

Network-driven hybrid control for smart grids communications with renewable energy integration

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Abstract

This article presents a comprehensive simulation framework for performance analysis of hybrid monitoring and control systems in power grids. The model integrates the dynamics of the power grid and the communication network to deal with how these two interact and the effects that arise due to the interactions between them. The framework is demonstrated on a 15-node MATLAB-based simulation of generation stations, substations, industrial and residential loads, and renewable energy sources, with a real-world topology. The simulation incorporates profiles of daily loads, renewable generation profiles, and various forms of system disturbances, and a distributed control system that considers the delay of communication and the loss of packets. Verify the framework with simulations of voltage drops, load surges, generation losses, and cyber-attacks, and examine their impact on system performance based on the Voltage Quality Index, Frequency Quality Index, and Communication Reliability Index. Findings show that communication performance contributes greatly to control performance, particularly when there is a cyber event characterized by high voltage-quality degradation. The suggested framework will offer a guide that a smart grid planner will use to determine resilience and develop the respective strategies, optimize communication infrastructure, and continue to introduce renewable energy into future power systems.

Keywords: Smart grid; Hybrid monitoring; Control systems; Communication networks; Cyber security; Renewable energy integration; Power system dynamics; Network congestion; Distributed control; Performance metrics; Broadband communication; Simulation framework.

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1. Introduction

The adoption of smart grids as a replacement for conventional power systems presents new challenges because it entails integrating power systems with information and communication technologies [1]. This evolution is not only better in terms of monitoring and control but also introduces dependencies with the resultant failures to diffuse across domains [2]. Modern electrical grids increasingly depending more and more on real-time

monitoring and control over the lines over communication networks and hence the stability and security of such communication links is of utmost importance in ensuring stability and resilience of the grids [3]. Recent progress in the penetration of renewable energy, distributed generation, and demand-side management would make the task of grid operators even more challenging introducing uncertainties and two-way flow of power [4]. The changes need stronger monitoring and control mechanisms that are capable of reacting fast to variable conditions whilst maintaining the stability of the system [5]. In addition, the broadband communication methods employed to attain this high-level control create a spectrum of performance-related problems, such as congestion, delay, packet drop, and cyber threats on the network [6]. Simulation frameworks must be capable of modeling both the electrical dynamics of power grids and the network of communication that operates and monitors them to model such complex interactions [7]. They are essential to simulate how the system will respond to various perturbations, analyze the quality of control strategies, and discover weaknesses (either to communication outages or to cyber-attacks) [8]. This paper aims to propose a generic environment for the hybrid monitoring and control systems of the electric power network using the technology of wide-area communication. The model is a time-varying load profile, renewable power generation, a heterogeneous 15-node power grid, and a realistic network topology. It simulates conditions in the communication systems, such as bandwidth, latency, packet loss, and network congestion. These properties are incorporated in the distributed control system, which enables the examination of the effectiveness of control and takes into consideration such properties.

The most important contributions of this paper are:

1. Elaboration of a sophisticated simulation model combining the dynamics of a power grid and the properties of a communication network.
2. Introduction of some realistic disturbances, such as voltage drops, load surges, generation losses, as well as cyber-attacks.
3. System performance analysis done through all-inclusive system voltage quality, frequency stability, and communication reliability measures.
4. Assessment of the effect of communicational failures on the effectiveness of control and system stability.
5. Effects of renewable energy integration on grid performance and stability.

The rest of this paper will be structured in the following way: Section 2 will review the available literature on smart grid communication and control. Section 3 explains the framework and methodology of the simulation. Section 4 discusses the results and analysis of the simulation, along with the implications for the smart grid design and operation. The paper ends with Section 5 that proposes the way forward in future research.

2. Literature review

2.1 Smart grid communication architecture

The transformation of power grids into smart energy systems has led to significant research on communication architecture that is able to support their complex monitoring and control demands. Gungor et al. [9] provided a detailed description of communication technologies that may be utilized in smart grid implementations, and the barriers of reliable and secure communication in power systems environments were established. They highlighted the importance of having quality-of-service (QoS) assurances for significant grid applications throughout domains of resources. Yan et al. [10] examined various communication infrastructures of smart grids and compared wireless and wired technologies in regard to reliability, security, and cost. The hierarchical design of the smart grid communication was proposed in [5]. [11], which proposed a three-tiered structure of communication comprising HANs, Nans, and WANs. This architecture has formed the basis of the majority of the successful smart grid implementations. Inspired by this paper, Kuzlu et al. [12] conducted a survey of the diverse communication requirements of the different layers of the smart grid, which presented bandwidth and latency requirements, which we used to select our simulation parameters. Ma et al. [13] reviewed recent

developments in wireless technologies for smart grid communications, considering ICN for 5G networks in the context of real-time grid monitoring and control. In line with this, Selim et al. [14] reviewed narrowband Internet of Things (NB-IoT) for advanced metering infrastructure and demonstrated that it can support low-power, wide-area coverage in the smart grid.

2.2 Cyber-physical system modeling

A recently developed model of cyber-physical systems (CPS) has come about as a result of the integration of power equipment and the internet. Sridhar et al. [15] suggested a comprehensive list of CPS vulnerabilities in power systems and highlighted interdependence between cyber and physical domains. This was the work we based our approach to modeling cyberattacks in the simulation framework. Lin et al. came up with co-simulation methods, which are unavoidable in studying the relationships between the cyber and the physical world. The simulation of interdependencies with power systems simulators and communication network simulators was the basis of [16]. Likewise, a review study by Mets et al. [17] presented a combined power-flow/network simulation environment and provided the results of communication failures on the voltage control. Wang et al. examined machine learning approaches to CPS modeling [18], in which reinforcement learning was used to optimize control strategy in the case of communication uncertainty. Similarly, Abur and Exposito [19] constructed state estimation strategies that are resilient to measurement errors and transmission lag and hence optimize our modeling of control actions in a noisy communication environment.

2.3 Control strategies for communication-constrained systems

Designing control strategies under communication constraints is challenging when designing control strategies of power systems that are under communication constraints. Zhang et al. [20] created a distributed control that is robust to packet loss and time lag to the advantage of more impressive voltage control performance as compared to the centralized approach. In the same manner, Liu et al. [21] suggested event-based control designs, which bypass bandwidth demands without compromising the controller performance. Bidram, Davoudi, Majd, and Fazel presented systematic design models of managing a type of hierarchical systems having communication restrictions. [22] where primary, secondary, and, tertiary control levels of decreasing time-criticality were to be designed. And this has been utilized in our distributed control implementation. In addition to this concept, Dehghanpour et al. [23] suggested a multi-agent control framework, which applies flexible communication policies to prioritize important messages when there is network congestion. Molzahn et al. [24] were also aware of control under the communication constraints and provided a constrained optimization problem with power system goals and communication constraints. Wu et al. [25] invented stochastic control techniques that they use in decision-making in the presence of random communication failures.

2.4 Renewable energy integration challenges

As renewable energy penetration increases, the operation and control of power systems become more and more complicated. Ackermann et al. [26] had a comprehensive description of the issues of wind power integration, and it is clear that more effective forecasting, as well as control mechanisms, are needed to deal with the variability of wind power. Yang et al. [27] studied the issue of solar power incorporation, but they specifically considered high ramp rates that may overburden conventional control systems. Bonfiglio et al. also examined the requirements of communication, monitoring, and control of renewable sources of energy. [28] which removed the bandwidth and latency constraints of the other renewable technologies.

Based on this, Kuzlu and Pipattanasomporn [29] came up with a priority-based communication design of integration of renewable energy, which emerges as one of our frameworks of prioritized communication. Pudjianto et al. suggested virtual power plant (VPP) methods of distributed renewable control. [30]. This implies that better system stability may be realised through synchronised control. Likewise, in the case of Morales et al. [31], in which we were informed about a model of renewable generation patterns, and [35], in which we were informed about the existence of stochastic optimization problems of renewable energy dispatch in the face of uncertainty.

2.5 Performance metrics and standards

There must be standardized measures to gauge the performance of power systems, so that they can be compared. Several reliability indices listed in the IEEE Standard 1366 [32], such as SAIFI, SAIDI, and CAIDI, are applied in our model. Equally, IEC 61000-4-30 [33] introduces the process of measurement of the power quality parameters, such as the change in voltage and frequency. Zaballos et al. [34] summarized communication performance metrics of smart grid applications by suggesting quality-of-service measures specific to power system control requirements. Continuing on this, Khan et al. [35] designed performance evaluation models, particular to advanced metering infrastructure communication. Grilo et al. [36] suggested comprehensive measures that combine the performance of power systems and communications by creating a smart grid performance index in the dimensions of reliability, efficiency, and security. Gharavi and Hu [37] specified the metrics of communication reliability related to smart grid implementation, which have shaped our Communication Reliability Index.

2.6 Simulation frameworks and toolsets

To research the work of smart grids, a variety of simulation models and frameworks have been created. Zimmerman et al. [38] created MATPOWER, which is an open-source power-systems-simulation package written in MATLAB and used extensively in load-flow analyses. Nonetheless, it does not have inbuilt support to model communication networks. Integrated power and communication simulation tools incorporate the efforts of Lin et al. [39], who created an integration of Power World with OPNET network simulator, and Godfrey et al. [40], who created an integration of Power Factory and NS-2 network simulator. Tan et al. [41] and Kezunovic et al. [42] designed MATLAB-based smart grid simulation frameworks, respectively, and designed a co-simulation platform and synchrophasor application evaluation tools, respectively. Our work is based upon these existing frameworks with a more thorough simulation environment in MATLAB, which incorporates the detailed models of the power system dynamics and network communication performance with a specific focus on their interactions and the effects on control performance.

3. Proposed model description

The suggested Hybrid Monitoring and Control System of Electrical Networks in Fig. 1 combines the power grid dynamics and communication technologies. It predicts the operation of the power grid, includes the effect of renewable sources of energy, and models the behavior of the communication system in real-life situations, and cyber-attacks are among these situations.

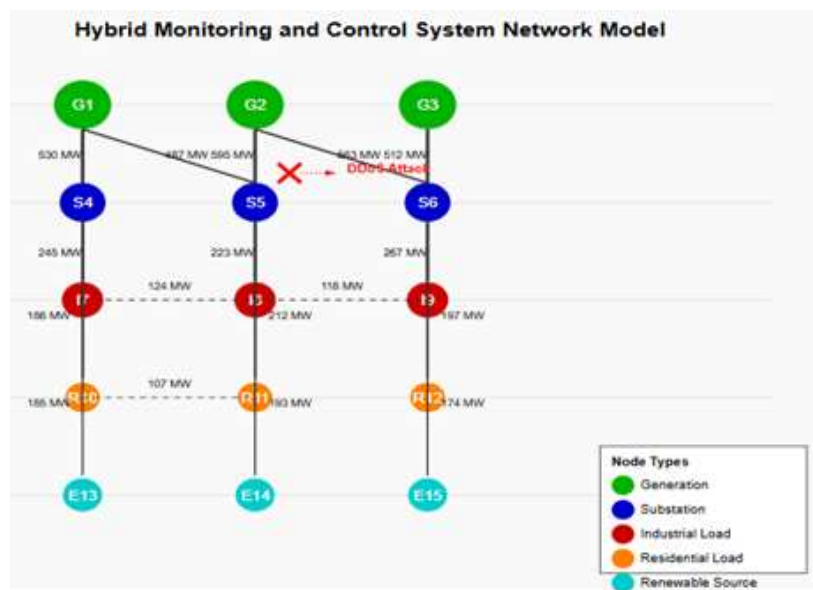


Figure 1. The proposed system - hybrid monitoring and control system of electrical networks

This model represents a simulated Advanced Hybrid Monitoring and Control System, the one that incorporates the power grid dynamics with the broadband communication technologies. The system evaluates:

- Electrical Performance: node voltages, currents, power, frequency, and reactive power.
- Renewable Integration: Integrating solar and wind generation profiles into the grid.

Communication system is made of:

- The performance of the network, congestion, delays, and data priorities.
- Cybersecurity Resilience: DDoS attacks and their imitation of grid stability and communication.
- Performance Measures: Calculate such indices such as Voltage Quality Index, Frequency Quality Index, Communication Reliability Index, and Power Balance Index.

3.1. Electrical network setup

3.1.1 Node

Node types are as following:

- Generation Nodes (1): Generate power.
- Substation Nodes (2): Transfer and regulate power.
- Industrial Load Nodes (3): High-demand loads.
- Residential Load Nodes (4): Moderate-demand loads.
- Renewable Source Nodes (5): Variable-output sources.

3.1.2 Connections

Nodes are probabilistically connected to represent a real-world grid topology:

- Generation (1) → Substations (2): 70% probability.
- Substations (2) → Loads (3, 4) and Renewables (5): 40% probability.
- Load (3,4) ↔ Load (3,4): 20% probability (redundancy).

3.1.3 Impedances and line capacities

- Generation → Substation:

$$Z_{ij} = 0.05 + 0.1 \cdot \text{rand}() \Omega$$

$$\text{Capacity} = 500 + 200 \cdot \text{rand}() \text{ MW}$$

- Substation → Load:

$$Z_{ij} = 0.2 + 0.3 \cdot \text{rand}() \Omega$$

$$\text{Capacity} = 200 + 100 \cdot \text{rand}() \text{ MW}$$

- Load → Load:

$$Z_{ij} = 0.5 + 0.5 \cdot \text{rand}() \Omega$$

$$\text{Capacity} = 100 + 50 \cdot \text{rand}() \text{ MW}$$

3.2. Electrical parameter modeling

3.2.1 Voltage

The voltage at each node is updated iteratively:

$$V_i(t) = V_i(t - 1) + \Delta V_i + \eta V \quad (1)$$

where

$$\Delta V_i = k_i \cdot (V_{nominal} - V_i(t-1)) + k_2 \cdot \frac{\text{Neighbor Effect}_V}{\text{Neighbor Count}} \quad (2)$$

where $\eta V \sim N(0, \sigma^2)$ is Gaussian noise.

3.2.2 Power Flow

Power flow between two nodes is calculated using:

$$P_{ij} = \frac{V_i(t) - V_j(t)}{Z_{ij}} \quad (3)$$

where:

Z_{ij} : Line impedance.

$P_{ij} > 0$: Power flows from i to j.

$P_{ij} < 0$: Power flows from j to i.

3.2.3 Current

The current at each node is determined based on its type:

- Load Nodes (3,4):

$$I_i(t) = I_i(1) \cdot \text{Load Factor} \quad (4)$$

- Renewable Nodes (5):

$$I_i(t) = I_i(1) \cdot \text{Renewable Profile} \quad (5)$$

3.2.4 Frequency

Frequency is influenced by neighboring nodes and updated as:

$$f_i(t) = f_i(t-1) + \Delta f_i + \eta f \quad (6)$$

where:

$$\Delta V_i = k_3 \cdot \frac{\text{Neighbor Effect}_f}{\text{Neighbor Count}} \quad (7)$$

$\eta f \sim N(0, \sigma^2)$: Gaussian noise.

3.2.5 Reactive Power

Reactive power is calculated as:

$$Q_i = P_i \cdot \tan(\phi) \quad (8)$$

where: ϕ is phase angle, randomly initialized and updated dynamically.

3.3. Renewable energy profiles

Solar Profile is calculated using:

$$G_{\text{solar}}(t) = \max\left(0, \sin\left(\frac{\pi}{12}(t - 6)\right)\right) \quad (9)$$

Wind Profile is calculated as:

$$G_{\text{Wind}}(t) = 0.3 + 0.7 \cdot \text{Random Walk}(t) \quad (10)$$

Variability is modeled as a random walk.

3.4. Communication system modeling

Communication Delay is:

$$\text{Delay}_i = \text{Base Congestion Factor} \cdot \text{Random Factor} \quad (11)$$

Packet Loss is:

$$\text{Packet Loss}_i \sim \text{Bernoulli}(p), p = \text{Function of Congestion} \quad (12)$$

3.4.1 Priority Levels

Data is prioritized based on node type:

- 3: High (generation/substations).
- 2: Medium (industrial loads).
- 1: Low (residential/renewable).

3.5 Performance metrics

Voltage Quality Index (VQI) is:

$$VQI_i = 100 \cdot \left(1 - \frac{\text{Mean}(|V_i - V_{\text{nominal}}|)}{V_{\text{nominal}}}\right) \quad (13)$$

Frequency Quality Index (FQI) is:

$$fQI_i = 100 \cdot \left(1 - \frac{\text{Mean}(|V_i - f_{\text{nominal}}|)}{0.5}\right) \quad (14)$$

Communication Reliability Index (CRI) is:

$$CRI_i = 100 \cdot (1 - \text{Mean}(\text{Packet Loss}_i)) \quad (15)$$

Power Balance Index (PBI) is:

$$PBI(t) = \min \left(100, 100 \cdot \frac{\text{Generation}(t)}{\max(1, \text{Load}(t))} \right) \quad (16)$$

3.6. Cyber-attack simulation

During a simulated DDoS attack:

- Delays and packet losses increase significantly:

$$\text{Delay}_i = \text{Maximum Latency} \cdot (1.5 + \text{Noise}) \quad (17)$$

Packet Loss_i = 80%.

- Communication reliability drops as:

$$\text{CRI}_i = 100 \cdot (1 - \text{Mean}(\text{Packet Loss}_i)) \quad (18)$$

3.7. Renewable energy impact

The integration of renewable energy is quantified as:

$$\text{Renewable Penetration} = \frac{\text{Total Energy (Renewable)}}{\text{Total Energy (Renewable + Traditional)}} \quad (19)$$

3.8. Reliability metrics

SAIFI (System Average Interruption Frequency Index) is:

$$\text{SAIFI} = \frac{\text{Total Interruptions}}{\text{Number of Customers}} \quad (20)$$

SAIDI (System Average Interruption Duration Index) is:

$$\text{SAIDI} = \frac{\text{Total Interruption Duration}}{\text{Number of Customers}} \quad (21)$$

CAIDI (Customer Average Interruption Duration Index) is:

$$\text{CAIDI} = \frac{\text{SAIDI}}{\text{SAIFI}} \quad (22)$$

4. Results and discussion

The MATLAB program, used in this research, creates a number of plots to examine the performance of the hybrid monitoring and control system. The detailed interpretation of each plot is presented below, and it is divided into electrical parameters, communication parameters, performance metrics, and visualizations of system performance.

Table 1. show the important parameter values.

Table 1. Parameter values

Parameter	Value	Description
$V_{nominal}$	230 V	Nominal voltage of the grid
$f_{nominal}$	50 Hz	Nominal frequency
Bandwidth	100 MHz	Network bandwidth
Packet size	1024 bytes	Size of data packets
Sampling time	0.1 s	Time resolution of the simulation

Fig. 2 is visualization of hybrid power grid network. This diagram shows the general form of the power grid with nodes (grid parts) and edges (connection between them). It gives a good graphic approach to the manner in which power moves around the system.

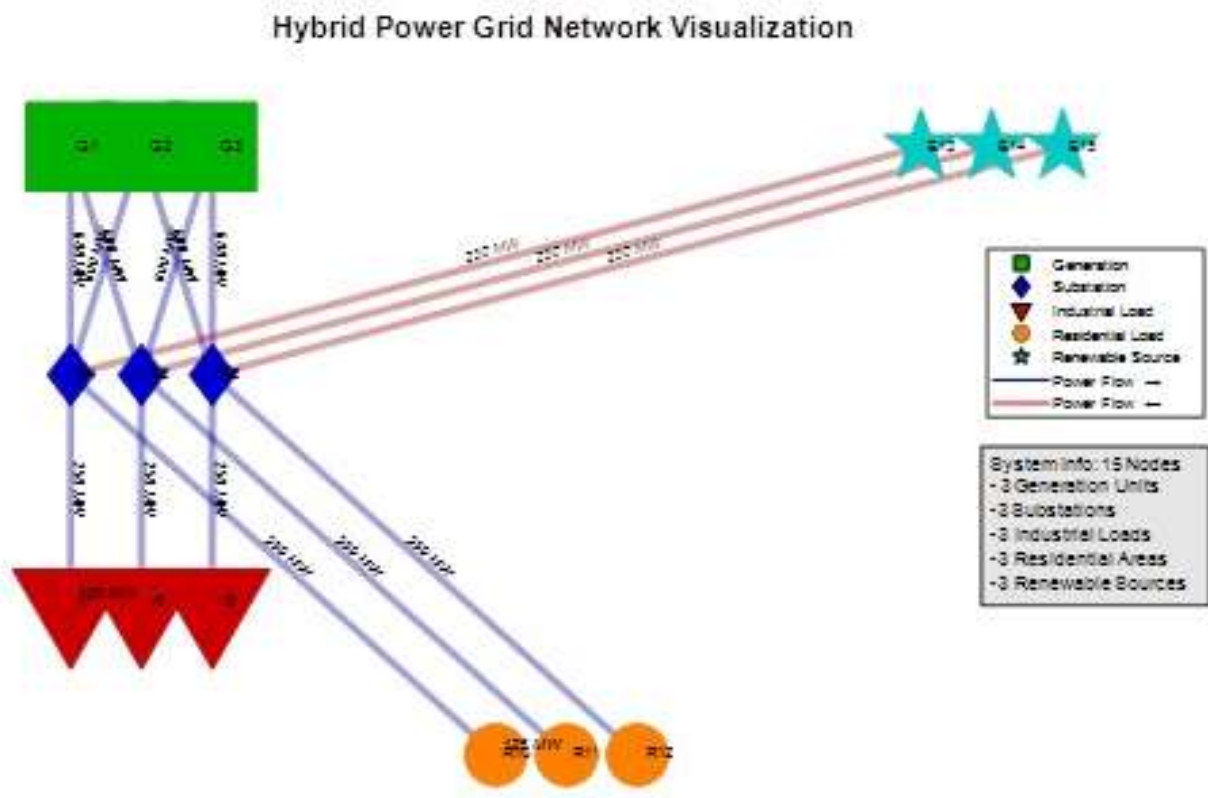


Figure 2. Hybrid power grid network visualization

Key features in Fig. 2:

- Nodes:
 - Represent different components in the grid:
 - Green squares: Generation units (e.g., power plants).
 - Blue diamonds: Substations (transfers and regulates power).
 - Red triangles: Industrial loads (high power consumption areas).
 - Circles with orange color: residential loads (moderate power consumption areas).
 - Cyan pentagons: Renewable sources (e.g., solar or wind farms).
 - Size: Reflects the magnitude of power at each node. Larger nodes indicate higher power production or consumption.

- Edges:
 - Represent connections between nodes:
 - Blue edges: Power flows from the source node to the destination node.
 - Red edges: Reverse power flow due to line losses or imbalances.
 - Width: Proportional to the magnitude of power flow along the connection.
- Node Labels:
 - Nodes are labeled based on their type and number:
 - G1, G2,...: Generation nodes.
 - S1, S2,...: Substations.
 - I1, I2,...: Industrial loads.
 - R1, R2,...: Residential loads.
 - E1, E2,...: Renewable sources.

Insights from Fig. 2 are as follows.

Patterns of Power Flow: The primary power flow directions are between the generation and the substations, and the substations to the industrial and residential loads. In the case of renewable nodes, even though they inject power to the grid, they have quite tethered offering curves as they are dependent on the next generation and demand variations.

Critical Nodes: Both the generation and renewable nodes contribute more power to the grid. A majority of the consumption is consumed in industrial load nodes.

Edge Behaviour: Blue edges, which are thicker, signify high power flow, usually the source of which is a generator, and usually the destination is a substation. Red edges represent recirculation, which is perceivable as inefficiencies or imbalances.

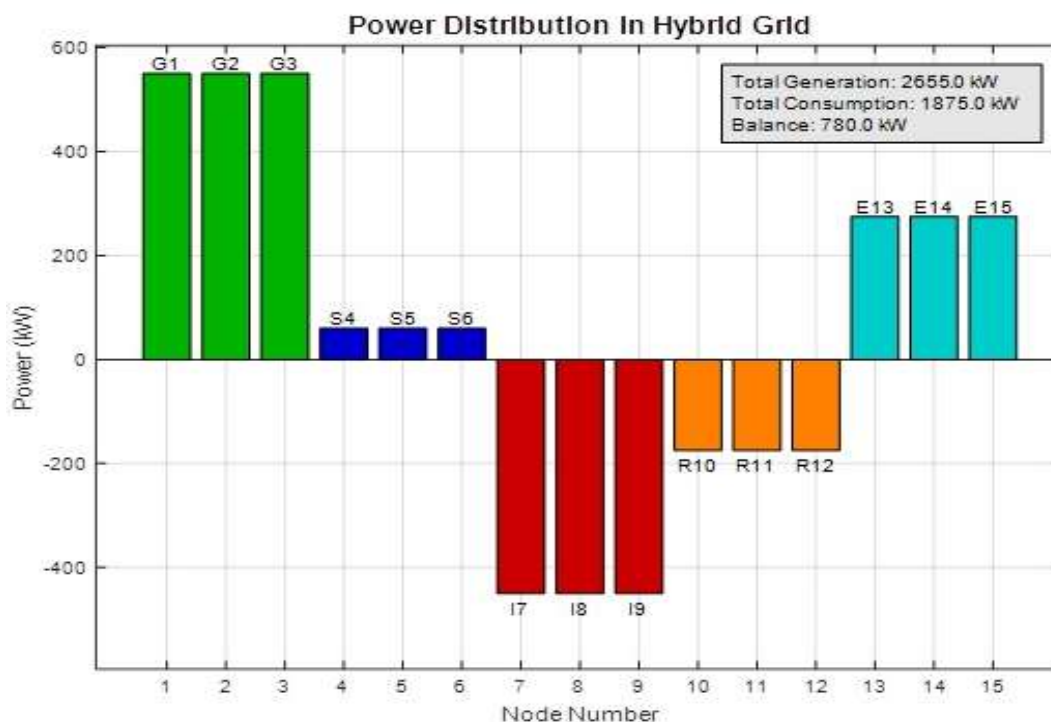


Fig. 3 Power flow summary. A bar chart displays the power values (production or consumption) at each grid node. Key Features

- Bars in Fig. 3 are:
 - Positive bars: Power-producing nodes (generation and renewables).
 - Negative bars: Power-consuming nodes (industrial and residential loads).
- Colors in Fig. 3 represent:
 - Each bar is color-coded based on the node kind:
 - Green: Generation nodes.
 - Blue: Substations.
 - Red: Industrial loads.
 - Orange: Residential loads.
 - Cyan: Renewable sources.
- Node Labels in Fig. 3 are:
 - Both bars are labeled with their node kind and number.

Insights from Fig. 3 are as follows.

Production vs. Consumption: Generation and renewable nodes show positive bars, contributing energy to the grid. Industrial and residential nodes show negative bars, indicating energy consumption.

Load Distribution: The loads that consume the highest power are industrial loads, as demonstrated by the lowest negative bars.

Residential loads: The usage of less power is seen in a more extensive area of the grid network.

Grid Balance: It would also be easy to compare aggregate production and aggregate consumption. Any deviation can signal a requirement to implement a remedial action, e.g., relying on reserve margins, load shedding, or more production of renewable sources.

Fig. 4 shows generation Mix - a pie chart showing the contribution of traditional and renewable sources to total power generation. Important features are:

- Segments:
 - Green: Contribution from traditional generation (e.g., fossil fuels or nuclear power).
 - Cyan: Contribution from renewable sources (e.g., solar or wind energy).
- Percentages:
 - Each segment in Figure 4 shows the percentage contribution of that source to the total power generation.

Insights from Fig. 4 are as follows.

Renewable Penetration: The size of the renewable sector in comparison to other power sources informs us of the size of renewable power in the mix. An increase in the proportion of renewables implies a shift to the sustainable energy system.

Generation Balance: It is dependent on it in terms of renewable and traditional sources, as indicated in the chart. There is a high dependency on traditional sources, which implies that more new and renewable sources should be introduced.

Energy Transition: The mix gives a detailed view of the process of the grid transitioning to cleaner sources of energy.

Generation Mix in Hybrid Power Grid

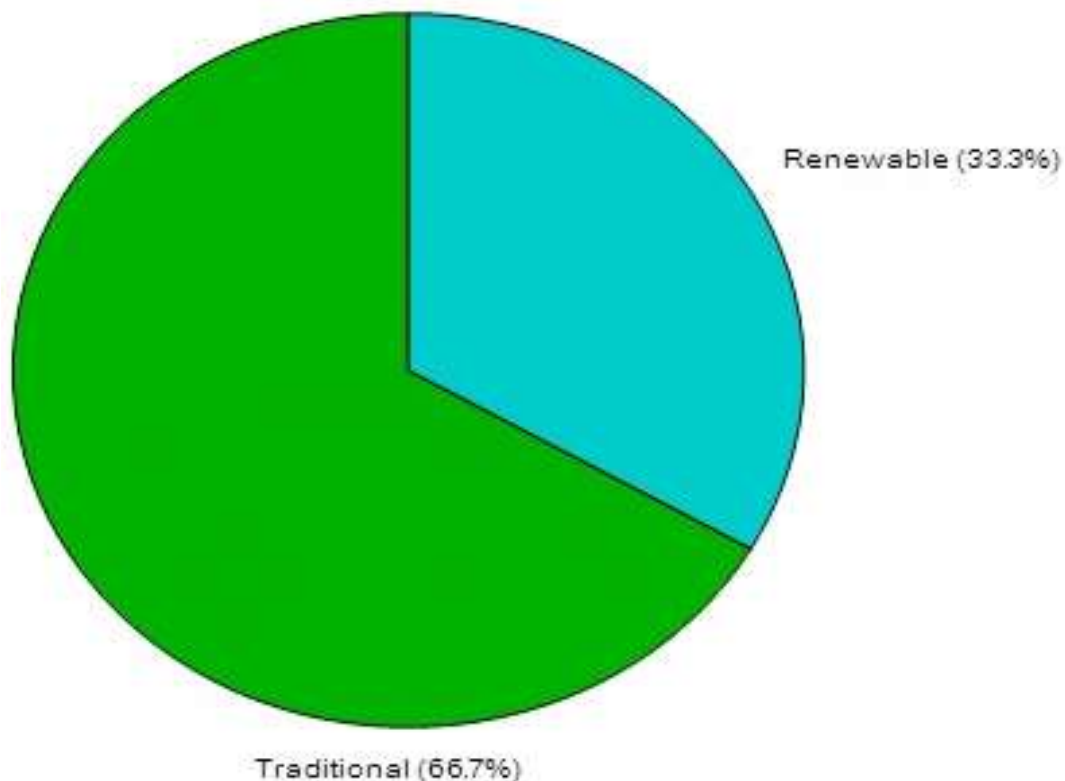


Figure 4. Generation Mix.

Fig. 5 shows electrical parameters. These plots offer insights into the power grid's performance over time.

Voltage vs. Time at Individual Nodes. This plot shows the switch of power of all the nodes. The nodes will be color-coded based on the type, e.g., generation, substation, industrial load/residential load, and renewable source. Remarkable remarks: Since the generation nodes (green lines) are voltage-controlled, their voltage is roughly $V_{nominal} = 230\text{ V}$. The nodes of substations are fairly stable and may undergo minor alterations, depending on the connection. The load nodes are said to be more varied, particularly at peak loads or during interruptions.

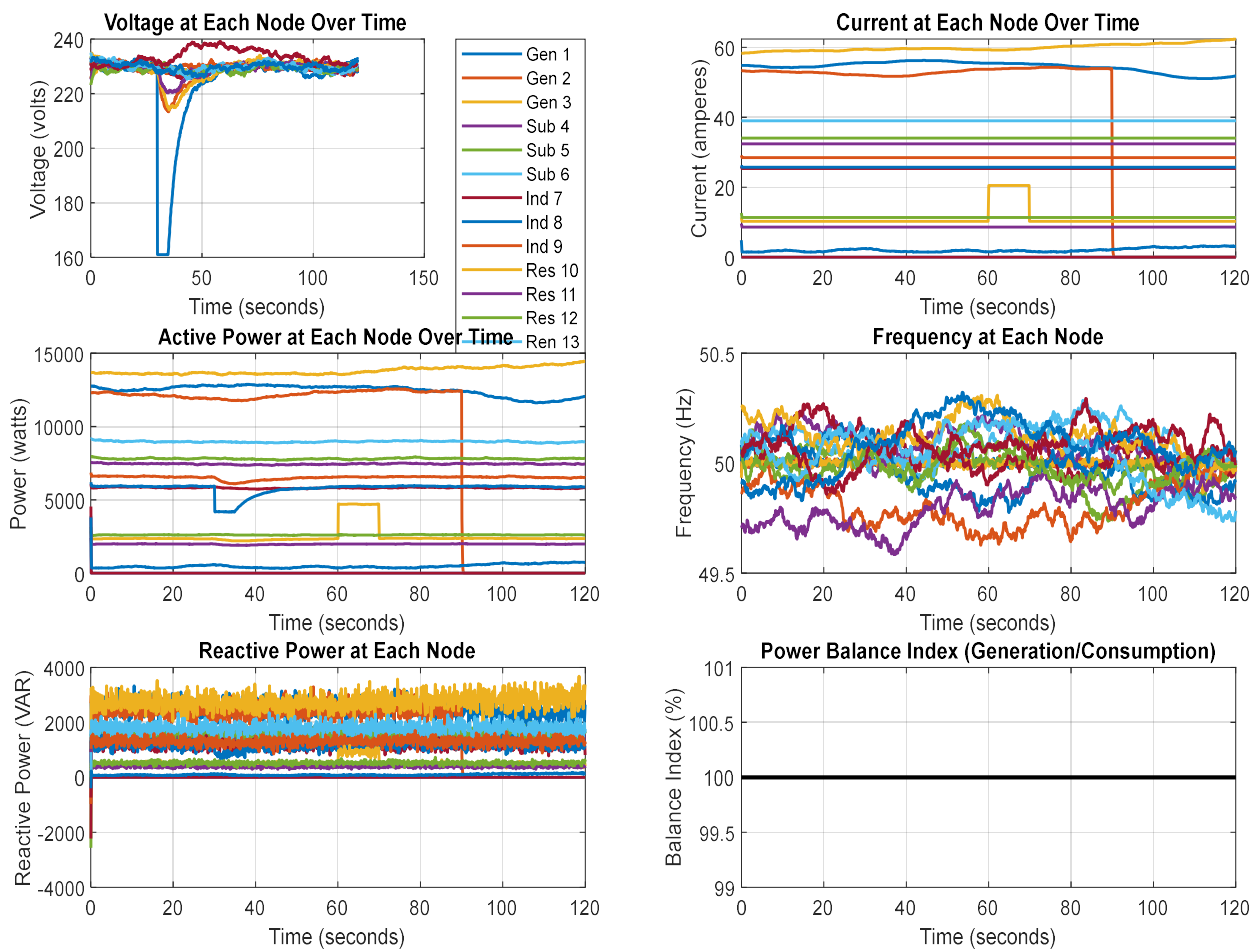
Current at Each Node over Time. The current consumption or generation in each node is represented. Notes: There is a fluctuating current profile due to the variation of the wind and the sun in renewable nodes. The industrial nodes contain higher currents that are constant and constant power requirements. Residential nodes have a varying current that relies on the day's load profile.

Time and Frequency Power per Node. Active power that is an input or output of all nodes is modelled. Noteworthy notes: Generation nodes are productive in terms of power. Load nodes depict a consumption pattern that is consistent with the daily load profile. Renewable nodes are intermittent and are seasonal (solar and wind).

Frequency at Each Node at Time. The frequency fluctuations in each node are presented. Observations: Frequency is well regulated at generation nodes. $f_{nominal} = 50\text{ Hz}$. Load nodes are more prone to disruptions, causing slight variations in the frequency.

Reactive Power at Each Node. Alteration in reactive power (Q) at each node. Important findings: Generation nodes have been raised to generate higher reactive power to stabilize the grid. The values of reactive power in load nodes are lower and relatively compared to the consumption.

Power Balance Index (PBI). This is a plot that dwells on the balance between the generation and the use of power over time. Notable findings: When the PBI is near 100 percent, this is a good balance. There can be a temporary imbalance induced by the renewable variability periods or disturbances.



5. Electrical Parameters

Fig. 6 shows communication system performance. These plots evaluate communication reliability and efficiency under normal conditions and cyber-attacks.

Communication Delay. The delay (in milliseconds) of communication by each node is indicated. Notable observations: Delay is insignificant under normal conditions but peaks in times of congestion or attacks. Priority data processing helps high-priority nodes (generation and substations) to reduce the amount of delay.

Packet Loss. Time-dependent loss of packets in each node. Significant observations: Packet loss is low under normal operation. A huge loss is experienced during a DDoS attack or severe network congestion.

Bandwidth Usage. The percentage of bandwidth utilization across all nodes. Key observations: Bandwidth usage increases during peak load periods or attacks. Nodes handling critical data exhibit higher usage due to prioritized communication.

Data Priority Levels. The levels of priority of the transmitted data are depicted (1: low, 3: high). Major observations: Generation and substation nodes will always be sending high-priority data. The priority is lower on renewable and residential nodes.

Network Congestion Level. The percentage network congestion versus time. Important observations: The congestion has a daily pattern, where it is high during peak hours. Random congestion events or cyber-attacks can lead to sudden spikes.

Cyber Attack Activity. Shows the number of nodes being attacked at any particular time. Acute considerations: The entire process of the simulated DDoS attack shows that communication is heavily disrupted in the affected nodes.

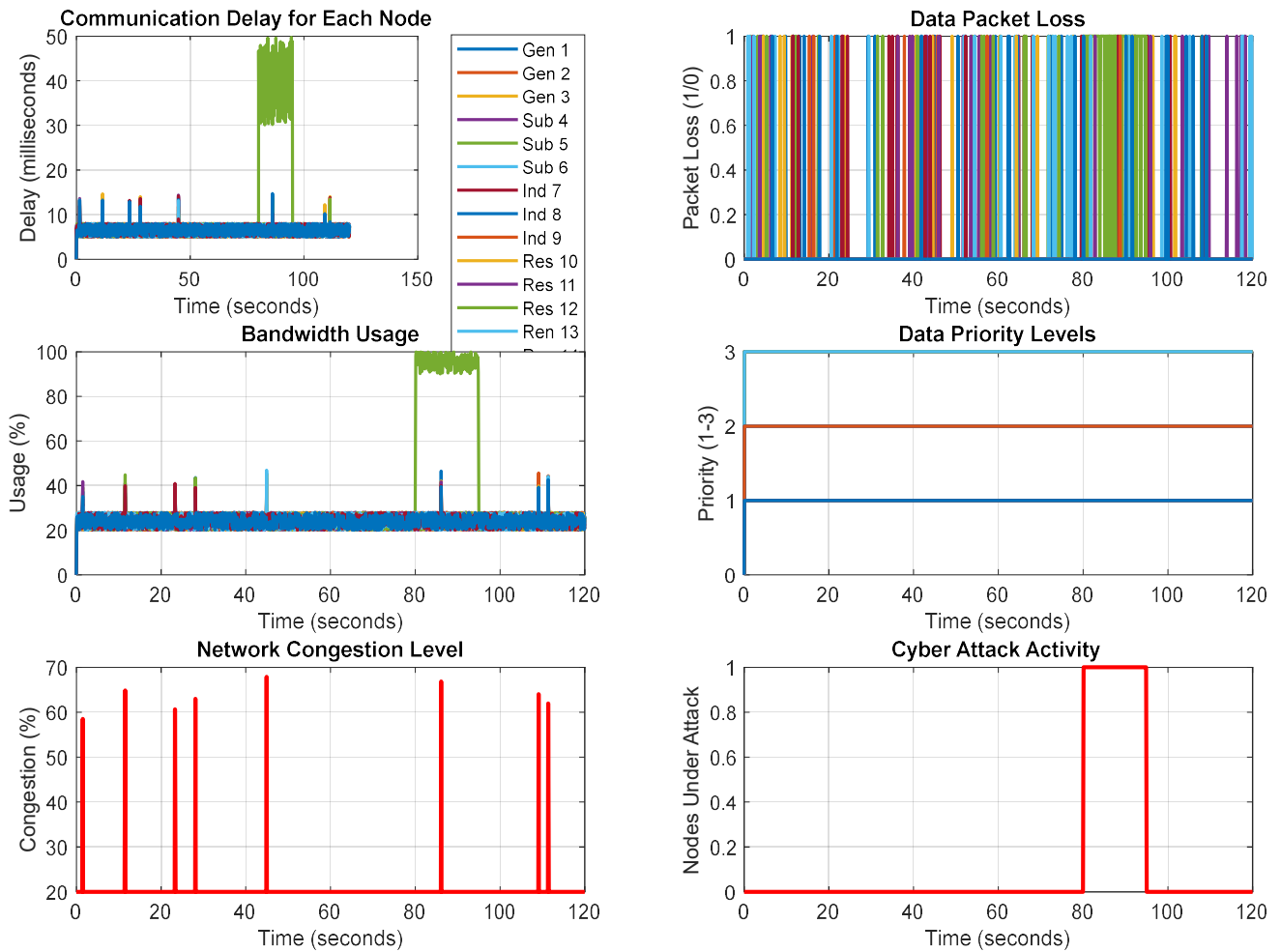


Figure 6. Communication System Performance.

Fig 7. Shows performance metrics. These metrics provide quantitative insights into the system's reliability and stability.

Voltage Quality Index (VQI). The VQI of all the nodes is depicted through the use of a bar chart. Important observations: This is because generation nodes achieve the highest VQI because the voltage out is regulated. Load nodes bear less VQI because they are vulnerable to upsets.

Frequency Quality Index (FQI). The bar chart of the FQI of generation nodes. Important Findings: Generation nodes have good frequency regulation.

Communication Reliability Index (CRI). A bar chart of the CRI of individual nodes. Important observations: CRI of high-priority nodes is observed to be higher even when there is congestion. Renewable and residential nodes exhibit lower CRI due to their lower priority.

Power Balance over Time. This plot shows the PBI over time. Key observations: Stable PBI indicates effective power management. Renewable variability and disturbances can cause temporary deviations.

For the discussion of results, the hybrid power system simulation is modelled with the help of MATLAB-based data and addresses the normal and challenging cases of the current grids, such as the load diversity, RER penetration, and the power flow dynamics. The metrics and visualizations are applied to explain the key points and findings. The analysis of network structure and power flow indicates that there are significant connections between renewable generation, generator nodes, substations, and loads. Substantial generators of electricity (e.g., power plants) are called Generation nodes, and power is then transmitted to industry and residential consumers via substations.

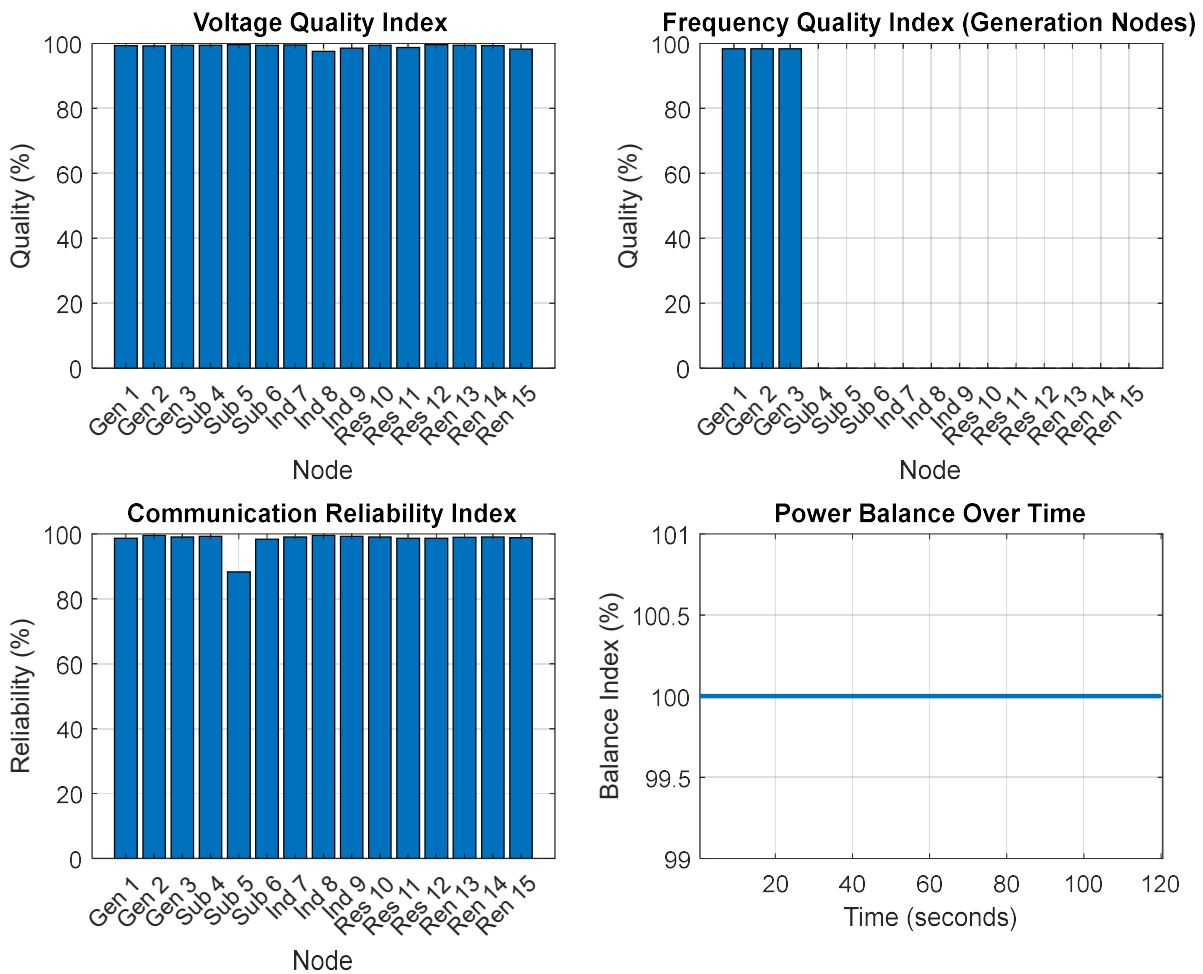


Figure 7. Performance Metrics.

Renewable (i.e., new or recently added) nodes supply more power, which indicates the ability of the grid to absorb an increased amount of power that has a cleaner origin. It is important to note that the important power transfer routes are emphasized by the visualization, with thickened edges indicating the areas of a high flux of energy. The area of red (overcoming) power flow denotes the power losses or grid imbalance risk. Power distribution and flow characteristics are visualized and understood by bar charting (production (positive) and consumption (negative) in the megawatts (MW) at each node. The total power demand is referred to as consumption, and it is between the largest industrial loads and the smaller domestic loads. This grid is set up in such a way that the high industrial load and low domestic load are kept at equilibrium without releasing heat in the system, thereby ensuring the stability of the system.

It is also evident that the integration of renewables is apparent on the generation mix; the solar and wind power contribute a lot to power generation, as presented in the pie charts. Going green will bring a shift toward sustainability. However, renewable sources become intermittent, and this will cause instability to the grid; the system will need advanced control systems and storage to buffer the system. Increased renewable penetration will reduce the dependence on fossil fuels, as it is considered by the environmental goals, but will need actions to deal with variability. High reliability at major nodes, e.g., the generation unit and substation, small time delay, and low loss of packets are also a characteristic of the communication system.

Priority assists in maintaining vital nodes operating despite the network being congested or being attacked. However, low-priority nodes can be influenced by congestion and, therefore, it is crucial to apply a lightweight communication protocol and dynamic congestion control techniques to enhance the reliability of the system. With a Power Balance Index (PBI) of around 100, successful power balance and grid efficiency are attained. This demonstrates that the grid has the potential to guarantee demand and supply stability under variable

conditions. The fluctuations in renewable generation and load peaks, with and without ESS and backup generation, respectively, cause minor excesses/ shortages of PBI. The grid is load-following, which means that under- or over-supply is kept to minimum.

Voltage stability is also synonymous with the renewable variability since changes in solar and wind power can influence the stability of the system. Such variations require sophisticated control algorithms to reduce them and keep the quality of electricity. The connection between renewable generation and the quality of power indicates the necessity of monitoring and remedial action. Such parameters as SAIFI, SAIDI, and CAIDI demonstrate that a few short-duration outages indicate a robust grid. (C) The resiliency of the system is exemplified by the fact that the system is resistant to typical forms of cyber-attacks (e.g., DDoS), and the most critical nodes will continue to be operational despite any communication delays or packet loss. An even higher level of reliability can be offered with the help of complex security systems, fault-tolerant protocols, etc. In conclusion, the hybrid power grid is doing well under the under-design conditions, hence ensuring stability, reliability, and sustainability.

The installation of renewable energy will put pressure on the use of advanced storage of energy, reactive controls, and effective communication. Additional developments will be made, such as enhanced security, flexible congestion management, as well as the next generation of energy technologies that will further inspire a healthy grid that can withstand longer disruption and promote a sustainable and efficient energy future.

5. Conclusions

This research shows that the hybrid power grid provides stable and efficient control of the generation, distribution, and consumption, and its PBI is around 100, which indicates a good supply-demand balance under normal circumstances. Although renewable energy sources are relevant sources to the global generation in the whole (namely sustainability), easier control regarding the case is to be carried out for energy sources such as HSE-IT; however, the fluctuations of solar and wind energy sources necessitate more novel control (e.g., energy storage and real-time control). They handle industrial and residential loads, and, therefore, are not really a big stability issue for the grid overall. The communication setup is highly dependable with low latency and loss to packet, and even in a state of traffic or cyber-attack, the critical nodes get preference.

We simulated faults and attacks to validate fast recovery, load surge resiliency and adequate monitoring and control. To enable a higher degree of renewable penetration, investments in storage, smart control, secure communication protocols, and predictive analytics are recommended. Overall, the results confirm the potential for renewable energy to be integrated into existing grids without threatening reliability, enabling a cleaner, more robust, and efficient electricity system. The results of this study open up a number of good directions for future research to continue the development of hybrid renewable power grid systems:

- Future research should focus on integration of next-generation energy storage, such as solid-state batteries, flow batteries, and hydrogen-based storage, which can mitigate intermittent nature of renewables, while also stretching the upper limit of maintaining grid balance during high renewable penetration scenarios.
- Development of deep reinforcement learning (DRL) and transformer-based forecasting models for real-time renewable generation and load demand prediction can play a great role in grid stability due to their continuous adjustment to changes in demand-supply network. The research should aim on controllers which can adapt and learn by itself to work in under constantly changing and uncertain grid conditions.
- As communication access makes power systems more susceptible, future works should formulate strong deviation detection and anomaly detection systems specific to smart grid settings. This encompasses the investigation of blockchain security protocols and zero-trust architectures for critical grid infrastructure protection.
- There is a potential research gap on decentralized control approaches to achieve independent coordination between multiple microgrids while enabling peer-to-peer energy trading and load sharing. This will enhance resilience and economic efficiency, especially in islanded or semi-islanded operating modes.

- The development of digital twin models of the hybrid power grid would enable the grid to be monitored in real time, as well as scenarios of failing elements and control strategies to be tested without putting actual infrastructure at risk. Future work does indicate high-fidelity digital twin approaches that include the physical and cyber aspects of the grid.
- With the increasing penetration of EVs, new analyses going forward should include strategies such as vehicle-to-grid (V2G), where EV batteries are operated as localized energy storage devices that can provide energy to the distribution system. This will involve smart charging algorithms to minimize grid load and the need for backup power, while maximizing convenience and battery life.
- Continued investigation of the role of high-frequency data in informing dynamic load-side balancing through improved demand response strategies -particularly those that take into account the role of IoT or advanced metering that can inform demand response action at scale - could increase load flexibility while alleviating peak loads.
- An encouraging trend in demand response systems is based in machine learning where those systems learn consumer behavior patterns (Higgins et al. GNN-based fault detection and self-healing grid mechanisms GNNs have shown great potential as future fault detection methods based on future work, which are based on distributed and privacy-preserving federated learning mechanisms to be fully reflected. Another area to consider is self-healing algorithms, which would enable lines to be automatically rerouted following any fault event.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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