Enhancing Power Quality in Solar, Wind, and Hybrid Systems Using Intelligent Converters

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Abstract:

Hybrid solar photovoltaic (PV) and wind energy systems have gained significant attention thanks to being efficient by enhancing the reliability and continuity of power supply needs for distributed generation (DG) applications. Consequently, however, the degradation of power quality, harmonic distortion, and discrepancies seen in the reactive power remaining under three load conditions, nonlinearly; balanced load; and unbalanced load still pose great challenges. The paper attempts to put forth the idea of a grid-integrated hybrid solar-wind energy system operating on single AC-coupling arrangement with advance-inverter control strategy to achieve better system performance. The three-phase IGBT-based voltage-source inverter is envisioned and developed in MATLAB/Simulink environment and controlled using SRFR on PI-current control. A multi-objective Adaptive Swarm Optimization (ASO) algorithm is introduced for an additional step of optimization in tuning of inverter-control parameters to further enhance system performance by means of dynamic manipulation of the PWM pulses.The new system seeks to reduce both voltage and current total harmonic distortion (THD) for improved active power transfer and better reactive power compensation under varying load circumstances. The efficiency of the conventional integral control system was analyzed by comparing it to the proposed ASO-based control. Simulation results show that voltage and current THD under non-linear load conditions may be reduced 5.40%–1.97% and 1.53%–0.32%, respectively, while with balanced loads, the voltage and current THDs were significantly reduced to 1.99% and 0.86%, respectively, and current THD drops down to 0.40% when unbalanced. Furthermore, the active power output was increased from 3535 W to 3785 W, that is, by almost 7%, and reactive power compensation was improved as well as power factor performance. These performances validate the proposed system based on the adaptive swarm optimization inverter methodology that promises renewable energy networks with better power quality and higher stability.

Keywords:*Hybrid renewable energy system, Solar PV–wind integration, Adaptive swarm optimization, Inverter control, Power quality improvement, Harmonic reduction, Distributed generation*

I.INTRODUCTION

Renewable energy today has significantly taken the higher position among utilities by becoming a global demand. A step further to the other demerits seems to be the energy industry need of the hour, as, owing to the explosive scarcity and corresponding environment concerns, good utility power can no longer await. With long-term warming projections on energy sources, power plants are finding themselves hard-pressed at a torrid pace to incorporate such technologies into effective practice. Out of solar, only wind power has turned out in the field as the most technically and economically feasible under-the-right-condition technology. Both are more promising in being economically viable and in the long run are going to improve environmental sustainability in power generation. However, all these technologies cannot keep opportunities for greater exploitability undiscovered. As soon as they are hooked up alongside the grid, two common problems vis-a-vis intermittency on the two utilities are increasingly anticipated to have serious implications: these problems are power stability and power quality.The hybrid solar-wind energy system technology presented herein will aim at tapping the promising advantages of tapping wind energy and solar energy at the same place. The site would, here, be used for converting wind power directly into electrical power either by means of wind-hybrid conversion systems or standalone wind conversion systems, if wind resource permits.In integrated renewable energy systems, the grid-connected inverter is the central converter. All the inverters perform power conversion, synchronization with the grid, harmonic mitigation, and reactive power control. Usually, conventional control methods are of a fixed-parameter type, less effective under dynamic operating conditions. Dynamic operating conditions being characterized by ever-changing irradiation patterns, gusty speeds, and disturbances on the grid, these control schemes have had to incorporate intelligent and adaptive controlling strategies for enhancing multiple performance objectives at once.

So far, multi-objective optimization (MOO) methods are presenting an appropriate tool to improve inverter control. Among these methods ASO is a meta-heuristic, based on collective behavior of natural swarms and both having good convergence speed, satisfactory adaptability, and robustness. The ASO model integrated with multi objectives offers great assurance of system performance, in which the primary objectives may be, inter alia, minimizing the THD and power losses, enhancing voltage regulation as well as dynamic response. This research is directed at the performance enhancement of a grid-interactive solar-wind energy hybrid when operated with a multi-objective control strategy using Adaptive Swarm Optimization-based inverters. The optimization aims to provide for optimal power quality, effective energy utilization, and improved grid interaction under various operational conditions. The success of this control scheme is substantiated by simulation results that show that the method is better than the classical control strategies in terms of stability, power quality, and system operation efficiency.

II. RELATED WORK

An established smart microgrid tightly stitches together three different strategies to manage AC, DC, and hybrid approaches to guarantee reliability and efficiency [1]. The assessments also suggest that hybrid approaches synergize flexibility and robustness due to a combination of several energy sources and layers of system controls specially coordinated, whereas their interactions through converters can also impede stabilizations. Component- and system-level optimization and control have gone through several research works in recent years for single micro- and the village microgrid: these include scheduling, economics, and multiple objectives [2]. The focus is given here on storage coordination and addressing renewable uncertainty, with the strengths and limits of centralization versus decentralization being laid out as well. There are now several compelling leads for AI-supported decision-making and transactive energy platforms to increase the automation of operation.

The integration of IoT technologies for smart agriculture gives a fresh perspective to monitoring and control; sensor networks, wireless communication, and cloud-based analytics facilitate irrigation control, environment monitoring, and predictive maintenance while challenges such as cybersecurity and energy constraints have been pointed out. The DFIG-based wind turbine system is ready for advanced control strategies to implement vector control, direct torque control, and predictive control [3]. Wind turbine system stability, fault ride-through capability, and wealth of power quality issues are greatly improved using such techniques. Intelligent and adaptive controls have been identified as representative of the future for turbin power law quality and output [4].

They apply smart energy management with advanced AI optimization algorithms, like fuzzy-PSO algorithms, involving multiple energy sources and storage devices [5]. Those algorithms reduce the operating costs, promote reliability and power quality, and are efficiently adaptable to renewableshed resource fluctuation. At the same time, it's important to underline that it is these grid-forming converters that drive the system for a renewable-based system [6] that provides inertia emulation (a necessary tool for such systems), sync, and transient behavior control; while, on the other hand, standards are brought in by interoperability and validation issues.

One of the transformative benefits of coherent human-machine systems is the invention of applications to support child-focused tourism destinations [7], giving a chance for sustainable development. Healthcare will further benefit from IoT through the merging advances in several health-bracelet technologies to create a multipurpose non-invasive tool [8]. Clean-energy application of fuel cell resources has been successfully combined with power management via energy storage [9] for advanced transportation systems. Although economically considerable consequences are evident at HTC, they are challenging for cost-effective businesses, as shown in private and road transportation scenarios [10] where fuel consumption and emissions are minimized with a sudden focus on power control and design.Recent studies assert an essential role for the integration of smart controls with hybrid intermittent systems that are instrumental in addressing power-qualty and stability issues prevalent in the modern grid. A myriad of procedures have been brought forth to deal with different types of uncertainties arising from the solar-wind generation. Hence, where earlier systems have proven to have system stabilization, curtailment reduction, and general efficient use of the system [11], coordinated control strategies second this claim by enhancing voltage control, distribution of power, and reduction of the harmonic content in hybrid systems [12]. However, when solar PV penetration becomes high posing voltage fluctuation and harmonics in the conventional grid, again the necessity for advanced filters and implementation of best engineering practices was noted [13]. Series active power filters in association with best compensation strategies are demonstrated to be helpful in improving the voltage profile and sustain dynamic behavior under the effects of disturbances [14]. Glimpses of investigations now probably suggest the implementation of an advanced grid code to address flicker, voltage imbalance, or harmonics in photovoltaics-integrated systems [15].

In case of PV-wind microgrids, intelligent forecasting and proactive shunt filters are used for harmonic control and power factor strengthening by overcoming the uncertainties [16]. The distributed generations introduce issues of voltage deviation, reverse power flow, and harmonic distortion that can be minimized by coordinated system architectures [17]. Other issues such as islanding are resolved through adaptive relaying mechanisms and closed-loop schemes [18]. Hybrid systems involving the optimal configuration of solar, wind, batteries, and electric vehicles have displayed apparent success for maintaining stable voltage levels in the system, suppressing harmonics, and hence ensuring power quality [19].

The integration of Unified Power Quality Conditioner (UPQC), new control schemes, and the use of ANFIS-FBSO have further improved power quality and transient response in hybrid systems [20]. The meta-heuristic and Gray Wolf optimization algorithms in conjunction with STATCOM and UPQC devices result in noteworthy advancements for harmonic suppression, voltage stability, and reactive power support [21]. The advanced techniques have called forth several hybrid control concepts for real-time decision making, future performance of microgrids, and coordinated flexibility management strategies [22-23]. In monitoring 3DOF PID control, further research for improved voltage, harmonics, and dynamic performance accuracy in renewable/battery microgrids [24].

Table 1: Review on Power Quality and Hybrid Renewable Energy Systems

Ref	Main Focus	Methods	Key Power-Quality or Stability Issues	Major Findings	Identified Gap
[25]	Hybrid RES with UPQC	Literature review and system integration	Harmonics, voltage deviations	UPQC integration improves PQ in hybrid systems	Experimental implementation is limited
[26]	Hybrid RES	Advanced control techniques	Voltage/frequency instability, harmonics	Advanced control improves grid stability	Validation in large grids needed
[27]	Grid-connected hybrid RES	ANFIS + metaheuristic optimization	Harmonics, reactive power, voltage sag	Significant PQ enhancement and control optimization	Real-time implementation missing
[28]	Hybrid RES with STATCOM	Advanced optimization and STATCOM-based PQ control	Voltage instability, harmonics	STATCOM + optimization improves PQ	High computational cost, needs hardware testing
[29]	UPQC-based hybrid RES	Metaheuristic optimization for PQ improvement	Voltage dips, harmonics	Effective PQ improvement	Scalability in real-time grids is limited
[30]	Hybrid RES + uPQC	Optimization-based uPQC design	Harmonics, reactive power compensation	Optimized uPQC enhances PQ	Hardware deployment not reported

III.RESEARCH OBJECTIVES

- Designing of a grid integrated solar wind hybrid energy system with common AC line for driving loads for improving its reliability and efficiency.
- Designing an inverter control that attains lower distortion level in the voltage as well as current waveforms.
- Designing of an effective artificial intelligence based algorithm that accommodates the fluctuations at the loading points. The system is subjected to three kinds of loads, non linear, unbalanced and balanced
- Improvement in the reactive power output from the system by the inverter control by designed hybrid system that can compensate the reactive power requirement when required

IV.RESEARCH METHODOLOGY

Hybrid Renewable Energy System (RES) Development

The modeling of a hybrid AC grid system has been done for feeding the load with either solar or wind resources depending on the availability thus making the system more reliable. The two resources have been connected to the load through a common AC line which is being fed by the either sources. According to the basic architecture of the system shown in Fig. 1, the system has been modeled such that they meet the requirements. Example of systems with PV and MPPT technicals, IE connecting to the AC grid with a bidirectional converter, PMSG from the wind turbine, are connected to AC loads.

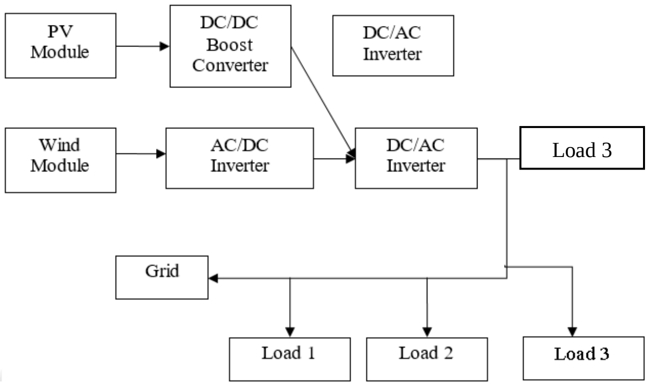

Figure 1: Hybrid energy system topology

Reference signal generation for PWM

The inverter system detailed in this manuscript is for a three-phase grid-tied inverter. The inverter uses a three-phase IGBT-based topology that is mostly used in distributed generation and renewable energy integration applications. A synchronous rectifying-based proportional-integral (PI) current controller is employed to guarantee accurate regulation of grid current, while a three-phase control strategy is used to decouple real and reactive power components effectively, enhance system dynamic response and guarantee grid code compliance.

In all cases, the solar panels in the solar power generation system are then connected to the electrical grid either directly or via a battery storage system for energy storage during non-productive hours or seasonal weather conditions-further emphasizing the changing requirements of matching to diverse operating situations. PV systems using DC–AC inverters are required for the excess electrical power generated by the PV source, most of which is fed into utility electricity grids or an alternate load of AC systems.

The inverters are custom-arranged and designed and depending upon the purpose, can either generate a sum of one-phase or the combination of three-phase power systems. From the four most commonly used inverters, employed in PV systems connected to the electricity grid, banks of inverters include the central inverters, string inverters, multi-string inverters, and microinverters (AC modules). The central inverter system is an outdated technology connecting large numbers of PV modules wired in series into strings, which are then combined in parallel to a high-capacity inverter. In spite of the fact that this approach is good for large power handling, it always proves inefficient, mainly due to fixed adjustments of MPPTs.

The multi-string inverter topology mainly consist of an inverter assigned to each photovoltaic string that operates independently, resulting in enhanced energy yield. In the multi-string, implemented in a central approach, there are multiple strings connected as the basic idea in the system. Thus, each string will have its own DC–DC converter, and MPPT will help with the central inverter, attaining the greatest engineering flexibility relative to performance. Following are the microinverter topology configurations fitted at the module level to include the most tolerant and best superior energy harvesting, ranging from high cost to high-reliability low tolerance. The string and multi-string inverters can further maintain the favorable performance of the central inverter systems since controlled at the maximum-fault-tolerant level compounded with prevailing partial-shading and mismatch considerations. The block diagram of the three-phase DC-AC inverter connected to the grid is shown in Figure 2.

The inverter control designing has been done so as to improve the system parameters. The designing has been done in dq0 reference frame to ease the study of the elemental parts and their respective changes. The system continuously keeps a check on the variable parameters and updates as per the requirement.

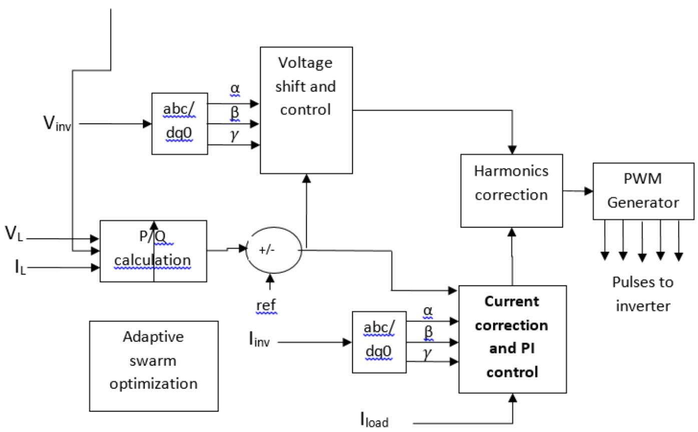

Figure 2: load line driving adaptive multi-objective PWM control

An adaptive swarm-based control strategy is employed to generate gating pulses for the three-phase inverter, which is accomplished by continuously monitoring the grid, the load, and the inverter parameters. Regulation of real and reactive power demands is made adaptive by tuning the gains of a PI controller, such that reactive power can be controlled efficiently while the active current can be held at almost zero. Harmonic compensation is being performed prior to PWM generation to improve power quality. In the present case, a sine-triangle is used with PWM that compares inverter switching with the current error signal using a carrier waveform. This is introduced to gain advantages in equally accretive tracking, dynamic response, and system stability in any given situation.

Adaptive Swarm Optimization Control for multi objective functions

The adaptive swarm optimization, which is a novel swarm optimization algorithm, was proposed by Kennedy for the first time as an evolutionary algorithm based on behavior of birds. This method uses a set of particles/signals where each represents a solution to the optimization problem. It is designed based on the signaling scheme where success of all the signal components, which synthesize the population, should be copied and direct the position of each particle to the agent position in order to solve all the best solutions P_{best} using current particles/signals from the population G. The position of any particle xi is adjusted by

$$x_i^{k=1} = x_i^k + v_i$$

where the velocity component vi represents the step size and is calculated by:

$$v_i^k = wv_i^k + c_1r_1\left(P_{best_i} - x_i^k\right) + c_2r_2\left(G - x_i^k\right)$$

where x is the inertial weight, c_1 and c_2 are the acceleration coefficients, r_1 and r_2 are random values that belong to the interval of [0, 1], $P_{best_i}$is the best position of particle i, and G is the best position in the entire population.

A flowchart specifies five steps of operation-analysis calories. Initialization, fitness evaluation, Individual and global best value updating, velocity, and position update for every particle and convergence detection. In the first step, the particles are randomly spread into the specified grid nodes over the search space.

Similarly, the initial velocity values are defined randomly. The next step consists of the evaluation of the fitness value of every particle. Fitness evaluations are carried in quest of the best solution to the objective function. The individual and global best fitness values are determined in the third stepwherep_{best_i}andg_{best} are respectively determined.Figure 3: Adaptive control algorithm design

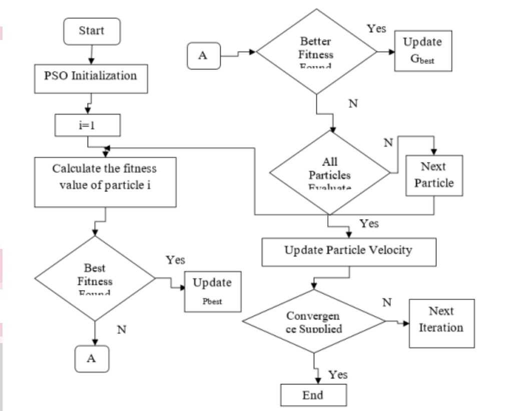

Figure 3: Adaptive control algorithm design

In step 4 of the flowchart, the PBCPSO algorithm allows the updating of the velocity of particles followed by the updating of their position. The process comes to a close if these particles satisfy a certain prescribed convergence criterion. Otherwise, the iteration number is increased and procedure returns to step 2.

V. RESULT AND DISCUSSION

CASE 1: Hybrid RES having Inverter control driven by Programmable integral control

In this connection, the Hybrid RES integrated with each converter has its control system driving it with programmable integral algorithms for generating pulses required for generating a communication inverter. The analysis will be expanded with the quality of the waveforms at various load terminals-such as non-linear, balanced and unbalanced, and harmonics of other orders.

Analysis of system in case 1 at the Non linear (NL) load terminal

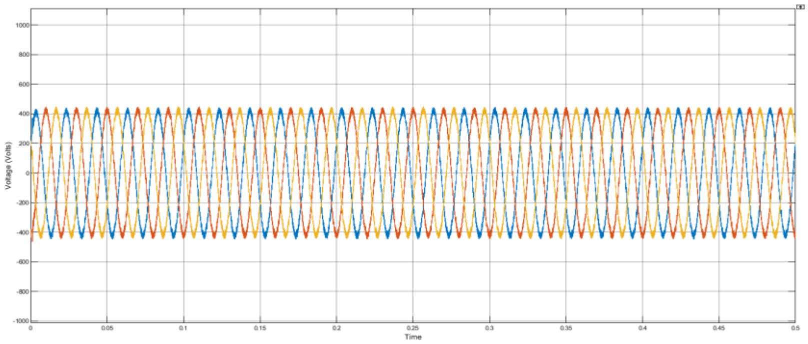

Figure 4: Voltage output available the NL load terminal in system described in case 1

The three phase voltage output fed to the load terminal is outlined in Figure 4 for the system wherein controller is driven by a programmable integral control element for interfacing with the hybrid system.

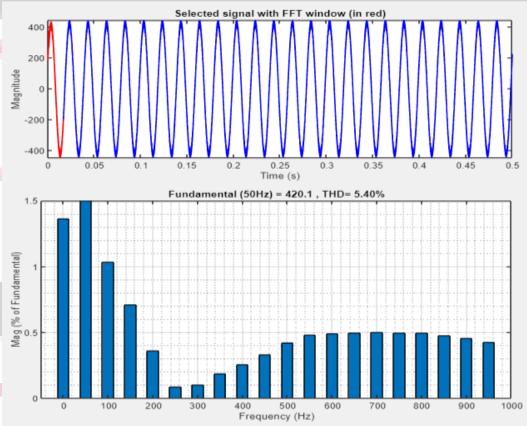

Figure 5: THD % in the Voltage output available the NL load terminal in case 1

The Total Harmonic Distortion is estimated at the power terminal of a stand-alone system net owing to programmed integral control for inverters and it turned out to be 5.40%.

Analysis of system in case 1 at the load terminal where the loads are balanced

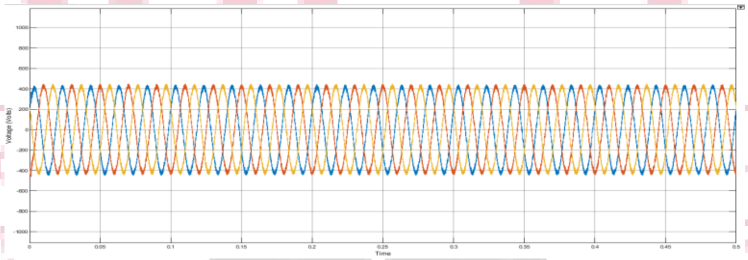

Figure 6: Voltage available at the terminal where there are balanced loads in system in case 1

The implemented system in a programmable controlling involves the display of the three-phase voltage output at the balanced load terminal, which is shown in Figure 6.

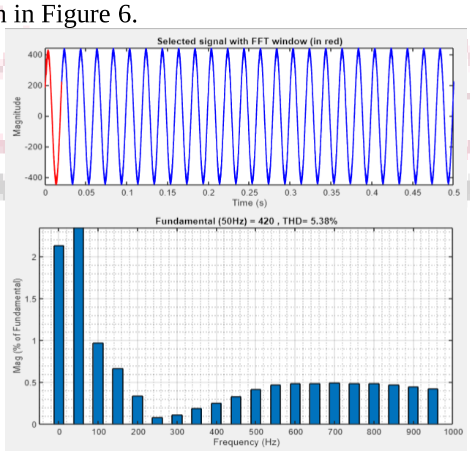

Figure 7: THD% evaluation of Voltage available at the terminal where there are balanced loads in system in case 1

The significance of total harmonic distortion in the voltage waveform is calculated at the terminal of a balanced load, given a system wherein the hybrid renewable energy sources are pursued active programs for the integral control on the inverter, and thereon, the total harmonic distortion proved to be 5.38%.

Analysis of system in case 1 at the load terminal where the loads are unbalanced

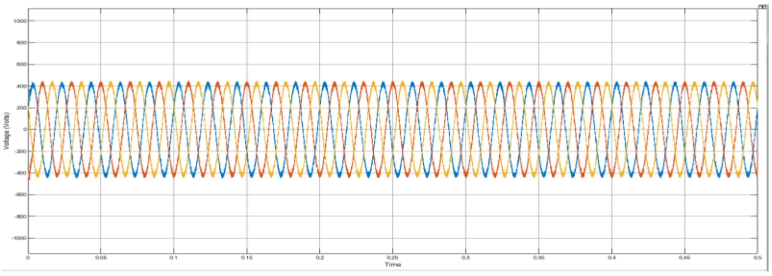

Figure 8: Voltage at the terminal where there are unbalanced loads in system in case 1

Figure 8 may indicate the three phase voltage output available at the unbalanced load terminal. For the hybrid system to operate, the controller is driven by programmable integral control.

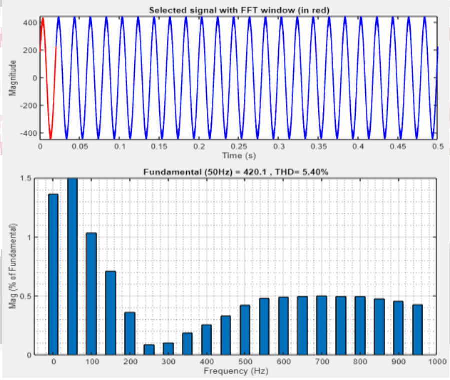

Figure 9: THD% evaluation of Voltage at the terminal where there are unbalanced loads in system described in case 1

The total harmonic distortion on the system load terminal of a network with combined REO is rated against 50Hz sine wave inverter and assessed at 5.40% of the terminal voltage.

Case 2: Hybrid RES with bridge Inverter control driven by adaptive swarm optimization controlfor stability enhancement

In this regard; the hybrid RES are interfaced through converter control system of various control algorithms related to proposed AI based Adaptive Swarm Optimization Integral technique model that generates required pulses to drive inverter. The analysis extends to discuss the effects on the waveform qualities available for different loads like non-linear, three-phase balance, and unbalance. Thus, while comparing the qualities of load driving, the system, when under operation, does well as being opposed to these two of lesser partner quantities of output.

Analysis of system in case 2 at the Non linear (NL) load terminal

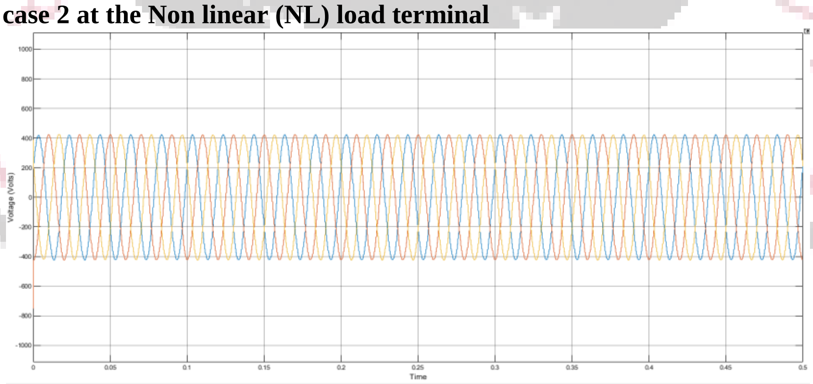

Figure 10: Voltage output available the NL load terminal in system described in case 2

The inverter driven with the adaptive swarm-optimized control is shown in Figure 10 together with the output of a hybrid RES operating on the basis of three-phase voltage during the boosting on the inverter.

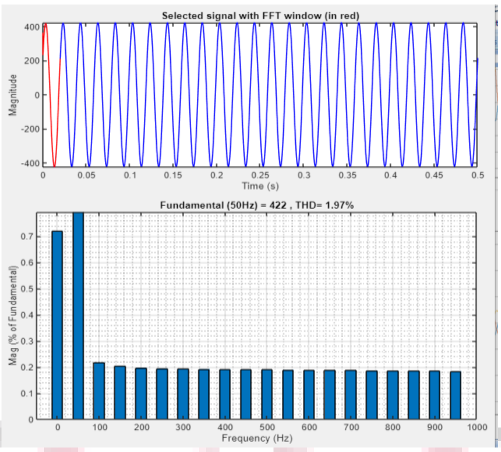

Figure 11: THD% evaluation of Voltage output available the NL load terminal in system described in case 2

As shown in Figure 5.20, THD% for the three-phase voltage output of the hybrid RES, where the inverter is controlled under adaptive swam optimization, amounts to 1.97%

Analysis of system in case 2 at the load terminal where the loads are balanced

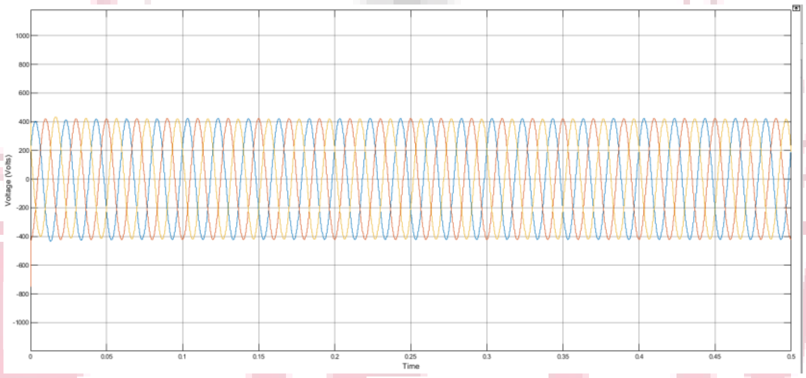

Figure 12: Voltage Available at the terminal where there are balanced loads in system in case 2

The three-phase voltage at the balanced load terminal available in the hybrid RES redesigned to run being operated by Adaptive Swarm Optimization control, as shown in Figure 12.

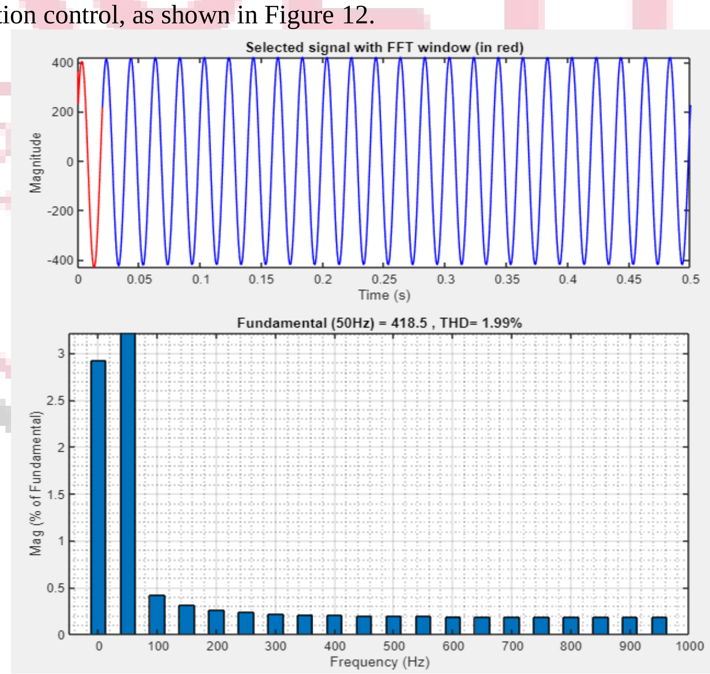

Figure 13: THD% in Voltage Available at the terminal where there are balanced loads in system described in case 2

THD% calculation of the three phase voltage output of the hybrid RES at the balanced load terminal where the inverter is redesigned to be driven by adaptive swam optimization control is shown in figure 5.26 which came out to be 1.99%.

Analysis of system in case 2 at the load terminal where the loads are unbalanced

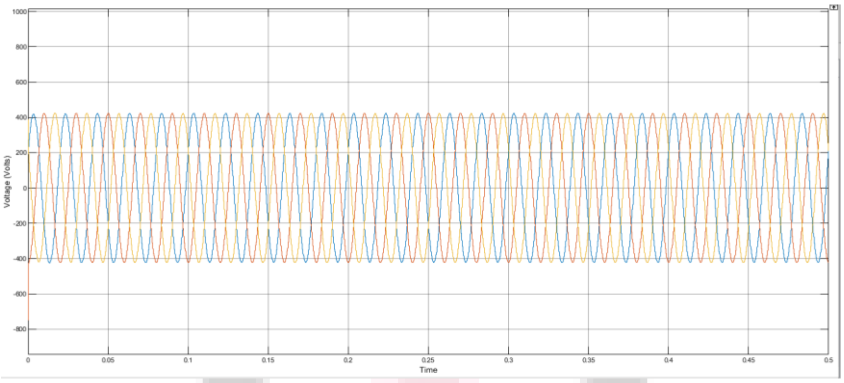

Figure 14: Voltage available at the terminal of unbalanced loads in system in case 2

The three phase voltage output of the hybrid RES at the unbalanced terminal where the inverter is redesigned to be driven by adaptive swam optimization control is shown in figure 14

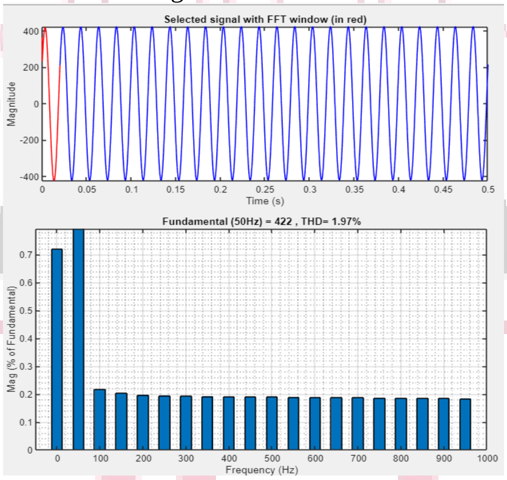

Figure 15: THD% of Voltage available at the terminal of unbalanced loads in system in case 2

THD% calculation of the three phase voltage output of the hybrid RES at the unbalanced load terminal where the inverter is redesigned to be driven by adaptive swam optimization control is shown in figure 15 which came out to be 1.97%.

Validation of Work

The system analysis is concluded in this chapter by making comparisons in between the systems designed with inverters driven by Programmable integral control regulators and the second system having adaptive controller for driving inverter that utilizes swarm optimization algorithm.

Table 2: Analysis of the systems designed with two UPQC controllers

Electrical Parameters/System under simulation	**Case 1 (Hybrid RES with Programmable inegral control)**			**Case 2 (Hybrid RES with proposed adaptive warm optimisation control)**		
	Non Linear loads	Balanced loads	Unbalanced loads	Non Linear loads	Balanced loads	Unbalanced loads
THD% in voltage	5.40	5.38	5.40	1.97	1.99	1.97
THD % in current	1.53	1.55	1.79	0.32	0.86	0.40

VI. CONCLUSION AND FUTURE WORK

This paper presents investigation into the enhancement of the performance in grid-integrated solar PV-wind power system using an inverter control strategy. The performance of the entire system has been modeled in the MATLAB/Simulink environment. Nonlinear, balanced and unbalanced loading conditions have fueled simulation. In the bid to improve power quality, stability, and energy efficiency against disturbance, the PI controller along with the proposed adaptive swarm-based multiobjectives optimization (ASO) controller gained considerable weight.Simulation results confirm the much superior ASO-based control in relation to the classical PI controller. This led to an increase of about 7%, the active energy growing from 3535 W to 3785 W with an improved reactive power and power factor. In line with this, significant inroads into harmonics were made in superior power quality. With nonlinear load, voltage THD was decreased from 5.40% down to 1.97%, and current THD was downtuned from 1.53% to 0.32%. On balanced loads, the voltage and current THDs were constrained to 1.99% and 0.86%, respectively; they changed for unbalanced loads, with current THD reduced to 0.40%. Our observations thus establish that it is their ability to flexibly optimize the control parameters of the inverter through the Adaptive Swarm Optimization technique which imparts in the sustainable operation of the system under various changing operation conditions. Future work could be focused on real-time hardware implementation of the proposed control strategy by utilizing embedded controllers or digital signal processors to substantiate practicality of this controller. A further extension of this control framework could be in coupling the swarm optimization with other AI techniques, the likes of fuzzy logic or neural networks to further its robustness. Further enhancement in convergence speed is anticipated. Further incorporation of energy storage system and extension to microgrid would result in superiorized reliability and scalability of the proposed hybrid renewable energy system.

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