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Evaluation of Robust Controllers in Photovoltaic Systems: A Comparative Analysis

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Abstract: The main objective of this work is to compare and evaluate the performance of three advanced control techniques, namely Sliding Mode Control (SMC), Synergetic Control (SC) and Adaptive Sliding Mode Control (ASMC) for Maximum Power Point (MPP) extraction in a photovoltaic system under different atmospheric conditions. This study aims to identify the most robust, fast and efficient control strategy to optimize solar power production, while minimizing oscillations and improving system stability. Through accurate modeling of the PV system and simulations under varying operating conditions, we highlighted the strengths and limitations of each technique. Synergetic Control demonstrated superior performance by ensuring fast and precise tracking of the maximum power point, while significantly reducing the chattering phenomenon commonly observed in classical SMC. ASMC also showed notable improvements in adaptability and robustness compared to traditional SMC. In conclusion, this study confirms that robust control techniques offer promising solutions to enhance the energy performance of photovoltaic systems, especially in a global context where renewable energy sources are playing an increasingly vital role.

Keywords: Photovoltaic system, Sliding mode control, Adaptive sliding mode control, Synergetic control, MPPT.

Introduction

Photovoltaic (PV) systems represent an efficient and sustainable solution for the production of clean electrical energy. They offer a wide power range, suitable for both stand-alone applications and grid feed (Green et al., 2021). A typical photovoltaic system generally consists of a PV array composed of a series of solar modules and a static DC-DC converter to transform the power supplied by the PV source to the load (Masters, 2013; Blaabjerg et al., 2017). This structure is characterized by non-linear dynamics that vary significantly with operating conditions related, for example, to climatic conditions, such as irradiation levels, shading, temperature, etc (Villalva et al., 2009; Esram & Chapman, 2007). These conditions make it difficult to predict voltage and current to ensure maximum power production. In a photovoltaic system, the maximum power point (MPP) corresponds to the operating point where the power delivered is at its maximum; it is therefore crucial to maintain the PV array at this point to optimize energy extraction (Messenger & Ventre, 2010). The Maximum Power Point Tracking (MPPT) strategy continuously adjusts the DC-DC converter to track this point despite variations in irradiation and temperature (Alik & Jusoh, 2023). While conventional algorithms like Perturb and Observe (P&O) and Incremental Conductance (IC) are widely used, they exhibit significant limitations (Kermadi & Berkouk, 2021). P&O is favored for its simplicity but is prone to misdirection and oscillation during rapid irradiation changes (Femia et al., 2005). The IC method offers greater accuracy but faces an inherent trade-off between tracking speed and residual oscillation in steady state (Mohapatra et al., 2022). Consequently, there is a clear need for robust MPPT techniques that can deliver stable and reliable performance despite environmental disturbances. Among robust nonlinear control techniques, Sliding Mode Control (SMC) is a prominent solution for managing dynamic systems affected by uncertainties or external disturbances. Its operation is based on two steps: first, establishing a "sliding surface" that defines the desired system performance, and second, designing a discontinuous control law that drives the system's state to this surface and maintains it there. This approach offers considerable benefits, such as exceptional robustness against parametric variations, rapid dynamic response, and relative ease of implementation (Singh et al., 2021; Fridman, 2014). The primary limitation of SMC, however, is the chattering phenomenon. These are high-frequency, destructive oscillations generated by the inherent discontinuity of the control signal, which may cause a decrease in precision, acoustic noise, and accelerated hardware wear. In an effort to overcome the disadvantages of conventional SMC, Adaptive Sliding Mode Control (ASMC) was developed. Unlike its forerunner, the novelty of this approach is that it possesses dynamic control gains, varied based on the state of the system. In this way, it can effectively deal with uncertainties without the use of an accurate model of the system. Moreover, ASMC approach employs continuous control laws that significantly reduce or eliminate the chattering phenomenon while preserving robustness and stability (Plestan et al., 2019; Liu et al., 2022; Ahmad et al., 2023). This makes ASMC very suitable for real systems, such as photovoltaic arrays operating under time-varying conditions Synergetic Control (SC) has, by now, clearly emerged as a very powerful tool for the design of nonlinear control systems, successfully overcoming some drawbacks typical of alternative approaches. This relatively recent paradigm shares conceptual foundations with SMC but offers distinct practical advantages. A key differentiator is its inherently continuous control law, which mitigates or entirely eliminates the chattering phenomenon prevalent in SMC. . In most reported applications, SC is designed to be asymptotically stabilizing, that is, to ensure that system trajectories will converge progressively, after some finite time, to an equilibrium state. This continuity property makes it particularly well-suited to physical systems requiring smooth control actions (Moya et al., 2020; Shi & Wang, 2023).

System Configuration

The diagram given in fig.1 shows a solar power system. The MPPT Controller continuously adjusts the DC/DC boost converter to ensure the PV Panel always operates at its most efficient voltage and current, thereby extracting the maximum possible power to deliver to the Load.

V_{pv} and I_{pv} represent respectively the voltage and the current delivered by the panel

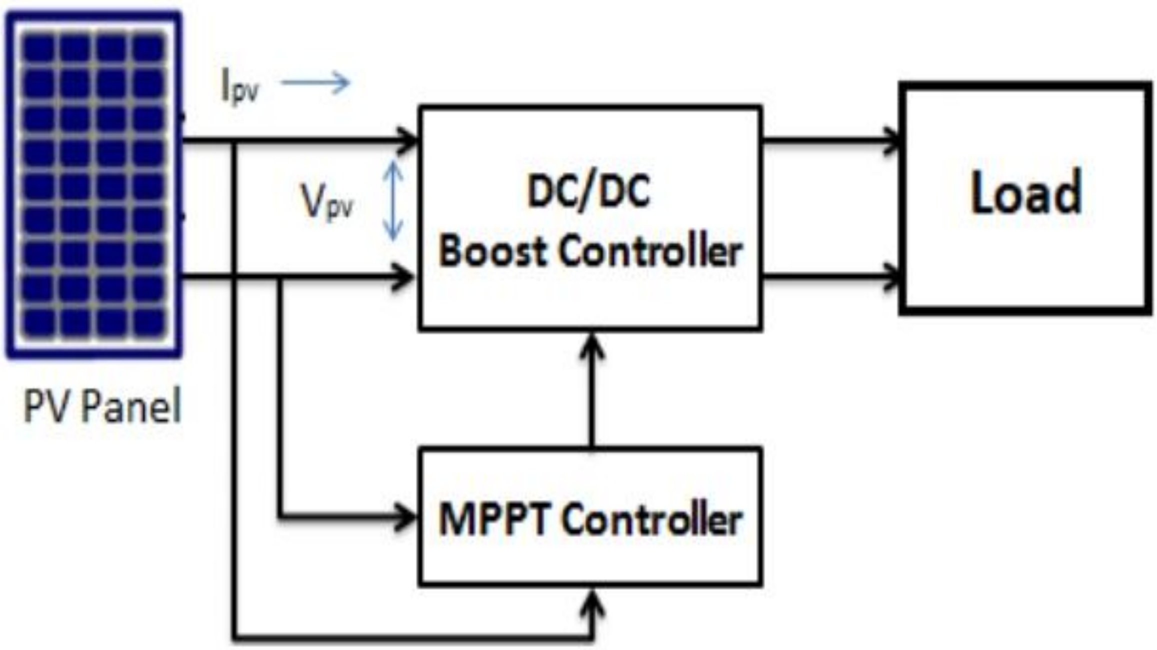

Figure 1. Photovoltaic energy conversion chain

The key challenge of an MPPT controller is to track this optimal operation point rapidly and stably in the presence of external disturbances, represented by irradiance and temperature changes. This robust performance can be achieved with the use of a Sliding Mode Control approach.

Sliding Mode Control Based MPPT

Sliding mode control belongs to the category of nonlinear controls. Initially developed for the control of variable structure systems (VSS). It is distinguished by the discontinuity of the control action when crossing a particular surface, called the sliding surface. Recently, this approach has been applied to photovoltaic (PV) systems to optimize maximum power extraction.
The design of a sliding mode controller consists of two main steps. First, a sliding surface is defined to guarantee the system converges to its desired state. Second, a control law is established to force the system's trajectory to reach this surface and remain on it.

For a photovoltaic (PV) system, the Maximum Power Point (MPP) is achieved when the derivative of power with respect to current is zero, as expressed by:

$$\frac{dP_{pv}}{dI_{pv}} = \frac{dI_{pv}V_{pv}}{dI_{pv}} = V_{pv} + I_{pv}\frac{dV_{pv}}{dI_{pv}} = 0 \quad (1)$$

Based on this condition, an appropriate sliding surface can be defined as:

$$s = V_{pv} + I_{pv}\frac{dV_{pv}}{dI_{pv}} \quad (2)$$

The general control law u consists of two parts: the discrete control u_{disc} and the equivalent control u_{eq}.
The discrete control u_{disc} is determined to ensure the attractiveness of the sliding surface and is defined as follows:

$$u_{disc} = k * sign\,(s); \quad k > 0\,; \quad (3)$$

The equivalent command u_{eq} is used to maintain the operating point on the sliding surface and move it towards the origin. It is given by:

$$u_{eq} = 1 - \frac{V_{pv}}{V_o} \quad (4)$$

Thus, the overall control law u is deduced as :

$$u = k * sign\,(s) + 1 - \frac{V_{pv}}{V_o} \quad (5)$$

While the control law in (5) is effective, its performance is sensitive to the choice of the fixed switching gain k.

A gain that is too low may not ensure robustness against parameter variations, while one that is too high can increase undesirable chattering (high-frequency oscillations). To overcome this limitation, an Adaptive Sliding Mode Control (ASMC) strategy is employed, where the gain is dynamically adjusted based on system conditions.

Adaptive Sliding Mode Control Principle

The application of Adaptive Sliding Mode Control (ASMC) to photovoltaic systems is characterized by a control law synthesized from the superposition of an equivalent control and an adaptive switching component.

This composite law, which dictates the discontinuous duty cycle for the DC/DC converter, operates based on a defined sliding surface whose robustness is ensured by an adaptively tuned gain. First, a sliding surface is chosen to guide the system towards the maximum power point (MPP). It is defined by the expression :

$$s = \frac{dP_{pv}}{dI_{pv}} = V_{pv} + I_{pv}\frac{dV_{pv}}{dI_{pv}} \tag{6}$$

The equivalent control u_{eq} is derived from the invariance condition $\dot{s} = 0$ and is responsible for the ideal sliding motion. It is expressed as:

$$u_{eq} = 1 - \frac{V_{pv}}{V_{out}} \tag{7}$$

While the adaptive correction term given by

$$u_{ad} = -\tilde{k}.sign\big(s(x)\big) \tag{8}$$

engages exclusively to counteract deviations from the sliding surface, providing robustness against disturbances and parameter variations.

$\tilde{k}$ is a dynamically adjusted gain.

The adaptation error is defined as follows:

$$\tilde{k} = k - \hat{k} \tag{9}$$

The estimated parameter $\hat{k}$ is dynamically adjusted according to:

$$\dot{\hat{k}} = \frac{1}{\gamma}\|s\| \tag{10}$$

Where γ is a positive constant.

Lyapunov Stability Analysis

To demonstrate the stability of the system controlled by the ASMC approach and to guarantee convergence towards the surface s=0, we propose the following Lyapunov function:

$$V = \frac{1}{2}s^2 + \frac{1}{2\gamma}\tilde{k}^2 \tag{11}$$

The derivative of Lyapunov function is given by the equation :

$$\dot{V} = s\dot{s} + \frac{1}{\gamma}\,\tilde{k}\,\dot{\tilde{k}} \tag{12}$$

$$\dot{V} = s[-k\ sign(s)] - \frac{1}{\gamma}\,\tilde{k}\,\dot{\hat{k}} \tag{13}$$

knowing that :

$$\dot{\tilde{k}} = \dot{\hat{k}} \tag{14}$$

Then we obtain:

$$\dot{V} = s\left[-k\left(\tilde{k} + \hat{k}\right)sign(s)\right] - \frac{1}{\gamma}\tilde{k}\,\dot{\hat{k}} \quad (15)$$

$$\dot{V} = -\hat{k}\, s.sign(s) - \tilde{k}[s.sign(s) + \frac{1}{\gamma}\dot{\hat{k}}\,] \quad (16)$$

Given that $s.sign(s) = |s|$, we will have :

$$\dot{V} = -\hat{k}\,|s| < 0 \quad (17)$$

Which proves that the system is asymptotically stable. The asymptotic stability of the Adaptive Sliding Mode Controller validates its design. However, the discontinuous $sign(s)$ function in its control law can lead to chattering. To circumvent this issue while retaining robustness, Synergetic Control presents an alternative methodology.

Synergetic Control Based MPPT

Synergetic control is a robust technique for nonlinear systems, sharing the invariance principle with sliding mode control. Its key distinction lies in the use of a continuous control law and a macro-variable, which can be a function of multiple state variables. System performance is governed by the strategic design of this macro-variable. An MPPT synergetic controller is designed by first selecting a macro-variable $\Psi(x, t)$given by :

$$\Psi(x,t) = \frac{dP_{pv}}{dI_{pv}} \quad (18)$$

This controller then forces the system trajectory to converge exponentially to the manifold defined by (19).

$$\Psi = \frac{dP_{pv}}{dI_{pv}} = \frac{dI_{pv}V_{pv}}{dI_{pv}} = V_{pv} + I_{pv}\frac{dV_{pv}}{dI_{pv}} = 0 \quad (19)$$

Once the trajectory reaches the desired attractor, the synergetic controller will maintain it on that manifold. The desired dynamic evolution of the macro-variable is chosen according to equation (20).

$$T_s\left(\frac{d\Psi}{dt}\right) + \Psi = 0;\ T_s > 0 \quad (20)$$

Where T_s is a positive value that influences the speed of convergence of the system towards the desired equilibrium point.
knowing that :

$$\frac{d\Psi}{dt} = \left(\frac{d\Psi}{dI_{pv}}\right)\left(\frac{dI_{pv}}{dt}\right) \quad (21)$$

we get:

$$T_S\left[\left(\frac{d\Psi}{dI_{pv}}\right)\left(\frac{dI_{pv}}{dt}\right)\right] + \Psi = 0 \quad (22)$$

where :

$$\frac{d\Psi}{dI_{pv}} = 2\left(\frac{dI_{pv}}{dt}\right) + I_{pv}\frac{d^2V_{pv}}{dI_{pv}^2} \quad (23)$$

$$\frac{dI_{pv}}{dt} = -(1-u)\frac{V_{out}}{L} + \frac{V_{pv}}{L} \quad (24)$$

Substituting equations (23) and (24) into equation (22) gives the control law described in (25):

$$u(t) = 1 - \frac{\Psi L}{V_{out}T_s\left(2\frac{dV_{pv}}{dI_{pv}} + I_{pv}\frac{d^2V_{pv}}{dI_{pv}^2}\right)} - \frac{V_{pv}}{V_{out}} \quad (25)$$

Simulation Results and Performance Comparison

This study evaluates and compares the performance of three modern MPPT techniques: Sliding Mode, Adaptive Sliding Mode, and Synergetic Control. Using the BP MSX 60 solar panel, we performed multiple simulations in Matlab/Simulink under strictly identical parameters and varying climatic conditions including irradiance (G) and temperature (T).

Case 1: Variable Irradiance

In this case, the simulation parameters are maintained at T = 25 C° while G varies in the range [1000 800 600].

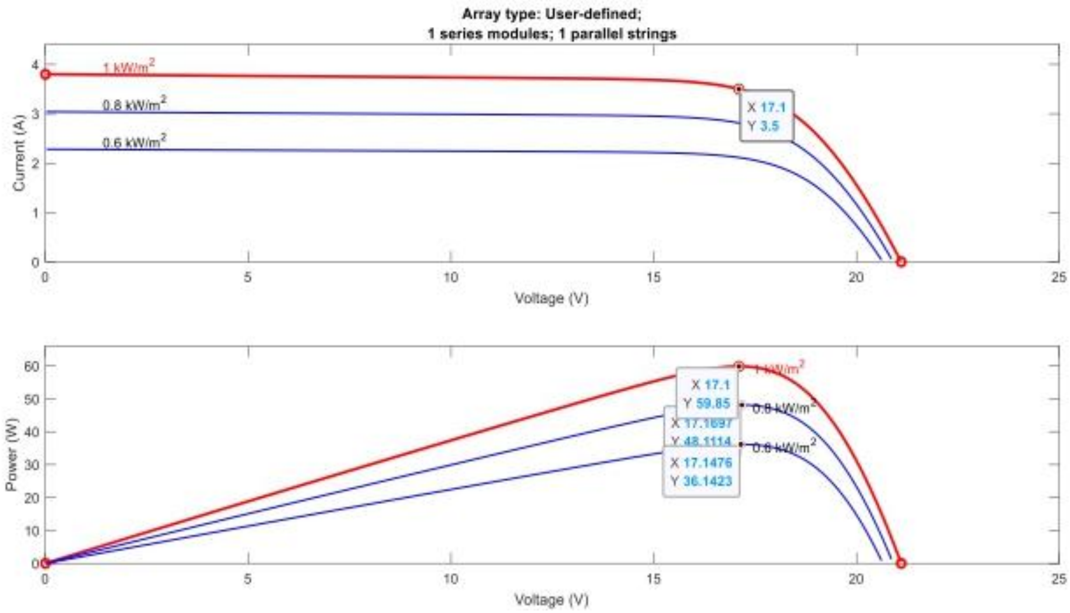

Figure 2. Panel characteristics for variable irradiance

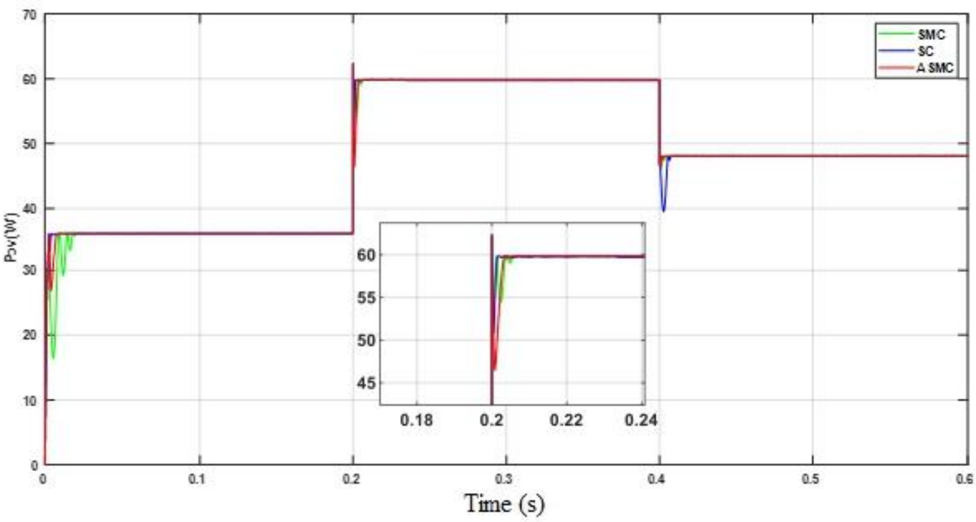

Figure 3. Evolution of Ppv

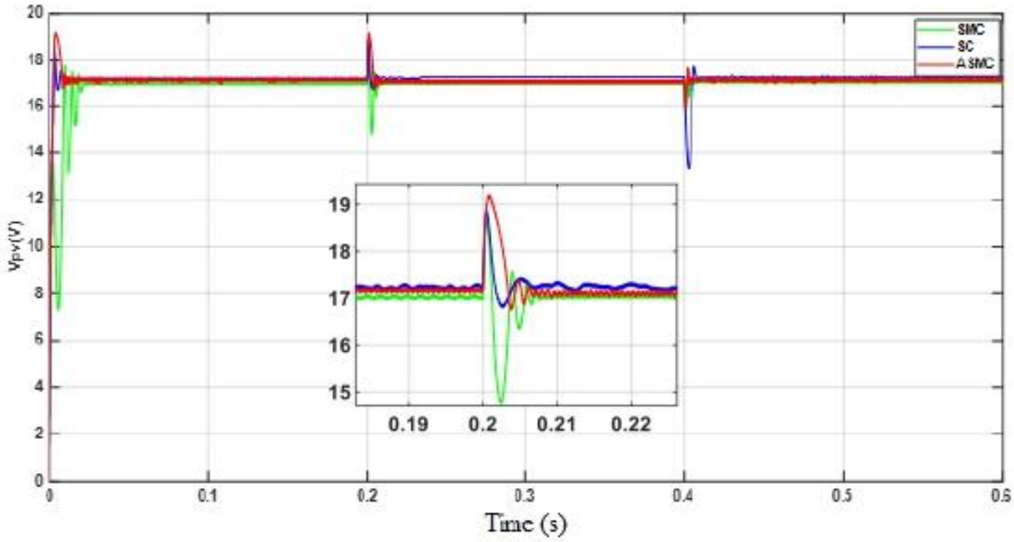

Figure 4. Evolution of Vpv

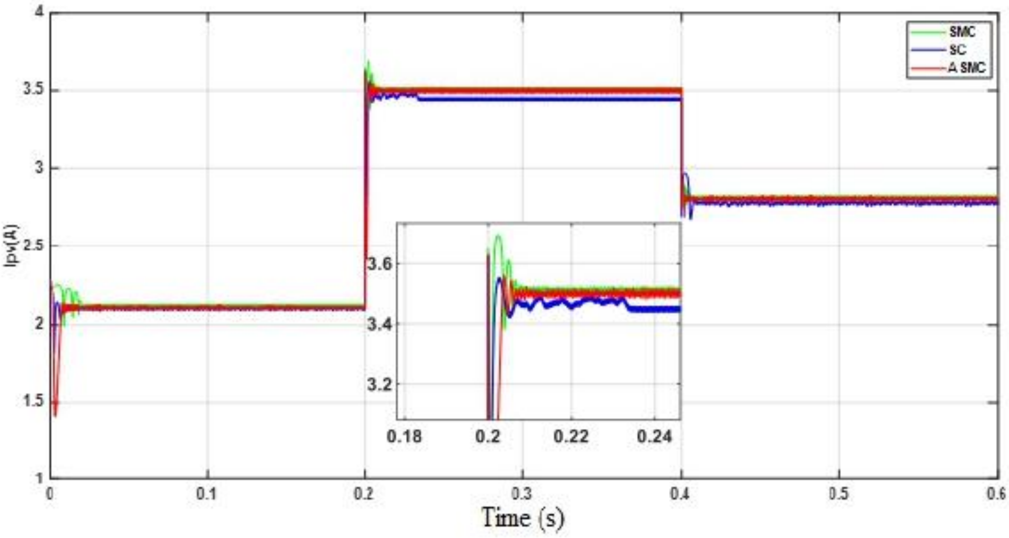

Figure 5. Evolution of Ipv

Table 1. Performance indicators of control systems for different levels of solar irradiation

Control System	Solar Irradiance (W/m²)	Efficiency (%)	Power Loss, ΔP (W)	Response Time (s)
SMC	600	95.23	0.02	0.02
	800	95.46	0.01	0.005
	1000	95.58	0.02	0.0056

(a)

Control System	Solar Irradiance (W/m²)	Efficiency (%)	Power Loss, ΔP (W)	Response Time (s)
SC	600	95.39	0.005	0.0045
	800	95.67	0.01	0.005
	1000	95.72	0.02	0.004

(b)

Control System	Solar Irradiance (W/m²)	Efficiency (%)	Power Loss, ΔP (W)	Response Time (s)
ASMC	600	95.29	0.006	0.0075
	800	95.54	0.01	0.003
	1000	95.62	0.01	0.005

(c)

Note: The values for Efficiency, Power Loss (ΔP), and Response Time are measured outcomes for each system under the specified solar irradiance.

Based on the obtained results, Synergetic Control (SC) demonstrates the highest performance in efficiency, power, and response time. However, Adaptive Sliding Mode Control (ASMC) emerges as an excellent compromise, delivering very good energy efficiency and a fast transient response while successfully minimizing the chattering phenomena associated with standard Sliding Mode Control (SMC). The conventional SMC method, though robust, is comparatively slower and less stable.

Case 2: Variable Irradiance and Temperature

In this case, the simulation parameters (temperature T and irradiance G) are maintained at : T varies within the range [25 30 35] °C, and G = [1000 800 600] W/m^2

Both Synergetic Control (SC) and Adaptive Sliding Mode Control (ASMC) demonstrate superior dynamic performance over conventional Sliding Mode Control (SMC), exhibiting a significantly faster response in tracking the Maximum Power Point (MPPT).

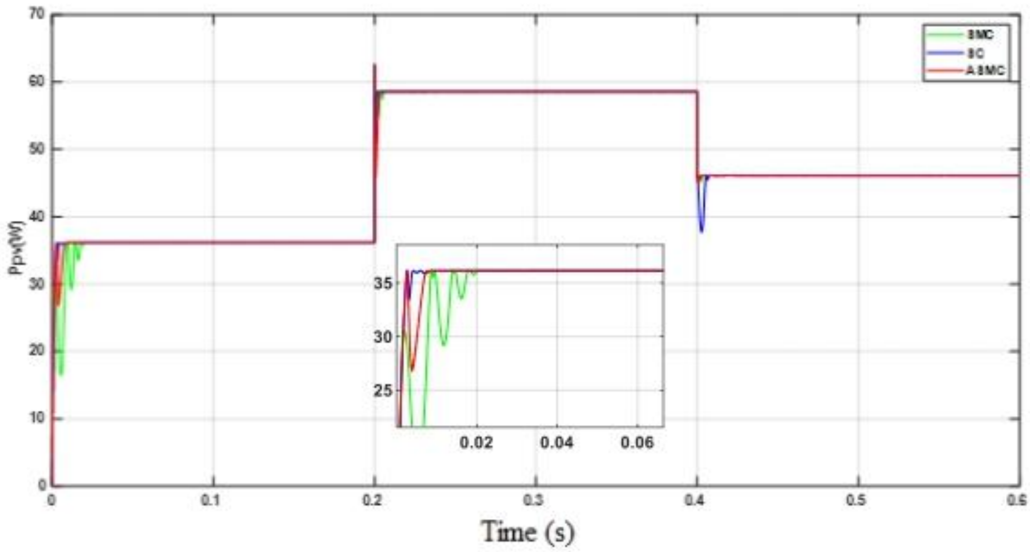

Figure 6. Evolution of Ppv

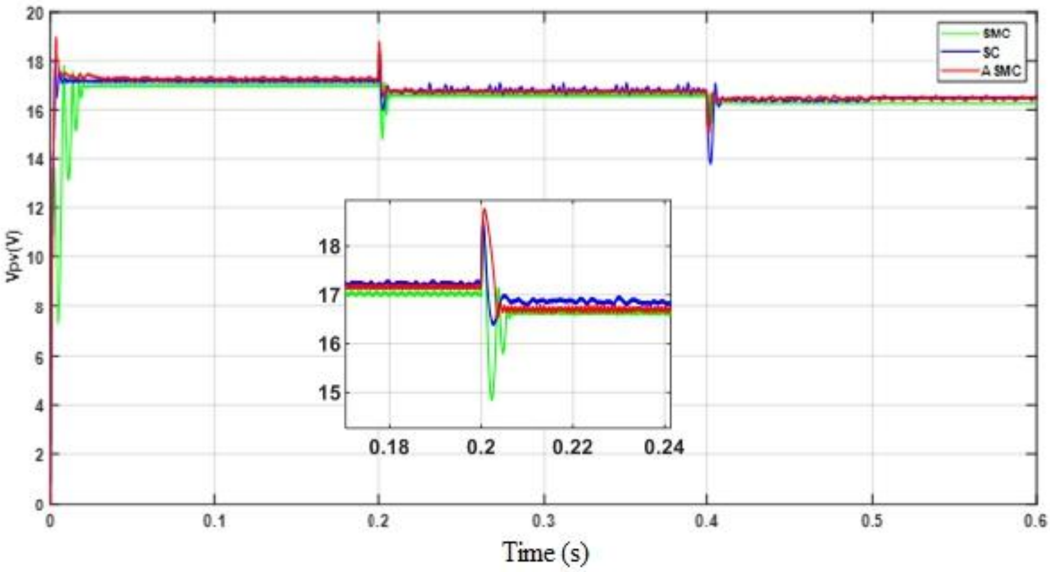

Figure 7. Evolution of Vpv

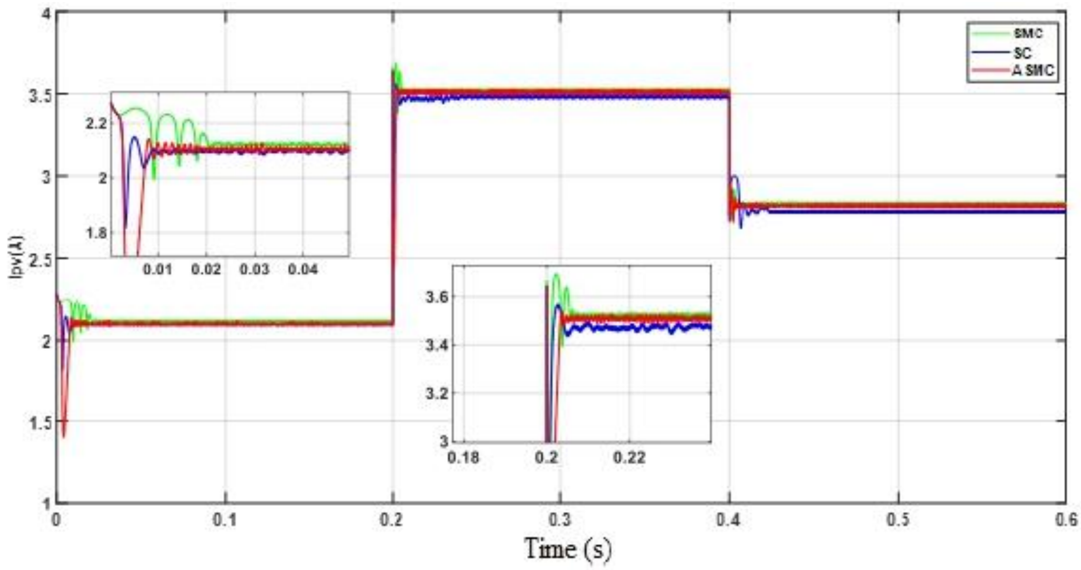

Figure 8. Evolution of Ipv

Conclusion

From these comparisons, it can be concluded that the three controllers are clearly classified in terms of performance. Though conventional SMC yields basic robustness, the ASMC has given a superior compromise in which chattering is significantly reduced and the response has been improved. SC will emerge as the most effective solution for delivering superior dynamic performance, high efficiency, and chatter-free smooth operation for maximum power point tracking.

Scientific Ethics Declaration

* The authors declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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References

Ahmad, A. Z., Al-Soeidat, H., & Lu, D. D. C. (2023). An adaptive sliding mode controller for PV maximum power point tracking with enhanced robustness and accuracy. *Solar Energy, 262*, 111846.

Alik, R., & Jusoh, A. (2023). An enhanced, adaptive, and artificial intelligence-based perturb and observe MPPT technique for the photovoltaic system. *Scientific Reports, 13*(1), 2054.

Blaabjerg, F., Yang, Y., Yang, D., & Wang, X. (2017). Distributed power-generation systems and protection. *Proceedings of the IEEE, 105*(7), 1311–1331.

Esram, T., & Chapman, P. L. (2007). Comparison of photovoltaic array maximum power point tracking techniques. *IEEE Transactions on Energy Conversion, 22*(2), 439–449.

Femia, N., Petrone, G., Spagnuolo, G., & Vitelli, M. (2005). Optimization of perturb and observe maximum power point tracking method. *IEEE Transactions on Power Electronics, 20*(4), 963–973.

Fridman, L. (2014). Chattering analysis in sliding mode systems with inertial sensors. *International Journal of Control, 87*(10), 1910–1925.

Green, M. A., Dunlop, E. D., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N., & Ho-Baillie, A. W. Y. (2021). Solar cell efficiency tables (Version 58). *Progress in Photovoltaics: Research and Applications, 29*(3), 657–667.

Kermadi, M., & Berkouk, E. M. (2021). A comprehensive review of maximum power point tracking algorithms for photovoltaic systems under partial shading. *Renewable and Sustainable Energy Reviews, 148*, 111293.

Liu, Z., Li, Y., & Zhang, W. (2023). Adaptive super-twisting sliding mode control for maximum power point tracking of photovoltaic systems under fast-changing irradiation. *IEEE Transactions on Industrial Electronics, 70*(5), 5095-5105.

Masters, G. M. (2013). *Renewable and efficient electric power systems* (2nd ed.). Wiley-IEEE Press.

Messenger, R. A., & Ventre, J. (2010). *Photovoltaic systems engineering* (3rd ed.). CRC Press.

Mohapatra, A., Nayak, B., & Mohanty, K. B. (2022). A comprehensive review on MPPT technologies in hybrid PV systems. *IEEE Journal of Emerging and Selected Topics in Industrial Electronics, 3*(4), 821-837.

Moya, P., Espinoza, E., Figueroa, M., & Lefranc, G. (2021). Synergetic control for maximum power point tracking in photovoltaic systems: A comparative analysis with sliding mode control. *IEEE Access, 9*, 111254-111265.

Plestan, F., Shtessel, Y., Brégeault, V., & Poznyak, A. (2020). New methodologies for adaptive sliding mode control. *International Journal of Control, 93*(3), 461-476.

Shi, J., He, X., & Wang, Z. (2023). Finite-time synergetic control for robotic manipulators with asymptotic disturbance rejection. *International Journal of Robust and Nonlinear Control, 33*(1), 189-207.

Singh, A., Suhag, S., & Kumar, N. (2021). A comprehensive review on sliding mode control for maximum power point tracking in photovoltaic systems. *International Transactions on Electrical Energy Systems, 31*(7), e12933.

Villalva, M. G., Gazoli, J. R., & Ruppert Filho, E. (2009). Comprehensive approach to modeling and simulation of photovoltaic arrays. *IEEE Transactions on Power Electronics, 24*(5), 1198-1208.

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