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A Comparative Analysis of P&O, IC and Supertwisting Sliding Mode based MPPT methods for PV and Fuel Cell sourced Hybrid System

Ruhi Zafer Caglayan[*], Korhan Kayisli[*‡], Mariacristina Roscia[**], Abdelhakim Belkaid[***], Abdelfatah Nasri[****]

[*]Electrical and Electronics Engineering, Engineering Faculty, Gazi University, Ankara, Türkiye

[**]DISA dipartimento di Ingegneria e Scienze Applicate, University of Bergamo, Bergamo, Italy

[***]Dept. of Automatic, Telecommunications and Electronics, Bejaia University, Algeria

[****]Lab. of Smart Grids & Renew. Energies (S.G.R.E), Fac of Tech., Dept of Elect Eng,, Tahri Mohamed Unv. Bechar, Algeria

(ruhizaf08@gmail.com, korhankayisli@gmail.com, cristina.roscia@unibg.it, belkaid08@yahoo.fr, :nasriab1978@yahoo.fr)

[‡] Corresponding Author; Korhan Kayisli, Gazi University, Ankara, Tel: +90 (312) 231 13 40,

Fax: +90 (312) 230 84 34, korhankayisli@gmail.com

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Abstract- The topic of renewable energy holds significant importance in the realm of energy production. Renewable energy systems embody cleanliness and sustainability. Reliability and robustness play a pivotal role in ensuring the effectiveness of these systems. This article focuses on a study involving hybrid Photovoltaic (PV) – Fuel Cell sources, which have been chosen as the energy sources. The system is subjected to testing under three distinct control methods. The primary objective is to discern the strengths and weaknesses of each control system concerning the specified hybrid setup. The control methods employed comprise the Super Twisting Sliding Mode Control, a PID-based Perturb and Observe Control (with the Integral constant set to zero), and Incremental Conductance (IC) Control. The simulation study undergoes testing across three different scenarios. The initial scenario entails ideal conditions, where both switching elements and circuit components are assumed to be ideal. The second scenario involves subjecting the system to varying load conditions. These loads encompass the required load and double the required load. The third scenario explores the impact of fluctuating solar radiation. The outcomes of the simulations are meticulously analysed, enabling the extraction of the advantages and drawbacks inherent in each control method based on the test results.

Keywords Photovoltaic Panel (PV), Fuel Cell, Renewable Energy, Super Twisting Sliding Mode Control, Conductance, Hybrid system, Maximum Power Point Tracking

1. Introduction

Energy consumption is an inherent part of daily life that cannot be avoided. Notably, energy usage, also known as energy consumption, demonstrates a consistent increase over time. To generate electrical energy, various energy sources such as fossil fuels, nuclear energy, and renewable sources are employed. Renewable sources, which encompass sustainable and clean alternatives, play a vital role in shaping the energy landscape. Ensuring system reliability and robustness emerges as a critical concern. Achieving a dependable and resilient system necessitates the implementation of effective control systems. In the context of renewable energy applications, the literature highlights the prominent use of Maximum Power Point Tracking (MPPT) methods as effective control mechanisms.

This study specifically focuses on the utilization of Photovoltaic (PV) - Fuel Cell sources as the primary energy sources. Three distinct MPPT control methods are individually integrated into the system. The resulting systems are subjected to testing across three different operational conditions. It's worth noting that all tests are conducted under the assumption of ideal components, effectively neglecting losses.

The first test is designed to observe the system's output behaviour under consistent conditions of both source parameters and load. In the second test, two distinct scenarios are explored: the connection of the required load value and twice the required load value. The subsequent outcomes provide insights into the system's performance within these load conditions. Finally, the third test maintains a constant load value while changes in solar radiation impact the source's response, leading to an investigation of the resultant output behaviour.

The Photovoltaic (PV) Panel constitutes a significant topic within the realm of renewable energy applications. Understanding the behaviour of PV panels and their equivalent circuit models is crucial during the design phase and for comprehending test results. Consequently, research and papers pertaining to modelling are extensively searched for within the literature. Sera, Teoderescu, and Rodriguez explored PV panel modelling in their paper [1]. Sahoo, Elamvazuthi, Nor, Sebastian, and Lim also investigated PV modelling using Simscape [2]. Another modelling study was conducted by Qi and Ming, focusing on standalone PV systems [3]. Rahman, Varma, and Vanderheide presented a generalized model of a PV panel in their study [4]. Hoang, Bourdin, Liu, Caruso, and Archambault modelled the PV panel by integrating optical and thermal considerations to enhance predictions of electricity production [5]. Aoun, Chenni, Nahman, and Bouchouicha evaluated the performance of the equivalent five-parameter model of PV panels, referencing a PV panel reference paper [6]. Vinod, Kumar, and Singh conducted another modelling study [7]. Belkaid *et.al* modelled a polycrystalline silicon PV panel using MATLAB-Simulink [8]. A study involving Adaptive P&O control employed the modelling of the PV panel [9]. Certain studies also delved into modelling and addressed the p-n junction characteristics of PV panels [10-11].

Another significant source is the Fuel Cell system. Fuel cells utilize renewable fuels such as hydrogen to generate electricity through chemical reactions. Modelling fuel cells presents a complex task. Bhuyan, Sao, and Mahaparta detailed a conference paper outlining the modelling of a fuel cell connected to the grid via an inverter [12]. Ural and Gencoglu examined the mathematical model of a Polymer Electrolyte Membrane (PEM) Fuel Cell [13]. Karanfil conducted research on Fuel Cells as well [14]. Other modelling articles tackled PEM fuel cell modelling [15].

Hybrid studies combining PV and Fuel Cells explored various aspects including design and simulation [16], load sharing principles [17], usage of solar and hydrogen fuel batteries, battery charger system design, and small electric car realization [18], optimization of grid-connected hybrid systems [19], hybrid systems integrating fuel cells, PV, and supercapacitors [20], and PV-Fuel Cell hybrid systems connected to the grid for University Building Power Systems [21]. Additionally, PV-Wind Turbine-Fuel Cell-Electrolyzer-Supercapacitor off-grid active and reactive power control systems were investigated [22]. There were modelling, control, and power management studies focusing on grid-integrated PV, fuel cells, and wind hybrid systems [23]. Another study employed wind, PV, and PEM fuel cells [24]. The subject of renewable energy holds paramount importance. During the MPPT and source selection phase, sources such as [25-26] are crucial for reviewing hybrid systems, sources, and MPPT techniques. Another source of significance is the Twisting Sliding Mode study conducted by Kayisli and Caglayan, which discusses PV panel modelling [27].

The objective of this article is to determine the advantages and disadvantages of the selected control techniques based on system results. To achieve this goal, three distinct tests are conducted. The conclusion section summarizes the identified advantages and disadvantages derived from the obtained results.

2. Design

The central focus of the article lies within the design phase. The intricacies of the designed system are rigorously tested across varying conditions and employing different control methods. This section comprehensively elaborates on the details of the control methods utilized and provides a thorough exposition of the system's design.

2.1. Photovoltaic Panel (PV)

A Photovoltaic Panel (PV) is a system that harnesses sunlight or sufficiently energetic light to generate electrical energy. This system operates based on p-n junction materials, which leads to characteristic equations differing from those of linear power sources. The modelled PV panel is illustrated in Fig. 1.

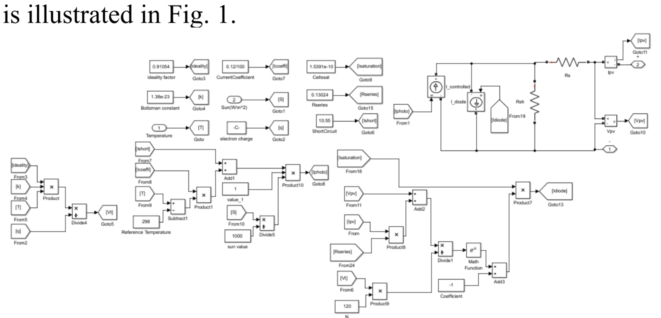


Fig. 1. Designed PV model

In Figure 1, the controlled current source $I_{\_diode}$ represents the diode equivalent system. Calculations are carried out within the mathematical blocks, and the results are subsequently fed into the current source component. The controlled current source $I_{\_controlled}$ represents the primary current of the system. An ammeter labelled I_{pv} measures the output current of the PV panel.

For the system's configuration, three PV panels are connected in series. Each panel can achieve a maximum current of around 10A and a maximum voltage of approximately 60V, summing up to a total output of 180V and 10A.

In the process of PV panel modelling, a review of literature sources [1-11] as well as examination of the datasheet of various PV panels [28] was conducted. Based on this accumulated knowledge, the specific values for the PV panel were defined. The PV panel involves crucial formulas that are utilized to create a mathematical equivalent circuit for the panel's design.

$$I_{cont}=[I_{SCref}+coeff_{Temp}(Temp-RefTemp)](Sun/RefSun) \quad (1)$$

where, I_{cont} is controlled current, I_{SCref} is short circuit current at reference temperature, $coeff_{Temp}$ is cell's short circuit current temperature coefficient. Equation 2 is mentioned different source in literature and [2-3], [7-8], [25], [27];

$$I_{diode}= I_{saturation}*(e\text{^}(V_{diode}/(num\_cell*V_{Thermal}))-1) \quad (2)$$

and the related knowledge is given [29].

$$I_{PVout}= I_{cont}-I_{diode}-(V_{PVout}+I_{PVout}*R_{series})/R_{Parallel} \quad (3)$$

2.2. .Fuel Cell

A Fuel Cell is a device that generates electrical energy through chemical reactions. The system utilizes renewable energy sources such as hydrogen as its fuel. For this specific system, hydrogen is chosen as the primary fuel. Various mathematical equivalent models exist for the fuel cell device. Within the equations, activation losses, ohmic losses, and concentration losses assume pivotal significance as they contribute to the overall losses. In terms of the design phase, references [13-14] and [25] were consulted to explore the design system as depicted in Fig. 2.

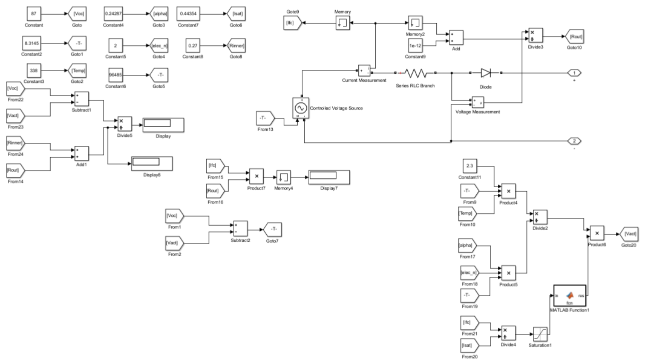


Fig. 2. Fuel Cell Model

Starting with the determination of parameters, a MATLAB Simulink Fuel Cell model is employed. However, the acquired results are subsequently applied to a simulated model of the fuel cell. Within this simulated model, activation losses are deducted from the calculated voltage, while ohmic losses and concentration losses are summed, subsequently yielding the determination of inner resistance. The design involves the serial connection of three Fuel Cell blocks, with a nominal voltage set at 59.2 V and 100A. Referring to [30], it's noted that the fuel cell's control under maximum conditions leads to efficiency reduction. Hence, an optimum point is identified and chosen for system design purposes. Within our system, the collective fuel cell blocks yield an output of 177.6 V and 100A. The important formulas are:

$$V_{act}= (2.3*gasconstant*Temp)/(alpha*elec*Faradaycons)*In(I_{Fuel}/I_{sat}) \quad (4)$$

$$V_{ohm}=I_{fuel}*R_{Fuel} \quad (5)$$

$$V_{concent}= -(gasconstant*Temp)/(elec*Faradaycons)*In(1-I_{Fuel}/I_{Limit}) \quad (6)$$

$$V_{Fuelout}=V_{Fuel}- V_{act}- V_{ohm}- V_{concent} \quad (7)$$

2.3. Boost Converter

In electrical circuits, energy holds remarkable significance, particularly when appropriate energy considerations are in play. The compatibility of source voltage or current levels and types with the demanded voltage or current levels and types is pivotal for the smooth operation of a system. However, numerous scenarios arise where achieving such compatibility isn't feasible. It is for this very reason that converter circuits come into play. These converters play the role of transforming energy into various formats, such as AC-DC or DC-AC (accommodating type changes) or DC-DC or AC-AC (addressing level changes).

Within the context of this article, the source voltage and the required voltage at the load side are both DC. However, the required voltage at the load side surpasses that of the source side. Consequently, a suitable converter needs to be selected with the purpose of increasing the average voltage value. In this particular case, the chosen converter type is a boost converter.

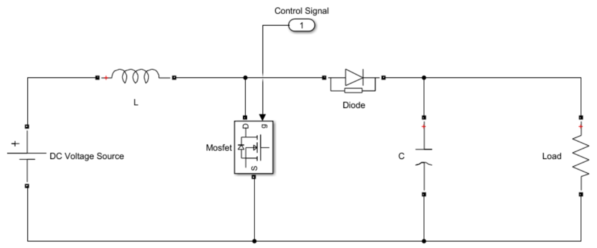


Fig. 3. Boost Converter

The parameters of boost converter can be optimized from using these formulas:

$$\Delta i_L=(V_{source}*Duty*t_{switching})/L= (V_{out}*(Duty-Duty)\text{^}2 *t_{switching})/L \quad (8)$$

$$\Delta V_{out}= I_{out}*Duty* t_{switching}/C \quad (9)$$

$$V_{out} =V_{in}/(1-Duty) \quad (10)$$

From using voltage and current relation:

$$R_{in}= R_{out}*(1-Duty)\text{^}2 \quad (11)$$

2.4. Super Twisting Sliding Mode Control (STSMC)

Sliding Mode Control stands as a prominent MPPT control technique. Its primary objective is to employ a sliding surface to detect the Maximum Power Point (MPP). Within this article, a sliding mode control-based approach is adopted, specifically involving a higher-order sliding mode control scheme. This sliding mode control approach is further augmented through its combination with the super twisting algorithm.

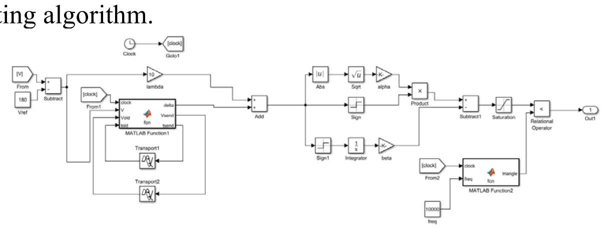


Fig. 4. Super Twisting Sliding Mode Control

Figure 4 illustrates one of the control mechanisms. The objective is to achieve a voltage of 180V, which aligns with the MPP voltage of the PV panel blocks. Notably, the fuel cell's optimum point closely approximates this voltage, being only 2.4V higher than the optimum value.

2.5. PID Combined Perturb and Observe Control (PID combined P&O)

In the testing phase, the Perturb and Observe (P&O) technique is initially assessed. However, the standalone Perturb and Observe system falls short in effectively controlling the system with a lower ripple value. Consequently, a smaller delta Duty change is chosen in comparison to the Incremental Conductance (IC) method, and the P&O control strategy is synergistically integrated with the Proportional Derivative Integral (PID) Control. In the pursuit of optimizing the system, adjustments are made to the coefficients of the PID control. Notably, during the design phase, the Integral coefficient is set to zero, rendering the PID control functionally equivalent to a Proportional-Derivative (PD) control approach. This modification serves to enhance the outcome of the controlled system.

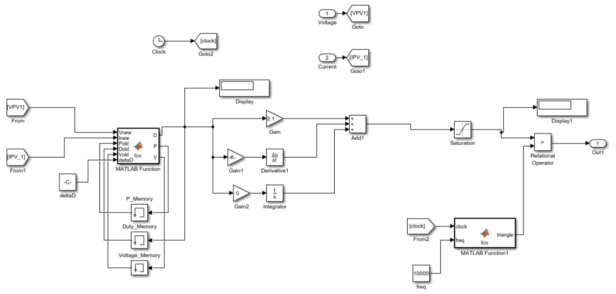


Fig. 5. Perturb and Observe Control with combined PD

Figure 5 depicts the combined system, designed with the goal of simultaneously identifying the MPP of the PV block and ascertaining the nominal point of the Fuel Cell device. The methodology hinges on variations in voltage, power, and the correlation between voltage and power. These influential factors collectively contribute to the subsequent alterations in voltage.

Table 1. Perturb and Observe Control Decision Table

Perturb and Observe Control		
ΔVoltage	ΔPower	Next ΔVoltage
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

2.6. Incremental Conductance Control (IC)

The Incremental Conductance (IC) method operates by utilizing the ratio of delta current to delta voltage, as well as the ratio of current to voltage, in order to determine the MPP. The control strategy employs a decision mechanism to identify the point's position relative to the MPP, along with subsequent step behaviour. In the testing phase, it is observed that the standalone IC control proves sufficient to initiate and sustain the desired circuit behaviour. As a result, the standalone IC control system is chosen, utilizing a greater duty changing value than the duty changing value of the Proportional-Derivative combined Perturb and Observe (PD combined P&O) control approach.

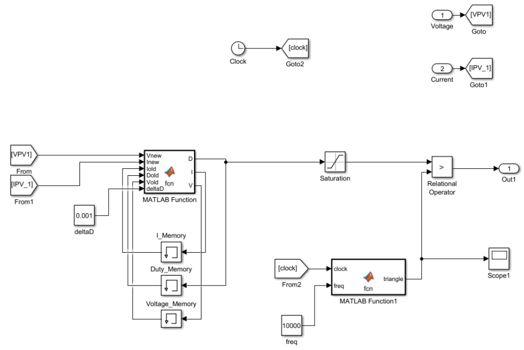


Fig. 6. Incremental Conductance Control

The MATLAB Function block calculates the required values, with the decision table being integrated into the function block. The specifics of this decision table are presented in Table 2.

Table 2. Incremental Conductance Control Decision Table

Incremental Conductance Control	
The equation	Position According to MPP
$\frac{\Delta I}{\Delta V} < -\frac{I}{V}$	MPP is on the left
$\frac{\Delta I}{\Delta V} > -\frac{I}{V}$	MPP is on the right
$\frac{\Delta I}{\Delta V} = -\frac{I}{V}$	MPP is founded

Based on the acquired results and the decision table, the duty cycle is adjusted to facilitate the search for the MPP of the PV panel and the nominal point of the Fuel Cell.

3. Simulated System and Test Results

The Designed System comprises two distinct renewable sources: PV and Fuel Cell. Each source is integrated with a boost converter, and these boost Converters are subsequently linked to a filter unit. This filter unit serves to combine the outputs of the diverse sources, sending the resulting voltage and current to the load side. The boost converters exhibit varying inductance and capacitance values, distinct from one another. However, a uniform switching frequency of 10 kHz has been designated.

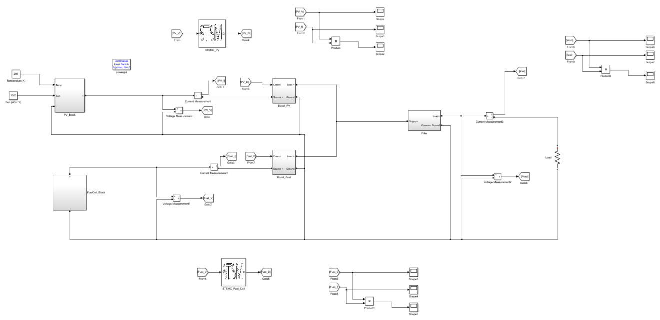
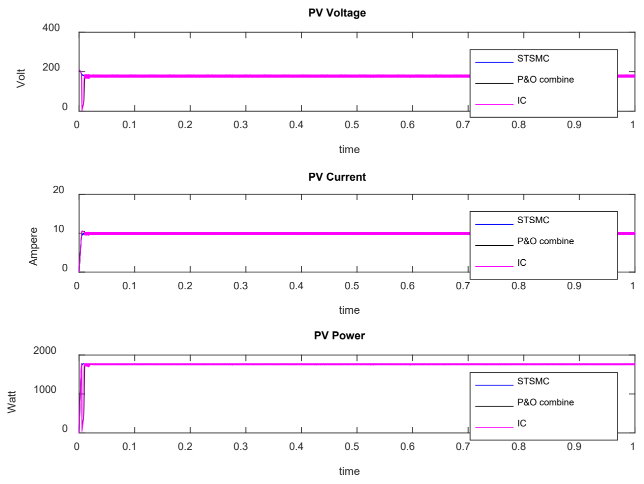


Fig. 7. The proposed system

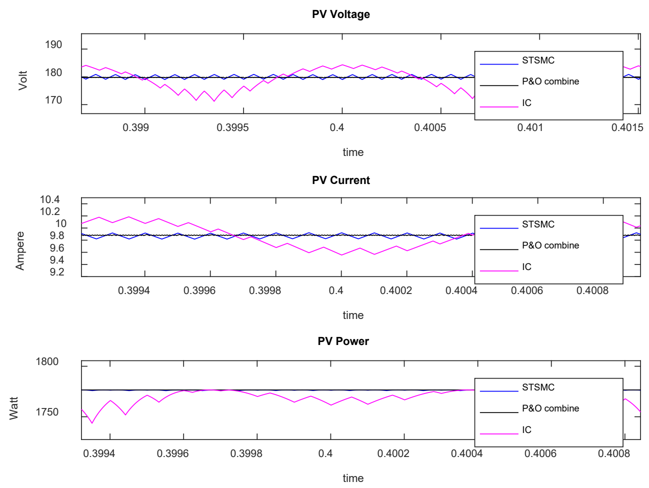
The control units undergo alterations, and these changes correspond to the varying load and solar radiation conditions during the test phase. In all test outcomes, the term "P&O combine" denotes the utilization of a control approach that combines Proportional-Derivative (PD) control with P&O control.

3.1. Ideal Operation Test

In this particular test, the solar radiation level is set at 1000 W/m², and the load's resistance is adjusted to 72/11 ohms. The primary objective of this test is to demonstrate the impact of the control mechanism on the behaviour of both sources and the resulting output behaviour.



(a)



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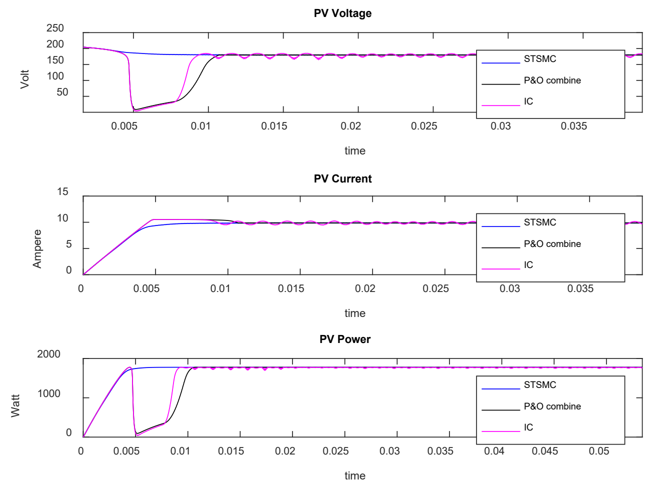
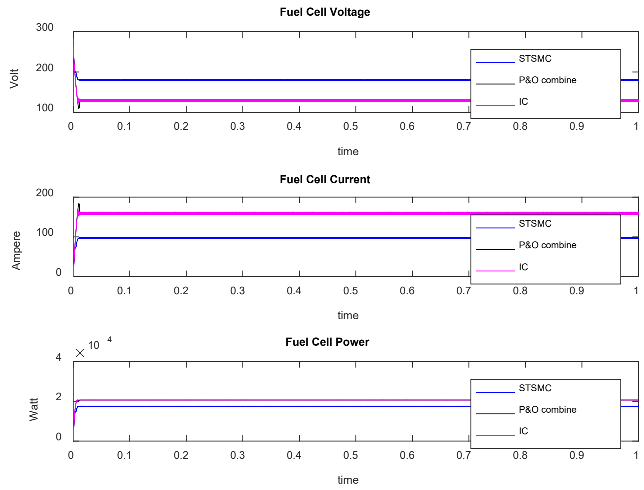


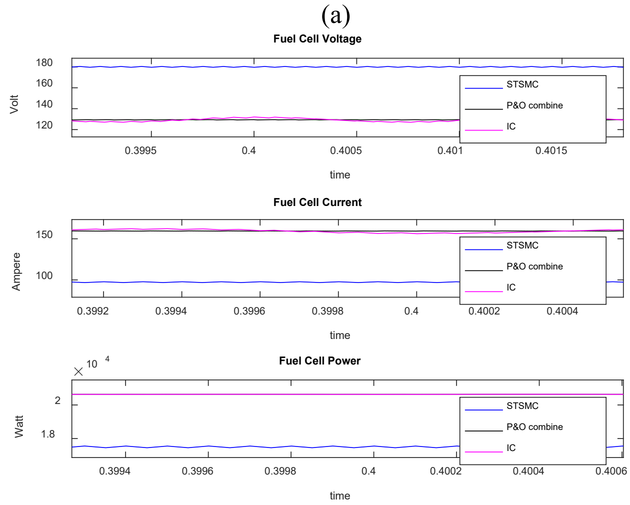
(c)

Fig. 8. (a)0-1s (b)Steady state (c)Transient PV panel Behaviour

The results indicate that IC control yields the highest ripple, followed by the STSMC with the second highest ripple. The PD combined P&O control strategy exhibits the lowest ripple. For stability, the STSMC approach reaches a stable point more rapidly, followed by the IC control which also exhibits a relatively fast stabilization. The PD combined P&O control shows the slowest stabilization process.



(a)



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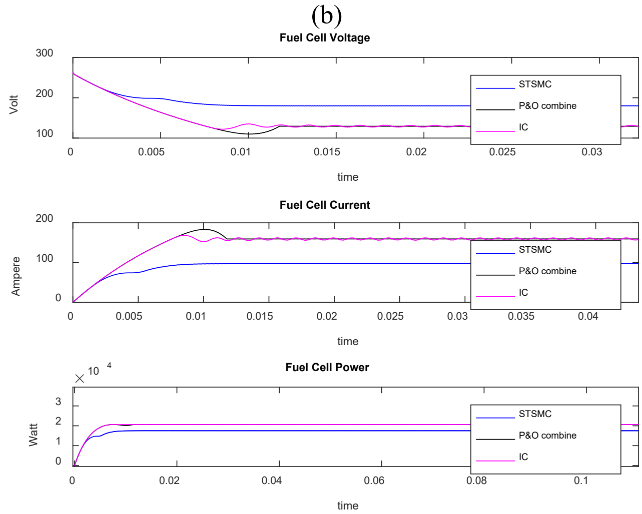
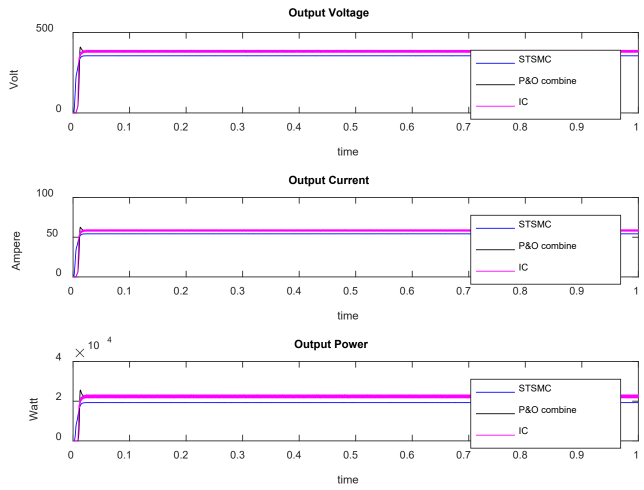


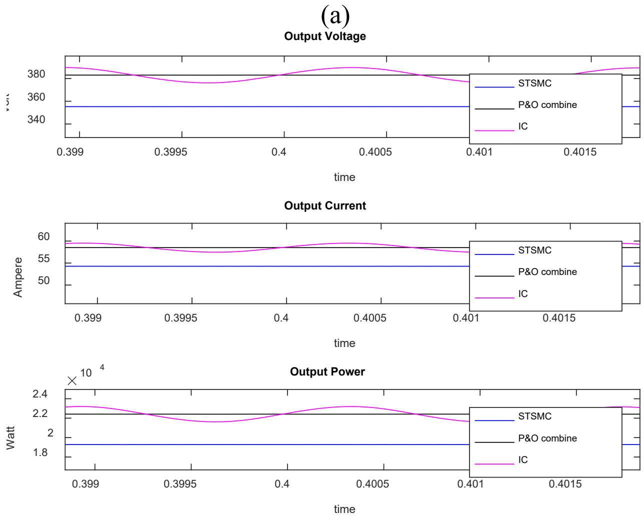
(c)

Fig. 9. (a)0-1s (b)Steady state (c)Transient Fuel Cell Behaviour

The results reveal that the STSMC successfully identifies the nominal point of the Fuel Cell. Conversely, both the PD combined P&O control and the IC control strategies identify the maximum point.



(a)



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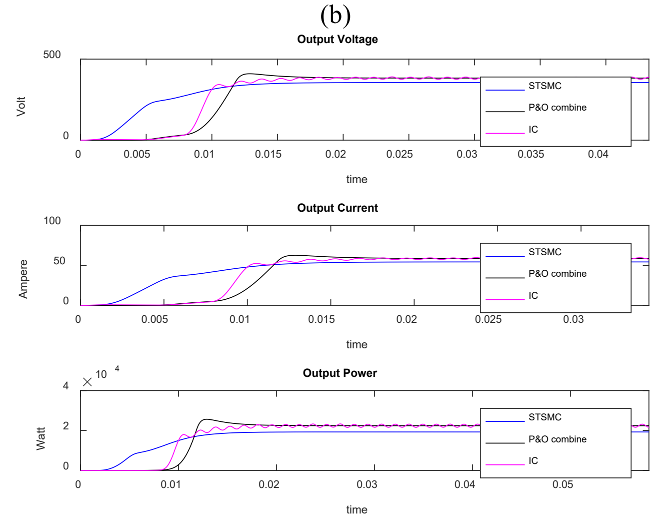


(c)

Fig. 10. (a)0-1s (b)Steady state (c)Transient System Output Behaviour

The outcomes of the study demonstrate that the STSMC accurately identifies the nominal point of the Fuel Cell. Conversely, both the PD combined P&O control and the IC control strategies pinpoint the maximum point. Notably, the output voltage, current, and power are higher in the cases of PD combined P&O and IC controls as compared to STSMC. This discrepancy in performance can be attributed to the distinct behaviour of the Fuel Cell. While STSMC seeks to identify the nominal operating condition, PD combined P&O and IC controls are aimed at maximizing performance by targeting the maximum point. This divergence in goals directly influences the duty ratio of the Fuel Cell, consequently impacting the output voltage.

3.2. Load Change Test

In this particular test configuration, the source parameters remain constant, while the load varies between 72/11 ohms and 144/11 ohms. The control signal corresponding to the 144/11 ohms load segment is depicted in Fig. 11.

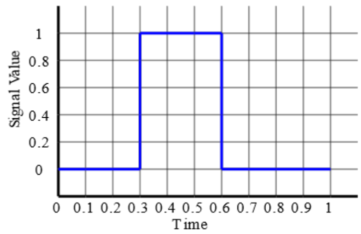
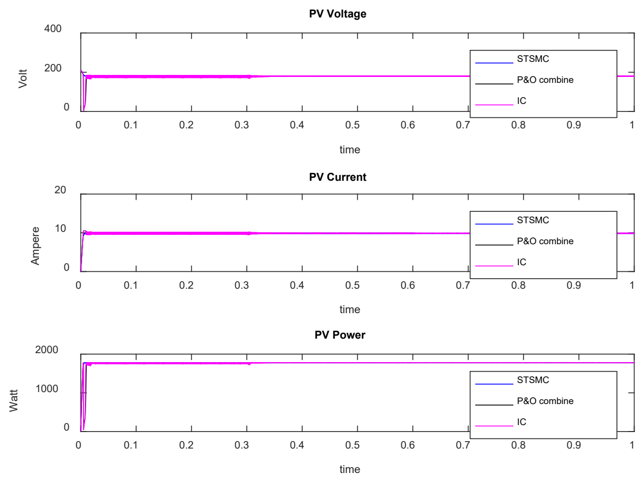
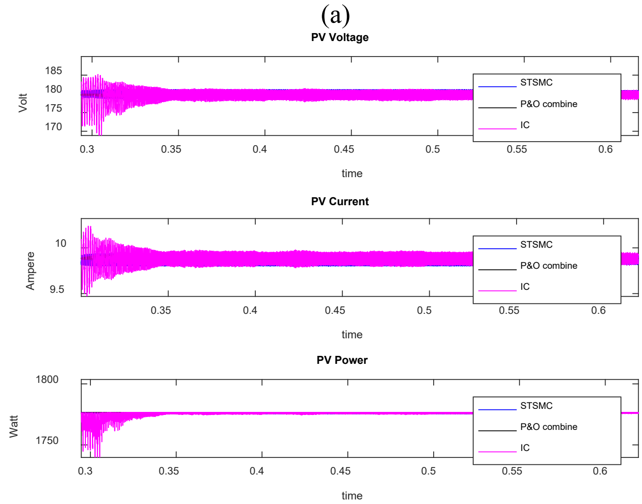


Fig. 11. 144/11 ohm control signal



(a)



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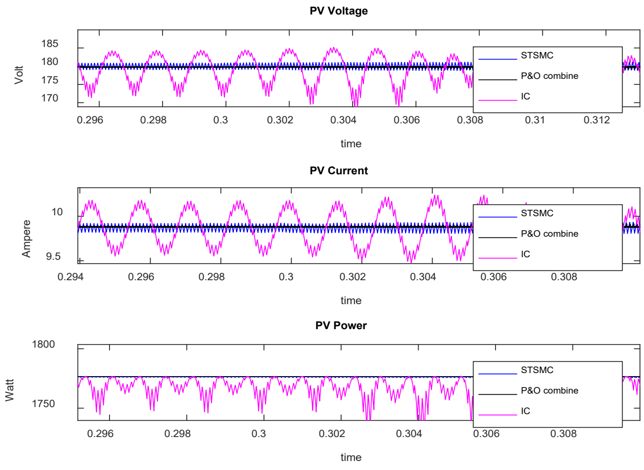

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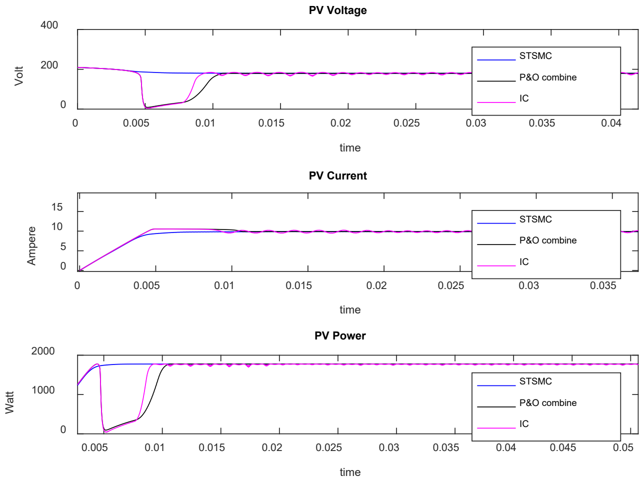
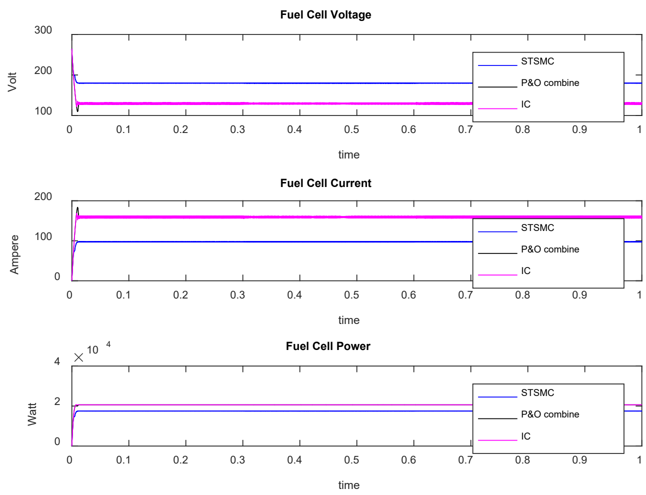


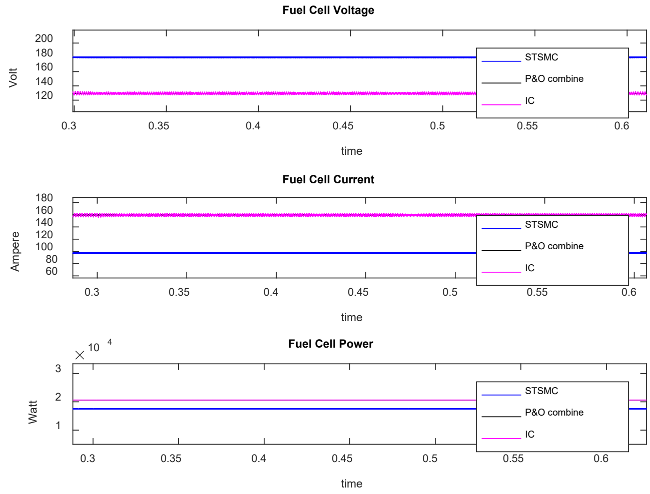
(d)

Fig. 12. (a)0-1s (b)0.3-0.6s Load Change (c)Steady state (d)Transient state of PV Behaviour

The test results demonstrate that all three control methods exhibit responsiveness to the changes. These results corroborate the findings of the initial test.



(a)



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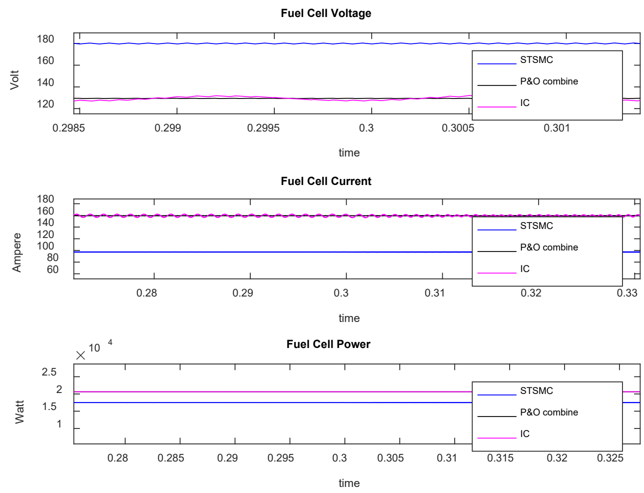

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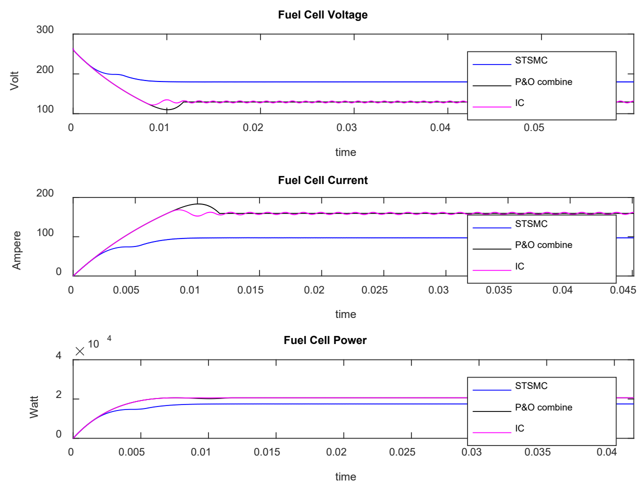
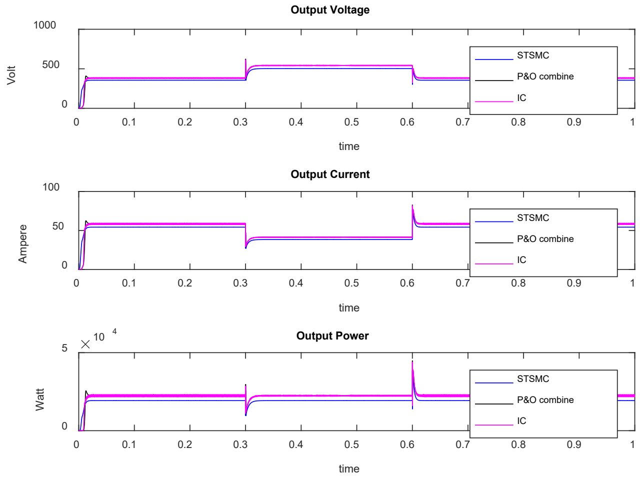
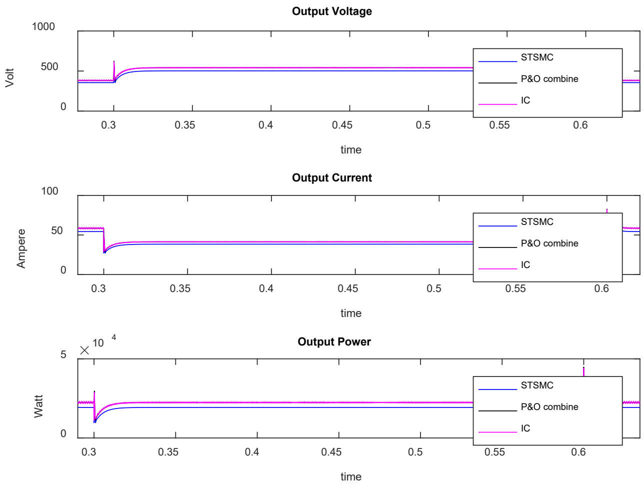


(d)

Fig. 13. (a)0-1s (b)0.3-0.6s Load Change (c)Steady state (d)Transient state of Fuel Cell Behaviour



(a)



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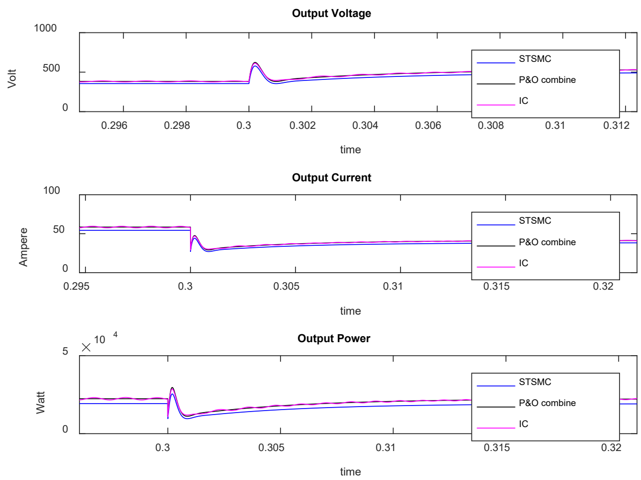

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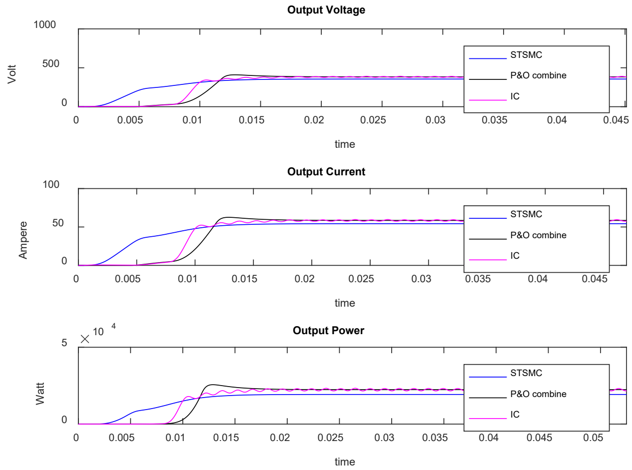


(d)

Fig. 14. (a)0-1s **(**b)0.3-0.6s Load Change (c)Steady state (0.3-0.32 interval the closer view of the changing) (d)Transient state of System output behaviour

The results illustrate that altering the resistance leads to changes in the output voltage and current values. Figure 12 and Fig.13 show that the average values of source voltage and current remain relatively constant, but the ripple is influenced by the behaviour of the PV panel. When the average value remains unaltered, yet the output values vary, it signifies that the control mechanism adapts to changes in the load and modifies the duty ratio accordingly. Consequently, the results obtained from the sources are substantiated by the observable output behaviour. Figure 14 show the load change performance of proposed system.

3.3. Irradiation Change Test

In this test the sun radiation is changing between 1000-800-600-1000 W/m^2 radiation values. The irradiation changing is shown in Fig.15

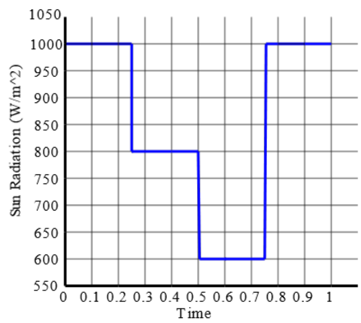
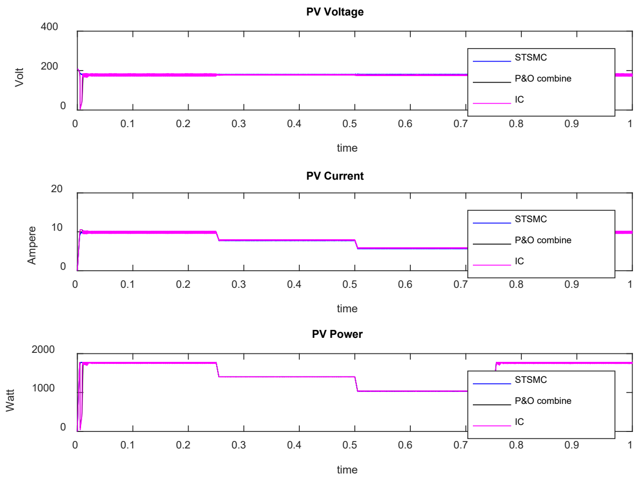
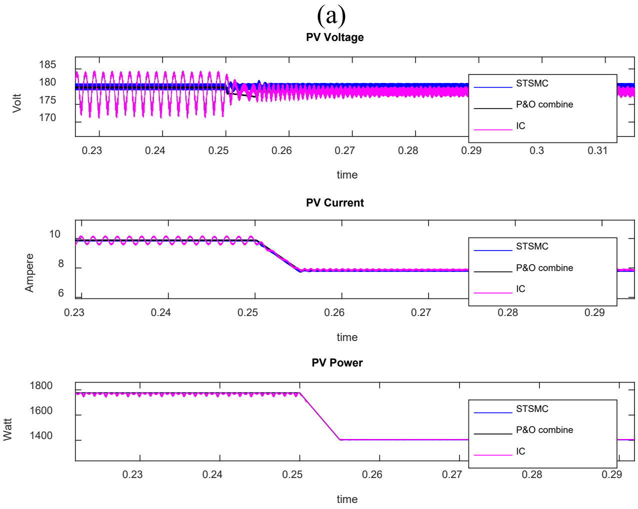


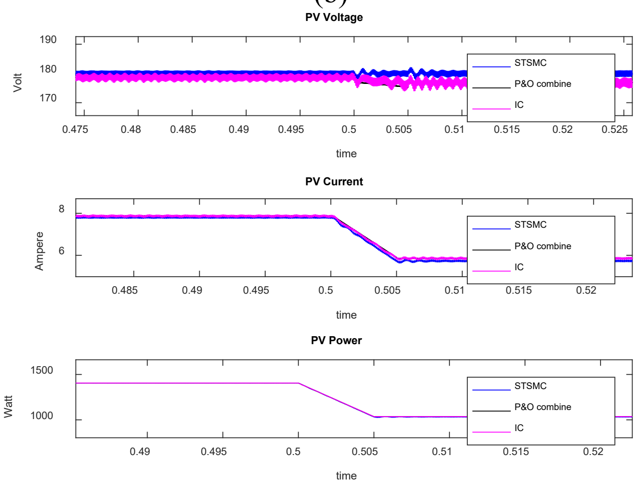
Fig. 15. Irradiation profile



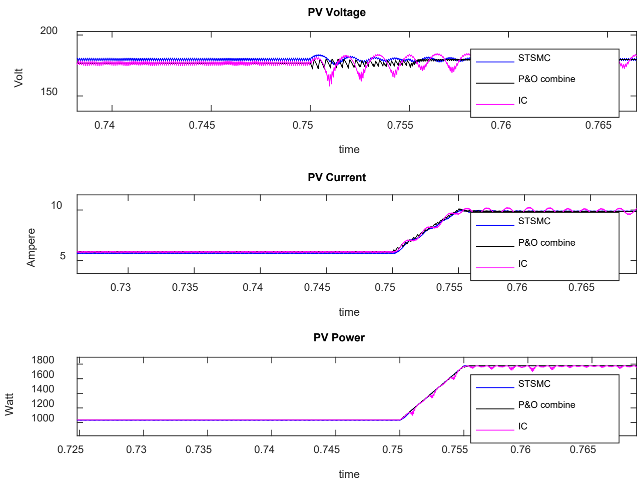
(a)



(b)



(c)



(d)

Fig. 16. (a)0-1s (b) Steady state (second changing) (c) 0.3-0.6s irradiation change (d)Transient state of PV behaviour

From the results, output voltage follows the reference voltage signal with STSMC. Current value is changing. In the PD combined P&O and IC control result, the voltage level is slightly reduced, but each time the voltage average is greater than 175V. The Current results shown that The IC and PD combined P&O controls current value is nearly higher than STSMC, but the change is nearly 0.1A. The power is slightly higher in the IC and PD combined P&O control according to the STSMC.

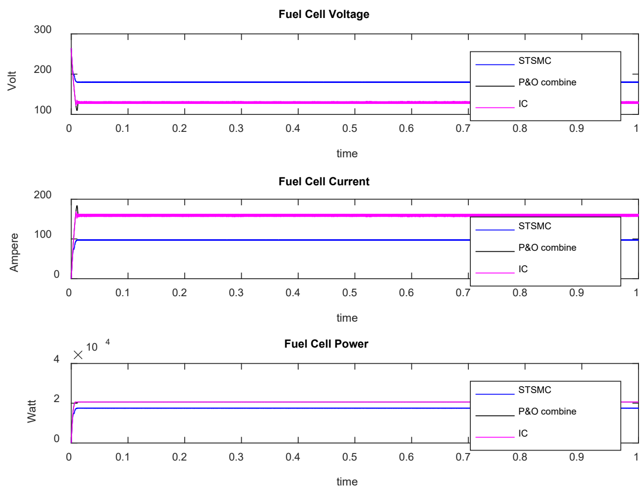
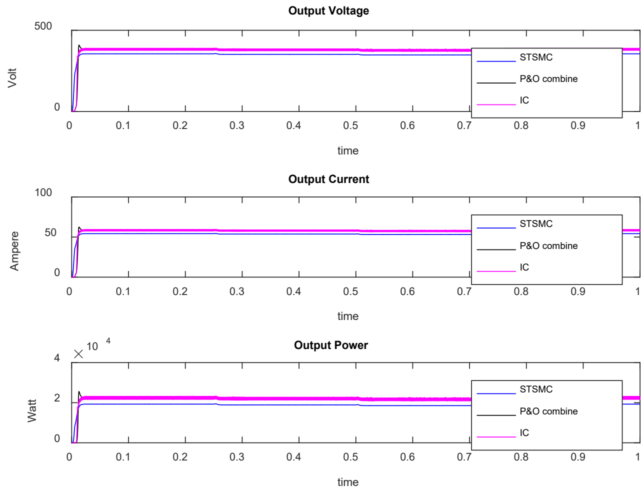
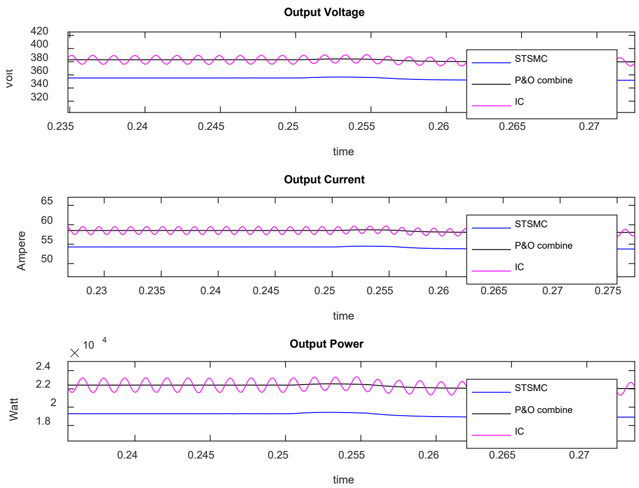


Fig. 17. Fuel Cell Behaviour

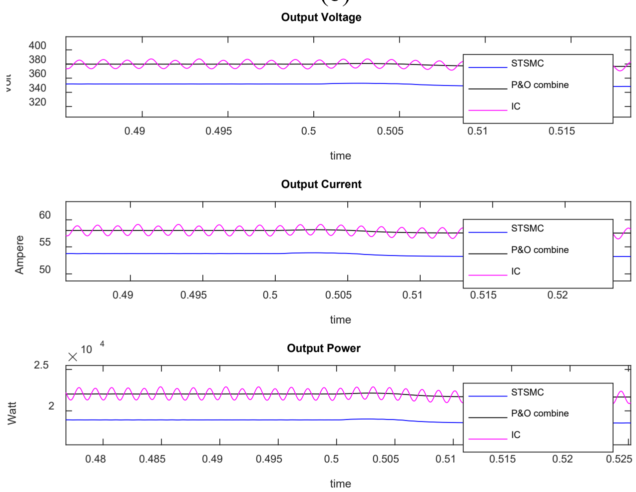
According to the results, the fuel cell is not affected under irradiation change with STSMC. Figure 16 and Fig.17 show PV and fuel cell performance under irradiation change, respectively.



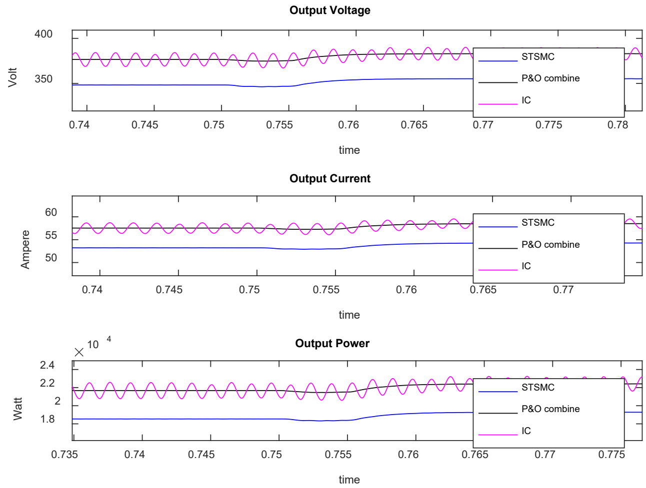
(a)



(b)



(c)



(d)

Fig. 18. (a)0-1s (b) Steady state (second changing) (c) 0.3-0.6s irradiation change (d)Transient state of system output behaviour

Figure 18 show the irradiation change performance of proposed system.

4. Conclusion

The control systems play a pivotal role in governing the behaviour of a proposed system. Their primary function is to regulate and manage system behaviour. This study delves into the investigation of control behaviours pertaining to the chosen system, which in this case, is a hybrid PV and fuel cell system. The study investigates the evaluation of three distinct control mechanisms: STSMC, PD combined with P&O control, and the IC method.

The paper's test content is structured as outlined below:

- Under ideal component and ideal source parameter behaviour of the system, the load is calculated, and the required load for the sources is determined.
- Under ideal component and ideal source parameter behaviour of the system, with the load varying over time, the chosen load values are the required load and twice the required load.
- Under ideal component behaviour and required load conditions, while Sun radiation is changing.

The obtained results indicate the following observations from the *Super Twisting Sliding Mode Control (STSMC):*

- In the first test, when considering the PV panel, the ripple in voltage and current remains moderate; however, the system rapidly attains stability. For the Fuel Cell, the nominal point is accurately determined.

- In the second test, the dynamic changes in the load are effectively tracked. The Fuel Cell continues to identify the nominal point accurately.

- In the third test, the control ensures that the PV panel's output voltage remains close to the reference value of 180V, while the current value responds to changing sun radiation. As anticipated, the Fuel Cell's results align with the expected behaviour of the load, and the system operates under nominal conditions.

Advantages:

- The Fuel Cell operates effectively under nominal conditions (its intended working state).
- The first test results of the PV panel demonstrate swift stabilization, and in subsequent tests, the system effectively tracks changing conditions (where voltage follows the reference value while the current value adjusts based on changing conditions such as load or sun radiation changes).

The only drawback is that the control requires a reference voltage value, and the voltage tracks this reference value.

PD combined P&O control:

- In the first test of the PV panel, the smallest ripple on the voltage and current values are observed.
- In the second test, changes in conditions are effectively tracked the load changing.
- In the third test, changes in conditions are effectively tracked the sun changing.

Advantages:

- In the first test, the ripple of voltage and current values within the PV panel system is at its minimum.
- The changing conditions are accurately followed [load changing and sun radiation changing is followed].

Disadvantages:

- The standalone P&O system is insufficient in reducing ripple of the voltage in PV voltage (the ripple is too large).
- For Fuel Cell behaviour, the desired condition is nominal operation; however, the control identifies the maximum working condition.
- The delta duty value is selected to be lower than IC to achieve a more precise solution.

IC control:

- In the first test, the ripple is voltage, current and power related to PV panel values. larger compared to the other controls.
- In the second test, changes in the load conditions are effectively tracked.
- In the third test, changes in sun radiation conditions are effectively tracked.

Advantages:

- The standalone system adequately controls the system. (however the P&O standalone system ripple is very big than the other according to PV Panel voltage, so the PD combined P&O is used)
- The changing conditions of load and sun radiation changes are accurately followed.

Disadvantages:

- In the first test, the PV behaviour exhibits a higher ripple in voltage, current and power values than observed with the other controls.
- Similar to the PD combined P&O control, for Fuel Cell behaviour, the desired condition is nominal operation; however, the control identifies the maximum working condition.

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