

Sliding Mode Control with Direct Power Control for Three-Phase AC-DC Converter

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Abstract

Three-phase AC-DC converters are common in the contemporary power electronic systems like power interfaces of renewable energy sources and sources, motor drive, electric vehicle charge stations, and high-voltage DC transmission. These applications need converters that have the ability to hold a steady DC-link voltage and at the same time achieve high power quality at the grid interface. The traditional diode rectifiers cannot fulfill these necessities because of low power factor and high levels of harmonic distortions. Thus, the pulse-width modulation (PWM) rectifiers along with the sophisticated strategies of control have been utilized as one of the vital solutions in power conversion systems of the modern era. This paper gives a Direct Power Control (DPC) approach to a three-phase AC to DC converter combined with Sliding Mode Control (SMC) to control DC-link voltage. The suggested solution applies a classical switching-table-based DPC scheme to directly control the active and reactive power exchanged between the converter and the grid at the moment. Sliding mode control would be introduced in outer control loop to make the voltage regulation more robust and dynamic performance of the system during disturbances and variations in parameters. A mathematical model of converter system is prepared and run in MATLAB/Simulink. It is tested on the proposed control system under various operating conditions such as steady-state operation, changes in loads, grid voltage disturbances and changes in the DC-link capacitance. The simulation findings reveal that the proposed DPC-SMC approach has faster transient response, better disturbance rejection capacity, less DC-link voltage ripple and less harmonic distortion than the traditional PI-based DPC control. The converter operates with almost unity factor power operation with sinusoidal input currents. The findings show that sliding mode control combined with direct power control serves as a viable and effective control device to power electronic devices when connected to the grid using AC-DC converters in contemporary power electronics.

Keywords

Direct Power Control, Sliding Mode Control, Three-Phase PWM Rectifier, AC-DC Converter, DC-Link Voltage Regulation

1. Introduction

Power electronic converters are a significant part of the current energy systems with the further adoption of renewable energy sources, electric vehicles, and smart grid technologies. Among the various converter topologies, the three-phase AC-DC converter, also known as the PWM rectifier, has become a key component in modern industrial and grid-connected applications. These converters offer regulated conversion of AC power to DC power and they retain high quality of power at the grid side [1]. The diode bridge rectifiers are commonly applied because of their simplicity and low cost. They however are afflicted with a number of shortcomings such as low power factor and high harmonic distortion in the input currents. These disadvantages render them inappropriate to contemporary uses where power quality and power saving are fundamental elements [2]. In order to address these shortcomings, controlled PWM rectifiers based on semiconductor switches like insulated gate bipolar transistors (IGBTs) have been created. These converters enable the two-way flow of power, better power factors correction, and less harmonic distortion. The level of their performance is greatly influenced by the control method employed to control the operation of the converters [3]. A number of control techniques have been suggested on PWM rectifiers such as Voltage-Oriented Control (VOC), Direct Power Control (DPC), predictive control, and nonlinear control techniques. The capability to decouple active and reactive current components in a synchronous reference frame has led to the wide use of voltage-oriented control. Nevertheless, this technique needs coordinate translations, phase-locked loops and fine-tuning of PI controllers, which complicate the system [4]. Direct Power Control has become one of the promising alternatives because it has a simpler structure and its dynamic response is very fast. In DPC, active and reactive power are directly regulated in real time without the utilization of inner current loops. Hysteresis comparators and switching tables are used to choose switching states of the converter depending on power errors and position of the grid voltage vectors [5]. Although it has its merits, classical switching-table-based DPC has a number of drawbacks including variable switching frequency and power ripple. These constraints drive the incorporation of new nonlinear control techniques in enhancing system performance [6].

The Sliding Mode Control (SMC) is a nonlinear control method that has been characterized by great ability to withstand changes in parameters and external interferences. SMC controls a system state by imposing force on the system to approach a predefined sliding surface and stay there in response to the system operating conditions that are uncertain [7]. There has been recent study on the imple-

2.1. System Modeling

The system is made of a three-phase AC source that is linked to a two-level voltage source converter (VSC) via an RL filter. It is constructed of 6 IGBT switches, and drives a DC link capacitor to a resistive load. The RL filter not only suppresses current ripple but also minimizes harmonic distortion but the DC-link capacitor stabilizes the output voltage.

The dynamic equations of the system in the reference frame of the abc are:

$$v_a = Ri_a + L \frac{di_a}{dt} + v_{ca}$$

$$v_b = Ri_b + L \frac{di_b}{dt} + v_{cb}$$

$$v_c = Ri_c + L \frac{di_c}{dt} + v_{cc}$$

R and L are filter parameters. The converter voltages are subject to switching states, which make eight possible combinations (six active and two zero vectors). A Clarke transformation is used to bring the variables into the $\alpha\beta$ frame in order to implement control. This makes the model simpler and makes it possible to directly compute the instantaneous power:

$$P = \frac{3}{2}(v_\alpha i_\alpha + v_\beta i_\beta)$$

$$Q = \frac{3}{2}(v_\beta i_\alpha - v_\alpha i_\beta)$$

The capacitor energy balance determines the DC-link voltage, in which the active power has a direct effect on the DC voltage.

2.2. Direct Power Control

Direct Power Control uses no inner current loop active or reactive power regulation. The errors in the power are determined as:

$$P_e = P_{ref} - P$$

$$Q_e = Q_{ref} - Q$$

Reactive power reference:

$$Q_{ref} = 0 \quad \text{to ensure unity power factor}$$

These inaccuracies are worked with by hysteresis controllers which produce switching decisions. The grid voltage vector position is calculated as:

$$\theta = \tan^{-1} \left(\frac{v_\beta}{v_\alpha} \right)$$

The $\alpha\beta$ plane is further subdivided into six sectors and a switching table is employed to choose the voltage vector that will lead to minimal power error. Despite the rapid response and easy implementation of DPC, the method has several disadvantages, such as changing switching frequency, power ripple, sensitivity to pa-

parameter changes, especially DC-link capacitance. These restrictions encourage the adoption of a stronger external control policy.

2.3. Sliding Mode Control

The use of Sliding Mode Control is used to control the DC-link voltage and enhance robustness.

$$e = V_{dc}^{ref} - V_{dc}$$

Sliding surface:

$$S = e$$

The control objective is to force $S \rightarrow 0$, ensuring voltage stability. The control law is given by:

$$P_{ref} = P_{eq} + k \text{sat}(S/\phi)$$

where P_{eq} is the equivalent active power needed to maintain energy balance at the DC-link, k is the gain of the sliding mode algorithm which determines the convergence speed towards the sliding surface and ϕ is the boundary-layer thickness in the saturation function to minimize chattering effect. The energy stored in the capacitor is proportional to the DC-link voltage, $E = 1/2 CV_{dc}^2$, and the active power flow is controlled by the sliding mode controller to ensure the voltage stability under the influence of parameter variations and external disturbances. The proposed control strategy not only enhances the robustness, but also maintains the fast dynamic response of Direct Power Control.

2.4. Simulation and Evaluation

MATLAB/Simulink with a discrete solver and small-time step is used to implement the system and capture switching dynamics. The primary parameters are a grid of 400 V (between-lines), a frequency of 50 Hz, a RL filter, DC-link capacitor, and resistive load. The test cases to be considered include: conventional DPC with PI control, DPC with SMC, capacitance variation ($C/2$ and $2C$), load step change and grid voltage disturbance. The evaluation criteria are performance (in terms of THD (through FFT analysis)), DC-link voltage ripple, settling time, overshoot, and power factor. The outcomes are contrasted with the current methods of DPC in order to confirm the efficiency of the offered control strategy. The simulation results are described in **Table 1**.

The tuning of the PI controller of the conventional DPC scheme was done for satisfactory dynamic performance under nominal operating condition. The final gains $K_p = 0.8$ and $K_i = 120$. With the proposed sliding mode controller, the sliding gain $k = 150$ and boundary layer thickness $\phi = 0.02$ were designed. The two controllers were tested under the same operating conditions, reference voltage and converter parameters for a fair comparison.

The capacitance in the nominal DC-link, $C = 2200 \mu\text{F}$, was chosen. The capacitance variation tests were performed for the robustness analysis as $C/2$, $1100 \mu\text{F}$ and $2C$, $4400 \mu\text{F}$. A load step variation from 100Ω to 50Ω was applied at $t = 0.50$

s. A 20% voltage sag (VS) was applied for 0.2 s from $t = 0.80$ s to $t = 1.00$ s to test the grid disturbance. To assess controller robustness and disturbance rejection capability these operating conditions were used.

Table 1. Simulation parameters.

Parameter	Value
Grid Voltage (Line-Line RMS)	400 V
Grid Frequency	50 Hz
Filter Resistance (R)	0.5 Ω
Filter Inductance (L)	5 mH
DC-Link Capacitance (C)	2200 μ F
Load Resistance	100 Ω
DC-Link Reference Voltage	700 V
Sampling Time	10 μ s
Solver Type	Discrete

2.5. Performance Metrics

Settling time is the time taken for the response of the DC-link voltage to be within $\pm 2\%$ of the final steady-state value. The rise time is the time it takes for the response to go from 10% to 90% of the final value. Steady state error is the percentage difference between the reference and final output voltage. Voltage ripple refers to the maximum deviation, from peak to peak, of the DC-link voltage from the steady-state operation. The measure of active power ripple is defined as the peak deviation of the active power from the average value. The evaluation of the Total Harmonic Distortion (THD) is performed with FFT analysis after the transient conditions have totally ceased in a steady state period of 0.2 s. The power factor is determined by the ratio between the active power and apparent power at the grid interface.

3. Results

Conventional Switching Direct Power Control (DPC) and proposed Sliding Mode Control-based DPC (DPC-SMC) are used to assess the performance of the three-phase AC-DC converter. The outputs are achieved when the operating conditions are varied such as nominal operation, change in parameters, and disturbances. The analysis is based on DC-link voltage regulation, power tracking, harmonic performance, transient response and robustness. The control strategies control the DC-link voltage to the reference under nominal steady-state conditions. Nevertheless, some distinct differences in dynamic behavior and steady-state quality are evident. The traditional DPC exhibits appreciable swinging of the DC-link voltage owing to reliance of the PI controller on the gain tuning. Conversely, DPC-SMC method converges quicker with lower ripple and better voltage stability. The

active power response also indicates the improvement with the proposed method exhibiting smoother response to the tracking with less oscillations about the reference value. The VDC with and without Sliding Mode Control is described in **Figure 2**.

Table 2 presents the performance parameters comparison in the quantitative manner. The settling time has been shortened to 12 ms versus 22 ms, the active power ripple has been lowered to ± 90 W versus ± 180 W. The consistent error value is also minimized, which implies there is enhanced accuracy in power control. **Table 2** gives the performance under a nominal condition of both the models.

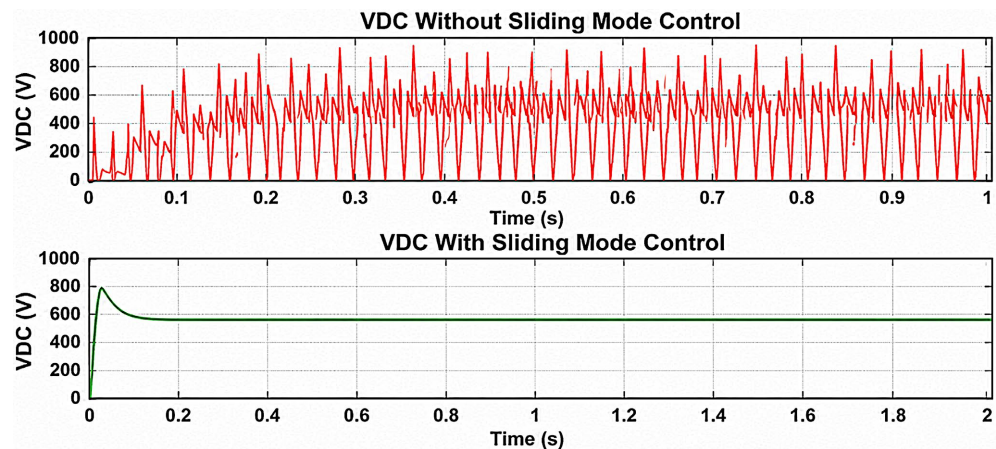


Figure 2. VDC without (Up) and with (Down) sliding mode control.

Table 2. Performance under nominal conditions

Parameter	Conventional DPC	Proposed DPC-SMC
Settling Time (ms)	22	12
Power Ripple	± 180 W	± 90 W
Steady-State Error	1.8 %	0.6 %

The active and reactive power reactions also confirm the enhanced performance. The two systems have almost zero reactive power under steady-state conditions, but when there are transient conditions, the traditional DPC shows short-term deviations. The suggested DPC-SMC is more stable that leads to a high performance of power factor. **Figure 3** characterizes the Active and Reactive Power Response sliding mode control.

The harmonicity of converter is measured by FFT analysis of the input current waveform. The standard DPC is a relatively distorted current generator by virtue of variable switching frequency. The suggested DPC-SMC will lead to a less distorted smooth waveform. The two systems meet the requirements of the IEEE-519 standard, but the planned approach has reduced the overall harmonic distortion. **Table 3** explains the harmonic performance of models.

The proposed DPC-SMC strategy caused a power factor to be 0.998 while the conventional DPC resulted in a power factor of 0.984. Both controllers meet the

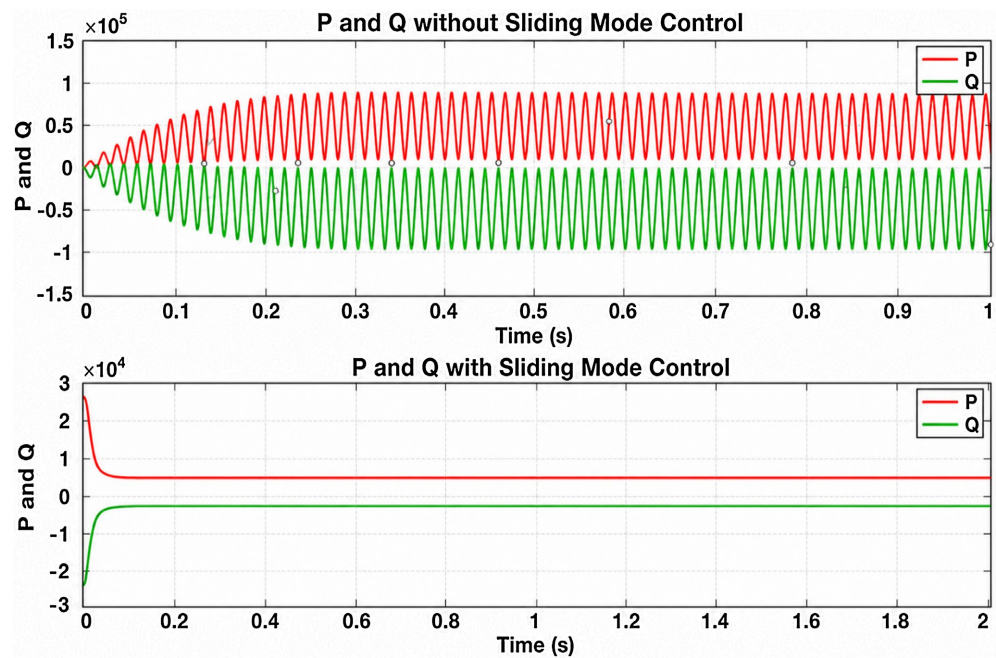


Figure 3. Active and reactive power response.

Table 3. Harmonic performance.

Parameter	Conventional DPC	Proposed DPC-SMC	IEEE Limit
THD (%)	4.7	2.9	<5
Power Factor	0.984	0.998	>0.95

standard for power quality in the grid, but the proposed controller exhibits a better power factor performance. The effect of the change in the DC-link capacitance is also studied. For both systems, the reduction in capacitance ($C/2$) would lead to a rise in voltage ripple due to the reduction of energy storage. With conventional DPC, however, the increase is much more, as the parameters are more prone to change. The suggested DPC-SMC is stable in operation and the ripple increase is less. Doubling the capacitance ($2C$) causes a reduction in the ripple in the voltage but slower system response. Nevertheless, even the proposed approach is still faster to stabilize than the conventional one. The VDC at $C/2$ and $2C$ was described in **Figure 4**.

The evaluation of disturbance response was carried out with a 20% grid voltage sag between 0.80 s and 1.00 s and a load-step variation between 100 Ω and 50 Ω at 0.50 s. In the voltage sag mode, the conventional DPC had the voltage offset of about 18 V at the DC-link and it took about 25 ms for the conventional DPC to recover. Again, when the load was increased, the conventional system had a voltage drop of around 12 V while the proposed controller had a voltage drop of around 5 V and recovered to the reference voltage in a much shorter time. The reason of the voltage and current during the disturbances of the two models are explained in **Figure 5**.

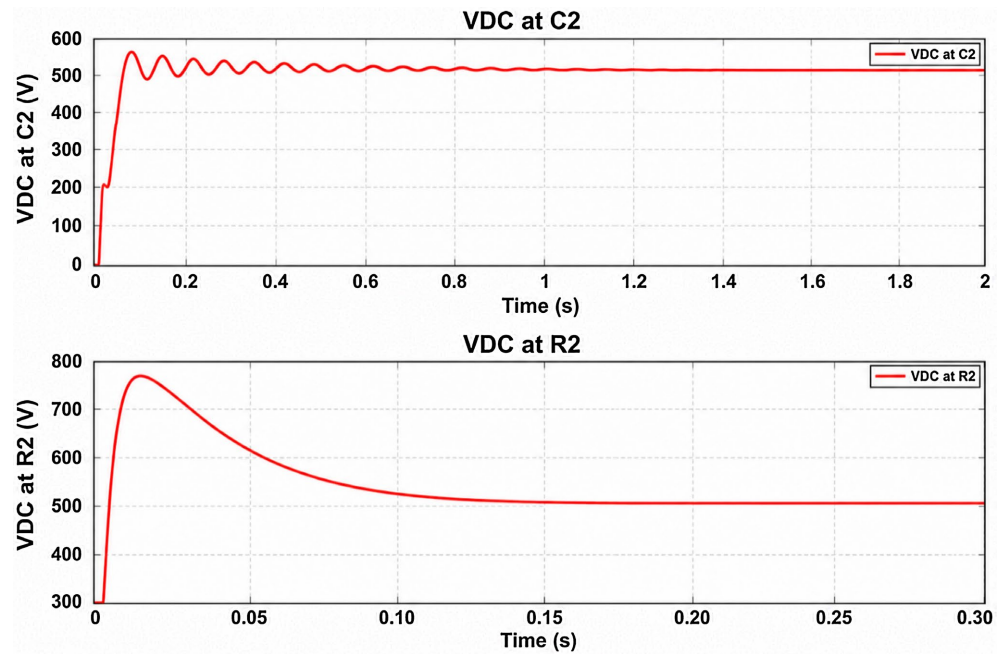


Figure 4. VDC at $C/2$ (Up) and $2C$ (Down).

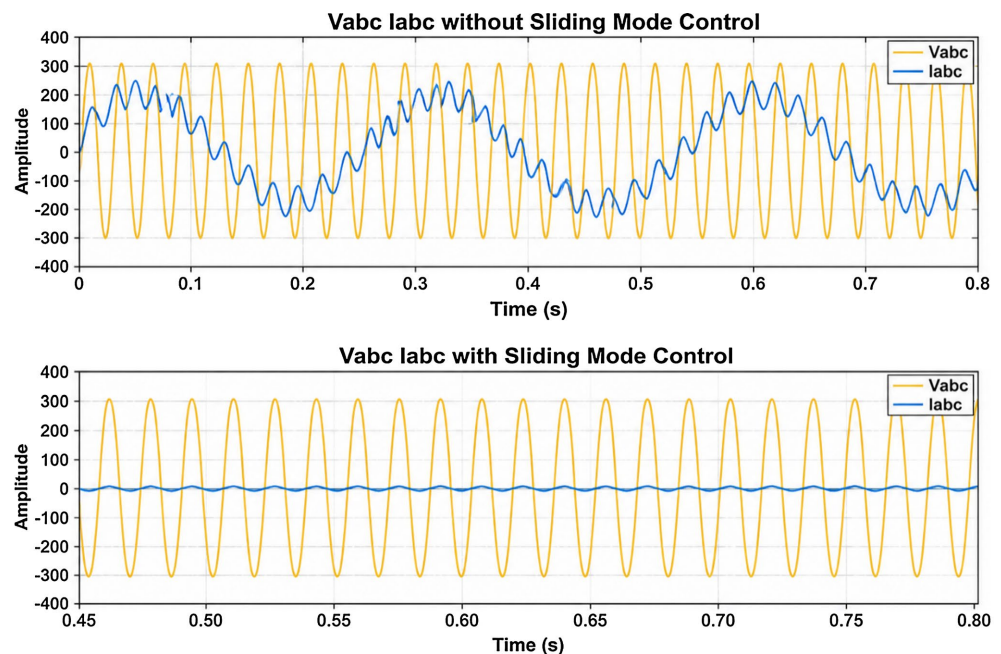


Figure 5. Voltage and current under disturbance.

Rise time, settling time, overshoot and voltage ripple are used to analyze the transient performance. The suggested DPC-SMC demonstrates a steady increase in all metrics, which means that the system is responding quicker and is more stable. **Table 4** explains the comparison of the dynamic performance of both models.

Lastly, the robustness is tested by considering the behavior of the system when parameters change and when there are disturbances. The conclusion is summarized in **Table 4**. Conventional DPC depicts greater ripple and slower reaction

with compressed capacitance and load variations. Conversely, the suggested technique has a stable operation with lesser ripple and quicker recovery. **Table 5** provides the scenario in different capacitive values of both models of ripple.

Table 4. Dynamic performance comparison.

Metric	Conventional DPC	Proposed DPC-SMC
Rise Time (ms)	15	9
Settling Time (ms)	22	12
Overshoot (%)	10	4
Voltage Ripple (V)	4.8	2.1

Table 5. Robustness under parameter variation.

Scenario	Conventional DPC	Proposed DPC-SMC
C	Stable	Stable
$C/2$	High ripple (~ 7 V)	Low ripple (~ 3 V)
$2C$	Slow response	Faster stabilization
Load Increase	Voltage dip ≈ 12 V	Smaller dip ≈ 5 V

On the whole, all the findings indicate that the suggested DPC-SMC control strategy enhances the voltage regulation, power tracking, harmonic performance, transient response, and resilience in various operating conditions.

4. Discussion

It is evident in the results obtained that the proposed control strategy enhances the performance of the three-phase AC-DC converter in general. This increase can be primarily attributed to the fact that the sliding mode control is used, a non-linear corrective mechanism is adopted rather than the linear PI regulation. In contrast to the traditional method, the performance is largely defined by the precision of the gain tuning, the sliding mode controller drives the system states to a certain surface, which results in the faster and more stable response. This difference is brought out by the behavior of the DC-link voltage. Oscillations are realized in the traditional DPC system as a result of the sluggish response of the PI controller particularly when the parameters of the system vary or disturbances are present. Conversely, DPC-SMC approach exhibits lower ripple and settling. This proves the fact that the nonlinear action of control is better in managing voltage deviations. The lower steady-state error also signifies that the system is able to control correct voltage regulation without repeated tuning. The active power tracking is also improved. The switching, which is based on the hysteresis in the classical form of DPC, makes the power to oscillate with respect to the reference value. The offered approach minimizes these oscillations since the scheme of the sliding mode controller modifies the reference more efficiently, depending on the

voltage difference. This translates to more stability and ease of power delivery. The decrease in the power ripple that is available in the results confirms this explanation. The benefit of the offered method is also manifested in reactive power behavior. Even though both of the control strategies seek unity power factor, the traditional system demonstrates short-lived deviations in transient situations. This is due to the fact that the DC-link voltage will need a longer time to stabilize. In DPC-SMC the quicker correction of voltage indirectly enhances the control of reactive power. Consequently, the system is able to keep reactive power very low even in disturbance, which is of interest when connected to a grid. Another aspect is important in the harmonic performance results. Although switching states are not directly changed by sliding mode control, stability of the system is enhanced, resulting in an improvement of current waveform quality. The decrease in the overall harmonic distortion between 4.7 percent and 2.9 percent reveals that stabilization of the DC-link voltage has a direct influence on the smoothness of the current. This trend is in line with the established findings in the power electronics field, in which harmonic performance is directly related to voltage stability.

The response to capacitance changes also justifies the strength of the suggested approach. A smaller capacitance means that the system will be sensitive in that the energy storage capability is lowered. This causes huge ripple on voltage and lower stability in the traditional DPC. Nevertheless, the DPC-SMC does not have a very high ripple and can be used at an acceptable performance. This demonstrates that controller does not rely on the system parameters. Increasing the capacitance slows down both systems by increasing energy storage and yet the proposed approach demonstrates quicker recovery. This implies that system dynamics have less influence on sliding mode control. Another improvement is disturbance rejection capability. The proposed controller exhibits reduced voltage variations and higher recovery during grid voltage sag, and abrupt load variations. This can be attributed to the powerful corrective response of the sliding mode control that responds instantly to the errors of the system. Conversely, the PI controller reacts slowly and thus it produces greater deviations. The findings verify the fact that the suggested approach is capable of dealing with real-life disturbances more efficiently. These observations are also backed by the transient response analysis. The decrease in rise time, settling time and overshoot indicates that the system takes less time to reach a steady-state, and the system has reduced fluctuations. This is through the direct consequence of finite-time convergence property of the sliding mode control. In contrast to linear controllers, which move the system to the desired operating point gradually, sliding mode control moves the system to the desired operating point in a short time. Comparing the results with the recent literature, the results obtained are within the reported ranges of performance or are even higher. Similar improvements can be obtained using many sophisticated methods of control, including predictive or adaptive control, but these methods usually involve more complex implementation and increased computation. The proposed DPC-SMC approach is a simpler one and still has good performance.

This simplicity/effectiveness balance can be considered a significant strength in the practice of its application. Comprehensively, it is evident in the analysis that when sliding mode control and direct power control are integrated, it results into better performance of the converter based on stability, dynamic response, harmonic quality and robustness. The gains are not made in one condition but are uniform in various operating conditions such as variations in parameters and perturbations. This renders the suggested approach applicable in the contemporary power electronic schemes in which dependability and quick reaction is essential.

5. Conclusion

This paper gave a comparative study of a three-step AC-DC converter with the traditional Direct Power Control (DPC) and the proposed Sliding Mode Control-based DPC (DPC-SMC). The test was conducted with varying operating conditions such as steady-state, parameter changes, and disturbances conditions. The outcomes indicate that the suggested DPC-SMC approach offers obvious gains in the overall system functioning. The DC-link voltage regulation is more stable, and it has lower ripple and shorter settling time. Active power tracking has display of lower oscillations and reactive power has been maintained nearer to zero, which guarantees the enhancement of power factor. The harmonic analysis also reveals that the suggested approach suppresses the total harmonic distortion, as compared to conventional DPC, yet meets the standard limits. The other significant result is the increase in the strength of the system. The suggested controller will be stable during capacitance change and load perturbation and experience smaller voltage change and rapid recovery. The response is also improved, and the rise time, settling time, and overshoot are minimized. These gains can be largely attributed to the fact that sliding mode control is nonlinear and exerts good corrective action and less reliance on fine-tuning of parameters. The proposed DPC-SMC method has a competitive performance relative to more complicated control methods that are reported in recent literature with a simple structure. This renders it applicable to real world implementation in the present day power electronic systems. Comprehensively, sliding mode control implementation in direct power control can provide a consistent and effective solution to grid-connected converters particularly in those cases where the response time, strength, and energy quality are of concern.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

Abbreviation	Description
V_{DC}	DC-link voltage across the capacitor
V_{DC}^{ref}	Reference (desired) DC-link voltage
C	DC-link capacitance
P	Active power
P^{ref}	Reference active power
Q	Reactive power
Q^{ref}	Reference reactive power
V_{abc}	Three-phase input voltages
I_{abc}	Three-phase input currents
e_v	DC-link voltage error
THD	Total Harmonic Distortion (measure of waveform distortion)
t_s	Settling time
t_r	Rise time
ΔV_{DC}	DC-link voltage ripple
ΔP	Active power ripple