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Original Article

Enhancing the Robustness of P and O Algorithm-Based MPPT Control in Stand-Alone PV Systems through Fine-Tuned PI Controller for Dynamic Load Variations

K. Keerthana[1], S. Singaravelu[2]

[1,2]Department of Electrical Engineering, Annamalai University, Tamilnadu, India.

[1]Corresponding Author : keerthanakamaraj27@gmail.com

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Abstract - *Solar power generation systems play a crucial role in the electricity generation network. However, standalone Photovoltaic (PV) systems exhibit several challenges, such as efficiency issues, non-linear waveforms, prolonged settling times for rapid load changes, and high ripple content in PV power output. These challenges need to be effectively addressed to operate PV systems at their maximum efficiency and reliability. Various Maximum Power Point Tracking (MPPT) algorithms have been proposed to track the maximum power from PV panels. Nevertheless, the power output tracked by these algorithms often exhibits significant oscillations, making it unsuitable for direct utilization by the load. In this research paper, we present an innovative control technology that utilizes a Perturb and Observe (P and O) algorithm-based MPPT with a fine-tuned Proportional-Integral (PI) controller to maintain a consistent power profile. Our primary objective is to enhance the voltage, current, and power characteristics on both the PV and load sides of the system. Additionally, our proposed system ensures system stability even in the face of sudden load variations. By addressing these issues comprehensively, our research aims to significantly improve the overall performance and reliability of standalone PV systems, thereby promoting their widespread adoption and integration into the electricity generation network.*

Keywords - *P and O algorithm, PI controller, Matlab/Simulink, Stability, MPPT.*

1. Introduction

Pollution is the introduction of Contaminants that can have a damaging effect on the natural environment. Air pollution is primarily introduced through the burning of fuels. Looking at the present scenario, insufficient fossil fuels and their higher costs and increasing energy requirements push the technology researchers to rush up with innovations on renewable energy resources. Among renewable energy resources, photovoltaic power generation has attracted more attention [1]. Photovoltaic systems are eco-friendly because they convert natural sunlight into electricity without pollution and waste. The power generated by the PV system has very little efficiency (less than 22.2%) due to its conversion efficiency. The generated PV power is subjected to varying climatic conditions such as irradiance and temperature. This drawback has been overcome by maximum power point tracking technology which was first introduced by a small Australian company called AERL. Nowadays many MPPT technologies are introduced to operate a PV system at its maximum efficiency. The simplest methods are constant voltage, parasitic capacitance, constant current, Incremental conductance algorithm, P and O algorithm. The incremental conductance method is complicated when compared with P and O algorithm-based MPPT technique. Among the above, the P and O algorithm is easy to implement and understand, but it has oscillation issues. In this paper, an intelligent control technology is proposed by using a PI controller associated with the P and O MPPT algorithm in order to improve efficiency, oscillations and overall system stability [2]. The proposed PV system contains a 100KW PV array, DC to DC boost converter, P and O MPPT controller, PI controller, PWM module, and resistive load, as shown in Figure 1.

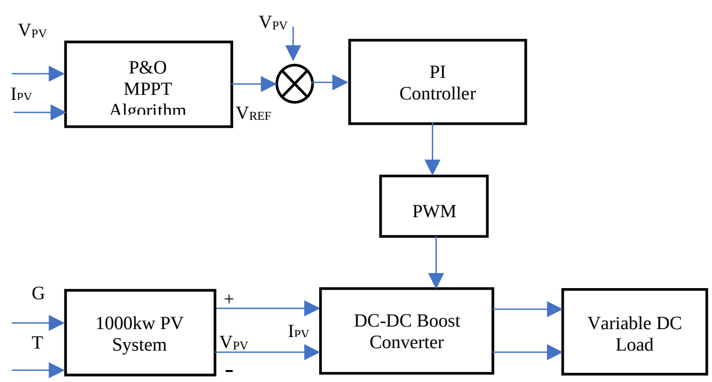

Fig. 1 Graphical abstract of proposed PV system

2. Literature Review

The author concludes with the P-V and I-V characteristics of the MXS60 solar array by comparing the performance of fuzzy logic MPPT and conventional P&O MPPT controllers. The primary objective was to control the boost converter duty cycle to maximize the power output from a PV generator under varying solar insolation and temperature conditions. The simulation results indicate that both controllers enable the PV panel to achieve maximum power output. However, the fuzzy MPPT outperforms traditional controllers in nonlinear systems by reducing voltage perturbations once the Maximum Power Point (MPP) is detected. These results in a more stable output power compared to conventional MPPT, which experiences fluctuations around the MPP (Bounechba et al., 2014). Initially, the system was tested by varying solar radiation and subsequently by altering temperature. The findings indicate that the output power and voltage delivered from the fuzzy logic-based MPPT systems surpass those of conventional solar molecules. Moreover, rapid changes in solar radiation and temperature do not impact the performance of the system. Consequently, the overall efficiency of the system has improved. The results conclude that employing a fuzzy logic controller in solar PV systems can enhance system efficiency. The design of this controller is simpler compared to other conventional MPPT techniques (Cheema and Kaur, 2014). Two groups of MPPT control algorithms, mainly direct and indirect methods, were discussed and examined. The study presents a comparative simulation of the performance of two algorithms: the P&O algorithm, which is the simplest method, resulting in low cost and implementation, and other MPPT algorithms. It was found that the P&O method is highly efficient and should be further refined and improved to achieve better outcomes. On the other hand, the indirect methods provide a more sophisticated approach, but they greatly depend on the user's knowledge of the system, particularly for the FLC parameter setting. The advantage of the indirect methods lies in their flexibility in adjusting parameters based on the system's input and output. The simulation results indicate that the indirect method achieves optimal performance in multiple cases established in the I-V characteristic curves for different types of photovoltaic modules.

Therefore, further research should be focussed on utilizing these methods more effectively from the PV system under non-uniform radiation conditions (Ngan & Tan, 2011) The combination of P&O and FLC techniques with the MPPT algorithm leverages simple features from both P&O and FLC, which reduces operational complexity while maintaining high-performance targets. It considers a wide range of irradiance levels, particularly at low irradiance. Previous studies have widely used steady-state operation analysis, but this study includes dynamic operation analysis for more comprehensive results. The proposed algorithm has been demonstrated and compared with conventional P&O and FLC algorithms, showing superior performance. Both steady-state and dynamic simulations confirm the high MPP ratio, with low oscillation and overshoot, leading to stable operation. The algorithm performs significantly better at low irradiance levels. To confirm its effectiveness, hardware implementation should be tested with a real PV module, considering possible noise during measurements. Although the lack of a real PV simulator is a limitation, the real PV module can be tested in real-field operations. Future work should include using a PV simulator that follows EN 50530 standards for direct comparison and further analysis. The existing work on hardware implementation and high irradiance levels justifies the proposed algorithm. The fast response of the boost voltage suggests significant reductions in calculation processes, accurate decision-making to achieve MPP, and better overall algorithm performance. Further evaluation could lead to higher efficiency in PV systems (Zainuri et al., 2014).

The open-loop Maximum Power Point Tracking (MPPT) technique aims to address problems encountered with two common techniques: the perturb and observe (P and O) method and the incremental conductance algorithm. The main drawbacks of the P and O technique are its poor dynamic response and oscillations around the maximum power point during steady-state operation. Rapid changes in atmospheric conditions can cause the P&O method to mistakenly move in the wrong direction on the PV power curve if each perturbation results in a power increase. Another issue is its steady-state behaviour when the maximum power point is reached, as it continuously perturbs the duty cycle of a DC converter to monitor power variations. Each control step requires several calculations to determine instantaneous and incremental conductance and then compare them. An open-loop MPPT technique that aims to provide an improved dynamic response time compared to the techniques. It also maintains low implementation complexity. There is a slight power loss from the solar panel to the boost converter output. This can be attributed to the switching losses and the losses in the inductor and capacitor of the boost converter. This is evident from the plots of the respective power curves (Singh & Ria Yadav, 2014)

3. Modeling of Proposed PV System in SIMULINK Environment

The modeling of Photovoltaic (PV) systems is a crucial step in understanding and optimizing their performance, as it allows for comprehensive analysis and simulation of their behaviour under various operating conditions. SIMULINK, a widely used simulation tool, offers a robust platform for developing intricate mathematical models that simulate the dynamics of PV systems with remarkable precision. The objective of this section is to explore the details of modeling a proposed PV system within the SIMULINK framework, focusing on the integration of key components such as the PV module, converter, and associated control systems.

3.1. Photovoltaic Array Model

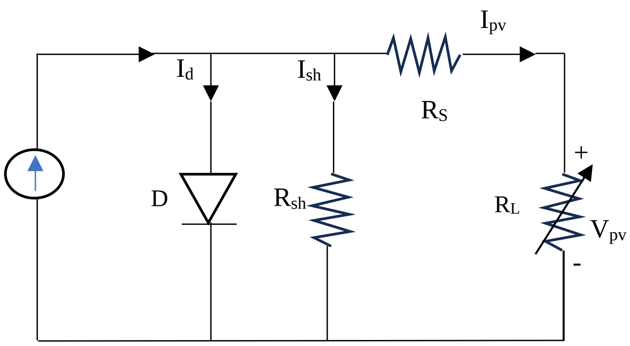

Fig. 2 Equivalent circuit of solar cell

The equivalent circuit model of a single solar cell is shown in Figure 2. In this circuit, I_d and I_{sh} diode current and shunt leakage current where I indicate the output terminal current. R_s is the series resistance of the pn junction cell, and R_{sh} is shunt resistance, which is inversely proportional to leakage current to the ground. I can be calculated by applying KCL to the equivalent circuit [3].

$$I = I_{ph} - (I_d + I_{sh}) \quad (1)$$

By taking the sum of diode current and shunt leakage current equals $I_{o,}$ the simplified equation is given as [3].

$$I = I_{ph} - I_o \quad (2)$$

The photocurrent is directly proportionate to the instantaneous magnitude of solar irradiance and temperature because photocurrent is generated on the absorption of solar radiation by a solar cell that is.

$$I_{ph} = (I_{rsc} + k_i \Delta T)\ G/G_r \quad (3)$$

Where I_{rsc} is rated solar current at nominal climatic conditions (approximately at 25°C and 1000w/m^2), k_i is short circuit temperature coefficient, G is irradiance, and G_r is nominal irradiance at normal climatic conditions (approximately at 25°C and 1000w/m^2). ΔT is the difference between operating temperature and nominal temperature. The Saturation current I_o is [3].

$$I_o = I_{rs}(T/T_{ref})^3 e[\left(\frac{qE_{go}}{AK}\right)\left(\frac{\Delta T}{T_{ref}T}\right)] \quad (4)$$

Where I_{rs} is the reverse saturation current of a cell at nominal temperature and irradiances, E_{go} is the bandgap energy of semiconductor material; A is the diode ideality factor, K is (1.38*10^{-23} w/m^{2}k) Boltzmann's constant and q is magnitude of charge on electron which is equal to 1.6*10^{-19}C. By substituting the values of I_{ph} and I_o, the PV cell current (I) will be [3] [4].

$$I = I_{pv} = I_{ph} - I_o\left[e\left(\frac{q(V_{pv}+I_{pv}R_s)}{AKT}\right) - 1\right] - \frac{(V_{pv}+I_{pv}R_s)}{R_p} \quad (5)$$

Table 1. Parameters specifications

S. No	PV system Parameters	values
1	Open circuit voltage/module	36.3V
2	Short circuit current/module	7.84A
3	Voltage at MPP/module	29V
4	Current at MPP/module	7.35A
5	Power at MPP/module	213.15W
6	Number of Parallel strings	47
7	PV array open circuit voltage (V_{oc})	363V
8	PV array Current at MPP (I_{mp})	345.45A
9	Number of series strings	10
10	PV array short circuit current (I_{sc})	368A
11	PV array Voltage at MPP (V_{mp})	290V
12	PV array Power at MPP (P_{mp})	100KW
13	Temperature coefficient of V_{oc} (%/deg.C)	-0.36099
14	Temperature coefficient of I_{sc} (%/deg.C)	0.102

This solar array is modelled by connecting 47 strings in parallel and 10 strings in series to achieve the required PV output power of 100KW. A typical PV cell produces approximately 0.605V at nominal climatic conditions (at 25°C and 1000w/m^2). 60 numbers of solar cells are assembled in one module. Open circuit voltage per module is.

$$\frac{V_{oc}}{Module} = 0.605 * 60 = 36.3V \quad (6)$$

Each module should generate 36.3V at nominal conditions. The number of modules connected in series and parallel combinations to form a solar array for pre-designed voltage and current requirements is shown in Table 1.

3.2. P-&-O MPPT Controller Model

There are some specific laws defined for the PV system to operate the system at its maximum power point characteristics. This is called "Maximum Power Point Tracking (MPPT) and these commands seek the maximum power point, thereby keeping the generating system and load at its maximum efficiency. The proposed intelligent control generates the duty cycle in an automated way to operate the generating system at its optimal region for any instabilities in climate and sudden changes in load.

The Perturb and observation algorithm is easy to implement, and it is commonly used in practice [5]. This algorithm is based on the perturbation of the system by the increase/decrease in reference PV voltage acting directly on the duty cycle of the boost converter, then observing the effect of the output power of the PV panel [5]. Then, the present value of the power P(k) panel is greater than the previous value P(k-1) is then retains the same direction of the previous disturbance, or we reverse the disruption of the previous cycle as shown in Figure 3.

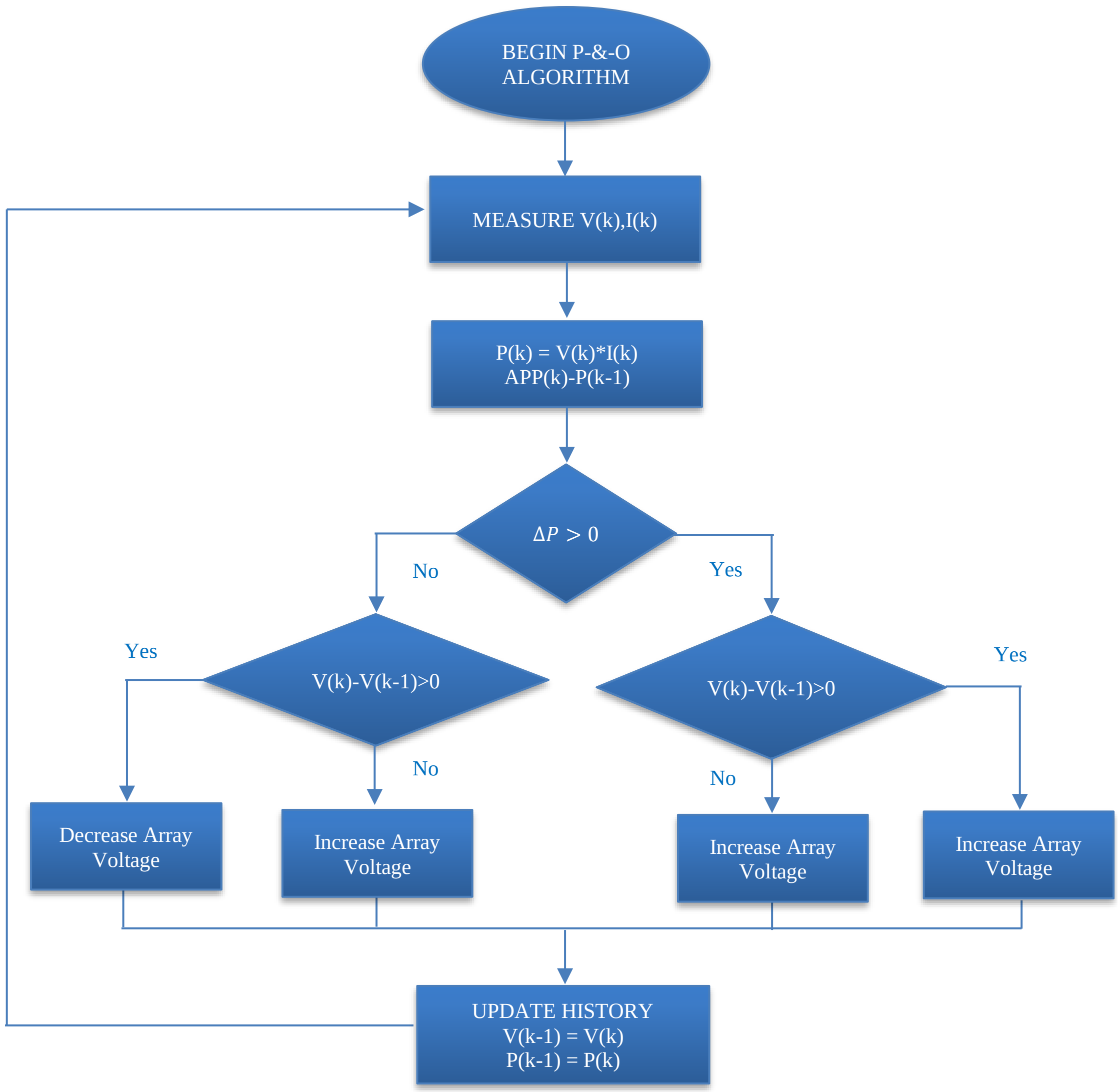

Fig. 3 Flowchart for P-&-O algorithm

3.3. DC-to-DC Boost Converter Model

The boost converter is an effective power conversion device in which the input voltage is boosted up without ant transforming device. In this process, the system power (input and output) is kept constant by adjusting the current [6].

This boost-up process is carried out by power electronic elements like an inductor, diode, power switch and filter capacitor connected in parallel with a PV array. In this paper, IGBT is utilized as a power switch, and it receives a gate pulse from the proposed intelligent controller. The Simulink model of the DC-to-DC Boost converter diagram is shown in Figure 4.

Duty Cycle (D)

$$D = 1 - \frac{V_{in}}{V_{out}} = 1 - \frac{290}{446} = 0.34$$

Ripple content (ΔI_o)

$$\Delta I_o = 20\% * I_o = 17.14A$$

Value of Inductor (L)

$$L = \frac{V_{in} * D}{\Delta I_o * f_s} = \frac{98.6}{85700} = 1.15Mh$$

Value of Capacitance (C)

$$C = \frac{D * I_o}{\Delta V_o * f_s} = \frac{75.82}{4.46 * 5000} = 3400\mu F$$

Load resistance (R_o)

$$R_o = \frac{V_o}{I_o} = \frac{446}{223} = 2\Omega$$

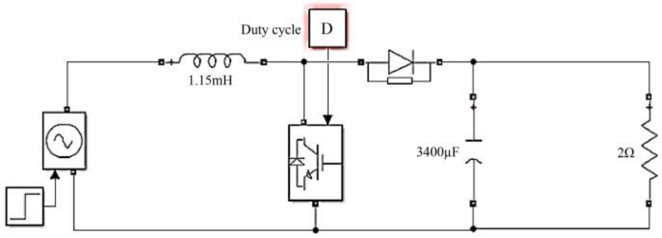

Fig. 4 Simulink model of DC-to-DC boost converter

3.4. PI Controller Model

In this paper, we developed an intelligent controller by the P and O algorithm based on the PI controller, which works well in minimizing the error between the PV voltage (V_{pv}) and the output reference voltage generated by the P and O algorithm or MPPT block (V_{ref}). An Error voltage (V_{error}) is measured by subtracting V_{ref} from V_{pv}, which is next fed to a fine-tuned PI controller. The V_{error} signal is fine-tuned in a transfer function-based auto-tuning application in Simulink, which is sent to the PWM generator to provide the duty cycle adopted next to drive the IGBT-based Boost converter. This proposed intelligent controller system forces the implemented system to operate using this value of duty cycle, ensuring that the system operates with negligible ripples and at the desired maximum power point [7]. The K_p and K_i values of auto tuned PI controller are 0.000229 and 0.0192462, respectively. The Simulink model of intelligent controller is shown in Figure 5.

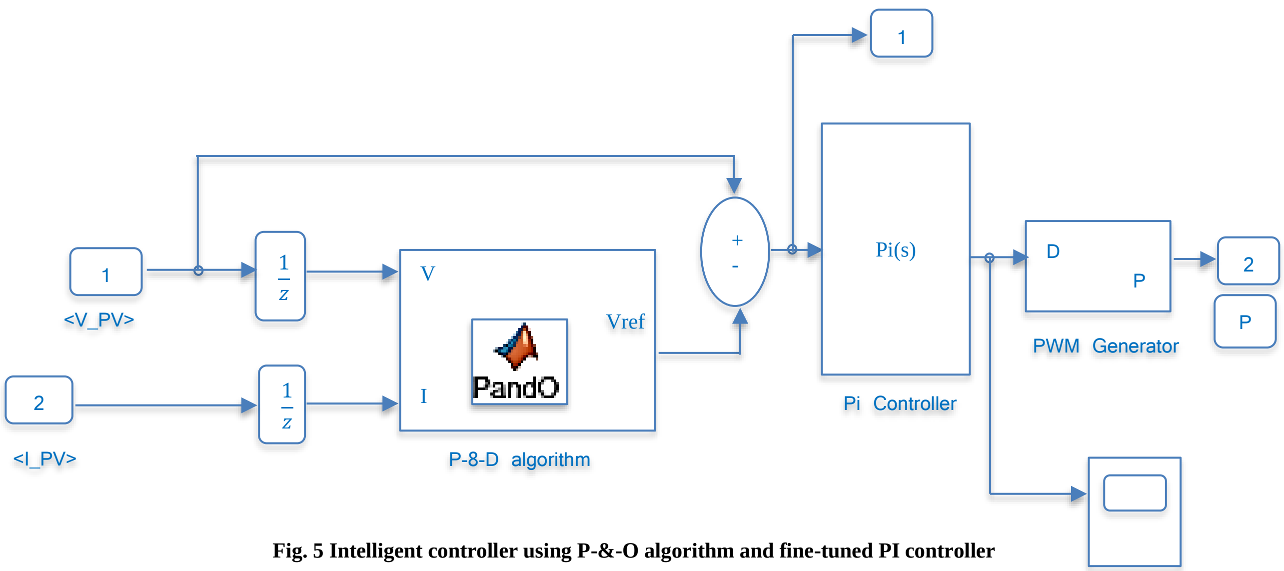

Fig. 5 Intelligent controller using P-&-O algorithm and fine-tuned PI controller

4. Simulation Results and Analysis

The Simulink model representing the proposed Photovoltaic (PV) system is comprehensively illustrated in Figure 6. This model serves as the foundation for the analysis and simulations presented in this paper, all of which have been meticulously conducted within the MATLAB/SIMULINK platform. Furthermore, the characteristics of the Voltage-Current (V-I) and Voltage-Power (V-P) curves are graphically presented in Figure 7. These curves describe the behaviour of the PV system under varying irradiance levels, specifically, at 1000W/m², 500W/m², and 100W/m²while maintaining a constant temperature of 25°C. Figure 7 provides valuable insights into how changes in irradiance affect the electrical characteristics of the PV system. Similarly, Figure 8 showcases the V-I and V-P curve characteristics under varying temperature conditions—namely, at 25°C, 15°C, and 10°C while keeping the irradiance constant at 1000W/m². This figure provides a comprehensive view of how alterations in temperature impact the electrical behaviour of the PV system. These graphical representations are instrumental in understanding the performance and responses of the proposed PV system under different environmental conditions, facilitating a more thorough analysis and optimization of its operation.

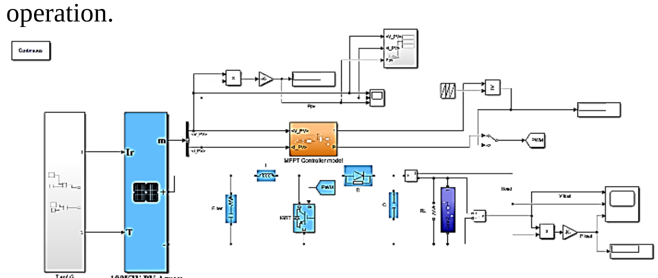

Fig. 6 SIMULINK model of the proposed system

At standard temperature and irradiance (25°C and 1000W/m^2), PV voltage at maximum power point is (V_{mp}) 290V, PV current at maximum power point is (I_{mp}) 345.45A and PV power at maximum power point is (P_{mp}) 100180W [approx. 100KW]. As the irradiation decreases to 500W/m^2 and 100W/m^2 the PV current decreases, and therefore, PV power at maximum power point also decreases, as shown in Figure 7.

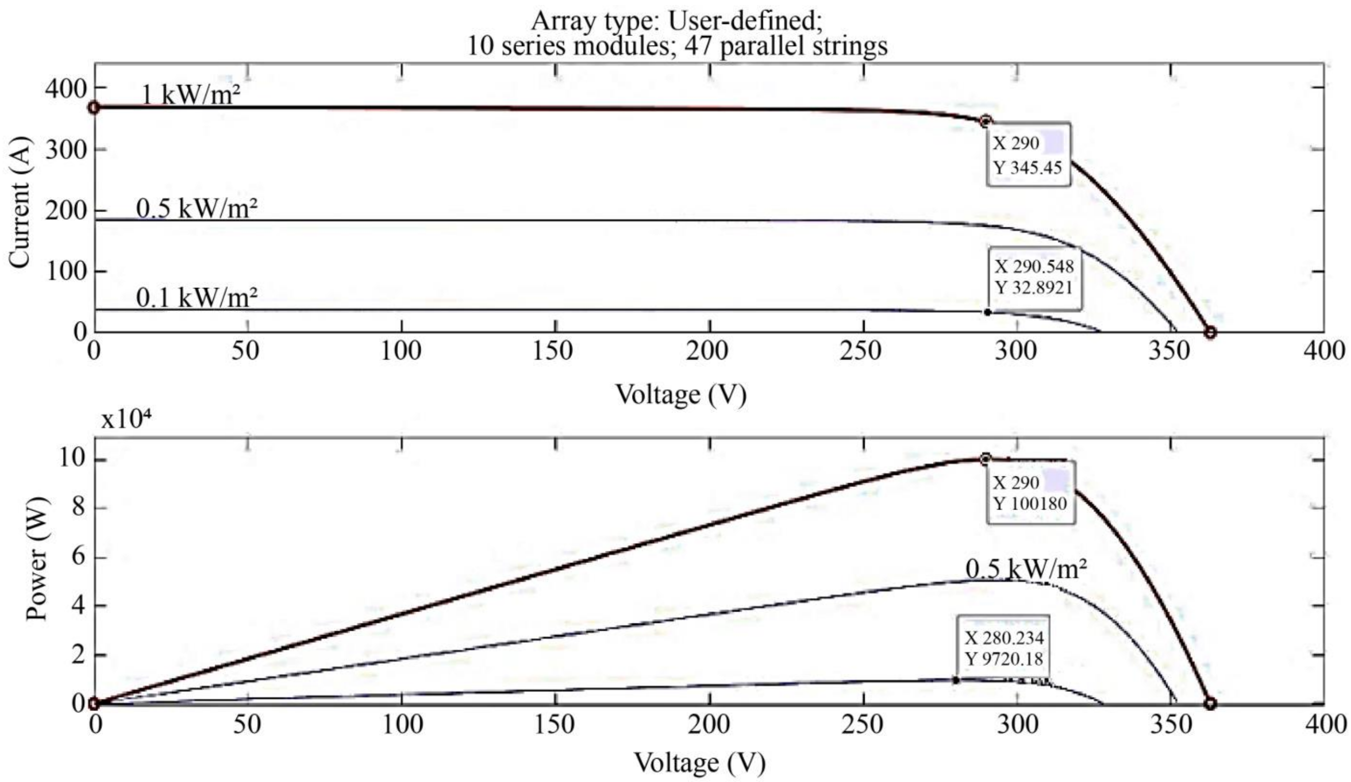

Fig. 7 V-I and V-P characteristics of 100KW solar array at constant temperature (25°C)

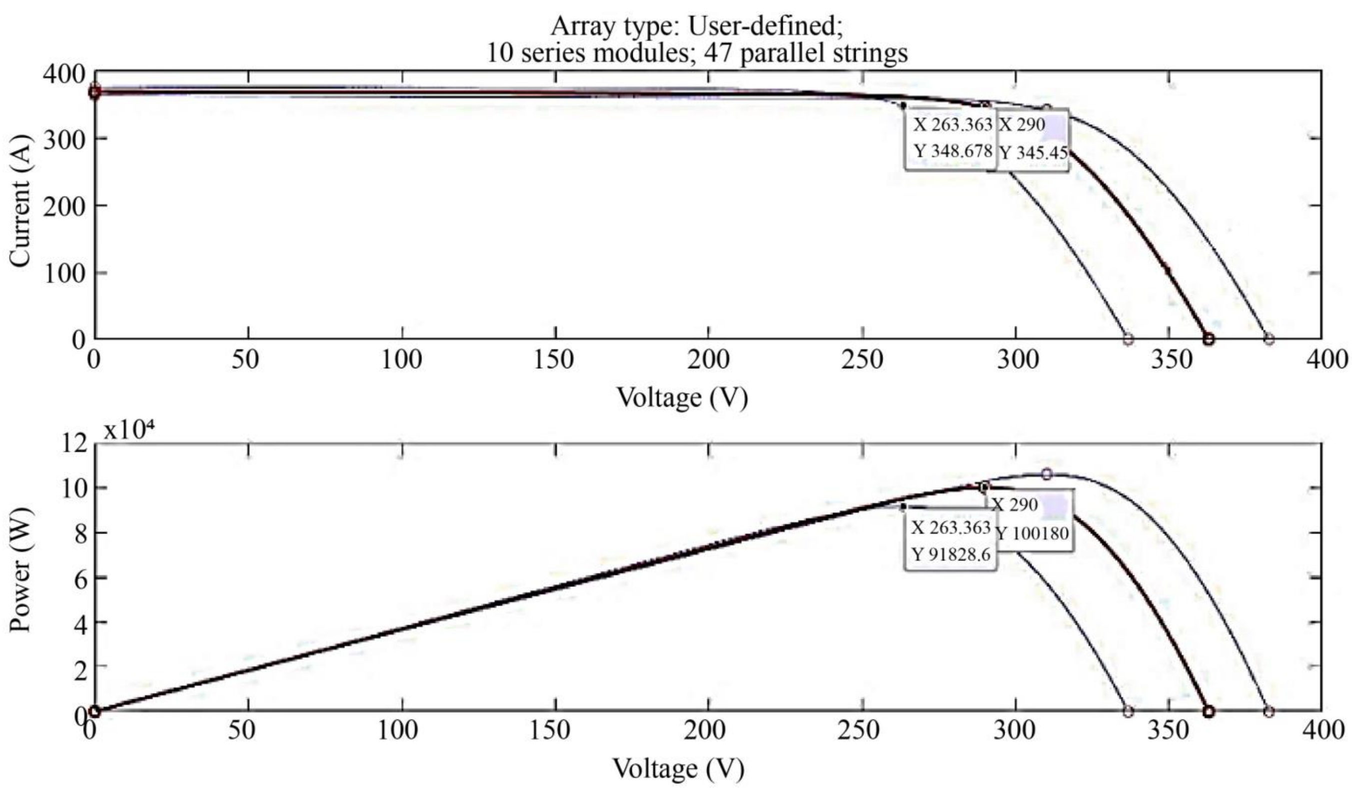

Fig. 8 V-I and V-P characteristics of 100KW solar array at constant irradiance (1000W/m^2)

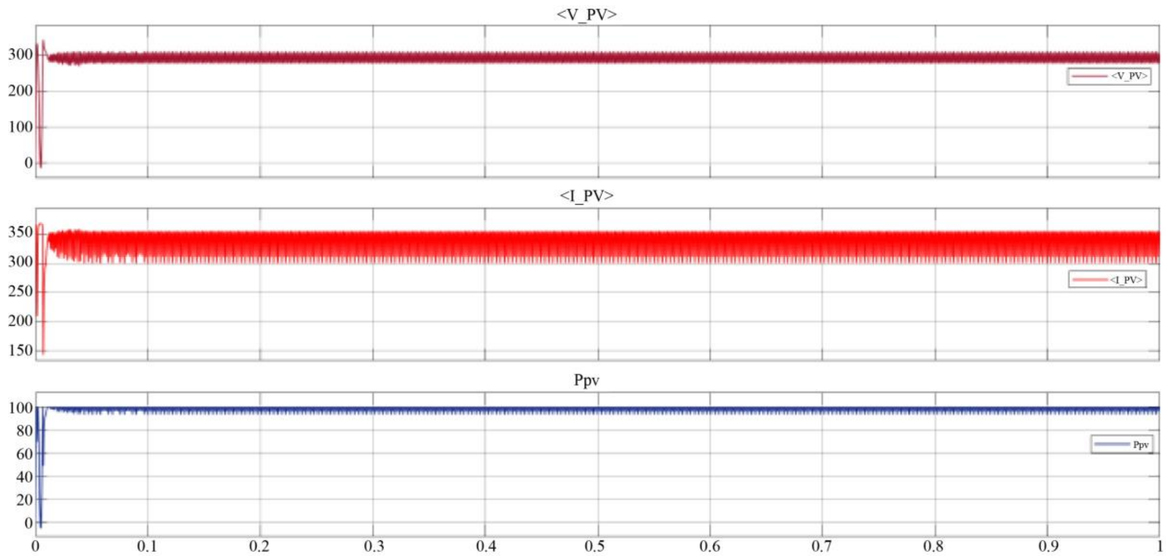

Fig. 9 PV system maximum voltage, current and power with MPPT and without PI controller

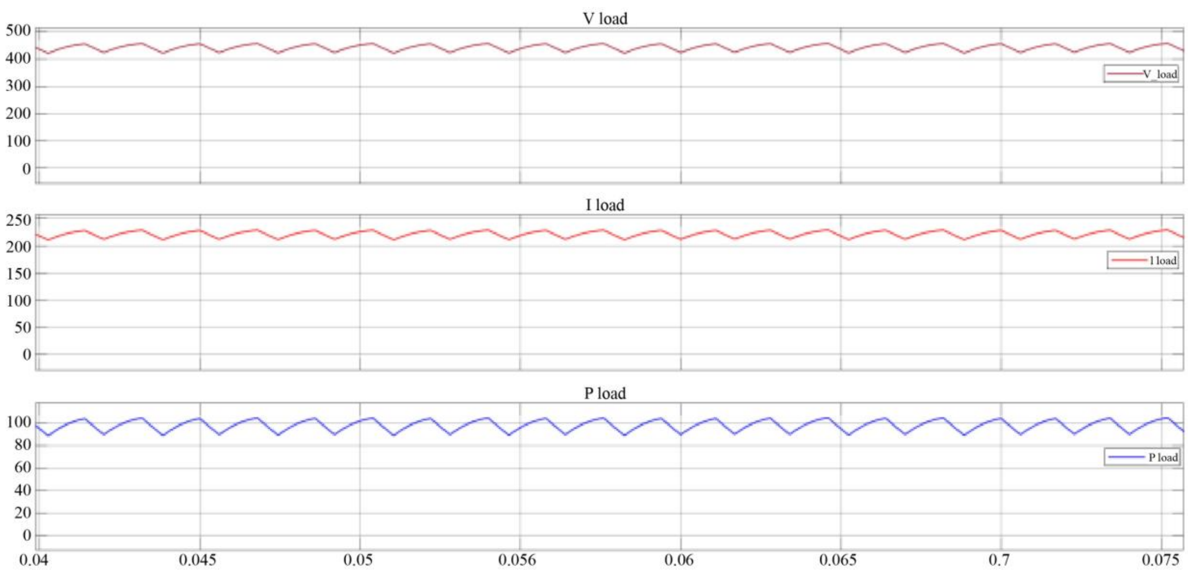

Fig. 9(a) Enhanced view of Figure 9

As shown in Figure 8, when the temperature of the Photovoltaic (PV) system remains constant at 45°C under a consistent irradiance level of 1000W/m², the PV current exhibits an upward trend. Conversely, when the temperature is reduced to 10°C while maintaining a constant irradiance of 1000W/m², the PV current experiences a noticeable decline. This phenomenon highlights a direct and significant correlation between temperature and PV current in a photovoltaic system. This relationship between temperature and PV current is a critical factor to consider when analyzing and optimizing the performance of PV systems, as it demonstrates the impact of environmental conditions on the electrical characteristics of the system.

While the conventional Perturb and Observe (P and O) Maximum Power Point Tracking (MPPT) algorithm is lauded for its simplicity and environmental friendliness, it does exhibit a notable drawback. As illustrated in Figures 9 and 9(a), the MPPT process yields a maximum power output that exhibits pronounced oscillations. These oscillations render the power output unsuitable for direct consumption by the load, as they introduce instability and inefficiency into the systems.

This oscillatory behaviour is not confined to the PV side alone; it also affects the load side of the system, as depicted in Figures 10 and 10(a). These figures demonstrate that the load experiences similar oscillations, further exacerbating the issues of system stability and power quality. Addressing this challenge is a critical objective of this research as we try to enhance the performance of the PV system and ensure that the derived power is stable and suitable for seamless utilization by the load.

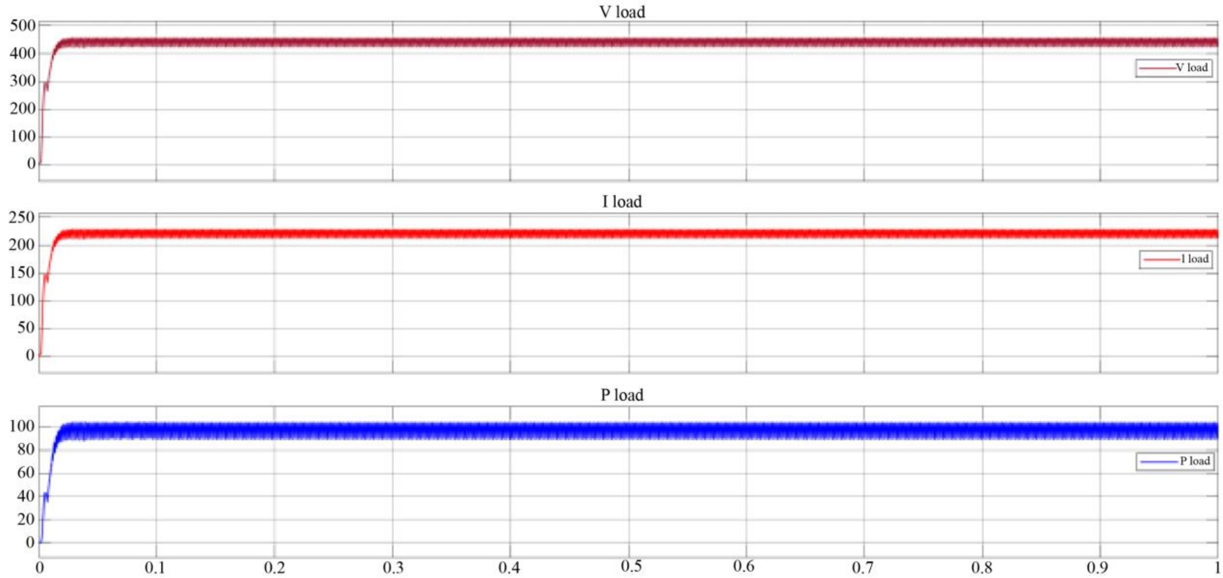

Fig. 10 Load voltage, current and power with MPPT and without PI controller

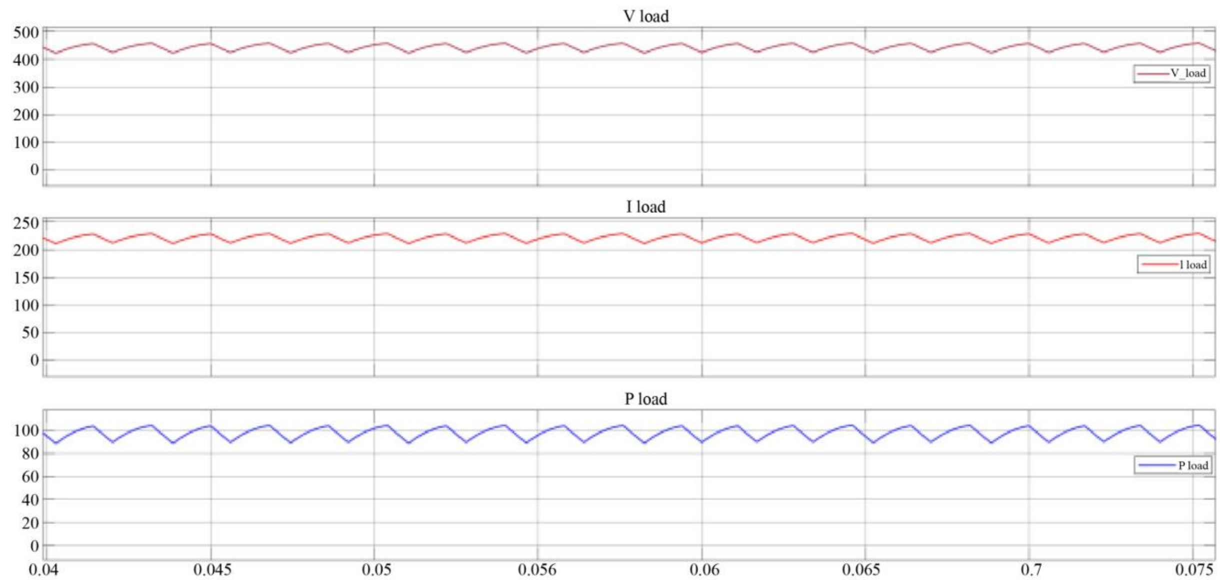

Fig. 10(a) Enhanced view of Figure 10

As previously outlined, this research paper introduces an intelligent control system comprising a P&O algorithm-based Maximum Power Point Tracking (MPPT) controller coupled with a Proportional-Integral (PI) control mechanism. This integrated controller demonstrates remarkable efficiency in mitigating oscillations and ensuring power stability on both the PV side and the Load side, as illustrated in Figures 11 and 12. In a comparison to the findings of a reference study [8], our proposed intelligent controller showcases superior performance, particularly under steady weather conditions and higher irradiance levels. These advantages are quantified and presented in Table 2, highlighting the enhanced power stability achieved by our intelligent controller when compared to the reference system. As we mentioned earlier, the proposed system behaves effectively and maintains system stability for sudden changes in load (load added at 0.4 seconds), as shown in Figure 13. The settling time is 0.04 seconds, as shown in Figure 14.

Table 2. Comparison of oscillation results with different MPPT methods

MPPT method	Load power oscillations (Peak to peak) [V]	Irradiance (W/m^2)
Reference 8 (PI method)	4	700
Reference 8 (FLC method)	0.6	700
Proposed Intelligent control	0.55	1000

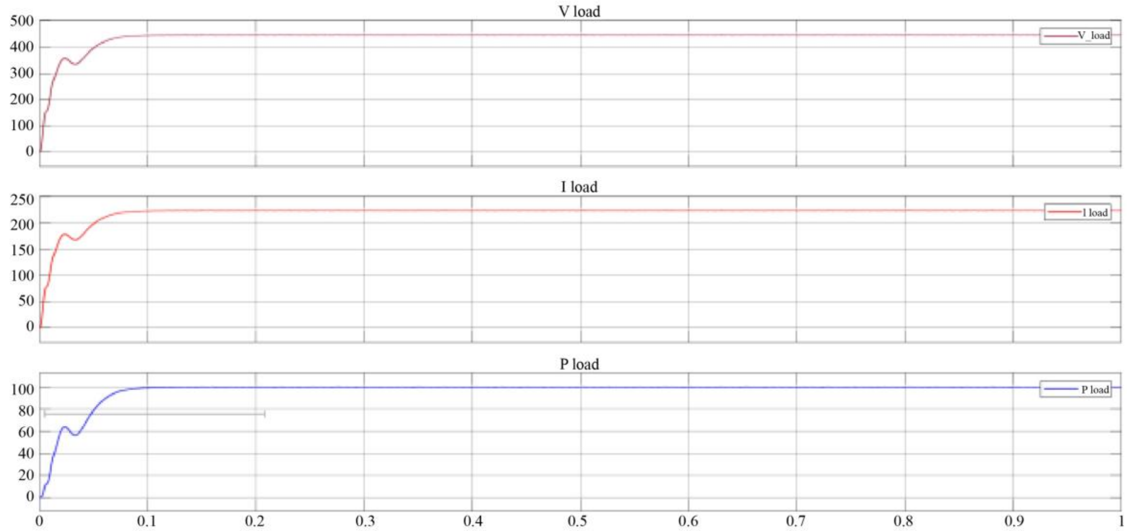

Fig. 11 Load voltages, current and power with MPPT and PI controller

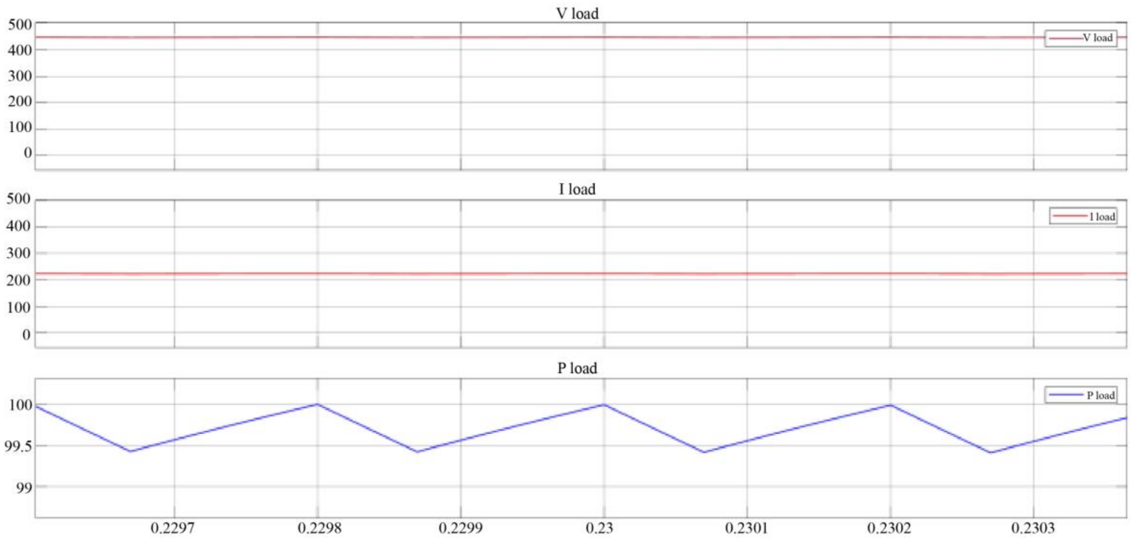

Fig. 12 Stabilized load power with 0.55 peak-to-peak oscillations

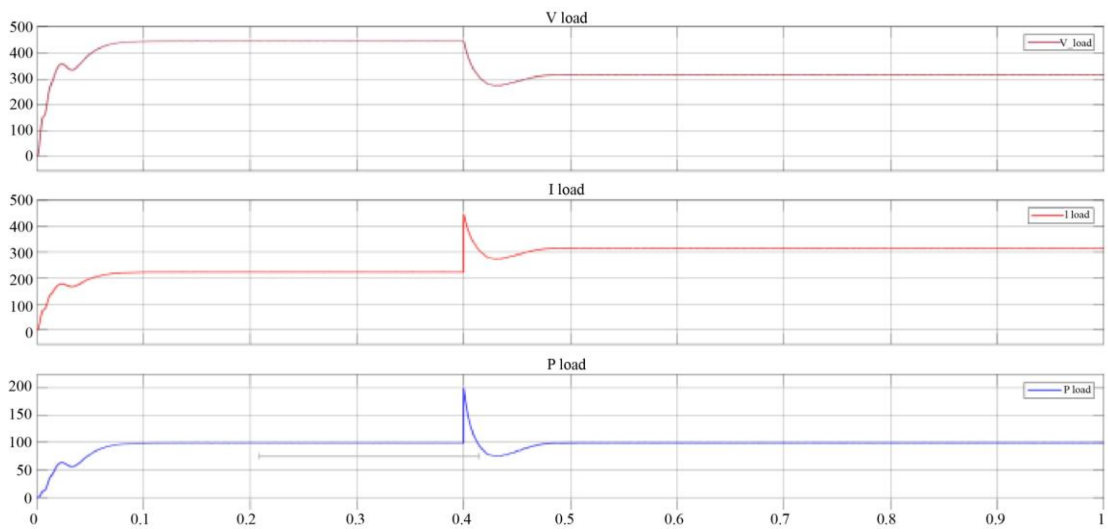

Fig. 13 Performance of the proposed system for load added in 0.4 seconds

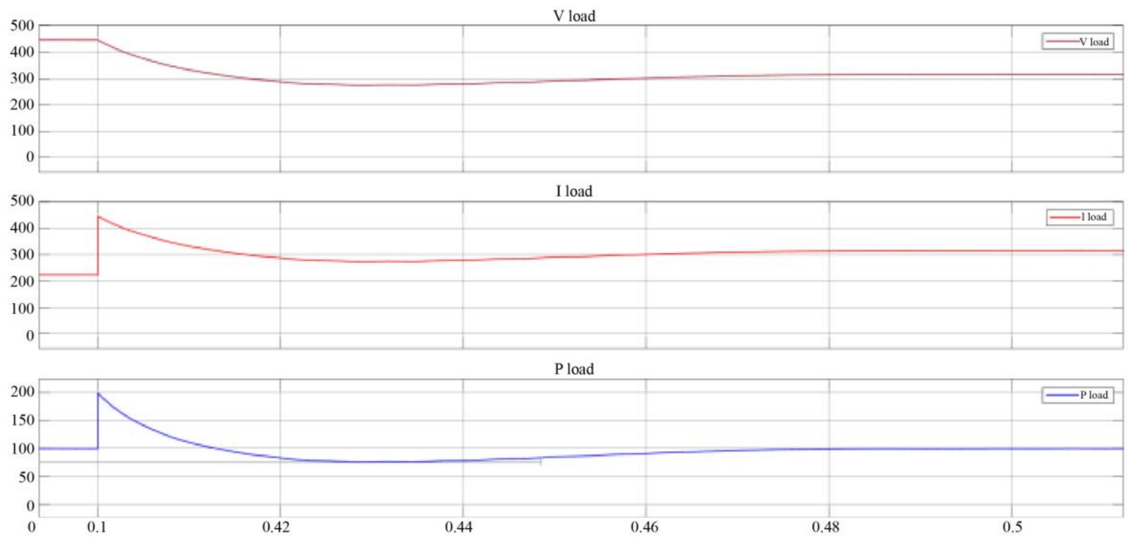

Fig. 14 Enhanced view of Figure 13

5. Conclusion

In the pursuit of optimizing Photovoltaic (PV) system performance, Maximum Power Point Tracking (MPPT) controllers serve as pivotal tools by minimizing the error between operational power and maximum achievable power. In this paper, we meticulously elucidate the comprehensive model of each constituent element within our proposed PV system, followed by rigorous simulations conducted within the Simulink platform. The empirical evidence derived from these simulations unequivocally validates the remarkable efficacy of our proposed intelligent controller. In contrast to conventional P and O controllers and Fuzzy Logic-based MPPT systems, as expounded in Table 2, our intelligent controller consistently outperforms in multiple facets.Notably, our proposed system exhibits rapid settling times (merely 0.04 seconds), minimal overshoot, heightened system stability, and an overall enhancement in efficiency. In summation, our research culminates in a resounding affirmation: the developed intelligent control system impeccably aligns with the predefined specifications, offering a substantial leap in PV system performance and reliability.

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