Research Article

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Voltage Profile Improvement in a Renewable Energy Based Hybrid Distribution System

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ABSTRACT

The integration of high photovoltaic (PV) and wind penetration into distribution networks is an important strategy for improving voltage performance while supporting cleaner and more sustainable electricity generation. This study evaluates a 33 kV, 14-bus distribution feeder to assess the influence of distributed generation (DG) on voltage regulation, reactive power management and network performance using ETAP software. The proposed hybrid configuration combines PV panels, wind turbines and strategically placed capacitors to address reactive power demand and reduce distribution losses. Particular attention is given to the voltage profile and power factor under the proposed renewable-energy configuration. The Adaptive Newton-Raphson method is employed to provide an efficient load-flow assessment of the distribution system. The study demonstrates how renewable distributed generation can contribute to improved power quality and more efficient utilization of distribution infrastructure. The findings also indicate opportunities for future integration of nano-enabled photovoltaic materials, nanostructured energy-storage components and advanced smart-grid technologies to further enhance renewable-energy conversion, environmental sustainability and grid performance. The framework therefore offers an environmentally relevant basis for future nano-enhanced renewable power conversion, storage and sensing in intelligent distribution networks and microgrids.

Keywords: ETAP; Distributed generation (DG); Photovoltaic (PV); Nano-enabled renewable energy; Load flow analysis.

1. INTRODUCTION

Energy demand continues to increase with urbanization, industrial development and the expansion of modern electrical services. Meeting this demand while reducing environmental pollution requires a transition from conventional generation toward renewable and distributed energy resources. Hybrid renewable energy systems that combine photovoltaic (PV) and wind generation can improve the utilization of locally available resources and reduce dependence on fossil-fuel-based electricity. Their integration at the distribution level can also reduce transmission requirements and support cleaner electricity delivery. However, the intermittent nature of solar and wind generation, together with the reactive power requirements of distribution loads, can produce voltage deviations and operational constraints. Therefore, systematic assessment of voltage regulation, power flow and power quality is essential when renewable distributed generation is introduced into existing networks. The environmental benefits of renewable integration can be strengthened further through emerging nano-enabled photovoltaic materials, nanostructured coatings and advanced energy-storage technologies that have the potential to improve conversion efficiency, durability and resource utilization.

A major challenge in renewable-rich distribution systems is maintaining acceptable voltage levels under changing generation and load conditions. Reactive power compensation, converter control and coordinated operation of distributed resources are consequently important for reliable network performance. Recent studies have examined coordinated control of On-Load Tap Changers (OLTCs), photovoltaic systems and converter-driven loads to improve voltage profiles in systems with high renewable penetration Zhang *et al.* (2022). Other approaches have considered the integration of wind generation, photovoltaic generation and reactive-power support through Flexible Alternating Current Transmission Systems (FACTS) devices, demonstrating the importance of coordinated control for voltage management (Ali *et al.* 2022). Optimization of OLTCs, photovoltaics and converter-based loads has also been investigated as a means of improving voltage regulation under variable operating conditions (Zhang *et al.* 2022). Dynamic voltage restorers have been proposed to detect and compensate voltage disturbances, providing another route for improving power quality in renewable-integrated networks (Kumari *et al.* 2022). Intelligent optimization approaches have likewise been applied to hybrid solar/wind distribution grids to address voltage-limit violations, feeder losses and power-factor degradation (Bhatt *et al.* 2022). Optimal distributed-generation

allocation using atom-search optimization has been reported for radial and weakly meshed networks, with the objective of reducing losses while improving voltage performance (Tahiliani *et al.* 2022). Multi-objective optimization approaches combining evolutionary and population-based algorithms have further demonstrated the value of coordinated renewable-resource placement and network control (Ali *et al.* 2022).

The distribution network is also affected by the characteristics of consumer loads. Many domestic and commercial appliances behave as inductive loads and therefore absorb reactive power, contributing to voltage drops and inefficient power transfer. The increasing penetration of distributed generation can alter fault currents, voltage profiles and short-circuit levels, making detailed network assessment necessary before interconnection. Studies of hybrid renewable-energy systems have examined their influence on short-circuit conditions and the suitability of distributed generation for network operation (Afifi *et al.* 2014). The effect of doubly fed induction generator wind turbines on short-circuit levels has also been investigated using ETAP-based distribution-network simulations (Afifi *et al.* 2013). Photovoltaic systems can provide decentralized electricity for residential and commercial applications, while appropriate placement of renewable resources and capacitors can improve voltage levels and support continuity during disturbances (Abdulkareem *et al.* 2014). Within this context, the present study investigates a hybrid renewable-energy distribution system consisting of PV panels and wind turbines integrated into a 33 kV, 14-bus network. ETAP is employed for load-flow analysis using the Adaptive Newton-Raphson method. The study focuses on the influence of distributed generation and capacitor placement on voltage regulation, reactive-power balance, active-power transfer and power factor. The proposed configuration is intended to improve the voltage profile while reducing distribution losses and making better use of renewable resources. Although the present work is based on electrical-network simulation rather than direct nanomaterial experimentation, its renewable-energy framework provides a relevant platform for future incorporation of nano-enabled PV devices, nanostructured energy-storage elements and advanced sensing technologies. Such integration could potentially improve energy conversion, storage efficiency and environmental performance in future smart distribution systems. The analysis therefore links renewable-energy integration and grid optimization with broader opportunities for sustainable and nano-enabled energy technologies. Nano-enabled energy technologies are relevant to the development of renewable systems because nanoscale engineering can modify optical, electrical, thermal and interfacial properties of materials. In photovoltaic applications, nanostructured absorbers, coatings and interfaces may improve light management and charge transport, while nano-engineered materials can support devices. Similar approaches may contribute to electrodes and other components used in energy-storage systems. From an environmental perspective, improved conversion and storage efficiency may reduce material and energy requirements per unit of useful electricity, although life-cycle impacts, resource demand and end-of-life management of nano-enabled components must be considered. These considerations make electrical-system analysis valuable because improvements at the device level need to translate into reliable network performance. Intelligent monitoring, communication and control are transforming distribution systems into smarter and more adaptive networks. Sensors, power-electronic converters and controllers can provide information for voltage management, fault identification and demand-side coordination. When combined with renewable generation, these technologies can improve the utilization of locally generated electricity and support resilient operation during disturbances. Nano-enabled sensors and advanced materials may provide opportunities for compact monitoring and energy harvesting. Nevertheless, the present study is limited to ETAP-based load-flow assessment and does not experimentally evaluate nanomaterials or nano-devices. The nano-oriented perspective is therefore a future technological extension. This distinction defines a practical pathway from renewable generation and grid optimization toward environmentally responsible, nano-enabled energy infrastructure.

2. HYBRID NETWORK

In this task, the aggregate of the solar PV panel and wind turbine are used for hybrid renewable power belongings. Using this renewable electricity resources to enhance the voltage degree inside the distribution network. In Solar energy is generating the power although the sun radiant slight and warmth. Solar energy is categorized into two main types: solar thermal and solar power. Solar thermal utilizes direct sunlight as a source of heat energy to generate hot water and fulfill household needs. On the other hand, solar power harnesses photovoltaic technology to convert sunlight into electricity. Photovoltaic systems are adept at transforming solar radiation into electrical energy efficiently, making them a preferred choice in this project. The photovoltaic (PV) panel functions as a semiconductor apparatus, converting solar radiation into electrical power (Afifi *et al.* 2014). Typically, it's miles few inches in period and produces about 1 Watt of electricity. In order to generate high power, PV cells are grouped in series and parallel circuits to shape a PV module. Hence, numbers of PV modules are electrically related in a chain-parallel configuration to generate the required cutting-edge and voltage. The PV array output electricity is stricken by the going for walks conditions and the net website online conditions inclusive of geometric location, irradiance level, and ambient temperature.

The mechanism of solar panels interlinks with the electrical grid in the ensuing way:

- As sunlight cascades upon the solar panels, they initiate the generation of direct current (DC) electricity.
- This DC electrical energy is conveyed into a solar inverter, which transfigures it into alternating current (AC) electricity at 240 V and 50 Hz.
- The 240 V AC electrical power is utilized to animate appliances within your dwelling.

In instances of sunlight exposure, including overcast conditions, the solar cells produce electrical energy. The grid-interconnected inverter alters the DC strength generated via the solar panels into 240 V AC power, that's then available for usage by the premises. In instances in which a grid-related gadget surpasses energy consumption, the excess energy is directed into the number one strength grid. Certain electricity providers meter the electricity contributed to the grid by your setup and issue a credit on your bill accordingly. The remuneration amount is contingent on the feed-in tariff. During periods of solar cell dormancy, such as nighttime, regular power is furnished by the primary power grid. The energy provider levies the standard rate for the electricity consumed. Given that all components of a grid-connected system lack movable parts, one can anticipate an extended and hassle-free operational lifespan from their solar energy system. Substantial governmental solar incentives and rebates facilitate considerable savings on a grid-connected system for a specified duration. The various stages in the design of PV based system is shown in Fig 1.

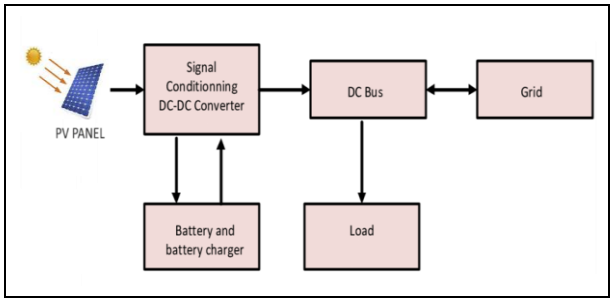


Fig. 1: Various stages in the design of PV panel-based system

Within the sector of wind turbines lies the tricky approach via which wind is harnessed to generate electricity. Wind generators, in essence, transmute the kinetic electricity inherent inside the wind into mechanical energy. Through the utility of a generator, this mechanical electricity may be in addition transmuted into strength. Alternatively, mechanical strength can be directly hired for precise undertakings, together with water pumping. The United States Department of Energy (DOE) has produced a concise animation elucidating the principles underlying wind electricity technology, thereby presenting a comprehensive expertise of wind turbine capability and the wind sources available across the US. Wind, a phenomenon spurred by the asymmetrical heating of the environment with the aid of the solar, the various topography of the Earth's floor, and the rotational movement of the planet itself, serves as the impetus for wind turbine operation. Various geographical features, consisting of mountains, bodies of water, and vegetative formations, exert impact upon the patterns of wind waft.

Wind mills harness the energy latent in the wind by means of propelling blade-like structures round a vital rotor. The rotational movement of the rotor impels the pressure shaft, thereby driving an electric generator. The efficacy of a turbine in harnessing wind energy is contingent upon 3 pivotal elements: wind velocity, air density, and the surface vicinity encompassed through the turbine blades. The equation governing wind electricity is expressed as follows:

$$P = ½ \rho A V^3 \quad (1)$$

2.1 Wind speed

The magnitude of energy within the wind is subject to fluctuations corresponding to the cubic function of wind velocity; put differently, if wind velocity undergoes a twofold increase, the energy within the wind escalates eightfold ($z^3 = 2 \times 2 \times 2 = 8$). Even minor alterations in wind velocity yield substantial ramifications on the available power potential within the wind.

2.2 Density of the air

The greater the density of the atmosphere, the higher the quantum of energy intercepted by the turbine. Atmospheric density is contingent upon factors such as altitude and temperature. At elevated altitudes, air tends to be less dense compared to sea level, and warm air exhibits lower density relative to cold air. All other factors held constant, turbines are poised to yield heightened power outputs when situated at lower elevations and in locales characterized by cooler mean temperatures. Owing to the influence of wind, the turbine initiates rotational motion driven by kinetic energy. This turbine, in turn, is linked to a generator via a shaft facilitated by a gearbox. The generator, in its operation, produces electrical energy which is subsequently integrated into the grid network. Notably, wind turbines have the capability to generate reactive power, which serves to offset the consumption of reactive power by

loads within the distribution network. However, a significant drawback is encountered in the form of its potential interference with military security radar systems.

3. EXISTING SYSTEM

Conducting a load glide evaluation at the IEEE 14-bus distribution take a look at gadget includes utilizing the ETAP software program as a simulation tool. This machine incorporates a novel generator and 14 bus gadgets within the network. Through this setup, diverse parameters inclusive of voltage regulation, actual and reactive electricity, and power element are scrutinized. Employing ETAP software program allows an in-intensity examination of load drift dynamics across the distribution community. Initial observations screen a suboptimal nation in which voltage regulation on the bus nodes is notably poor, observed with the aid of a decline in energy component. Addressing these issues necessitates the method of solutions geared toward enhancing voltage law and power issue. The single-line diagram depicting the existing system is illustrated in Fig. 2.

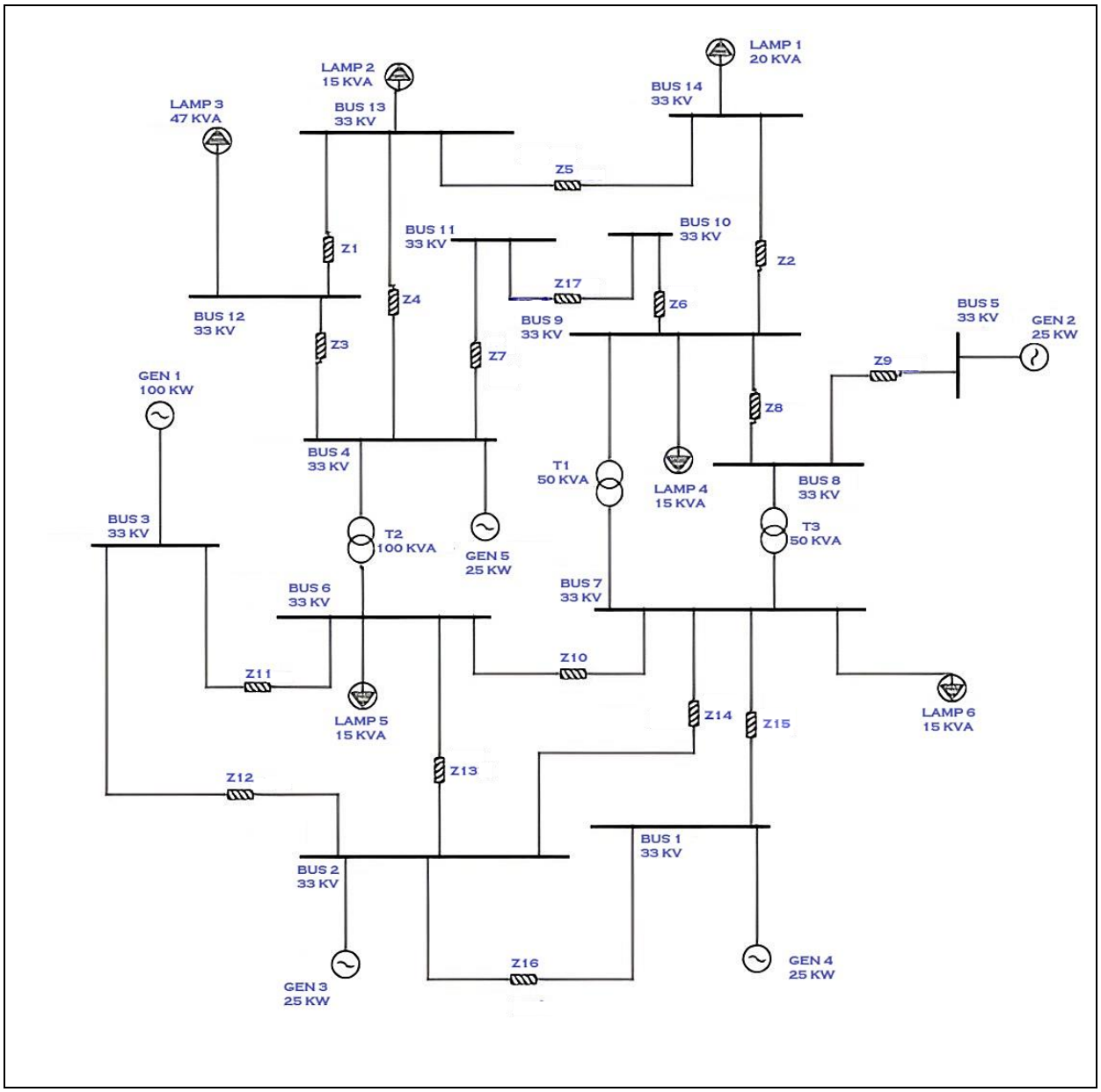


Fig. 2: Single Line Diagram of the IEEE 14-Bus Distribution System (Existing system)

4. PROPOSED SYSTEM

The primary objective of this proposed system revolves around enhancing voltage stability and power factor within the distribution network. In contemporary times, consumers predominantly rely on inductive loads, resulting in the absorption of reactive power from the distribution system and subsequent voltage degradation. Addressing this problem entails the injection of reactive electricity into the community, executed with the aid of integrating capacitors into the distribution gadget. Additionally, the incorporation of renewable power assets together with PV panels and wind turbines serves to mitigate transmission losses within the gadget.

There are six sources of power generation, one synchronous generator it must be used as slack bus, two PV panels and three wind turbines are used in this distribution system. There are three rating of transformers are used 100 KVA, 50KVA, 50KVA and the output is connected with the Loads. There are six different lumped loads are connected in the 14-bus test.

In this network there are five sources are used to reduce the losses in the network and four capacitors have been used to improve the voltage level in the distribution feeder. The single line diagram of the proposed hybrid system is shown in Fig 3.

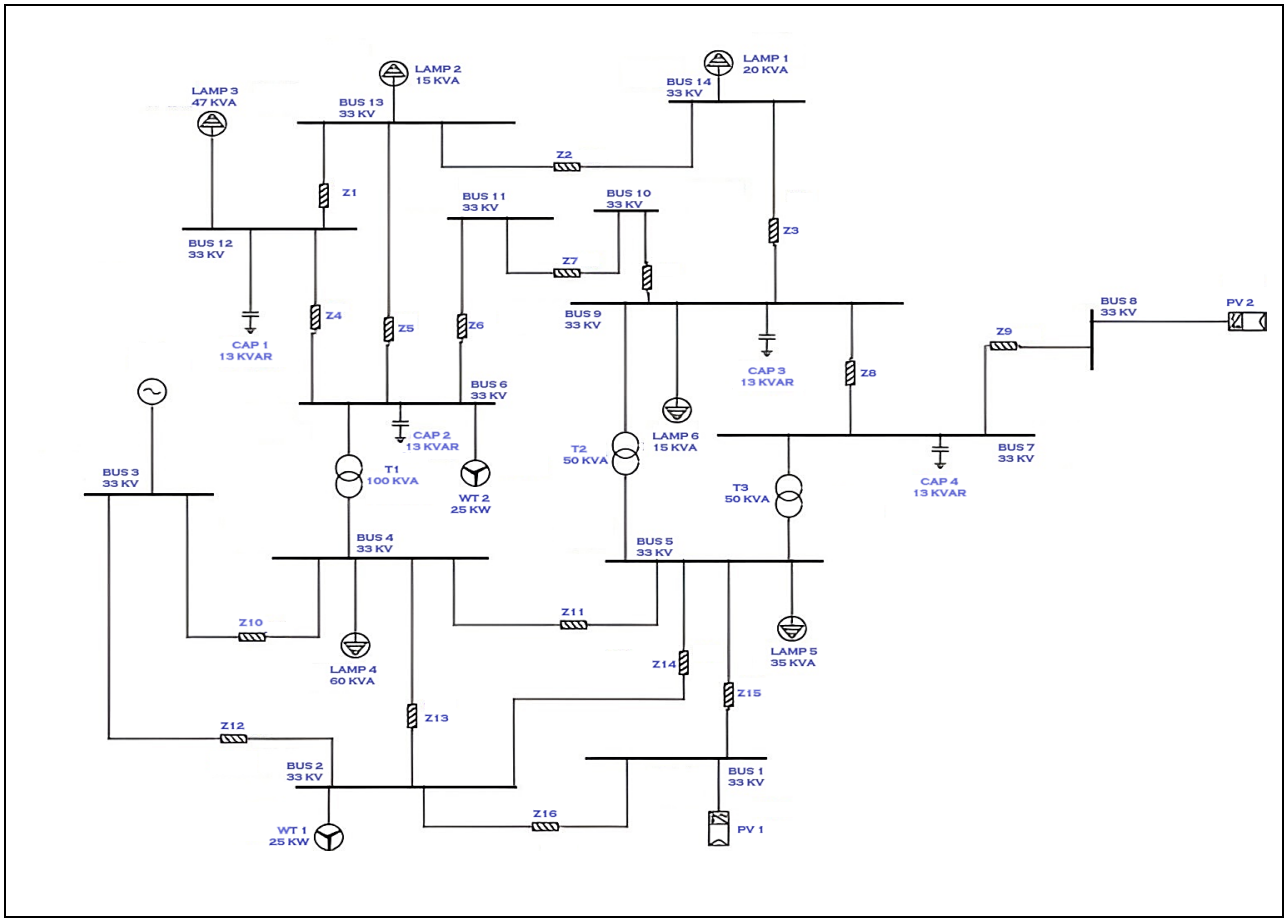


Fig. 3: Single line diagram of hybrid system using ETAP software

Table 1. Capacitor ratings

Capacitor	KVAR	Bus
Capacitor 1	13	6
Capacitor 2	13	7
Capacitor 3	13	9
Capacitor 4	13	12

In the both solar panels are YINGLI manufacture, YL 280 P-35b at 1000 max Vdc, 185 size(w), 7.64 imp(A) and 8.27 Isc (A). Cells are 10 in series and 1265 in parallel. Synchronous Generator was used as a swing. In the realm of contemporary power system simulation, ETAP emerges as a cutting-edge software solution, amalgamating both standard and advanced models to facilitate the meticulous modeling and simulation of diverse power systems. ETAP stands

out by offering a comprehensive array of analyses, encompassing Load Flow, Short Circuit, Arc Flash, Transient Stability, and more. Notably, within this network configuration, four capacitors have been strategically integrated and its ratings are shown in Table 1.

5. SIMULATION RESULT

The final results of the Existing and Proposed system are tabulated in Table 2 and Table 3. The burden flow evaluation for the hybrid gadget is revealed through the usage of ETAP software program. In this state of affairs, upgrades in voltage ranges throughout the distribution network are executed by way of integrating hybrid renewable power sources with capacitors. Within the distribution network, the absorption of reactive strength because of inductive hundreds necessitates the usage of wind energy and capacitors to strengthen reactive energy levels, facilitated through the ETAP simulator software.

Table 2. Existing system report

FROM BUS	TO BUS	KW	KVAR	VOLTAGE REGULATION	I (AMPS)	POWER FACTOR (%)
Bus 1	Bus 2 Bus 5	3.622 21.378	-10.110 10.110	99.992	187.9 413.8	62.6 90.4
Bus 2	Bus 3 Bus 1 Bus 5 Bus 4	-24.039 -3.622 26.510 26.150	-33.478 9.823 13.995 9.660	99.993	721.1 183.2 524.5 487.8	58.3 63.7 88.4 93.8
Bus 3	Bus 4 Bus 2	58.470 24.040	41.168 33.242	100	1251.1 717.7	81.8 58.6
Bus 4	Bus 3 Bus 2 Bus 5 Bus 6	-58.467 -26.150 -0.180 17.543	-41.349 -9.862 17.088 24.073	99.990	1253.0 489.0 299.0 521.2	81.6 93.6 68.7 58.9
Bus 5	Bus 2 Bus 1 Bus 4 Bus 9 Bus 7	-26.510 -21.378 0.180 8.767 8.734	-14.179 -10.377 -17.158 12.023 12.012	99.989	526.0 415.8 300.2 260.4 259.9	88.2 90.0 41.8 58.9 58.8
Bus 6	Bus 12 Bus 13 Bus 11 Bus 4	12.673 33.817 -3.971 -17.529	12.622 13.998 -3.656 -22.964	96.956	322.8 660.4 97.4 521.2	70.9 92.4 73.6 60.7
Bus 7	Bus 9 Bus 8 Bus 5	33.722 -25.000 -8.722	11.459 0.001 -11.460	96.961	642.6 541.1 259.9	94.7 100.0 60.6
Bus 8	Bus 7	25.000	0.000	96.961	541.1	100.0
Bus 9	Bus 10 Bus 14 Bus 7 Bus 5	3.971 26.042 -33.722 -8.754	3.656 10.923 -11.456 -11.469	96.959	97.4 509.6 642.6 260.4	73.6 92.2 94.7 60.7
Bus 10	Bus 9 Bus 11	-3.971 3.971	-3.656 3.656	96.958	97.4 97.4	73.6 73.6
Bus 11	Bus 6 Bus 10	3.971 -3.971	3.656 -3.656	96.956	97.4 97.4	73.6 73.6
Bus 12	Bus 13 Bus 6	-28.288 -12.673	-10.428 -12.620	96.949	544.1 322.8	93.8 70.9
Bus 13	Bus 12	28.289	10.430	96.954	544.1	93.8
Bus 14	Bus 6 Bus 14 Bus 9 Bus 13	-33.817 -7.080 -26.041 7.081	-13.997 -4.559 -10.922 4.559	96.956	660.4 152.0 509.6 152.0	92.4 84.1 92.2 84.1

6. CONCLUSION

This study evaluated the IEEE 14-bus distribution network using ETAP to examine the effect of integrating photovoltaic and wind-based distributed generation with capacitor support. Comparison of the existing and proposed configurations indicates that hybrid renewable generation can improve voltage regulation, reactive-power management, power factor and overall distribution performance under the

investigated operating conditions. Strategic placement of renewable sources and capacitors reduced network losses and improved the voltage profile, with the proposed configuration producing particularly strong performance around the weaker buses. These results demonstrate the value of combining renewable distributed generation with coordinated reactive-power compensation for cleaner and more reliable electricity distribution.

The findings are also relevant to the broader development of sustainable and nano-enabled energy systems. Future photovoltaic technologies based on nanostructured absorbers, nano-engineered interfaces and advanced functional coatings could potentially increase energy-conversion efficiency and improve the utilization of solar resources. Similarly, nanostructured electrodes and other nano-enabled components may support higher-performance energy storage for balancing the intermittency of renewable generation. Advanced nano-enabled sensors could further contribute to distributed monitoring, fault detection and intelligent control in smart-grid environments. Such technologies should, however, be assessed through life-cycle, environmental and safety considerations before large-scale deployment under diverse climatic conditions. The present work is limited to electrical-network simulation and therefore does not directly evaluate nanomaterials, nano-devices or their environmental impacts. The proposed nano-oriented extensions should consequently be treated as future research directions. Subsequent studies can combine ETAP-based network optimization with experimental evaluation of nano-enabled PV materials, energy-storage systems and sensing technologies to establish links between material-level performance and grid-level benefits. Further work can also investigate additional renewable sources, larger distribution networks, demand-side management, IoT-based monitoring, fault restoration and adaptive smart-grid control. Extending the analysis to life-cycle assessment and techno-economic evaluation would help determine whether nano-enabled components provide measurable environmental and operational advantages for practical deployment scenarios. Such integrated approaches could support resilient, resource-efficient and environmentally responsible distribution systems while strengthening the practical connection between renewable-energy engineering and environmental nanotechnology.

Table 3. Proposed system report

FROM BUS	TO BUS	KW	KVAR	VOLTAGE REGULATION	I (AMPS)	POWER FACTOR (%)
Bus 1	Bus 2	3.865	-8.976	99.994	171.0	95.5
	Bus 5	23.124	8.976		434.0	93.2
Bus 2	Bus 3	-25.492	-22.767	99.995	598.0	74.6
	Bus 1	-3.865	8.689		166.4	60.2
	Bus 5	28.492	12.019		541.1	92.1
	Bus 4	3.858	0.200		67.6	99.9
Bus 3	Bus 4	73.999	20.762	100	1344.6	96.3
	Bus 2	25.492	22.531		595.2	74.9
Bus 4	Bus 3	-73.995	-20.942	99.992	1345.5	96.2
	Bus 2	-3.858	-0.218		67.6	99.8
	Bus 5	-5.408	3.643		114.1	82.9
	Bus 6	16.008	7.467		309.1	90.6
Bus 5	Bus 2	-28.498	-12.203	99.991	542.4	91.9
	Bus 1	-23.123	-9.243		435.7	92.9
	Bus 4	5.408	-3.649		114.2	82.9
	Bus 9	8.008	3.717		154.5	90.7
	Bus 7	7.998	3.699		154.2	90.8
Bus 6	Bus 12	18.118	17.167	99.034	279.7	99.2
	Bus 13	31.693	4.612		565.8	99.0
	Bus 11	-4.811	-4.503		116.4	73.0
	Bus 4	-15.999	-7.077		309.1	91.5
Bus 7	Bus 9	10.992	19.200	99.042	390.8	49.7
	Bus 8	-2.999	0.000		53.0	100.0
	Bus 5	-7.993	-3.505		154.2	91.6
Bus 8	Bus 7	2.999	0.000	99.042	53.0	100
Bus 9	Bus 10	4.811	4.503	99.038	116..4	73.0
	Bus 14	26.721	10.072		504.5	93.6
	Bus 7	-10.992	-19.199		390.8	49.7
	Bus 5	-8.004	-3.522		154.5	91.5
Bus 10	Bus 9	-4.811	-4.503	99.036	116.4	73.0
	Bus 11	4.811	4.503		116.4	73.0
Bus 11	Bus 6	4.811	4.503	99.035	116.4	73.0
	Bus 10	-4.811	-4.503		116.4	73.0

Bus 12	Bus 13 Bus 6	-26.336 -14.625	-0.192 -7.166	99.031	474.2 279.7	100.0 89.2
Bus 13	Bus 12	26.843	0.193	99.033	474.2	100.0
Bus 14	Bus 6 Bus 14 Bus 9 Bus 13	-31.692 -7.759 -26.720 7.759	-4.611 -3.708 -10.071 3.708	99.035	565.8 151.9 504.5 151.9	99.0 90.2 93.6 90.2

SCOPE FOR FUTURE STUDY

The conception of a self-repairing power grid capable of anticipatory response to disturbances holds promise for elevating system dependability and customer contentment in forthcoming power networks. This research endeavors to pioneer novel methodologies and apparatuses in this realm, fostering the capacity of expansive national infrastructures to autonomously rectify in the face of hazards, material deficiencies, and other destabilizing factors. Against the backdrop of burgeoning global concern for energy governance and preservation, diminutive energy regulators the Internet of Things (IoT) are poised to propagate the advantages of interconnectedness beyond the precincts of dispensation, automation, and surveillance currently overseen by utility purveyors. Oversight systems tailored for domestic and commercial usage will empower consumers to scrutinize their energy consumption and modulate their behaviors an endeavor known as Demand Side Management (DSM). These frameworks will gradually evolve to effectuate automatic regulation, functioning during periods of minimal energy demand and interfacing with sensors to monitor occupancy, luminance levels, and sundry other parameters. Yet, the genesis of this paradigm shift lies in the establishment of a smarter, more interlinked grid.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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