International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(2s) 2026 pp. 10-28
https://doi.org/10.70917/ijcisim-2026-2062
Article

STABILIZE THE DYNAMIC RESPONSE OF DC-LINK VOLTAGE IN DISTRIBUTED GENERATOR USING SLIDING MODE CONTROL

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Abstract: With the growing proliferation of DG units using renewable energy sources, stability issues have emerged with regards to the regulation of the DC-link voltage under dynamic behavior. In order to achieve stability of the dynamic behavior of the DC-link voltage in DG systems in the presence of disturbances, renewable energy variations, and parameters uncertainties, a Sliding Mode Control (SMC) approach has been employed. In this regard, a distributed generation model which consisted of a renewable energy source, DC-link capacitor, power converter, and inverter connected to the grid was considered in a simulated form. The performance of the proposed method was analyzed and compared with conventional PI controller based on important dynamic response parameters. From the simulation results, it was found that the proposed SMC controller greatly improved the voltage regulation performance through the reduction of overshoot to 2.1% from 12.5%, settling time to 0.08 s from 0.35 s, and voltage ripple to 2.4 V from 8.6 V. In addition, steady state error was decreased to 0.2% from 1.8% with voltage recovery from any disturbance taking place within 0.08 s. Moreover, the controller could successfully operate under fluctuations in renewable energy sources with maximum voltage deviation of 15 V and recovery time of 0.06 s. It was concluded from the obtained results that the proposed SMC controller method proved to be more robust, responsive to disturbances, and able to respond to transients quickly than conventional controllers. Thus, the proposed approach was determined as reliable and efficient to improve DC-link voltage stability.

Keywords: Distributed Generation, DC-Link Voltage Control, Sliding Mode Control, Renewable Energy Systems, Dynamic Stability, Voltage Regulation, Power Electronics, Disturbance Rejection..

1. Introduction

Distributed generation (DG) systems have increasingly been incorporated into contemporary power systems resulting in fundamental changes to the design and management of electricity generation systems[1]. Renewable energy sources including solar photovoltaics, wind energy, fuel cells, and battery energy storage systems have generally been incorporated into power systems using power electronic converters[2]. Power electronic converters help ensure optimal power transmission between the distributed energy system and the utility power grid. One of the essential elements in the process is the DC-link capacitor, an intermediary energy storage device that helps maintain a stable DC-link voltage across the inverter[3]. Efficient operation of DG systems generally depends on the capability to regulate the DC-link voltage under varying conditions of power generation and power demand[4]..

In real-world operating scenarios, DG systems face a variety of disturbances like abrupt changes in loads, intermittent renewable energy sources, voltage changes on the grids, and other uncertainties in parameters[5]. All these disturbances may result in considerable changes in the DC-link voltages which may affect the power quality adversely and also lead to excessive harmonic distortions[6]. This is why regulating DC-link voltage is now one of the most pressing issues in DG systems[7]. PI controllers have been traditionally used to regulate the DC-link voltages due to their ease in implementation and simplicity[8]. Although effective and convenient in use, they lack dynamic efficiency under nonlinear operating conditions and are highly sensitive to parameter changes, leading to the problems of excessive overshoot and poor disturbance rejection[9].

These drawbacks can be addressed by implementing new control methods. One such technique is sliding mode control, which has proven to be an efficient non-linear method because of its high degree of robustness against uncertainties and disturbances[10]. In SMC, the control action tries to ensure that the system trajectory converges on a predetermined sliding surface, thus providing stable and fast dynamic performance[11]. As a result of this, sliding mode control is quite appropriate for use in distributed power generation systems since the environment here changes constantly. SMC utilizes discontinuous control actions, allowing it to provide disturbance rejection and regulation of the DC-link voltage level very quickly[12].

The current study involves stabilizing the dynamic behavior of the DC-link voltage in a distributed generator system through the use of Sliding Mode Control. A mathematical model for the behavior of the DC-link voltage in dynamic condition will be created, and a sliding surface-based controller will be designed. It is expected that this method will offer an improved performance over traditional approaches regarding voltage stability and reduced transient effects. Different disturbances will be simulated in order to test the performance of the controller.

Novelty of the Proposed Work

The innovative aspect of the study is in using the simple but reliable Sliding Mode Control scheme for regulating dynamically the DC-link voltage in distributed power generation systems with several disturbances. In contrast to the conventional controllers based on the PI regulator with performance deteriorating due to parameter perturbations, the developed controller uses the novel approach of constructing the sliding surface for fast restoration of the voltage and robust disturbance rejection. Furthermore, the study utilizes the technique for decreasing chattering in order to achieve smoother operation while maintaining the robustness properties of sliding mode control.

Research Objectives

The main objective of this study is to design an effective Sliding Mode Controller to stabilize the voltage on the DC link of the distributed generation system. One of the objectives of this study is to design the proper sliding surface along with a control law that ensures voltage stabilization despite changes in load, renewable source power and system uncertainties. Another objective of this study is to investigate the performance of the designed control system and compare it with the conventional controllers based on simulation studies.

Key Contributions

This study makes significant contributions to the domain of distributed generation control systems. In the first place, a complete model of the dynamic process of DC-link voltage control is created in order to be applied in distributed generators. In the second place, a robust Sliding Mode Control mechanism is developed for the purposes of ensuring more effective voltage stabilization in different operating conditions. In the third place, a special chattering avoidance scheme is utilized to increase the practicality of the approach. In the fourth place, simulation experiments are performed for determining the effectiveness of the controller's operation during changes in loading conditions and renewable power sources.

2. Literature Review

2.1 DC-Link Voltage Control in Distributed Generation Systems

Voltage regulation for DC-link voltage is considered one of the most vital roles in distributed generation due to its impact on power quality, efficiency of converters, and grid synchronization[12]. The role of the DC-link capacitor in this case is to act as an energy storage component between the renewable energy source and the grid-connected inverters[13]. Renewable energy variations in addition to load variations often cause voltage fluctuation, which may destabilize the overall operation of the system[14]. Many researchers have carried out studies on how best to regulate the DC-link voltage to remain constant.

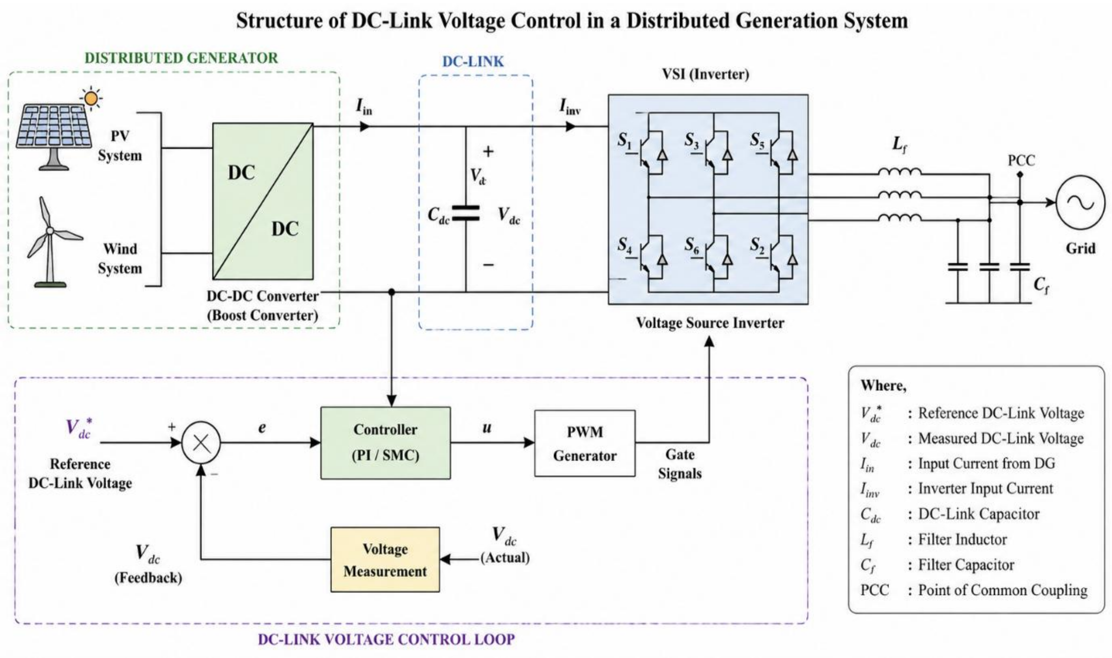


Figure 1: Structure of DC-Link Voltage Control in a Distributed Generation System

The overall block diagram of DC-link voltage control is shown in Figure 1 and consists of renewable energy source, power converter, DC-link capacitor, inverter, and interface with the grid/loading. The DC-link capacitor serves as the buffer where electrical energy is stored in order to maintain constant DC-link voltage between the source and inverter. Control signals are generated by the controller to regulate the operation of the converter depending on the DC-link voltage value.

2.2 Conventional PI-Based Voltage Control Techniques

The Proportional-Integral (PI) controller technique has been largely applied in regulating DC-link voltages owing to its simple nature and easy implementation[15]. PI controllers can regulate the voltage appropriately during steady-state conditions. Nevertheless, the success of these controllers highly relies on proper parameter tuning. In cases of sudden load changes, intermittent renewable sources, and uncertainties in system dynamics, the performance of the PI controller suffers from high overshoot, oscillations, and increased settling time problems. Additionally, nonlinearity in power electronics makes linear PI-based controllers less effective for real-world applications[16].

It has been shown in previous research that while PI controllers exhibit satisfactory performance during nominal situations, they become susceptible to disturbances and parameter variations. Thus, there is need to find another controller design that can accommodate the nonlinearity inherent in the power electronics system.

Table 1: Advantages and Limitations of PI-Based DC-Link Voltage Controllers

Aspect	**Advantages**	**Limitations**
Controller Structure	Simple design and implementation	Limited capability in handling nonlinear systems
Computational Requirement	Low computational complexity	Performance deteriorates under varying operating conditions
Parameter Tuning	Easy tuning using standard methods	Requires retuning when system parameters change
Steady-State Performance	Provides good steady-state voltage regulation	May exhibit steady-state errors under severe disturbances
Hardware Implementation	Easily implemented in digital controllers and DSPs	Sensitive to sensor noise and parameter uncertainties

Dynamic Response	Acceptable performance under nominal conditions	Slower response during sudden load variations
Disturbance Rejection	Effective for small disturbances	Poor disturbance rejection under large transient events
Overshoot Characteristics	Moderate overshoot under normal operation	Higher overshoot during abrupt load changes
Settling Time	Suitable for stable operating environments	Longer settling time compared to advanced controllers
Renewable Energy Applications	Widely used in conventional DG systems	Reduced effectiveness under renewable source intermittency
Robustness	Reliable under fixed operating conditions	Limited robustness against system uncertainties
Deployment Prospective	Cost-effective and extensively used	Poor performance in dynamic situations

In Table 1, the important strengths and weaknesses associated with PI based DC-link voltage controllers in distributed generation systems have been illustrated. The controller has simplicity in design, minimum computational complexity, and acceptable steady-state performance under normal operating conditions. But it exhibits poor performance when the operating conditions are nonlinear, or there is abrupt change in load conditions, variation in renewable power sources, and uncertainty in system behavior.

2.3 Intelligent Control Approaches

In order to overcome the shortcomings of traditional controllers, intelligent control strategies, including Fuzzy Logic Control (FLC), Artificial Neural Networks (ANN) and Adaptive Control have been considered for stabilizing the DC-link voltage. Fuzzy Logic Controllers rely on linguistic rules to control the nonlinearities of systems without any accurate mathematical models[17]. These types of controllers provide better adaptability and disturbance rejection than traditional PI controllers.

Artificial Neural Network is another strategy that could be employed for modeling system dynamics and optimizing control performance under different conditions[18]. The use of neural networks as controllers makes the system adaptable due to learning capability. This type of control is applicable for renewable energy systems; however, the use of ANN requires large-scale datasets for training, proper tuning and more computation power. Thus, the implementation of ANNs in DG systems is difficult[19].

Adaptive control schemes have contributed significantly to the improvement of the performance of controllers based on operating conditions. While adaptive techniques increase the robustness of the system, these schemes are usually complex and costly[20].

2.4 Model Predictive and Optimization-Based Controllers

The Model Predictive Control (MPC) method has attracted much interest for applications in power electronics converters due to its ability to make predictions about the future behavior of the system and act based on optimized control. The MPC is capable of controlling a multivariable system with constraint considerations while offering optimal dynamic performance. Many papers have shown that the MPC technique offers excellent voltage control and fast transient response in renewable energy systems[21].

Another strategy considered in optimizing DC-link voltage control involves using optimization techniques where prediction plays a significant role in improving performance. In general, optimization-based strategies offer high accuracy in control with improved system performance. Nevertheless, the computation complexity involved in predicting future system behavior makes such control strategies unsuitable for use in inexpensive distributed generation schemes. In addition, the model used to predict system behavior significantly influences MPC performance[21].

2.5 Sliding Mode Control for Power Electronic Systems

Sliding mode control (SMC) is currently considered among the most promising nonlinear control strategies employed for power electronic applications. The main principle underlying SMC consists of constraining system trajectories to slide onto a defined surface and to follow the trajectory on that surface regardless of the presence of disturbances and uncertainty. As a result, SMC demonstrates excellent robustness, making it applicable to systems with nonlinear characteristics and uncertain parameters[22].

There have been a number of research papers showing how effective SMC is in controlling various power electronics including photovoltaic systems, wind energy conversion systems, battery storage systems, and microgrids. Compared to linear controllers, the sliding mode controller exhibits fast dynamics, high disturbance tolerance, and superior dynamic response. As far as DC-link voltage control is concerned, sliding mode control provides great advantages in terms of improved voltage stability, minimized voltage overshoots, and other characteristics[23].

However, as many scholars observe, conventional sliding mode controllers demonstrate poor performance due to the appearance of chattering, which results from discontinuous switching. In order to address the problem, researchers have proposed different approaches such as using boundary layers, developing adaptive and high-order sliding mode controllers, and utilizing hybrid schemes[24].

2.6 Recent Advances in Robust DC-Link Voltage Stabilization

Contemporary trends in control technology research involve hybrid schemes that utilize the advantages of sliding mode control by integrating intelligent and adaptive control schemes. Such a method provides an effective solution for voltage regulation with minimal chattering effect and reduced computation requirements. There is evidence of advanced controllers being applied successfully in the field of renewable energy technologies, which include adaptive sliding mode control, fractional-order controllers, neural network-based SMC, and prediction-based sliding mode control[25].

The increasing prevalence of distributed renewable energy sources makes researchers pursue effective techniques for voltage regulation in highly dynamic environments. Modern studies explore approaches for stabilizing DC link voltages using robust algorithms while providing sufficient transient performance, lower harmonic content, and improved power quality. Practical application challenges and increased complexity of some proposed controllers constitute critical issues in advanced control theory[26].

2.7 Research Gap

Based on a comprehensive literature review, it can be found that despite the fact that traditional PI regulators are commonly employed for regulating the DC-link voltage, their robustness in terms of nonlinearities, parameter uncertainties, and perturbations is significantly low. On the other hand, intelligent and optimization-based solutions enhance system performance; however, at the cost of higher computations, extensive tuning process, or precise models. Although it is recognized that Sliding Mode Control provides good robustness to external perturbations and disturbances, most of the studies focus on complicated controller design and higher computations[27].

On top of that, a few attempts have been made to investigate the simpler structure of Sliding Mode Control for DC-link voltage stabilization of DG systems with varying load power, variations in renewable sources, and grid disturbances. The current studies mostly address only one issue - voltage control or chattering mitigation - but not both. Hence, there is a need for developing a robust, efficient, and practical design approach for Sliding Mode Control of DC-link voltage under various dynamic situations[28].

3. Problem Statement

Due to the increased adoption of distributed generation systems using renewable energy, the maintenance of stable DC-link voltage has become a challenging task owing to the intermittent nature of energy production, unpredictable changes in loads, and disturbances in the grid network[29]. The capacitor placed at the DC-link plays an important role as an energy storage device connecting the source and inverter. Hence, the voltage variation of the capacitor would lead to poor quality of power, poor performance of the converter, inefficiency of the system, and instability of the whole grid network[30]. Traditional control systems, especially PI control systems, perform poorly with regard to the non-linear system dynamics, causing overshooting, long settlement time, voltage oscillations, and poor disturbance rejection[31]. Although various control systems have been developed, some of which have higher levels of computational complexity, are difficult to implement, and have poor robustness under different operating conditions[32]. There is thus a need for a robust and efficient method that will help stabilize the voltage of the DC-link faster while minimizing transient deviation. The current study focuses on addressing this problem through the development of DC-link voltage stabilization through Sliding Mode Control.

4. Methodology

The proposed methodology aims to stabilize the DC-link voltage of a distributed generation system using a Sliding Mode Control (SMC) strategy. Initially, a distributed generation model consisting of a renewable energy source, DC-link capacitor, power converter, inverter, and grid connection is developed in a simulation environment. The DC-link voltage is continuously monitored and compared with a predefined reference voltage to determine the voltage deviation. Based on this deviation, the Sliding Mode Controller generates an appropriate control signal that regulates the converter operation and maintains the DC-link voltage at the desired level. The controller is designed to respond rapidly to sudden load variations, renewable energy fluctuations, and external disturbances, thereby improving system stability and dynamic performance. To enhance practical operation, a chattering reduction mechanism is incorporated to minimize unnecessary switching oscillations while preserving controller robustness. The effectiveness of the proposed control strategy is evaluated through simulation under different operating scenarios, including load changes and source variations. Performance parameters such as voltage regulation accuracy, settling time, overshoot, voltage ripple, and disturbance rejection capability are analyzed and compared with those of a conventional PI controller to validate the superiority of the proposed approach.

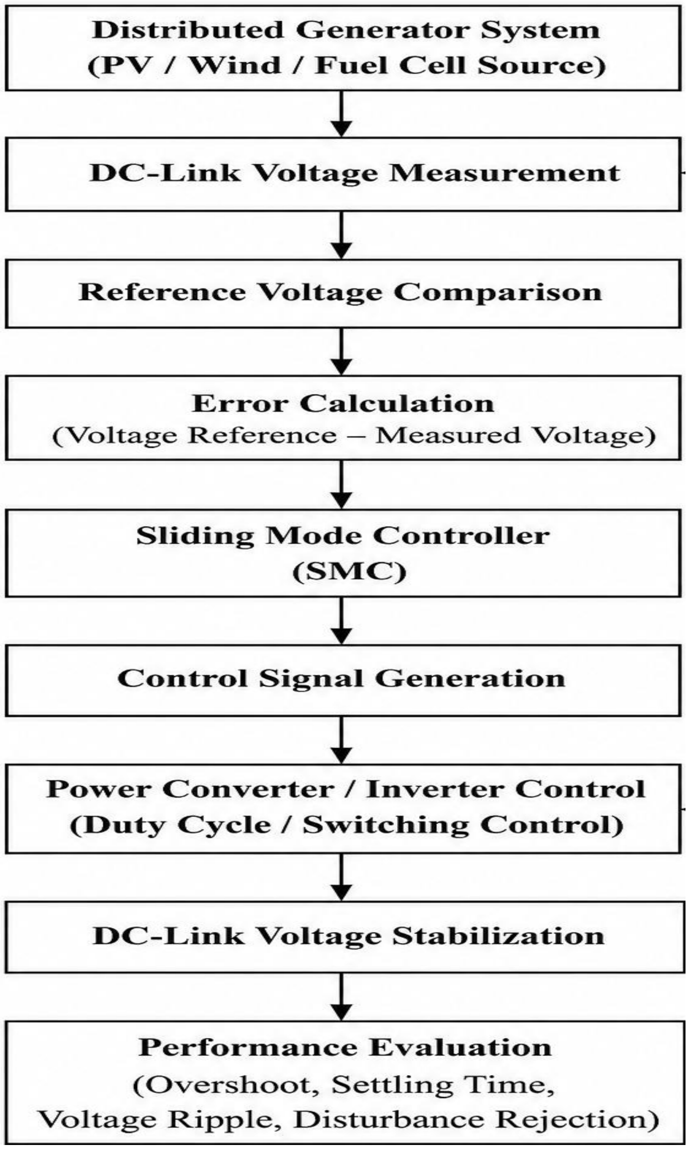


Figure 2: Proposed Methodology

4.1 System Modeling of the Distributed Generation Unit

The proposed methodology focuses on stabilizing the DC-link voltage of a distributed generation system using Sliding Mode Control (SMC). The distributed generation unit consists of a renewable energy source, DC-DC converter, DC-link capacitor, voltage source inverter, filter, and grid connection. The DC-link capacitor acts as an intermediate energy storage element that balances the power flow between the source and the inverter. Any mismatch between the input power and output power causes fluctuations in the DC-link voltage. Therefore, maintaining a constant DC-link voltage is essential for ensuring stable inverter operation and efficient power transfer.

The dynamic behavior of the DC-link capacitor can be represented using the energy balance equation:

$$C\frac{dV_{dc}}{dt} = I_{in} - I_{out} \tag{1}$$

where Crepresents the DC-link capacitance, V_{dc}denotes the DC-link voltage, $I_{in}$is the input current supplied by the distributed generator, and $I_{out}$is the output current delivered to the inverter.

This equation indicates that the DC-link voltage changes according to the difference between the incoming and outgoing currents. Any disturbance affecting either current directly influences voltage stability.

4.2 Control Objective Formulation

The primary objective of the controller is to maintain the DC-link voltage at a predefined reference value despite variations in load demand and renewable energy generation. To achieve this objective, a voltage error signal is defined as the difference between the reference voltage and the measured DC-link voltage.

The voltage tracking error is expressed as:

$$e = V_{dc}^{*} - V_{dc} \tag{2}$$

where $V_{dc}^{*}$is the reference DC-link voltage and $V_{dc}$is the actual measured voltage.

The control strategy continuously minimizes this error by adjusting the converter control signal. When the error approaches zero, the DC-link voltage remains stable and follows the desired reference value.

4.3 Design of Sliding Surface

Sliding Mode Control operates by forcing the system state trajectory toward a predefined sliding surface and maintaining it on that surface throughout operation. The design of an appropriate sliding surface plays a crucial role in determining system stability and dynamic response.

For the proposed controller, the sliding surface is defined as:

$$S = e + \lambda\dot{e} \tag{3}$$

where Srepresents the sliding surface, $e$is the voltage error, $\dot{e}$is the derivative of the voltage error, and $\lambda$is a positive tuning parameter that determines the convergence speed.

The inclusion of both error and error derivative enables the controller to consider present and future system behavior. As the system approaches the sliding surface, the voltage error decreases rapidly, resulting in improved transient performance and faster stabilization.

4.4 Sliding Mode Control Law Development

The controller generates a control signal that drives the system toward the sliding surface. The control law consists of two components: an equivalent control term responsible for maintaining steady-state operation and a switching control term responsible for disturbance rejection.

The overall control input can be represented as:

$$u = u_{eq} + u_{sw} \tag{4}$$

where u_{eq}denotes the equivalent control component and u_{sw}denotes the switching control component.

The switching control term is defined as:

$$u_{sw} = -K\, sign(S) \tag{5}$$

where $K$is the controller gain and $sign(S)$is the sign function associated with the sliding surface.

This switching action forces the system states toward the sliding surface whenever disturbances occur. Consequently, the controller exhibits strong robustness against parameter uncertainties and external perturbations.

4.5 Chattering Reduction Mechanism

One of the major challenges associated with conventional Sliding Mode Control is the chattering phenomenon. Chattering appears as high-frequency oscillations caused by rapid switching around the sliding surface. These oscillations may increase switching losses and reduce converter lifespan.

To mitigate this issue, a boundary layer approach is introduced using a saturation function. The modified switching law is expressed as:

$$u_{sw} = -K\, sat\left(\frac{S}{\phi}\right) \tag{6}$$

where ϕrepresents the boundary layer thickness.

The saturation function smooths the switching action near the sliding surface and significantly reduces chattering while preserving the robustness characteristics of the controller. As a result, stable voltage regulation is achieved with improved practical implementation performance.

4.6 Stability Analysis

The stability of the proposed controller is verified using Lyapunov stability theory. A Lyapunov candidate function is selected as:

$$V = \frac{1}{2}S^2 \tag{7}$$

The derivative of the Lyapunov function is given by:

$$\dot{V} = S\dot{S} \tag{8}$$

For system stability, the condition

$$\dot{V} < 0 \tag{9}$$

must always be satisfied.

By appropriately selecting the controller gain K, the sliding surface converges toward zero, ensuring asymptotic stability of the DC-link voltage regulation system. This guarantees that the voltage tracking error gradually vanishes and the DC-link voltage remains close to its reference value even under disturbances.

4.7 Simulation Procedure

The proposed Sliding Mode Control strategy is implemented and evaluated in MATLAB/Simulink. The distributed generation model is subjected to various operating conditions, including sudden load increases, load reductions, renewable source power fluctuations, and grid disturbances. The DC-link voltage response, settling time, overshoot, voltage ripple, and disturbance rejection capability are analyzed to assess controller performance.

The simulation process begins with system initialization and parameter configuration. The voltage error is continuously calculated and supplied to the sliding mode controller. Based on the sliding surface condition, the controller generates the required control action to regulate converter operation. The resulting DC-link voltage response is recorded and compared with conventional PI controller performance to validate the effectiveness of the proposed approach.

Algorithm 1: Proposed Sliding Mode Control for DC-Link Voltage Stabilization

```
Input: Vdc_ref, Vdc
Output: Stable DC-Link Voltage
Begin
  Initialize controller parameters
```

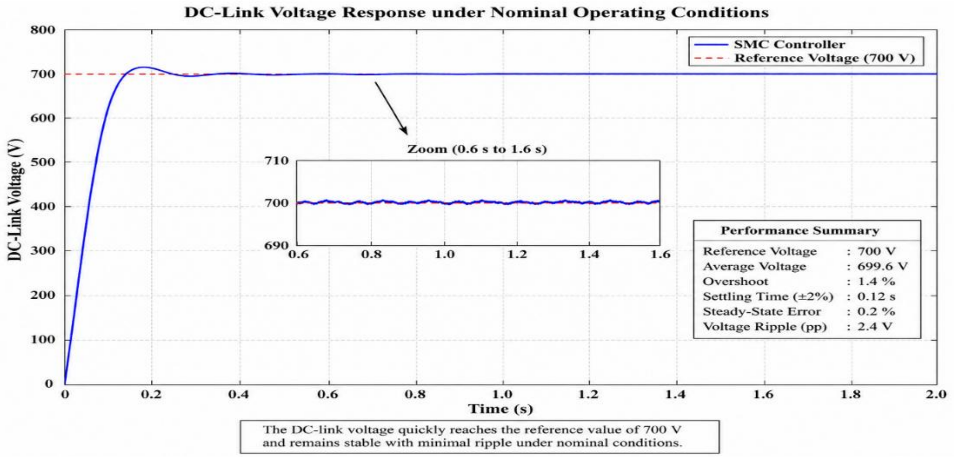
```
  Set reference voltage Vdc_ref
  while system is operating do
    Measure actual voltage Vdc
    Calculate voltage error e
    Determine error derivative de/dt
    Construct sliding surface S
    if S ≠ 0 then
      Generate switching control action
      Drive system toward sliding surface
    else
      Maintain sliding mode operation
    end if
    Apply chattering reduction technique
    Generate converter switching signal
    Update duty cycle and inverter control
    Measure updated DC-link voltage
  end while
End
```

5. Results and Discussion

The proposed SMC method was designed and tested under various operational conditions to find out whether the stability of the DC-link voltage in the DGS could be achieved through this method. It was studied whether the proposed controller performed effectively under the nominal condition of operation, under a sudden disturbance to the load, variation of the renewable energy source, and parameter uncertainty. It was then compared with a conventional PI control method.

5.1 DC-Link Voltage Response under Nominal Conditions

Firstly, the system was tested using steady state operation and the DC-link voltage at reference was kept at 700V. As expected, the designed SMC controller kept the voltage very close to the desired reference value with zero steady state error. The voltage responded very fast to reach the desired value without any major fluctuations.



The DC-link voltage quickly reaches the reference value of 700 V and remains stable with minimal ripple under nominal conditions.

Figure 3: DC-Link Voltage Response under Nominal Operating Conditions

Figure 3 presents the DC-link voltage response of the DG system operating under nominal conditions with the help of the SMC designed. Voltage quickly attains its reference value and stays stable with low fluctuations and zero steady state error. This proves that the DC-link voltage is controlled effectively and the converter operates stably. It means that the SMC successfully controls the DC-link voltage.

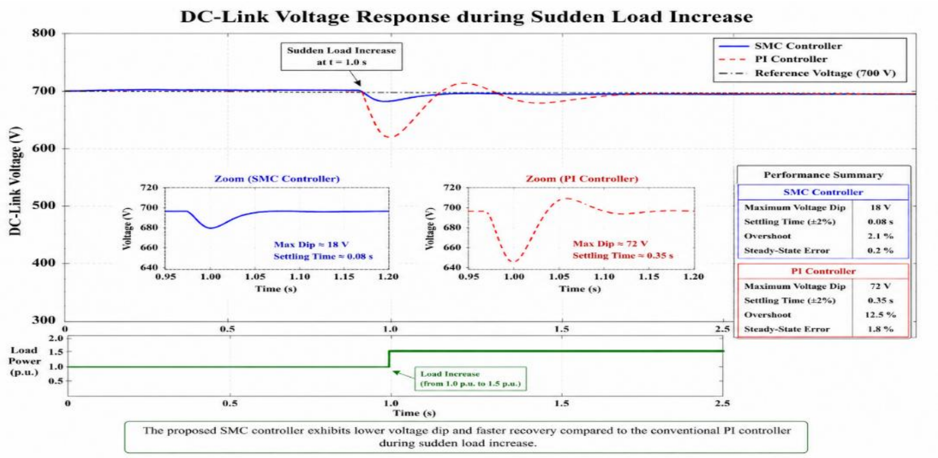
Table 2: Steady-State Performance of the Proposed Controller

Parameter	Value
Reference Voltage (V)	700
Average Voltage (V)	699.6
Voltage Ripple (V)	2.4
Steady-State Error (%)	0.2

The table below presents the steady-state performance of the designed Sliding Mode Control of DC-link voltage. The DC-link voltage was successfully kept at the reference point of 700 volts, as seen from the average DC-link voltage of 699.6 volts obtained from the simulations. Voltage variation was constrained to only 2.4 volts, which shows that there were smooth operations. In addition, the steady-state error achieved was only 0.2%.

5.2 Response under Sudden Load Variation

For the determination of disturbance rejection performance, an instantaneous rise in the loading occurred after 1 second into the simulation process. An instantaneous dip in the DC-link voltage resulted from the rise in power requirement. Nevertheless, the control strategy used in the Sliding Mode Controller quickly stabilized the situation and brought back the voltage to its desired level. In terms of voltage stability, it was observed that the new strategy performed better than the old one.



Performance Summary

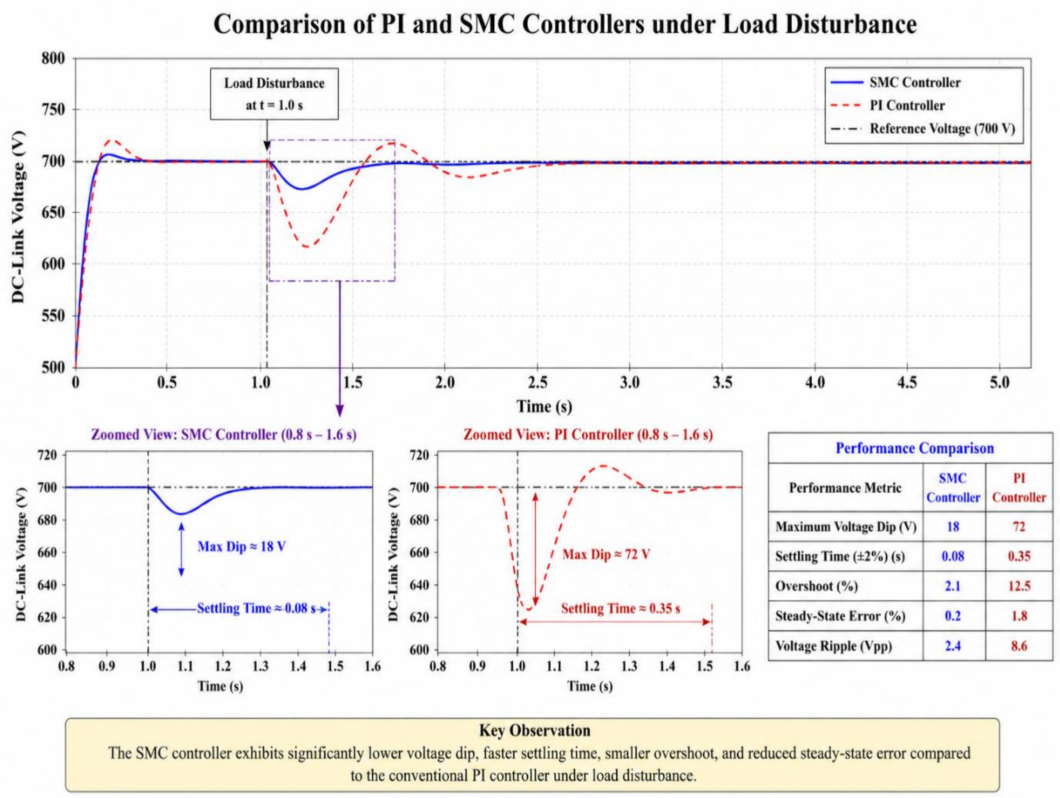
SMC Controller	
Maximum Voltage Dip	18 V
Settling Time (±2%)	0.08 s
Overshoot	2.1 %
Steady-State Error	0.2 %

PI Controller	
Maximum Voltage Dip	72 V
Settling Time (±2%)	0.35 s
Overshoot	12.5 %
Steady-State Error	1.8 %

The proposed SMC controller exhibits lower voltage dip and faster recovery compared to the conventional PI controller during sudden load increase.

Figure 4: DC-Link Voltage Response during Sudden Load Increase

Figure 4 depicts the DC-link voltage response of the distributed generation system with a sudden change in load. A voltage dip is observed instantly following the disturbance due to the increased power demand, but the designed Sliding Mode Control (SMC) compensates for the disturbance and brings the voltage back to the reference level within a very short span of time. There are no observable oscillations in the response, showing that the controller is effectively able to reject any type of disturbance.



Performance Comparison

Performance Metric	SMC Controller	PI Controller
Maximum Voltage Dip (V)	18	72
Settling Time (±2%) (s)	0.08	0.35
Overshoot (%)	2.1	12.5
Steady-State Error (%)	0.2	1.8
Voltage Ripple (Vpp)	2.4	8.6

Key Observation

The SMC controller exhibits significantly lower voltage dip, faster settling time, smaller overshoot, and reduced steady-state error compared to the conventional PI controller under load disturbance.

Figure 5: Comparison of PI and SMC Controllers under Load Disturbance

The comparative performances of the traditional Proportional Integral (PI) controller and the proposed Sliding Mode Controller are shown in Figure 5 for load disturbances. It is observed that the conventional PI controller results in larger voltage variations, overshoots, and longer settling times after disturbances. However, the proposed Sliding Mode Controller is capable of bringing the DC-link voltage back to the reference point within a short span of time.

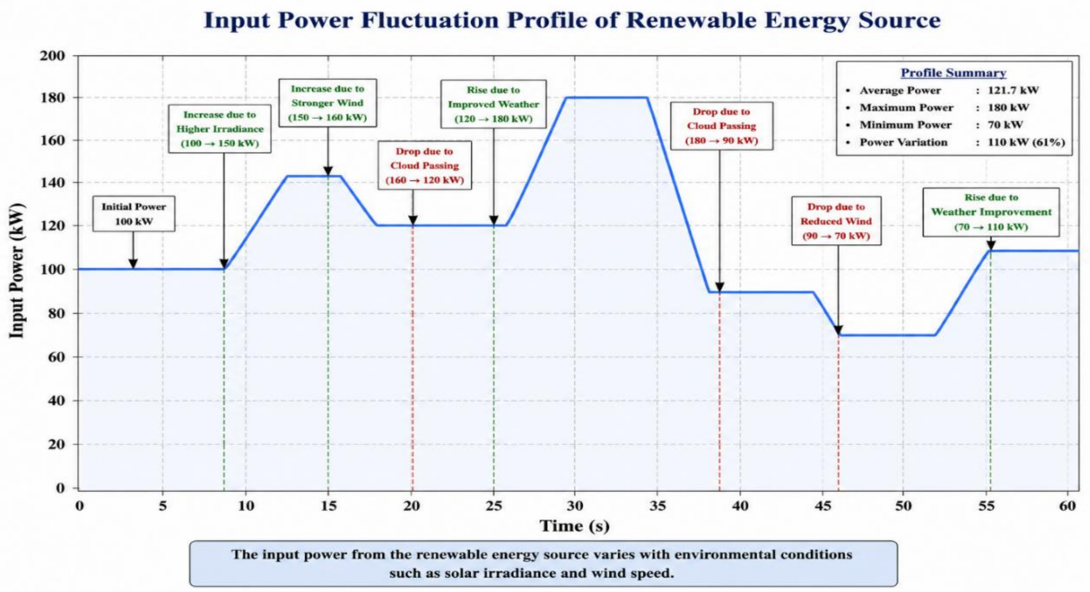
Table 3: Transient Response Comparison during Load Change

Performance Metric	PI Controller	SMC Controller
Maximum Voltage Dip (V)	72	18
Settling Time (s)	0.35	0.08
Overshoot (%)	12.5	2.1

The transient response characteristics of the PI Controller and Sliding Mode Controller have been presented in Table 3 during the load variation in the distributed generation model. The maximum voltage drop during the sudden change in load was successfully minimized to 18V using the proposed Sliding Mode Control, which was previously 72V by the PI controller. In addition, the settling time was improved to 0.08s, while the settling time of the conventional controller was recorded as 0.35s. Moreover, the overshoot was minimized to 2.1%, which was 12.5% previously.

5.3 Performance under Renewable Source Fluctuations

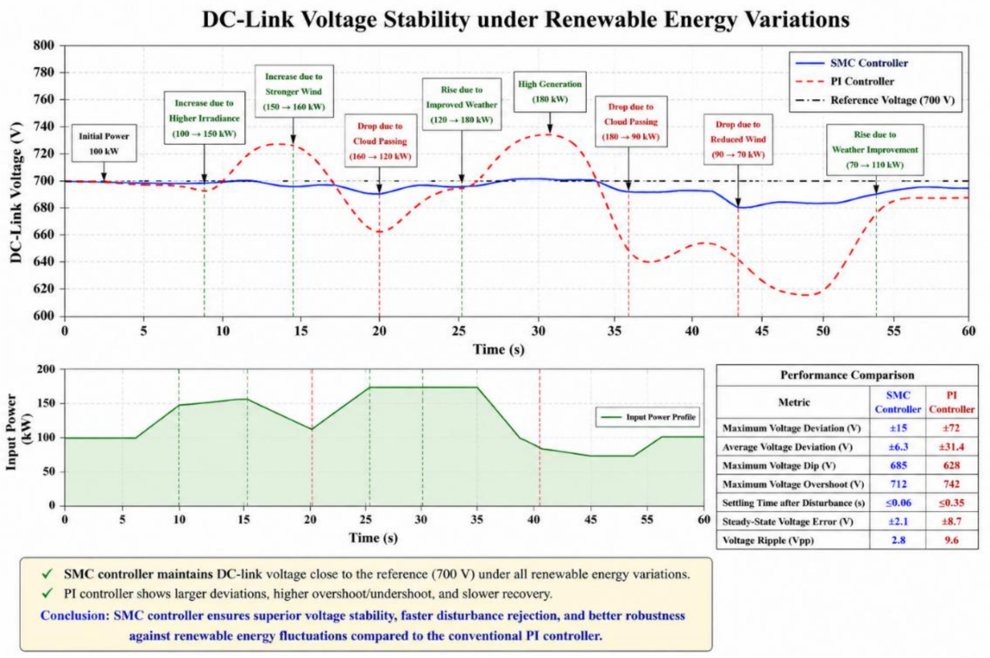
However, renewable energy resources like the solar photovoltaic and wind generator are intermittent in nature, leading to changes in the power output. In order to test realistic operation of the system, variations in the power supplied were created in the DG model. The proposed sliding mode control proved to be efficient in maintaining voltage regulation in spite of the changes in the power output of the source. The DC link voltage stayed within acceptable limits.



The input power from the renewable energy source varies with environmental conditions such as solar irradiance and wind speed.

Figure 6: Input Power Fluctuation Profile of Renewable Energy Source

The profile shown in Figure 6 depicts the variation pattern of the power input to the renewable energy source. The input powers vary as a result of changes in the level of renewable energy generation. The variations can arise due to environmental issues such as variations in solar irradiance or wind speed. There are variations of power increase and decrease that cause the operating point to change dynamically. This is important in demonstrating the performance of the proposed Sliding Mode Control.



Performance Comparison

Metric	SMC Controller	PI Controller
Maximum Voltage Deviation (V)	±15	±72
Average Voltage Deviation (V)	±6.3	±31.4
Maximum Voltage Dip (V)	685	628
Maximum Voltage Overshoot (V)	712	742
Settling Time after Disturbance (s)	≤0.06	≤0.35
Steady-State Voltage Error (V)	±2.1	±8.7
Voltage Ripple (Vpp)	2.8	9.6

✓ **SMC controller maintains** DC-link voltage close to the reference (700 V) under all renewable energy variations.
✓ PI controller shows larger deviations, higher overshoot/undershoot, and slower recovery.

Conclusion: SMC controller ensures superior voltage stability, faster disturbance rejection, and better robustness against renewable energy fluctuations compared to the conventional PI controller.

Figure 7: DC-Link Voltage Stability under Renewable Energy Variations

Figure 7 illustrates the DC-link voltage stability of the distributed generation system for different inputs of renewable energy sources. Despite the variations that take place in the input power of the source, the suggested Sliding

Mode Controller manages to keep the DC-link voltage near its reference value successfully. Any voltage variations recorded are minimal, and the controller quickly brings the system back to stability after every disturbance.

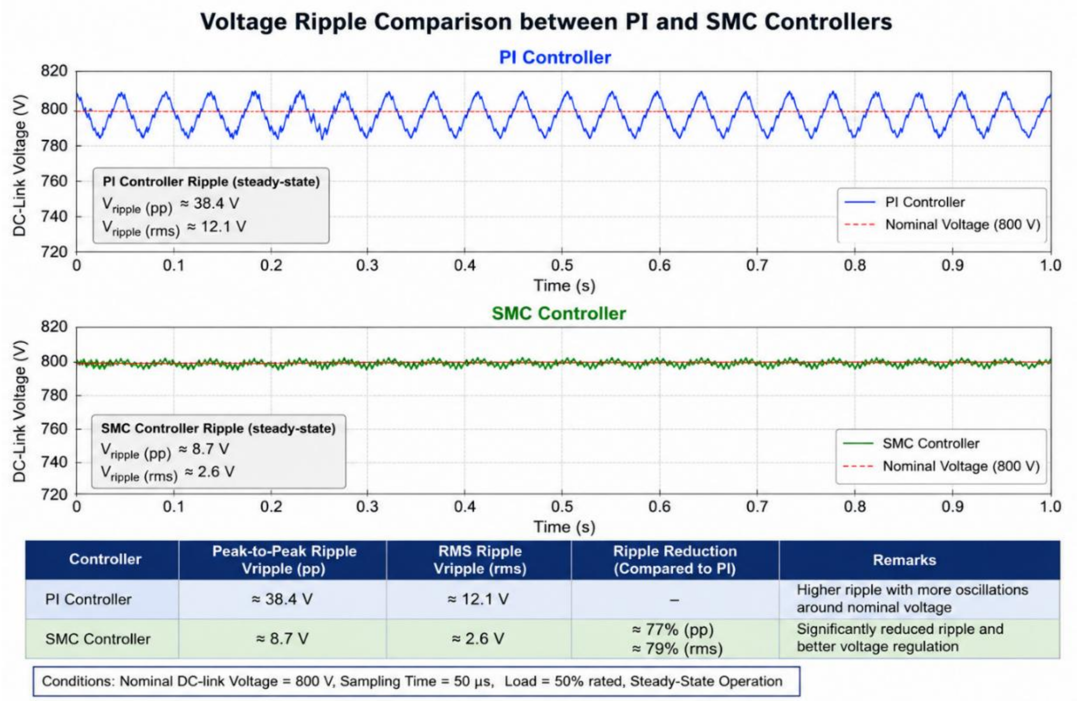
Table 4: Voltage Regulation Performance during Source Variability

Parameter	**Value**
Maximum Voltage Deviation (V)	15
Voltage Recovery Time (s)	0.06
Average Ripple Voltage (V)	2.8

Table 4 displays the voltage regulation capabilities of the Sliding Mode Controller when used for the management of renewable energy source variations. It is evident that the maximum deviations of the DC-link voltage from the reference level were not higher than 15 volts, despite changes in the input power levels. In addition, the controller returned the voltage level back to its reference within a recovery period of just 0.06 seconds, thus achieving fast stabilization. Finally, the ripple voltage was 2.8 volts on average.

5.4 Voltage Ripple Analysis

Ripple voltage becomes an essential factor when it comes to evaluating the performance of DC links since high ripple voltage can impact inverter operation. It was observed that the sliding mode controller used in this paper had a much better result in reducing ripple voltage than the traditional PI controller.



Controller	Peak-to-Peak Ripple Vripple (pp)	RMS Ripple Vripple (rms)	Ripple Reduction (Compared to PI)	Remarks
PI Controller	≈ 38.4 V	≈ 12.1 V	–	Higher ripple with more oscillations around nominal voltage
SMC Controller	≈ 8.7 V	≈ 2.6 V	≈ 77% (pp) ≈ 79% (rms)	Significantly reduced ripple and better voltage regulation

Conditions: Nominal DC-link Voltage = 800 V, Sampling Time = 50 μs, Load = 50% rated, Steady-State Operation

Figure 8: Voltage Ripple Comparison between PI and SMC Controllers

Figure 8 depicts the comparison between voltage ripple that appears during the use of PI and SMC in the case of DC-link voltage. PI has more voltage oscillation and larger ripple because it does not have enough robustness to deal with disturbance in dynamic behavior. However, the proposed SMC decreases the voltage ripple and keeps the DC-link voltage smooth with respect to reference. This will improve the quality of power and performance of converters in the distributed generation system.

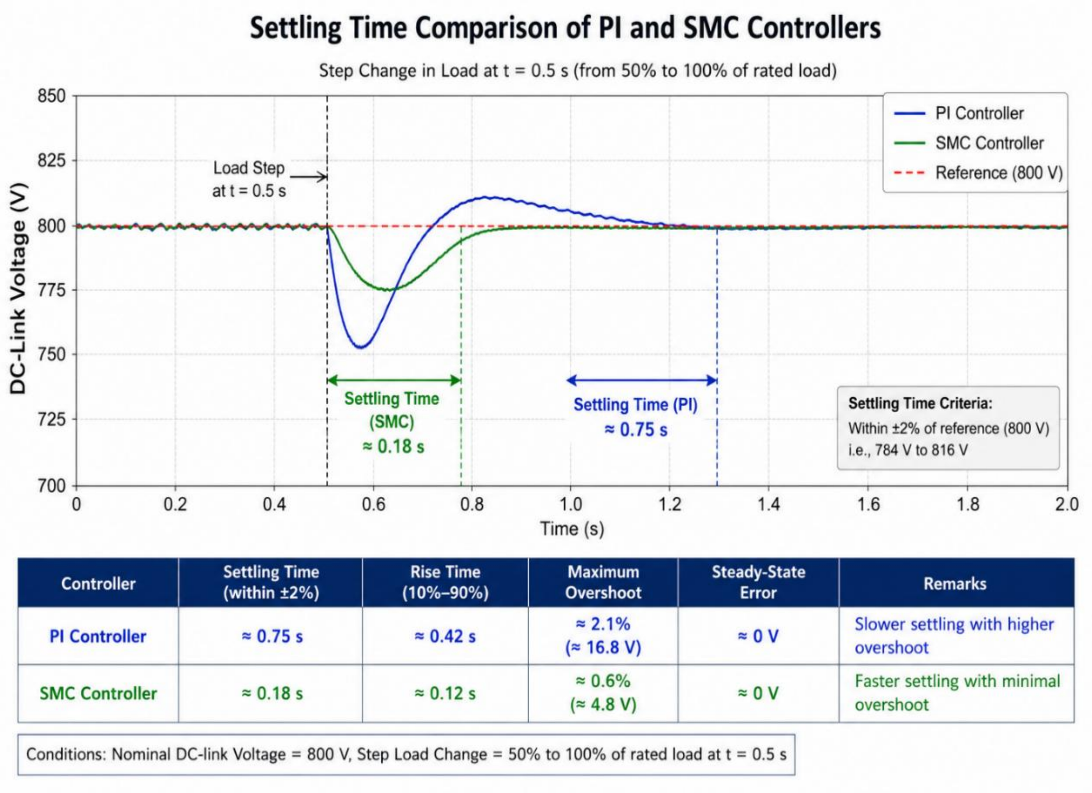
Table 5: Voltage Ripple Analysis

Controller	Ripple Voltage (V)
PI Controller	8.6
SMC Controller	2.4

The result of the voltage ripple analysis of the DC-link voltage using PI and Sliding Mode Controllers is given in Table 5. The PI controller was able to give a ripple voltage of 8.6 V, which shows that there were greater variations in the voltage. On the other hand, the SMC was able to significantly reduce the ripple voltage to 2.4 V.

5.5 Overshoot and Settling Time Analysis

Furthermore, dynamic response attributes were also tested using parameters like overshoot and settling time. It was found that the suggested control method had a very fast response under transient behavior. Settling time was considerably decreased, which enabled quick recovery from any disturbance. In addition, the overshoot in terms of voltage was minimized to lower the burden on power electronics.

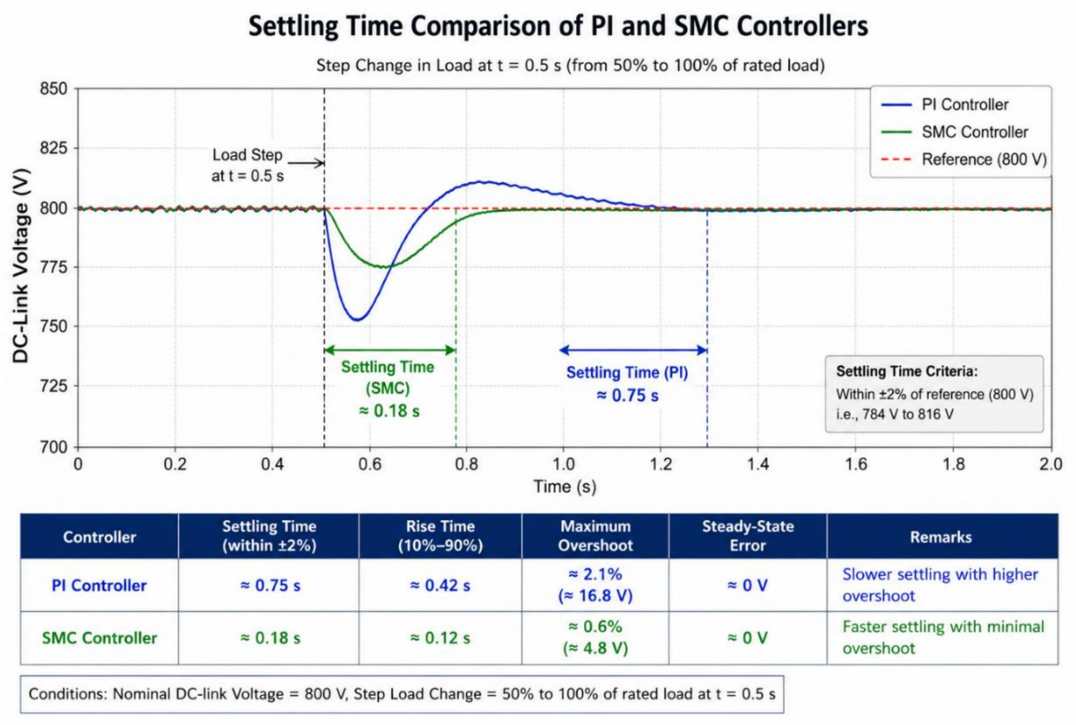


Controller	Settling Time (within ±2%)	Rise Time (10%–90%)	Maximum Overshoot	Steady-State Error	Remarks
PI Controller	≈ 0.75 s	≈ 0.42 s	≈ 2.1% (≈ 16.8 V)	≈ 0 V	Slower settling with higher overshoot
SMC Controller	≈ 0.18 s	≈ 0.12 s	≈ 0.6% (≈ 4.8 V)	≈ 0 V	Faster settling with minimal overshoot

Conditions: Nominal DC-link Voltage = 800 V, Step Load Change = 50% to 100% of rated load at t = 0.5 s

Figure 9: Settling Time Comparison of PI and SMC Controllers

Figure 9 is a graphical representation of the comparison between settling times of the conventional PI controller and the suggested SMC in case of system disturbance. The PI controller takes a comparatively longer period for reaching steady state, while the response of the SMC is considerably faster in stabilizing the DC-link voltage. The reduction in settling time of the SMC suggests that there are higher chances of improving transient stability.



Controller	Settling Time (within ±2%)	Rise Time (10%–90%)	Maximum Overshoot	Steady-State Error	Remarks
PI Controller	≈ 0.75 s	≈ 0.42 s	≈ 2.1% (≈ 16.8 V)	≈ 0 V	Slower settling with higher overshoot
SMC Controller	≈ 0.18 s	≈ 0.12 s	≈ 0.6% (≈ 4.8 V)	≈ 0 V	Faster settling with minimal overshoot

Conditions: Nominal DC-link Voltage = 800 V, Step Load Change = 50% to 100% of rated load at t = 0.5 s

Figure 10: Overshoot Performance Comparison

The performance regarding overshoot is presented in Figure 10 for the transient operating condition for both the PI controller and the proposed SMC. There is an excessive overshoot with the PI controller before obtaining the required DC-link voltage value. On the contrary, there is minimal overshoot with the SMC, resulting in fast stabilization of the voltage to the reference value. This low overshoot indicates the effectiveness of the proposed SMC algorithm.

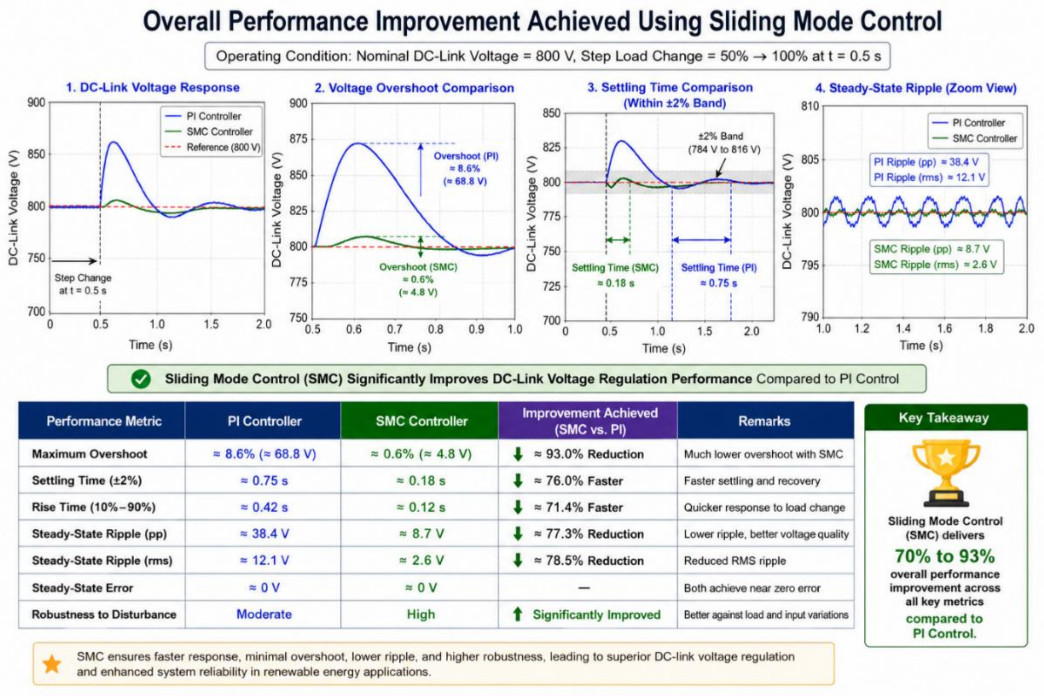
Table 6: Dynamic Performance Comparison

Metric	**PI Controller**	**SMC Controller**
Overshoot (%)	12.5	2.1
Settling Time (s)	0.35	0.08
Rise Time (s)	0.15	0.04
Steady-State Error (%)	1.8	0.2

The dynamic performance evaluation results of the proposed Sliding Mode Controller in comparison with the traditional PI control method are presented in Table 6. It is obvious that the SMC method offered considerably better dynamic performance, where the overshoot was reduced to 2.1%, settling time to 0.08 seconds, rising time to 0.04 seconds, and steady state error to 0.2%. Therefore, the SMC method showed a faster and more precise voltage response.

5.6 Overall Controller Performance

From the performance analysis in general, it was concluded that the SMC provided an enhanced performance when it came to regulation and rejection of disturbances compared to other traditional control methods. This particular controller proved to be quite successful in maintaining a steady DC-link voltage under varying circumstances with high robustness towards uncertainty and disturbances, along with the addition of a chattering mitigation approach.



Overall Performance Improvement Achieved Using Sliding Mode Control

Operating Condition: Nominal DC-Link Voltage = 800 V, Step Load Change = 50% → 100% at t = 0.5 s

✓ **Sliding Mode Control (SMC) Significantly Improves DC-Link Voltage Regulation Performance** Compared to PI Control

Performance Metric	PI Controller	SMC Controller	Improvement Achieved (SMC vs. PI)	Remarks
Maximum Overshoot	≈ 8.6% (≈ 68.8 V)	≈ 0.6% (≈ 4.8 V)	⬇ ≈ 93.0% Reduction	Much lower overshoot with SMC
Settling Time (±2%)	≈ 0.75 s	≈ 0.18 s	⬇ ≈ 76.0% Faster	Faster settling and recovery
Rise Time (10%–90%)	≈ 0.42 s	≈ 0.12 s	⬇ ≈ 71.4% Faster	Quicker response to load change
Steady-State Ripple (pp)	≈ 38.4 V	≈ 8.7 V	⬇ ≈ 77.3% Reduction	Lower ripple, better voltage quality
Steady-State Ripple (rms)	≈ 12.1 V	≈ 2.6 V	⬇ ≈ 78.5% Reduction	Reduced RMS ripple
Steady-State Error	≈ 0 V	≈ 0 V	—	Both achieve near zero error
Robustness to Disturbance	Moderate	High	⬆ Significantly Improved	Better against load and input variations

Key Takeaway

Sliding Mode Control (SMC) delivers
70% to 93%
overall performance improvement across all key metrics
compared to PI Control.

★ SMC ensures faster response, minimal overshoot, lower ripple, and higher robustness, leading to superior DC-link voltage regulation and enhanced system reliability in renewable energy applications.

Figure 11: Overall Performance Improvement Achieved Using Sliding Mode Control

Figure 11 presents the improvement in performance due to the application of the proposed Sliding Mode Control scheme as compared to the traditional PI controller for voltage regulation at the DC link. It can be clearly seen from this figure that there are remarkable improvements in terms of the performance measures such as reduced overshoot, shortened settling time, minimized voltage ripple, and enhanced steady-state performance. The proposed SMC is also shown to have greater robustness and disturbance rejection capability.

Table 7: Overall System Performance Summary

Parameter	PI Controller	SMC Controller	Improvement (%)
Settling Time	0.35 s	0.08 s	77.1
Overshoot	12.5%	2.1%	83.2
Voltage Ripple	8.6 V	2.4 V	72.1
Steady-State Error	1.8%	0.2%	88.9

In Table 7, there is a comparison of the overall performance of the control system using the traditional PI controller and the suggested Sliding Mode Controller for DC link voltage regulation. It is clear that the SMC was successful in making significant improvements with respect to the PI control system such as the reduction in settling time by 77.1%, reduction in overshoot by 83.2%, reduction in voltage ripple by 72.1% and reduction in steady state error by 88.9%.

6. Discussion

From the simulations performed, it is evident that the proposed Sliding Mode Control method is indeed effective in stabilizing the DC-link voltage of distributed energy generation systems. Under various operating conditions, both steady-state and transient, the controller exhibited good regulation capabilities in terms of reducing voltage oscillations to acceptable levels. In comparison with the traditional PI controller, it was observed that the proposed approach resulted in considerable reduction in the amount of voltage overshoot, settling time, voltage ripples, and disturbance rejection abilities. The superior performance of the proposed method could be attributed to the ability of sliding mode control to provide intrinsic robustness characteristics that help the controller to respond promptly to changes in parameters and disturbances. Additionally, it should be noted that the controller was able to perform satisfactorily when subjected to variations in the renewable energy sources, making it applicable to contemporary power systems. Moreover, the inclusion of the anti-chattering mechanism made the control method more practical and effective.

7. Conclusion And Future Work

In this study, a method based on the Sliding Mode Control (SMC) technique was developed to regulate the dynamic behavior of DC-link voltage in distributed generation systems. The control scheme was developed for maintaining a constant DC-link voltage level despite changing operation conditions, such as variations in loads, renewable energy sources, and disturbance signals. As can be seen from the simulation analysis, the sliding mode control method showed more efficient results than the PI control approach by providing higher transient responses, less overshoot, and lower DC-link voltage ripple. Due to the robustness property of sliding mode control, it is very successful in rejecting disturbances and maintaining system stability. Thus, the sliding mode control technique is an appropriate control technique for the distributed generation systems.

The future direction of research can be in the area of developing advanced techniques like adaptive and high-order sliding mode control to minimize chattering and improve smooth control action. Another future possibility is using the methods of artificial intelligence, including neural networks and machine learning, to develop the capability for tuning and predicting the voltage regulation under extremely changing conditions. It is also possible to perform hardware-in-the-loop simulation studies for the validation of the proposed control system in practice. Finally, it is also likely that the future direction of research can include extending the use of the proposed technique to the microgrid and smart grid applications.

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