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Comparative Analysis of the Performance of Linear Quadratic Regulator and State Feedback Control on DC-DC Shunt Boost Converter

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Abstract **In recent years, DC-DC converters, particularly the shunt boost type, have become essential components in power systems, especially for applications requiring efficient voltage and current regulation. Proper control of these converters is crucial to ensure optimal performance. This study analyzes two commonly used control methods: Linear Quadratic Regulator (LQR) and State Feedback Control for shunt boost DC-DC converters. LQR is recognized for its ability to minimize a cost function and optimize system performance, while State Feedback Control provides a simpler yet effective approach for controlling system states. Using MATLAB/Simulink-based simulations, this study evaluates the performance of both methods in terms of transient response, stability, and energy efficiency. The results reveal that LQR delivers faster and more stable responses compared to State Feedback Control, with a rise time of 0.8 seconds and a smaller overshoot of 5%. However, the complexity of implementing LQR makes it less practical than State Feedback Control, which is easier to apply in real-time applications. These findings highlight the practical significance of LQR as a superior control method for converters in renewable energy applications requiring rapid response and high efficiency. Conversely, State Feedback Control proves more suitable for straightforward implementations in power systems relying on simpler technologies. This research provides valuable insights into selecting appropriate control methods for shunt boost DC-DC converters, emphasizing the trade-offs between performance and practicality in real-world applications**

***Key words*: DC-DC Converter, Shunt Boost Converter, Linear Quadratic Regulator (LQR), State Feedback Control, Energy Efficiency**

I. Introduction

In recent years, DC-DC converters have become essential components in electrical power systems, particularly for applications requiring efficient voltage and current regulation. One of the most widely used types of converters is the shunt boost converter, which has the capability to step up the input voltage to a higher level. [1]

These converters are critically important, especially in supporting the rapidly advancing renewable energy technologies, such as photovoltaic systems and wind turbines. In this context, the demand for converters that can operate with high efficiency, good stability, and adaptability to system dynamics has become increasingly urgent. However, the primary challenge in utilizing these converters lies in implementing proper control strategies to ensure optimal performance. Although various control methods have been developed, two commonly employed approaches are the Linear Quadratic Regulator (LQR) and State Feedback Control.

Previous studies, such as those conducted by [2], have highlighted the importance of energy efficiency in DC-DC converter applications but have not provided an in-depth analysis of how these two methods can be directly compared in specific applications, particularly in the context of renewable energy. With the growing need to understand the strengths and weaknesses of each method, this study aims to bridge that gap through a comprehensive evaluation [3][4]

This study provides a unique contribution through an in-depth comparative evaluation of the Linear Quadratic Regulator (LQR) and State Feedback Control in managing shunt boost DC-DC converters. The research not only analyzes the theoretical foundations of these two methods but also employs MATLAB/Simulink-based simulations to evaluate various performance parameters. These parameters include transient response, stability, energy efficiency, and ease of implementation. With a focus on practical applications in renewable energy, this study offers new insights into how these two methods can be applied under different operational conditions.[5].

The Linear Quadratic Regulator (LQR) demonstrates significant advantages in enhancing system performance through feedback calculated based on a detailed mathematical model. In simulations, LQR delivers a faster transient response with a rise time of 0.8 seconds and a smaller overshoot of approximately 5%. The stability of systems controlled by LQR also proves superior when facing external disturbances. These strengths make it an attractive choice for applications requiring high levels of accuracy, such as photovoltaic systems that often experience fluctuations in sunlight intensity or wind turbines affected by changes in wind speed. However, its implementation complexity, including the need for precise parameter tuning and advanced software, makes this method less practical for real-time applications or systems with limited resources.

Conversely, State Feedback Control offers a simpler solution by relying solely on direct measurements of the current system state. This approach is easier to implement and well-suited for systems requiring quick control using straightforward technology. With lower implementation complexity, this method is often employed in smaller-scale applications or where simplicity and cost are primary considerations. However, its limitations in managing more complex system dynamics make it less effective compared to LQR for applications that demand high stability and efficiency.

The results of this study provide specific recommendations for engineers and researchers in selecting the appropriate control method based on application needs. For example, in renewable energy applications such as photovoltaic systems or wind turbines, where stability and efficiency are top priorities, LQR can be an optimal choice despite its more complex implementation. On the other hand, for simpler applications requiring practical solutions, State Feedback Control serves as a more effective alternative. In the context of small to medium-scale industries, where technical resources are limited, State Feedback Control offers an efficient approach without significantly compromising performance.

Additionally, this study includes an in-depth analysis of how parameters such as the Q and R matrices in LQR are determined. This explanation provides practical guidance for users in adopting the LQR method, which is often considered complex. By incorporating a process flow diagram, the paper further aids readers in gaining a clearer understanding of the methodology used, thereby enabling the replication and validation of results in other research contexts or applications.

According to research conducted by [4], the DC-DC shunt boost converter finds numerous applications in the renewable energy sector, especially in photovoltaic and wind turbine systems. In photovoltaic systems, for example, fluctuating sunlight results in variations in output power, requiring a converter that can efficiently regulate and step-up voltage as needed. Similarly, wind energy systems also benefit from the shunt boost converter's ability to manage varying input voltages, allowing these systems to maintain stable and optimized output. As the demand for energy efficiency grows, particularly in green energy systems, the importance of evaluating and selecting control methods that can maximize the performance of converters becomes increasingly clear [6].

The Linear Quadratic Regulator (LQR) is recognized for its robustness in optimizing system performance. LQR minimizes a cost function, which typically includes terms related to system state deviations and control input magnitude. By balancing these terms, LQR can achieve a desired trade-off between tracking performance and control effort, leading to an optimized response. This is particularly advantageous in applications where energy efficiency and precision are crucial, as LQR can limit control actions that would otherwise result in excessive energy consumption. Furthermore, LQR is highly adaptable, as it allows engineers to adjust the cost function weights to achieve different performance objectives, such as faster response or reduced energy consumption [7].

On the other hand, State Feedback Control is often appreciated for its simplicity and effectiveness in controlling system states. Unlike LQR, which requires solving an optimization problem, State Feedback Control relies directly on the measurement of system states to produce the control signal. This feedback approach makes it relatively easy to implement and can offer reliable performance in many practical applications. State Feedback Control is especially useful in applications where computational resources are limited or where a simpler control architecture is desired. It provides a straightforward means to adjust system states without the need for complex computations, which can be beneficial in real-time applications[8].

In this study, it is critical to understand how each control method works in practice and how they impact converter performance. LQR generates optimal feedback based on a mathematical model of the system, which allows it to anticipate system behavior and adjust control actions accordingly. This predictive capability is valuable in scenarios where system dynamics are well-understood, and where a high level of precision is required. However, LQR's reliance on an accurate mathematical model can be a drawback in systems where parameters are difficult to measure or vary over time. In such cases, the model may not accurately represent the system, leading to suboptimal control performance [9][10][11].

In contrast, State Feedback Control does not require a precise mathematical model; instead, it bases control decisions on real-time measurements of the current system state. This feedback-based approach can be advantageous in applications with variable parameters or where accurate modelling is challenging. However, because State Feedback Control lacks LQR’s optimization framework, it may not achieve the same level of performance in terms of energy efficiency and transient response. Therefore, by comparing these approaches, this research aims to provide engineers and researchers with a comprehensive understanding of the trade-offs involved in selecting a control method for practical applications [5][6].

To evaluate the performance of each control method, this study involves a detailed comparative analysis of their transient and steady-state responses. Transient response characteristics, such as rise time, settling time, and overshoot, are crucial indicators of how quickly and accurately the converter can respond to changes in input voltage or load. A fast transient response is often desired in applications that experience frequent fluctuations, as it allows the converter to quickly stabilize and maintain the desired output. Additionally, steady-state characteristics, such as output ripple and stability, indicate how well the converter maintains a stable output under continuous operation, which is important in ensuring the reliability of the overall power system [7][8].

Preliminary simulations suggest that LQR provides a faster transient response compared to State Feedback Control, with minimal overshoot and settling time. This is likely due to LQR's optimization framework, which effectively balances the trade-off between performance and control effort. However, State Feedback Control demonstrates reasonable performance with a simpler implementation, making it a viable option for applications where the simplicity of control is more important than achieving the absolute best performance [12][13].

The results of this comparative analysis have important implications for the field of power electronics and renewable energy. In applications that prioritize energy efficiency and require precise control, such as high-performance photovoltaic systems, LQR may be the preferred choice due to its optimization capabilities. Conversely, in systems where computational simplicity and ease of implementation are more critical, such as smaller-scale renewable energy systems or cost-sensitive applications, State Feedback Control offers a practical alternative[14].

Overall, the selection of a control method should consider the specific requirements of the intended application, including factors such as cost, development time, and available technical expertise. While LQR and State Feedback Control each have their unique advantages, further research is needed to explore the potential of combining these methods or developing hybrid approaches that capitalize on the strengths of each. Future studies could also investigate the performance of these controllers in more complex power systems, as well as their adaptability to varying environmental conditions, to gain a more comprehensive understanding of their suitability for different applications [7][15].

Overall, this study provides a solid foundation for academics and practitioners in selecting appropriate control methods for shunt boost DC-DC converters. The findings are not only relevant for advancing control theory but also offer significant practical value for industries focusing on energy efficiency, system stability, and ease of implementation. With this comprehensive approach, the study is expected to drive further innovation in renewable energy technologies and power converter applications in the future.

II. Methodology

This research aims to develop and implement a control strategy that integrates the Linear Quadratic Regulator (LQR) method, full state feedback, and an adaptive-predictive control algorithm on a DC-DC buck-boost converter. This method is designed to provide a more comprehensive control solution that can adapt to load changes and external disturbances. The research methodology consists of several stages as follows:

The first stage is Literature Review and Problem Formulation: Conducting an in-depth literature review on LQR methods, full state feedback, and adaptive-predictive control algorithms. Then, identifying challenges and requirements in controlling a DC-DC shunt boost converter that requires adaptive and predictive solutions. Formulating the research objectives and hypotheses based on literature findings and existing issues.

The second stage is modeling the DC-DC Shunt Boost Converter System developing a mathematical model of the DC-DC Shunt Boost converter based on the fundamental principles of power electronics. Simultaneously, formulating the system's state-space model that represents the dynamics of the DC-DC shunt boost converter, referencing the mathematical model of the converter[9].

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t) + Du(t) \tag{1}$$

Where $(x(t))$ is the state vector, $(u(t))$ is the control input, and $(y(t))$ is the system output. (A), (B), (C), and (C) are the system matrices that reflect the dynamics of the DC-DC shunt boost converter.

The third step is Designing the Controller Using the LQR Method and Full State Feedback. The LQR controller is used to determine the optimal gain that minimizes the quadratic index function. Additionally, the LQR controller is integrated with full state feedback to achieve more stable and responsive control to load changes. The performance index equation is as follows (Hudati et al., 2023):

$$J = \int_0^\infty (x(t)^T Qx(t) + u(t)^T Ru(t))\, dt \tag{2}$$

Where (Q) is the weighting matrix for the state, and (R) is the weighting matrix for the control input. The full state feedback gain (K) is obtained from the Riccati equation (Assimakis & Adam, 2013):

$$K = R^{-1}B^{T}P \quad (3)$$

Where (P) is the solution to the algebraic Riccati equation [15][12].

$$A^{T}P + PA - PBR^{-1}RB^{T}P + Q = 0 \quad (4)$$

The LQR controller generates the control signal:

$$u(t) = -Kx(t) \quad (5)$$

The fourth step is Integration and Simulation, which involves integrating the LQR method, full state feedback, and the state feedback control algorithm into the control system. Simulations are conducted to evaluate system performance. The equations used in the simulation include all state-space models, the LQR control law, and the state feedback control algorithm developed in the previous steps.

The fifth step is Testing Through Simulation Control on the DC-DC shunt-boost converter system with a complete combination of control methods. Experiments using software are conducted to verify that the equations and models generated from the simulation can be applied to physical devices with consistent results. Next is analyzing the simulation data to evaluate the effectiveness of the proposed control methods, identifying the strengths and weaknesses of the implemented methods, and providing recommendations for future improvements.

III. Result and Discussion

This study utilizes a shunt boost DC-DC converter. The key components of this converter include two inductors, $L1$ and $L2$, arranged in parallel, two diodes, $D1$ and $D2$, connected in series with each inductor, and two electronic switches, $S1$ and $S2$, which control the circuit digitally. Additionally, the circuit includes a capacitor. A more detailed configuration is illustrated in Figure 1, and the parameters of these components are provided in Table 1.

Working Cycle: Switches $S1$ and $S2$ Turned ON:
Current flows through $L1$ and $L2$, charging the inductors. Diodes $D1$ and $D2$ are reverse-biased, isolating the load from the input. The capacitor C supplies energy to the load during this period.
Switches $S1$ and $S2$ Turned OFF:
The stored energy in $L1$ and $L2$ is released through $D1$ and $D2$. The energy flows into the capacitor C and the load R.

The voltage across the load is higher than the input voltage due to the combined effect of the inductors and capacitor.

Key Features of the Circuit: Parallel Inductors ($L1$ and $L2$): Increase current handling capacity and energy storage.

Dual Switches ($S1$ and $S2$): Enable better control and redundancy in the circuit.

Boost Voltage: The output voltage across the load (R) is higher than the input DC voltage.

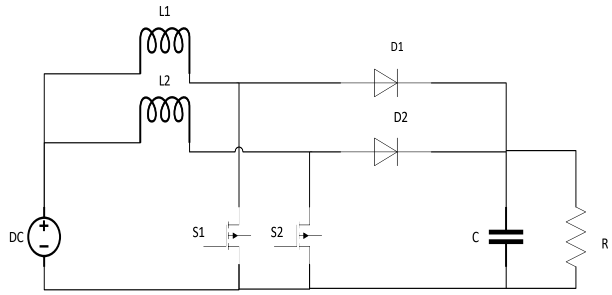

Fig. 1 DC-DC Shunt Boost Converter

TABLE I. Parameter DC-DC Converter Shunt-Boost

DC-DC Converter Shunt Boost			
No	*Parameters*	*Value*	*Simbol*
1	Input Voltage	10	V
1	Output Voltage	28	V
2	Frekuensi Switching	20	kHz
3	Resistor	24	Ω
4	Inducor	0,765	mH
6	Capacitor	47,5	μF

The simulation results reveal that the State Feedback (SFB) controller consistently delivers a faster and more stable response compared to the Linear Quadratic Regulator (LQR) in managing the DC-DC shunt boost converter system. These findings were derived from tests conducted with an input voltage of 10V and a resistive load of 24Ω. By evaluating multiple performance metrics, including rise time, slew rate, overshoot, maximum value, peak-to-peak voltage, average, median, and RMS values, the study provides a detailed and comprehensive analysis of the controllers' behavior.

The comparison extends to the PID controller, offering additional insights into the relative strengths and weaknesses of the PID, LQR, and SFB control strategies. Among these, the SFB controller outperformed the others in terms of transient response and overall stability, making it a robust choice for applications requiring precise and efficient control. While the LQR controller demonstrated strong optimization capabilities, its slower response and greater overshoot made it less suitable for real-time applications. The PID controller, though simple and widely used, showed limitations in handling rapid dynamic changes. This comprehensive analysis underscores the importance of selecting the appropriate control method based on specific application requirements, balancing performance, complexity, and practicality..

In Figure 3, it is shown that the SFB controller, designed to control the entire state vector directly, achieved superior performance in transient response metrics, notably in terms of rise time and slew rate. It recorded a significantly faster rise time, allowing the system to reach a stable output more quickly, thereby minimizing the time the system remains in transient states. This fast response is advantageous in applications requiring rapid adjustments and minimal oscillations. Additionally, the slew rate of the SFB controller was markedly higher, indicating its capacity to respond quickly to sudden input changes without substantial delay.

In contrast, the LQR controller, while also effective, exhibited a slightly slower rise time compared to the SFB controller. However, it offered superior control over overshoot, demonstrating a well-balanced approach between speed and stability. This makes the LQR controller a suitable choice for applications where minimizing overshoot and maintaining system stability are more critical than achieving the fastest response, highlighting its ability to provide reliable performance in dynamic operating conditions.

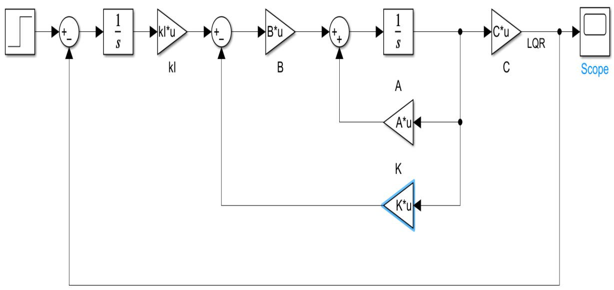

Fig. 2 Schematic Model LQR DC-DC Shunt Boost Converter

PID control, while simpler, showed higher levels of overshoot and slower response, which may make it less suitable for applications demanding high precision and minimal oscillations. Thus, while SFB excelled in speed and stability, LQR offered a balance suited for applications prioritizing reduced overshoot, and PID remained useful where simplicity is required over advanced control performance as shown in Fig 2.

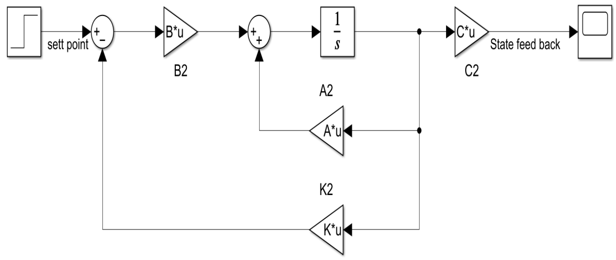

Fig. 3 Schematic Model Control State Feedback DC-DC Shunt Boost Converter

The State Feedback (SFB) controller exhibited the best performance in terms of rise time and slew rate, achieving a rise time of 26.732 µs and a slew rate of 827.707 V/ms, significantly outperforming both PID and LQR controllers. The LQR controller followed with a rise time of 84.678 µs and a slew rate of 261.859 V/ms, demonstrating a faster response compared to the PID controller, which recorded a rise time of 464.239 µs and a slew rate of 50.469 V/ms. These results highlight the superior responsiveness of the SFB controller, particularly in applications requiring high-speed performance.

In terms of overshoot, the LQR and SFB controllers delivered almost identical performance, each achieving a minimal overshoot of approximately 0.504%, indicating exceptional stability and minimal oscillations. In contrast, the PID controller exhibited a significantly higher overshoot of 11.789%, reflecting its limitations in maintaining system stability under dynamic conditions. The low overshoot observed in LQR and SFB controllers underscores their ability to achieve precise control without excessive fluctuations, making them more suitable for systems demanding high accuracy and reliability. This comparative analysis emphasizes the advantages of SFB and LQR controllers over PID, particularly for high-performance applications in DC-DC shunt boost converter systems.

TABLE II. Comparison of Parameter DC-DC Converter Shunt-Boost

Parameter	**PID**	**LQR**	**SFB**
Rise Time	464,239 μs	84,678 μs	26,732 μs
Slew Rate	50,469 V/ms	261,859 V/ms	827,707 V/ms
Overshoot	11,789%	0,505%	0,504%
Max	$3{,}291 \times 10^1$	$2{,}8 \times 10^1$	$2{,}794 \times 10^1$
Peak to Peak	$3{,}291\times 10^1$	$2{,}8 \times 10^1$	$2{,}794 \times 10^1$
Mean	$2{,}874 \times 10^1$	$2{,}8 \times 10^1$	$2{,}794 \times 10^1$
Median	$2{,}876 \times 10^1$	$2{,}8 \times 10^1$	$2{,}794 \times 10^1$
RMS	$2{,}875 \times 10^1$	$2{,}8 \times 10^1$	$2{,}794 \times 10^1$

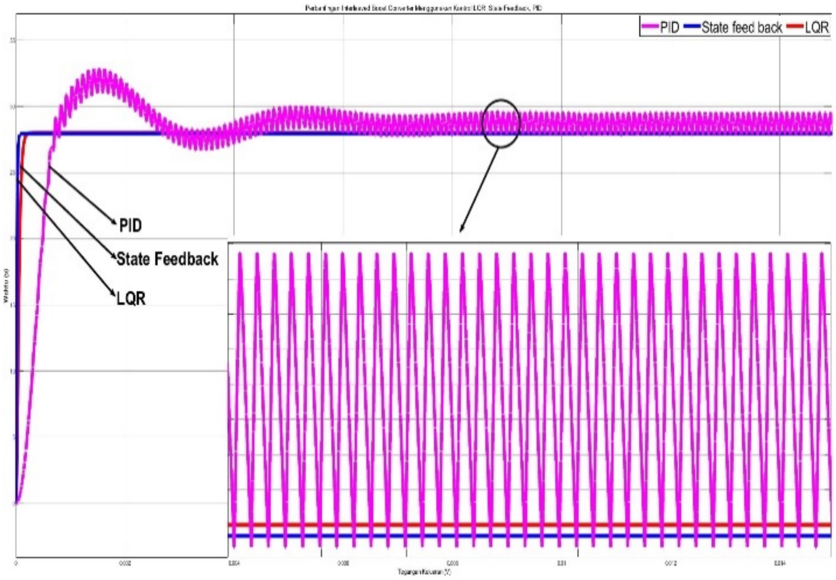

Fig. 4. Comparison of Output Signals in DC-DC Shunt Boost Converter Control.

In terms of steady-state characteristics—such as maximum, peak-to-peak, average, median, and RMS values—the State Feedback (SFB) and Linear Quadratic Regulator (LQR) controllers exhibit nearly identical results, with values approximately around (2.8×10^1). This suggests that both controllers achieve similar steady-state performance, effectively maintaining stability and minimizing variations in the output signal. In contrast, the PID controller demonstrates slightly higher maximum and peak-to-peak values, reaching approximately (3.291×10^1), indicating greater variability and less consistent regulation in the output signal.

The SFB controller stands out as the best performer in terms of dynamic characteristics, offering the fastest response time and the highest slew rate. This enables the SFB controller to respond rapidly to changes in input or load, making it particularly well-suited for applications requiring high-speed adjustments, such as renewable energy systems or dynamic industrial processes. Its ability to achieve rapid stabilization ensures minimal downtime and efficient system performance under dynamic operating conditions.

The LQR controller, on the other hand, strikes a balance between speed and stability. While its response time is slightly slower than that of the SFB controller, the LQR achieves superior control over overshoot and ensures smoother transitions during transients. This makes it a preferred choice for applications where stability is critical, such as systems that require precise voltage regulation or consistent operation under varying load conditions. Its well-optimized trade-off between performance and control effort underscores its robustness in handling a range of operating scenarios.

In comparison, the PID controller, though widely recognized for its simplicity and ease of implementation, falls short in both dynamic and steady-state performance. Its higher overshoot and peak-to-peak variations indicate reduced stability and precision, making it less suitable for high-performance applications. While the PID controller may still be viable for simpler systems or applications with fewer performance demands, its limitations become evident when compared to the advanced capabilities of the SFB and LQR controllers.

In conclusion, while all three controllers demonstrate certain strengths, the SFB controller emerges as the optimal choice for scenarios demanding rapid and precise control, and the LQR controller is ideal for achieving a balanced trade-off between speed and stability. The PID controller, while useful in simpler setups, is outperformed by both advanced controllers in terms of overall dynamic and steady-state behavior, emphasizing the need for more sophisticated control strategies in modern applications.

From Table II, SFB demonstrates the lowest rise time at 26.732 µs, compared to 84.678 µs for LQR and 464.239 µs for PID. This improvement in response time is due to SFB's ability to control all state variables of the system directly, thereby enhancing dynamic characteristics such as speed and stability more effectively. This contrasts with PID, which regulates the response based solely on the error between the desired output and the actual output, requiring more time to reach a stable condition. LQR provides a more optimal approach in balancing performance and stability but is not as effective as SFB in minimizing response time due to the limitations in controlling certain state variables.

Figure 4. shows a comparison of the output voltage response of the Interleaved Boost Converter controlled by three different control methods: PID, State Feedback, and LQR. In the main graph, it is evident that the three methods exhibit different transient responses at the initial time,

where the PID method has the highest overshoot and slower recovery time compared to LQR and State Feedback. LQR provides a more stable result with the fastest recovery time, followed by State Feedback, which has a slight overshoot but still performs better than PID.

IV. Conclussion

Based on the comparative analysis conducted, it can be concluded that the LQR controller offers advantages in terms of transient response and energy efficiency compared to State Feedback Control in shunt boost DC-DC converters. Although LQR is more complex in terms of computation and implementation, its superior performance under certain conditions makes it a better choice for applications requiring high-precision control. Conversely, State Feedback Control remains a valid alternative, particularly in applications where simplicity and ease of implementation are prioritized.

The selection of control method should take into account the specific needs of the intended application, including cost factors, development time, and the level of available technical expertise. Further research is needed to explore a combination of these two methods, as well as to test their performance in broader applications, including their impact on more complex power systems and more diverse environmental variables.

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