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VSC-STATCOM Performance Under Different Fault Sensing using PSO Tuned Hybrid SMC

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ABSTRACT- In this paper, we investigate the PSO-tuned hybrid SMC performance based VSC-STATCOM under different conditions of fault using hybrid renewable energy sources (HRES). A hybrid renewable energy resource system (HRES) consists of PV, wind power, and batteries. Here the Irradiance is the PV input and the wind energy is Wind Input. The storage of energy is used for battery. The battery is used for changing weather condition or the changing the condition of the environment. Hybrid VSC-STATCOM controller based on SMC to reduce power quality issues like sag, swell, harmonics etc. associated with HRES system mainly due to non-linear load conditions. The novelty of our proposed PSO-tuned hybrid Sliding Mode Controller (SMC) method lies in its integration of Particle Swarm Optimization (PSO) as a tuning mechanism within the SMC framework. The Harmonic reduction and efficiency improvement is verified by using the Simulation. Therefore, the proposed system performance is simulated and to optimize the terms are real and reactive power, Total Harmonic Distortion (THD) and Voltage Sag.

Keywords: Hybrid Renewable Energy System (Photovoltaic (PV), Wind, Battery), VSC based STATCOM, Sliding Mode Controller (SMC), PSO (Particle Swarm Optimization), Reactive power compensation, Real power compensation and Power Quality.

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1. INTRODUCTION

Renewable Energy Sources (RES) have been instrumental in electricity generation in recent decades. The foundation of hybrid power systems relies on both Wind Energy Conversion Systems (WECS) and Photovoltaic (PV) systems [1]. However, these systems may not supply adequate reactive power during system faults, leading to fluctuating voltage profiles at common connection points and adverse effects on power streams [2]. Issues such as system stability, power factor, and PQ (Performance and Quality) parameters can have undesirable consequences if not appropriately managed, in accordance with relevant grid codes [5]. Grid preparations for fault ride-through (FRT) are essential for ensuring continuous operation and determining fault and trip zones [4].

The benefits of the fact device include its high speed and flexibility in delivery. In system development, various sources are linked at a common point, enhancing efficiency and flexibility. The utilization of STATCOM has effectively eliminated harmonics produced by different grid-connected sources. The book emphasizes the significance of collaborative power in family studies.

Certainly! Here's a concise statement motivating the use of PSO-tuned hybrid Sequential Monte Carlo (SMC) by highlighting specific challenges addressed compared to existing controllers:

The adoption of the PSO-tuned hybrid SMC stems from its ability to address key challenges unmet by existing controllers [6-9]. Unlike conventional methods, our approach excels in handling complex optimization tasks with improved scalability and adaptability. The integration of Particle Swarm Optimization (PSO) optimizes SMC parameters, mitigating convergence issues and outperforming existing controllers in real-world applications. This novel hybridization offers a unique solution to challenges not adequately tackled by traditional control strategies [10,11].

This statement provides a clear motivation for the use of the proposed PSO-tuned hybrid SMC method, emphasizing its advantages over existing controllers in addressing specific challenges.

Among the existing transfer systems, the STATCOM holds the capability to regulate the power system. With the evolution of the current online system, novel avenues emerge not only for power control but also for fostering online expansion. Various algorithmic methods such as the Best Wolf Algorithm, Gray Wolf Algorithm, Whale Optimization Algorithm, Harris Hawks Algorithm, along with data analytics, are employed to address power-related challenges.

The power control system of photovoltaic-wind hybrid power is provided by VSC-STATCOM using intelligent control system. This paper organized as follows: *Section 2* deals with the Proposed system HRES. STATCOM is presented in *section 3* and *section 4* design an overview of optimization technique details is given. In *section 5* explains the Simulation results are given and the research work conclusion is in *section 6.*

2. HYBRID RENEWABLE ENERGY SOURCE

The proposed HRES system is working on standby or grid connected mode. The PV deliver DC voltage, the wind produced AC, so rectifier is added to convert the AC to DC and the two renewable energy output voltage DC is combined and stored in the battery. The battery delivers constant voltage to the converter. Here the charging and discharging condition of the battery is depending on the operating mode. The RES is controlled by using the maximum power point tracking (MPPT). *Figure 1* shows the hybrid renewable energy system.

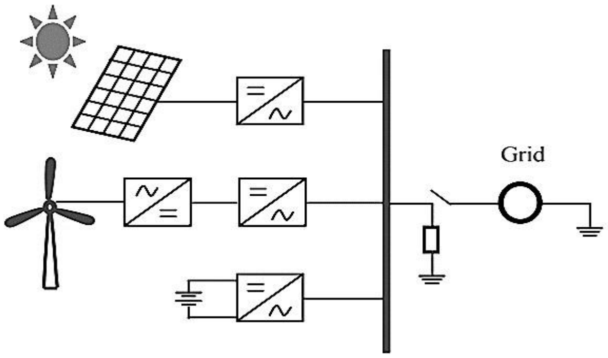


Figure 1. The Hybrid Renewable Energy System [3]

3. STATCOM

In this STATIC Compensator is denoted as STATCOM. The voltage source Converter (VSC) based STATCOM switch is built by the IGBT. The Switches are operating in the PWM (Pulse width Modulation). STATCOM is connected in shunt at point of common coupling to the grid through the transmission line LCL filter. In this Particle Swarm Optimization (PSO) based Slide mode controller (SMC) is used to create the pulses for the STATCOM switches. *Figure 2* shows the STATCOM with LCL filter.

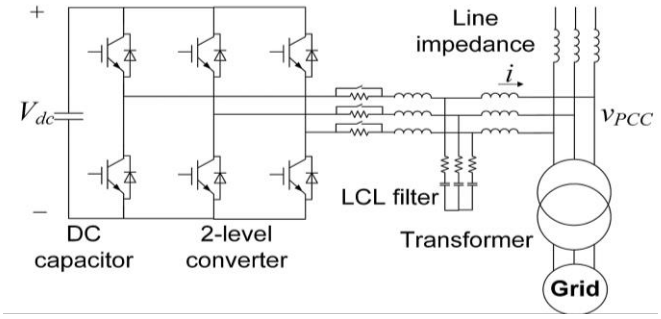


Figure 2. STATCOM with LCL Filter [5]

3.1. STATCOM mathematical modelling:

The power quality control one of the tools is STATCOM with LCL Filter. STATCOM model diagram is shown in *figure 3.* From the figure the phase difference is denoted as θ.

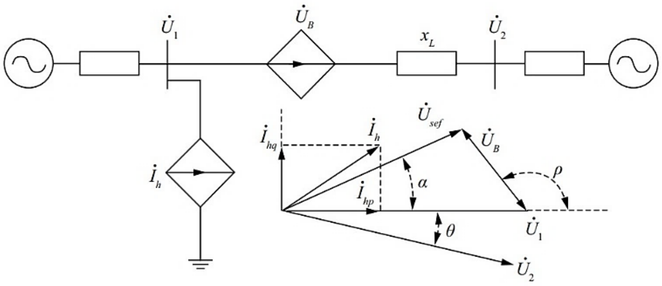


Figure 3. STATCOM model diagram [15]

The line power and reference vector is denoted as U₁, the STATCOM output line power is $P_0 = \frac{U_1 U_2}{x_L} sin\theta$ (1)

$$Q_0 = \frac{{U_2}^2}{x_L} - \frac{U_1 U_2}{x_L} cos\theta \quad (2)$$

$U_{sef}(U_{sef} = U_1 + U_2)$. Meanwhile, line power is

$$P' = \frac{U_{sef} U_2}{x_L} \sin{(\theta + \alpha)} \quad (3)$$

$$Q' = \frac{{U_2}^2}{x_L} - \frac{U_{sef} U_2}{x_L} cos(\theta + \alpha) \quad (4)$$

The injected reactive power and active power is denoted as, $I_{hq} > 0.\ I_{hp} < 0$

4. PARTICLE SWARM OPTIMIZATION (PSO)

Particle Swarm Optimization (PSO) stands out as a straightforward yet widely embraced optimization technique. It facilitates the movement of multiple permissions across the search space, each assigned with distinct values [18]. Throughout the search process, the speed of each particle undergoes continuous updates.

$$v_i^{k+1} = \omega v_i^k + c_1 rand_1 \left(P_{i,pbest}^k - x_i^k\right) + c_2 rand_2 \left(P_{i,gbest}^k - x_i^k\right) \quad (5)$$

When initial weight is ω which is varies between 0.4 to 0.9, random selection rand$_1$ and r$_2$ varies in range [0, 1] and c$_1$ and c$_2$ are the acceleration coefficients are. The position of the crowd is revived by

$$x_i^{new} = x_i + v_i \tag{6}$$

With more iteration, the best solution can be found by

$$x_i^{k+1} = \left\{\frac{x_{i,new} iff(x_{i,new}) \leq f(x_i)}{x_i \; Otherwise}\right\} \tag{7}$$

4.1 Implementation of STATCOM Using PSO:

Finding the right amounts of heavy objects is usually done using artistic data. In this function, the defined error is used as the object function, defined as:

$$Minimize\ F = \sqrt{\frac{\sum_{k=1}^{N}\left[p_k^{observed} - p_k^{forecasted}\right]^2}{\sum_{k=1}^{N}\left[p_k^{observed}\right]^2}} * 100\% \tag{8}$$

when N defines the amount of artistic detail, $p_k^{observed}$ recognized the power of HERS in kth recognition, and $p_k^{forecasted}$ the predicted power at kth output times in the optimization process.

Step by step operation of PSO tuned Hybrid SMC Structure as follows:

1. Initialization:

- Initialize the parameters required for both the PSO and SMC algorithms, such as inertia weight, acceleration coefficients, control gains, population size, maximum iterations, etc.
- Set up the initial population of particles for PSO with random positions and velocities.

2. PSO Optimization:

- Evaluate the fitness of each particle in the population using the performance index related to the VSCSTATCOM system.
- Update the particle's velocity and position using the best-known position of the particle, the best-known position of any particle in the population, and the global best-known position found so far.
- Repeat the evaluation and update process until the termination condition (e.g., maximum iterations reached) is met.

3. SMC Controller Design:

- Utilize the optimized parameters obtained from PSO to design the sliding mode controller.
- Formulate the sliding mode control law based on the system dynamics and the desired performance criteria.

4. Hybrid SMC Operation:

- Implement the sliding mode controller in parallel with the traditional control strategy within the VSCSTATCOM system.
- Monitor the system states and switch between the controllers based on predefined conditions (e.g., reaching a certain error threshold, system instability).

5. Performance Evaluation:

-Simulate the hybrid SMC operation within the VSCSTATCOM system.
- Assess the system's performance in terms of stability, response time, overshoot, settling time, etc.
- Compare the performance with alternative control strategies or unoptimized controllers.

6. Fine-tuning and Validation:

- Fine-tune the parameters of the hybrid SMC system based on simulation results and practical considerations.
- Validate the performance of the tuned system through extensive simulation studies and possibly experimental tests on hardware-in-the-loop setups.

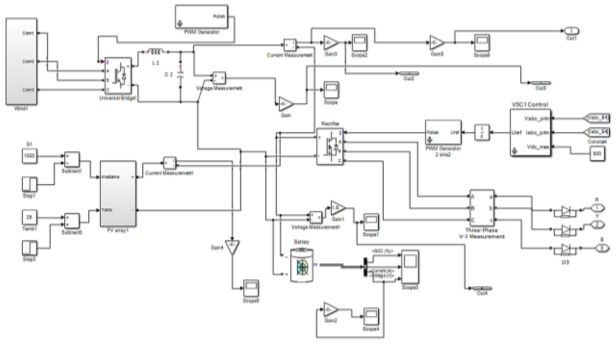
7. Documentation and Reporting:

- Document the entire process, including the PSO optimization, SMC controller design, implementation details, simulation results, and performance evaluation.
- Prepare comprehensive reports or papers detailing the methodology, findings, and contributions of the PSO-tuned hybrid SMC operation within the VSCSTATCOM system.

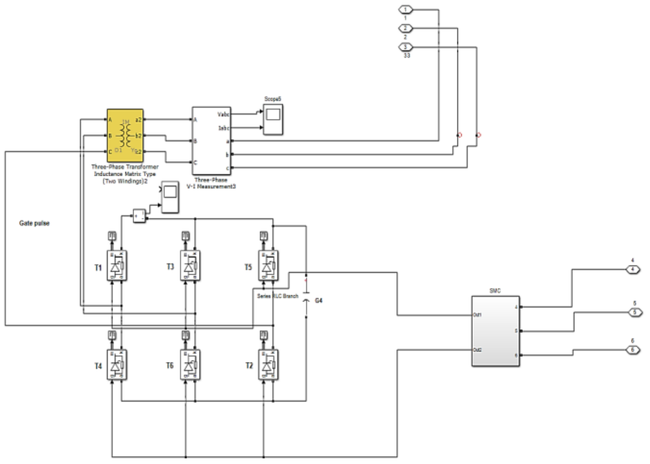
5. SIMULATION RESULTS

The proposed system comprises a High Renewable Energy System (HRES) connected to the grid via a transmission line. Fault clearance is achieved using a STATCOM-based LCL filter. The Simulink implementation of this system is depicted in Figure 4. There are two operational modes: in the first mode, the grid supplies power to loads unaffected by power quality issues such as voltage sag or current sag, ensuring guaranteed active power without the need for VSC-STATCOM control. However, when connected loads increase or conditions on the distribution side lead to power supply distortion, a 3-phase, 50Hz, 415V supply line may suffer. This distortion can be mitigated by employing VSC-STATCOM.

This study focuses on load increases or failures occurring within the time range of 0.08 seconds to 0.15 milliseconds. Fault signals are controlled and generated by a pulse generator, which then triggers the injection of pulses into the three-phase power outlet via a voltage source inverter and injection transformer during fault occurrences or load increases. Three primary cases are considered: three-phase fault compensation, Line-to-Line fault compensation, and Single Line to Ground Fault Compensation, along with Double Line to Ground Fault Compensation.



(a)



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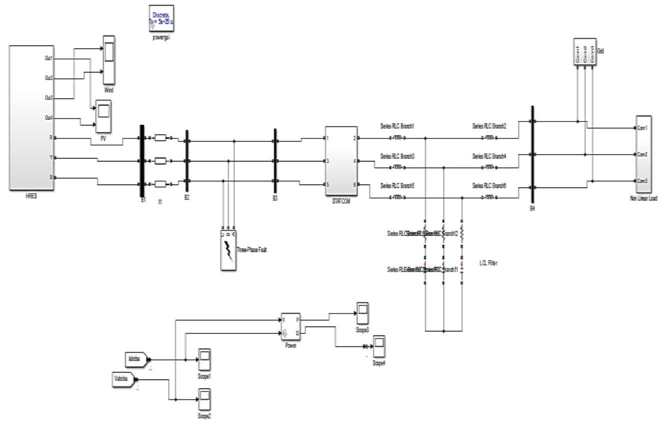


(c)

Figure 4. The proposed system Simulink representation (a) HRES Subsystem (b) Subsystem model of Hybrid SMC with LCL filter (c) Overall proposed system

The PV and WT frameworks serve as the foundation for this study. To maintain control characteristics, the key parameters of PV and WT irradiance and wind speed are set at consistent levels. PV irradiance is standardized at 1000W/m2, determining the structural integrity required to harness this irradiance effectively. Similarly, a wind speed of 12m/s is chosen to optimize WT power generation. Consequently, the Hybrid Renewable Energy System (HRES) is designed to meet high demand and mitigate power quality (PQ) issues. Complementing these frameworks, a battery system is integrated to ensure continuous power supply based solely on PV and WT energy inputs. *Figure 5* illustrates the PV output voltage, while *figure 6* depicts the wind output voltage. Additionally, *figure 7* provides insight into solar irradiation levels."

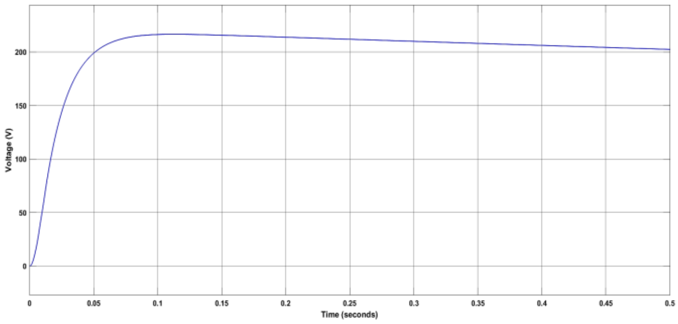


Figure 5. Voltage of the Solar/PV

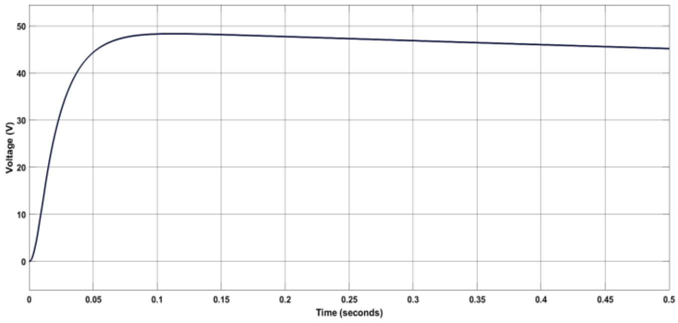


Figure 6. Voltage of the wind

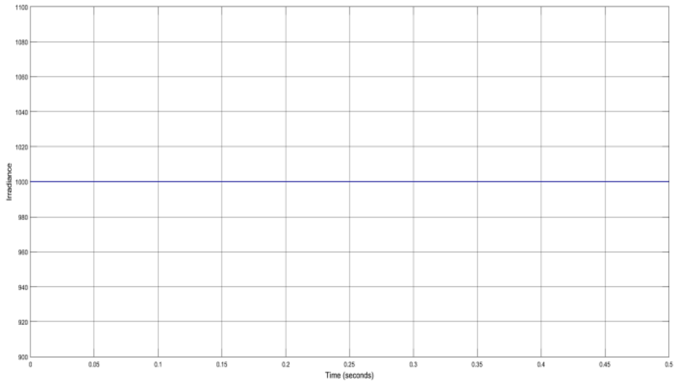
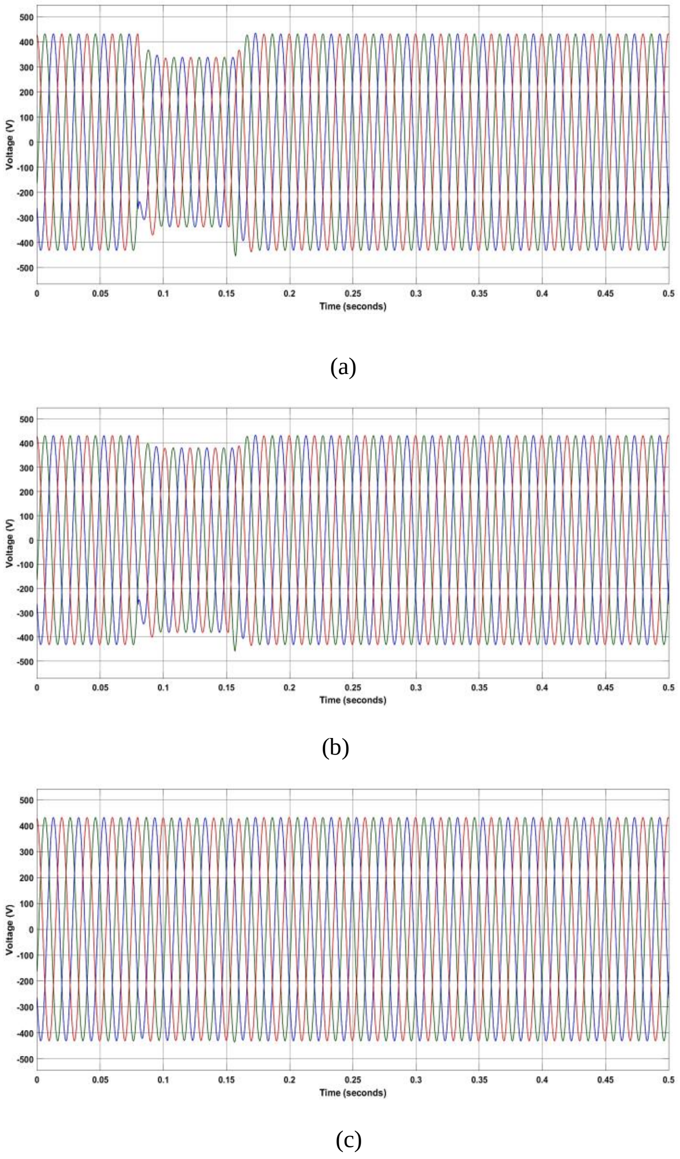


Figure 7. Solar Irradiance Curve

Case 1: Compensation of Three phase fault

In this scenario, a three-phase fault occurred at 0.08 seconds, resulting in a voltage dip across all three phases. The voltage dipped to 310 volts (30% sag) when utilizing PSO-PI of STATCOM, 390 volts (10% sag) with SMC, and 413 volts (3% sag) with PSO-SMC based STATCOM. At 0.08 seconds, the VSC-STATCOM became active and injected 101 volts for PSO-PI of STATCOM, 22 volts for SMC, and 2 volts for PSO tuned SMC. The uncompensated load voltage was 415 volts for PSO-PI of STATCOM and SMC. This information is depicted in Figure 8 (a) and 8(b). The proposed PSO-SMC effectively compensated the sag voltage to 415 volts, with the VSC-STATCOM injecting 2 volts, as illustrated in *figure 8 (c).*



(a)

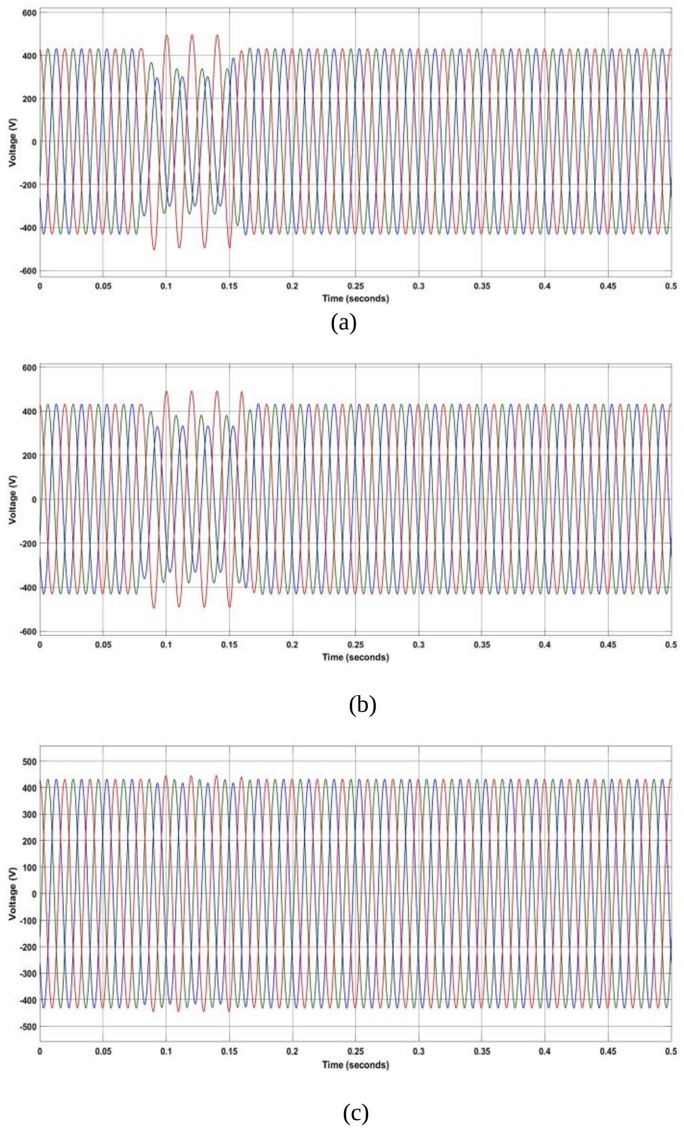
(b)

(c)

Figure 8. Three phase fault voltage sag compensation of using (a)PSO - PI (b) Slide Mode Controller (c) PSO-SMC based STATCOM

Case 2: The compensation of Line-to-Line fault

In this scenario, a line-to-line fault occurs at 0.08 seconds, causing a voltage dip. During this event, the voltage in phase A drops to 320 V (a 30% sag) and in phase B to 330 V (a 25% sag) without compensation. When utilizing PSO-PI control for STATCOM, phase A is maintained at 395 V (a 10% sag) and phase B at 405 V (a 5% sag). With SMC, phase A rises to 412 V (a 3% sag) and phase B to 413 V (a 2% sag). At 0.08 seconds, the VSC-STATCOM activates, injecting 80 V into phase A and 70 V into phase B with PSO-PI control. With SMC, the injection is 18 V into phase A and 9 V into phase B, while PSO tuned SMC injects 3 V into phase A and 2 V into phase B. Without compensation, the load voltage remains at 415 V, as depicted in *figures 9 (a)* and *9 (b)*. However, with the proposed PSO-SMC approach, the sag voltage is compensated, maintaining a stable 415 V. This is evident in *figure 9 (c)*, where the VSC-STATCOM injects 3 V into phase A and 2 V into phase B.



(a)

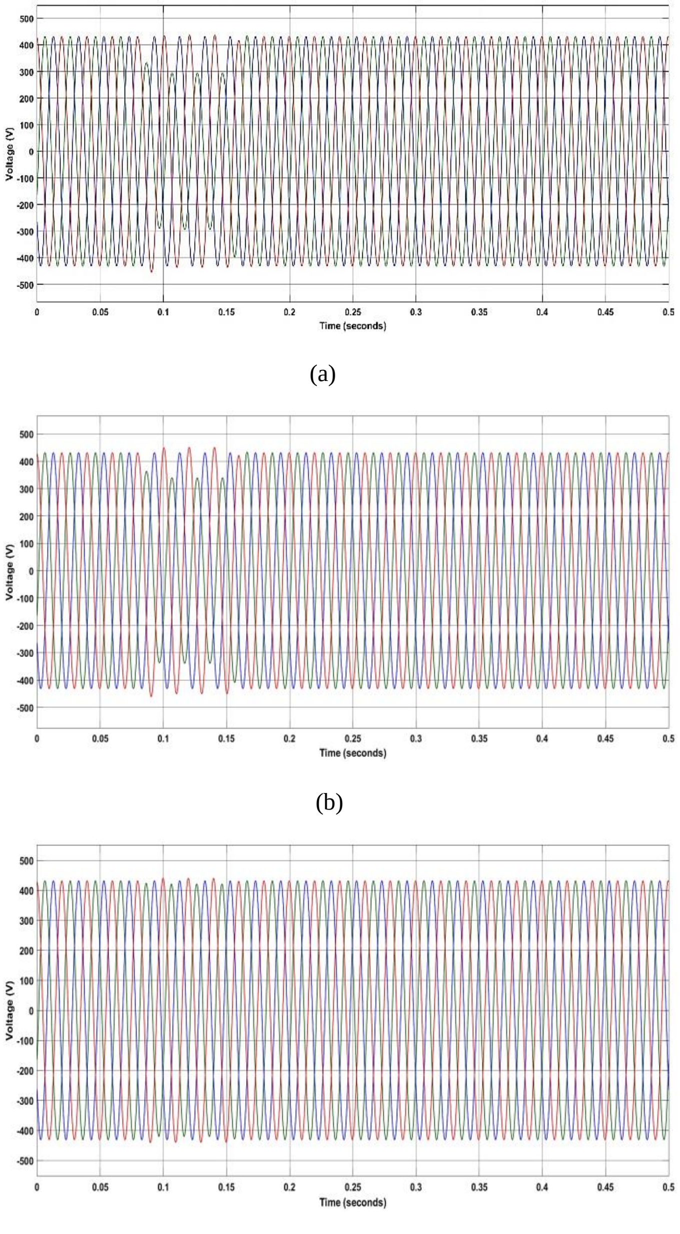
(b)

(c)

Figure 9. Compensation of Line-to-Line Fault Voltage Sag of using (a)PSO - PI (b) SMC (c) PSO-SMC based STATCOM

Case 3: Compensation of Single Line to Ground Fault

At 0.08 seconds, a single line to ground fault occurred, causing a voltage dip in all three phases. Specifically, the voltage in phase A dropped to 280V (a 40% sag) when employing PSO-PI of STATCOM, to 395V (a 10% sag) with SMC, and to 405V (a 6% sag) with PSO-SMC based STATCOM. Upon activating the VSC-STATCOM at this time, 130V was injected into phase A. For PSO-PI of STATCOM, the injection was 18V, for SMC it was 10V, and for PSO-SMC it was 10V. The uncompensated load voltage was 415V for PSO-PI of STATCOM and was depicted in *figure 10(a)*, while for SMC it is shown in Figure 10(b). The proposed PSO-SMC effectively compensated for the sag voltage, maintaining it at 415V, with the VSC-STATCOM injecting 10V, as illustrated in *figure 10(c)*.



(a)

(b)

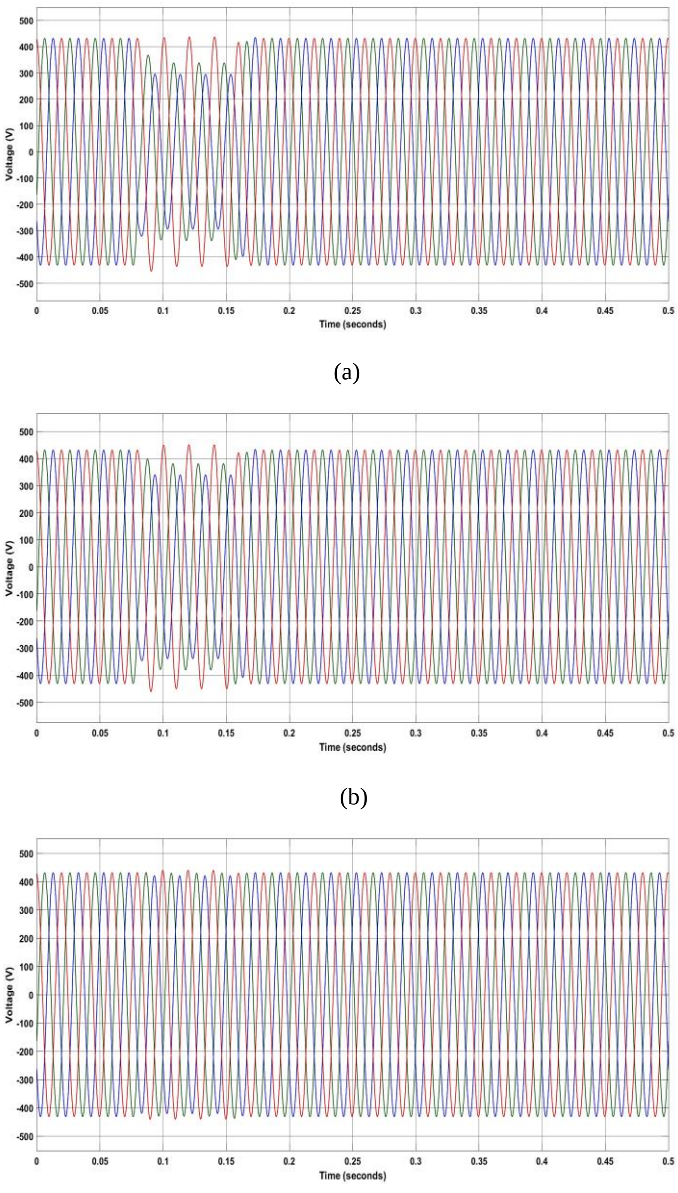
(c)

Figure 10. Compensation of Single line to ground fault voltage sag using (a)PSO - PI (b) SMC (c) PSO-SMC based STATCOM

Case 4: Double Line to Ground Fault Compensation

In this scenario, a double line to ground fault occurs at 0.08 seconds, causing a voltage dip. Initially, the voltage sags to 315V (30% sag) for phase A and 320V (25% sag) for phase B. The PSO-PI controlled STATCOM compensates phase A to 390V (10% sag) and phase B to 395V (5% sag), while the SMC controlled STATCOM further improves phase A to 413V (2% sag) and phase B to 413V (2% sag). At 0.08 seconds, the VSC-STATCOM activates, injecting 80V for phase A and 70V for phase B in the PSO-PI controlled STATCOM, 18V for phase A and 9V for phase B in the SMC controlled STATCOM, and 3V for phase A and 2V for phase B in the PSO-SMC controlled STATCOM. Without compensation, the load voltage remains at 415V for the PSO-PI controlled STATCOM and SMC. However, the proposed PSO-SMC effectively compensates, restoring the sagged voltage to 415V. The injected voltages by VSC-STATCOM for phase A and phase B are both 2V, as illustrated in *figure 11 (c)*.

Table 1 and *table 2* illustrate a comparison of compensated voltages between the proposed techniques and existing methods. It is evident from the tables that the compensated voltage generated by the proposed techniques is notably lower when compared to other existing methods such as PSO-PI of STATCOM, SMC, and PSO-SMC.



(a)

(b)

(c)

Figure 11. Compensation of Double Line to Ground Fault Voltage sag using (a)PSO - PI (b) SMC (c) PSO-SMC based STATCOM

Table 1. The proposed and existing techniques compensated voltage comparison

Optimization techniques	Three phase faults		Line to line fault				Single line to ground fault		Double Line to ground fault			
	Voltage (V)	Injected Voltage (V)	Phase A	Injected Voltage (V)	Phase B	Injected Voltage (V)	Phase A	Injected Voltage (V)	Phase A	Injected Voltage (V)	Phase B	Injected Voltage (V)
PSO tuned PI	310	101	320	80	330	70	280	130	315	80	320	70
SMC	390	22	395	18	405	9	395	18	390	18	395	9
PSO-SMC	413	2	412	3	413	2	405	10	413	3	413	2

Table 2. The proposed and existing techniques compensated voltage comparison

Optimization techniques	Three phase faults		Line to line fault				Single line to ground fault		Double Line to ground fault			
	Current (A)	Injected Current (A)	Phase A	Injected Current (A)	Phase B	Injected Current (A)	Phase A	Injected Current (A)	Phase A	Injected Current (A)	Phase B	Injected Current (A)
PSO tuned PI	11	11	16	9	18	7	14	10	16	7	17	9
SMC	18	9	19	5	21	4	19	5	20	5	21	5
PSO-SMC	22	3	22	3	24	1	22	3	23	2	24	1

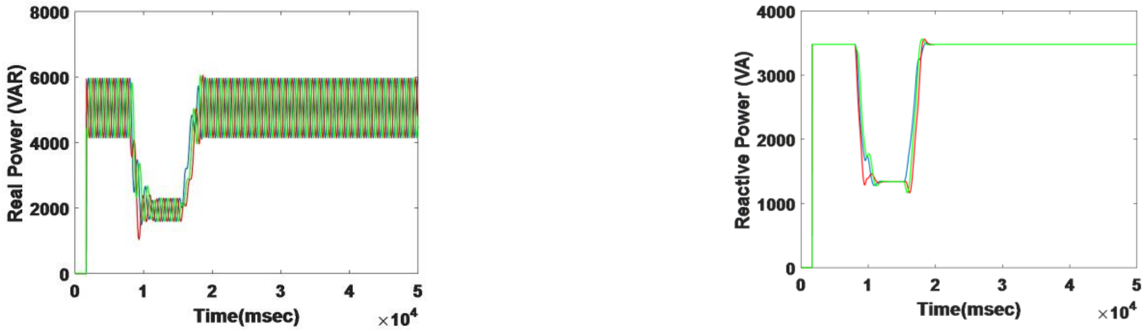


Figure 12. Real and Reactive power using PSO-PI of STATCOM

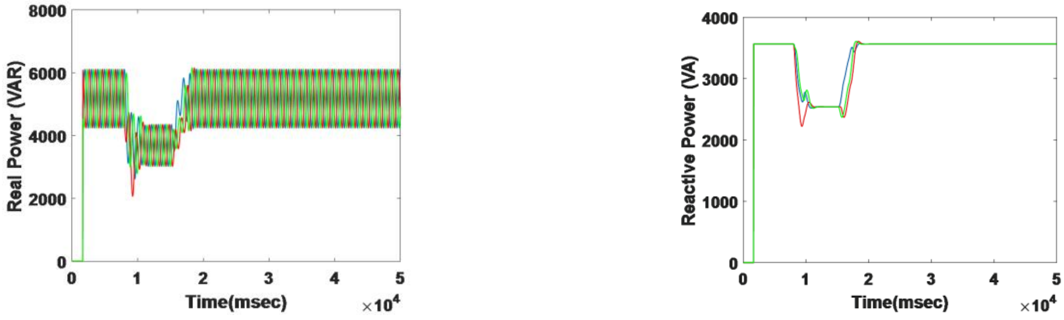


Figure 13. Real and Reactive power using SMC based STATCOM

The evaluation of the Simulink parameters is listed in the *table 3*. Here the transmission line voltage is 415V. The Efficiency comparison is shown in table 4. In this the proposed PSO-SMC controller archives the efficiency is 99.2% compared to the other existing algorithms are 95.1% for Fruit fly Optimization, Cuckoo search is 96.3% and 98.5% is grey wolf algorithm. This is real and reactive power using PSO-PI, SMC, and PSO-SMC-based STATCOM, as shown in *12, 13, and 14.*

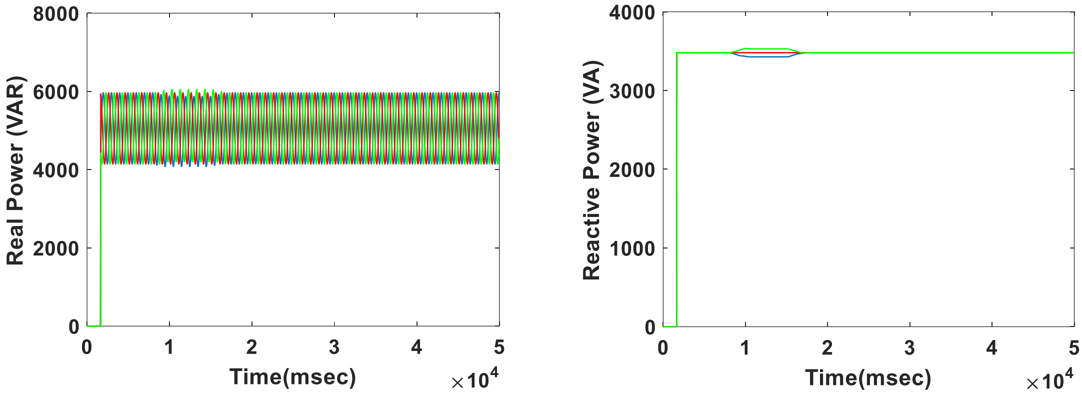


Figure 14. Real and Reactive power using PSO-SMC based STATCOM

Table 3. Parameter evaluation

Three phase voltage	**415V**
Real power	5800VA
Reactive Power	3600VAR

Table 4. Efficiency Comparison

Optimization Algorithm	**Efficiency (%)**
CS [12]	95.1
Fruit Fly [13]	96.3
GWO [14]	98.5
PSO-SMC (proposed)	99.2

6. CONCLUSIONS

This paper presents a novel approach, termed Particle Swarm-based Hybrid SMC, for optimizing power quality through the implementation of a VSC-STATCOM controller. The VSC-STATCOM serves to regulate voltage levels during different types of faults. Various control techniques are explored to enhance the efficiency of the proposed VSC-STATCOM. Among these techniques, the particle swarm optimization-based sliding mode controller demonstrates superior performance in real and reactive power compensation. The application of the proposed STATCOM with LCL Filter-based PSO-SMC controller achieves a voltage compensation rate of 99.2%. In future the proposed model is developed with the various machine learning algorithms for developing a new model.

Author Contributions: The authors confirm contribution to the paper as follows: study conception and design: S. Rajendran, A. Muthukumar; data collection: K. Vijayakumar; analysis and interpretation of results: K. Rajesh; draft manuscript preparation: S. Rajendran, A. Muthukumar All authors reviewed the results and approved the final version of the manuscript.

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Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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