A Simulation-based Evaluation of Smart Grid Applications for Resilient and Energy-Efficient Power Distribution Networks

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***Abstract*—Advanced smart grid applications are needed to enhance the resilience of power distribution networks, minimize energy losses, optimize the use of renewable energy resources, and ensure sustainable operation of the grid while power distribution networks are modernized. The paper evaluates smart grid applications to ensure resilient and energy-efficient power distribution systems using simulation. A traditional distribution system was compared to a smart grid-based distribution system that features demand response, advanced monitoring, renewable energy coordination, distribution automation, fault location, fault isolation, fault restoration, and volt/VAR control and energy management. A 24-hour simulation model was developed to calculate technical, reliability, economic, and environmental performance indicators. The results indicate that smart grid-based operation lowered the peak demand from 104 MW to 90 MW (a 13.46% reduction). The distribution losses were reduced from 133.37 MWh to 86.28 MWh, with a reduction percentage of 35.31% on a daily basis. Renewable energy use rose by 21.17%, and outage duration shortened by 61.88 min/event, a 65.90% improvement in outage restoration performance. Additionally, the daily operating cost was lowered from 199,489 USD to 182,648 USD, and the emissions related to the grid were lowered from 1,283.76 tCO_2 to 1,209.60 tCO_2 per day. The voltage deviation from the nominal value was also reduced by 72.58% through smart grid volt/VAR control. The outcomes show that coordinated smart grid applications can have a significant impact on the resilience of the distribution network, its operational efficiency, the use of renewable energy, power quality, and sustainability.**

Keywords— Smart grid, distribution network, demand response, renewable energy utilization, distribution automation, FLISR, volt/VAR control, resilience, energy efficiency

I. INTRODUCTION

Electricity distribution networks are going through a significant restructuring in response to high demands for reliable power delivery, the incorporation of renewable power sources, a rise in flexible loads, and low-carbon and energy-efficient grid operation. Traditional distribution systems typically run in a state of low levels of real-time monitoring, manual restoration processes, passive load profiles and limited interaction between distributed energies and grid control devices. Such constraints can lead to higher peak demand, greater technical loss, voltage deviations, longer outage durations, and reduced utilization of renewable energy.

Smart grid technologies offer a viable means to enhance the operational efficiency of today's distribution systems. Recent developments in renewable energy systems and smart-grid-supporting technologies have further enhanced grid reliability, operational efficiency, and sustainable power delivery in modern electricity networks [1] [2]. The smart grid includes advanced metering infrastructure, communication technologies, distribution automation, demand response, distributed energy resource coordination, voltage regulation and intelligent energy management. Intelligent energy management systems have demonstrated significant potential for reducing energy consumption, optimizing load distribution, and improving operational efficiency in smart energy networks [3]. These technologies actively enable the operation, monitoring, and control of the distribution network. Smart grid applications can lower energy losses, increase resiliency, optimize use of renewables, help to hold voltage steady and reduce operating cost in real time, thanks to sensing and coordinated control [4].

Demand response is one of the significant applications of smart grid operation. It enables the flexible loads to be shifted or reduced during peak load periods, resulting in a smoother load profile and reducing peak demand. This is especially significant in distribution networks, since high peak loading results in higher stress on the feeders, transformer loading, line losses, and higher energy procurement costs. With sophisticated metering systems and demand-based control, demand response allows consumers and aggregators to be active players in grid operations.

Resilient distribution networks also must incorporate distribution automation and fault location, isolation and service restoration. Conventional systems primarily rely on manual fault detection and restoration, resulting in prolonged interruptions. Smart grid automation can aid in quicker fault detection, isolation of faulted feeder sections and restoration of healthy feeder areas. This adds greater reliability and minimizes disruption time for customers. Likewise, volt/VAR control is used to improve power quality by controlling the behaviour of voltage and reactive power. This approach is

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particularly relevant in active distribution systems with the integration of renewable energy, where voltage fluctuation and power loss variations can result from variable generation.

There are other smart grid applications as well, such as renewable energy coordination. To effectively use renewable energy sources, we must monitor and forecast their variability, ensure demand-side flexibility, and coordinate energy management. If smart grid coordination is not present, renewable generation could be under-used or curtailed when there is a mismatch. Smart grid operation optimizes the utilization of renewable sources to match the availability of renewable energy with demand on the network and the network's operating conditions.

This paper proposes a simulation study to assess the applicability of smart grid applications for resilient and energy-efficient power distribution networks. The study compares the conventional distribution network with the smart grid-enabled distribution network. The smart grid-enabled system features demand response, renewable energy coordination, distribution automation, FLISR, volt/VAR control, advanced monitoring and energy management. These are assessed based on peak demand, distribution losses, renewable utilization, outage duration, voltage deviation, operating cost and carbon emissions from the grid. The primary contribution of the study is to present a performance-based simulation framework that illustrates the simultaneous benefits of various smart grid applications on distribution network resilience, efficiency and sustainability.

II. Related Work

The research in smart grids has greatly accelerated due to the requirements and demands of the modern distribution networks, such as renewable energy, flexible demand, active consumers, electric vehicles, distributed storage, and bi-directional power flows. Kiasari et al. [5] discussed smart grid technologies for renewable energy integration, emphasizing the importance of machine learning and energy storage solutions for enhancing grid flexibility, renewable energy prediction, and operational control. Their review revealed in their study that to achieve future smart grid operation, coordinated efforts are necessary among renewable energy resources, energy storage, monitors based on data, and intelligent control systems. This reinforces the current research, which encompasses renewable utilization and energy management as performance indicators.

Mahmood et al. [6] gave an overview of the influence of digitalization on smart grids, renewable energy, and demand response. They spoke about the use of digital technologies like artificial intelligence, the Internet of Things, blockchain, and digital twins for enhancing the functioning of smart grids. According to them, digitalization enhances monitoring, forecasting, demand-side management, and coordination of renewable energy. The information is directly applicable to the present article, as the proposed smart grid-enabled network involves monitoring and control to reduce peak demand, improve utilization of renewables, and reduce network losses.

Almihat and Munda [7] studied the use of smart grid technologies for sustainable energy planning. They highlighted that the implementation of smart grid infrastructure can enhance the resiliency and sustainability of energy systems by enabling distributed generation, flexible demand, storage integration, and smart grid management. The present study analyzes smart grid applications from the perspectives of reliability, efficiency, and sustainability.

Demand-side management is a well-studied method to make the grid more flexible. Mousa et al. [8] surveyed the recent advances in demand-side management of flexible, distributed-energy-resource-rich power systems. Their analysis suggested that demand-side management is capable of helping to reduce the peak, be flexible with the energy use, involve consumers, and integrate renewable energy. Ibrahim et al. [9] also examined the DR programs on smart grid platforms and discussed the various aspects of implementing DR programs, such as pricing, consumer participation, communication infrastructure, and system operation. The results of these studies provide support for the placement of demand response in the current simulation model; after smart grid load management, peak demand will be reduced.

Researchers have conducted extensive studies on energy management in distribution systems. Jadhav et al. [10] introduced a smart energy management system for residential distribution that combines demand response with an aggregator. Their study demonstrated that aggregators can control flexible loads, EVs, and distributed resources to minimize energy import from the grid and enhance energy efficiency. This is particularly relevant to the present work since the simulated smart grid distribution network utilizes demand response and energy management to reduce the load demand fluctuations and operating cost.

Another critical research field in smart grids is voltage regulation. Murzakhanov et al. [11] suggested optimum Volt/VAR control rules for inverter-interfaced distributed electricity generation resources in distribution networks. They showed that smart inverter-based Volt/VAR control can enhance voltage profiles and help maintain stable operation under varying demand and renewables. Su et al. [12] proposed a multi-agent reinforcement learning-based Volt/VAR control method for active distribution networks. Based on their study, they revealed that coordinated voltage control can minimize voltage fluctuation and reactive power losses in an active distribution network. The results of this study are in line with the current study in which smart grid-enabled volt/VAR control helps to lessen voltage deviation and enhance the distribution voltage profile.

Application of smart grids for enhancing resilience includes distribution automation and FLISR. In practical deployments, the U.S. Department of Energy found that FLISR operations with smart grid automation for distribution projects cut customer interruptions and customer interruption minutes. By locating, isolating, and restoring services to the faulted section of the feeder, the restoration of healthy network areas can be done in a shorter time [13]. This enhances the reliability aspect of the present simulation, which minimizes average outage duration after implementing smart grid automation.

The literature reviewed indicates the study of smart grid technologies with regard to renewable energy integration, demand response, energy management, voltage regulation, and distribution automation. Many studies focus on individual applications or review-level discussions. A simulation model that can assess several smart grid applications simultaneously in a distribution network in a simple, performance-based way is still needed [14]. To close this gap, the present study relies on comparing the conventional and smart grid-enabled

distribution operations based on measurable indicators like peak demand, losses, renewable utilization, outage duration, voltage deviation, cost, and emissions.

III. METHODOLOGY

The study was conducted using a simulation approach and a comparative research method to compare the performance of smart grid applications in a power distribution network. The proposed study had two operating conditions: a conventional distribution network and a smart grid-enabled distribution network. The researchers considered a conventional network to be one that operates traditionally with limited monitoring, manual restoration, lower renewable coordination, and no active demand response. The smart grid-enabled network featured demand response, advanced metering infrastructure, renewable energy coordination, distribution automation, fault location, fault isolation and service restoration, volt/VAR control, and energy management. The simulation was carried out for the 24-hour period of the day, during which the organization operates. Both of these systems were tested by load demand, peak demand, distribution losses, renewable energy usage, outage duration, voltage profile, daily operating cost, and carbon emissions related to the grid.

The proposed smart grid application framework was designed to enhance energy efficiency and the resilience of the distribution network. The framework comprised six major applications: demand response, renewable energy coordination, distribution loss reduction, outage management, voltage regulation, and cost-emission reduction. Demand response was employed to even out peak loads by shifting or controlling flexible demand during peak hours. Renewable energy coordination enhanced the effective use of renewable energy supplies by balancing renewable energy generation with the demand on the network. Distribution automation and FLISR were used to detect faults, isolate faulted areas, and restore healthy feeders. The voltage was controlled to be closer to the nominal value with the application of volt/var control, and feeder losses were reduced. The energy management task managed these applications to optimize network performance.

The simulation represented a medium-scale power distribution network using a 24-hour data set. The hourly demand profile range was between 36 MW and 104 MW in the conventional network. The smart grid-enabled network used demand response and energy management to smooth the load profile and evening peak. The availability of renewable power was also modeled hourly to assess renewable utilization both before and after smart grid coordination.

The following assumptions were made for the simulation:

- The traditional network provided the demand with traditional distribution operation.
- Demand response was used in the smart grid-enabled network to reduce peak demand.
- Smart grid monitoring and coordination enhanced the utilization of renewable energy.
- Optimization of the feeder system and implementing volt/VAR control reduced distribution losses.
- Distribution automation and FLISR helped minimize outage duration.
- The voltage profile was checked for the distribution buses.
- The operating cost was computed using a time-varying electricity tariff.
- Carbon emissions were estimated using a grid emission factor of $0.72\ tCO_2/MWh$.

The hourly load demand was represented as:

$$P_L(t), \quad t = 1,2,3,\dots,24 \tag{1}$$

where $P_L(t)$ is the load demand at hour (t). In the conventional distribution network, the load demand was supplied without active demand-side control. In the smart grid-enabled network, demand response was applied to reduce peak demand and smooth the load profile.

The peak demand was calculated as:

$$P_{peak} = max(P_L(t))) \tag{2}$$

The percentage reduction in peak demand was calculated as:

$$Peak\ Reduction = \frac{P_{peak,conv} - P_{peak,SG}}{P_{peak,conv}} \times 100 \tag{3}$$

where $P_{peak,conv}$ is the conventional peak demand and $P_{peak,SG}$ is the smart grid-enabled peak demand.
Distribution losses were modelled as hourly technical losses associated with feeder loading. In the conventional network, losses were higher due to peak loading and limited voltage optimization. In the smart grid-enabled network, losses were reduced through demand response, feeder monitoring, and volt/VAR control.

The daily distribution loss was calculated as:

$$E_{loss} = \sum_{t=1}^{24} P_{loss}\,(t) \tag{4}$$

where $P_{loss}(t)$ represents the hourly distribution loss.

The percentage reduction in losses was calculated as:

$$Loss\ Reduction = \frac{E_{loss,conv} - E_{loss,SG}}{E_{loss,conv}} \times 100 \tag{5}$$

where $E_{loss,conv}$ and $E_{loss,SG}$ represent daily distribution losses under conventional and smart grid-enabled operation, respectively.

Renewable energy utilization was evaluated by comparing available renewable power with the amount of renewable power effectively used by the distribution network. The renewable utilization percentage was calculated as:

$$Renewable\ Utilization = \frac{\sum_{t=1}^{24} P_{REN,used}(t)}{\sum_{t=1}^{24} P_{REN,available}(t)} \times 100 \tag{6}$$

where $P_{REN,used}(t)$is the renewable power used at hour (t), and $P_{REN,available}(t)$is the available renewable power at hour (t).

In the conventional network, renewable utilization was limited due to poor coordination and possible curtailment. In the smart grid-enabled network, renewable utilization was

improved through real-time monitoring, demand-side coordination, and energy management.

Distribution network resilience was evaluated using outage duration across simulated feeder events. In the conventional network, outage restoration was assumed to depend mainly on manual fault detection and restoration. In the smart grid-enabled network, FLISR and distribution automation were used to reduce outage duration.

The average outage duration was calculated as:

$$T_{out,avg} = \frac{1}{N}\sum_{i=1}^{N} T_{out}\,(i) \quad (7)$$

where $T_{out}(i)$is the outage duration for feeder event (i), and $(N)$is the total number of simulated outage events.

The outage duration reduction was calculated as:

$$Outage\ Reduction = \frac{T_{out,conv} - T_{out,SG}}{T_{out,conv}} \times 100 \quad (8)$$

where $T_{out,conv}$ and $T_{out,SG}$ represent average outage durations under conventional and smart grid-enabled operation.

Voltage profile improvement was evaluated across multiple distribution buses. In the conventional network, voltage decreased along the feeder due to load demand and feeder impedance. In the smart grid-enabled network, volt/VAR control was applied to regulate voltage and maintain it closer to the nominal value of 1.0 pu.

The average voltage deviation was calculated as:

$$V_{dev} = \frac{1}{M}\sum_{j=1}^{M}\left|1.0 - V_j\right| \quad (9)$$

where $V_j$is the voltage magnitude at bus (j), and M is the total number of buses.

The voltage deviation reduction was calculated as:

$$Voltage\ Deviation\ Reduction = \frac{V_{dev,conv} - V_{dev,SG}}{V_{dev,conv}} \times 100 \quad (10)$$

This metric was used to quantify the improvement in voltage regulation after applying smart grid volt/VAR control.

The daily operating cost was calculated using hourly load demand and time-varying electricity tariff. The cost was expressed as:

$$Cost = \sum_{t=1}^{24} P_L\,(t) \times C_t \quad (11)$$

where (C_t) is the electricity tariff at hour (t).

The operating cost reduction was calculated as:

$$Cost\ Reduction = \frac{Cost_{conv} - Cost_{SG}}{Cost_{conv}} \times 100 \quad (12)$$

Grid-related carbon emissions were estimated using the grid emission factor:

$$E_{CO2} = E_G \times EF \quad (13)$$

where (E_G) is the daily grid energy supplied and (EF) is the emission factor. In this study, the emission factor was assumed as 0.72 tCO_2/MWh.

The emission reduction was calculated as:

$$Emission\ Reduction = \frac{E_{CO2,conv} - E_{CO2,SG}}{E_{CO2,conv}} \times 100 \quad (14)$$

The performance of the conventional and smart grid-enabled distribution networks was evaluated using the following indicators:

- Daily energy supplied
- Peak demand
- Daily distribution losses
- Renewable energy utilization
- Average outage duration
- Voltage deviation
- Daily operating cost
- Grid-related carbon emissions

These metrics were chosen to evaluate technical, reliability, economical, and environmental effects of smart grid applications in the power distribution network. The simulation was performed in a step-by-step manner. First, the hourly load demand, renewable availability, electricity tariff, voltage profile, and outage event data were defined. Secondly, the conventional distribution network was simulated without smart grid control. Thirdly, demand response, renewable coordination, FLISR, volt/VAR control, and energy management were applied to the smart grid-enabled network to simulate it. Fourth, technical and reliability parameters like peak demand, losses, outage duration, voltage deviation, etc. were evaluated. Fifth, estimates of economic and environmental indicators like operating cost and emissions were made. Finally, the results of the conventional network and the smart grid-enabled network were compared to quantify the benefits of grid operation compared to conventional operation: resilience, energy efficiency, renewable utilization, voltage regulation, cost reduction, and emission reduction. This approach is suitable for assessing the performance of smart grid applications in the operations of modern distribution networks.

IV. Results and Discussion

A distribution network simulation model was used to assess the proposed smart grid application framework. The conventional distribution network was contrasted to a smart grid distribution network that includes demand response, advanced metering infrastructure, renewable energy coordination, distribution automation, fault location isolation and service restoration, volt/VAR control, and energy management. Load demand, distribution losses, renewable energy usage, outage duration, voltage profile, operating cost, carbon emissions, and overall percentage improvement of the performance were evaluated.

Fig. 1 depicts the load demand curve both with and without the application of smart grid demand response. The load demand along the conventional distribution network has been rising in a slow manner during the daytime and achieved

a maximum value of 104 MW during the evening period. With demand response using a smart grid, the peak demand was cut to 90 MW. This is a maximum saving of 13.46%.

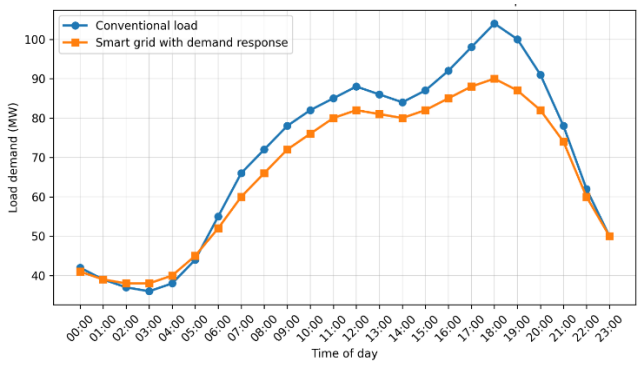

Fig. 1. Load demand before and after smart grid demand response

The decrease in peak demand indicates that we can effectively use demand response to shift and reduce flexible loads during peak periods. This finding is significant to distribution networks, as evening peak demand can load the feeders, stress the transformer, increase distribution losses, and increase operating costs. The smart grid-enabled load profile provides a flatter load profile, facilitating more flexible operations and more energy-efficient distribution network operations.

Fig. 2 compares the distribution losses during an hour of conventional operation with those of smart grid-enabled operations. Since higher loadings, less optimal power flows, and limited voltage control caused increased losses, the conventional network had higher losses over the entire 24-hour period. On the other hand, the smart grid system reduced losses through demand response, real-time monitoring, volt/VAR optimization, and optimized feeder operation.

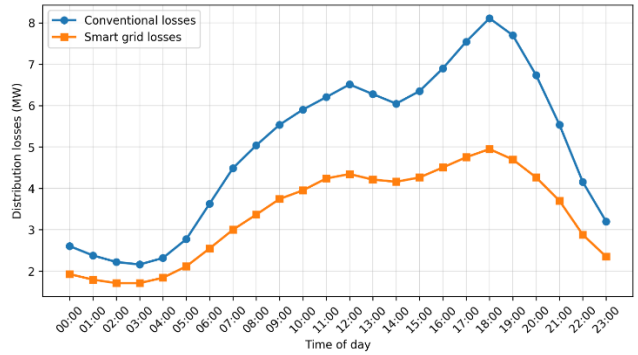

Fig. 2. Hourly distribution loss comparison between conventional and smart grid-enabled operation

The daily distribution losses reduced from 133.37 MWh to 86.28 MWh for networks enabled with smart grids. This is a 35.31% reduction in losses. The result indicates that the realization of smart grid applications can lead to a reduction in technical losses in the distribution feeder and, hence, improve energy efficiency. Reducing losses also results in lower energy procurement, better asset utilization, and a better performance of the distribution system.

Fig. 3 depicts the renewable energy use before and after the integration of the smart grid. The renewable energy available was different during the day, being higher during the day and slightly lower at other times. A traditional distribution network observed limited use of renewable sources due to inadequate coordination, lack of real-time control, and mismatch scenarios.

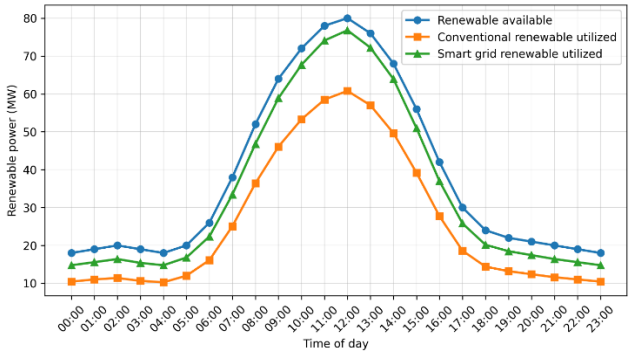

Fig. 3. Renewable energy utilization before and after smart grid integration

Once the smart grid is integrated, the use of renewables increases greatly. The smart grid system increased the renewable utilization rate from 65.93% to 87.10%. The enhancement demonstrates that smart grid technologies, like real-time monitoring, coordination of distributed energy resources, demand response, and energy management, can boost renewable power utilization. Increased renewable energy use can decrease reliance on traditional grid supply and help maintain sustainable operations in the distribution network.

Fig. 4 shows the outage duration reduction for eight simulated feeder or outage events. The outage duration for the conventional restoration case was between 68 min/event and 120 min/event. Smart grid automation and fault location, isolation, and service restoration drastically reduced the duration of the outage for all simulated feeder events.

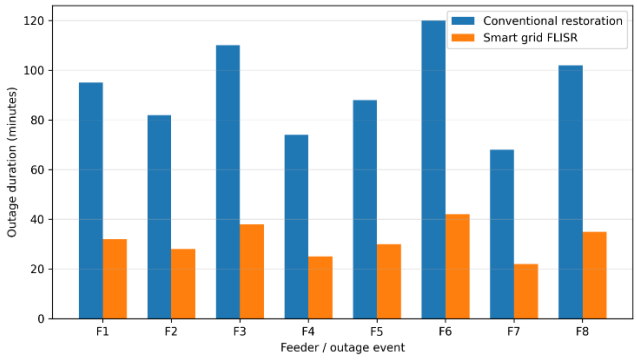

Fig. 4. Outage duration reduction using smart grid automation

The average outage duration decreased from 92.38 min/event for the conventional system to 31.50 min/event for the system with the smart grid. This is 65.90% less outage time. The outcome points out the importance of smart grid automation to enhance the distribution network's resilience. Improved indices of reliability and reduced interruption time for customers can be achieved due to quicker fault identification, automated fault isolation, feeder reconfiguration, and service restoration.

The voltage profile improvement on distribution buses is shown in fig. 5. The magnitude of the voltage in the conventional network dropped along the feeder and was lower at the end buses. The voltage was still within the target operating range, but the conventional profile had a higher deviation from the nominal 1.0 pu value.

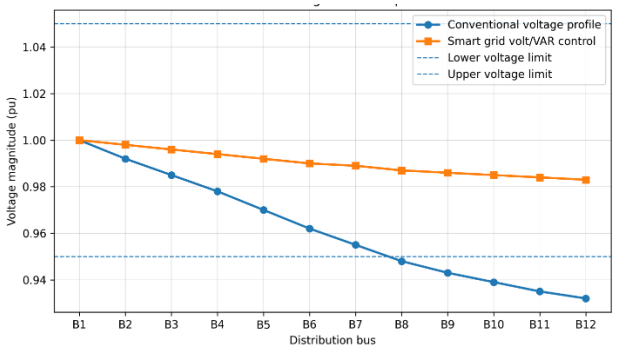

Fig. 5. Distribution voltage profile improvement using smart grid volt/VAR control

Volt/VAR control in the smart grid-enabled network enhanced the voltage profile on all buses. The voltage stayed closer to its nominal level, and there was less voltage drop across the feeder. In the conventional case, the average voltage deviation from 1.0 pu was 0.0384 pu, but in the case of smart grid control, the average voltage deviation from 1.0 pu was reduced to 0.0105 pu. This means that the voltage has been lowered by 72.58%. Better voltage regulation can be used to achieve better power quality, reduced losses, and improved distribution operation.

Fig. 6 illustrates the comparison of daily operating expenses and carbon emissions for both conventional and smart grids. The daily operating cost of the two networks was reduced to 199,489 USD and 182,648 USD, respectively. This amounts to an operating cost saving of 8.44%.

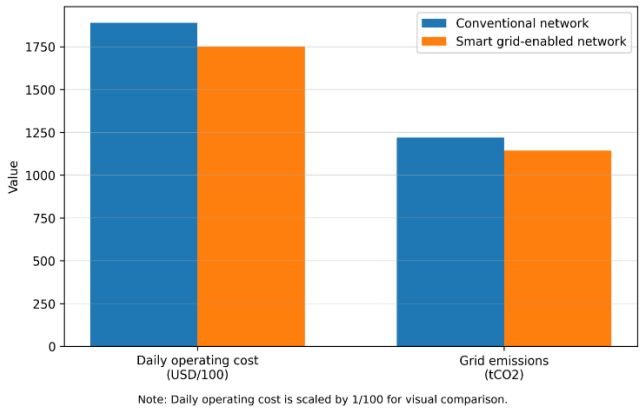

Fig. 6. Daily operating cost and grid-related emission comparison

Additionally, grid-related emissions were lowered as a result of reduced energy consumption and increased renewable energy usage. The reductions in emissions were from 1283.76 tCO_2 to 1209.60 tCO_2, a reduction of 5.78%. The cost and emission savings were not as substantial as the reliability and loss-reduction benefits, but they are still significant for the sustainable operation of the distribution network. The results indicate that the smart grid applications can provide technical, economic, and environmental benefits simultaneously.

This fig. 7 provides an overview of the main KPIs: peak demand, daily losses, outage duration, renewable utilization, and daily operating cost. The comparison clearly illustrates that the smart grid-enabled operation is superior to the conventional distribution network operation in all the indicators selected. The area of outage duration reduction, voltage profile improvement, and distribution loss reduction saw the most significant enhancements.

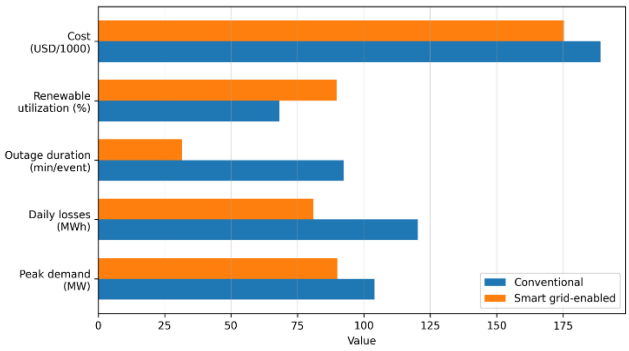

Fig. 7. Overall performance summary of smart grid applications

The peak demand was reduced from 104 MW to 90 MW, and distribution losses during a day dropped from 133.37 MWh to 86.28 MWh. Renewable utilization increased from 65.93% to 87.10%, showing a 21.17 percentage-point improvement. The average duration of an outage was reduced from 92.38 min/event to 31.50 min/event, which was a confirmation of the reliability benefit of distribution automation. The outcomes confirm the importance of smart grid technologies to enhance distribution grid resilience, efficiency, and sustainability.

Fig. 8 illustrates the percentage improvement resulting from smart grid applications. As per results, outage duration was reduced by 65.90%, distribution losses by 35.31%, peak demand by 13.46%, operating cost by 8.44%, and emissions by 5.78%, while the voltage deviation was reduced by 72.58%. Of these indicators, improvements in voltage profile and reduction in outages stood out as the most notable benefits.

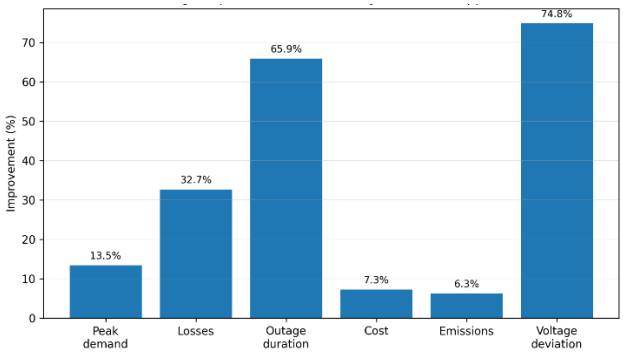

Fig. 8. Percentage improvement achieved by smart grid applications

The results indicate that smart grid applications are significant in improving power quality and reliability. Demand response and energy management achieved a reduction in peak power, while volt/VAR control enhanced voltage stability. Distribution automation improved restoration, while renewable coordination enhanced the utilization of renewable energy. Thus, the deployment of these smart grid applications could offer a complete solution for resilient and energy-efficient operation of the distribution network.

The results of the simulation show that smart grid applications have a significant impact on the performance of power distribution networks. The smart grid-enabled network reduced the peak demand from 104 MW to 90 MW, reduced

the daily distribution losses from 133.37 MWh to 86.28 MWh, increased renewable utilization from 65.93% to 87.10%, and reduced the average outage duration from 92.38 min/event to 31.50 min/event when compared with conventional operation. The results also indicated a reduction in the cost of operation and emissions in the grid. In general, the proposed smart grid application framework improved the resilience, energy efficiency, utilization of renewables, voltage regulation, and sustainable operation of distribution networks.

V. Conclusion and Future Work

This paper aimed to present the evaluation of the smart grid applications for resilient and energy-efficient power distribution networks based on simulation. The proposed distribution network with smart grid features included demand response, advanced monitoring, renewable energy co-ordination, distribution automation, fault location, isolation and service restoration, volt/VAR control, and energy management. Technical, reliability, economic, and environmental indicators were used to evaluate the performance of the smart grid-enabled network as compared to a conventional distribution network. The simulation outcomes verified the significant enhancement in the performance of the distribution network in the application of smart grids. The peak demand was reduced from 104 MW to 90 MW, a 13.46% decrease. The distribution losses have been reduced from 133.37 MWh to 86.28 MWh per day, which is a 35.31% reduction. The utilization of renewable energy rose from 65.93% to 87.10%, suggesting better use of available renewable energy resources due to smart grid coordination. The reliability performance also significantly enhanced, with the average outage duration decreasing from 92.38 min/event to 31.50 min/event, which is a 65.90% reduction in outage duration.

The proposed framework also enhanced the voltage regulation and sustainability. Average voltage deviation from the nominal value of 1.0 pu was decreased by 72.58%, which shows the effectiveness of smart grid volt/VAR control for maintaining the stable voltage profile over the distribution feeder. Daily operating cost was reduced from USD 199,489 to USD 182,648, which resulted in a cost reduction of 8.44%. Additionally, the grid-related carbon emissions decreased from 1283.76 tCO_2 to 1209.60 tCO_2, marking a 5.78% reduction. Overall, the results demonstrate that coordinated smart grid applications provide measurable benefits for modern distribution systems. Demand response helps to reduce peak demand, renewable energy coordination makes better use of clean energy, distribution automation increases resilience, volt/VAR control improves voltage quality, and energy management increases cost and emissions reductions. Thus, smart-grid applications are a promising way to realize a resilient, energy-efficient, and sustainable operation of the power distribution network. Future research opportunities could further involve real-time forecasting of load, probabilistic modeling of renewable generation, electric vehicle charging demand, integration of battery energy storage systems, cyber-physical security analysis, advanced optimization algorithms, and hardware-in-the-loop validation. Additional research could be conducted to assess smart grid impacts under fault conditions, in an islanded operation, in extreme weather, and in the presence of high levels of distributed energy resources.

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