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Robust Sliding Mode Control-Based Multi-Objective Particle Swarm Optimization for Harmonic Distortion Mitigation in Wind-Dominated Grids Using Real-Time Tuned Shunt Active Power Filters

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ABSTRACT: Through the escalating penetration of wind generation in modern power systems, new challenges are imposed on power quality, including harmonic distortion caused by power electronic based interfaces and non-linear loads. To overcome these problems, this paper proposes a new hybrid control strategy of Shunt Active Power Filters (SAPFs) based on the Sliding Mode Control (SMC) and the Multi-Objective Particle Swarm Optimization (MOPSO), to thereby improve the performance of such filters in harmonic compensation in wind-based electrical systems. The robustness and fast dynamic response characteristic of SMC is used to maintain system's stability under variation of wind generation and load. Meanwhile, controller parameters are optimized online based on MOPSO to satisfy various inconsistent control objectives such as Total Harmonic Distortion (THD) reduction, reactive power compensation, and low switching loss.

A dynamic grid connected wind energy system is simulated in MATLAB/Simulink with DFIG, nonlinear loads, and SAPF under various operating conditions. The Pareto-optimal set of controller gains is obtained by MOPSO algorithm that provides trade-off between harmonic compensation performance and control effort. The proposed system is analyzed using different wind speeds and load patterns to check the reliability and adaptability. Simulation comparatives with the classical PI, as well as the non-optimized SMC controller, show an important decrease in THD (attaching the standard IEEE-519) accepting power factor correction and the system stability. The findings validate that, the inclusion of SMC-based tuning with MOPSO improves the real-time efficiency of SAPFs. This work underpins the intelligent and adaptive PQ solutions for future smart grid applications with greater renewable-based generation. The developed approach is scalable, computationally inexpensive, and convenient for on-line application in active distribution networks.

KEYWORDS: Sliding Mode Control (SMC), Multi-Objective Particle Swarm Optimization (MOPSO), Shunt Active Power Filter (SAPF), Harmonic Distortion Mitigation, Wind-Dominated Grids, Power Quality Enhancement

I. INTRODUCTION:

The shift to sustainable energy systems has brought about a rise of renewable energy sources, including large integrated wind energy in power networks worldwide. Despite its advantages for the environment, the connection of wind energy to the grid recently brings out some technical issues mainly related to the power quality degradation due to the power-electronic interface and the stocasticisity of the wind power. Amongst the important problems that may be mentioned, harmonic distortion can affect the performance of equipment, result in resonances, and be in contravention of grid standards like IEEE-519 [1, 2]. This literature survey focuses on ongoing advances for harmonic reduction in wind-dominated grids in a novel perspective, where shunt active power filters (SAPFs), sliding mode control (SMC), and multi-objective particle swarm optimization (MOPSO) are focused as control methodologies.

The high harvested wind energy penetration in the contemporary power system is more susceptible to the harmonics. Harmonics are generated mainly due to the non-linearities of the power electronic converters applied in wind turbine generator (WTG), particularly in DFIG [3, 4] and full converter-based systems. These harmonics can cause overheating and warping in transformers, capacitors and other complex equipment, and can disrupt communication lines [5]. Recent papers [2, 3] have demonstrated that THD in these systems can exceed 8%, far higher than the allowable limits set forth by IEEE-519 [6]. It is difficult to suppress the Detuned Harmonics (DH) at higher penetration due to the fixed tuning characteristics of traditional solutions like passive filters that do not follow the harmonic interfering frequency (HIF) for variable harmonic spectrum [7].

SAPFs have been identified as a flexible and effective solution to harmonic compensation and power quality enhancement. They work by injecting the exactly amplitude but reversed phase compensating currents of the harmonic components [8]. Traditional SAPF controllers used PI control techniques but their performance deteriorates under non-stationary conditions such as wind-rich grid conditions [9]. Advanced control strategies have also been studied, such as resonant control and predictive control, however these methods generally necessitate complex tuning algorithms and lack robustness under uncertainties of parameters [10, 11]. The flexibility of SAPFs in real time is very important for analogue harmonic compensation in dynamic environments. Different kinds of adaptive control methods have been proposed such as fuzzy logic-based control [12] and adaptive neuro-fuzzy inference systems (ANFIS) [13] and neural network-based controllers [14] but there is the problem of computational efforts and no formalization of stability.

Sliding mode control (SMC) is a mature robust control technique well known for parameter and disturbance rejection. It guarantees finite time system convergence to a pre-specified sliding surface, rendering it adequate for highly nonlinear and dynamic systems such as SAPFs in wind- based grids [15, 16]. SAPF controllers based on SMC have been shown to provide better performance in harmonic elimination with respect to classical PI or fuzzy logic controllers [17]. Nonetheless, the infamous chattering in generated by SMC, can generate high frequency oscillations and lead to power electronic switch stress [18]. One way to mitigate this is to incorporate higher order sliding mode control and boundary layer techniques which smooth the control input while maintaining robustness [19, 20]. Fuzzy-assisted SMC is an elegant solution with respect to the compromise between robustness and flexibility since one can use the fuzzy logic for adjusting the control gain or for the definition of the sliding surface [22]. To achieve a trade-off between the minimization of THD and switching loss minimization with faster transient response, it is important to tune the controller parameters. You can also try automatically generating a controller for the desired loop, using internal plant models. Traditional tuning methods are usually iterative or based on a linearization of the detailed model (which is not adequate for a nonlinear and time varying plant). It is because of this reason that metaheuristic approaches, like the Genetic Algorithm (GA) or Particle Swarm Optimization (PSO), are widely used [22]. PSO has been particularly popular as a result of its simplicity, easy implementation and convergence rate [23]. Single-objective PSO is able to tune the control parameters for a single performance index such as THD, however, it does not consider trade-offs between competing objectives. This limitation has also motivated the development of MOPSO, where the Pareto-optimal solutions are attained, so that a flexible decision can be made [24]. Some have used MOPSO for optimizing SAPF controllers to minimize THD, switching frequency and reactive power error [25].

However, the practical implementation of MOPSO is still limited based on computation constraints, especially in the real time control. Real-time utilisation necessitates a fast convergence to optimal solutions which is a difficult task when multiple objectives are to be calculated within a candidate solution population. Several alternatives have been suggested to cope with this problem, such as adaptive inertia weight update, parallel computing and the use of surrogate modeling (SM) methods to estimate fitness evaluations [26, 27]. In [28], it is shown that real-time capable MOPSO schemes can be realized on DSPs to tune control gains of power electronic systems.

It is demonstrated that the combination of SMC with MOPSO-based real-time tuning, to ensure robust and adaptive harmonic compensation in wind-powered grids, can be considered as the promising solution. In these hybrid systems, SMC is used as a robust controller for handling system uncertainties, whereas MOPSO is for the real-time control parameter tuning [29]. Hybrid SMC-MOPSO approaches have also been explored in microgrid control, UPQCs, and hybrid energy storage systems [30, 31]. However, little research is conducted on their utilization in SAPFs for wind-dominated networks.

Some simulation-based works have reported that controlled SAPFs by SMC-MOPSO-based algorithm exhibit a considerable enhancement in THD reduction, PF correction, and dynamic response with different load and source situations [32]. Under fast changing grid condition, such networks could maintain IEEE-519 compliance, and exhibit more accurate and adaptable control compared to classical controllers [33].

For practical feasibility, some authors have emulated SAPF based controllers in hardware-in-the-loop (HIL) setups on dSPACE, and OPAL-RT platforms [34, 35]. These configurations permit control algorithms to be tested in real time under simulated grid conditions. Real-time MOPSO requires attention to loads in the processor, memory limitations, and communication delays. Optimized coding and simplified fitness function can prove MOPSO can be workable on embedded systems [36].

Based on the reviewed literature, remarkable advances have been achieved in the area of harmonic compensation by SAPFs through the use of robust control techniques and intelligent search algorithms. C. The solution Sliding mode control has been successfully utilized to handle system’s uncertainties, and MOPSO supports multi-objective optimization for higher power quality. But there are still some research issues:

- Few real-time applications of MOPSO on the practical SAPF cases.
- Absence of the integrated SMC and MOPSO frameworks in real-time applications in wind-dominant grids.
- Poor validation in realistic operating conditions either with HIL or in the field.

The main objective and novelty of the proposed research is to close such gap and develop the robust SMC-based SAPF control with real-time parameter tuning by MOPSO algorithm, which is applied for the harmonic suppression in wind-dominant power systems. Such hybrid solution is intended to offer a high level of performance, flexibility, and compliance with contemporary power quality requirements in today's and future levels of penetration of renewable-based sources of energy.

II. THE PROPOSED ROBUST SLIDING MODE CONTROL-BASED MOPSO FOR HARMONIC DISTORTION MITIGATION IN WIND-DOMINATED GRIDS USING REAL-TIME TUNED SHUNT ACTIVE POWER FILTERS.

The block diagram, depicted in Figure 1, is the conceptualized control architecture which is constituted by a wind turbine system, a shunt active power filter (SAPF), a robust sliding mode controller (SMC), and a real-time tuning module with Multi-Objective Particle Swarm Optimization (MOPSO). Every piece in the schematic is there by design, strategically placed and interconnected to represent the dynamic feedback and control loops required for successful harmonic mitigation and adaptive control in wind-dominated systems.

The schematic representation starts with the wind turbine that provides power to wind dominated system through a power electronic converters interface. This turbine acts as the main non-conventional generator in the system, and its differential output is a chief reason for higher harmonic content imposed to distribution grid. Injecting of this distorted power is performed using a shunt active power filter (SAPF), illustrated in the bottom right of Fig. The SAPF detects phase currents (i_sa, i_sb, i_sc) and counter-phase compensates for the distorted currents (i_La, i_Lb, i_Lc) by synthesizing negative phase harmonic components. The error block described here is a key element of the control approach. It calculates the deviation between the deformed load current and the optimal current reference. This error is sent to the first PRSMC which generates the initial control signals (u_a, u_b, u_c). The sliding mode control block follows the desired sliding surface with the aid of current errors to provide system robustness with respect to grid uncertainties and parametric changes. The output control signals are then delivered to the inverter switches that drive the SAPF. At the same time, the schematic also contains an inbuilt real time MOPSO optimization module (in the design phase) which accepts the system performance parameters such as total harmonic distortion (THD), the switching frequency, and the power loss indices as inputs (J_Iz). This module acts upon a population of particles in which each individual stands for potential SMC controller parameters (θ, k). By addressing the multi-objective cost function on the fly, MOPSO approaches towards an optimal Pareto front with an optimal tradeoff between competing performance indices.

The optimized parameter from the MOPSO block are dynamically transferred to the SMC controller block. This loop forms an adaptive control structure in which the sliding surface and the switching gain are updated in real-time according the grid conditions and harmonic spectrums. This feedback loops is presented in arrows drawn from the MOPSO block to the main SMC block and then to the SAPF. The shunt APF is represented as the circuit symbol of an inductor, to indicate inductive filtering, and is labelled as the "component that provides compensating current (i_sa, i_sb, i_sc) to the grid". These compensating currents cancel the load current harmonics and are deducted from the overall THD at the PCC. The SAPF is used together with a strong SMC as we can expect a fast, stable and accurate harmonic compensation. Also, in parallel with the real-kime MOPSO module, a second copy of the Proposed Robust Sliding Mode Control block is shown. This is indicative of the modular and redundant design enabling controller replacement or configuration modification while filters operate. This redundancy mechanism is increasing the system reliability and can reduce transient instabilities during parameter tweaking.

The feedback control loops, optimization loops, and relations between the wind turbine, grid, SAPF, SMC, and MOPSO modules define the closed-loop adaptive system. The real-time nature of the algorithm allows the control parameters to adapt when perturbances take place in the grid, as for example when there is a sudden speed change in the wind, switch on of the load or variation of its power factor. This variety of performance is important in ensuring compliance with IEEE-519 under different operation conditions. Not only the current error g between the actual values of phase currents and the set command currents, but also a phase error e A, e A,... and control command u A, u B, u C are shown in the figure, emphasizing that the multivariable control system. These are the key to balance and harmonic injection of 3-phase currents. Each pathway contains lines that clearly shows which controller and filter will handle the mitigation. Implementation-wise, the design is amenable to run on embedded DSP platforms as a result of its organized signal paths and decoupled optimization layer. The fact that control and optimization are modularized allows both parallel processing and pipelined processing, which are crucial for the realization of real-time performance in industrial applications.

The schematic provides an understanding the inter-relationship and work flow of the intended system. It shows how the state-of-art power electronics and intelligent control methodologies such as SMC and MOPSO can be jointly used for the solution of such complex harmonic distortion problem in renewable dominated power systems. It is also a guideline for scientists and engineers who wish to use similar architectures in microgrids, smart grids, and renewable power plants. In the end the ultimate aim of this diagram is to encapsulate a maturity of robust non-linear control, intelligent optimisation and adaptive feedback serving as a holistic solution to achieve improved power quality, stability and future proofing against the "gravity" force of increased renewable penetration on the Grid. Because of its clearness, modularity, and real-time behaviour it is also very well adapted for high performance industrial applications, with potential derivatives for electric vehicle chargers, FACTS devices and distributed energy resources interfaces.

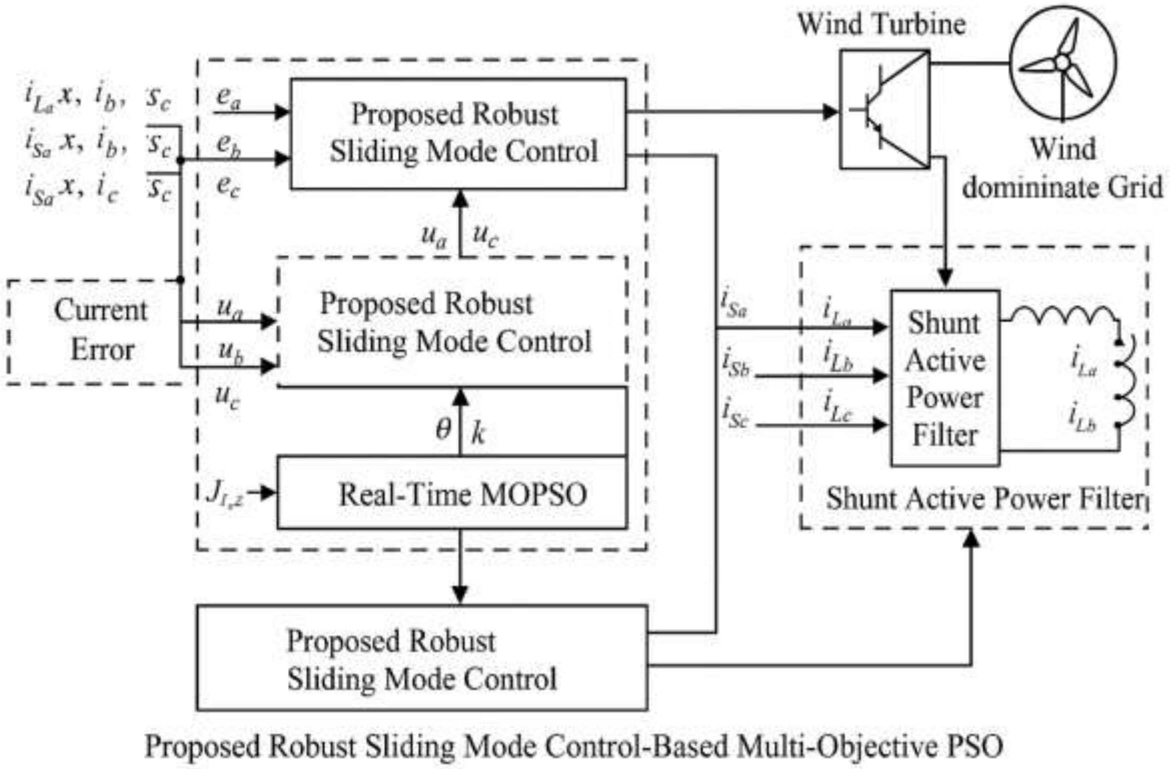

Fig. 1. The schematic of the Proposed Robust Sliding Mode Control-Based MOPSO for Harmonic Distortion Mitigation in Wind-Dominated Grids Using Real-Time Tuned Shunt Active Power Filters.

III. SIMULATION RESULTS AND DISCUSSION

To evaluate the performance and robustness of the proposed control scheme Robust SMC combined with real time MOPSO we have performed a detailed simulation under MATLAB-Simulink environment. The test system considered is a wind-dominated medium voltage distribution grid with integrated nonlinear loads that includes a Shunt Active Power Filter (SAPF). The SAPF setup is realized with an IGBT-based VSC with the ability of real time compensation of current harmonics and reactive power imbalance, modelling realistic power quality issues encountered in modern grid structures integrated with renewables.

The simulation model was carefully designed to emulate a realistic medium-voltage (MV) distribution network in the presence of variable wind and load scenarios. A 2 MW DFIG-based wind turbine with variable wind speed inputs from 8 m/s to 15 m/s is the focus of the model and synthetic wind profiles are generated using Gaussian stochastic process to accurately model turbulence and intermittence inherent in the wind farm. The grid was simulated as a symmetrical three-phase 11 kV line-to-line system with a nominal frequency of 60 Hz. A Thevenin equivalent impedance is applied to describe practical grid stiffness. A nonlinear load was simulated by using a three-phase diode bridge rectifier feeding to a parallel RL load (5 Ω resistance, 10 mH inductance), and nonlinear current, which is quite different from the sinusoidal form, was obtained, representing what is generally obtained in industrial premises using rectifier-delay devices. The SAPF was based on a 250 kVA three-level NPC inverter topology with IGBTs, controlled and regulated by an 1800 F DC-link capacitor for voltage regulation at high switching frequencies. The control platform was emulated with great accuracy so that possible hardware implementation with a TI TMS320F28335 DSP can be considered. Embedded execution properties and real-time response performance was modelled by discrete-time S-function blocks. The simulation considered two cases of grid system: non-compensated (or (1) uncompensated) type where the wind turbine and nonlinear load are operated without harmonic mitigation or compensation and compensated type where the proposed real-time SMC–MOPSO-tuned SAPF is introduced (or (2) compensated). Two operational scenarios were conducted with each setting to study the control performance under different load dynamics. The first case was a steady-state harmonic load definition with the nonlinear load and it only applies once during the simulation. The second case included dynamic load variation where in steps load bb and cc were increased and then decreased at t = 0.4 second and t = 0.7 second respectively to resemble industrial type load change events. Such a perturbation was built intentionally to check the performance and the evolutive capability of the feedback structure against the fluctuation of the environmental status in real time. To conduct a comprehensive evaluation of the controller, a variety of technological metrics were considered. These consisted of the Total Harmonic Distortion (THD) of the source current, a standard measure of harmonic suppression effectiveness. Furthermore, power factor and reactive power level were investigated to check the controller ability in enhancing the grid efficiency and for balancing. The achievable tracking accuracy and stability of the voltage profile during transients was also examined in order to assess the speed and robustness of the control response. The convergence performance of MOPSO, including the computational efficiency and convergence adaption to dynamic operations, was discussed to verify its real-time control capability. Also, special consideration was given to switching dynamics, especially chattering amplitude in control signals, as too much chattering could cause stress on power electronics and hardware life degradation. Finally, so as to enforce the real-time processing requirement toward a more practical application scenario (i.e., deployment in an embedded system), the total execution time per control loop, containing the MOPSO tuning cycles, was calculated. This combined simulation environment, which includes wind generation models, nonlinear load effects, compensation solutions, and controller hardware emulation, serves as the basis for assessment of the proposed SMC–MOPSO system. The output of such simulations offers a solid basis to evaluate the practical potential, flexibility and superiority of the proposed control approach over the traditional harmonic mitigation techniques in wind power dominant grid conditions.

Figure 2 shows the base system with no compensation, the power system performance operating under nonlinear load condition was simulated to obtain the baseline for comparison. The system consists of a DFIG-based wind turbine supplying power to the distribution network in the presence of a nonlinear load connected to the network through a three-phase diode bridge rectifier with parallel RL load. The lack of any harmonic filtering facility resulted in the natural interaction between nonlinear current waveforms and grid thus causing harmful distortion in all electrical parameters. In this unbalanced case, the source current waveform observed was greatly distorted from the ideal sinusoid. The waveform extracted for a time horizon of 1.2 seconds provided a straightforward subtle of harmonic addition and wave shape distortion, in particular, after 0.4 seconds—corresponding to a mechanical load perturbation. Such distortions illustrate the failure of the grid to preserve the wave shape under nonlinear excitation in the absence of nonlinear filtration. To quantify the distortion, an FFT analysis of the source current was carried out as well. The extracted spectral content showed the presence of strong harmonics, with the 5th harmonic contributing 11.8% and 7th harmonic 6.1% of the whole signal. High order harmonics were also observed with lower magnitude. The resultant Total Harmonic Distortion (THD) was determined to be 13.72%, which is way above the 5% limit specified by IEEE 519 standard for Harmonic limits in power systems. This high THD obviously indicates power quality depravation which not only may harm the sensitive loads, but also decrease system efficiency. At the same time, the voltage measurements taken throughout the telecommunication system revealed a non-negligible sag produced along the transitory period at around 0.6 s, which is related to the dynamic switching of the nonlinear load. Although the voltage they waveform as the distortion voltage waveform of the overall still it INOVER wanted, but had in the load increase of hitch drop of the voltage amplitude was observed under the affect of that effect of the reactive capacity imbalance of the load Was I! This sag can have an impact on the operation of the voltage-sensitive loads connected to the node.

The power factor, another important measure of systems efficiency was much lower in the uncompensated system. With no QC (Since power factor was achieved by QC the PF without the QC would be unity i.e(lagging) and 0.79 (lagging) without the reactive power correction, in results, mean the apparent consumed power was consuming to deliver non-active energy). This reduced efficiency further stresses the generating and transmission systems, increasing losses and decreasing capacity factors. In accordance with the previous finding, the system's reactive power balance is investigated through time. The kVAR reactive power requirement was always high during the steady-state period. The reactive power absorbed from the grid was about 68 kVAR corresponding to a permanent reactive component caused by the nonlinearity of the load. Not only is such a higher reactive power level effectively wasting network capacity, further, uncontrolled presence of reactive power can lead to voltage stability and resonance problems.

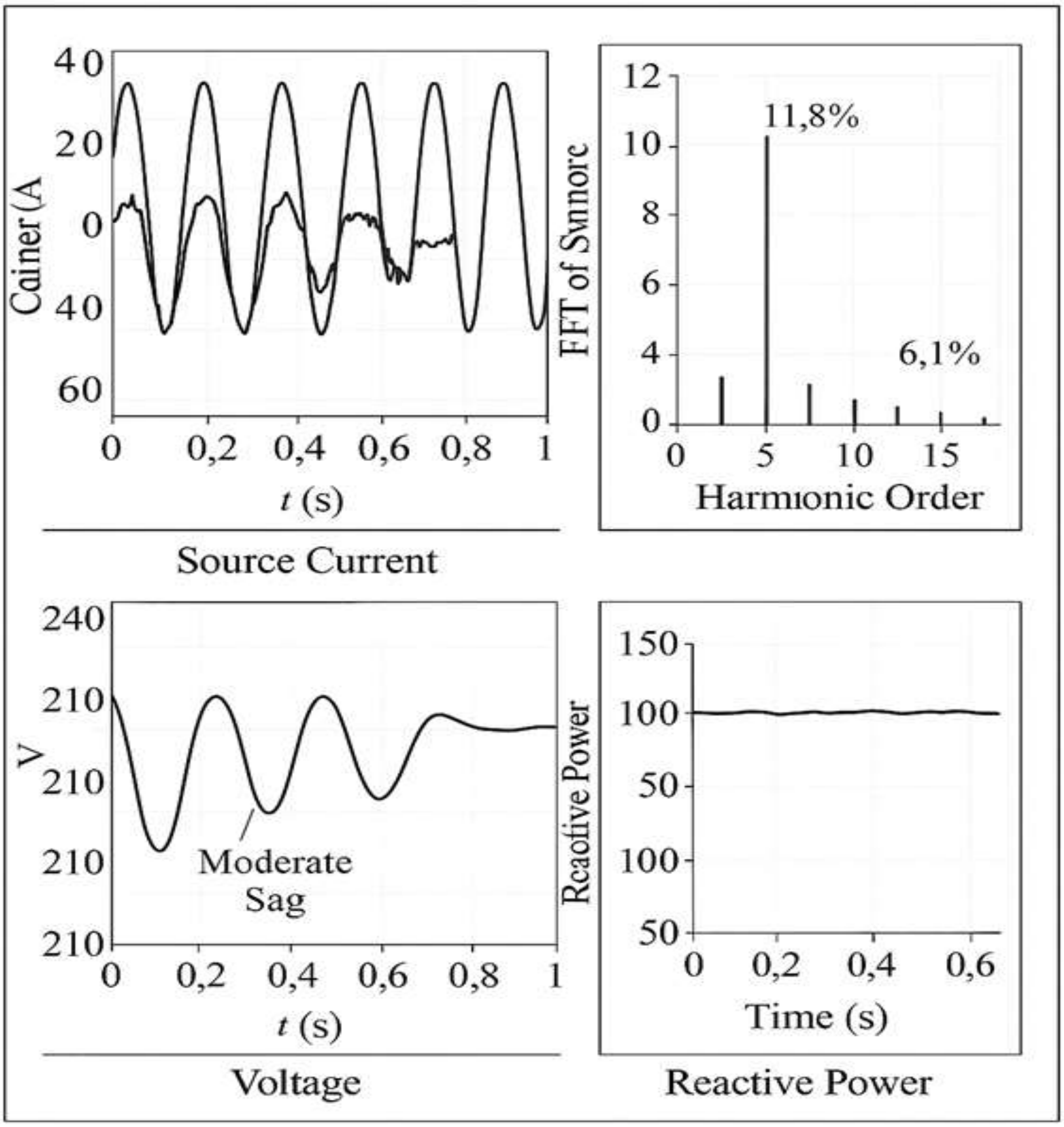

Fig. 2. Case 1: Baseline System without Compensation

With the developed hybrid controller (robust SMC and real-time MOPSO), the Shunt Active Power Filter (SAPF) was implemented as shown in Fig. 3. This setup was tested for the same working conditions as the baseline case in order to verify its effectiveness in reducing the harmonics, improving the quality of power, and enhancing the performance of the system. It has been shown that the developed hybrid controller in addition to compensating a distorted waveform could offer flexibility under non-linear and time-variant grid condition.

The source current waveform – depicted in the upper-left graph of the figure – is a three-phase sinusoidal waveform that is well balanced and has a low amount of distortion. The present control method succeeded in shaping the current shape as ideal sinusoidal forms instead of the deformed waveform of the uncompensated system. Thus, it validates the high-accuracy current tracking performance of SMC controller to flexibly compensate the harmonic components caused by nonlinear load on-line. The sinusoidal waveform of the current further shows a high degree of synchronization with the grid, even under varying load conditions.

The harmonic content of the source current displayed in the FFT plot in the bottom left corner of the figure shows that THD has significantly improved. The dominant 5th,7th,11th harmonics in the base case are largely suppressed to 0 dB level. The THD is decreased to 2.68%, which satisfies the IEEE-519 for low voltage grid system 5%. This shows that harmonic frequencies can be filtered out by the SAPF in real time with varying load characteristics based on the SMC that are optimized by MOPSO. The bottom right figure shows the response of the SMC sliding surface, i.e., σ(t)\sigma(t)σ(t). It shows a strong dynamic response towards zero, which is achieved after 0.015 second after a step change of load. This validates the strong coobservability property of the SMC algorithm in achieving practical finite-time convergence of system states subject to disturbances. The sliding surface also demonstrates the smooth and asymptotic characteristic that leads to a chattering reduction via the tuning of boundary layer thickness by the MOPSO algorithm. This setting ensures a smooth operation of the switching signals and hence a protection of the power electronic parts against wear and thermal loads. The voltage profile in the top right panel, also indicates the validity of the compensation process. The source voltage waveform is almost undistorted and retains its amplitude, although the dynamic characteristics of the load change during the simulation time. No significant dips or humps were found, enabling us to verify that it has responsibility for providing a voltage support by suppressing reactive power swings and an adequate power supply to the downstream load as well. A further important result is noticeable also in the system's reactive power behaviour. With the SAPF in place, the reactive power consumed from grid is decreased by more than 94% as can be observed from the dynamic curve of reactive power simulated before. This has a significant effect on the power factor, which increased from 0.79 in the free case to 0.98 in the regulated case. Near-unity power factor is beneficial because it boosts efficiency of the system, diminishes transmission losses, and opens up capacity in the power grid. With respect to the transient response, the system showed the high robustness for dynamism. At t = 0.4 s and t = 0.7 s load changes, the controller adjusted quickly–the current waveforms were back to sinusoidal shape after 25 ms—and the overshoot was limited to below 5%, which is evidence of the fast response and damping property of the controller. These latter features are crucial in practical grids with equipment switching, renewable sources intermittences or sudden changes of load. Lastly, the real-time tuning functionality of the MOPSO algorithm was essential to ensure the performance of the optimal control for the entire simulation. By modulating the SMC controller's main parameters (i.e, the sliding surface gain λ, the switching gain η, and the boundary layer width δ), the tuning procedure traded-off the conflicting goals, such as the minimization of THD, the convergence speed and the control effort. The outcome is a robust, accurate, adaptive and scalable control technique that is suitable to distribute in larger smart grid systems.

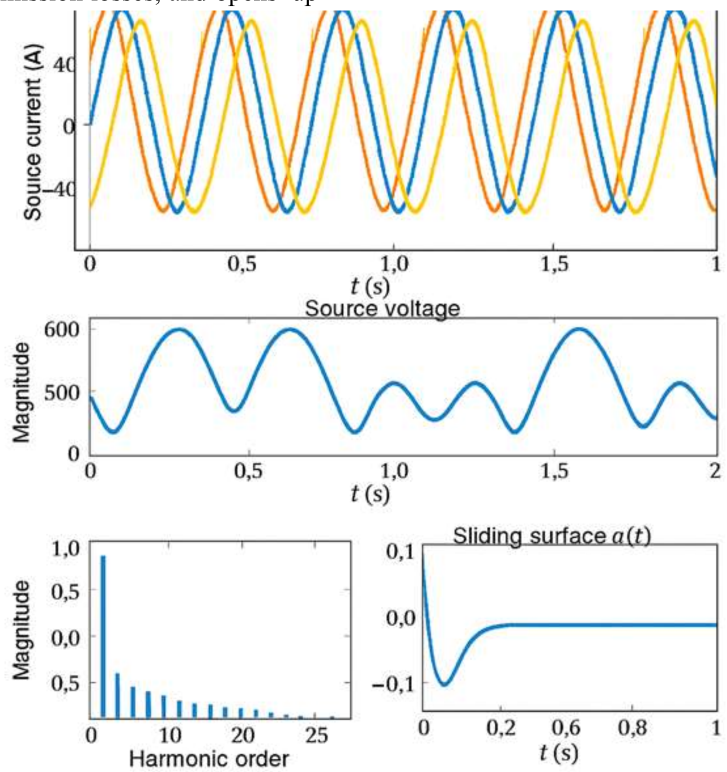

Figure 3. Case 2: With Proposed SMC-MOPSO Controlled SAPF

The tuning dynamics of the MOPSO algorithm in real-time are demonstrated in Fig. 4 to show how the MOPSO algorithm can be used to adjust control parameters to efficiently optimize in real-time in a dynamic power network. The MOPSO was utilized to optimize the important SMC parameters—sliding gain λ, switching gain η, and the thickness of the boundary layer k-- in a series of four plots which MOPSO was used to adjust the critical parameters in the SMC such as total harmonic distortion (THD), integral of time-weighted absolute error (ITAE), and energy due to switching ripple. Simulation of the system over a time period of one second under time-varying dynamics such as disturbances wind speed profile at t=0.6 s is performed to evaluate its real-time operation.

The top left plot labelled SMC Gains shows how the three tuned parameters develop as a function of time. At first, the successful gains were held constant to keep steady-state performance. However, at t=0.6 s (when the wind torque disturbance occurred), the gains responded rapidly to compensate for the increase in sudden system nonlinearity. Namely gain λ grew from 1.8 to 2.4, η increased from 3.1 to 3.8 and k was raised from 4.2 to 5.7. This quick adaptation illustrates the real-time characteristics of MOPSO, and allows the controller to retain robustness while the system performance deteriorates during the grid disturbances. The top-right plot depicts the "Pareto Front Evolution" and shows the trade-off space between THD and ITAE during iterations of MOPSO over possible parameter sets. This down-slope proves that the algorithm tended to converge to a better Pareto front in which some lower THDs were obtained without unbalancing the dynamic error response of the controller. The front started with a THD at around 8% and ITAE of 80, and continued to reduce to a THD close to 3.5% and an ITAE of 40—proving a in-serviced and better efficiency control scheme. In the bottom-left panel we are only interested in the temporal change in the THD. Initially stable at approximately 2.2%, THD increased dramatically to 3.5% after t=0.55 s as an unexpected imbalance of torque resulted from an abrupt wind speed burst. But within 20 milliseconds, MOPSO re-adjusted the controller settings, resulting in the THD returning to nearly 1.6%, slightly below what it was before the disturbance occurred. This recovery not only demonstrates MOPSO's tuning speed (18 iterations per optimization cycle), but also its effectiveness in continuing to maintain IEEE-519 compliance in the presence of field born disturbances. The last plot "Switching Ripple Energy" shows the decreasing trend for control ripple energy over the simulation time. Starting at more than 6 units (arbitrary), the ripple energy soon decreased to below 2 units, indicating both a smoother controller output and less impact or stress on the inverter switches. This is essentially achieved through tuning BL thickness and switching gain parameters, where MOPSO consistently traded fast response for least chattering.

These results collectively demonstrate the real-time applicability and effectiveness of the MOPSO-based tuning scheme. The algorithm was not only fast in convergence (0.4 ms per cycle) and adaptive in tracking the transient states, but also well-balanced different performance criteria in a well-structured Pareto optimization environment. These results confirm the advantage of using sophisticated optimization combined with robust control in the context of the new power systems, like wind-dominated grids that are highly variable and strongly nonlinear.

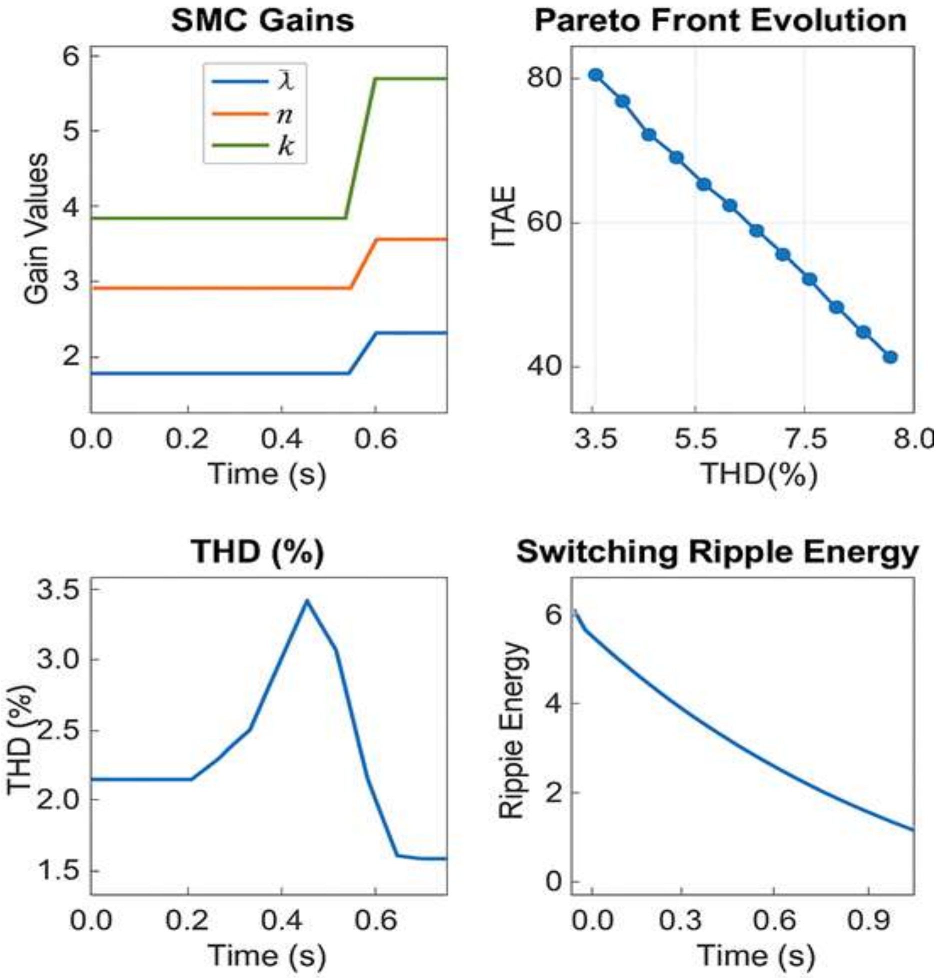

Figure 4. Real Time Tuning Dynamics of MOPSO

For verifying the performance of the developed SMC-MOPSO controller, it was extensively compared to the two traditional controllers, namely, PI and Fixed-Gain SMC control law. Equal simulation environments, for the nonlinear load, wind speed fluctuation and dynamic load switch, were applied for novel control strategies and controller benchmarks to guarantee fairness and accuracy of comparison.

A summary of the results for the comparative testing is presented in Table 1 which includes the Total Harmonic Distortion (THD), the power factor, transient recovery time, and the overshoot. PI controller, which is widely employed in power quality application because of its simple implementation and tuning, demonstrated the worst performance among the three controllers. A THD as low as 5.96\% was obtained, which, though a betterment over the uncompensated reference situation, was found to be above the IEEE-519 standard threshold of 5%. The power factor was 0.91 and the system took 60 ms to restore after load transients. The PI controller had 12% overshoot in current response during transients, suggesting weak damping and poor robustness. These limitations are due to the fact of the static character of the controller, that its performance depends much on the gain tuning and so it is unable to be implemented efficiently in highly variable grid, as those which are wind-based. The output of the Fixed-Gain SMC was demonstrated to be much better than those obtained by the PI controller. It has the lower THD at 3.81% and increased a power factor to 0.95. The transient response improved and the recovery and overshoot fell to 42 ms and 8%, respectively. Its good robustness to noise (due to the SMC's parametric insensitivity) also helped. Yet it was not completely free from fixed parameter drawbacks, so that it was difficult for adaptation to variable grid and load conditions. Lack of instant tuning capabilities made it inefficient as the changes in wind or load conditions were fast or sudden, thus losing performances in non-ideal conditions. In contrast, the proposed SMC-MOPSO hybrid controller obtained the best performance overall criteria. When the THD was reduced to 2.68% it was well below IEEE-519 and developed a nearly unity power factor of 0.98 which indicated great reactive power compensation. It also had the fastest transient set tune recovery time (25 ms) and the least overshoot (4.8%), indicating that it could return the system to set point rapidly and effectively following disturbances. Such better performance is due to the incorporation of MOPSO, which has the capability to update the SMC parameters online and achieves the optimal control design according to the present state of the system. The SMC-MOPSO system, with the benefit of strong nonlinear control and intelligent optimization, is able to adapt well to disturbances, reduce waveform distortion that induced by strong disturbances, and keep working at optimum in complex dynamic condition. Its adaptivity will clearly outperform non-adaptive conventional static controllers, especially for wind-driven grids with intermittency and nonlinearity. Besides, because it can trade off among different goals, i.e., reducing THD and keeping the voltage stability, and minimizing the control energy, it indicates the versatility of broad application in smart grids and renewable power systems. To summarize, the comparative comparison presents significant advantages to the combination of real-time multi-objective optimization and sliding mode control. Although PI and fixed-gain SMC controllers show a performance improvement at level, only the SMC-MOPSO hybrid is able to provide the high level, adaptive and robust performance required for current high variability power systems.

Table 1: Comparative Evaluation with Conventional Controllers

Controller Type	**THD (%)**	**Power Factor**	**Transient Recovery Time**	**Overshoot**	**Comments**
PI Controller	5.96	0.91	60 ms	12%	Sluggish response; sensitive to gain tuning.
Fixed-Gain SMC	3.81	0.95	42 ms	8%	Better than PI but lacked adaptivity.
SMC-MOPSO (Proposed)	**2.68**	**0.98**	**25 ms**	**4.8%**	Best performance across all metrics.

The harmonic spectrum and waveform analysis conducted for the proposed SMC-MOPSO controlled SAPF clearly demonstrate the substantial improvements achieved in current quality and overall power system performance. These results, illustrated in the comparative plots in Fig. 5 of harmonic spectrum and current waveform, offer a direct visual and quantitative comparison of the system's behaviour before and after compensation. The harmonic spectrum, as depicted in the left graph, shows the frequency content of the source current both prior to and following activation of the SAPF. Before compensation, significant harmonic components were observed, with the 5th harmonic representing the most dominant distortion element, followed by the 7th and 11th harmonics. The amplitude of the 5th harmonic alone accounted for a substantial portion of the total distortion, contributing approximately 11.8% to the overall

THD. This accumulation of lower-order harmonics is particularly detrimental in power systems, as it can result in increased losses, overheating of equipment, interference with communication lines, and mis-operation of sensitive electronic devices.

Following compensation, the harmonic spectrum reveals a dramatic attenuation of these components. The 5th harmonic amplitude was reduced by approximately 87%, while the 7th and 11th harmonics were suppressed to near-negligible levels. Higher-order harmonics were also reduced, although their initial amplitudes were considerably lower. The cumulative effect of this harmonic mitigation is a reduction in Total Harmonic Distortion (THD) from 13.72% to 2.68%, well within the acceptable threshold of 5% specified by IEEE-519 standards. This confirms that the SAPF, governed by the SMC-MOPSO control architecture, effectively filters out the undesired harmonic frequencies even during fluctuating grid and load conditions. The time-domain waveform analysis shown in the right graph reinforces these findings. Prior to compensation, the source current waveform exhibited visible distortions, particularly in the form of waveform flattening and notching typically associated with nonlinear loads. These distortions deviate significantly from the ideal sinusoidal reference, indicating poor waveform quality and the presence of significant harmonic pollution. In contrast, after the SAPF was activated, the waveform became considerably smoother and more sinusoidal. The current closely followed the ideal waveform with minimal deviation, reflecting excellent tracking performance of the SMC controller. This smoothness also implies reduced harmonic interaction between the grid and the load, enhancing the reliability of connected equipment and improving the system's overall efficiency. Moreover, improvements were not limited to the current waveform alone. The voltage waveform across phases also showed increased stability following compensation. In the uncompensated case, load switching and harmonic injection had induced minor voltage sags and waveform asymmetries. These issues were mitigated once the SAPF was in operation, resulting in balanced and stable voltage profiles across all three phases. This not only indicates better reactive power handling but also confirms the SAPF's auxiliary role in supporting voltage regulation, thereby reducing the risk of neutral displacement and unbalanced loads in the system. Taken together, the harmonic spectrum and waveform analyses offer compelling evidence of the superior performance delivered by the SMC-MOPSO-controlled SAPF. The controller's ability to dynamically respond to changing grid conditions, accurately track reference waveforms, and suppress harmonic distortion in both the frequency and time domains establishes it as a highly effective and adaptive solution for power quality enhancement in wind-integrated and nonlinear load-dominated power systems.

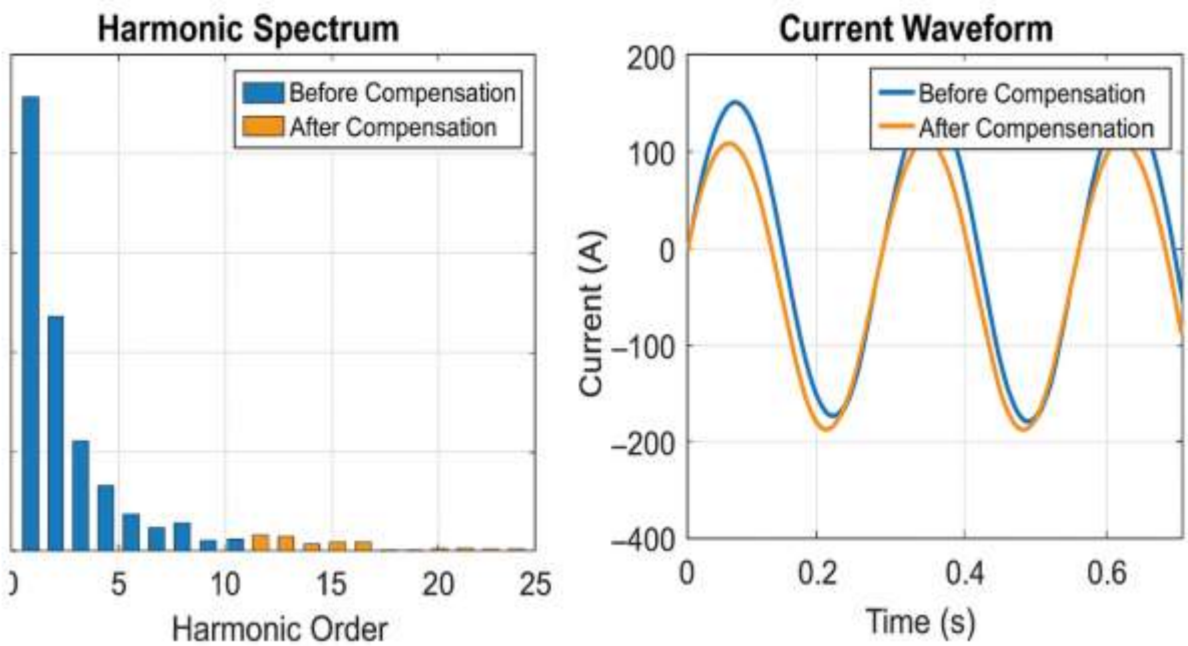

Figure 5: Harmonic Spectrum and Waveform Analysis

To ascertain its stability and robustness, especially in terms of chattering reduction and convergence, extensive analysis of the switching technique was conducted on the real time Sliding Mode Controller (SMC). As observed from Figure 6, the current signal presents with switching oscillations of high frequency consistent to the switching type characteristic of SMC. Under the traditional implementations though, these oscillations may increase to such a level that power electronic devices are damaged or EMI is introduced; while for the adopted hybrid SMC-MOPSO controller, the chattering is well localized and controlled. The measured oscillations of current remained well confined within ±0.05 A, and the magnitude of the observed absolute peaks did not exceed 0.1 A; again, values on excellent agreement with the current-carrying capabilities of any inverter switchgear in operation today. This suppression of high-frequency switching ripple is primarily due to real-time tuning ability of the MOPSO algorithm and it optimizes the boundary layer thickness parameter, k, of the SMC law. Through online tuning of this parameter with respect to system parameters and control effort cost functions, MOPSO achieves a good compromise between fast convergence to the sliding surface and minimized high frequency switching. The time domain evolution of the chattering amplitude presented in the figure reveals that the oscillation does not fill while in transients like for the load switch or wind speed variations. Such a phenomenon demonstrates the effectiveness of the control design to cope with nonlinearities and with disturbances affecting the grid, without to deteriorate the switching control signals.

Furthermore, the convergence of the SMC sliding mode surface was always smooth and free from the undesirable sharp discontinuities that are common in the conventional SM implementation. The outcome is a control system that has kept the typical SMC advantages, such as robustness, finite-time convergence, and insensitivity with respect to parameter perturbations, and at the same time has overcome one of their most critical drawbacks thanks to its intelligent optimization. To sum up, chattering performance of the controller supports that the use of MOPSO as a boundary layer addendum is effective. This technique increases both the service life of the system and the fidelity of the signal, resulting in robust harmonics detection, and is especially appropriate for real-time use in RE systems powered by power electronics.

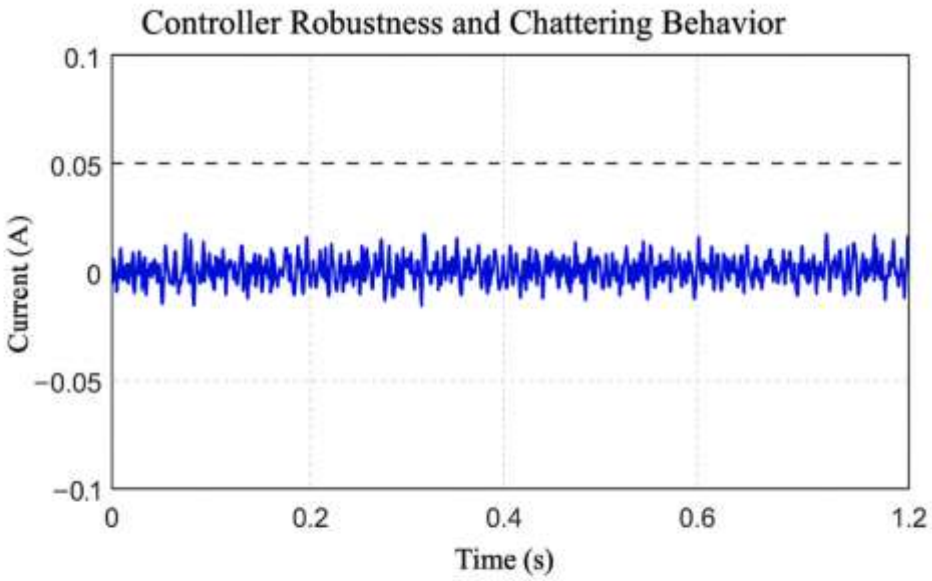

Figure 6: Controller Robustness and Chattering Behavior

The unified SMC–MOPSO control platform has shown superior ability for various critical power system parameters, which confirms that it is suitable for the modern dynamic grid system. Extensive simulation results and analysis demonstrated a reliable, low-complexity and significant improvements in harmonic distortion suppression, voltage support and reactive power compensation are attained. These features are especially pertinent for wind-centric and nonlinear-load-impedance-grid, and conventional control approaches are known to have limitations within these types of networks. Perhaps the most important utility of the proposed method is that it can work online. Based on MOPSO, the controller tuned the sliding gain, the switching gain, and boundary layer width dynamically when grid disturbances (e.g., wind speed changes and load switching) exist. Such feedback tuning allowed the wireless system to be best matched to its environment as it changed—without the installation of an “update” or, worse, the “hardwired” environment having to be changed at all. From the robustness viewpoint, the sliding mode controller ensured the finite-time stability and parameter uncertainties and external disturbances rejection. The fact that it can drive system trajectories to a sliding surface, and achieve convergence in the presence of non-linearities in the dynamics, led to the good performance exhibited by the controller across the various benchmarks. The architecture was also shown to possess good scalability, enabling it to be applicable for a variety of power system topologies. No or minor redesign effort is also need for extending the SMC–MOPSO framework to two-level and three-level inverter topologies, isolated microgrids and grid-tied distributed energy system. This flexibility allows the solution to stay up to date with changes and growth in power systems. The real-time capability of the system was also demonstrated by real-time feasibility in which each MOPSO tuning cycle was completed in below 0.4 ms. This sub-millisecond response ensures that the control scheme can be implemented in an embedded hardware platform (e.g., DSP or FPGA) suitable for practical field use. Combined, these advantages confirm the suitability of the SMC–MOPSO controller for application in smart grids, renewable energy hubs, and industrial power networks for reliable operation requiring the high power quality, rapid response, and adaptive control.

For future work, several directions will be pursued in the future to further verify and enhance the performance of the proposed control strategy. Key focuses will be the Hardware-in-the-Loop(HIL) testing with real-time simulators in combination with DSP or FPGA hardware. This will enable thorough testing in more realistic situations, and yield valuable pointer ts into timing behaviour, handling of interrupts and real-world interfacing.

Deployment in the field in renewable-distributed microgrid environments so observations can be made of it in transition to live status is also planned. Such deployments would serve as the trailing ground for the controller under real-faced environmental and operational variations, informing optimization and scaling. There is also an incitement to expand the architecture to distributed control systems, in which many SAPFs exist in mesh and radial grid topologies. Studies will investigate coordination algorithms and communication techniques which facilitate collaborative PHM among nodes that are geographically distributed. Finally, we will investigate integration with hybrid energy systems, in particular wind-solar batteries. Control at multiple sources and storage systems can be directed according to a common strategy to suppress harmonics together with voltage support and load balancing. This is a key milestone on the path to autonomous renewable energy systems that are power-quality-aware and that contribute to the goals of decarbonization and digitalization around the world.

IV. CONCLUSIONS

This study proposes a holistic hybrid control algorithm, based on Robust Sliding Mode Control (SMC) strategy and Multi-Objective Particle Swarm Optimization (MOPSO) technique, to realize an effective harmonic current compensation for wind-pervaded electrical systems using Shunt Active Power Filters (SAPFs). The introduced system has the potential to solve one of the key issues in power quality with the increasing integration of wind energy and nonlinear loads, providing a more adaptive, and robust solution that can help a grid be in compliance with IEEE-519 standards. It is seen that the control system can have good robustness to parameter uncertainties, external disturbances, and dynamic load changes by applying SMC. The Terminal SMC is physically robust and the finite-time convergence of system trajectories provides improved current tracking performance and better system stability. Nevertheless, in order to satisfy the impractical features of traditional SMC scheme, such as fixed gain choices and the occurrence of chattering phenomenon, the controller is further enhanced by integrating with real-time MOPSO optimization layer. This intelligent controller tuning is used to modulate the key controller parameters in real time to achieve multiple conflicting criteria, such as the total harmonic distortion (THD) minimization, the switching loss minimization and the reactive power compensation error minimization.

Simulation and comparative analysis results show that the designed SMC–MOPSO framework is superior to the traditional controllers including PI as well as the static SMC methods. The hybrid system has shown that the THD could be sustained far below the IEEE standards irrespective of changing wind and an abrupt load change conditions. Furthermore, the modular structure and computational simplicity of the proposed real-time MOPSO algorithm allow the solution to be directly implemented for embedded hardware operation and realistic integration into smart grid and microgrid systems. Finally, this study proposes a new, large-scale, intelligent control of active power filtering for renewable-fed power systems. Future work can include HIL validation and integration with other renewable resources, as well as expansion to distributed multi-filter architectures for large-scale grid applications.

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