from line to line should be limited. The suggested inverter controller may restrict the RMS of the line voltage to the limit shown in Fig. 9(c). According to Fig. 9(c), the rising in line voltage at 1.5 sec is limited with substantial changes in DC link voltage. Furthermore, THD should be within allowable limits in grid-connected distribution generators, according to IEEE standards, and little THD (2.41, which is within allowable limits) has been detected in injected currents into grid from inverter. Figure 10 of line current shows the FFT spectrum of THD.



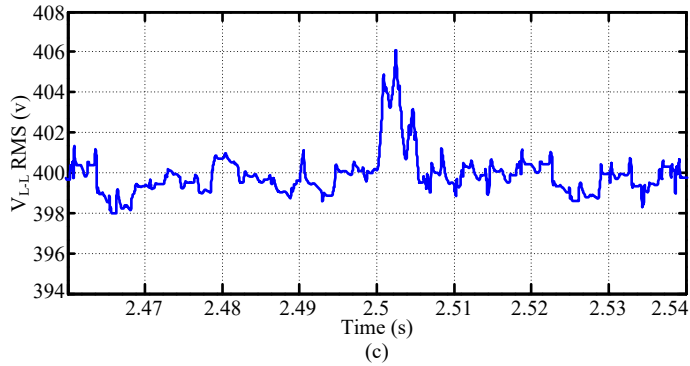


Fig. 9: Changes in (a) DC link voltage, (b) 3- $\phi$  currents, and (c) RMS L-L voltage.

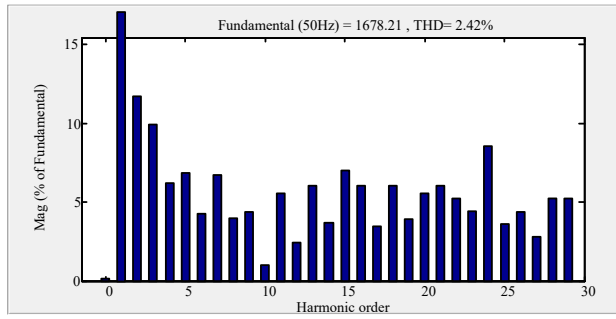


Fig. 10: THD of line current injected to utility grid through inverter.

**Case-III: Performance comparison between PI & TS-Fuzzy:**

The suggested control approach is evaluated under 250% load change using PI and TS-Fuzzy controllers at  $t=1.0$  sec. When there is a sudden change in a huge quantity of load at PCC, the line to line RMS voltage drops. However, the inverter's control will steady the voltage. Because of its fixed gains that are set at certain conditions, the control approach with PI controllers performs poorly when compared to TS-Fuzzy. Furthermore, the TS-Fuzzy controllers will give control method compatibility by delivering correct output during large rapid changes. Figure 11 depicts the reaction. As a result, the suggested technique is given high priority in a single stage grid-integrated PV unit for increasing the quality of power at load bus.

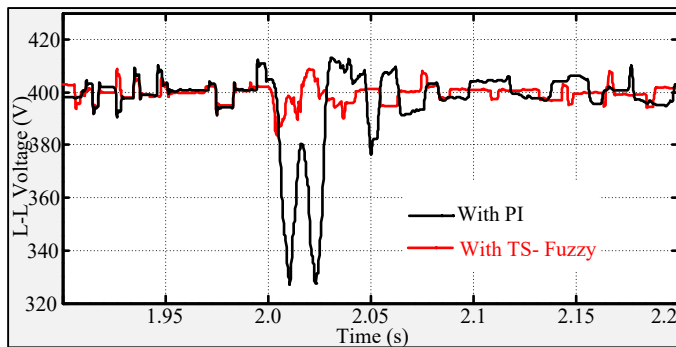


Fig. 11: Line-to-line RMS voltage response using PI and TS-Fuzzy controllers with a rapid change in load.

## 6. Conclusion

A single stage grid integrated 1MW PV plant employs a hybrid -P&O-WOA mechanism, as well as TS-Fuzzy and H controllers. This work proposes a hybrid control system that uses TS-Fuzzy controllers and H controllers to achieve quick response. The replies of maximum power, tracking time, and efficiency are compared with PSO, GA, and GWO, and it is stated that the suggested technique has a considerable priority. Aside from that, the H controllers based inverter controller is intended to regulate inverter currents fed into the utility grid. The suggested inverter controller provides a reliable and rapid reaction as well as smooth operation. With the assistance of HIL, satisfactory outcomes are incorporated.

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