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ETAP-Based Analysis of Hybrid Energy Systems in Smart Grids

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ABSTRACT

Recent developments in smart grid technologies have essential implications for meeting the growing global energy demand sustainably. In this study, the performance of a hybrid renewable energy system combining wind turbines, photovoltaic arrays (PVAs), and diesel generators (DGs) is designed and analyzed to improve power generation efficiency and sustainability. The system features eight wind turbines (225-600 kW), PVAs for daytime energy capture, and a DG for backup, ensuring reliability during periods of low renewable generation. Reactive power compensation through capacitor banks enhances voltage stability and power factor, while improved infrastructure reduces transmission losses. The performance analysis results using ETAP software demonstrate the system's ability to adapt to variable renewable inputs, dynamic loads, and operational disturbances. It also reflects its scalability, flexibility, and potential as a cost-effective solution for sustainable smart grid applications.

1. INTRODUCTION

In recent years, modern society has made great efforts to develop smart grid technologies to respond to the steadily increasing worldwide energy demand sustainably. Efforts and advances in different disciplines converged to improve the performance of energy production, distribution, and transmission infrastructures, leading to a more efficient handling of the electricity grid. In particular, the relevance of the smart grid as a more environmentally friendly solution lies in reducing energy losses at every level, thus creating an energy system that is more reliable and efficient. Several advanced control and computing methodologies must be applied to shape this smarter approach to electricity use. Among them, a growing interest is dedicated to integrating programmable logic devices into energy automation systems. Programmable logic devices are already intensively used to improve the performance of the output of the industrial machines where they are placed to increase their efficiency and reliability [1, 2].

Part of this research aims to explore these opportunities by carefully analyzing the Integration between cloud computing technologies and systems at work in the energy automation domain [3]. At the beginning of the twenty-first century, people made a difficult and complex transition from traditional energy systems to modern advanced smart grids. This technically means that electrical energy has been generated from several water, oil, coal, and gas power stations and transmitted to the bus stations many miles away through a stepped-up voltage. Then, the energy moves down from the bus station's high-tension power grid to residential or industrial levels and all corners of the country through low-tension conductors. The construction of smart grids requires a large amount of funds because it introduces many advanced fields of bus technology, communication technology, and control technology into the automation of distribution networks and substations [4, 5].

Automation is an effective means of dealing with the unpredictable output of distributed generation. The core of automation is to use advanced high-tech to understand energy demand and make decisions that benefit the power grid operation. Smart grids save many resources every year by improving energy efficiency. Many studies have shown that the optimal control of distribution networks can greatly improve the reliability of power supply. Therefore, the launch of the smart grid is conducive to developing an environmentally friendly society; in the long run, people can break away from the constraints of coal, reduce carbon emissions, and contribute to energy security. Many consumers and power supply departments are beginning to use renewable energy for distributed generation; this means that consumers, power providers, and power demand need a new way of thinking to optimize [6]. Automation and control are the most critical catalysts for deploying the smart grid. The advance of control is virtually synchronous with the advance of hardware and communication equipment in the past decade. Because modern control technologies introduce many complex algorithms and control calculation steps into the intelligent electrical energy automation system, the research for replacing powerful and weak separation modes with technology has become active in the past two or three years. Thus, cloud computing has become a hot topic. Research on cloud computing for energy automation systems for smart grids can improve the performance of modern electric power supply [7].

Smart grid technology is the next-generation leap in power distribution management, marrying digital communication with the conventional grid infrastructure to bring better efficiency, reliability, and sustainability. This newer philosophy of technology promotes two-way interaction between utility providers and consumers for real-time observation and control over energy consumption patterns; this further strengthens the efficiency at the distribution end and empowers consumers to make choices regarding their energy use pattern. This will also facilitate a significantly enhanced utilization of renewable sources of energy towards a more sustainable and more resilient grid. This is a tectonic shift towards renewability, efficiency, and sustainability in smart grids to battle the rising demand for energy resources against the bane of climate change [7]. By utilizing renewable energy sources such as wind, solar, and hydroelectric power, smart grids offer a simple way of integrating clean energy into their systems, reducing fossil fuel dependence and greenhouse gas emissions. A few of the advanced technologies in the smart grid system include real-time monitoring, adaptive control systems, and machine learning algorithms that enable a balance between fluctuating renewable generation and dynamic load demand while maintaining grid stability and reliability [8, 9]. Energy storage facilities such as batteries and pumped hydro storage smooth the variability of such systems and have, therefore, become highly critical under renewable energy intermittency. Besides, smart grids enable decentralized power production, as distributed energy resources and consumer enablement to participate actively in energy management through demand-side response mechanisms. Their integration of renewable energy and smart grids enhances energy security and increases economic efficiency with reduced operational costs and full utilization of resources [10, 11]. Convergence to these technologies proves that innovation, policy leadership, and international collaboration are critical in spearheading transformation to a cleaner, greener, more secure energy future. Automation and the smart grid are intimately interconnected, resulting in a groundbreaking integration in modern energy systems. It also leverages cutting-edge automation technologies to monitor, manage, and optimize energy flows or consumption in real-time for effective and dependable service. In addition, smart automation connects renewable sources, responds dynamically to demand fluctuations, and limits human intervention in key processes. This interdependence makes the infrastructure resilient: predict maintenance, self-heal, and adaptively act. Finally, smart grids and automation are the most important steps toward sustainable, efficient, and future-proof power grids [8].

The integration of renewable energy sources (RES) and energy storage systems (ESS) into hybrid smart grids is a revolution in modern power distribution systems. Past studies have underscored both opportunities and challenges in achieving this shift, pointing to the need for advanced control strategies, optimization techniques, and real-time monitoring to enhance grid stability and efficiency [12]. The incorporation of distributed energy resources (DERs), microgrids, and intelligent communication technologies further accentuates the revolutionary potential of hybrid smart grids for constructing flexible and resilient energy systems [13]. However, the increasing reliance on interdependent systems and digital communications has also conferred these grids enormous cyber-physical threats to security. Securing these weaknesses with robust security infrastructures is crucial to the reliability and robustness of hybrid smart grids in the face of evolving threats [14]. This paper seeks to build on these initial observations, analyzing the technical, operational, and security complexities of hybrid smart grids to enhance the move toward sustainable and secure energy systems.

2. SMART GRID SYSTEM ANALYZING

To model and analyze the smart grid system mathematically, all the equations would include a combination of power flow, generator, and control equations for the various system components. Below is a breakdown of the essential equations for each part of the system [15].

2.1 Power flow equations

The grid system is typically analyzed using AC power flow equations. For each bus i in the network, the real and reactive power injected into the bus are calculated as:

•Real power balance

$$P_i = \sum_{j=1}^{n} V_i V_j \left(G_{ij}\cos\ \theta_{ij} + B_{ij}\sin\ \theta_{ij}\right) \tag{1}$$

•Reactive power balance

$$Q_i = \sum_{j=1}^{n} V_i V_j \left(G_{ij}\sin\ \theta_{ij} - B_{ij}\cos\ \theta_{ij}\right) \tag{2}$$

where:

P_i: Real power injected at bus *i.*

Q_i: Reactive power injected at bus *i.*

V_i , V_j Voltage magnitudes at buses *i* and *j.*

$\theta_{ij} = \theta_i - \theta_j$: Phase angle difference between buses i, j.

G_{ij}, B_{ij}: Conductance and susceptance between buses i, j.

2.2 Generator equations

Each generator (diesel and wind) has its operational characteristics:

•DG

Real power output

$$P_{\text{Gen}} = P_{\text{demand}} + P_{\text{losses}} \tag{3}$$

The DG supplies any remaining load after contributions from renewables.

Reactive power capability

Governed by the generator's capability curve:

$$Q_{min} \leq Q_{\text{Gen}} \leq Q_{max} \tag{4}$$

Generator swing equation

$$2H\frac{d\omega}{dt} = P_{\text{m}} - P_{\text{e}} - D(\omega - \omega_0) \tag{5}$$

where:

H: Inertia constant

ω: Rotor speed

P_{m}: Mechanical input power

P_{e}: Electrical output power

D: Damping coefficient

Wind Turbine Generators (WTGs)
Power output:

$$P_{\mathrm{WT}} = 0.5\rho A C_p \frac{v^3}{\eta} \tag{6}$$

where:
ρ: Air density
A: Rotor swept area
C_p: Power coefficient (depends on turbine design)
v: Wind speed
v: Efficiency of the turbine

2.3 Transformer equations

Transformers are modeled using their admittance matrix. The real and reactive power flows through the transformer are:

$$P_{\mathrm{T}} = V_{\mathrm{H}} V_{\mathrm{L}} (G\cos\,\theta + B\sin\,\theta) \tag{7}$$

$$Q_{\mathrm{T}} = V_{\mathrm{H}} V_{\mathrm{L}} (G\sin\,\theta - B\cos\,\theta) \tag{8}$$

where:
$V_{\mathrm{H}} V_{\mathrm{L}}$: Voltages at the high and low voltage sides
G, B: Transformer conductance and susceptance
θ: Phase angle difference

2.4 Capacitor bank equations

The reactive power supplied by the capacitor bank is:

$$Q_{\mathrm{CAP}} = V^2 B_{\mathrm{CAP}} \tag{9}$$

where:
V: The voltage at the bus where the capacitor is connected
B_{CAP}: Susceptance of the capacitor bank

3. RELATED WORKS

The study [16] provides a comprehensive overview of smart grid technologies, emphasizing advanced metering, demand response, grid automation, and renewable energy integration. It adopts a holistic approach, addressing technical, economic, and regulatory aspects while highlighting the importance of consumer engagement. Despite limited detail on cybersecurity and data analytics, it offers valuable insights into the complexities of smart grids.

The research [17] emphasizes the integration of smart grids with broader smart energy systems to support renewable energy adoption and improve efficiency. It underlines the interdisciplinary nature of the research required from technical, economic, and social perspectives. While comprehensive, it lacks detail on specific technologies and policies for achieving these goals.

Mengelkamp et al. [18] discussed blockchain technology for peer-to-peer energy trading in microgrids, using the Brooklyn Microgrid as a case study. It highlights the benefits of decentralized markets, such as enhanced security, transparency, and reduced costs, but also addresses challenges like scalability and regulatory compliance. The work is novel, but further research is required to evaluate the broader applicability of blockchain in smart grids.

Omitaomu and Niu [19] overviewed AI and machine learning applications in smart grids, focusing on demand forecasting, fault detection, and optimization. While this review underlines AI's potential for enhancing grid efficiency and reliability, it also highlights some drawbacks regarding data quality and algorithm transparency. The paper offers an overview but lacks important case studies and empirical validations.

The work [20] presents a method to model smart sensor interoperability in smart grids using labeled transition systems and finite state processes. This approach systematically solves interoperability issues, enhancing data exchange reliability. It has been illustrated for IEEE C37.118 protocols. The proposed methodology can be extended to other communication standards, enhancing sensor data interoperability in smart grids.

Masera et al. [21] placed smart energy networks within the architecture of smart cities and propose an extended CBA methodology that embraces environmental, social, and security factors. They present a European development-based methodology that frames up a broader impact valuation of smart grid deployment: It is extensible towards evaluating proposals for smart city development.

Ullah and Park [22] had proposed a distributed energy trading mechanism in smart grids. Their main concern is voltage and congestion management. The mechanism employs a distributed consensus algorithm to optimize generation and demand-side cost functions. Thus, it provides an efficient solution for managing energy trading within smart grid environments.

Sha et al. [23] discussed the issue of the security of the data readings of the isolated smart grid devices by proposing a secure framework using a two-phase authentication protocol with smart intermediate readers. The proposed scheme considers physical device constraints and is proven to be safe against the most common attacks. Performance evaluations ensure the efficiency of the proposed scheme, revealing a robust solution for secure data readings in smart grid systems.

Srivastava et al. [24] proposed the use of MESS in augmenting cost saving in smart grids with many microgrids because it can outdo some limitations of fixed-based ESSs. The authors present an algorithmic framework for allocating MESS to microgrids optimally for a number of days such that cost savings are maximized and routing expenses minimized.

The study [25] is on optimal distributed generation (DG) planning in radial distribution networks, using enhanced particle swarm optimization (EPSO) and ant lion optimization (ALO). EPSO outperforms ALO in terms of actual loss reduction, convergence speed, and voltage stability improvement. The paper stresses the superior precision of EPSO for determining the optimal size and location of DG.

The study [26] investigates maximum DG placement and size in distribution systems using the Coronavirus herd immunity optimizer (CHIO). Simulations in an IEEE 69-node system show CHIO's improved performance over other metaheuristic methods, with significant improvements in loss minimization, voltage profile, and voltage stability index (VSI).

4. PROPOSED SYSTEM

The proposed system shown in Figure 1 focuses on designing and analyzing an advanced smart grid integrating multiple energy sources and components to ensure efficient, reliable, and sustainable power generation and distribution. It is interfaced with a hybrid configuration of photovoltaic (PV) panels, wind turbines, a DG, capacitor banks, and transformers through a well-structured network of buses and cables. The system focuses on the best approach to manage energy to attain grid stability and resilience in response to fluctuating demands. The main power supply source is a high-capacity grid connection rated 597.958 MVA at 34.5 kV within the grid system. This is supplemented by renewable energy sources consisting of eight wind turbines, each with capacities of 225 kW to 600 kW. These wind turbines are connected to low-voltage buses at appropriate locations to ensure a steady contribution of clean energy to the grid. Additionally, the backup is also offered by a 600kW DG during periods of low generation from renewable sources, thus improving the reliability of the grid.

The PV panels of the system are an important component of harnessing solar power to complement other renewable sources and decrease the reliance on conventional generation. The panels, which are linked together on Bus 14 with six arrays PVA1-PVA6, are linked through a 0.22 kV network and stepped up through transformer T5 in an effort to feed into the main grid. This configuration makes the grid more sustainable by adding a clean and renewable source that maximizes energy utilization during the times of peak sun and improves the overall reliability and resilience of the system. Energy is consumed with very little greenhouse gas emission when wind turbines and PV panels are used. Their integration into the microgrid underlines the potential of hybrid renewable systems in modern energy networks.

Within the system, several different-capacity transformers manage voltage levels across the network. A 20 MVA transformer steps down the voltage from 34.5 kV to 4.16 kV, with others of lower rating, 2.5 and 1 MVA. Such transformers provide an interface between the different voltage levels, thus enabling compatible power flow and compatibility with the loads connected. It also includes a capacitor bank rated at 1000 Kvar for reactive power compensation to improve the power factor and reduce energy losses. The system integrates renewable energy sources with conventional generation to develop a sustainable and resilient power system. By integrating the latest grid technologies with sound design principles, the proposed system will hopefully make useful contributions toward global changes necessary for the world's energy systems to be cleaner and more reliable. This system is supposed to act as a model for future smart grid development in integrating energy efficiency, environmental sustainability, and operational reliability.

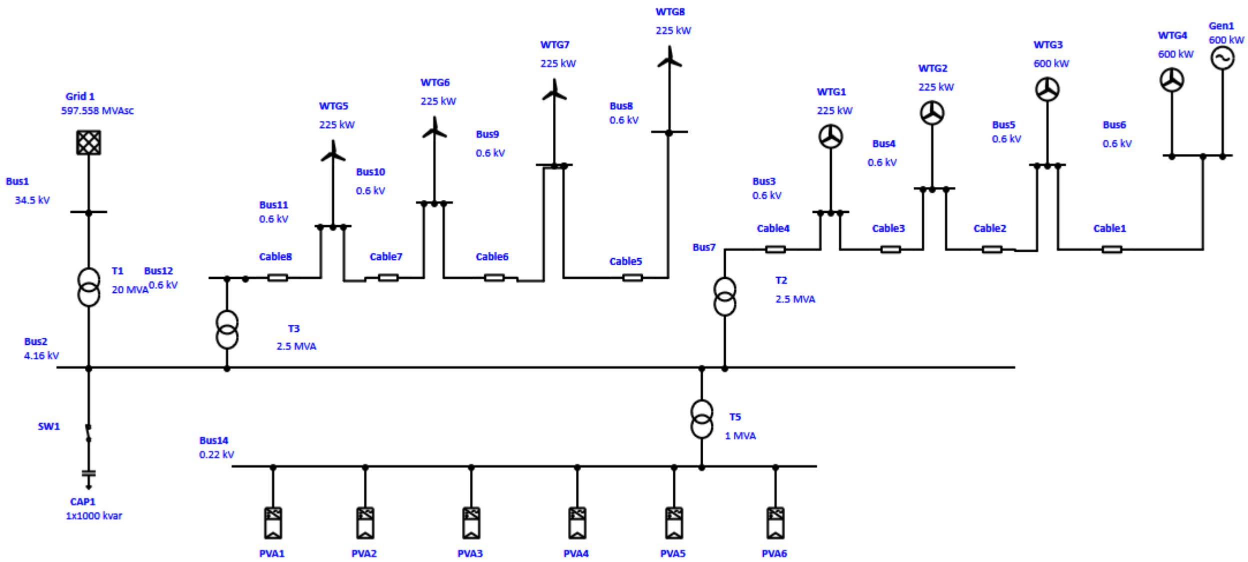

Figure 1. The proposed system

Table 1. System ratings

Component	Label	Voltage (kV)	Capacity/Rating	Details
Grid	Grid 1	34.5 kV	597.558 MVAsc	Connection to external grid
Transformer	T1	34.5/0.6 kV	20 MVA	Steps down voltage from 34.5 kV to 0.6 kV
Bus	Bus1	34.5 kV	-	Connects Grid 1 to T1
Bus	Bus2	4.16 kV	-	Downstream of transformer T1
Switch	SW1	-	-	Allows control of power flow
Capacitor	CAP1	-	1,000 kvar	Reactive power compensation
Transformer	T3	0.6/4.16 kV	2.5 MVA	Steps up voltage from 0.6 kV to 4.16 kV
Bus	Bus3	0.6 kV	-	Connection for WTGs and cables
Transformer	T2	0.6/4.16 kV	2.5 MVA	Steps up voltage for WTGs
Bus	Bus7	4.16 kV	-	Intermediate bus connecting T2
Transformer	T5	0.6/0.22 kV	1 MVA	Steps down voltage for PVAs
Bus	Bus14	0.22 kV	-	PVAs connection
PVAs	PVA1-PVA6	0.22 kV	-	Six PVAs connected to Bus14
WTGs	WT1-WT8	0.6 kV	WT1-WT4: 600 kW, WT5-WT8: 225 kW	Connected to individual buses and transformers
Generator	Gen1	0.6 kV	600 kW	Standalone synchronous generator

Table 1 highlights the main components of the energy system, describing their ratings and functions. The external grid (Grid 1) is at 34.5 kV and has a short-circuit capacity of 597.558 MVAsc. It is connected through (Bus1) to transformer T1, which decreases the voltage to 0.6 kV at a rating of 20 MVA. The 1,000 kvar capacitor (CAP1) gives the reactive power compensation. Transformer T3 steps up the voltage to 4.16 kV for integration with WTGs (WT1 - WT8) and intermediate buses such as (Bus7) downstream. PVAs, PVA1-PVA6, are connected at 0.22 kV through transformer T5 at 1 MVA, while one stand-alone generator (Gen1) feeds in 600 kW at 0.6 kV. Further, switches, additional transformers, and buses allow power flow control flexibly, hence efficient energy distribution in the system.

The dataset provides comprehensive measurements from the smart grid system, integrating PV generation, wind turbines, battery storage, diesel and gas generators, and grid interconnections. The data is collected at a frequency of one-second intervals, ensuring high temporal resolution for real-time monitoring and analysis. The dataset includes data from high-precision voltage, current, and power meters, with an accuracy of ±0.2% for voltage and current measurements and ±0.5% for power calculations. Environmental sensors, such as those monitoring solar irradiance and wind speed, have an accuracy of ±2% and ±0.5 m/s, respectively. All sensors undergo periodic calibration to maintain measurement reliability. Short circuit analysis involves selecting fault types (phase-to-ground, phase-to-phase, or three-phase) and coordinating relay settings with analysis results. Transient stability and dynamic analysis include fault simulation scenarios such as generator loss, short circuit, and load shedding employing IEEE standard models of governor control and excitation to simulate voltage and frequency stability. Harmonic and power quality analysis deals with nonlinear load modeling for analysis of harmonics generated by inverters and power electronics and meets IEEE 519 total harmonic distortion (THD) levels.

ETAP (Electrical Transient Analyzer Program) is a powerful power system analysis and simulation software package to design, operate, and automate electrical systems. It provides load flow analysis, short circuit studies, relay coordination, arc flash analysis, and renewable energy integration. ETAP is widely utilized in the power generation, transmission, and distribution sectors to ensure system reliability and efficiency. Its real-time monitoring and forecast analysis features are utilized to maintain optimal performance and prevent failure. With its easy-to-use interface and advanced modeling capability, ETAP is now a popular tool among electrical engineers and power grid operators.

5. SYSTEM PERFORMANCE ANALYSIS AND RESULTS

The microgrid presented has been analyzed based on the system performance by determining how well it integrates and coordinates multiple energy sources, such as wind turbines, PVAs, DGs, and main utility grid configuration. The configuration is developed to supply electrical power reliably in an efficient and loss-minimizing approach while ensuring the utilization of renewable resources. The analysis will focus on power flow, voltage stability, and the overall contribution of renewable energy sources under different operating scenarios. Transformers and transmission cables play an important role in system stability by matching voltage levels and ensuring efficient power transfer between components. Wind turbines operating at a nominal power output of 225 kW and 600 kW are the major contributors to the renewable energy generation of the system. Interfacing these units is done through interfacing low-voltage buses and step-up transformers for compatibility with grid voltage levels. Different characteristics of variable-speed wind generation units are presented for performance analysis to reflect further on the power capability of wind farms supplied under constant power, problems of fluctuating output, or other related negative impacts on the system stability concerns. The load flow analysis indicates how these turbines reduce conventional generating units' consumption, leading to a more sustainable system. Huge value is added by these PVAs, connected to Bus14 via a 0.22 kV network, by harnessing energy from the sun and feeding the same into the grid. In addition, their performance was analyzed in conjunction with solar radiation and their operational contribution to steady system voltage at peak generation periods. The transformer T5 integrates the PVAs with the larger grid infrastructure. These results show the maximum utilization of the PVAs at periods of high solar intensities. This is also seen to substantially reduce fuel consumption from the DG and contribute to a reduction in greenhouse gas emissions. The DG, which serves as a backup and peak load support unit, provides critical power during periods of low renewable generation or high load demand. Its performance is evaluated in scenarios where quick ramp-up is necessary to maintain system balance. Simulation results show its reliability in ensuring the continuity of power supply while minimizing operational hours due to environmental and economic costs. The coordinated generator operation with renewable sources effectively maintains the system frequency and stability for continuous power delivery to the loads.

Voltage regulation across the system is another important aspect of performance analysis in which transformers and capacitors participate. Connecting a capacitor bank CAP1 at Bus2 will assist in compensating reactive power, thus improving the power factor and voltage profiles across the network. It is observed from the study that proper sizing and placing of capacitors avoid voltage drops during high load conditions and maintain the operational efficiency of the system. Furthermore, the load flow analysis shows minimal power losses, emphasizing the system's design and component selection effectiveness.

Integrating the utility grid adds reliability and stability as a backup utility grid. The interconnection of the two circuits at Bus1 enables bidirectional power flow; excess renewable energy export is thus enabled, which draws power in deficit periods. Analysis of the system operating in grid-connected and island modes allows flexibility and resilience.

The DG is a crucial backup in hybrid power systems, ensuring reliability when renewable generation is insufficient. Its dispatch strategy depends on renewable availability, load demand, and grid stability, activating automatically or manually when renewable output falls below a set threshold. Operated in load-following mode to optimize fuel consumption and minimize emissions, the generator adjusts its output to match demand while avoiding unnecessary operation. Effective dispatch planning considers ramp rate, minimum load, and fuel efficiency, ensuring system stability and cost-effectiveness while enhancing grid resilience against renewable energy fluctuations.

Figure 2 shows the system's total active and reactive power components for Phase (A) during July 2024. The blue line in the graph is the active power, which, as seen in this graph, is periodic-oscillating to indicate recurrent fluctuations in demand load throughout the day. The green line represents the reactive power, which has a negative constant value to show inductive load in the system. The periodicity in the source active power, represented by the red line, is similar to that of the load active power but of a higher magnitude. The orange line further reflects reactive power losses, which are small and flat; hence, good system operation with minimum losses in reactive power is depicted. Such fluctuations depict a system that dynamically reacts to the varying demands of the load while balancing it between generation and distribution. Regularities in the pattern suggest stable operating conditions with minimum disturbance within the system. This has become significant in power system management for better energy utilization while ensuring performance in realistic applications.

Figure 3 shows the behavior of the generator, Gen1, regarding active power in MW and reactive power in MVAr for a certain period, starting from July 1, 2024, and ending on July 29, 2024. It is observed that the active power continuously oscillates within a very narrow range of approximately 0.18 to 0.23 MW, while the reactive power inversely oscillates in the range of -0.24 to - 0.19 MVAr. The periodicity of these oscillations indicates a cycle pattern of operation, perhaps caused by load variations or external factors in the generator. Reactive power also shows a negative trend consistent with power systems supplying capacitive loads. The stability of these oscillations over the observation window implies that the regime of operation is controlled, but the peak and trough indicate dynamic behavior that can potentially require further optimization. The analysis lies in the manner in which the active and reactive power is quantified for reliability and efficiency of generator operation. Secondly, the synchronism of the two graphs shows that all active and reactive power are connected for the stability of the total electrical system. Reactive power compensation is required for voltage stability and optimal power systems, and capacitor banks are the standard solution. Located strategically based on load patterns and voltage profiles, capacitor banks reduce generator burden and enhance voltage regulation. Parallel setups are widely applied for local compensation, typically controlled through automatic switching to react to reactive power demand. The appropriate-sized capacitor banks decrease loss and raise efficiency, and adversary sizing will yield overcompensation and overvoltage and thus lead to instability. Careful planning in consideration of reactive power requirements and fluctuating loads is important to ensure effective working and stability within the system.

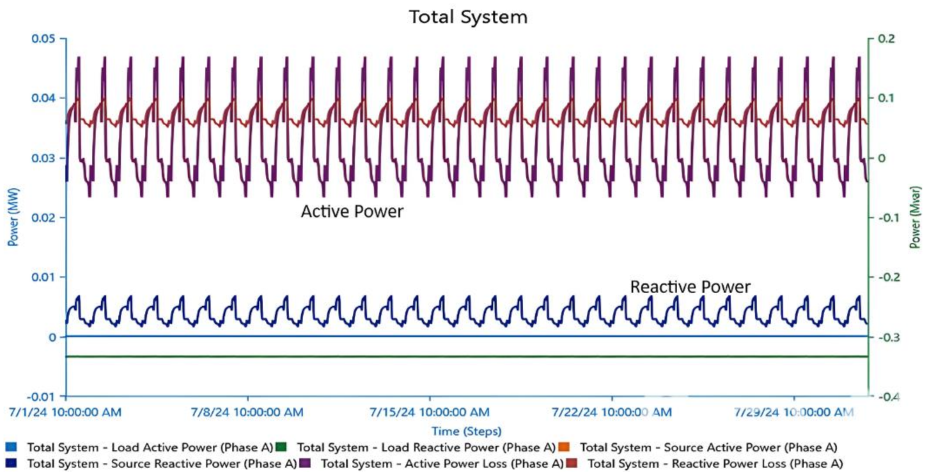

Figure 2. Active and reactive power components behavior of the total system

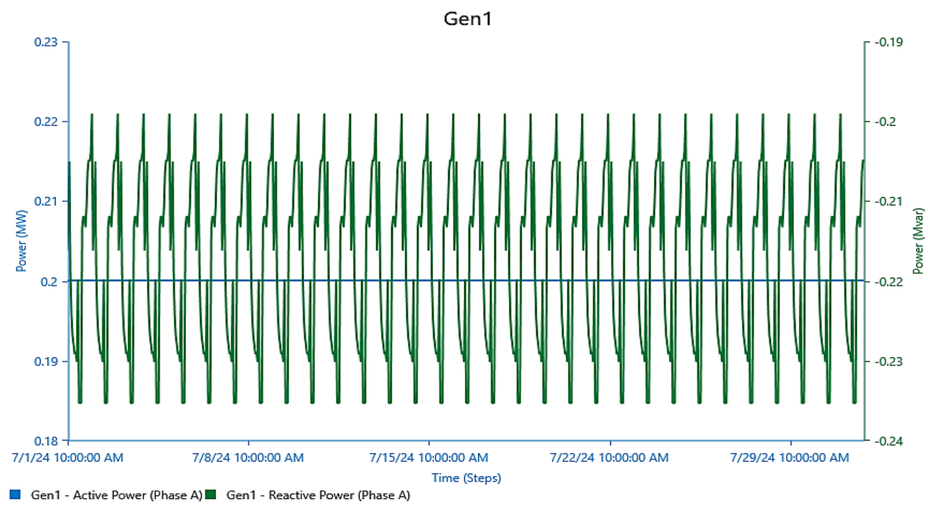

Figure 3. Active and reactive power behavior of Gen1

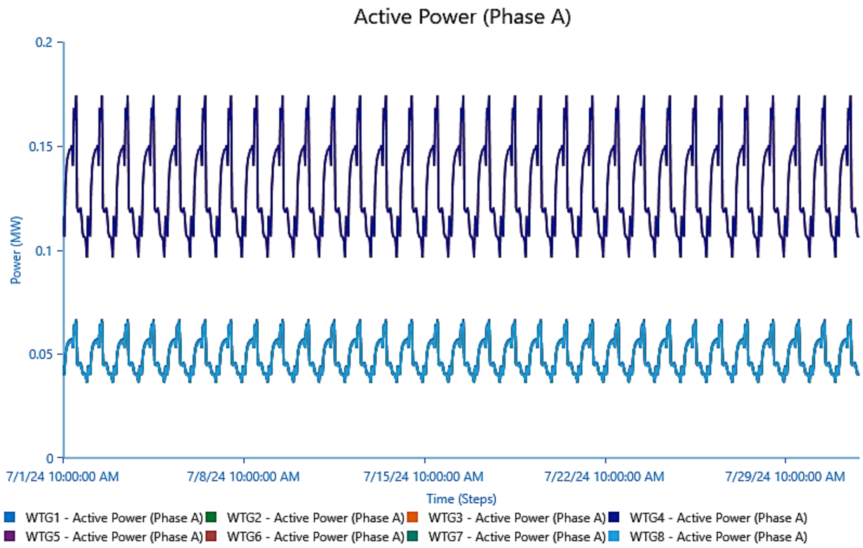

Figure 4. Active power behavior of WTG1-WTG8

Figure 4 represents the active power output for Phase A from eight wind turbine generators. The period extends from July 1, 2024, to July 29, 2024. It can be analyzed that the power outputs reflect periodicity and that the WTGs operate in two distinct output ranges. The first group of turbines, WTG1-WTG4, operates within higher power values that vary around 0.1 MW to 0.2 MW, while the second group, WTG5-WTG8, keeps their power output lower, between 0.03 MW and 0.07 MW. Cyclic behaviour in the fluctuations shows normal environmental effects, such as wind speed or direction changes, are affecting all turbines similarly. The steady ramping between the turbines indicates the system's overall stability. However, a difference in the power outputs of the two sets of turbines might hint at their different capacities, positions, or strategies. It is important to know the variation in knowledge and bring out optimum energy production with improved efficiency at the farm level. The stability of the pattern over the observed period indicates well-maintained equipment, while further analysis can be required for an in-depth investigation and resolution of the observed disparities among the WTGs for maximum energy output.

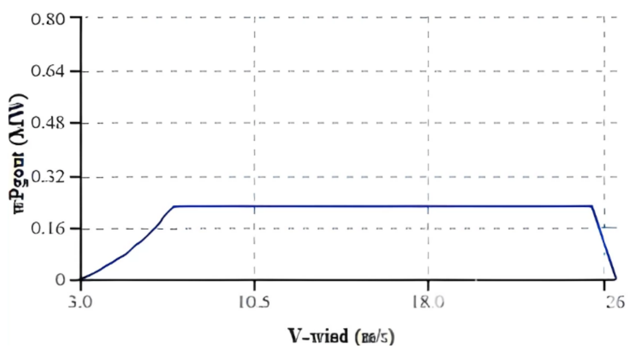

Figure 5. Wind turbine performance

Figure 5 gives the curve of the relation between the parameters. $\lambda_{P_{goor}}$ and V_{wind} , which is one of the most important features of wind turbine performance. Where $\lambda_{P_{goor}}$ is the performance coefficient related to the power generation efficiency of the wind turbine. In wind energy systems, the performance coefficients (λ) measure how well the turbine converts wind energy into mechanical or electrical energy. The subscript P_{goor} refers to a specific aspect of the turbine's operation or power-related metrics, such as power output under particular conditions. V_{wind} denotes the wind speed in meters per second (m/s). Wind speed is one of the most important factors in the performance of a wind turbine since it determines how much energy can be received from the wind. The graph evidences that there is a wide increase in $\lambda_{P_{goor}}$ and V_{wind} while V_{wind} increases from 3 m/s to an almost flat value of around 10.5 m/s, showing the operational area where the system should operate. Beyond this range, the curve falls off steeply at approximately 25 m/s, with a cut-off point that is associated with system protection functions against high wind speeds. All these results show that the turbine will be able to optimize efficiency for a certain range of wind speeds, being safe and reliable under different conditions. This analysis is very critical in the optimization of energy generation in smart grid applications.

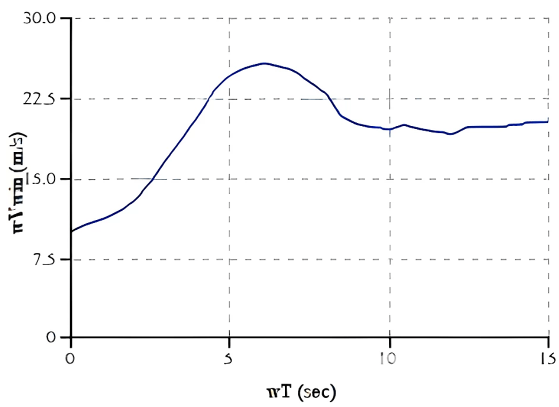

Figure 6. The dynamic response of WTG

The curve provided in Figure 6 indicates the dynamic response of the system to external factors by presenting the trend of wind turbine rotor speed (wT) with respect to time. The rotor speed increases sharply at the beginning and reaches its peak at approximately 5 seconds due to possibly increased wind speed or alteration of operation parameters. The curve stabilizes later, which indicates the ability of the system to adapt and offer reliable performance under varied conditions. The settling in speed smoothness reflects the degree of control mechanisms in the turbine for optimality and reliability of operation. This discussion points to dynamic stability as key to ensuring the optimal performance of wind turbines in sustainable energy generation.

The active power output (Phase A) of six PVAs (PVA1-PVA6) from July 1, 2024, to July 29, 2024, is plotted in Figure 7. All arrays' power output has a clear periodic trend with daily cycles indicating regular solar energy production based on sun availability. The highest power output, which is close to 0.001 MW, overlaps with daytime, and near-zero values overlap with night when solar panels are not in use. This periodicity is due to the dependency of PV systems on day solar radiation. The homogeneity of all the PVAs in structure, direction, and environment is indicated by the comparable output of all the PVAs. The constancy of the day peaks across the month indicates homogeneous weather conditions, such as low cloud cover, to result in consistent energy production. The small power output scale, however, might indicate tiny-scale systems or backup installations rather than a primary source of energy. In this analysis, the necessity of using energy storage technologies or additive power sources to mitigate intermittency and ensure constant power supply in solar power systems is indicated.

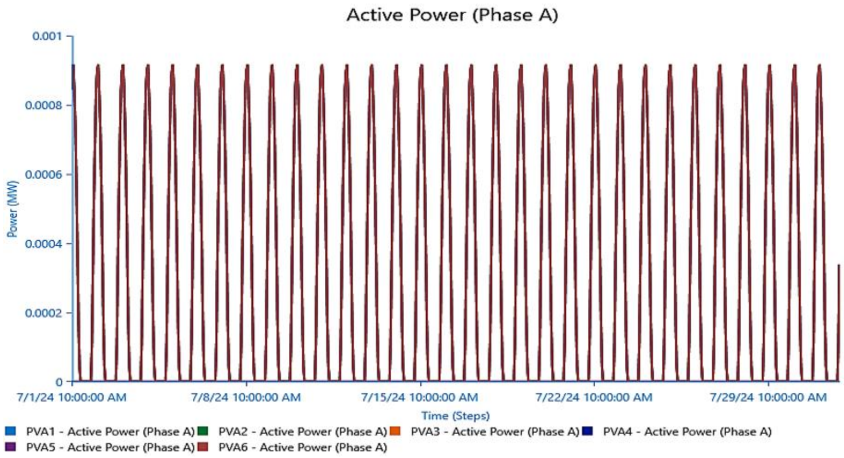

Figure 7. The active power output (phase A) of PVAs (PVA1-PVA6)

Figure 8 illustrates the power output vs. voltage for various operating conditions, presumably corresponding to a range of irradiance or other environmental conditions. Each of these curves possesses a well-defined peak corresponding to the MPP. Power rises rapidly as voltage increases, up to a peak, and then falls off, illustrating the system's nonlinearity.

The discrepancies between the curves reflect the sensitivity of the generated power concerning external parameters and, therefore, require an accurate strategy to operate at MPP. These results improve performance and efficiency in PV or energy conversion systems facing variable conditions.

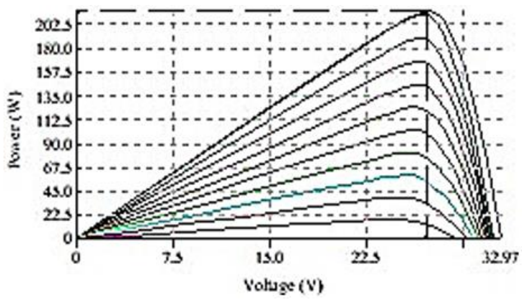

Figure 8. Power-voltage relationship in PV

Table 2. Analysis data of the system

ID	Rating/Limit	Rated kV	MW	Mvar	Amp	% PF	% Generation
Gen1	0.6 MW	0.6	0.6	-0.525	767.2	-75.25	100
Grid 1	597.558 MVA	34.5	-3.001	0.176	50.31	-99.83	-
WTG1	0.225 MW	0.6	0.229	0	223.1	100	102
WTG2	0.225 MW	0.6	0.225	0.1	237.9	91.38	100
WTG3	0.6 MW	0.6	0.6	0	577.3	100	100
WTG4	0.6 MW	0.6	0.6	-0.372	679.2	-85	100
WTG5	0.225 MW	0.6	0.225	0	214.5	100	100
WTG6	0.225 MW	0.6	0.225	0	213.4	100	100
WTG7	0.225 MW	0.6	0.225	0	210.5	100	100
WTG8	0.225 MW	0.6	0.225	0	209.1	100	100
PV1-PV6	22 5KW	0.22	0.225	0	1022.73	100	~16.67
CAP1	1000 KVAr	4.16	0	1	138.99	0	100

Table 2 illustrates the proposed power system data analysis and discloses essential aspects related to the performance and stability of the grid and its components. Gen1 is the main generator, and it operates with a power factor of -75.25%, indicating high consumption of reactive power and possible system instability. Conversely, WTGs are highly effective with well-matched power factors: WTG1 and WTG3 operate at 100% PF and show consistent active power output. Grid 1 presents a power factor close to zero (-99.83%), which suggests that this grid is either delivering or consuming very little active power while supplying a lot of reactive power. Such a situation may involve sophisticated control strategies or reactive power compensation. The discrepancies in the current magnitude of the WTGs-for instance, 577.3 A in WTG3 and 210.5 A indicate variations in either load conditions or cable configurations. The data also shows that stability in the system is key, as negative values of reactive power, like -0.525 MVar in Gen1, may lead to voltage regulation issues. This analysis, therefore, calls for advanced monitoring and dynamic control mechanisms to ensure efficiency and reliability within grid operations.

The table details the rating and operational parameters of the various power generation sources and other grid system components. The data included are rated capacity, voltage, active and reactive power outputs, current, power factor, and percentage of generation. These parameters will indicate the performance and functionality of each component and its contribution to the system.

Gen1 operates at a capacity of 0.6 MW but at an impressively low power factor of -75.25%, depicting this generation unit's heavy consumption of reactive power, which is typical in certain types designed for specific grid-support roles. Grid 1 has a rating of 597.558 MVA and, nevertheless, exhibits little demand for reactive power, 0.176 Mvar. Thus, it is a strong supply source, bringing stability to the network.

The WTGs have relatively steady active power output, close to their rated values. For example, WTG3 and WTG4 are rated at 0.6 MW each; they operate with full active power output. However, WTG4 has a reactive power consumption of -0.372 Mvar, resulting in a lower power factor of -85%. This probably means that this WTG is compensating for the demand for reactive power in the overall system for voltage regulation at the grid level.

Smaller WTGs, such as WTG1, WTG2, and WTG5-8, operate at or near their rated capacities at power factors of 100%, efficiently converting the captured wind energy into electrical power. On the other hand, the power factor for WTG2 is 91.38% since the generated reactive power is 0.1 Mvar, showing its double role of active and reactive power supply.

The result reveals the generating units' manifold contribution, ranging from the bulk supply of active power to providing reactive power compensation. Because of stability and efficiency in the power grid, it is necessary to balance both active and reactive power contributions. A quantitative measure of the overall system efficiency is required in order to develop an appreciation of the performance of the hybrid power system, particularly in terms of energy utilization efficiencies and system losses. A power system's efficiency is typically established by comparing the quantity of useful energy output to the load and the total energy input, founded on all generating sources and losses in the system. Rates of energy utilization can be found here by analyzing the percent of the energy produced from renewable sources, i.e., the wind turbine and PV plant, that is effectively used toward load demand fulfillment. Each generation source's energy conversion efficiency has to be considered because both renewable and backup sources take part in overall system performance.

The paper highlights the dual role of generating units in supplying active power and compensating reactive power, both of which are crucial for grid stability and efficiency. Active power sustains system frequency, while reactive power stabilizes voltage levels and power factors. Their imbalance can lead to voltage instability, efficiency losses, and equipment damage. Real-time monitoring via SCADA and adaptive control algorithms is thus essential for power balance and optimal grid operation.

6. CONCLUSION

The system analysis emphasizes the efficient integration of renewable energy resources, conventional generators, and novel power management strategies to optimize the operating performance of the hybrid power system. The synchronized operation of WTGs, and the grid helps in efficient active power balancing and reactive power balancing for varying load conditions. The wind turbines are efficient with minimal power fluctuation of reactive power, affirming that they are an efficient and reliable source of the energy mix as a whole. The PVAs reflect a distinct trend of generation coinciding with solar irradiance and providing energy needs effectively during maximum periods. Stabilization of the system lies with the main grid, regulation of power imbalance, and making the system reliable. Nevertheless, dynamic optimization of reactive power in the grid remains an area for improvement.

Capacitor banks are employed to perform a crucial function in reactive power compensation, voltage regulation, and system power factor correction. The system's transformers suffer low losses when transferring energy across voltage levels. There is scope for improving the interaction between active and reactive powers, particularly in sections like Generator 1 and Grid 1, where the analysis must be carried out to minimize losses and increase the overall stability of the system.

While the system shows immense resilience and versatility, which are so fundamental to contemporary grid planning, it is evident that strategic upgrades are required to maximize the performance of the system to the ultimate potential. Ongoing monitoring and the use of sophisticated control algorithms are vital to guaranteeing consistent operational efficiency and dependability. The study points out the prospect of such hybrid energy systems to be a prototype for the future of efficient and sustainable power grids.

In the future, studies can focus on improving the integration of energy storage systems and developing more efficient control strategies to manage the uncertainty of renewable energy sources. Optimization of reactive power management and minimization of system losses could further improve the efficiency of the system. In addition, research on the potential of smart grid technologies and their utilization in dynamic control and real-time monitoring could provide valuable inputs towards the creation of energy systems. Lastly, this study provides a good foundation for the creation of sustainable, efficient, and resilient power systems, and it offers promising areas of research for future studies in the field of smart grid technology and hybrid energy systems.

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