Innovative GMPPT searching algorithm and precise backstepping control for grid-connected PV system in challenging shading environments

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ABSTRACT

Photovoltaic (PV) systems encounters different problems of weather conditions that lowers their generated power. For this reason, maximum power point tracking (MPPT) have been designed to track the maximum power at all times and thus minimize these losses. However, under complexes partial shading condition (PSC) these losses are even higher. Classical MPPT algorithms fails to track the global MPP (GMPP) which further augment the power losses. Alternately, a grid connected topology of the PV system is chosen but needs a control method to phase the inverter current with the grid. This paper introduces a novel algorithm named power search algorithm (PSA) that memorizes the highest peak as it scans the PV curve then returns and locks it. Due to its simplicity, this proposed method is suitable for practical use and manages to track the GMPP with high efficiency of 99.5% and a mean response time of 0.04 s. Comparison was made with a gray wolf optimization (GWO) technique. Simulation was done in MATLAB/Simulink. Results shows that the proposed algorithm performed better than the GWO in all aspect of efficiency, tracking time and oscillations around GMPP. Also, a backstepping control was used to inject a good synchronized power to the grid.

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1. INTRODUCTION

Renewable energy is the core of the modern era, particularly with the decline in natural reserves of fossil energy, which contributes to the raise of global energy prices. Investing in solar energy appears to be a natural move in this regard, given its availability, relative low production expenses, low maintenance, and absence of air pollution. Solar energy, particularly photovoltaic (PV) systems, has gained prominence over other renewable sources due to their long lifespan (up to 20 years) and eco-friendly use even in residential properties [1], [2]. They do, however, have a low power efficiency. Researchers in [3]–[5] have investigated various approaches for collecting the maximum power from a PV system. This obtained PV power fluctuates nonlinearly with solar irradiance and temperature, presenting a curve with a single maximum. This raises the significance of optimizing the extracted energy.

Numerous academics have developed maximum power point tracking (MPPT) algorithms to maximize the available power from a PV system. Classical methods including perturb and observe (P&O) or incremental conductance were amongst these algorithms (InC). In the literature, comparisons have been done between various MPPT algorithms such as artificial intelligence and hybrid algorithms that incorporate two or more algorithms [6], [7]. Others have tried to modify existing MPPT algorithms to increase their efficiency [8], [9].

According to the literature reviews, there are two scenarios in which an MPPT algorithm could be applied. In normal climatic conditions, when irradiance is uniform across all PV panels, and partial shading condition (PSC), where there are discrepancies, indicating that not all PV panels received the same amount of irradiance due to trees, high buildings, clouds, and other causes. The problem with PSC is that it induces several peaks in the PV curve, resulting in local maximum power points (LMPP), which are the lower peaks, and global maximum power point (GMPP), which is the greatest peak [10], [11]. Many MPPT algorithms fails to track the GMPP because they drop into LMPPs which decreases enormously the extracted power form the PV system. However, advance GMPPT algorithms have been used in recent literature [12]–[16] to lock the GMPP for PV systems operating under PSC.

GMPPT algorithms are critical for PV systems because they consistently extract the maximum available power from them even under PSC. As a result, numerous research papers produced various GMPPT approaches, which are meticulously explained in their articles. Particularly prominent optimization methods including the high efficiency swarm intelligent algorithm [3], a hybrid shuffled frog leaping and pattern search (HSFL–PS) method [17], musical chair algorithm [18], GWO [19], novel search and rescue (SRA) optimization algorithm [20], Improved team game optimization [21], Q-learning hybrid type-2 fuzzy logic control approach based MPPT [22], a hybrid adaptive controller for MPPT [23]. Under extreme PSC, it is not certain for GMPPT algorithms to locate the global peak, especially when the local peak is close enough to the global peak, they become locked in local peaks. This problem is typically caused by insufficient randomization in the algorithm; consequently, Ram and Rajasekar [24] developed a new flower pollination algorithm (FPA) that is ideal for GMPPT due to its dual mode search capabilities, which creates the required randomness in each iteration. Comparison was made with P&O, and PSO. Result showed good result in tracking the GMPP, but the response time remain slow with 0.47 s in the best scenario, and high oscillations around GMPP were also present. The modified improved squirrel search algorithm (ISSA) is used by Fares *et al.* [25] to develop GMPPT approach. In comparison to the conventional SSA technique which wasted time in exploring values that are already explored due to the metaheuristic behavior of the algorithm, ISSA improved the tracking time by 50%. ISSA was compared to the well-known genetic algorithm (GA) and PSO. The findings demonstrated the algorithm's capacity to track the GMPP with a response time of 0.6 s which remain slow even after the optimization, and also notable power oscillations could be seen around the GMPP.

This paper provides a new method, which is apart from any conventional method, such as P&O or InC, that accurately tracks the GMPP with high efficiency, low oscillations around the GMPP and fast response time under complicated PSC. Furthermore, the proposed GMPPT method is implemented in grid connected topology which is preferred over standalone PV systems, due to its advantages and the new opportunities that bring either from energetic or economical aspects [26], [27], which enhance the need for a second control strategy to ensure total accordance with the grid code requirements. To do so a backstepping control based on Lyapunov function is implemented to optimize the power transferred to the grid by successfully synchronizing the inverter current with the grid with a good unity power factor (UPF) which ensure stability of the grid and less harmonics in the current inverter.

In order to test the proposed method, a comparison is made under four different scenarios of PSC in MATLAB/Simulink, between this later and a GWO algorithm which is based on an optimization method. The PV system consists of 47 parallels and 3 series panels to produces up to 115 kW of power under irradiance of 500W/m^2. Results showed the superiority of the proposed method with a tracking ability of 100% in four scenarios, 99.5% efficiency, very low oscillations around GMPP between 10 W and 20 W and very fast mean response time of 0.04 s. In other hand, the GWO failed to track the last scenario, scored 99% efficiency, very large oscillations around GMPP between 400 W and 450 W and 0.06 s in response time for the GWO. With the major advantage to keep in mind that the proposed algorithm is much simpler than the GWO and faster which makes it a great difference and that’s the ultimate purpose of optimization, same or greater results with much less complexity which was done successfully in this paper.

2. METHOD

In a partially shaded PV system, LMPPs are present. In such case, classical MPPT algorithms like P&O and InC may not be able to accurately track the global MPP under this condition of PSC and generally are trapped in one of the LMPPs [10], [28], leading to a decrease in PV power of the system. The PSC can have a substantial impact on PV system performance, and accurate modelling of this PSC as shown in Figure 1, is critical for PV system design and optimization. Improved MPPT algorithms, such as the one suggested here, can assist reduce the detrimental effects of PSC and assure optimal energy extraction from the

PV system. Table 1 shows the irradiance values for each PSC scenario, and Figure 2 shows the simulation of these PSC. Table 2 contains the cell module specifications and system settings used in this work.

Table 1. Partial shading scenarios of the study

		PV1	PV2	PV3	PV4	PV5	PV6	PV7	PV8
Irradiation [W/m2]	PSC1	200	900	600	300	300	800	500	800
	PSC2	500	200	800	300	600	900	500	800
	PSC3	100	1000	400	300	400	200	700	700
	PSC4	700	700	400	300	700	700	200	100

Table 2. Cell model specifications and system parameters

Description	Specifications	GMPPT parameters	System parameters
Maximum power point (MPP)	200.143 W	ΔS = 0.8 V	Switching frequency = 20 KHz
Circuit voltage (VOC)	32.9 V	ΔV = 0.0001 V	PI proportional coefficient = 10
Short circuit current (ISC)	8.21 A	T = 20 KW	PI integral coefficient = 20
Voltage of maximum power point (VMPP)	26.3 V		
Current of maximum power point (IMPP)	7.61 A		

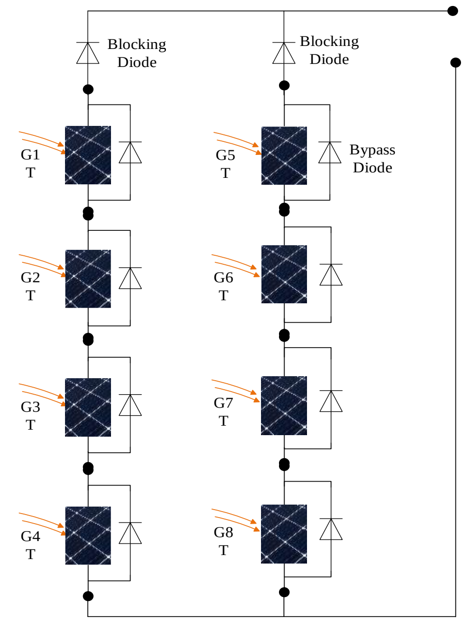

Figure 1. Modelling of the partial shading used in the study

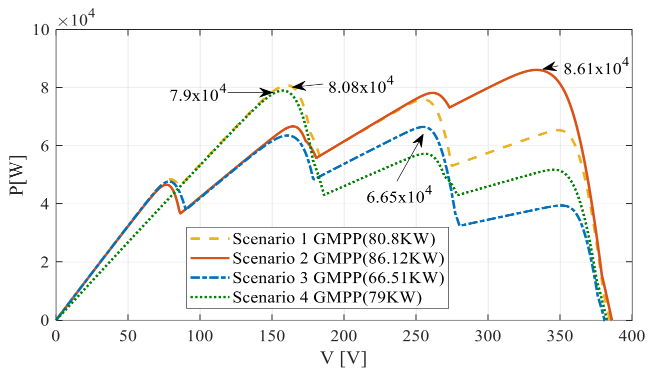

Figure 2. Partial shading scenarios simulated for the study

2.1. MPPT controller

This research paper provides a novel GMPP algorithm for PV systems affected by PSC. This method employs a power-based searching technique that quickly locates the GMPP while effectively avoiding the

LMPP. The algorithm's working idea is as follows: After initializing the parameters of the algorithm, a variable scan is set to 0 in order to begin the search, the algorithm then conducts a comprehensive scan of the PV curve of the PV system by incrementing the reference voltage V_{ref} and searches for the maximum power value reached. During the scan, an iterative comparison is performed between the instant power P (i) and the previous power P (i-1) of the PV system. The highest value resulting from this comparison is then stored as P_{max} and V_{max}, that serves as the reference value for further comparisons. Subsequently, every new instant power value P (i) is compared to the reference value P_{max}, and if necessary, P_{max} is updated. After sweeping the entire curve, a threshold value T is necessary to determine whether to increment V_{ref} and continue to search or to stop. This decision is based on the operating side of the algorithm towards the PV curve. If it's on the left side, even if the threshold value is reached but P(i-1)is lesser than P(i) this means that the scan has already begin, in that case the voltage is incremented to keep scanning the whole PV curve, otherwise if the previous value of power P(i-1) is bigger than the instant value P(i) it means that the algorithm operates at the right side of the PV curve meaning the end of the search. The variable scan is then set to 1 and the corresponding couple (P_{max}, V_{max}) is able to track the GMPP with high precision. The algorithm also includes a reset mechanism triggered by change in irradiance in order to track newer GMPP if necessary. The flowchart of the proposed algorithm is presented in Figure 3. The working principle of the proposed algorithm could be extracted from the PV simulation of scenario 1 as illustrated in Figure 4 which clearly highlights the scanning behavior and the return to lock the GMPP for this complex scenario.

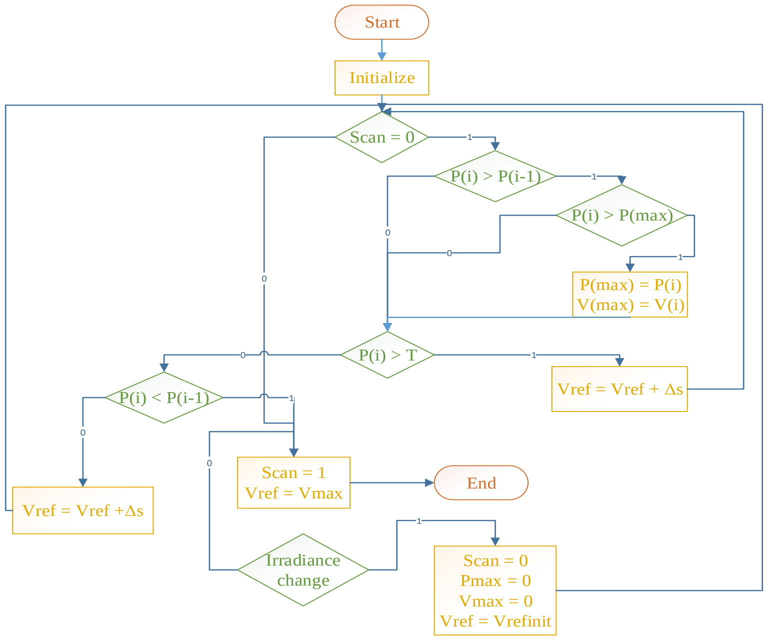

Figure 3. Flowchart of the proposed power search algorithm

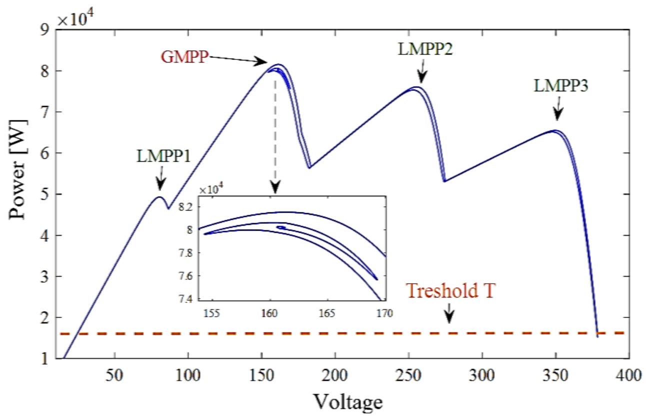

Figure 4. Scanning behavior and lock of the GMPP for the proposed algorithm in scenario 1

3. INVERTER CONTROLLER

A backstepping control is used to synchronize the inverter current to the grid with the use of a phase locked loop [29] as well as maximizing the power distribution from the boost converter to the inverter [30]. The reactive power can be written in dq axis by (1).

$$Q = -\frac{3}{2}V_d i_q \tag{1}$$

Also, the active power is as in (2).

$$P = \frac{3}{2}V_d i_d \tag{2}$$

By expressing active and reactive power in the dq axis, the relationship between i_d and i_q is decoupled. To maximize power transfer between the inverter and boost converter, i_q is regulated to its desired value (i_{qref}=0) for optimal reactive power control. Simultaneously, active power P is maximized by regulating i_d to its reference value i_{dref} at all times as in (3).

$$i_{dref} = \frac{2}{3}\frac{P_{max}}{V_d} \tag{3}$$

To control the reactive power with the backstepping control, an error should be defined as (4).

$$\varepsilon_{iq} = i_q - i_{qref} \tag{4}$$

Its integral action is as in (5).

$$\delta_{iq} = \int_0^t i_q(z) - i_{qref}(z)\, dz \tag{5}$$

Step 2 defines the Lyapunov function of $(\varepsilon_{iq}, \delta_{iq})$ as in (6).

$$V_{iq}(\varepsilon_{iq}, \delta_{iq}) = \frac{1}{2}\varepsilon_{iq}^2 + \frac{1}{2}\delta_{iq}^2 \tag{6}$$

Where $\dot{V_{iq}}$ its time derivative, as shown in (7).

$$\dot{V_{iq}}(\varepsilon_{iq}, \delta_{iq}) = \varepsilon_{iq}[\delta_{iq} - \omega i_d - \frac{r}{L_f} i_q - \frac{1}{L_f} V_q + \frac{V_{dc}}{L_f} C_q] \tag{7}$$

Finally, the control law C_q could be extracted as (8).

$$C_q = \frac{L_f}{V_{dc}}[-K\varepsilon_{iq} - \delta_{iq} + \omega i_d + \frac{r}{L_f} i_q + \frac{1}{L_f} V_q] \tag{8}$$

With k=300000 a setting parameter. The derivative of the Lyapunov function must be negative, as given in (9).

$$\dot{V_{iq}}(\varepsilon_{iq}, \delta_{iq}) = -K\varepsilon_{iq}^2 \tag{9}$$

This stabilizes the q component of the inverter currents which equals zero, and manages to annulate the effect of the reactive power. In the latter stage of the control process, to maximize the active power injected by the PV system into the grid, a new tracking error of the inverters current d component is defined as (10).

$$\varepsilon_{id} = i_d - i_{dref} \tag{10}$$

Its integral action expressed in (11).

$$\delta_{id} = \int_0^t i_d(z) - i_{dref}(z)\, dz \tag{11}$$

Its Lyapunov function is as given in (12).

$$V_{id}(\varepsilon_{id}, \delta_{id}) = \frac{1}{2}\varepsilon_{id}^2 + \frac{1}{2}\delta_{id}^2 \quad (12)$$

The Lyapunov function derivation is expressed as (13).

$$\dot{V_{id}}(\varepsilon_{id}, \delta_{id}) = \varepsilon_{id}[\delta_{id} + \omega i_q - \frac{r}{L_f} i_d - \frac{1}{L_f} V_d + \frac{V_{dc}}{L_f} C_d - \frac{d_{idref}}{d_t}] \quad (13)$$

Finally, the control law C_d could be given as (14).

$$C_d = \frac{L_f}{V_{dc}}[-K\varepsilon_{id} - \delta_{id} - \omega i_q + \frac{r}{L_f} i_d + \frac{1}{L_f} V_d + \frac{d_{idref}}{d_t}] \quad (14)$$

With k=300000 a positive gain. The Lyapunov function is negative as it should be (15).

$$\dot{V_{id}}(\varepsilon_{id}, \delta_{id}) = -K\varepsilon_{id}^2 \quad (15)$$

This control law delivers maximum active power to the grid with almost zero reactive power, despite system disturbances. The flowchart of this control law is depicted in Figure 5. While the overall control strategy is illustrated in Figure 6.

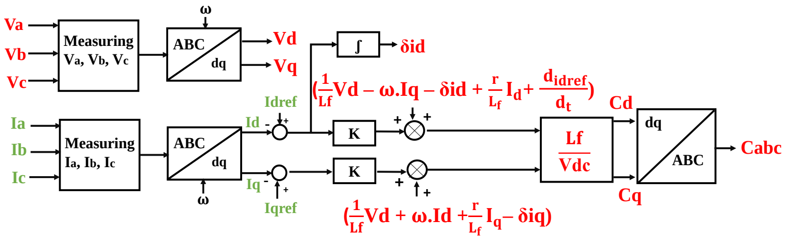

Figure 5. Flowchart of the backstepping control

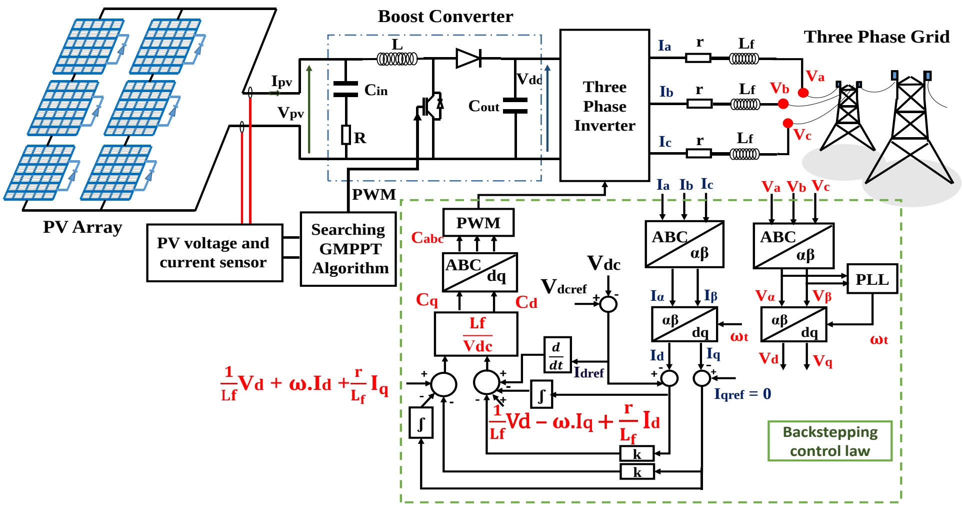

Figure 6. Control strategy of the complete system

4. SIMULATION AND RESULTS

The proposed algorithm's validity was tested using MATLAB/Simulink. Simulation scenarios are presented in Figure 2 above, and shows complex pattern variations in PSC that are hard to track which mean the GMPP could be in the first, middle or last peak. The LMPP created by these scenarios makes it impossible to track the GMPP by conventional method like P&O and InC that falls in LMPP. The GWO algorithm manages to track the GMPP for the first three scenarios 1, 2, and 3 but fails in scenario 4 resulting in significant loss in power output as shown in Figure 7, while the proposed searching algorithm is simple to implement and manages to successfully track the GMPP in all four scenarios as shown in Figure 8, the response time of the proposed algorithm for all four scenarios are also visible. The results of the proposed algorithm and the comparison with the GWO are presented in Table 3. In scenario 1 a challenging PSC is depicted, where the GMPP is located on the second peak. Both the proposed and GWO algorithms highlights the same performance in both efficiency and response time. But in terms of oscillations, the proposed algorithm has small oscillations around the GMPP compared to large oscillations for the GWO. On the other hand, scenario 2 highlights the second PSC, where the GMPP is situated in the last peak, which is also challenging. Both algorithms manage to track the GMPP, however, noticeable oscillations are present in the GWO around the GMPP, which negatively affects the extracted PV power. In scenario 3 the GMPP is on the third peak, both the GWO and the searching algorithm locks the GMPP with also clear oscillations for the GWO. Finally, the scenario 4 presents a GMPP in the first peak. The proposed algorithm, manages to successfully track the GMPP with high accuracy and response times, while the GWO fails in this scenario and exhibits a significant loss in power output. Also, it is important to state that the gray wolf optimization (GWO) is an optimization method that is complex to elaborate and to implement in microcontrollers and demands great resources, in contrast to the proposed algorithm which is very simple to implement in low budget microcontrollers.

In other hand, the second part of this work consist of synchronizing and injecting a perfect sinusoidal inverter current in the grid by a nonlinear backstepping control. The results showed in Figure 9 demonstrate that the inverter current of the PV system is in phase with grid voltage meaning that the PV power could be efficiently injected into the grid in a synchronized manner and with minimum harmonics as reported in Figure 10. The proposed GMPP tracking algorithm combined with the backstepping control is effective, fast, and performs optimally under complexes PSCs.

Table 3 summarizes the comparison between the proposed algorithm and the GWO. The proposed algorithm exhibits improved performance with a tracking time of 0.036 seconds and 99.81% efficiency in best scenario. The algorithm's ability to track the GMPP accurately in all scenarios of partial shading tested in this study makes it a more reliable and efficient GMPPT solution for PV systems.

Table 3. Performances comparison of the proposed algorithm and GWO

Scenarios	GMPP (KW)	Obtained GMPP (KW)		Efficiency (%)		Response time (s)		Oscillations around GMPP (W)	
		Proposed method	GWO	Proposed method	GWO	Proposed method	GWO	Proposed method	GWO
Scenario 1	80.8	80.23	80.3	99.3	99.38	0.053	0.05	20	200
Scenario 2	86.12	85.96	85.8	99.81	99.62	0.036	0.051	15	400
Scenario 3	66.5	66.3	66.2	99.7	99.54	0.046	0.056	10	400
Scenario 4	79	78.32	51.7	99.14	65.4	0.04	0.08	20	450

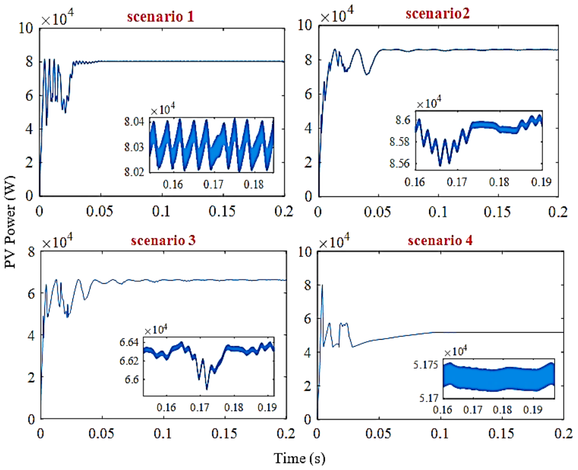

Figure 7. PV power using GWO MPPT algorithm for scenario 1, 2, 3, and 4

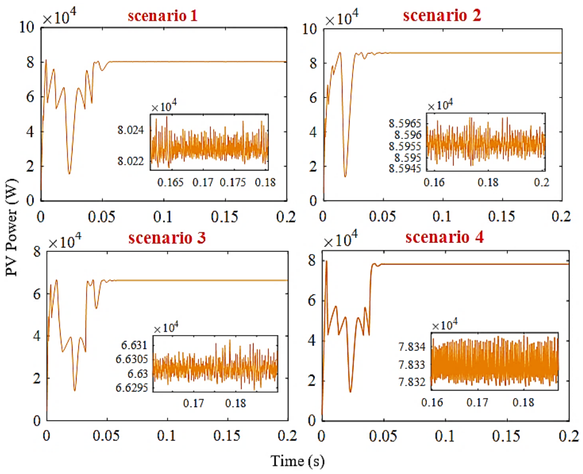

Figure 8. PV power using proposed GMPPT algorithm for scenario 1, 2, 3, and 4

The results of the study suggest that the proposed algorithm is a more robust and effective GMPPT algorithm for grid-connected PV systems, especially under complexes scenarios of partial shading where the response time of most MPPT methods takes longer and thus the efficiency decreases. However, advanced GMPPT methods are quiet fast with 78 s and 262 ms reported in [31] but still up to 5 times slower than the proposed method with 36 ms and 53 ms. Furthermore, the study emphases the tracking scenarios where the GMPP is in middle peaks, and did not tested it for first and last peaks which are considered also challenging for the algorithm. Preview study [32] unnecessary scans were applied to determine the GMPP, which increases the complexity of the algorithm without guaranteed results under complexes scenarios. In contrast the proposed algorithm performs one simple scan and effectively reaches the GMPP. Başoğlu [33] tried to limit the scanning interval, but the response time remain slow in comparison with 0.1 s and with degraded efficiency. Bahri *et al.* [34] managed to successfully combine a classical method that is P&O with a scanning algorithm in order to resolve the problem of PSC. Result showed good performances in response time, but non negligible oscillations with a magnitude of 1000W were present around GMPP. The proposed method suggests a searching algorithm that is independent from any classical algorithm, and manages to successfully track the GMPP with good response time and high efficiency with practically no oscillations, only 20W, around GMPP. As a result, the suggested algorithm provides a viable alternative to existing sophisticated GMPPT algorithms for grid-connected PV systems with reduced complexity.

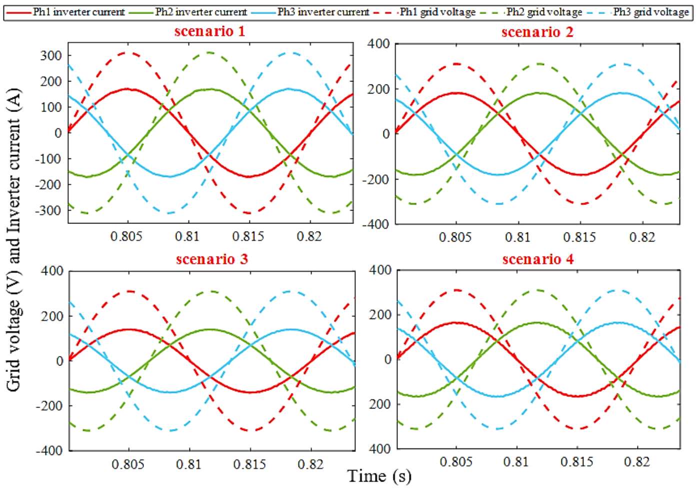

Figure 9. Synchronization and waveform of inverter current and grid voltage for scenarios 1, 2, 3, and 4

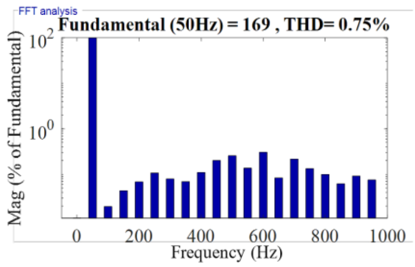

Figure 10. THD analysis for scenario 1

5. CONCLUSION

Various GMPPT algorithms were applied to extract the maximum available power from the PV system under difficult PSC, particularly optimization and intelligent methods that are efficient but complicated in structure and are difficult to implement. However, even if the conventional techniques are practical and easier to implement, they suffer the disadvantages of dropping into LMPP rather than pursuing GMPP under PSC. In this paper, a new power-based searching algorithm is proposed to efficiently track the GMPP in these difficult PSC thus optimizing power production of the PV system, with high response time. The proposed algorithm scans the whole PV curve searching for the maximum power point, store it and compares it to instant power values recorded. The comparison final result is then considered as the GMPP. The coordinates of this point are stored as a reference voltage that will command the PWM based boost converter to deliver a real time maximum power. The efficiency of the proposed algorithm was very high with an average of 99.5% and a mean response time of 0.04s compared to the GWO algorithm. Future works will highlight the practical implementation of this technique in a real situation of PSC.

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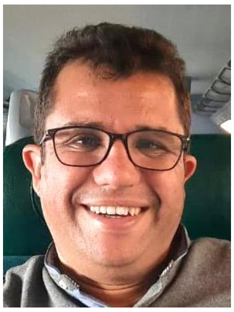

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