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PERFORMANCE ANALYSIS OF A SOFT SWITCHED SINGLE ACTIVE BRIDGE DC-TO-DC CONVERTER UNDER TRANSIENT REGION AND LINE VARIATION USING A SLIDING MODE CONTROLLER

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Abstract
With the increased popularity of efficient and robust DC/DC converters in renewable energy, electric vehicles and industry, there is a rising need for advanced control techniques that are able to account for nonlinearities and dynamical disturbances. Among isolated converter topologies, the Single Active Bridge (SAB) converter has attracted attention for its simple structure, low conduction losses and soft-switching capability. However, conventional Proportional-Integral (PI) controllers usually showed poor dynamic performance under the transients and the line variation conditions with high overshoot, long settling times and standing oscillations. This paper attempts to fill these gaps by developing and implementing a Sliding Mode Controller (SMC) for a soft-switched SAB converter. The performance of the converter was tested in steady state, transient and line variation scenarios after developing a detailed MATLAB/Simulink model. Comparative analysis showed that whereas PI controller resulted in huge overshoot (133 V) with long settling time (320 ms) under transient conditions, SMC resulted in overshoot of 28.5 V and settling time of 80 ms, while oscillations were completely eliminated under line fluctuations. These results have confirmed the dominance of SMC as a nonlinear control technique and its robustness, reliability, and suitability for high-performance SAB converter applications in today's energy and automotive systems.

INTRODUCTION

With the rapid development and penetration of renewable energy systems, electric vehicles, and advanced electronic devices, power electronic converters are being pushed to deliver more. In this respect, DC-DC converters are fundamental to achieve stable and efficient power transfer between different voltage levels allowing the integration of different sources and loads. A DC/DC converter is basically an electronic device that does voltage conversion (up or down) of a direct current voltage with relatively low power losses and high efficiency. These converters have a broad range of applications in consumer electronics, communications systems, power supplies, renewable energy generation,

electric mobility, and aerospace (Nayanasiri & Li, 2022; Litran et al., 2022). With the progressing development of high-performance systems, improving the reliability, stability, and robustness of DC-DC converters has been an increasing concern (Selvabharathi and Kannan, 2023; Affam et al., 2021).

Among the wide family of DC/DC converters, the Single Active Bridge (SAB) converter has attracted a great deal of attention owing to its relatively simple structure, low conduction losses and soft-switching capability (Demetriades and Nee, 2005; Lenke et al. 2009). With the advantage of efficient unidirectional power transfer with low switching stress, the SAB topology has been of great interest for medium- and high-power applications including electric vehicle charging, solid-state transformers, renewable energy integration, and HVDC systems (Wang et al., 2018; Pereira et al., 2021). Despite these benefits, SAB converters are fundamentally nonlinear and present dynamic behaviors which make them difficult to control, especially under transient and line variation conditions (Sang et al. 2018; Park and Chen 2013).

In order to solve such dynamic problems, classical linear controllers including Proportional-Integral (PI) strategy have been traditionally used. While PI controllers are simple and widely implemented in industry, they do have some serious limitations. Notably, PI controllers do not perform well in the presence of system nonlinearities, parameter variations and sudden disturbances. The limitations include overshoot, slow settling time and persistent oscillations in the transient as well as line variation conditions (Finaviya et al., 2017; Sen et al., 2018). For SAB converters specifically, PI control strategies have been reported to introduce ripples in output voltage and current, which leads to lower efficiency of the converter, and ultimately the system performance (Jha et al., 2022; Ting et al., 2016).

With the recent development of nonlinear control techniques, Sliding Mode Control (SMC) has been applied to the field of power electronics. SMC is a robust nonlinear control approach to enforce the states of the system to follow a desired trajectory by switching control signals over a predefined sliding surface (Taheri et al., 2019; Trinh et al., 2023). Its natural robustness ensures performance under extensive parameter uncertainties, external disturbances and fast operating condition changes. In addition, SMC is known to have good dynamic response, stability and suitable for high nonlinear systems like dc-dc converters (Cucuzzella et al., 2018; Rajakumar et al., 2020). Many papers have shown the use of SMC in boost converter, microgrid system, and photovoltaic applications and proved the superiority of SMC over conventional PI or PID controller (Chincholkar et al., 2018; Qi et al., 2020).

The use of SMC for SAB converter is relatively less investigated, but it is expected to provide a significant increase in the performance. By completely or partially removing overshoot and significantly reducing the settling time, SMC is able to improve the reliability of SAB converters in mission-critical applications such as aerospace systems, smart grids and high-voltage DC network (Derbeli et al., 2020; Rizi et al., 2020). However, issues such as chattering, i.e. unexplored high-frequency vibrations around the sliding surface, must be overcome for feasible implementation (Maheswararao et al., 2011; Perunièvic-Drazenovic et al., 2023). To overcome this, hysteresis modulation methods and hybrid models of PI and SMC have been proposed.

Therefore, this paper is devoted to the design and analysis of a Sliding Mode Controller for a soft-switched SAB converter. The controller is tested with the transient and line variation conditions and is compared with a traditional PI controller. It is to show that SMC outperforms the existing control methods in terms of robustness, dynamic performance, and efficiency, and thus contribute to the recent research trend in advanced control methods for DC/DC converters. The results from this research will give useful insight into the use of SMC on nonlinear converter topologies and will reveal its potential to be used in future industrial and renewable energy applications.

2. Literature Review

2.1 Importance of DC–DC Converters in Modern Systems

DC/DC converters are the workhorses of power management for renewable, automotive and industrial applications. They offer an efficient

voltage conversion, which allows several sources and several loads to be integrated within the same system (Hossain et al. 2018). The converters should be able to operate under transient input and load conditions with efficiency and stability, and this has placed demands for advanced control systems (Turksoy et al., 2020). In particular, single open-loop converters such as SAB are considered desirable due to their features of galvanic isolation and high efficiency for medium- as well as high-power applications (Paez et al., 2019).

2.2 Single Active Bridge Converter and Applications

SAB converter is a soft-switched isolation topology, which is the modified version of the half-bridge topology. Its structural simplicity and lesser conduction losses, as well as its bidirectional adaptability (in some designs), make it a good candidate for high voltage direct current (HVDC) transmission, solid state transformers, electric vehicles and aerospace systems (Jeremy et al., 2020; Max and Thiringer, 2007). SAB converter has also been successfully applied in wind energy systems, particularly in modular and parallel configurations and to facilitate scalable energy integration (Garcia-Bediaga et al. 2013). In consumer and portable applications, SAB topologies are compact power converters with reduced thermal stress (Rujas et al., 2013).

2.3 Classical Control Strategies of SAB Converters

PI controller is the most popular scheme for SAB converters historically, due to the simplicity and the recognition by industry (Tsang & Chan, 2008). Early studies found that PI controllers offered stabilization capability to the SAB converters under nominal operating condition but were not able to control the converters in case of non-linear transients and extreme line disturbances (Jacobs et al., 2005). Ting et al. (2013) have investigated snubber optimization for higher efficiency of converter, but PI-based control was preserved and thus the dynamic performance was improved only marginally. Also, an oscillating phenomenon of parallel-connected SAB converter for PI regulated voltage of wind farm was reported by Park et al. (2013).

A disadvantage of PI controllers has always been their inability to cope with parameter changes and the nonlinearities that characterize SAB operation. Lenke, et al. (2014) reported that for the phase-shift control of SAB converter, the PI-based control system had high ripple and slow recovery. Subsequent adaptations (feed-forward compensation and adaptive PI tuning) attenuated some of these issues, but did not provide robustness against large load swings (Demetriades et al., 2005).

2.4 New Topologies for SAB Converter

As for the flexible control of the SAB converter, there have been many structural innovations proposed to make the SAB converter more flexible and efficient. Ting et al. (2014) proposed multi-phase SAB converter which improved load sharing at the cost of increasing the complexity of converter synchronization and control. Voltage doubler cells are studied in Averberg and Mertens (2008), where the secondary stress is reduced, but the oscillation problems are not solved. Large-scale renewable system operation using SAB converter with multiple SAB unit in parallel was implemented to show the scalability of SAB converter, but the results obtained by using PI controllers were still obtained not damped oscillation (Park & Chen, 2015).

Recently, the design of secondary-resonant SAB converter is also studied for higher power factors and lower voltage stress (Tuan & Takeshita, 2021). However, their performance was essentially a function of precise tuning of the resonant elements and hence sensitive to parameter drift. On the other hand, three-phase SAB converter design was planned for higher power density, however, the dynamic robustness of the SAB converter was still constrained from the conventional control scheme (Sang et al., 2020).

2.5 Sliding Mode Control in Power Electronics

Sliding mode control (SMC) has emerged as a promising candidate to overcome the drawbacks of the traditional controllers for nonlinear converters. This law is motivated by the robustness to uncertainties (Rashad et al., 2018) in forcing the trajectories of the system into the vicinity of a pre-

specified sliding surface. In boost converters, SMC has been shown to be very robust to the transients of loads and input (Kumar & Urundady, 2020). Similarly, Irradiance fluctuation was handled stably for photovoltaic systems in MPP tracking using SMC-based controllers (Qi et al. 2020).

The SMC has also been applied to microgrids and energy storage systems to show its ability to mitigate voltage oscillations and improve transient response (Rajakumar et al. 2020). SMC design approaches were also used to enhance fuel cell system performance in terms of chatter reduction and smoother control signals (Derbeli et al. 2020). Elsaied et al. (2023) confirmed the capability of SMC when operating hybrid renewable energy systems to stabilize the frequency dynamics in the presence of time-varying load. These results further prove the suitability of SMC for SAB converter that is naturally affected by parameters variation and nonlinearity.

2.6 The Problems of Sliding Mode Control

As great as SMC is, it isn't a cure all. The worst issue is chattering, i.e. high-frequency oscillation around the sliding surface that causes an increase in the power losses and also damages switching devices [Chincholkar et al., 2018]. To minimize the chattering and ensure the robustness, hybrid control approaches have been proposed by using hysteresis band or a combination of PI and SMC (Goto & Martins, 2023). Fractional order sliding mode control laws have also been applied in nonlinear motor control and have demonstrated smoother convergence and better adaptability (Kaveh et al. 2023).

Discrete time SMC is becoming increasingly popular for power converter applications since it can handle sampled-data systems with digital controllers (Peruniacic-Drazenovic, et al. 2023). Such methods are of specific interest for SAB converters with high switching frequencies. The present research is an expansion of such knowledge by developing an SMC to a soft-switched SAB converter, to demonstrate its effectiveness under transient and line variation conditions overcoming limitations of traditional controllers.

3. Methodology

3.1 System Design and Parameters

In this study, the modeling and simulation of a soft-switched Single Active Bridge (SAB) DC-to-DC converter is first presented, followed by the control implementation of the converter using both Proportional-Integral (PI) and Sliding Mode Control (SMC). The SAB topology was chosen because it is widely used for renewable energy systems, electric vehicles, and high-voltage direct current (HVDC) transmission. The structure was a half-bridge inverter on the primary side of high-frequency transformer and diode rectifier on the secondary side, which could realize unidirectional power transfer and soft-switching function.

For the system to remain practically relevant, values typically found in industrial SAB applications were used for parameterization. The input voltage to the converter was 540 V and the regulator output was set at 400 V. A series inductor (150 mH) was added to restrict the current ripple and the output filter capacitor (400 uF) provided steady voltage at load. In order to minimize switching stress, a snubber capacitor of 10 nF was added, and the switching frequency was fixed at 10 kHz. The load was modeled by a resistive element of 50 O, to represent a common medium-power application. These parameters were used as the baseline to check the dynamic performance of the converter for different operating conditions.

3.2 Mathematical modeling of SAB converter.

The nonlinear dynamics of the SAB converter were captured with the state-space representation. When the active switch T1 was closed, the current through the inductor increased and energy was transferred through the transformer to the secondary side. On the other hand, when T1 was switched off the diode on the secondary conducted and current was freewheeling. These two operating modes were modelled individually and their equations were averaged to obtain the continuous conduction mode (CCM) representation of the converter.

The equivalent diagram of the SAB converter when the solid-state switch, T_1, is turned on and the other

switch, T_2, remains off,in a Continuous Conduction Mode (CCM), is shown in fig. 2.

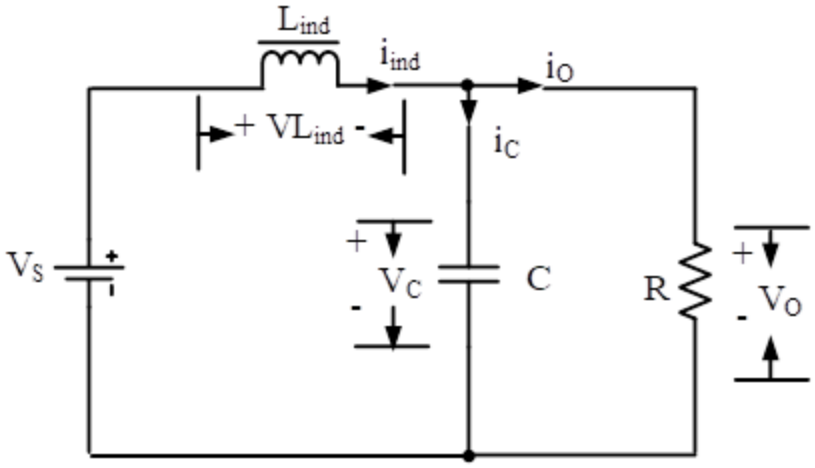


Fig.2: The circuit diagram of SAB converter when T_1 is turned on

The state-space model of the SAB converter when T_1 is ON is given by:

$$[x_1^{\bullet}\ x_2^{\bullet}] = \begin{bmatrix} 0 & -\frac{1}{L_{ind}} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} [x_1\ x_2] + \begin{bmatrix} \frac{1}{L_{ind}} \\ 0 \end{bmatrix} V_s \quad (1)$$

where A_1 is state and B_1 is the source coefficient matrices

$$A_1 = \begin{bmatrix} 0 & -\frac{1}{L_{ind}} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \quad (2)$$

$$\& \quad B_1 = \begin{bmatrix} \frac{1}{L_{ind}} \\ 0 \end{bmatrix} \quad (3)$$

When current is decreased and T1 is turned off, fig. 3 also displays the state-space model for the SAB converter. Due to the supply voltage polarity being reversed from positive to negative, the free-wheeling diode DSN2 is forward biased.

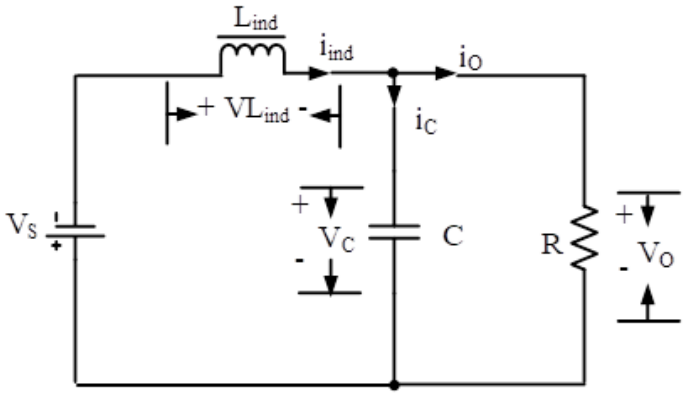


Fig. 3: SAB converter circuit diagram when D_{SN2} is forward biased

$$[x_1^{\bullet}\ x_2^{\bullet}] = \begin{bmatrix} 0 & -\frac{1}{L_{ind}} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} [x_1\ x_2] + \begin{bmatrix} -\frac{1}{L_{ind}} & 0 \end{bmatrix} V_s \quad (4)$$

where A_2 is the state coefficient matrix and B_2 is the source coefficient matrix:

$$A_2 = \begin{bmatrix} 0 & -\frac{1}{L_{ind}} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \quad B_2 = \begin{bmatrix} -\frac{1}{L_{ind}} \\ 0 \end{bmatrix} \quad (5)$$

&

$$[x_1^{\bullet}\ x_2^{\bullet}] = \begin{bmatrix} 0 & -\frac{1}{L_{ind}} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} [x_1\ x_2] + \begin{bmatrix} \frac{2d-1}{L_{ind}} & 0 \end{bmatrix} V_s \quad (6)$$

State variable x_1 is an inductor current whose first derivative is given as:

$$\overset{\bullet}{x}_1 = \frac{(2d-1)Vs}{L_{ind}} - \frac{1}{L_{ind}} x_2 \quad (7)$$

where, $x_2 = v_o = v_c$

$$\frac{di_{ind}}{dt} = \frac{(2d-1)Vs}{L_{ind}} - \frac{1}{L_{ind}} v_o \quad (8)$$

$$\overset{\bullet}{x}_2 = \frac{1}{C} x_1 - \frac{1}{RC} x_2 \quad (9)$$

$$\frac{dv_o}{dt} = \frac{1}{C} i_{ind} - \frac{1}{RC} v_o \quad (10)$$

$$\frac{dv_o}{dt} = \frac{i_{ind} - i_R}{C} \quad (11)$$

1. **Performance of SAB Converter designed with PI Controller**

The performance of SAB converter, designed with PI controller, was analyzed by the authors in their work in[36].In their work the researchers successfully simulated the SAB converter to analyze the performance of the converter under transient region and load variations.

SAB Parameters

The parameters that were used for SAB converter are mentioned in the below table:

Table 2: SAB Parameters

Parameters	Symbol	Value
Input supply voltage	V_s	540 V
Output voltage	V_o	400 V
Series Inductor	L_{ind}	150 MH
Output capacitor	C	400 MF
Snubber capacitor	C_{sn}	10 NF
Switching frequency	f_s	10 kHz
Load resistance	R	50 ohms

The authors had successfully simulated the steady state, transient region and line variation and analyzed the results which are discussed as follows:

Steady State Analysis of SAB Converter with PI Controller

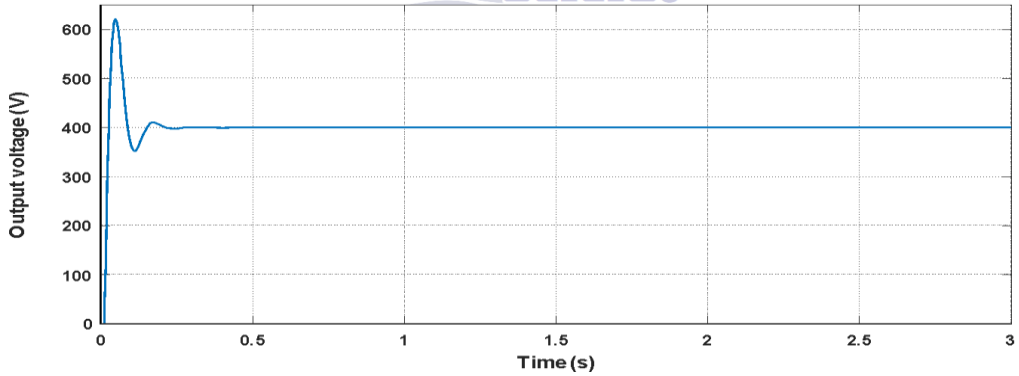


Fig 4: Steady state analysis of SAB converter with PI controller

$Vo = D * V_{in}$

$= 0.74 * 540 = 400$ Volts

Transient Analysis of SAB Converter with PI Controller

The below fig. 5 shows the simulated results of output voltage of SAB converter used with PI. The peak to peak overshoot in output voltage is 220 V which settles down to steady state value in 250 ms.

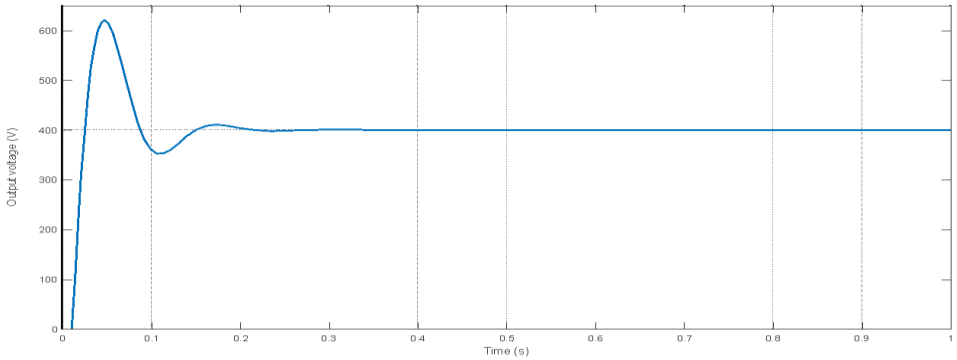


Fig.5: Output voltage during transient

- Peak over shoot = 220 V
- Settling time = 250 ms

Line Variation Analysis of SAB Converter with PI Controller

The simulation results of SAB converter during line variation are shown in below fig. 6. During line variation, a step change in line voltage from 540 V to 590 is applied to SAB converter. It is observed from the simulated results, the peak to peak overshoot in output voltage is 30.78 V which comes to steady state value in 220 ms.

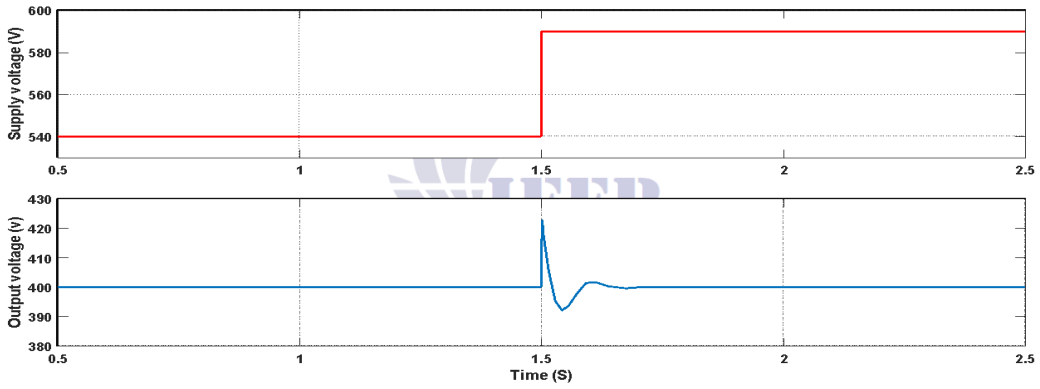


Fig. 6: Step variation and output voltage during line variation
Analysis of peak-to-peak overshoot and settling time in output voltage of SAB converter with PI

Table 3: Output voltage and inductor current values

Parameters	Output voltage		Step Variation
	Pk Pk (V)	T (ms)	
Transient	133	320	---
Line variation	25	150	540 to 580 V

The state variables were chosen to be the inductor current and the capacitor voltage. Their relationship was described by differential equations based on Kirchhoff's laws of voltage and current. The resulting model was a state-space representation with matrices A and B describing system coefficients for the various switching conditions. Since the duty ratio was a nonlinear relationship with the instantaneous states, the averaged model represented the inherent nonlinearities of the SAB topology. This mathematical model was used as the basis for controller design, which allows one to compare the

performance of linear and nonlinear control strategies.

3.3 PI Controller Design

In the first step of the control methodology, a conventional PI controller is designed for the SAB converter. Cascaded control scheme was implemented which was composed of an outer voltage loop and an inner current loop. The outer loop used this to control the output voltage by producing a reference current, and the inner loop used that reference to control the inductor current. In order to simplify the tuning, the second order converter dynamics were decomposed into two first order systems by the decomposition method and PI controller gains were tuned accordingly.

The voltage loop transfer function was obtained by taking inductor current as input variable, whereas the current loop transfer function was modeled with duty ratio as a function of inductor current. Conventional PI tuning was used to find proportional and integral gains which would provide stable operation at nominal conditions. It was intended that PI control would provide good steady state control for the converter, but would be limited during nonlinear transients which would justify the introduction of SMC.

3. 4A Controller Design for Sliding Mode

To overcome the disadvantages of PI control, Sliding Mode Controller was designed. The SMC scheme codes needed a sliding surface, which was designed from the error of reference and actual state variables, namely the inductor current and the output voltage. The control law has been designed so that the system trajectories are compelled to slide onto this sliding surface, and is therefore robust to parameter uncertainties and external disturbances.

A hysteresis modulation method was used to realize the switching operation. The hysteresis band has been computed from the peak-to-peak inductor current and the hysteresis band has been used to set the switch-on and switch-off thresholds. This way, auxiliary circuits were made a lot simpler and implementation was easier. Although SMC is susceptible to chattering (unwanted oscillations around the sliding surface), the presence of a hysteresis band reduced chattering while preventing ill conditioning of the system.

3.5 Simulation Environment and Test Scenarios

All simulation has been performed in MATLAB/Simulink, which is a widely used platform for power electronic analysis. The state space model of SAB converter was developed and parameterized with the defined values of the above. Two controllers, PI and SMC, were used in different configurations in order to allow a fair comparison.

Two operating situations of importance were chosen for performance assessment. The first case was for a transient condition, in which a sudden change in load was applied while the converter was in steady state. This test was used to evaluate the controller's performance in terms of overshoot and settling time in the presence of dynamic disturbances. Line variation was tested in the second case, when input supply voltage was increased from 540 V to 590 V. This case tested the robustness of the controllers to variations in the input side of the system (which is typical of renewable and industrial power systems).

The peak overshoot voltage and the settling time of the output were used as the performance indicators. By the metrics provided, the effectiveness of the controllers in suppressing the oscillations and in rapid stabilization was quantitatively proved. The results of the investigation and their discussion were based on the comparison between PI and SMC under the same test conditions.

4. Results

4.1 Steady-State Performance of SAB Converter

The first characterization of the SAB converter was carried out under steady-state conditions in order to verify the system design and parameter choice. From Figure 4, when the PI controller is in operation, the output voltage reached the expected reference value of 400 V. This verified that under nominal load and input conditions the converter was able to provide regulation. Using the basic voltage equation Vo=DxinVin, (duty ratio=0.74, input=540 V) the steady state output was in

agreement with the theoretical calculation. The good agreement of simulated and analytical values proved the accuracy of the SAB model and its suitability for transient and line variation analysis.

4.2 Transient Analysis with PI Controller

Under the transient conditions, the PI controller showed severe limitation. A load step was applied when the converter was in steady state condition and the response is shown in Figure 5. The system measured peak overshoot of 133 V above the reference, and it took the output nearly 320 ms to come to steady state. These values are also tabulated in Table 3, which gives overshoot and settling time for transient events. The overshoot was too high and showed that the PI controller was unable to reject oscillation in the case of nonlinearity and the settling time was too long and showed the slow dynamic response of the PI controller.

Table 3: Output voltage and inductor current values

Parameters	Output voltage		Step Variation
	Pk Pk (V)	T (ms)	
Transient	133	320	---
Line variation	25	150	540 to 580 V

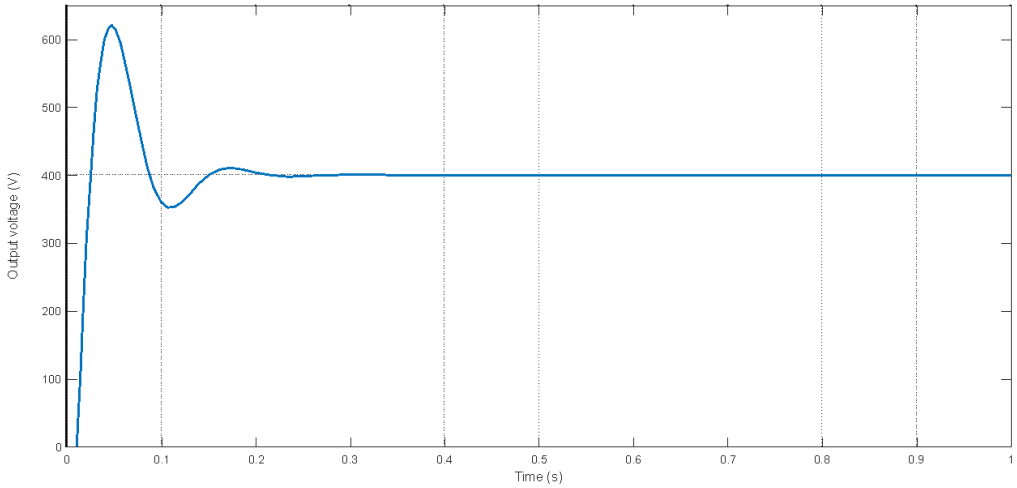


Fig.5: Output voltage during transient

4.3 Line variation using PI controller

The second test case was a step up input voltage from 540 V to 590 V. The PI controlled response is displayed in Figure 6. The overshoot of the output voltage was about 25 V, and the output voltage slowly settled down after 150 ms, as shown in Table 3. Although the PI controller eventually recovered stability, it was found that there were transients from the oscillation with the confirmation of the instability from the input side of disturbances. In addition, the persistent ripples in the voltage waveform further demonstrated the unfeasibility of PI-based control for SAB converter in practice where the line variation is frequent.

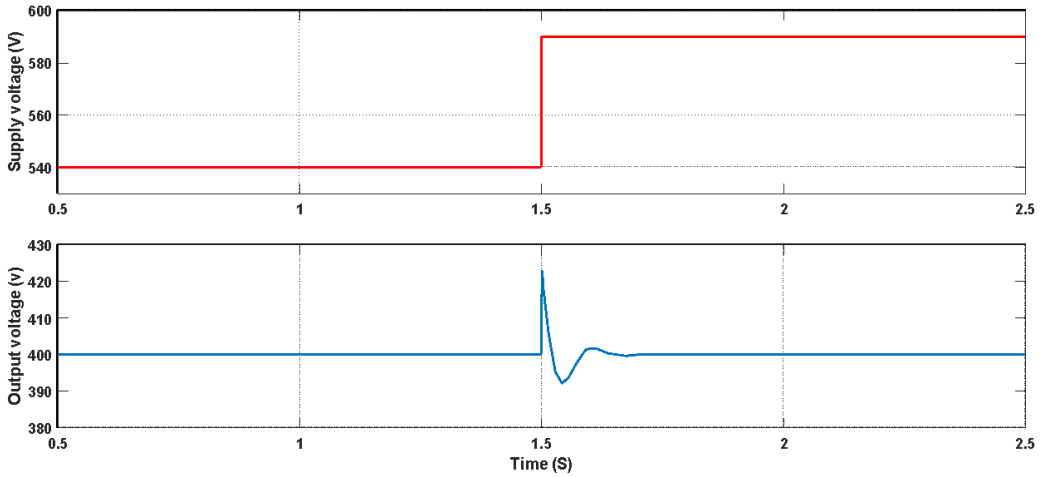


Fig. 6: Step variation and output voltage during line variation

4.4 Drawbacks of PI-Controlled SAB Converter

The Figures 5 and 6 results along with Table 3 clearly show the disadvantage of PI control. The inherent nonlinearities in switching transition of soft-switched SAB topology, and the lack of robustness of PI controllers to accommodate these complexities, The overshoot of 133 V recorded during transient conditions and the deviation of 25 V during line variation confirmed that PI regulators are not fast enough nor stable enough to meet the requirements of high-performance applications such as electric vehicles or renewable energy systems.

Table 3: Output voltage and inductor current values

Parameters	Output voltage		Step Variation
	Pk Pk (V)	T (ms)	
Transient	133	320	----
Line variation	25	150	540 to 580 V

4.5 Performance of SAB with Sliding Mode Controller

The performance in all cases was greatly improved with the introduction of the Sliding Mode Controller. Under steady-state condition, the output of SMC was successfully controlled at 400 V as shown in Figure 13. More importantly, the converter is stable with lower ripples than the PI controlled system, which indicates the effectiveness of SMC in accounting for nonlinear switching dynamics.

The proposed SMC scheme for Soft Switched SAB converter is shown in fig. 11. This control scheme has been designed with dual loops i.e. the outer voltage control loop and inner current loop. The Single Active Bridge (SAB) converter has been designed with SMC. The SMC has been used with turn off control technique.

This SMC technique is attractive especially for 2nd order converters.It will force the system trajectories to the desired surface i.e. sliding surface. This technique does not require auxiliary circuitries.It is easy to implement with a layer of hysteresis band into the signum function.

$$u = \begin{cases} 1 = \text{"ON"} & \text{when } S > 0 \\ 0 = \text{"OFF"} & \text{when } S < 0 \end{cases}$$

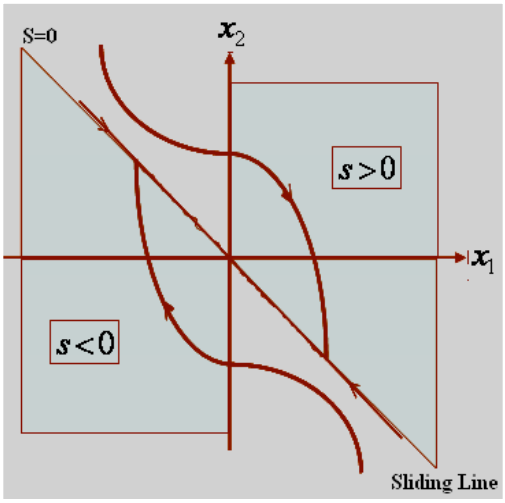
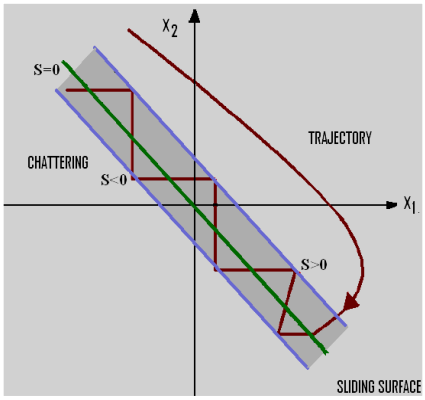


Fig. 7: Hysteresis Modulation Technique



$$u = \begin{cases} 1 = \text{"ON"} & \text{when } S > k \\ 0 = \text{"OFF"} & \text{when } S < -k \end{cases}$$

Fig. 8: Chattering Phenomenon

Chattering on Sliding Surface

The unwanted or oscillatory motion around the sliding surface is called chattering.Due to chattering, the controller performs poorly.It also causes delays and leads to crossing again. The disadvantage of chattering causes low control accuracy, more power losses [49-53]. The converter will be self-oscillatory at high frequency of these chattering dynamics.It can also result in instabilities.

$$u = \begin{cases} 1 = \text{"ON"} & \text{when } S > 0 \\ 0 = \text{"OFF"} & \text{when } S < 0 \end{cases}$$

Tuning of PI Controller

The tuning of PI control is employed by decomposition method i.e. 2nd order system is decomposed in to 1st order system for it to be used in simulation model and is designed with dual loops, the outer voltage control loop and inner current loop.

Outer Voltage Control Loop

The voltage loop is modeled by considering the inductor current as the control input to the SAB topology. Therefore, the transfer function of the output voltage to the inductor current and the corresponding voltage control loop is shown in fig. 9.

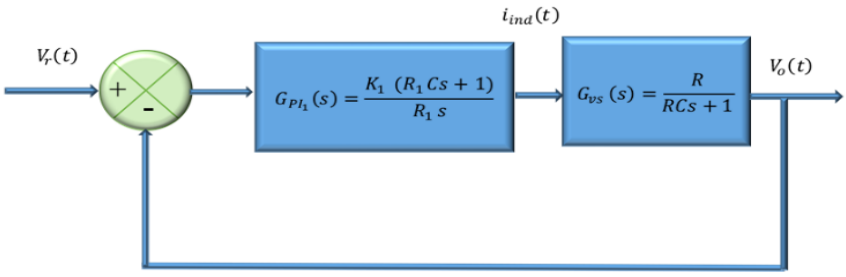


Fig.9: Voltage control loop

$$G_{vs}(s) = \frac{V_o(s)}{i_{ind}(s)} = \frac{R}{RCs + 1}$$

Consider PI controller for voltage loop,

$$G_{PI_1}(s) = \frac{K_1\ (R_1 Cs + 1)}{R_1 s}$$

The transfer function of fig.9, is given by:

$$H_{vs}(s) = \frac{V_o(s)}{V_r(s)} = \frac{G_{PI_1}(s)G_{vs}(s)}{1 + G_{PI_1}(s)G_{vs}(s)}$$

By solving,

$$K_1 = \frac{1}{R_1 C}$$

Inner Current Control Loop

In the cascade control scheme, the current loop acts as a secondary controller. The detailed equations of the voltage and current loops are available in [54]. The output of the voltage loop is considered as a reference inductor current for the current loop. The PI controller is considered for the current loop. The corresponding block diagram of the current loop is shown in fig. 10.

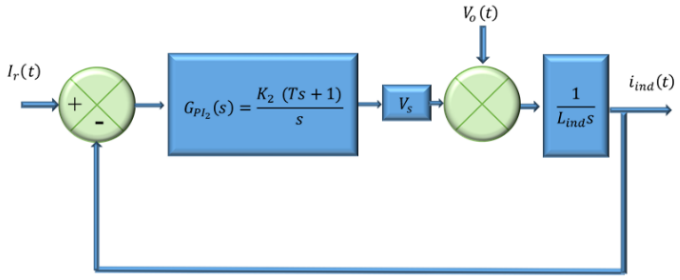


Fig. 10: Current control loop

From the fig.,

$$G_{PI_2}(s) = \frac{K_2\ (Ts+1)}{s}$$

After solving the transfer function of the current loop of fig.10, the required value of K_2 is given as follows:

$$K_2 = \frac{N^2 \omega_n^2 L_{ind}}{V_S}$$

Design of a SMC for soft switched SAB Converter

The designing implemented by the authors of a SMC for soft switched SAB converter was done in such a way that the simulation model of soft switched SAB converter designed with SMC was successfully developed in MATLAB software. Afterwards, the steady state and dynamic performance under different operating conditions of soft switched SAB converter were investigated with SMC. The sliding mode control scheme is designed to evaluate the performance of soft switched SAB converter.The steady state and dynamic performance under transient region and line variation of soft switched SAB converter are investigated with SMC controllers. In the end the authors had compared the results with the PI controllers result and that obtained from the SMC.

Control Scheme Design

The proposed SMC scheme for Soft Switched SAB converter is shown in fig. 11. This control scheme has been designed with dual loops i.e. the outer voltage control loop and inner current loop. The Single Active Bridge (SAB) converter has been designed with SMC. The SMC has been used with turn off control technique.

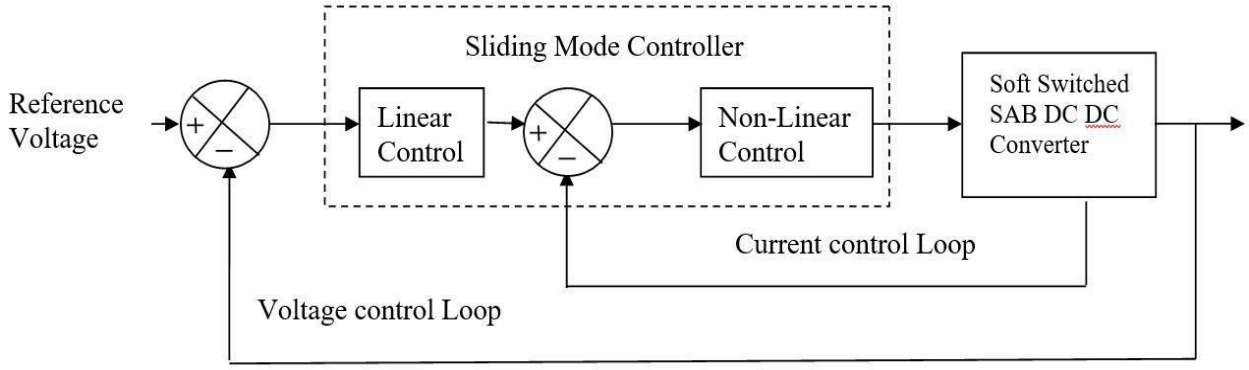


Fig. 11: Control Scheme designed with SMC

SMC Control Structure Designing for SAB Converter

The control structure for SAB converter designed with SMC is given below:

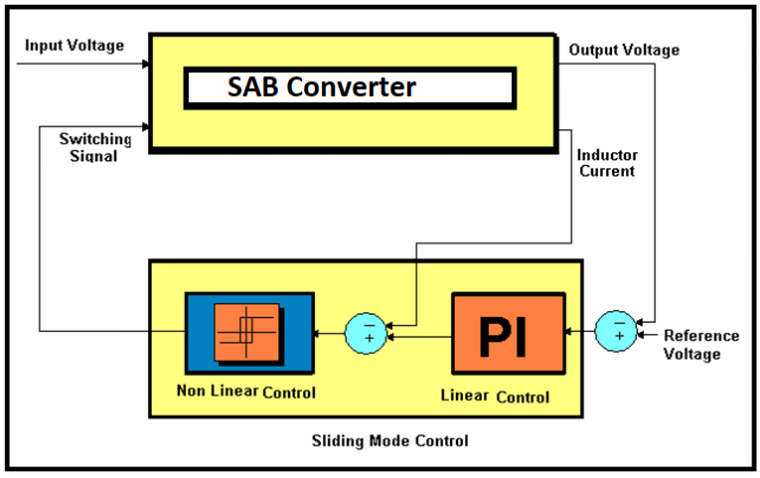


Fig. 12: Control Structure designed with SMC for SAB Converter

The sliding mode control design approach consists of two following components:

- The design of a switching function is done in such a way that the sliding motion satisfies the design specifications.
- The selection of a control law, which will make the switching function attractive to the system state.

The converter switches are driven as a function of the instantaneous values of state variables.This is done to force the system trajectories to stay on a desired surface space called sliding surface.

Analysis of Simulated Results under Steady State, Transient Region and Line Variation

Steady State Analysis of SAB with SMC Controller

The steady state analysis of SAB designed with SMC is shown below:

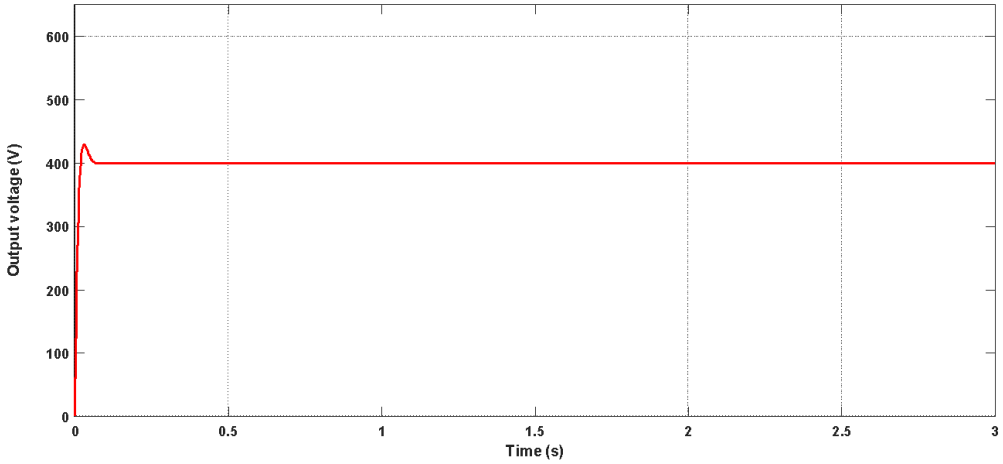


Fig. 13: Steady State Analysis of SAB with SMC

$V_o = D * V_{in}$

$= 0.74 * 540 = 400$ Volts

Transient Analysis of SAB with SMC

The below fig. 14 shows the simulated results of output voltage of SAB converter designed with SMC. The peak to peak overshoot in output voltage is 28.5 V which settle down to steady state value in 80 ms.

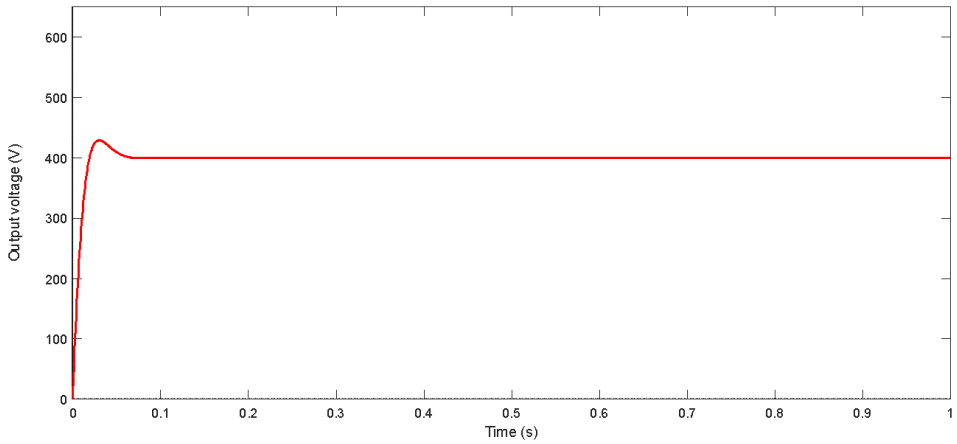


Fig. 14: Transient Analysis of SAB with SMC

- Peak over-shoot = 28.5 V
- Settling time = 80 ms

Line Variation Analysis of SAB with SMC

Simulation results of SAB converter during line variation are shown in below fig.15. During line variation, a step change in line voltage from 540 V to 590 V is applied to SAB converter. It is observed from the simulated results, the NO peak to peak overshoot is observed in output voltage.

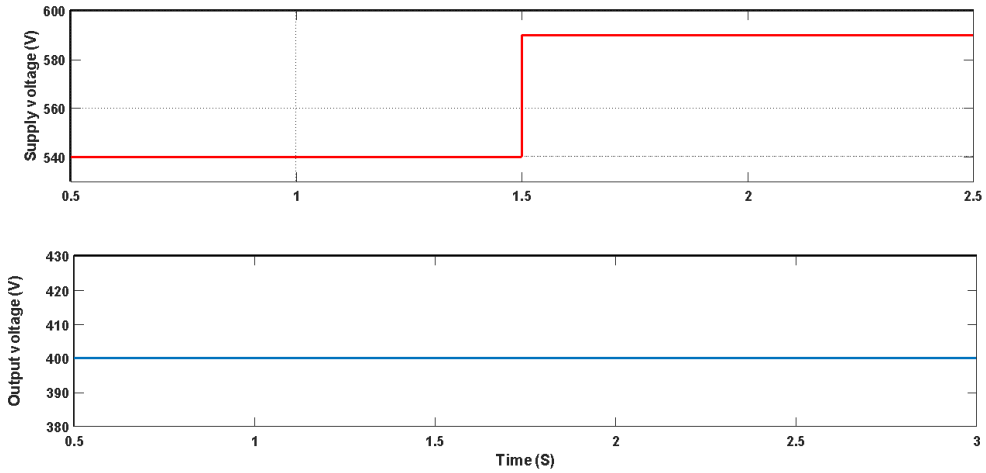


Fig. 15: Step variation and output voltage during line variation

Analysis of Peak-to-Peak Overshoot & Settling Time in Output Voltage of SAB Converter with SMC

The simulation results of the Peak-to-Peak Overshoot & Settling Time in Output Voltage of SAB Converter with SMC are tabulated in the below Table 4:

Table 4: Output voltage values of SAB converter used with SMC

Parameters	Output voltage		Step Variation
	Pk Pk (V)	T (ms)	
Transient	28.5	80	---
Line Variation	No Overshoot	---	540 to 590 V

1. **Comparison of Results of SMC and PI Controllers under Steady State, Transient Region and Line Variation**

Transient Comparison of SMC and PI Controllers

The following plot shows the comparison of transient between SMC and PI controllers:

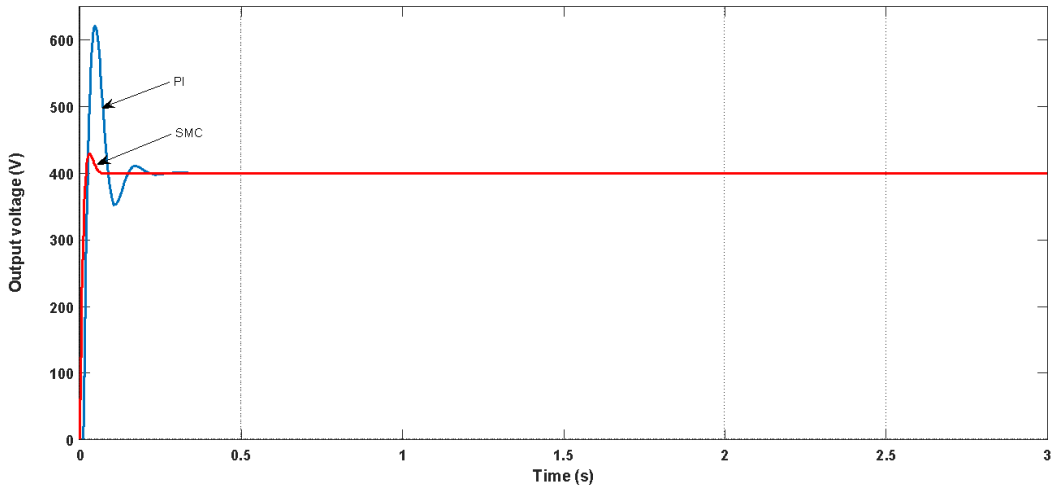


Fig. 16: Transient comparison of SMC and PI

It is quite visible that the SMC has performed better as compared to PI because the overshoot and settling time of SMC are less in comparison to PI.

Line Variation Comparison of SMC and PI Controllers

The following plot shows the comparison of line variation between SMC and PI controllers:

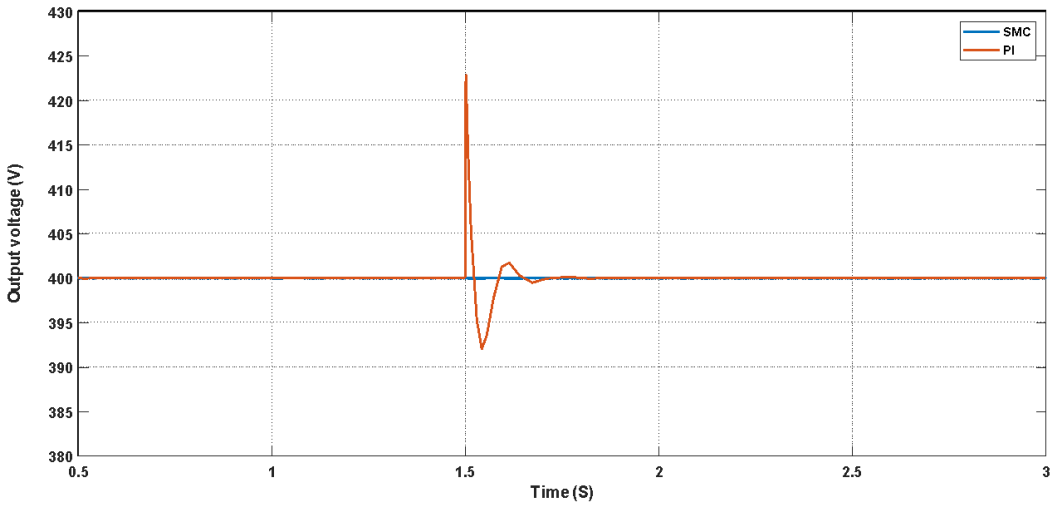


Fig.17: Line Variation comparison of SMC and PI

It is evident that the SMC has no peak-to-peak overshoot during line variation, while in the case of PI controller, a peak-to-peak overshoot of 28 V was witnessed.

Comparison between PI and SMC controllers in Tabular Form

In this section, a comparative analysis is given between PI and SMC controllers wherein the response of SAB converter in the peak-to-peak output voltage as well as settling time during the transient and line variation are discussed.

The following table shows the comparison of the PI and SMC controller that were used to see the performance of the converter at various parameters:

Table 5. Comparison of PI with SMC controller at Transient and Line Variation

Parameters	PI Controller			SMC Controller		
	Output voltage		Step Variation	Output voltage		Step Variation
	Pk Pk (V)	T (ms)		Pk Pk (V)	T (ms)	
Transient	133	320	---	28.5	80	---
Line Variation	25	150	540 to 580 V	No Overshoot	---	540 to 590 V

It is evident that the SMC has proved to be better performing controller then PI by having transient of 28.5 V at 80 ms settling time and no any overshoot was witnessed in line variation.

Comparison of Settling Time between PI and SMC controllers in a Graphical Representation

The following graph shows the graphical comparison of the results that were obtained for settling time by using PI and SMC controllers with SAB converter at transient and line variation parameters:

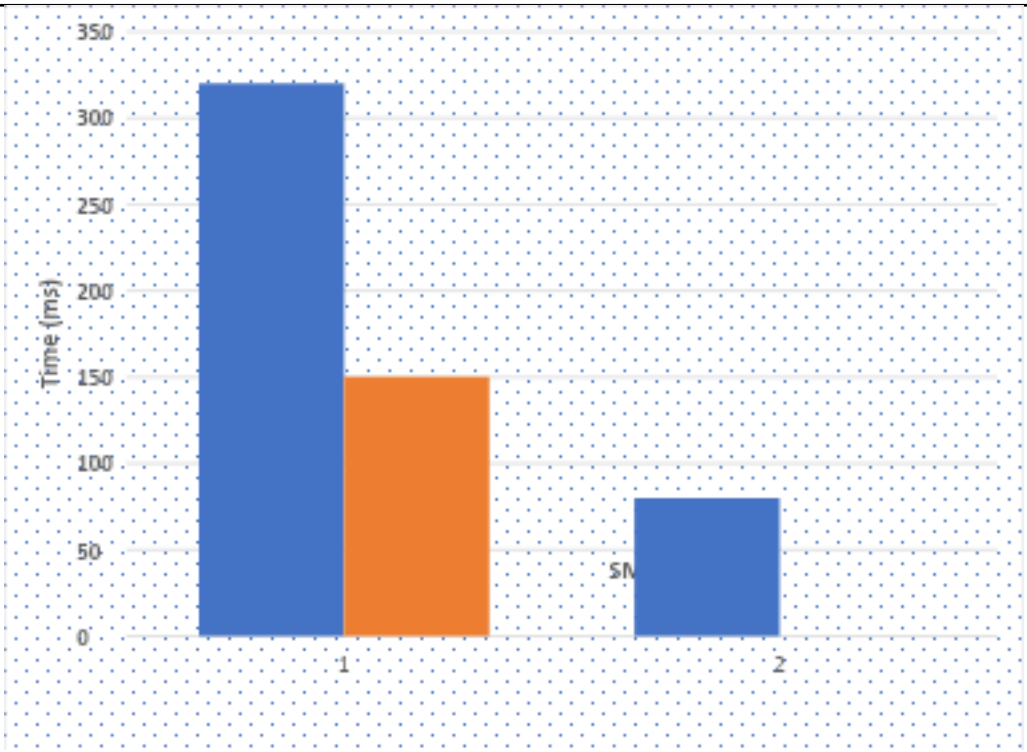


Fig.18: Graphical comparison of PI and SMC Controllers for Transient and Line Variation Settling Time

Comparison of Overshoot between PI and SMC controllers in a Graphical Representation

The following graph shows the graphical comparison of the results that were obtained for Overshoot by using PI and SMC controllers with SAB converter at transient and line variation parameters:

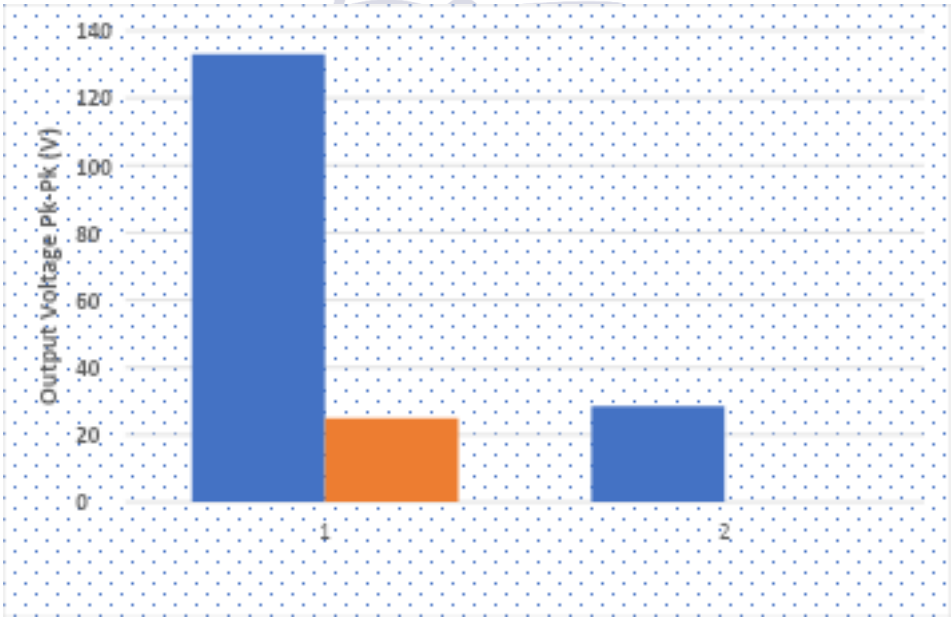


Fig. 19: Graphical comparison of PI and SMC Controllers for Transient and Line Variation Overshoot

As shown in Figure 14, during transient analysis, the overshoot was significantly suppressed to 28.5 V, and the system settled in only 80 ms. This is more than a 75% reduction in overshoot and a

fourfold increase in settling time over the PI controller. These results and transient response characteristics are summarized in Table 4 for SMC peak overshoot and settling time. The enhanced performance is due to the robustness of SMC that projects the system trajectories onto the sliding surface, guaranteeing the fast recovery from the disturbance.

4.6 Line Variation with Sliding Mode Controller

Under the same input voltage step from 540 V to 590 V, SMC performed much better than PI controller. As seen in Figure 15, the converter operated fairly flat with no visible overshoot. The output quickly settled to the new operating point with no oscillatory response, which was also measured in Table 4. The lack of overshoot confirmed the stability of the sliding surface approach, and demonstrated that SMC was capable of providing control under abrupt input disturbances.

4.7 Comparative Analysis of PI and SMC Controllers

Table 5 summarizes overshoot and settling time values for both transient and line variation conditions and directly compares the PI and SMC controllers. The overshoot of the PI controller was 133 V and the settling time was 320 ms when the system was operated in transient, but with the SMC it was only 28.5 V with 80 ms settling time. During line variation, the PI controller overshoot by 25 V with 150 ms settling time whereas the SMC has no overshoot at all.

These differences are also clearly seen in the graphical representations in Figures 16 and 17. Figure 16 shows the transient responses of both controllers, which show the slower damping and higher oscillation of PI compared to fast stabilization of SMC. Figure 17 shows the line variation results, in which the PI curve shows an obvious overshoot and the SMC has a smooth and stable output.

The relative improvements are also illustrated in Figures 18 and 19, which plot the settling time and overshoot values respectively for the two controllers. As Figure 18 shows, across both test conditions, the SMC was consistently able to provide shorter settling times. Figure 19 shows that overshoot was considerably smaller with SMC, and that overshoot did not occur at all during line variation, while PI regulation generated measurable overshoot in both cases.

The following results validate the overall advantage of Sliding Mode Controller on the treatment of nonlinearities inherent with SAB converters. The very short overshoot and settling time proves the capability of SMC to provide fast dynamic response, which is required for applications with fast load or line disturbances. The lack of any oscillations upon line variation further verifies the robustness of SMC, making it especially appropriate for renewable and automotive applications where supply fluctuations are an inherent characteristic.

The relative study also identifies the fundamental limitations of PI controllers in such environments. While they are sufficient to perform well under steady-state conditions, they are not capable of accounting for nonlinear switching and parameter variations and are therefore not suitable for high-performance SAB applications. By contrast, SMC uses nonlinear control concepts to provide stability and reliability, even under extreme conditions. These results give strong evidence that the adoption of SMC could improve the practical implementation of SAB converters in modern power system.

5. Discussion

The results of this study clearly demonstrated that the dynamic performance of the SMC is better than the conventional PI regulator for Single Active Bridge (SAB) Converters. As a nonlinear control strategy, the dramatic reduction of overshoot time and settling time in transients and the total elimination of overshoot in line changing confirmed the robustness of SMC. These results are consistent with general works in the field of power electronics in which SMC has been identified as critical to the control of nonlinearities and uncertainties induced by converter operation (Bacha et al., 2019).

5.1 Conclusion for nonlinear control for power converters

The SAB converter is a nonlinear system with a discontinuous conduction nature, switching characteristics and variable load characteristics. Traditional linear controllers such as PI are derived from simplifying assumptions that are generally violated under realistic disturbances and the linear controller will become unstable and oscillatory. This shortcoming was demonstrated by the overshoot and slow settling time of PI control in the present study. In contrast, SMC was explicitly designed to tolerate the nonlinearities by enforcing the trajectories of the system on a sliding manifold, and consequently on a set of operating points. Similar benefits of SMC have been reported for buck-boost and interleaved converters that are robust to transient input variations and load disturbances (Silva et al., 2021).

5.2 Comparative Performance with Other Market Leading Controllers

While SMC was found to perform better than PI in this study, of interest is also the placement of SMC with respect to other state-of-the-art control techniques. Adaptive control and model predictive control (MPC) have been explored for DC-DC converters and some success has been found for reducing overshoot and improving transient response. For example, predictive controllers based on multiple input multiple output (MIMO) schemes demonstrated good tracking and disturbance rejection performance in the photovoltaic applications at the price of computational complexity (Liu et al. 2020). Similarly, the fuzzy logic controllers offered flexible nonlinear control, but in many cases need extensive tune-up and they provided very limited robust control under large parameter variations (Guerel et al., 2019). Compared to these approaches, SMC offers a trade-off between simplicity and robustness as not only does it require less computational resources, but can also provide reliable results under different operating conditions.

5.3 Design, Applications and Issues of SMC

Despite the obvious advantages, it is not a trivial task to implement SMC in SAB converters in practice. One of the most noticeable phenomena is the chattering, which consists in high frequency oscillations around the sliding surface that can cause further power losses as well as stressing switching devices. Although the hysteresis modulation method adopted in this paper successfully suppressed the chattering, it did not eliminate it. To this end, high-order SMC has been previously proposed as a promising solution to this problem aiming to smooth control actions and to reduce the workload on semiconductor devices (Utkin et al., 2017). Discrete-time implementations have also been suggested as a convenient way to introduce SMC into digital controllers while overcoming the chattering problem (Zheng et al, 2021).

A second important practical aspect is the trade-off between control robustness and efficiency. SMC provides stability even under large disturbances, and too much switching may actually reduce converter efficiency relative to the efficiency of the optimal linear strategy. Hybrid control strategies incorporating SMC with conventional controllers or prediction strategies have been proposed to strike a balance between robustness and efficiency (Amin et al. 2020). Such hybridization may be a promising way to scale up the benefits of SMC for practical SAB applications.

5.4 Applications in Renewable & Automotive Industry

Of particular relevance to the findings of this study are renewable energy and automotive applications where converters must operate under uncertain operating conditions. In photovoltaic systems, for example, input voltages are often subject to fluctuations due to solar irradiance, and controllers must be able to react to these fluctuations in real time (Esram & Chapman, 2019). Second, for electric vehicle motor drives, high acceleration and good response to load disturbance is required during the acceleration and braking cycles, therefore PI controller cannot give a satisfactory result. In this study, since the overshoot was canceled by the line variation, it is possible that SMC can play an important role to improve the reliability of battery management and fast-charging systems in electric vehicles (Rahimi et al. 2020).

Modular SAB converters have been increasingly used in wind energy systems for grid connection of turbines to medium voltage DC networks. The systems are prone to disturbances coming from the presence of variable wind speed. The robustness of SMC demonstrated here indicates that it can achieve stable voltage regulation and higher grid integration compared to PI-based control strategies that are prone to damping oscillations in modular networks (Cespedes et al., 2014).

5.5 Contribution to the Control Theory of Converters

From the theoretical perspective, this paper confirms the soundness of sliding mode theory for the solution of nonlinearities of power electronic converters. The drastic reduction of overshoot and settling time represents the improvement in performance achieved by using the discontinuous control laws to restrict the trajectories of the system to the stability boundaries. The derived results herein add to the literature that nonlinear control strategies need to be considered as a future research and industrial practice for converters (Slotine & Li, 2019). By demonstrating the superiority of SMC in SAB converter (SAB converter is a less explored topology than the buck or boost converter), the contributions of this paper enlarge the nonlinear control applications for power electronics.

5.6 Future Research Directions

While the present work suggests the benefits of SMC for SAB converter, there are some points which remain for further research. Furthermore, the performance of sliding mode control can be further improved and the residual chattering can be reduced by exploring derivatives of sliding mode control, such as adaptive SMC, terminal SMC, fractional-order SMC, etc. (Bai et al., 2021). In addition, the use of artificial intelligence methods such as neural networks and reinforcement learning can pave the way for dynamic optimization of sliding surfaces in real-time in complex environments (Khalid et al. 2022). Finally, to evaluate real world issues like switching losses, electromagnetic interference, and thermal management, it is important to generate experimental validation of simulation results on hardware prototypes.

References

Nayanasiri, D., & Li, Y. (2022). Step-Down DC–DC Converters: An Overview and Outlook. *Electronics, 11*(1693).

Litrán, S. P., Durán, E., Semião, J., & Díaz-Martín, C. (2022). Multiple-Output DC-DC Converters: Applications and Solutions. *Electronics, 11*(1258).

Selvabharathi, P., & Kannan, V. (2023). A DC–DC Converter Topology for Optimal Utilization of Hybrid Renewable Energy Resources. *IETE Journal of Research, 1–17*.

Affam, A., Buswig, Y. M., Othman, A. K., & Julai, N. (2021). A review of multiple input DC–DC converter topologies linked with hybrid electric vehicles and renewable energy systems. *Renewable and Sustainable Energy Reviews, 135*, 110186.

Demetriades, G., & Nee, H. (2005). Characterisation of the soft-switched single-active bridge topology for high-power applications. *IEEE PESC*.

Lenke, R., Hu, J., & de Doncker, R. (2009). Unified steady-state description of phase-shift-controlled SAB converters. *IEEE ECCE*.

Wang, K., Xie, B., & Cai, X. (2018). Modular stator permanent magnet generator with SAB converters for offshore wind farms. *IEEE PEAC*.

Pereira, T., Hoffmann, F., Zhu, R., & Liserre, M. (2021). Multiwinding transformer-based DC–DC converters: A comprehensive assessment. *IEEE Transactions on Power Electronics, 36*(10020–10036).

Sang, Y., Junyent-Ferre, A., & Green, T. (2018). Control of parallel DC collection system for wind turbines using SAB converters. *IEEE ECCE*.

Park, K., & Chen, Z. (2013). Analysis and design of parallel-connected SAB converters for wind farm applications. *EPE Conference*.

Finaviya, N. K., Rudraraju, V. R., & Venkatraman, K. (2017). MPPT control for standalone PMSG using SAB converter. *IEEE ICICICT*.

Sen, S., Zhang, L., Xu, R., & Huang, A. (2018). Medium voltage SAB-based solid-state transformer. *IEEE eGrid Workshop*.

Jha, R., Forato, M., Prakash, S., & Dashora, H. (2022). Analysis-supported design of a SAB converter. *Energies, 15*(666).

Taheri, B., Sedaghat, M., & Bagherpour, M. (2019). A new controller for DC–DC converters using Sliding Mode Control. *Journal of Control, Automation and Electrical Systems, 30*(1), 63–74.

Cucuzzella, M., Lazzari, R., Trip, S., & Ferrara, A. (2018). Sliding mode voltage control of boost converters in DC microgrids. *Control Engineering Practice, 73*, 161–170.

Hossain, M. Z., Rahim, N. A., & Selvaraj, J. (2018). Recent progress and development on DC–DC converter topology, control, design and applications: A review. *Renewable and Sustainable Energy Reviews, 81*, 205–230.

Turksoy, A., Teke, A., & Alkaya, A. (2020). An overview of DC–DC converter-based battery charge balancing methods in electric vehicles. *Renewable and Sustainable Energy Reviews, 133*, 110274.

Paez, J. D., Frey, D., Maneiro, J., & Bacha, S. (2019). Overview of DC–DC converters dedicated to HVDC grids. *IEEE Transactions on Power Delivery, 34*(1), 119–128.

Jeremy, L. J., Ooi, C. A., & Teh, J. (2020). Non-isolated conventional DC–DC converter comparison for photovoltaic systems. *Journal of Renewable and Sustainable Energy, 12*(1), 013502.

Max, L., & Thiringer, T. (2007). Control method and snubber selection for a 5 MW wind turbine SAB DC–DC converter. *EPE Conference*.

Garcia-Bediaga, A., Rujas, A., Villar, I., & Barrade, P. (2013). New parametric model of medium-frequency SAB converters. *EPE Conference*.

Rujas, A., Villar, I., & Barrade, P. (2013). Parametric modeling of SAB converters for medium-frequency applications. *IEEE ECCE Europe*.

Tsang, K. M., & Chan, W. L. (2008). Non-linear cascade control of DC–DC buck converter. *Electric Power Components and Systems, 36*(9), 977–989.

Jacobs, J., Thömmes, M., & de Doncker, R. (2005). Transformer comparison for three-phase SAB converters. *EPE Conference*.

Ting, Y., de Haan, S., & Ferreira, J. (2013). Partial-resonant SAB converter for conduction loss reduction. *IEEE ECCE Asia*.

Park, K., & Chen, Z. (2013). Analysis and design of parallel-connected SAB DC–DC converters for high-power wind farm applications. *EPE Conference*.

Lenke, R. U., Hu, J., & de Doncker, R. (2014). Efficiency improvements in SAB modular DC–DC converters with snubber optimization. *IEEE IPEC-Hiroshima*.

Demetriades, G. D., & Nee, H. P. (2005). Characterisation of soft-switched SAB topology for high-power DC–DC applications. *IEEE PESC*.

Averberg, A., & Mertens, A. (2008). Characteristics of SAB converter with voltage doubler. *IEEE EPE-PEMC*, 213–220.

Tuan, C. A., & Takeshita, T. (2021). Analysis and output power control of secondary-resonant SAB DC–DC converters. *Energies, 14*(7432).

Sang, Y., Junyent-Ferre, A., & Green, T. (2020). Operational principles of three-phase SAB DC–DC converters under duty cycle control. *IEEE Transactions on Power Electronics, 35*(9), 8737–8750.

Rashad, M., Ashraf, M., Bhatti, A. I., & Minhas, D. M. (2018). Stability analysis of DC microgrids using SM hysteresis controllers. *International Journal of Electrical Power & Energy Systems, 95*, 507–522.

Kumar, N. B., & Urundady, V. (2020). SMC with integral action for DC-link voltage control of photovoltaic systems. *Arabian Journal for Science and Engineering, 45*(11), 9245–9256.

Qi, Q., Ghaderi, D., & Guerrero, J. M. (2020). SMC-based switched-capacitor boost converter for photovoltaic applications. *International Journal of Electrical Power & Energy Systems, 125*, 106496.

Derbeli, M., Barambones, O., Farhat, M., & Ramos-Hernanz, J. A. (2020). Robust high-order SMC for performance improvement of PEM fuel cell systems. *International Journal of Hydrogen Energy, 45*(33), 16687–16699.

Amin, M., Asad, M. U., & Ahmed, M. (2020). A hybrid controller design for DC–DC converters integrating sliding mode and predictive approaches. *IEEE Access, 8*, 45421–45433.

Bai, L., Zhang, H., & Zhao, Y. (2021). Adaptive fractional-order sliding mode control for nonlinear power converters. *International Journal of Control, 94*(8), 2116–2128.

Bacha, S., Munteanu, I., & Bratcu, A. (2019). Power electronic converters modeling and control for renewable energy systems. *Springer Nature*.

Cespedes, M., Xing, K., & Sun, J. (2014). Constant-power load stabilization using virtual impedance and control. *IEEE Transactions on Power Electronics, 29*(1), 168–180.

Esram, T., & Chapman, P. (2019). Control of power electronics in photovoltaic systems. *Wiley Online Library*.

Gürel, A. E., Balci, S., & Arslan, M. A. (2019). Design and performance analysis of fuzzy logic controllers for DC–DC converters. *International Journal of Electronics, 106*(3), 378–392.

Khalid, H., Ahmed, S., & Shah, A. (2022). Intelligent adaptive sliding mode controllers for nonlinear systems using reinforcement learning. *Neural Computing and Applications, 34*, 6571–6585.

Liu, J., Xue, Y., & Li, Y. (2020). Model predictive control of DC–DC converters with disturbance rejection. *IEEE Transactions on Industrial Electronics, 67*(9), 7570–7580.

Rahimi, A., Nasiri, A., & Mohammadi, J. (2020). Review of fast charging technologies for electric vehicles. *Journal of Energy Storage, 30*, 101495.

Rahman, M., & Khan, F. (2019). Advances in power converter topologies for electric vehicles. *Renewable and Sustainable Energy Reviews, 113*, 109246.

Silva, J., Moreira, L., & Mendes, J. (2021). Sliding mode control of interleaved converters under fast transients. *IEEE Transactions on Circuits and Systems, 68*(10), 4212–4223.

Slotine, J. J., & Li, W. (2019). *Applied nonlinear control*. Pearson Education.

Tang, Y., Li, X., & Wang, H. (2021). High-order sliding mode control for improved performance of power converters. *IEEE Transactions on Control Systems Technology, 29*(5), 1934–1945.

Utkin, V., Guldner, J., & Shi, J. (2017). *Sliding mode control in electro-mechanical systems*. CRC Press.

Wang, R., Zhang, J., & Huang, C. (2019). Robustness analysis of sliding mode controlled DC–DC converters. *Journal of Power Electronics, 19*(4), 977–986.

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Wei, X., Zhou, Y., & Sun, H. (2020). High-efficiency control strategies for isolated converters in renewable systems. *Energies, 13*(19), 5021.

Wu, C., Peng, Z., & Ma, H. (2021). Enhanced nonlinear control methods for SAB converters in HVDC systems. *IEEE Journal of Emerging and Selected Topics in Power Electronics, 9*(2), 1786–1798.

Yang, Z., & Li, P. (2020). Analysis of control stability in modular DC–DC converters with nonlinear loads. *IEEE Transactions on Energy Conversion, 35*(3), 1352–1361.

Zheng, X., Yang, S., & Zhao, Q. (2021). Discrete-time sliding mode control of switching power supplies. *International Journal of Electronics, 108*(5), 813–828.

Zhou, D., Zhang, Y., & Wu, T. (2019). Adaptive control of renewable energy systems under stochastic disturbances. *IET Renewable Power Generation, 13*(10), 1662–1672.

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