AI BASED STATCOM CONTROL IN HYBIRD SOLAR WIND ENERGY SYSTEM

[1]Anil Kumar Vishwakarma, [2]Amit Kumar Asthana
[1]Research Scholar, Department of Mechanical Engineering, Truba Institute of Engineering & Information Technology Bhopal (M.P.) India
[2]Assistant Professor, Department of Mechanical Engineering, Truba Institute of Engineering & Information Technology Bhopal (M.P.) India
[1]vishwakarma.av22@gmail.com, [2]asthana603@gmail.com

* Corresponding Author: Anil Kumar Vishwakarma

Abstract:

The large-scale integration of hybrid solar–wind energy systems into utility grids introduces significant challenges related to voltage instability, reactive power imbalance, harmonic distortion, and reduced power factor due to the intermittent and nonlinear nature of renewable sources. The proposed technique optimally tunes the control parameters by minimizing power quality indices and maximizing active power delivery at the load terminal. A detailed hybrid system model consisting of a photovoltaic array, wind energy conversion system, DC–DC boost converters, voltage source inverter, and cascaded H-bridge STATCOM is developed and simulated in MATLAB/Simulink. Performance evaluation is carried out under heavy load conditions and compared with (i) conventional voltage regulation–based STATCOM control and (ii) PQ–PI–controlled compensation. Simulation results demonstrate that the DE-optimized STATCOM significantly improves system performance. The total harmonic distortion (THD) of grid voltage is reduced from 2.19% (conventional control) and 2.17% (PQ–PI control) to 2.10% with the proposed DE-based controller. Similarly, current THD is reduced from 2.32% and 2.06% to 2.02%, satisfying IEEE-519 standards. Active power delivered to the load increases from 27.88 MW to 28.1 MW, while reactive power demand is reduced from approximately 6.2 MVar to 5.8 MVar, resulting in an improved power factor of 0.91.The results confirm that the DE-optimized STATCOM provides superior voltage regulation, harmonic mitigation, and power transfer capability, making it a robust and efficient solution for enhancing power quality in grid-connected hybrid renewable energy systems.

Keywords:*Hybrid Solar–Wind System, STATCOM, Differential Evolution Algorithm, Power Quality Improvement, Harmonic Reduction, Reactive Power Compensation, Grid Integration.*

I.INTRODUCTION

The energy sector is witnessing a huge exodus toward spread-out renewable sources considering depleting fossil reserves with coupled increased energy demand, while the environment itself is riddled with concerns over pollution and climate change. Thus, non-renewable resources are hardly viable under such circumstances [1]. Among a plethora of renewable flushes, the most recognized, most established, and maturing are the solar and wind taps at disposal for gorging. Remember that, however, getting the quantum of these installments into our grids is full of many big technical setbacks in the power quality, voltage stand, and reliable operation [2].Hybrid solar-wind energy systems are extensively used to overcome the limitations of single-source renewable generation. Solar and wind are in alternate natural conditions and thus complement each other in terms of enhancing energy delivery while also reducing the reliance on storage devices [3]. In general, solar power is perceived as dimming into oblivion during daytime hours at clear sky conditions, as wind power gains more clout during the night or during cloudy conditions. With both sources combined in hybrid systems, supply continuity, operational reliability, and overall system efficiency are comparatively guaranteed. Such advantages notwithstanding, inherent intermittency and stochastic behavior render rapid fluctuations of the voltage, current, and power flow when there are grid connections [4].

Hybrid solar wind systems require sophisticated power converters at every critical link like a dc–dc power converter followed by voltage source inverters (VSIs) in order to connect renewable sources and the utility grid. While these power converters enable ease and efficiency of conversions, they cause a series of power quality disturbances like harmonics and reactive power imbalance etc [5]. In the long run, converting the status quo power quality problem in hybrid solar wind energy seems to be inevitable, and likewise, effectively designed mitigation strategies influence the power quality issues, safeguard grid sustainability, and compliance with global benchmarks such as IEEE-519 [6].Voltage stability is crucial in the case of renewable energy projects being related to the grid (for example, transmission interconnections). Synchronous generators always provide necessary reactive resources in the traditional power system. Renewable energy-based reserves do not provide von Neumann equilibrium, on the contrary increased fluctuation as a consequence of a desired voltage range, especially by point of connection fluctuations, are typical and due to instantaneous shifts in irradiation and wind speeds resulting in voltage sag, swell, and flicker [7]. It is therefore admissible to add advanced reactive power devices for the seamless grid integration and reliable operation of hybrid renewable projects.

FACTS devices have been extensively utilized in addressing the voltage regulation, power flow control, and system stability aspects present in today's modern power systems. Among them, STATCOM has attracted a significant degree of notice mainly because of its fast dynamic response, compact size, and excellent performance under low-voltage conditions [8]. STATCOM is essentially a shunt-connected FACTS device featuring a voltage source converter that has the capability to inject or absorb reactive power, independent of grid voltage magnitude. This feature makes STATCOM particularly useful for controlling voltage fluctuations and improving power quality in renewable-energy-dominated grids [9].

Certainly, STATCOM provides several attractions, though its functioning is primarily bound to the nature and robustness of the control strategy in use. Conventional STATCOM-control strategies, which involve fixed parameters with voltage regulation-based control or fixed-parameter proportional-integral (PI) control strategy, show disadvantageous characteristics when rapidly changing conditions are faced [10]. The exact tuning is practically difficult with an unadaptable system, and these controllers generally perform poorly under load nonlinearities, uncertain parameters, and grid uncertainty. Consequently, there is an increasing craving for intelligent and adaptive control schemes that can operate with a due consideration of the system in real time [11].Power system control scenarios have been particularly replete with dynamical interventions rooted in optimization and AI in recent times. There is abundant capacity for the genetic algorithm (GA), particle swarm optimization (PSO), differential evolution (DE), and their class, which can solve nonlinear optimization problems involving multitudes of objectives [12]. Having these algorithms as front-running would suggest that DE, meanwhile, capitalizes on its simplicity and quick convergence rates for satisfactory handling of continuous optimization tasks. Differential Evolution pair optimization, whatever size of the system at any particular time, will minimize harmonic distortion, ameliorate voltage profiles, and increase active power transfer [13].When using evolved algorithm settings, optimizing the STATCOM control in the partially realized solar-wind grid can promise a solution to the existing power quality problems. The optimized STATCOM can improve power factor, reduce the total harmonic distortion of voltage and current, and ensure that the active power supplied to the load is increased by changing controller parameter values [14]. In addition to this, the system operating under optimization-based control also had better resistance against disturbance and higher load dynamism, thereby paving the way towards ensuring flexibility when it comes to incorporating the energy produced by renewable energy on a large scale [15].In this light, this research impart focal pertinence to the development and analysis of an optimized STATCOM for power quality enhancement in a grid-connected solar-wind hybrid energy system. It is based on control optimization to obtain better results in voltage regulation, low distortion of harmonics, and improved compensation for reactive power with higher and lower aim of penetration of renewable energy sources. Simulation studies are carried out for various operating conditions and compared with the traditional control schemes to test the developed optimized STATCOM. Outcomes of the analysis will be helpful towards more reliable and efficient power systems, which can venture their way through a greater segment of hybrid renewable energy sources.

II. RELATED WORK

Reactive power compensation and voltage regulation are challenges in modern power systems facing an increasing penetration of renewable generation sources. Tracking optimal reactive power distribution between fixed capacitors and a STATCOM with an effective need for voltage support under load variations has been studied [1]. Mathematical modeling and optimization of such decision-making techniques finally showed what a proper reactive power allocation may do to regulation enhancement. STATCOMs were truly faster than any passive compensator of the same. On the other hand, there was no explicit reference to adaptive and intelligent control strategies.

One notable bit from the literary contributions would include: STATCOM stands out for providing enhanced voltage stability, instantaneous response, increased power factor, and reduced voltage perturbation when compared with SVC in the arena of reactive power compensation in microgrids [2]. Despite efforts to reinforce trading agreements, no single paper from any of the intelligent or learning-based control approach types was seen. However, on the other hand, some studies focused on increasing SVC's potential as far as maintaining voltage and power factor in transmission and distribution systems [3]. The provision of advanced FACTS devices is vital in the eventuality that SVC proves wanting under rapid dynamic working conditions. STATCOM reactive power compensation based on the application in rural distribution systems was also explored [4]. Distribution. The strategies hence implied for compensation were essential to obtain effective voltage regulation and decreased losses along with moderate load variation thereby improving power quality. However, there is scarce attention to various control approaches for STATCOM applications to distribution systems. The suggestion here is based on the presence of Adaptive STATCOM control strategy predicated on identifying the entire order of dynamics of this system and releasing the system from the needs of statistical modeling precisely [5]. Through these pets, highly robust reactive power compensation and fast dynamic responses were eventually achieved; however, computational complexity still bounds them.These influenced papers saw a whole lot of release within less time[5]. Some studies have seen grounds on some good implementation challenges with highlights on the RC-type-load-tapping transformer and its mode of operation from the initial gate triggering to thyristor bridge firing, AC/DC converters, and onto DC/DC converters, the methodologies mapping of Embedded AI with the technology of FACTS [6].

In fact, these studies aim to handling the bid sets and optimizing the parameters. Also these require storage as well for these coordinates within the STATCOM or FACTS controller having a frequency adaptive phase-locked loop (FAPLL), which is also modified for SC inclusion, further for rapid voltage regulation. Subsequently, results may differ according to the analyzed grid conditions like weak-to-voltage initial parameters or fault transition conditions. Second, STATCOM plus PV inverter integrated as an effective solution for reactive power shall show significant contra-testified with line restoration in voltage control and inverter protection with high PV penetration of communicational and incremental demands. Considering the positive results reported on the use of STATCOM in wind power plants for less voltage fluctuation, higher power factor, and faster reactive power support as compared to conventional methods [11]. Control system of the STATCOM has been revealed to be effective in voltage maintenance in the face of load changes or fault conditions in medium-scale power systems [12]. The real-time-intelligent control has not been addressed. Experiments with low-rating DSTATCOM technology and improvements also generated eliminated harmonics and improved power factor in radial systems, hence demonstrating a pilot possibility [13].

Advanced Disturbance Rejection Control (ADRC) Benefited DSTATCOM with excellent voltage regulation, fast dynamic response, and good robustness against plant parameter variations, demonstrating their effectiveness [14]. The integration of STATCOM into RES further contributed to the social responsibility of the project, enhancing voltage stability, the mitigation of harmonics, and their service as support system [15].Increased interest has been noted in the role played by artificial intelligence in renewable energy systems. The deep neural network implemented controllers were found to be useful as feedforward adaptive power controllers and in imporoving the dynamic response in photovoltaics [16], albeit incurring vast requirements of learning data, which, in consequence, increased the computational load. The application of the combination of fuzzy and deep learning controllers showed promise in alleviating frequency degradation in photovoltaic (PV) microgrids with accelerated convergence rate as compared to conventional controllers [17], yet the resultant complexities need be addressed. Comprehensive criticism was made on the application of AI to power system operations to improve system operation in terms of stability, efficiency, and reliability, and challenges include data availability and interpretability [18]. Likewise, hybrid AI-based optimization controllers have escalated conventional solutions towards the enhancement of microgrid robustness and dynamic performance [19]. An AI-based control study for doubly-fed induction generator wind turbines demonstrated improved dependability on faults and fast dynamic responses when compared with classical methods. However, a crucial observation was made with respect to the lack of real-time validation [20].
Artificial intelligence-based control approaches have garnered increasing attention in enhancing the efficacy of renewable energy systems integrated with the smart grid. The application of AI control strategies in the operation of DFIG wind turbines has considerably improved its low-voltage ride-through capabilities and contributed to enhanced converter management through different grid faults [21]. By comparison, these intelligent control schemes outperform the traditional PI-based control methods for being adaptable and articulate in fit-ins and also have a better tracking ability. However, the implementation of these controllers was reported to be real-time, hence making them robustly dependent on data and calling upon more practical and scaled solutions.

Further, intelligent energy management systems have been proposed and utilized for hybrid energy systems where advanced design neural architectures are employed along with optimization algorithms, highly efficiently managing the exchange of notable power amongst various energy sources [22]. by accommodating nonlinear system dynamics, their works have resulted in reduced energy consumption and operation optimization efficiency although the greatest limitation lies in the immense need for model complexity and tuning effort. The hybrid optimization approach results in, through the integration of evolutionary algorithms and adaptive neuro-fuzzy controllers, larger system damping and transient stability enhancement, specifically for power systems [23]. Real-time simulation established that higher oscillation suppression could be maintained compared to classical tuning efforts, although they could have limited applications because of the heavy computation loads. The use of artificial intelligence techniques in control has also spread to photovoltaic systems, especially for maximum power point tracking under partial shading conditions [24]. Hybrid neuro-fuzzy controllers showed much faster tracking, better robustness, and an exponential increase in power extraction efficiency than conventional MPPT techniques, although at the cost of increased control complexity. Similarly, intelligent systems combining adaptive neuro-fuzzy inference systems with swarm intelligence were successfully applied to evaluation of voltage stability margins [25]. These systems provided accurate predictions of the voltage stability limits with various operating load conditions, thereby paving the way for preventive control actions; however, they necessitated substantial amounts of training datasets. Aiming to reflect the real scenarios concerning artificial intelligence support at microgrid integration presented machine and deep learning approaches for the aforementioned subsystems like forecasting, control, fault protection, and optimization within hybrid pathways of renewable energy [26]. Major contributions of AI solutions have been shown to enhance reliability, energy consumption, and power quality, but then on the flipside; the main challenges lie in interoperability, cybersecurity, and deployment intricacy involved. AI-based optimisation of power electronics to operate converters has further been shown to carefully stabilize voltages and damp oscillations under dynamic operation [27]. Nevertheless, it was pointed out that despite the desirable traits of the technique for the improved performance reported, high cost of implementation and excessive computational demands remain, causing constraints. Advanced deep learning architectures-a combination of optimization algorithms and modelshave made some entry into the domain of energy consumption prediction in smart grids. They tend to perform best with respect to nonlinear demand pattern extraction, as optimization algorithms help model convergence to arrive at the perfect prediction figure with optimized values. Big data sources have exhausted a lot of computational means and need a large amount of RAM. There is a need to further investigate these potential broader applications of AI-infused digital transformations with refined automation, optimization, and decision-making in the smart grid-energy field [29]. However, several things related to data security, ethics, and complexity of systems still mostly remain as open questions. At last, AI and machine learning applications in wind turbine control systems opened up avenues for improved fault detection, pitch control, power optimization, and so forth [30]. While intelligent controllers showed overall adaptability and efficiency; they did not consider the hardware side as far as real-time implementation and integration of hardware is considered a major issue.

Table 1: FACTS Devices, STATCOM Control, and Microgrid Applications

Ref.	Context	Technique	Major Contributions	Limitations / Research Gap
[1]	Distribution grid	STATCOM & capacitor placement	Enhanced voltage stability	No adaptive intelligence
[2]	Prosumer microgrid	SVC vs STATCOM	STATCOM showed superior dynamic response	Cost not analyzed
[3]	Power system	SVC compensation	Improved power factor	Limited dynamic capability
[4]	Rural distribution	DSTATCOM	Voltage profile improvement	Scalability issues
[5]	Single-phase grid	Model-free STATCOM control	Robust reactive power control	Computational burden
[6]	FACTS devices	Review study	Identified STATCOM dominance	Lack of AI control discussion
[7]	Wind farm (DFIG)	STATCOM integration	Enhanced fault ride-through capability	High investment cost
[8]	Weak grid	STATCOM case study	Improved dynamic voltage support	Region-specific study
[9]	PV inverter	Coordinated STATCOM control	Improved voltage regulation	Communication overhead
[10]	Distribution system	DSTATCOM with Y-Y transformer	Enhanced reactive compensation	Hardware complexity
[11]	Wind farm	STATCOM	Reduced voltage fluctuations	No controller optimization
[12]	Power system	STATCOM voltage control	Improved voltage stability	No AI integration
[13]	Radial distribution	30-kVAr DSTATCOM	Experimental validation	Limited scalability
[14]	Distribution grid	ADRC-based DSTATCOM	Fast disturbance rejection	Tuning complexity
[15]	Renewable power plant	STATCOM modeling	Improved power factor	Classical controller
[16]	Hybrid PV system	Deep neural network	Enhanced power management	Training overhead
[17]	PV microgrid	Fuzzy + deep learning	Improved frequency regulation	Model complexity
[18]	Power systems	AI applications review	Comprehensive AI integration overview	Practical deployment issues
[19]	PV microgrid	ANFIS + DL	Fast frequency response	High computation
[20]	Wind turbine	AI-based DFIG control	Improved dynamic response	Limited real-time testing

III.RESEARCH OBJECTIVES

- To design a simple but highly viable compensator for a gird connected solar wind hybrid system that is capable of feeding less distorted voltage to the load along with enhancement in power output.
- Designing of a compensating device and compare it with the basic STATCOM with voltage regulation control for active power output enhancement in the system
- The compensating device control has to be designed with an AI based optimization algorithm where in this case differential evolutionary algorithm is selected for analysis algorithm to obtain a smooth voltage and current waveform.

- Reduction in the distortion level of the voltage output at the grid system is to be done by using the proposed optimizer.

IV.RESEARCH METHODOLOGY

The large-scale wind/solar hybrid system is connected to a grid through a booster station. The system comprises the wind power and the photovoltaic systems. The reactive power compensation device, called STATCOM, which is connected to the grid, aims at improving the transient voltage stability of the large-scale wind/solar hybrid system Furthermore, the compensator is being suggested to bring about improvements in the output parameters such as total harmonic distortion, THD in current, and active power output.

The control strategy that is presented in this study manages a standard single-phase Cascaded H-Bridge multilevel converter which consists of N H-Bridges brought in a series connection like in the case of N=2 in Figure1. The STATCOM device is connected to the power grid through a coupling inductance. For the sake of clarity, grid voltage and output current expressions are assumed to be.

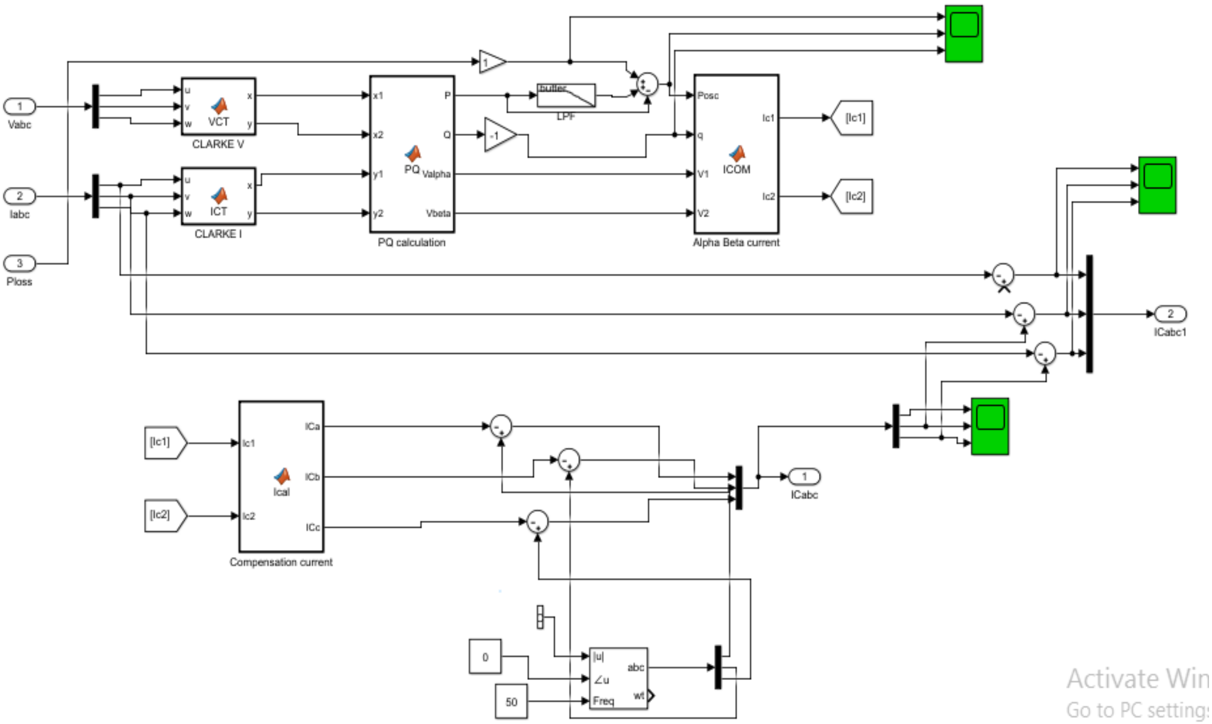

Figure 1: Active and Reactive Power control loops

The angle between the grid voltage and the current injected by the STATCOM is determined. The active power is directly related to the current component that is in phase with the grid voltage (active component), while the reactive power is via the current component that is orthogonal to the grid voltage (reactive component). Thus, for the active power control the active component of the current is varied, and conversely for the reactive power control the reactive component is adjusted. A real-time current reference could be created from these two current components.

P_{TOTAL}* and Q_{TOTAL}* are respectively the active power and reactive power references. From the regulation loops of both active and reactive power, the two current components described above are obtained. From these current components the instantaneous current reference i_f^* is achieved. The output of the current control loop is the STATCOM output voltage reference v_{inv}^* , which is the signal introduced to the PWM modulator.

The active power reference comes from the controls of the DC Bus voltage. When the DC-Bus voltage of one of the H-Bridges in series is lower than the reference voltage, this indicates that the H-Bridge needs to be fed with active power for the capacitor to absorb energy and thus raise its voltage. Conversely, when the DC-Bus voltage is above the reference voltage, it means that the energy should be drained from the Bus capacitor. In this manner, each DC-Bus voltage controller outputs a specific active power reference for every Bridge.

The control is enhanced through the use of the differential evolutionary technique. The method takes the power at the load line as the optimizing equation for balancing quality and adjusting according to the load changes, thus it is claimed that the quality of service is not compromised. The flow chart of the optimization algorithm depicted in the figure below has been implemented in MATLAB as the governing equations and codes for generating pulses for the per-phase converter as well as the boosting pulses.

Differential Evolutionary Optimization

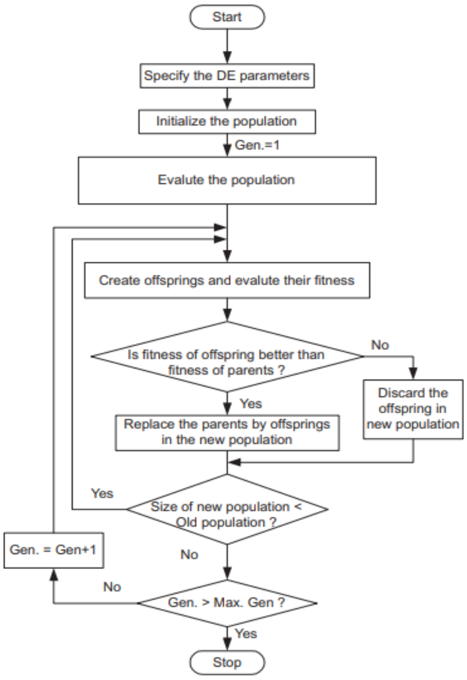

Figure 2:Flow chart of proposed Differential Evolutionary Algorithm for converters

Differential Evolution (DE) is a population-based heuristic algorithm known for its versatility in solving global optimization problems with various characteristics in the continuous domain. In spite of its straightforward nature, DE has been a very effective approach for solving the problems of non-differentiability, non-continuity, and multimodality. In the standard DE variation, DE/rand/1/bin, the first step is the random creation of the initial population consisting of NP individuals (X_j)⃗ , where j=1, 2,…, NP, chosen uniformly from the lower and upper boundaries (x_j^L ,x_j^U). Mutation and crossover are then applied to the individuals in order to produce a trial vector. The trial vector is then compared with its parent for the purpose of inheriting the fittest individual in the next generation. Figure 2Flow chart of proposed Differential Evolutionary Algorithm for converters

The process of DE consists of the following steps:

Initialization of a population

Initial population in DE, as the starting point for the process of optimization, is created by assigning a random chosen value for each decision variable in every vector, as indicated in equation:

$$x_{ij}^{0} = L_j \ + rand_j \ * (U_j - L_j) \qquad (1)$$

Where ,L_j, U_j, arethe lower and upper boundaries for $x_{ij} rand_j$ random number uniform [0, 1].

Mutation

A mutant vector V_i^{G+1} is generated for each target vector x_i^Gat generation G according to equation (2)

$$V_i^{G+1} = \ x_i^G + F * (x_2^G - x_3^G), r_1 \ \neq r_2 \ \neq r_3 \ \neq i \qquad (2)$$

Where r_1 ,r_2 ,r_3 are randomly chosen from the population. The mutation factor F ∈[0,2]. A new value for the component of mutant vector is generated using (1) if it violates the boundary constraints.

Recombination (crossover)

The converter is linked to the grid via a three-phase coupling transformer. The grid model includes standard 20-kV distribution feeders and an equivalent transmission system.

In the average model, the boost and VSC converters are modeled as equivalent voltage sources producing the AC voltage averaged over one cycle of the switching frequency. Although such a model does not account for harmonics, it captures the dynamics due to the interaction of the control system and the power system proposed.

V. RESULT AND DISCUSSION

The performance of the solar PV hybrid system under different compensation strategies was analyzed in terms of **voltage and current quality, active and reactive power, THD%, and power factor**. The study compared three configurations: a basic **voltage regulation controller**, a **STATCOM with PQ-PI controller**, and a **DE optimization-enhanced PQ-PI controller**.

Case 1: Hybrid renewable energy model driving heavy loads with STATCOM controlled by basic voltage regulation control.

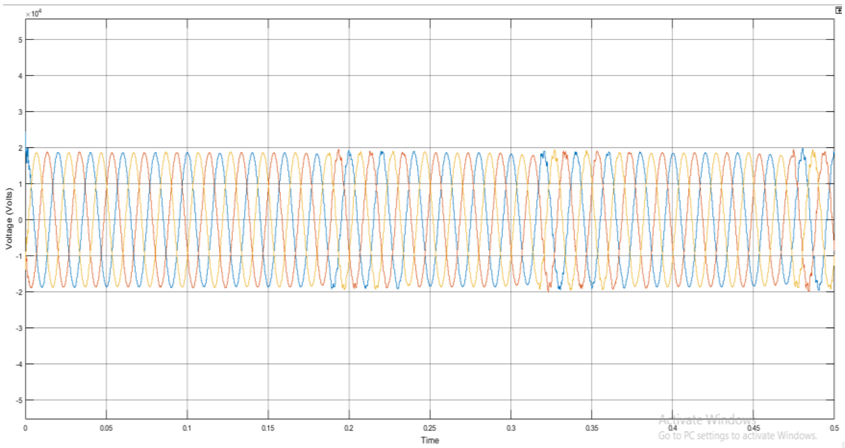

Figure 3: AC Voltage available at the loading point in system having voltage regulation control for compensation

The voltage at the load terminal under voltage regulation based compensation is shown in Figure 3. Voltage magnitude is considerably improved when so treated compared to the uncompensated case.

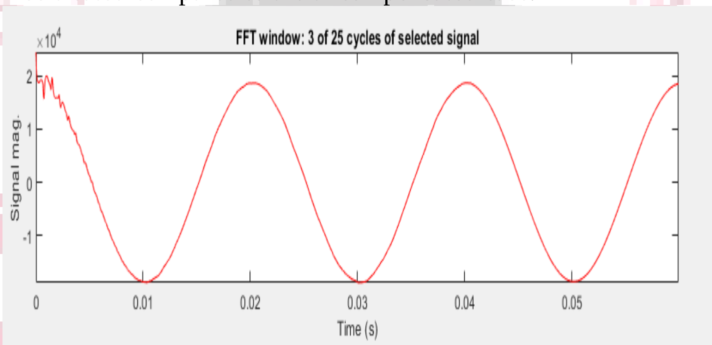

Figure 4: FFT analysis of Voltage in system having voltage regulation control for compensation

The figure 4 is FFT analysis video imaging of the waveform of the voltage with voltage-regulation-based compensation; it can be noted that the presence of some compensation reduces the harmonic components when compared to the uncompensated case.

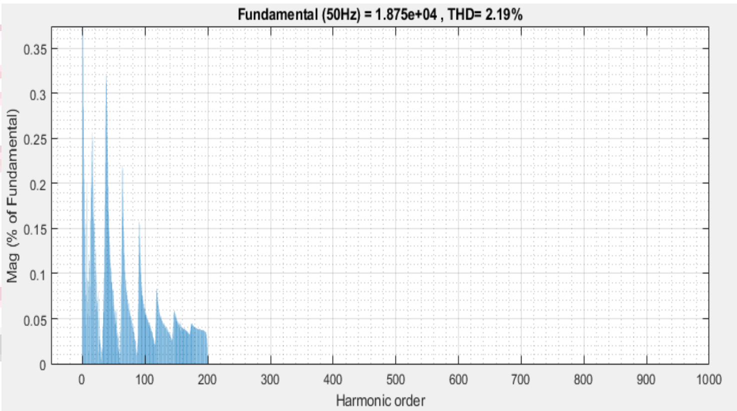

Figure 5: THD % of Voltage in system having voltage regulation control for compensation

Figure 5 shows the percentage THD of the voltage waveform in the system using voltage regulation–based compensation, where the THD is approximately 2.19%. This indicates partial harmonic mitigation but highlights the limitations of conventional control in achieving lower distortion levels.

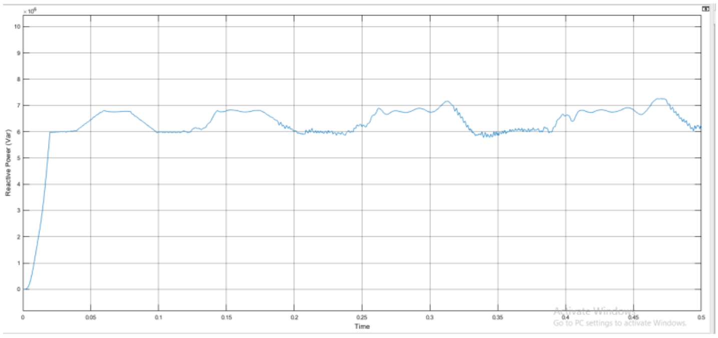

Figure 6: Reactive Power at the line in system having voltage regulation control for compensation

Figure 6 depicts the reactive power flowing in the line when voltage regulation–based compensation is applied, showing a reactive power demand of around 6 MVar. This indicates limited reactive power compensation capability with conventional voltage regulation control.

Case 2: Hybrid renewable energy model driving heavy loads with compensation controlled by PQ_PI controller

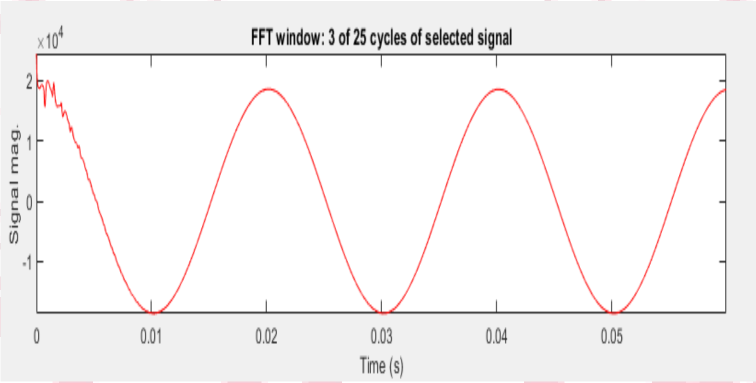

Figure 7: FFT of the AC voltage at the loading point in system having PQ_PI controller for compensation

The FFT in Figure 7 shows the frequency spectrum of the AC voltage at the load point with the PQ-PI controller. It demonstrates effective harmonic reduction and improved voltage quality.

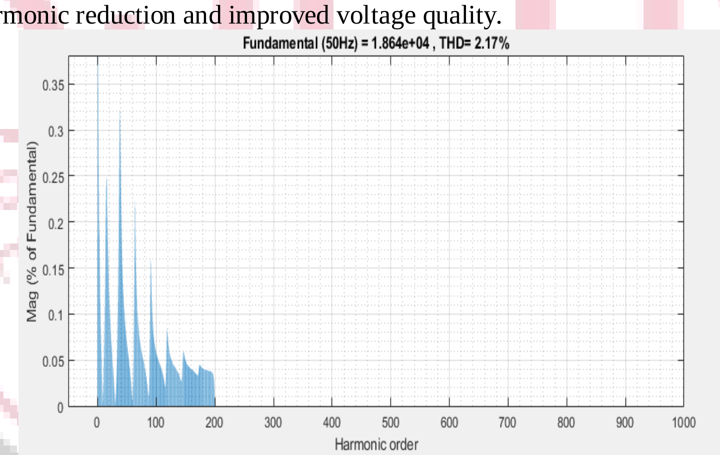

Figure 58: THD% of AC voltage at the loading point in system having PQ_PI controller for compensation

The THD% plot in Figure 8 shows that the PQ-PI controller effectively reduces harmonics in the AC voltage. This ensures better voltage quality at the load point.

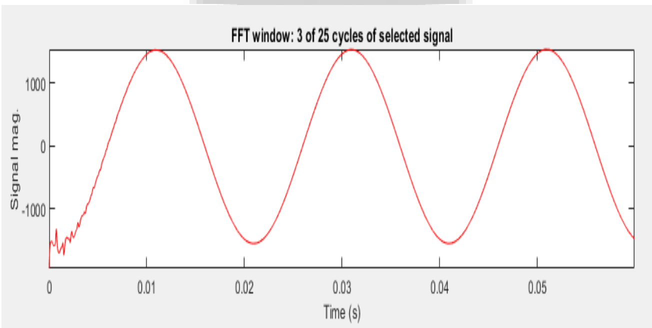

Figure 9: FFT analysis Current driven at the loading point in system having PQ_PI controller for compensation

Figure 9 shows the FFT of the load current, indicating that the PQ-PI controller effectively suppresses higher-order harmonics. This results in a cleaner, near-sinusoidal current waveform.

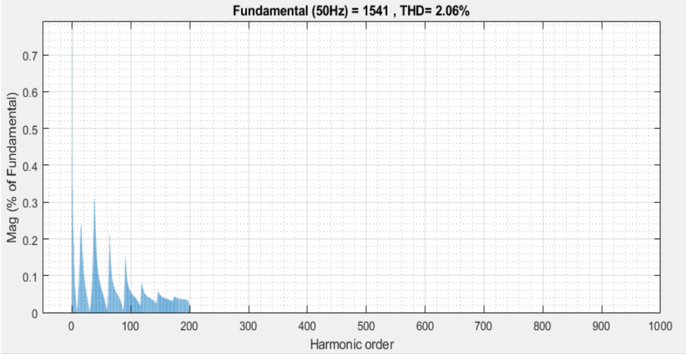

Figure 10: THD% in the Current driven at the loading point in system having PQ_PI controller for compensation

The THD% in Figure 10 demonstrates that the PQ-PI controller significantly reduces current harmonics. This ensures a smoother and more stable current waveform at the load.

Case 3: Hybrid renewable energy model driving heavy loads with compensation controlled by DE optimization controller

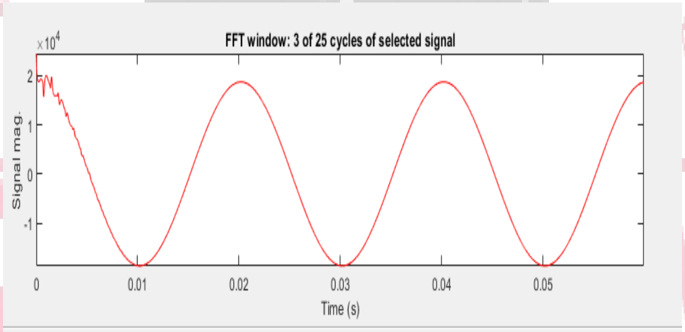

Figure 11: FFT window of the voltage in system having DE optimization controller for compensation

Figure 11 shows that the DE-based controller effectively suppresses higher-order voltage harmonics. This results in a cleaner, near-sinusoidal voltage waveform at the load.

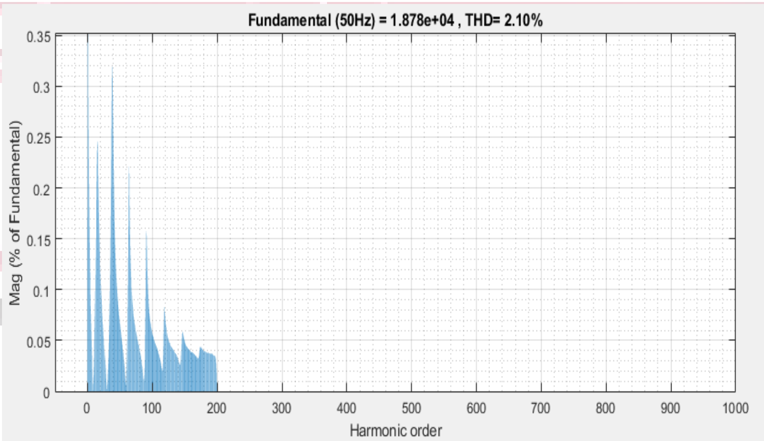

Figure 12: THD% in the voltage in system having DE optimization controller for compensation

Figure 12 demonstrates that the DE-based controller significantly lowers voltage THD. This ensures improved voltage quality at the loading point.

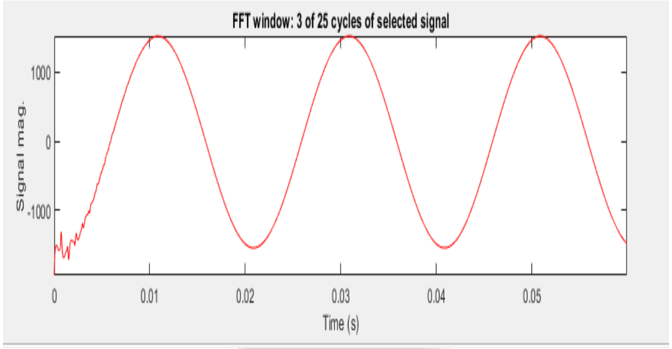

Figure 13: FFT window of the current in system having DE optimization controller for compensation

Figure 13 shows that the DE-based controller effectively suppresses higher-order current harmonics. This results in a smoother, near-sinusoidal current waveform at the load.

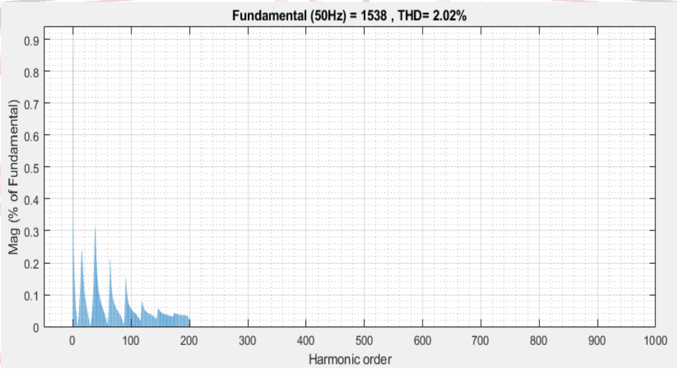

Figure 14: THD% in current in system having DE optimization controller for compensation

Figure 14 demonstrates that the DE-based controller significantly lowers current THD. This ensures a cleaner and more stable current at the loading point.

Validation

The outcomes of the compensators in comparison will be the subject of this chapter. The compensator that has been designed using differential evolutionary algorithm is anticipated to give superior results in contrast to the conventional controllers which have been used for STATCOM.

Table 2: Comparison of System Performance Parameters under Different Compensation Controllers

Parameters/system	system having voltage regulation control for compensation	System having PQ_PI controller for compensation	DE optimization controller for compensation
Active power output	27.88 MW	27.89 MW	28.1 MW
Line Voltage	20 x 104 V	20 x 104 V	20 x 104 V
THD% in voltage	2.19 %	2.17 %	2.10 %
THD % in current	2.32 %	2.06 %	2.02 %
Reactive Power output	6.2 MVar	6.01 MVar	5.8 MVar
Power factor in the system	0.90	0.90	0.91

The outcomes detailed earlier represent the parameters' comparative values. The power which is active and the load distribution bus in the system with STATCOM have been increased from around 27.88 MW to 28.1 MW at the DE optimization controller made for compensation system.

VI. CONCLUSION AND FUTURE WORK

The present research confirms that large-scale grid-connected wind–solar hybrid energy systems offer strong potential for future power generation due to their improved reliability, complementary generation profiles, and suitability for supplying heavy loads. However, the inherent intermittency of renewable sources and the employment of power electronic converters do have some potential influences on power quality by voltage transients, harmonic distortion, and reactive power imbalance, for which compensation strategies need to be applied for effective action. In this work, a DC microgrid was connected to the utility grid via an optimized STATCOM-based compensator for enhancing power quality and voltage stability under dynamic operating conditions. Simulation results clearly show the effectiveness of the proposed control strategy in comparison with the control strategy under relevant conventional compensators or under PQ–PI. Specifically, the VI waveform total harmonics are regularized for sure, with a slight downhill trend if considered under all the rest was pressure. Also, Current THD goes from 2.32% to 2.06% and was further targeted downward to 2.02% by employing DE, thereby ensuring full compliance with IEEE power quality standards. The optimized compensator also pushed up the real power delivered to the load terminal from some 27.88 MW to 28.1 MW by an increase in power factor, while its reactive power demand was just stepped down a little from around 6 MVar to 5.8 MVar. The system further supported the heavy-load operation at 20 kV of phase-to-phase voltage with a lesser wave distortion. The findings maintain the view that the DE-optimized STATCOM greatly improves voltage quality, diminishes harmonic distortion, and bolsters the transfer of active power within the proposed strategy when enhancing power quality within these systems are in question.

REFERENCES

[1] Saxena, Nitin Kumar. "Voltage control by optimized participation of reactive power compensation using fixed capacitor and STATCOM." *Optimization of Power System Problems: Methods, Algorithms and MATLAB Codes*. Cham: Springer International Publishing, 2020. 313-363.
[2] Qi, Jun, Wenbin Zhao, and Xiaoyan Bian. "Comparative study of SVC and STATCOM reactive power compensation for prosumer microgrids with DFIG-based wind farm integration." *IEEE Access* 8 (2020): 209878-209885.
[3] Kocaman, Behçet, and Nurettin Abut. "The role of static Var compensator at reactive power compensation." *European Journal of Technique (EJT)* 10.1 (2020): 143-152.
[4] Nassif, Alexandre B., and Dawit Fedaku. "A reactive power compensation scheme using distribution STATCOMs to manage voltage in rural distribution systems." *2020 IEEE Electric Power and Energy Conference (EPEC)*. IEEE, 2020.
[5] Guo, Cheng, et al. "Single-Phase Reactive Power Compensation Control for STATCOMs via Unknown System Dynamics Estimation." *Mathematical Problems in Engineering* 2020.1 (2020): 8394513.
[6] Chorghade, Aditya, and Vandana A. Kulkarni Deodhar. "FACTS devices for reactive power compensation and power flow control–recent trends." *2020 International conference on industry 4.0 technology (I4Tech)*. IEEE, 2020.
[7] Karaagac, Ulas, et al. "STATCOM integration into a DFIG-based wind park for reactive power compensation and its impact on wind park high voltage ride-through capability." *Electric Power Systems Research* 199 (2021): 107368.
[8] Opana, Samwel, Julius Kilonzi Charles, and Amos Nabaala. "STATCOM application for grid dynamic voltage regulation: a Kenyan case study." *2020 IEEE PES/IAS PowerAfrica*. IEEE, 2020.
[9] Fatama, Al Zoya, et al. "Coordinated reactive power strategy using static synchronous compensator for photovoltaic inverters." *International Transactions on Electrical Energy Systems* 30.6 (2020): e12393.
[10] Wang, Zhen, et al. "DSTATCOM integrated with Yy connection transformer for reactive power compensation." *International Journal of Electrical Power & Energy Systems* 117 (2020): 105721.
[11] Khuntia, Ganesh Prasad, Ritesh Dash, and Saratchandra Swain. "Compensation of Reactive Power Using STATCOM for Wind Farm." *International Conference on Emerging Trends and Advances in Electrical Engineering and Renewable Energy*. Singapore: Springer Nature Singapore, 2020.
[12] Yousif, Sabah Abdulkareem, and Saad Enad Mohammed. "Reactive power control using STATCOM for power system voltage improvement." *Al-Rafidain Engineering Journal (AREJ)* 26.2 (2021): 124-131.
[13] Rafi, K. Mahammad, and P. V. N. Prasad. "Design and development of 30 kVAr DSTATCOM for reactive power compensation in an 800 kW radial distribution system." *ARPN Journal of Engineering and Applied Sciences* 15.12 (2020): 1346-1354.
[14] Zhou, Xuesong, et al. "Control strategy research of D-STATCOM using active disturbance rejection control based on total disturbance error compensation." *IEEE Access* 9 (2021): 50138-50150.
[15] Tariq, Maria, Hina Zaheer, and Tahir Mahmood. "Modeling and analysis of STATCOM for renewable energy farm to improve power quality and reactive power compensation." *Engineering Proceedings* 12.1 (2021): 44.
[16] Sahoo, Satyajeet, et al. "Artificial deep neural network in hybrid PV system for controlling the power management." *International Journal of Photoenergy* 2022.1 (2022): 9353470.
[17] Sharma, Deepesh. "Fuzzy with adaptive membership function and deep learning model for frequency control in PV-based microgrid system." *Soft Computing* 26.19 (2022): 9883-9896.
[18] Pandey, Utkarsh, et al. "Applications of artificial intelligence in power system operation, control and planning: a review." *Clean Energy* 7.6 (2023): 1199-1218.
[19] Sharma, Deepesh. "Frequency control in PV-integrated microgrid using hybrid optimization-based ANFIS and deep learning network." *Electric Power Components and Systems* (2023): 1-14.
[20] Behara, Ramesh Kumar, and Akshay Kumar Saha. "artificial intelligence control system applied in smart grid integrated doubly fed induction generator-based wind turbine: A review." *Energies* 15.17 (2022): 6488.
[21] Behara, Ramesh Kumar, and Akshay Kumar Saha. "artificial intelligence control system applied in smart grid integrated doubly fed induction generator-based wind turbine: A review." *Energies* 15.17 (2022): 6488.

[22] Kamoona, Mustafa A., Omer Cihan Kivanc, and Oday A. Ahmed. "Intelligent Energy Management System Evaluation of Hybrid Electric Vehicle Based on Recurrent Wavelet Neural Network and PSO Algorithm." *International Journal of Intelligent Engineering & Systems* 16.1 (2023).
[23] Shafiullah, Md, et al. "Real-time solution of PSS parameter tuning by GA-ANFIS in stabilizing the electrical power system." *Arabian Journal for Science and Engineering* 48.5 (2023): 6925-6938.
[24] Ahmad, Waleed, et al. "Optimizing large-scale PV systems with machine learning: A neuro-fuzzy MPPT control for PSCs with uncertainties." *Electronics* 12.7 (2023): 1720.
[25] Adewuyi, Oludamilare Bode, et al. "Power system voltage stability margin estimation using adaptive neuro-fuzzy Inference system enhanced with particle swarm optimization." *Sustainability* 14.22 (2022): 15448.
[26] Talaat, Mohamed, et al. "Artificial intelligence applications for microgrids integration and management of hybrid renewable energy sources." *Artificial Intelligence Review* 56.9 (2023): 10557-10611.
[27] Gros, Ioana-Cornelia, et al. "Artificial intelligence (AI)-based optimization of power electronic converters for improved power system stability and performance." *2023 IEEE 14th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)*. IEEE, 2023.
[28] Ahmadi, Mohsen, et al. "Developing a deep neural network with fuzzy wavelets and integrating an inline PSO to predict energy consumption patterns in urban buildings." *Mathematics* 10.8 (2022): 1270.
[29] Malik, Hasmat, Gopal Chaudhary, and Smriti Srivastava. "Digital transformation through advances in artificial intelligence and machine learning." *Journal of Intelligent & Fuzzy Systems* 42.2 (2022): 615-622.
[30] Farrar, Nathan Oaks, Mohd Hasan Ali, and Dipankar Dasgupta. "Artificial intelligence and machine learning in grid connected wind turbine control systems: A comprehensive review." *Energies* 16.3 (2023): 1530.