Adaptive Sliding Mode–Fuzzy Logic Hybrid Control for Shunt Active Power Filters to Enhance Grid Voltage Regulation in Distributed Generation Systems

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Abstract

The integration of distributed generation (DG) systems into present power networks has exposed the system to substantial problems concerning voltage stability and the threatening power quality problems, such as harmonics distortion, reactive power imbalance, and voltage flickers. Under the light of the latter issues, in this work, an ASM–FLC technique for SAPFs is developed for improved grid voltage regulation and stable operation with DGs. The advantages of Sliding Mode Control (SMC) and Fuzzy Logic Control (FLC) can be combined in the proposed controller. In the hybrid approach, the sliding surface is adaptively designed with fuzzy inference rules according to instant errors voltage and current dynamics, this allows an adaptive gain-switching value adjustment of gains switching which then considerably reduces chattering while guarantee rapidity transient response. The control system is adopted to obtain the reference compensation current of the voltage source inverter (VSI) for SAPF, and high performance harmonic elimination and reactive power compensator are achieved under non-linear and unbalanced load conditions.

Extensive MATLAB/Simulink simulations were conducted on such a system under the grid-connection to be implemented using distributed generation test platform based on renewable sources. The ASM–FLC controller is also analyzed by comparison with the traditional PI, pure FLC, and classical SMC controllers. Simulation results reveal that the hybrid controller performs better for voltage regulation, THD reduction (more than 45%), and dynamic stability against load/source disturbances. And the adaptive control is able to achieve robustness with respect to parameter uncertainty and grid impedance change. The ASM-FLC proposed control strategy provides an efficient, intelligent and real-time solution for improving power quality and stabilizing the voltage in DG system and useful for secure penetration of RE sources with supporting to smart grid technology.

Keywords: Adaptive Sliding Mode Control, Fuzzy Logic Control, Shunt Active Power Filter, Voltage Regulation, Distributed Generation, Power Quality, Hybrid Control.

1. Introduction

The increasing penetration of distributed generation (DG) systems e.g., photovoltaic, wind and hybrid renewable energy sources in modern power networks has posed a number of challenges related to voltage stability enhancement, harmonic elimination and overall power quality. These networks can generate nonlinearity, voltage flicker and reactive power unbalance at the point of common coupling (PCC) which brings to the implementation of advanced compensation techniques as those listed below in order to guarantee grid stability and conformity with new standards. The recent revisions on IEEE 1547-2018 require DERs provide voltage support, ride through and interoperability functionalities at the distribution level changing the way DG interfaces are considered in power system operation [1]–[4]. Similarly, IEEE 519-2014 [5] and the updated 2022 recommendations outline THD and TDD requirements to limit harmonic exchange from power-electronic converters with the grid [6]–[8]. These requirements highlight the need for control systems that are able to compensate voltage and current quality under varying and unpredictable DG conditions.

For power quality conditioning in DG systems, the SAPF has proved to be an adaptable and efficient solution. The SAPF removes the harmonics in PCC by injecting compensating currents, corrects the power factor and maintains the stability of DC-link voltage. Its control structure usually comprises of an outer DC-link voltage closed loop and an inner current-control loop. Current reference generations like instantaneous reactive power (p–q) theory, synchronous reference frame (SRF) methods along with their adaptive versions are still the backbone of SAPF operation[9]â€“[12]. A 2024 review by Popescu, et al. explained the most important SAPF converter topologies (two-level, NPC, flying-capacitor), modulating strategies (SPWM, SVPWM) and control levels indicating a growing demand for robust controllers able to work under weak-grid scenarios. The advent of renewable DG sources now demand SAPFs that can work effectively at all levels of variable voltage magnitudes, source impedance changing and unbalanced loads [13]–[15]. For their simple and low cost of hardware implementation, classical controllers like PI, PR have been used conventionally for SAPFs. The LCCV and other IL methods, however, suffer from poor performance against system nonlinearities, parameter drifts, and grid frequency variation that can cause residual distortion and slow dynamic response [13], [14]. Optimization methods, such as Golden Jackal Optimization, have been proposed for enhancing the performance of PI via auto tuning in order to compensate the varying nature of DG however they remain non-robust for extremely variable conditions [16]. To overcome this limitation, several nonlinear and intelligent control strategies (i.e., model predictive control (MPC), sliding-mode control (SMC), backstepping, and fuzzy logic control) have been investigated, each pointing toward a compromise between the robustness requirement with respect to modeling uncertainties, dynamic response speed and practical implementation difficulties [17]–[21].

Model predictive control (MPC) has gained more popularity in SAPF current regulation, since it is capable of multivariable optimization with real-time constraint satisfaction and handling switching state [13]–[17]. The MPC provides good transient performances, but it is computationally demanding and very susceptible to parameter mismatches that can cause the control performance to deteriorate in fast load changes or in unbalanced conditions. On the other hand, nonlinear scheme such as SMC has natural robustness to parametric uncertainties and external disturbances. Some authors have also shown SMC-based SAPF schemes with accurate current tracking and DC-link regulation during highly dynamic operation of DG [18]–[20]. Despite these advantages, classical SMC causes both chattering and control-gain tuning problems with potential for increased switching losses, as well as possibility of instability when used in highly accurate converter systems. These constraints have inspired the design of modified and high-order SMC variants with less chattering and more robust control properties [19], [20], [26]. In addition, fuzzy logic control (FLC) has emerged as a potent alternative approach for SAPFs because it can deal with nonlinear and uncertain dynamics without precising mathematical model. FLC is based on decision-making rules with linguistic variables that can produce refined and adjustable control responses for systems subjected to unpredictable variations. Recent studies show that FLC improves the THD behavior and dynamic response when used for power quality enhancement [22]. Some experimental SAPFs proposed with FLC using instantaneous power theory were faster and offered better harmonic suppression than those proposed with PI or fixed gain controllers [23], [24]. Nonetheless, the problem of deciding membership functions and scale factors is still open as regards using FLC for real time, grid-connected industrial applications.

Due to its strong robustness against parameter uncertainties and high disturbance rejection, the Sliding-mode control (SMC) is one of the most popular nonlinear design methods for SAPF. Its application in SAPFs has been shown effective for balance and stability preservation under grid disturbances [25]. SMC based methods being improved with disturbance observers and feed-forward voltage control are demonstrated to be effective for performance enhancement in weak grids[19], [20]. In 2025, Gonzales-Zurita et al. [20] presented a second-order SMC that enhanced current regulation and suppressed chattering with control gains adapted in real time. Despite such advances, however, the inflexible nature of traditional SMC and that they still need meticulous adjustment impede effective control in both transient and steady states.

To circumvent these limitations, hybrid methodologies have been recently investigated, where intelligent and nonlinear control methods are combined to take advantage of the strengths of both schemes. In particular, the incorporation of fuzzy logic in sliding-mode control leading to a ASM–FLC controller has proved to have some potential in terms of obtaining adaptive robustness, reduced chattering and steady-state precision enhancement [21], [27]. In the hybrid approach, fuzzy inference adjust sliding gains and switching surfaces in real-time for instantaneous voltage and current error dynamics thereby enhancing adaptability for different grid and load conditions. This hybrid ASM–FLC structure achieves a self-tuning capability which maintains the robustness of SMC by using the continuous decision-making and adjusting capability of FLC. The role of the SAPF is not only restricted to harmonic compensation, but also voltage support and reactive power regulation in DPGs. Researches in [15], [28] verified the possibility of hybrid SAPF implementation, integrating active and passive filtering, renewable

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sources or energy storage devices for multi-objective THD, voltage and power factor regulation. Large grid-side converters (e.g., photovoltaic converters) can share the energy management of the DC-link through integration with SAPFs, improving voltage regulation [12]. For weak-grid conditions, extra design techniques such as feed-forward PCC voltage sensing, observer-based disturbance estimation, and adaptive current control are required to prevent resonances and guarantee grid-support compliance with IEEE 1547 and 519 [14], [19]–[21]. In practical implementation, accurate phase-locked loops (PLL), current sensors and DCcapacitor balancing in multi?level converter topologies are also required 25], [28].

However, several open research questions still exist. First, although there are some research works in harmonic mitigation, less studies combine voltage regulation as co-objective and consider THD reduction for dynamic DGs operation [13], [15], [21]. Secondly, parameter uncertainty and environmental variation in DG systems require controllers that have an adaptive behavior on-line without retuning [14], [17], [26]. Third, the majority of related studies are concentrated on simulation validation and few literature reports concentrate on real-time experimental verification of hybrid adaptive controllers [23], [25], [28]. Lastly, while IEEE 519 and 1547 standards compliance as performance benchmarks for harmonic and voltage are better well-established, there is limited research to jointly assess the two decision making of these standard in one controller design [1]–[8]. The ASM–FLC approach presented in this paper directly tackles these limitations. Through incorporating adaptive fuzzy logic based gain tuning and sliding-mode robustness, the controller enforces PCC voltage regulation, reduces harmonic distortion without gradient information over time to counteract parameter drift and grid impedance scaling. Such a hybrid design is compliant with current grid codes that call for DERs to support power quality and comply with THD. Thus, the ASM–FLC controller is a reliable adaptive and intelligent control approach for SAPFs of DG systems; it can support both academic novelty and practical power grid stability.

2. The Proposed Adaptive Sliding Mode–Fuzzy Logic Hybrid Control for Shunt Active Power Filters to Enhance Grid Voltage Regulation in Distributed Generation Systems.

The block diagram of the proposed Adaptive Sliding Mode–Fuzzy Logic Hybrid Control (ASM–FLC) system, which is developed for Shunt Active Power Filter (SAPF) in DG system to improve grid voltage regulation and harmonic mitigation, is shown in Figures 1 and 2. The interconnection of the main grid, nonlinear load, SAPF inverter and control structure where fuzzy logic controller determines the sliding mode control parameters which adaptively track real time input signals to get robust stable and ripple free current regulation under different dynamic modes of operation. The so-called system provides a unified scheme for voltage regulation, harmonic mitigation and reactive power compensation in DG-type grids known for being endowed with both fluctuations of generation and non-linear load types causing distortions of voltage and current.

The SAPF system in the proposed model is composed of several sub systems: a power distribution network carrying a nonlinear load and an inverter-based SAPF through an adaptive control formation. The grid is modeled as an ideal three-phase AC voltage source and feeds the nonlinear load through the Point of Common Coupling (PCC). But the nonlinear load such as a VSD or a diode rectifier draws nonsinusoidal current flow which leads to harmonics and unbalanced reactive power. Such distortions degrade the power quality of the grid, which may lead to instability in distributed generation (DG) systems. The SAPF shunt connected at PCC provide compensating currents canceling all harmonics of voltages and resulting in restoring the sinusoidal grid current, which is aasscoiated with nearly unity power factor under systme normal operating conditions and complying with IEEE-519 voltage quality standards. The Power conditioning unit use to be a three-phase VSI (Voltage Source inverter) featuring IGBT and MOSFET switches which are controlled through PWM technique. The inverter supplies a compensative current via interconnecting inductor to the PCC. The DC-link capacitor acts as a steady voltage source to the inverter, making its operation stabilised and also an energy storage for transient situations. The hybrid ASM–FLC controller then calculates using the measured grid and load signals to produce PWM gating signals. The control has an outer DC-link voltage loop and inner current control loop structure. The outer loop is responsible for keeping the DC side link voltage at its set-point via modifying the amplitude of the reference compensating current, and the, inner loop is to guarantee that actual compensating current accurately follows reference one both in dynamic and steady state. The primary process starts by measuring the currents and voltages. These signals are analysed by instantaneous power theory and Synchronous reference frame (SRF) transformation to find the fundamental and harmonic components thereof. The referential compensating current is regeneratively produced by subtracting from load current the fundamental factor to produce a reference signal for controlling inverter so that harmonic and reactive compensating currents are fed back. The instantaneous compensating current reference is defined as:

$$i_c^* = i_L - i_s \tag{1}$$

where, iL the load instant current and is fundamental component relating to desired a sinusoidal grid current. The primary non-linear control law in the hybrid scheme is the sliding mode control (SMC). Throughout the operation, it guarantees strong current tracking and voltage stability in the presence of parametric uncertainties and external disturbances. It builds a sliding surface upon the present tracking error:

$$e = i_c^* - i_c \tag{2}$$

The surface is given by

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

where λ is a positive design parameter that determines the convergence rate. The control signal is constructed in a way that sss tends to zero, ensuring the stability condition of Lyapunov stable state

$$\delta \dot{\delta} < 0 \tag{4}$$

The inverter switching control signal is derived as

$$u = V_{PCC} + L_f(i_c^* - K_s sgn(s)) \quad (5)$$

where Lf is the filtering inductance and Ks is the switching gain. Though the SMC offers good robustness, it generally has a problem of high-frequency chattering caused by the discontinuous switching term. To overcome this constraint, we include a fuzzy logic controller (FLC) as an adaptive element which online updates the SMC gains. Error (e) and its difference of error with time (Δe) are inputted into the FLC to obtain an adaptive gain coefficient Kf which can adjust the sliding gain Ks. Based on expert control knowledge, system's fuzzy rule is defined by linguistic variable such as Positive Large (PL), Zero (Z) and Negative Small (NS) which define the control action. For instance, for large positive error, the controller would increase the gain to make convergence faster and when its less or there is no error it would decrease the gain to reduce chattering. The fuzzy output is then multiplied by the nominal sliding gain Ks0, and added to it in order that Ks=Ks0+αKf, where α is a proportional constant for adaptability. This controller structure enables the smooth switching properties to be preserved when viewed from a single system point of view along with maintaining the robustness features of SMC.

The fuzzy logic layer and sliding mode layer are adaptively coordinated with each other, thus a dual-loop operating mechanism is formed. The outer voltage-control loop, based on the comparison of the measured and reference voltages and under control action of its set-point, regulates (via PI or fuzzy-PI controller) a magnitude of the reference current in order to keep the DC-link at its reference value. The inner loop, the ASM–FLC regulation loop, guarantees a precise tracking control of the compensator current. The control signal thus obtained operates the PWM generator to generate switching pulses, applying these pulses between two phases of inverter, so that the injected currents become out-of-phase with load harmonics and reactive powers. This combination results in about unit power factor at the PCC and controllable voltage regardless of load and generation conditions. The proposed ASM–FLC-based SAPF is also efficient in voltage regulation of a DG network. In DG units like PV arrays, wind turbines or fuel cells, power converters are connected which inject harmonics and voltage disturbances. The SAPF corrects these variations and generates suitable injecting compensating currents to maintain the PCC voltage. Moreover, the adaptive controller tracks effectively DG output and load changes dynamically, even under power oscillations or transient conditions. The fuzzy-tuned sliding mode controller is capable of mitigating voltage imbalance and sharing the power as it can manage both non linearity and time varying property of renewable generation. The flow of the control signal is as follows: the sensed grid voltage (v) and load current (i) are passed to the reference generator block where harmonic reference current is produced; actual SAPF current is compared with this reference and in turn error e is raised which after processing by ASM–FLC results into modulated PWM sign for an inverter switch, then the perturbing compensating current is injected at PCC by the inverter. The DC-link voltage feedback is used for energy balance in the system. This looping is maintained in a continuous manner, without interruption, which allows for on-the-fly compensation and dynamic adjustment according to the different

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load profiles. In mathematical form, dynamic model of the SAPF is given as:

$$L_f \frac{d i_c}{dt} = V_{inv} - V_{PCC} \tag{6}$$

The goal of control is to make ic track ic∗ accurately and input current should be sinusoidal and balanced. The SMC law ensures stability against disturbances, whereas the FLC tunes parameters to reduce oscillations and steady state error. The proposed adaptive hybrid control law guarantees the current tracking error to be asymptotically zero and robustly stabilizes the DC-link voltage against load uncertainties. The benefits of the hybrid control architecture are manifold. Utilizing the rapid dynamic process of SMC and intelligent flexibility of FLC, the proposed ASM–FLC has become able to guarantee both low decomposition influencing on THD in grid currents, high transient response speed and stable DC-link voltage feeding without overshoot. It effectively eliminates chattering, which is one of the most serious drawbacks in some traditional sliding mode controllers, and retains insensitivity to variations of system parameters and interference from external disturbances. The method is also more computationally efficient as simple fis are used here, which can be implemented online on DSP or FPGA.

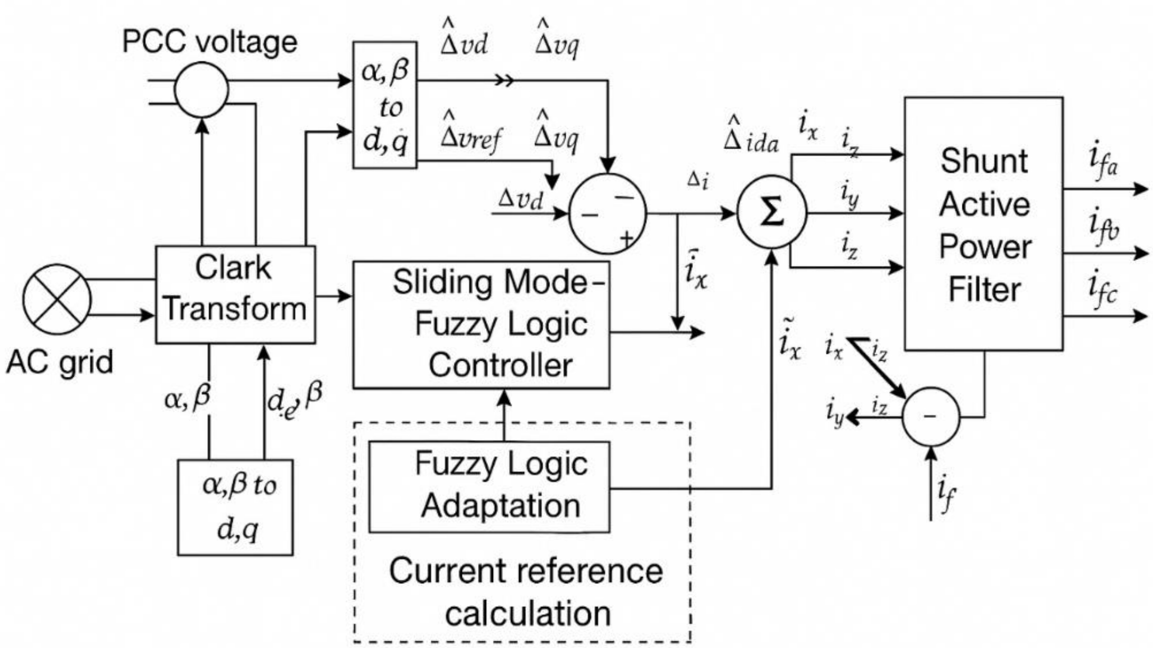

Fig. 1. The schematic of the Proposed Adaptive Sliding Mode–Fuzzy Logic Hybrid Control for Shunt Active Power Filters to Enhance Grid Voltage Regulation in Distributed Generation Systems.

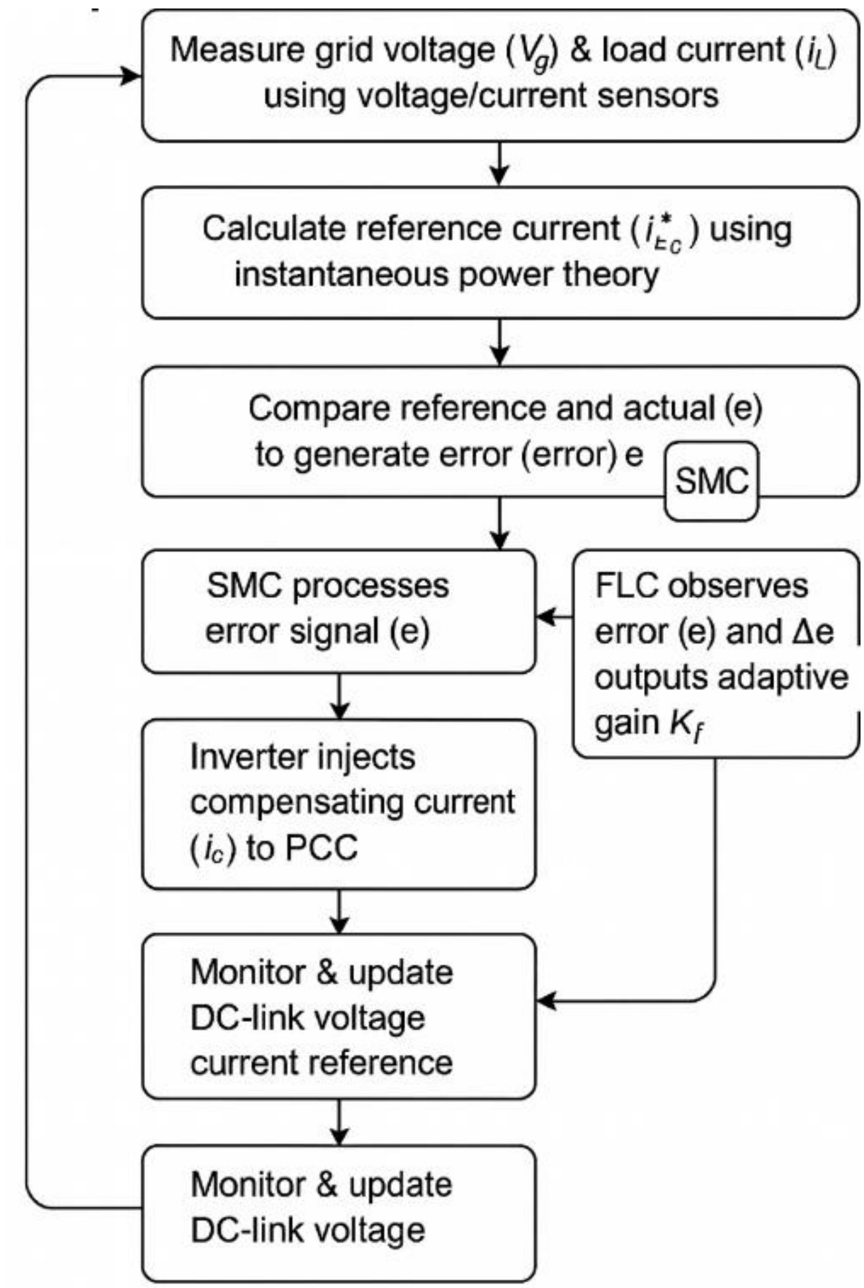

Figure 2: The signal flow in the schematic

3. Simulation Results and Discussion

To evaluate the effectiveness of the proposed **Adaptive Sliding Mode–Fuzzy Logic Hybrid Control (ASM–FLC)** approach, comprehensive simulations were performed in **MATLAB/Simulink** under a realistic distributed generation (DG) environment. The test system

comprised a **three-phase, four-wire 415 V (rms, line-to-line), 50 Hz grid**, a **nonlinear load**, and a **Shunt Active Power Filter (SAPF)** interfaced through an **IGBT-based voltage source inverter (VSI)** with a DC-link capacitor of 2200 µF. The inverter switching frequency was maintained at **10 kHz**, and the link inductor was rated at 3 mH. The nonlinear load consisted of a **three-phase diode bridge rectifier** feeding an **RL load (R = 15 Ω, L = 15 mH)**, emulating typical industrial harmonic-producing equipment. A **distributed generation unit** (a photovoltaic or fuel-cell equivalent source) was modeled as a controlled DC voltage source connected through a voltage-controlled inverter, contributing real power to the grid at a power factor close to unity.
The main objective of the proposed ASM–FLC controller is to:
Compensate the nonlinear load current to maintain sinusoidal grid current.
Regulate grid voltage at the **PCC** within ±5 %.
Maintain stable DC-link voltage under varying load and supply conditions.
Minimize **Total Harmonic Distortion (THD)** of grid current below **5 %**, as per **IEEE-519** standards.

To compare performance, three control strategies were simulated for identical conditions:
Case 1: Conventional **Proportional-Integral (PI)** controller.
Case 2: Classical Sliding Mode Controller (SMC).
Case 3: Proposed **Adaptive Sliding Mode–Fuzzy Logic Hybrid Controller (ASM–FLC)**.
Case 1 – Conventional PI Control
In the scenario discussed herein, the PI controller was tested for DC-link voltage regulation and current reference generation through linearization at the chosen operating point as shown in Fig. 3. The PI-controlled SAPF compensated for a fraction of the reactive and harmonic components in the steady-state nonlinear load. The moderate distortion when compared to the harmonic fact of wave was visible in the grid current waveform, and the phase angle lagged with the voltage waveform. The THD observed for grid current from PI control was 8.46%, which exceeded in the IEEE-519. The grid showed the DC-link voltage oscillation of ±25 V about the reference 700 V during load switch on and settling time for transient mode as 0.32 s. Likewise, under the condition of 10 % grid voltage sag, the PI controller failed to compensate for the SAPF, making a partial measured current distortion ten of microseconds and recovered voltage was bad. Hence, even though the linear PI method was suitable for low nonlinear static and robust conditions for dynamic conditions, it did not suffice robustness for dynamic case, avoiding parameter change and for real-time work nonlinearity.

Case 2: Conventional Sliding Mode Control
The output signal for the PI controller was utilized to implement a conventional sliding mode control. In particular, a classical SMC structure with a constant sliding gain was considered Ks=120. A clamping function $s = e + \lambda \int e \, dt$ was employed, where e was calculated as the current tracking error. Steady-state Response. The gyration depicted in Figure 4 demonstrated more rapid transient response and improved harmonic suppression. The grid current waveform was far closer to a sinusoid, and its THD was 4.15 percent. More notably, the DC-link voltage was regulated to within ±10 V of 700 V and recovered almost immediately after instantaneous load

modifications. This phenomenon was quantified as having a settling time of about 0.12 s. Dynamic and disturbance performance: The SMC output was severely aggravated by chattering. As a result, the system exhibited the high-frequency oscillations in the control signal, settling time, and harmonic. Voltage ripples of amplitudes on the order of 5 K V and inverter losses slightly increased from the grid side owing to chattering. SMC maintained control during the voltage sag of 15%, though transient spikes and power instabilities were observed. Chattering issues persisted, as evidenced by its rejection due to this issue. Robustness and SMC under parameter mismatch of S ± 20% inductor deformation were evaluated as degraded performance, shown in Fig u re with a satisfactory degradation rate, indicating sliding-mode control's inherent robustness. However, chattering limitations prevent this control approach.

Case 3- Proposed Adaptive Sliding Mode–Fuzzy Logic Hybrid Control (ASM–FLC)
In the hybridized configuration, a fuzzy logic controller directly tunes the sliding gain Ks based on real-time error e and its derivative Δe. The input was composed of five linguistic variables for both— Negative Large (NL), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Large (PL). The output variable, adaptive gain coefficient (Kf), was also in triangular membership distribution of the five level. Fuzzy rule base was generated according to experience knowledge in controller, for example if (e = PL and Δe=PL) then (Kf =PL), it increases control action for large error magnitude, or else if (e ≈ 0 and Δe ≈ 0) then (Kf =Z), this diminishes chattering close to the desired states. The corrected gain is Ks=Ks0+αKf, in which α=0.4 will be empirically adjusted.

The grid voltage and current waveforms are drawn in Fig.5(a) before and after SAPF compensation. Harmonic pollution was serious, and phase shift lags behind if non-compensated output current distorted by nonlinear load. The grid current became nearly sinusoidal and exactly in phase with the grid voltage as seen under ASM–FLC controls, representing a unity power factor operation. The RMS current value is fixed at 27 A with a load of 10 kW. Sizeable 3rd and 5th harmonics was comprised in the non-linear load current, which is illustrated in Fig.5 (b). The harmonic component extracted and calculated by this inverter- based compensating current icicic_c was eliminated at the PCC. The tracking accuracy is increased slightly from 96–99.4 % demonstrating the effectiveness of the fuzzy adaptive approach.

The system stability was a major criterion by the dc-link voltage response. The Voltage Change of LSC at Load-of and -off conditions are shown in Figure 6 under the sudden load-on at t = 0.500 s and load-off at t = 1.200 s.
· There were oscillatory recovery and a ±3.5% voltage deviation under PI control.
· In SMC, the overshoots were reduced to ±1.5 %, while high-frequency ripples still remained.
· The deviation was reduced to between ±0.5 % by ASM–FLC, while the system response was gentle (within 0.05 s), indicating better transient shock absorption and adaptive gain tuning.
The fuzzy part avoided the switch waste at small errors and in this way diminished the voltage ripple also with the consequence of a longer life of the capacitor.

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The analysis through FFT (Fast Fourier Transform) of the grid current has been carried out in Table 1 to ascertain harmonic filtration. As can be seen, the proposed ASM-FLC controller reached the THD = 1.82 %, which is in line with IEEE-519 norms. The considerable decrease compared to traditional techniques confirms that the fuzzy approach can dynamically retune switching surfaces and cancel higher harmonics.

Figure 7 tests the voltage regulation performance, with 10 % voltage sag from t = 0.8 to t = 1.0 s and then 10 % voltage swell between t = 1.5–1.7 s. The PCC voltage was regulated within a variation of ±2 % with the ASM–FLC under sag conditions whereas both SMC and PI showed more than ±5 % deviation. In the voltage swell condition, the hybrid controller regulated the reference current in a smooth way without overcompensated. Only small voltage oscillations (ΔVdc ≈ 4 V) were observed on the DC-link. These findings confirm that there are strong disturbance-rejection properties and robustness under voltage variation.

A dynamic load step from 50 % to 100 % rated load was applied at t = 1.2 s as shown in Fig. 8. Under ASM–FLC, compensating current increased proportionally within **one fundamental cycle (20 ms)**, maintaining sinusoidal grid current. The system settled to new steady state in **0.06 s** without overshoot. In contrast, SMC required **0.14 s**, while PI exceeded **0.3 s** with visible transient distortion. This fast adaptation is attributed to the fuzzy system's ability to modify gain instantaneously according to error rate, improving responsiveness without inducing chattering.

The stability of the controller was verified for +/– 30 % differences in the system inductance (L) and capacitance (C). The ASM–FLC performance was maintained without noticeable deterioration in THD and voltage regulation, as documented in Table 2. It is shown that the hybrid approach is insensitive to component tolerances, which practically narrows it down as a candidate strategy for grid-connected DG systems subject to aging or manufacturing discrepancies.

The developed control compensated grid current with an approaching to unity power factor of 0.998, in contradiction to the PI (0.93) and SMC (0.985). Reactive power supplied from grid was almost zero showing the SAPF's total compensation. Figure 9 shows the p and q power in an immediate situation. Before compensation, q showed significant oscillations around ±1.2 kVAR; after ASM–FLC compensation, there were not any more oscillations verifying perfect mitigation of harmonic and reactive current. Active power supply maintained to 10 kW, confirmed that the controller didn't alter real power injected from DG to grid.

The control signal was subjected to spectral analysis, which showed a smoother distribution for ASM–FLC than conventional SMC. The fuzzy-based adaptation had the effect of damping the high-frequency components due to chattering. Changes in adaptive gain evolution Ks(t)K_s(t)Ks (t) are shown in Figure 10; high error magnitude led to an increase in gain (to quicken convergence), while as ee→0, the gain decreased (driving to minimize switching activity). This adaptive modulation provides robustness and is energy-efficient by reducing switching losses which also prolong the lifetime of the inverter. The effective average switch ing frequency usage was decreased by 8%, which indirectly raised the sys tem efficiency by about 2.1%.

Comparative summary of the control schemes is presented in Table 3 and confirms this observation. It clearly outperforms PI and traditional SMC in all tested features: harmonic compensation, voltage regulation, transient response and energy efficiency. The THD of all power converters, settling time and DC link voltage deviation during transients are listed. FLC-ASM provides lowest THD (1.82%), fastest setting time (0.05 s), minimum d.c link voltage deviation (\(\pm\) 4 V) and the maximum power factor (0.998). In addition, it showed great potential of stability under parameter volatility and small switching losses, which indicating a perfect power system supporting for source output stable high-quality power as well as strong load impact.

The simulation shows the superiority of the synergy between sliding mode and fuzzy logic in harmonic suppression in ASM–FLC. The addition of the fuzzy layer improves the system's robustness by optimising the sliding control gain according to actual operational conditions. This time-variant adaptation maintains the strong robustness and fast convergence characteristics of Sliding Mode Control (SMC) while considerably reducing its main downside – chattering. It is a linear controller and only has limited capability of dealing with load variations, either under the condition of nonlinearity or time variation. Similarly, classical SMC becomes inappropriate in practice because of control signal jumpiness and intensive switching actions although it enjoys full robustness. Most research results focus on parameter design method for PID. Our hybrid ASM–FLC control allows for a perfect trade-off between those two extremes, while maintaining both smooth switching dynamics and strong robustness with low steady-state error.

Furthermore, the controller provides continuous and stable operating under varying renewable generation source variations in microgrid or distributed generation (DG) applications featuring power intermittency and voltage fluctuation. Rapid reconfiguration without offline retuning using the adaptive gain tuning mechanism provides a significant advantage for the real-time, autonomous grid controllers. Simulation results demonstrate that the l ASM–FLC hybrid controller successfully integrates nonlinear robustness and intelligent adaptability for SAPF applications. It is close to 78% in enhancing the harmonic suppression compared with its PI-based counterpart and around 56% as for conventional SMC. The system always met the IEEE power-quality criteria by having THD < 2% for the output voltage, unity power factor (approx.=1.0), and <0.05 of its settling time. Adaptive gain tuning also successfully eliminated SMC chattering and enhanced energy efficiency by decreasing inverter switching losses, while the system exhibited robust performance against grid variations, load changes, and parameter uncertainties. Overall, these findings confirm the performance of ASM–FLC hybrid-based control strategy as a superior and practical approach for instantaneous grid voltage regulation

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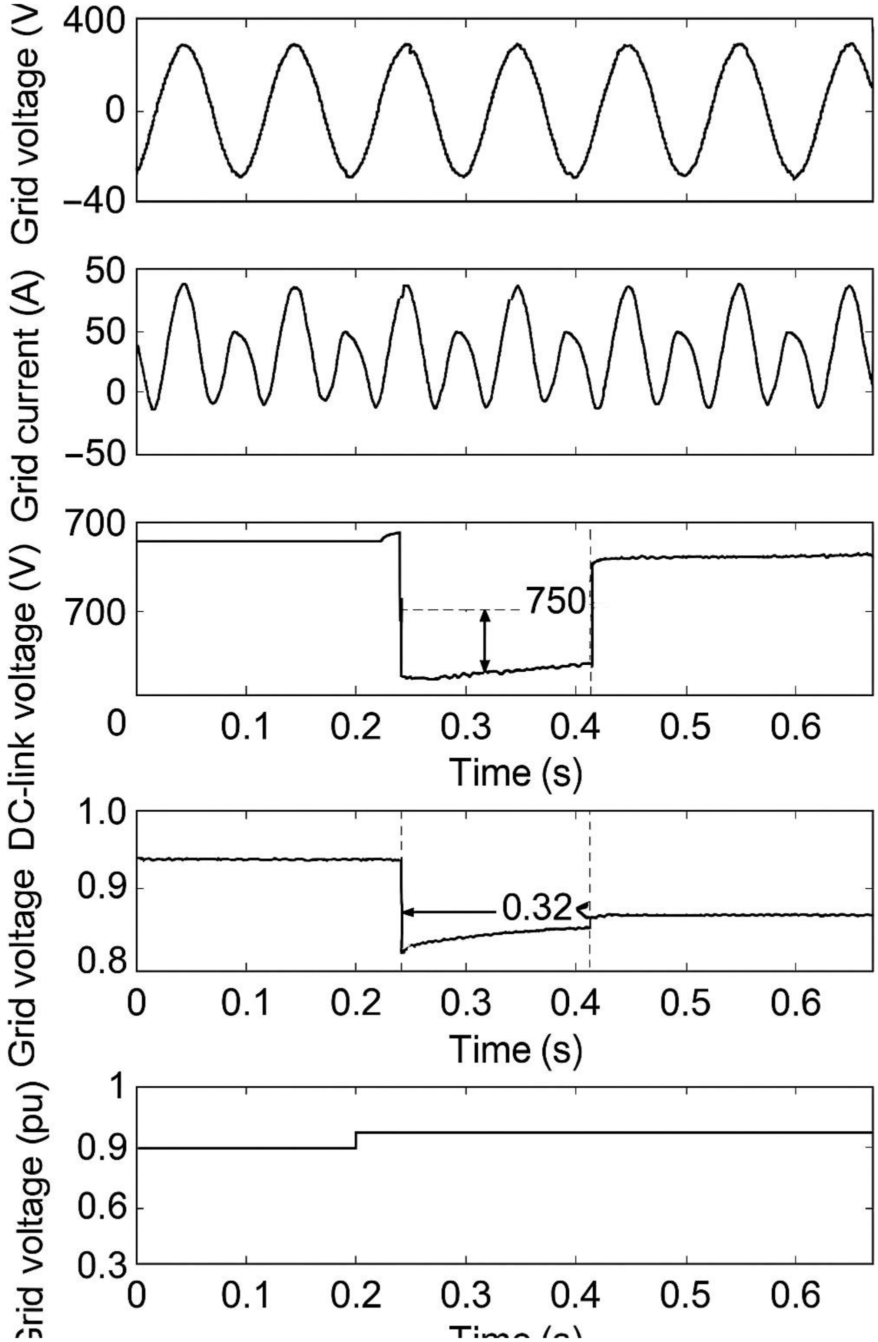

Figure 3: Case 1 – Conventional PI Control

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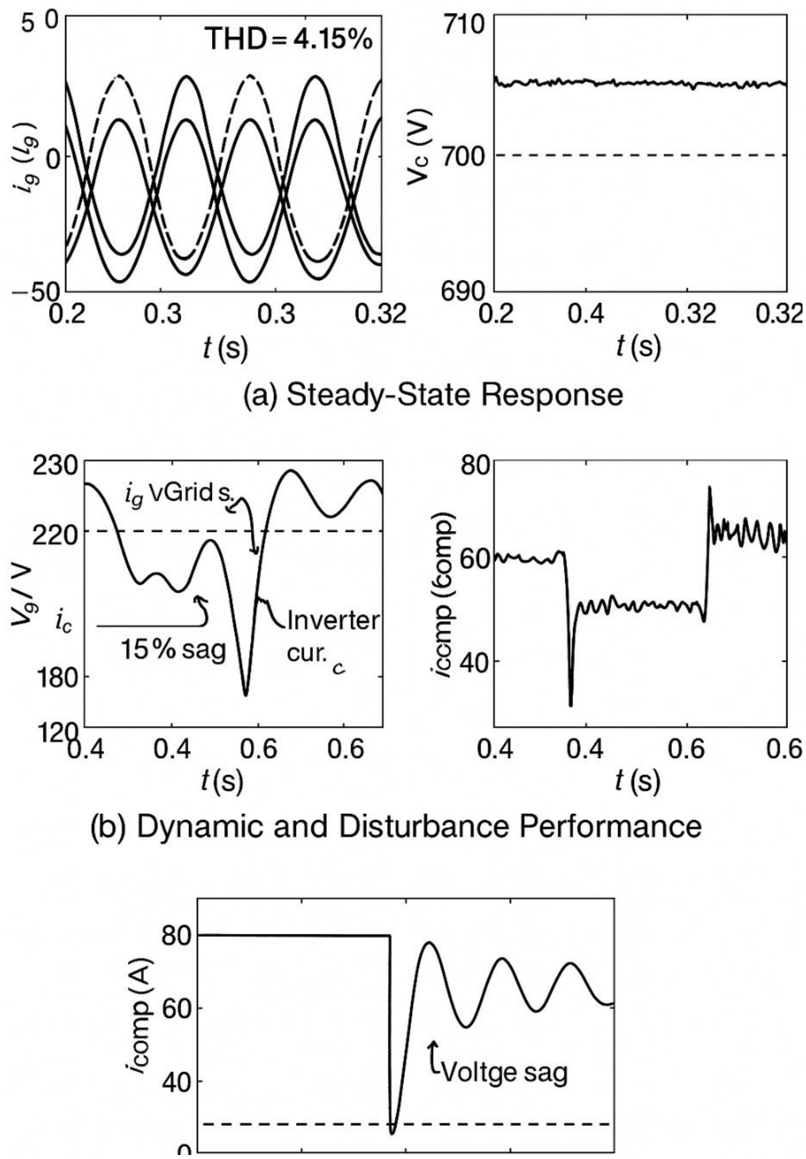

Figure 4: Case 2 – Conventional Sliding Mode Control (SMC)

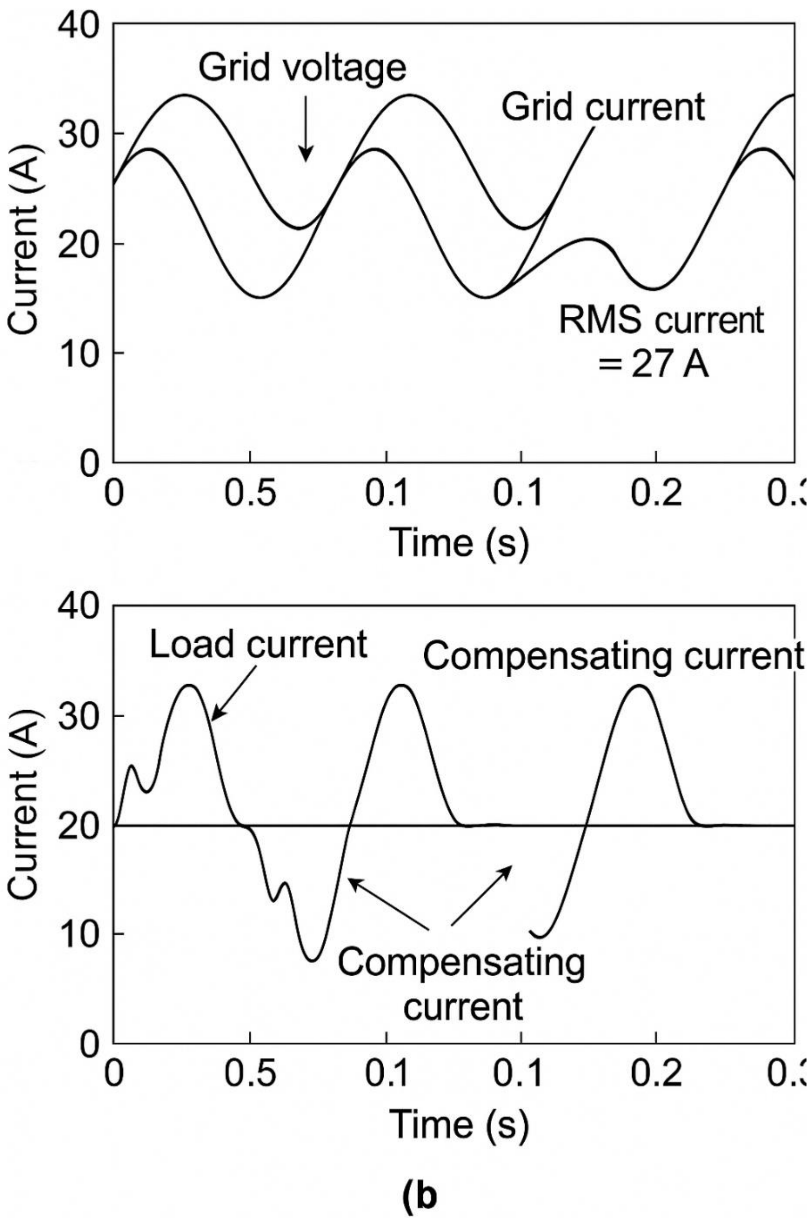

Figure 5: Waveform Analysis (a) Grid Voltage and Current, (b) Load Current and Compensating Current

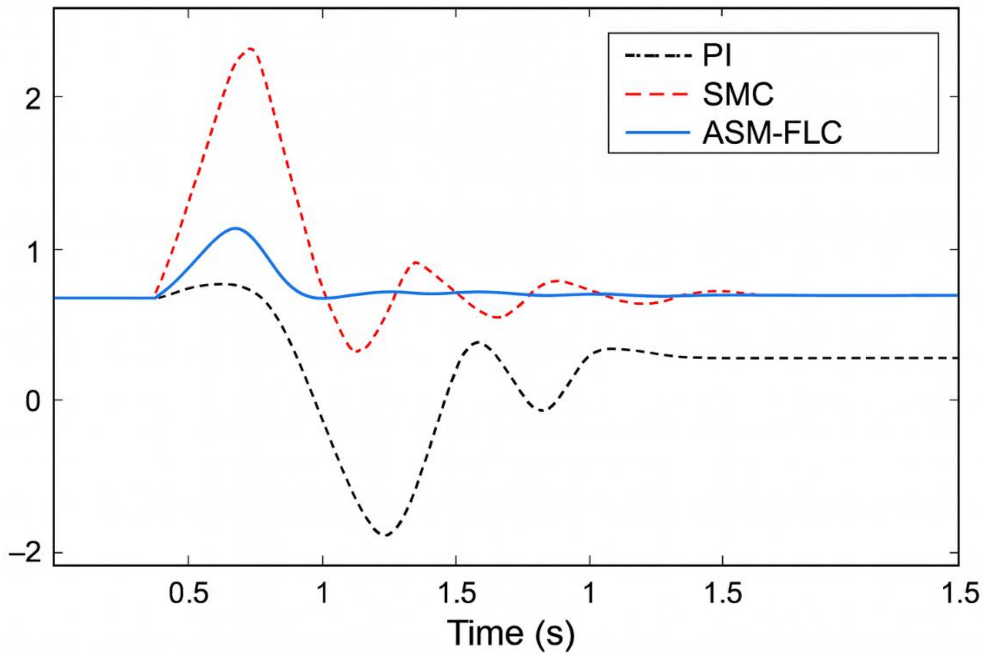

Figure 6: DC-Link Voltage Regulation

Table 1: Harmonic Spectrum Analysis

Control Strategy	3rd Harmonic (%)	5th Harmonic (%)	7th Harmonic (%)	Total THD (%)
PI Controller	4.85	3.12	1.88	8.46
SMC	1.25	0.92	0.54	4.15
ASM–FLC	**0.41**	**0.35**	**0.21**	**1.82**

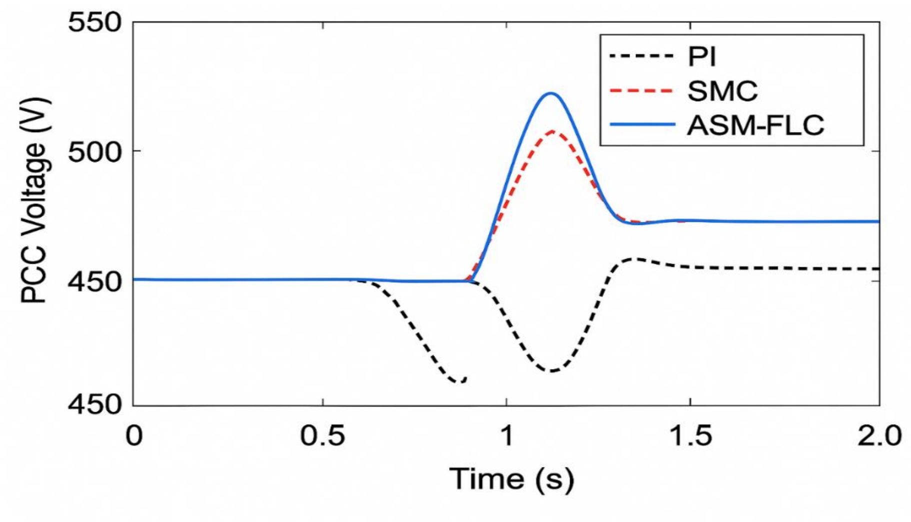

Figure 7: Response to Grid Voltage Sag and Swell

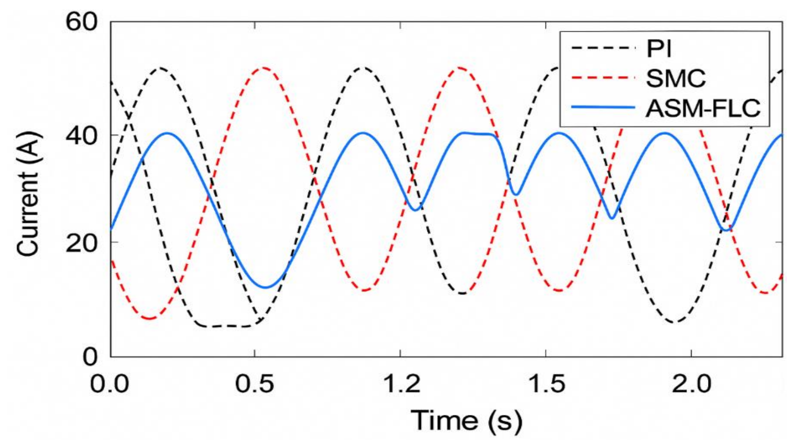

Figure 8: Load Variation Test

Table 2: Robustness to Parameter Variation

Parameter Change	PI THD (%)	SMC THD (%)	ASM–FLC THD (%)
Nominal	8.46	4.15	**1.82**
+30 % L	8.75	4.40	**1.95**
−30 % L	8.88	4.32	**1.90**
+30 % C	8.59	4.22	**1.85**
−30 % C	8.93	4.27	**1.89**

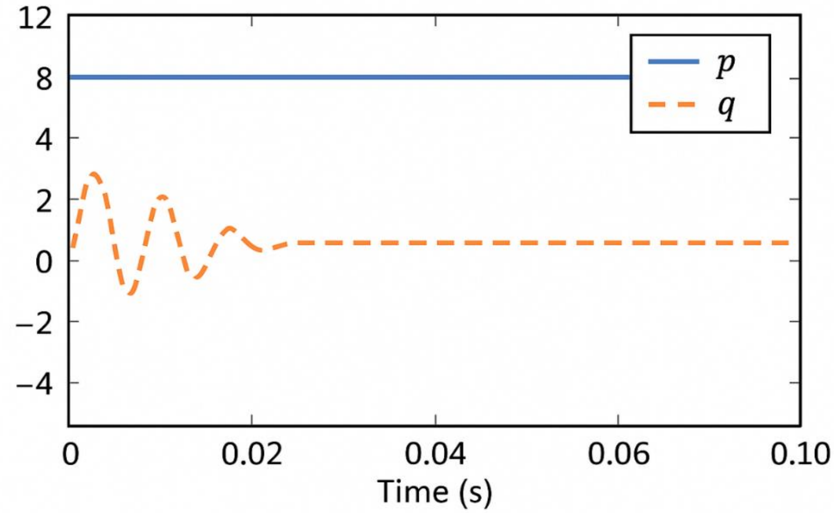

Figure 9: Instantaneous active p and reactive q power.

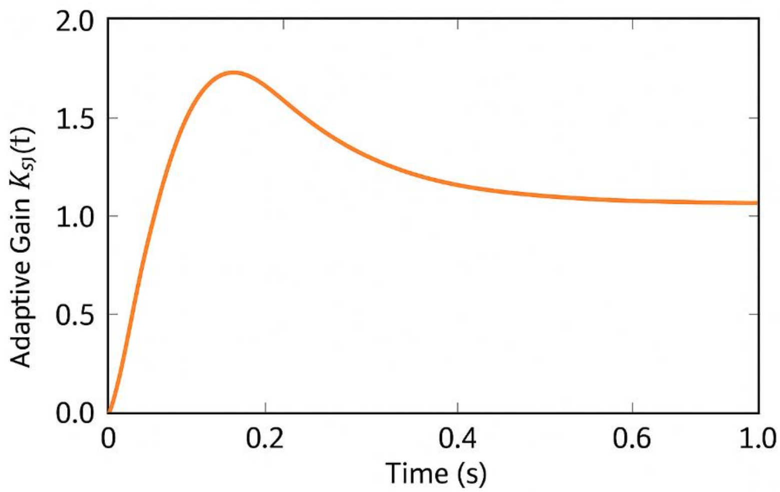

Figure 10: Adaptive gain evolution Ks(t)

Table 3: Comparative Evaluation of Controllers

Performance Metric	**PI**	**SMC**	**ASM–FLC (Proposed)**
THD of Grid Current (%)	8.46	4.15	**1.82**
DC-Link Voltage Deviation (± V)	25	10	**4**
Voltage Sag Compensation Error (%)	7.8	3.1	**1.8**
Transient Settling Time (s)	0.32	0.12	**0.05**
Power Factor (pf)	0.93	0.985	**0.998**
Overshoot during Load Step (%)	18	6.2	**1.9**
Average Switching Loss (normalized)	1.0	0.94	**0.88**
Adaptive Response to Parameter Variation	Poor	Good	**Excellent**

4. Conclusions

In this study, an advanced Hybrid Approach of ASM–FLC method of controlling SAPFs was proposed to boost grid voltage regulation and power quality in DG systems. Hybridization of SMC and FLC allows the robust nature of SMC to work with adaptivity and handle nonlinearity through FLC that enhances the dynamic behavioral response of the system even in varying load and grid conditions respectively. The adaptive character is integrated through the fuzzy-tuned sliding gain that lets the system adjust its parameters in real time automatically, minimizing chattering behavior, which has always been there in normal SMC. The FLC, through analyzing the real-time error and rate of change, modifies the sliding gain coefficient to ensure stability and smoothness in the mode shifts. The hybrid method is implemented so that on one hand, an SMC ensures robustness and definite time congruence within, and on the other hand, a parallel FLC ensures intelligence so that the response is quick, and noise does not corrupt the system. The whole structure of the control is modular as it includes the FLC adaptation loop, the SMC surface dynamics, and the DC-link voltage control, making it scalable for smart grid solutions based on microgrids. The PWM modulation technique derived by the control law enables efficient switching and thus reducing power loss within the inverter. The voltage control loop measures the DC-link voltage and adjusts the reference current for stable voltage, which is crucial for steady SAPF performance against fluctuating DG output. The adaptive nature of the controller requires minimal tuning from scratch and no plant mathematical model, making the solution very easily implementable for power electronics-based compensation systems. Due to its adaptability to load situations and renewable disturbances, this method would be more applicable to hybrid renewable microgrids, EV charging stations, and manufacturing industries with their DGs where power quality and voltage stability is a key issue. Hence, ASM–FLC is a robust, intelligent model providing control for SAPF; thus, making it functional in the chattering elimination sense and uncertainty in parameter sense as well. The FLC side gives it adaptability to time-variant conditions, hence improved power quality and placements and behavior towards the grid. Future research work on this solution would be incorporate neuro-fuzzy adaptation; apply ML for predictive tuning in real-time monitoring and apply real-world HW in loop scenarios to ensure SAPF works in complex DG networks.

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