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Enhanced Maximum Power Point Tracking for Hybrid Solar and Wind Systems Using Fractional-Order Constant Voltage Topology: A Novel Approach in Power Electronics

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ABSTRACT- The growing demand for renewable energy has led to the integration of solar and wind systems as sustainable power sources. Efficient energy harvesting from these systems requires precise tracking of the maximum power point (MPP) under varying environmental conditions. The integration of solar and wind energy systems is vital for achieving sustainable power generation. The objective of this research is to develop an efficient Maximum Power Point Tracking (MPPT) technique that addresses the variability of environmental conditions in hybrid solar and wind systems. This study introduces a novel approach using Fractional-Order Constant Voltage (FO-CV) topology for MPPT. The proposed method leverages fractional-order calculus to enhance the adaptability and accuracy of traditional MPPT techniques. In this approach, the constant voltage technique is applied to maintain the system's operating point near the Maximum Power Point (MPP) under fluctuating solar irradiance and wind speeds, while the fractional-order controller ensures improved dynamic response. Simulation results demonstrate that the FO-CV topology outperforms conventional MPPT methods, achieving faster convergence to the MPP, higher energy efficiency, and greater system stability. The findings highlight that the FO-CV method not only optimizes power extraction but also reduces fluctuations in power output during sudden changes in environmental conditions. The novelty of this approach lies in the combination of fractional-order control with constant voltage tracking, which provides a more robust and adaptable solution for hybrid renewable energy systems.

Keywords: Fractional order-constant voltage, Maximum power point tracker, Power electronics, Solar, Wind.

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1. INTRODUCTION

The global shift towards renewable energy sources has necessitated the development of efficient methods for harnessing and optimizing power from solar and wind energy systems[1]-[2]. Among the key technologies enabling this transition is power electronics, which plays a crucial role in controlling and managing the energy flow between renewable energy sources and the grid or storage systems[3]-[4]. Power electronics facilitate the integration of renewable energy by enabling real-time control, voltage regulation, and the maximum power point tracking (MPPT) of variable energy sources. As such, they are essential in ensuring that energy harvested from solar panels and wind turbines can be efficiently utilized or stored[5]-[6].

Over the years, numerous topologies and MPPT techniques have been developed to address the inherent challenges of renewable energy systems, which include fluctuating energy generation due to changing environmental conditions[7]-[8]. These techniques, however, face limitations in terms of their ability to quickly and accurately track the maximum power point under rapidly changing conditions[9]. For instance, the P&O and IncCond methods suffer from oscillations around the MPP and slow response times during environmental variations, which can result in suboptimal power extraction[10].

In recent years, advancements in control theory have led to the introduction of fractional-order control techniques, which provide a more flexible and dynamic approach to system optimization[11]-[12]. Fractional-order controllers offer superior adaptability by incorporating non-integer order derivatives and integrals, allowing for better tuning of system dynamics and enhanced tracking precision[13]. This has led to the development of Fractional-Order Constant Voltage (FO-CV) topologies, which combine the robustness of fractional-order control with the simplicity of constant voltage tracking to achieve higher efficiency in MPPT[14]-[15].

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1.1 Literature Review

Several studies have explored the application of fractional-order control in renewable energy systems. A study by Rezk et al. (2020) demonstrated that fractional-order PI controllers could significantly enhance the performance of MPPT algorithms by improving the response time and reducing steady-state oscillations[16]. Similarly, Ratnakar Babu et al. (2020) compared traditional MPPT methods with fractional-order methods in hybrid energy systems and found that fractional-order control outperformed conventional techniques in terms of convergence speed and power efficiency[17].
Another study by Mohammad Faridun Naim et al. (2022) investigated the use of constant voltage (CV) techniques for MPPT in solar systems, noting that while the CV method is simple and effective for steady-state conditions, it struggles to maintain optimal performance under dynamic environmental changes[18]. Combining this with fractional-order control provides a novel solution that addresses both the simplicity and adaptability challenges of existing MPPT topologies[19].

Building upon this existing body of research, the proposed Fractional-Order Constant Voltage (FO-CV) topology aims to optimize power extraction from hybrid solar and wind systems by combining the advantages of fractional-order control with the well-established CV method[20]-[21]. This paper focuses on the development and simulation of an FO-CV-based MPPT for hybrid systems.

1.2 Block Diagram

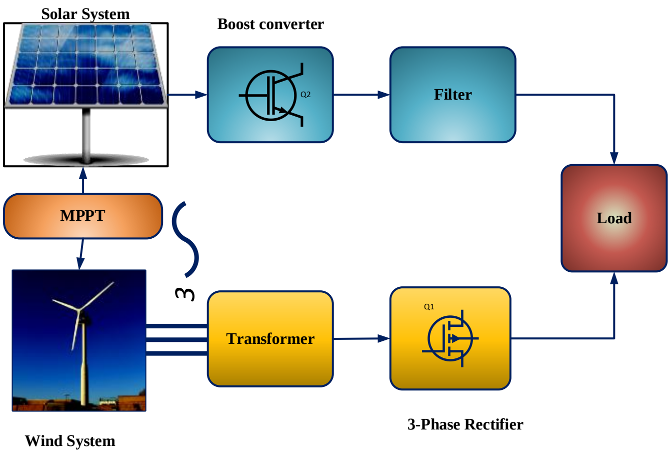

Figure 1. Block diagram representation of hybrid energy system

Figure 1 block diagram represents a hybrid solar and wind energy system that combines both renewable sources to supply power to a load[22]. The two energy sources (solar and wind) are integrated in such a way that both contribute to supplying power to the load. The solar energy is processed through a boost converter, while the wind energy is converted to DC through a rectifier[23]-[24]. This hybrid system ensures continuous power generation by utilizing both solar and wind energy, improving the reliability and efficiency of the system, especially in conditions where one source (*e.g.*, solar or wind) is unavailable or less efficient[25].

2. PROPOSED METHOD

The Fractional-Order Constant Voltage (FO-CV) topology holds significant importance in the field of renewable energy systems, particularly in optimizing Maximum Power Point Tracking (MPPT) for hybrid solar and wind systems.

The FO-CV topology combines fractional-order control and constant voltage tracking to maximize the power extraction from solar and wind energy systems. It adapts more dynamically to varying environmental conditions, such as fluctuations in solar irradiance and wind speed, ensuring that the energy harvested is consistently close to the maximum power point (MPP). This results in higher overall energy efficiency compared to traditional MPPT methods. Traditional MPPT methods often exhibit power oscillations around the MPP, especially in conditions of rapidly changing wind speeds or solar irradiance. The FO-CV topology, with its fractional-order control, reduces these oscillations, allowing for smoother and more stable power output. This is particularly beneficial in grid-connected systems where consistent power supply is critical[26].

2.1 Mathematical representation for maximum power

The total power generated from hybrid system is

$$\mathrm{Ptotal} = \mathrm{Psolar} + \mathrm{Pwind} \tag{1}$$

Where P_{solar}, P_{wind} are power outputs from solar panels and wind turbine.

The power output from solar panels is given by

$$P_{solar} = V_{solar} \times I_{solar} \tag{2}$$

Where V_{solar} is voltage across the solar panels & Isolar is current generated by solar panels.

Power output from the wind turbine is

$$\mathrm{Pwind} = 0.5 * \rho * A * \vartheta^3 * \mathrm{Cp}(\alpha, \beta) \tag{3}$$

Where
ρ = air density
A = swept area of the turbine blades
ϑ = wind speed
$\mathrm{Cp}(\alpha, \beta)$ = power coefficient

2.1.1 constant voltage MPPT equation

The constant voltage MPPT method aims to maintain the panel voltage near the maximum power point. The control law for the CV method can be expressed as

$$\mathrm{Vref} = \mathrm{Vmpp} \tag{4}$$

Where Vref is reference voltage typically set to predefined value close to the maximum power point voltage Vmpp.

2.1.2 Fractional Order Controller

The fractional order controller in the system modifies the behaviour of traditional PID controller by including fractional derivatives and integrals.

$$U(t) = Kp * e(t) + Ki * D_{\tau}^{-\sigma} * e(t) + \frac{1}{gf(n-a)} \int_0^t \left[\frac{f(\tau)}{(t-\tau)^{\alpha+1-n}}\right] dt \quad (5)$$

Where

$U(t) =$ control output

Kp, Ki, Kd are gain values

$D_{\tau}^{-\sigma} =$ fractional orderof inteegral controller

$gf(n - a)$ is gamma function

α is fractional order of the derivative

2.1.3 Overall system Dynamics

The dynamics of the hybrid system combining solar and wind MPPT with FO-CV topology can be described by a set of differential equations, that consider the interaction between the two energy sources, the control algorithm and environmental variables.

$$\frac{dPtotal}{dt} = Kmppt(Vref - Vactual) - \alpha\, Ptotal + \beta * \vartheta^3 \quad (6)$$

Where,

Kmppt is mppt gain factor

Vactual = actual voltage of th system

α, β are constants that account for system losses and wind energy contribution.

2.2 Boost converter for PV system in proposed Topology

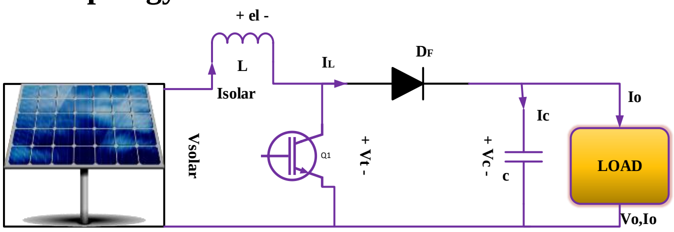

Figure 2. Solar energy system

Figure 2 illustrates the circuit schematic of a boost converter fitted with an IGBT switch. In accordance with its name, the output voltage is consistently higher than the input voltage. Upon activation of the power device, the solar panel links the inductor L, which stores energy for the duration of the first period. As a result, diode D_f is reverse biased, effectively separating the output voltage. Upon turning off the power device, both the inductor and the input power semiconductor device supply energy to the output stage. The electric current that was previously passing through the power device will now pass through the resistors L, D_f, C, and the load[27].

Given the assumption that the inductor current increases linearly from I1 to I2 during the Ton,

$$Vsolar = L * \frac{dIL}{dt} \quad (7)$$

$$Vsolar = L * \frac{(I1-I2)}{dt} \quad (8)$$

$$Vsolar = L * \frac{d(I1-I2)}{Ton} \quad (9)$$

$$Ton = \frac{L*(I1-I2)}{Vsolar} \quad (10)$$

$$Ton = \frac{L*\Delta I}{Vsolar} \quad (11)$$

During the Toff, by assuming that the inductor current falls linearly from I_2 to I_1, therefore

$$Vsolar - Vo = -L * \frac{dIL}{dt} \quad (12)$$

$$Vsolar - Vo = -L * \frac{(I2-I1)}{dt} \quad (13)$$

$$Vsolar - Vo = -L * \frac{(I2-I1)}{Toff} \quad (14)$$

$$Toff = \frac{-L*\Delta I}{Vsolar-Vo} \quad (15)$$

$$Toff = \frac{L*\Delta I}{Vo-Vsolar} \quad (16)$$

Where $\Delta I = I1 - I2$ or $I2 - I1$ is called peak to peak ripple current of Inductor L.

From the equations

$$\Delta I = \frac{Vsolar*Ton}{L} = \frac{(Vo-Vsolar)*Toff}{L} \quad (17)$$

Let $Ton = \alpha T$ and $Toff = (1 - \alpha)T$, therefore average output voltage is

$$Vo = Vsolar * \frac{T}{Toff} = \frac{Vsolar}{1-\alpha} \quad (18)$$

Assuming lossless circuit $Pinput = Poutput$

$$Vsolar * Isolar = Vo * Io = \frac{Vsolar*Io}{1-\alpha} \quad (19)$$

Therefore, average input current is

$$Isolar = \frac{Io}{1-\alpha} \quad (20)$$

2.3 Three phase Rectifier for wind system in proposed Topology

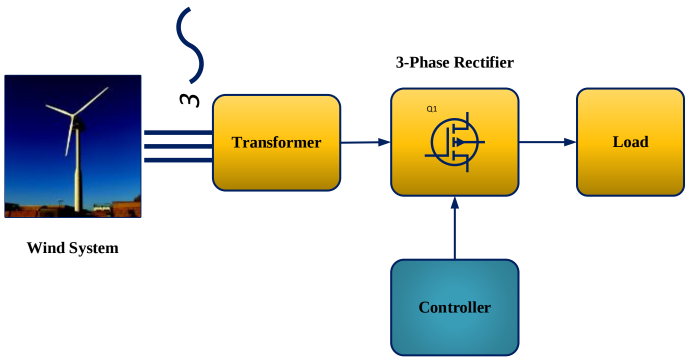

Figure 3. Block diagram of wind energy system

Figure 3 depicts block diagram of electricity generation from wind energy. In which load is fed *via* three-phase rectifiers, Transformer with wind system. If transformer is used, third hormonic current does not appear in the line which is an advantage. When rectifier connected to Transformer ,firing gate pulses will be delivered to the power switches in the correct sequence[28].

Consider rectifier operation is continues conduction ($\alpha < 60°$)
Let general equation for the average load voltage Vow is

$$\mathrm{Vow} = \frac{1}{2\pi}\int_0^{2\pi} \mathrm{Vac.dwt} \tag{21}$$

For ($\alpha < 60°$)

$$\mathrm{Vow} = 6 * \frac{1}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \mathrm{Vac.dwt} \tag{22}$$

$$\mathrm{Vow} = 6 * \frac{1}{2\pi}\left(\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{3} * \mathrm{Vm} * \sin\left(\mathrm{wt} + \frac{\pi}{6}\right).\right)\mathrm{dwt} \tag{23}$$

$$\mathrm{Vow} = \frac{3\sqrt{3}\mathrm{Vm}}{\pi}\left(2.\cos\frac{\pi}{3} * \cos\alpha\right) \tag{24}$$

$$\mathrm{Vow} = \frac{3\sqrt{3}\mathrm{Vm}}{\pi}(\cos\alpha) \tag{25}$$

2.4. Working of FO-CV in Wind and Solar Systems

The Fractional-Order Constant Voltage (FO-CV) topology is a type of Maximum Power Point Tracking (MPPT) method that can be applied in hybrid systems combining both wind and solar energy[29]. This method focuses on optimizing the power extraction from these renewable energy sources under varying environmental conditions. Fractional-order control refers to using a control system that operates with non-integer order differentiation or integration. This approach offers more flexibility and control accuracy than traditional integer-order systems, which can be especially beneficial for managing nonlinear and dynamic systems like wind and solar energy. In a hybrid system, fractional-order control can help fine-tune the response of MPPT algorithms to changes in environmental conditions, such as wind speed or sunlight intensity[30].

Constant voltage control maintains the voltage at the input to the load or storage system at a constant level, ensuring the system operates at optimal efficiency[31]. In solar energy systems, the voltage is kept close to the Maximum Power Point (MPP) voltage, which allows the system to extract the maximum power from the photovoltaic (PV) panels. In wind energy systems, constant voltage control ensures that the rectified output from the wind turbine maintains an appropriate level to supply the load[32].

The FO-CV topology in a solar energy system helps maintain the operating voltage at or near the Maximum Power Point Voltage (Vmpp). This ensures that the photovoltaic cells are generating maximum power under different light conditions, particularly during variations in solar irradiance. Fractional-order control further fine-tunes the response time and stability of the voltage regulation, allowing quicker adaptation to changing sunlight conditions[33].

In wind systems, the FO-CV topology is used to maintain a steady output voltage after the alternating current (AC) generated by the wind turbine is rectified to direct current (DC). The fractional-order control allows for precise voltage adjustments in response to fluctuating wind speeds, ensuring the turbine operates at the maximum power point for the given wind conditions[34].

The FO-CV topology is particularly useful in hybrid renewable energy systems where both solar and wind energy sources are combined. It ensures the system operates efficiently under varying environmental conditions, maximizing power extraction from both energy sources while maintaining a stable voltage output[35].

2.5. Standard pseudocode for the FO-CV MPPT algorithm

// FO-CV MPPT Algorithm Pseudocode

```
Initialize:
  Measure initial open-circuit voltage (Voc_initial) of the PV panel
  Set the proportional constant k (typically around 0.7 to 0.8)
  Vmp_estimated = k * Voc_initial // Initial estimate of Vmp

Loop (Continuously execute for tracking):
  Measure Voc (open-circuit voltage) of the PV panel

  // Estimate maximum power point voltage
  Vmp_estimated = k * Voc

  // Set PV panel operating voltage to Vmp_estimated
  Set PV voltage to Vmp_estimated

  // Measure power output at Vmp_estimated
  P_current = Measure power output at Vmp_estimated

  // Check if power has increased
  If P_current > P_previous:
    // Update tracking
    P_previous = P_current
    Continue with current Vmp_estimated
  Else:
    // Adjust Vmp_estimated or modify k if necessary
    Adjust k slightly if oscillations are observed
    Continue with new estimate of Vmp
```

Repeat the loop for continuous tracking.

3. RESULTS AND DISCUSSION

In this proposed Topology fractional Order Constant voltage method has been considered. For integration of energy system wind and solar have been considered. *Table 1* depicts requirements of solar panel parameters. *Table 2* indicates parameters required for wind energy system. *Table 3* indicates parameters required for boost converter. MATLAB Simulink software has been used for results.

Table 1. Required parameters for PV Panel

Type	User defined
Series modules	36
Paralle strings	01
Open circuit voltage	21.1V
Short circuit current	3.8A

Table 2. Required parameters for Wind energy system

Model	A doubly-fed induction generator driven by a wind turbine
Generator nominal power	1.5 x e^6 VA
Stator [Rs, Lls] (pu)	0.00706 & 0.171
Nominal wind turbine mechanical output power (W)	1.5 x e^6
Converter maximum power (pu)	0.5

Table 3. Required parameters for Boost Converter

Switches	IGBT
Series Inductor	1xe^{-3}H
Capacitor 1&2	1000 x e^{-6} F & 250 x e^{-6}
Diode F.V	0.8V

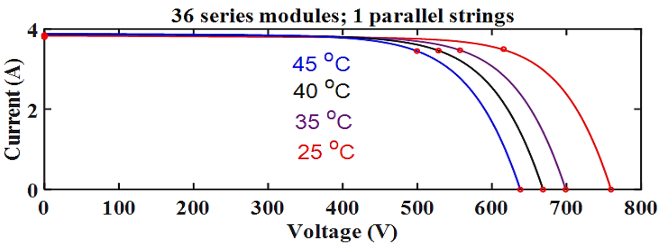

Figure 4. Representation of I-V characteristics of solar panel

The *figure 4* illustrates the current voltage (I-V) properties of a photovoltaic (PV) panel consisting of 36 series modules and 1 parallel string, measured under various temperature conditions. An increase in temperature leads to a drop in the voltage at maximum power, but the current stays almost constant. This observation suggests that when temperature increases, PV panels generate a reduced voltage, therefore impacting the total power distribution. As the temperature drops, the voltage rises and the current stays nearly constant. These findings demonstrate that photovoltaic (PV) panels have superior performance at lower temperatures, as increased voltage leads to increased power generation.

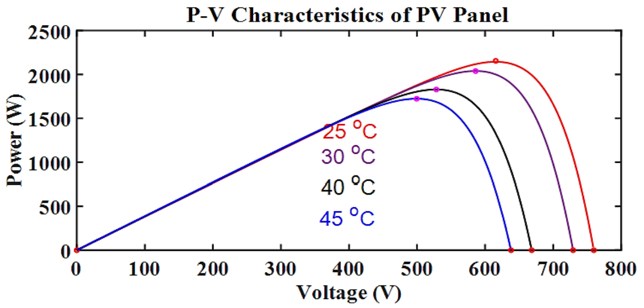

Figure 5. representation of P-V characteristics of solar panel

The presented *figure 5* illustrates the power-voltage (P-V) properties of a photovoltaic (PV) panel under various temperature conditions. It elucidates the relationship between the voltage and temperature of a PV panel and its power production.

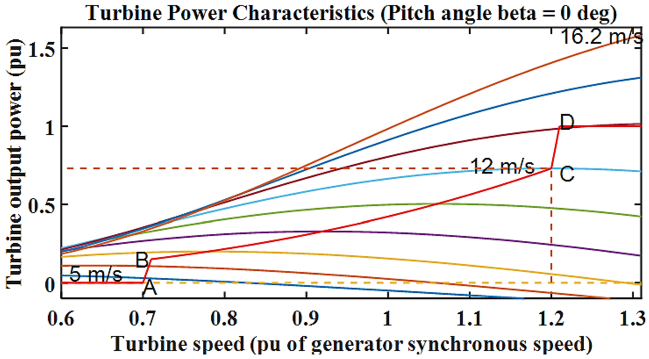

Figure 6. Representation of wind turbine characteristics

The *figure 6* depicts a wind turbine's power-speed properties at different wind speeds while maintaining a pitch angle of beta = 0 degrees. The primary factors at play in this graph are the turbine's speed and its output power, both of which are dependent on wind speed. Below wind speeds of 5 m/s (seen in the bottom curve), the power generation remains minimal. The turbine achieves its peak power rating at a rather modest speed, then experiences a decline in power as the speed increases. At wind speeds above 12 m/s (as seen by the middle curve), the turbine produces a greater amount of power. The power output rises in direct proportion to the turbine speed until it reaches point C, which represents the peak power production at this selected wind speed.

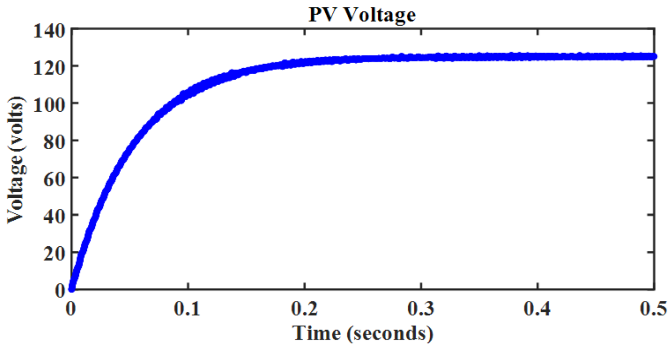

Figure 7. voltage of PV panel

This *figure 7* illustrates the temporal variation of PV voltage in a system employing a Maximum Power Point Tracking (MPPT) extraction technique. During the first phase of the graph (about 0 to 0.1 seconds), the photovoltaic voltage experiences a rapid and significant rise. This observation suggests that the system is rapidly adapting to identify the highest power point by raising the voltage towards its ideal operating point. Within approximately 0.15 to 0.2 seconds, the voltage stabilises at a consistently high level, perhaps above 120 volts. This observation indicates that the system has reached a state of stability at the highest power point.

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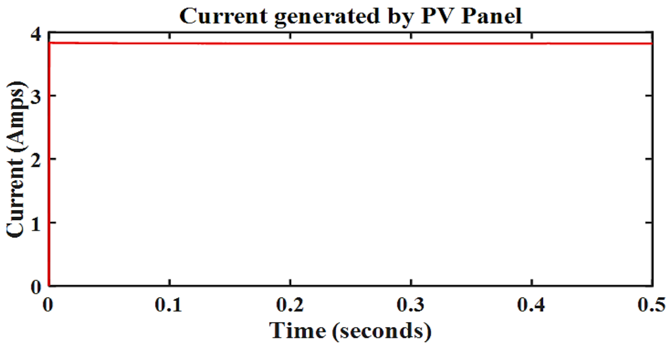

Figure 8. Current generated by PV panel

This *figure 8* shows how a photovoltaic (PV) panel produces current over time. This graph is associated with the concurrent Maximum Power Point Tracking (MPPT) technique, which utilizes a constant voltage architecture. The photovoltaic (PV) panel produces an electrical current that steadily increases to around 4 Amps almost immediately and remains consistent throughout the measured time of 0 to 0.5 seconds. Following its maximum magnitude, the current remains consistent at around 4 Amps for the entire period of the graph. The absence of substantial change or fluctuation indicates a steady current output.

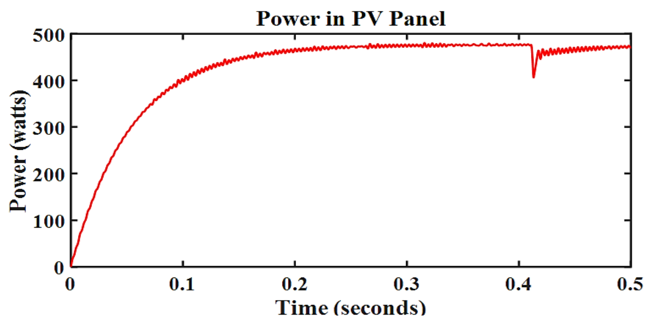

Figure 9. Power production in PV panel

This *figure 9* depicts the dynamic behaviour of a PV system utilising an MPPT approach with constant voltage structure. Within a short period of time, the system rapidly adapts to achieve an ideal value (around 480 w) and then stabilizes, ensuring precise power extraction. The primary function of the MPPT system is to monitor and sustain the ideal value for achieving the highest possible power generation, as demonstrated by the steady state response following the first adjustment phase.

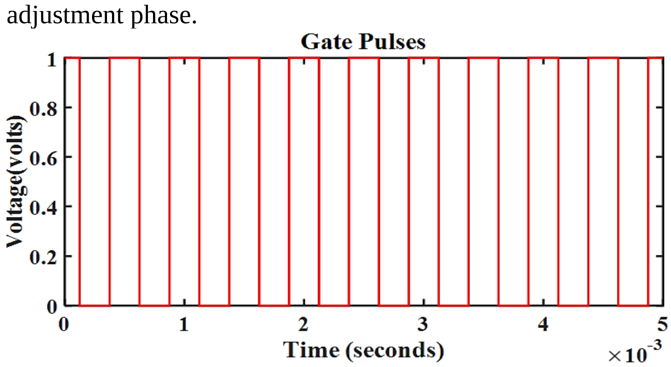

Figure 10. Representation of gate pulses

Figure 10 illustrates the time course of gate pulses necessary for the operation of a boost converter. In power semiconductor devices such as IGBTs operating in boost converters, gate pulses manage voltage conversion.

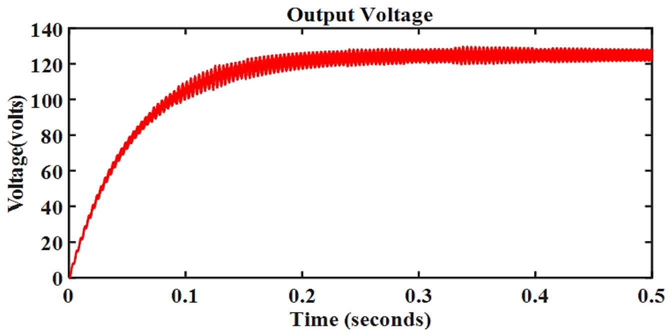

Figure 11. Output voltage of Hybrid energy system

Figure 11 depicts hybrid energy voltage over time in a system using a Maximum Power Point Tracking (MPPT) extraction method with a FO-Constant Voltage topology. The MPPT technique functions by adaptively modifying the voltage of the hybrid energy system to a predetermined ideal level. The mechanism calibrates the voltage to a consistent level that aligns with the highest power point. In this scenario, the system achieves voltage stabilisation at around 120V, which is the desired value for maximising power extraction. The rapid increase in voltage at the beginning of the graph corresponds to the system's temporary reaction as it adapts to the ideal voltage level. Following initialisation, Maximum Power Point Tracking (MPPT) systems typically require voltage stabilisation. The flat section of the graph indicates that the system has achieved the optimal voltage for optimum power extraction and is effectively sustaining that voltage to guarantee a steady power production.

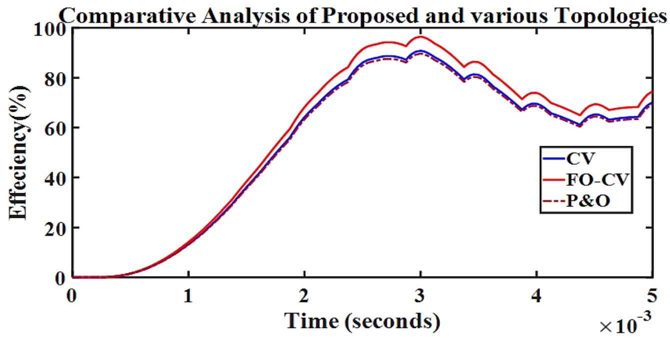

Figure 12. comparative analysis of efficiency with various topologies

This *figure12* depicts a comparative efficiency examination of many MPPT (Maximum Power Point Tracking) topologies over time. All three techniques (CV, FO-CV, and P&O) exhibit a consistent increase in efficiency from an initial condition of 0%. This suggests that the Maximum Power Point Tracking (MPPT) systems are adapting to the highest power point. Nevertheless, the FO-CV mode (red line) often exhibits superior efficiency in comparison to the P&O (dashed black line) and CV (blue line) approaches. The FO-CV approach exhibits superior performance within 2 milliseconds, achieving stability at a faster rate than P&O. The suggested approach is an enhanced implementation of the constant voltage technique. Fractional-order control improves the system's dynamic responsiveness, enabling faster and more precise monitoring of the maximum power point. As a result, FO-CV achieves superior efficiency at a faster rate and exhibits enhanced stability with fewer variations compared to alternative approaches.

4. CONCLUSION

Superior performance has been shown by the suggested Fractional-Order Constant Voltage (FO-CV) architecture for Maximum Power Point Tracking (MPPT) in hybrid solar and wind energy systems in comparison to traditional approaches such as Constant Voltage (CV) and Perturb and Observe (P&O). The FO-CV method enhances total system efficiency, especially in dynamically changing weather circumstances, by closely measuring the highest power point with more precision. The innovative control approach not only facilitates faster reaction times but also guarantees consistent power generation, rendering it a feasible option for incorporating renewable energy sources into the national power system. This research emphasises the critical role of sophisticated Maximum Power Point Tracking (MPPT) algorithms in optimising power generation in hybrid systems, thereby guaranteeing energy efficiency. The results show that the FO-CV topology is more accurate and more efficient than other methods. These two factors are very important for the performance of renewable energy systems in a variety of settings.

5. FUTURE SCOPE

- Potential future research might investigate the incorporation of hybrid energy storage technologies, such as batteries and supercapacitors, into the FO-CV MPPT approach to enhance energy dependability and grid stability in hybrid solar-wind energy systems.

- It is helpful to investigate real-time implementations of the FO-CV topology on a larger scale or in grid-connected situations to learn more about practical issues and scalability issues, such as controlling power quality, managing demand response, and minimising losses during energy transmission.

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