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Evaluation of grid performance under time-series DERs and storage penetration scenarios

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ABSTRACT

The electricity grid plays a pivotal role in facilitating the transition to a carbon-neutral economy. Concurrently, there has been a marked increase in the generation of renewable energy. Energy storage is imperative to ensure the balance between generation and consumption demand in weather- and time-dependent systems, such as photovoltaic and wind energy. This article presents the modeling, simulation, and performance study of a grid fed from a substation connected to DERs, and an assessment of its impact on the grid for steady state and 24-hour time-series conditions between generation and consumption. All models are derived probabilistically for time-series simulations and steady-state load flow analysis. According to the simulation results, DERs have a beneficial effect on voltage stability, provided the penetration level is appropriate. At the optimal penetration level, the short-circuit contribution of DERs is estimated to be between 1.5% and 2%. However, when the penetration level is increased, the contribution increases to 3.5%, resulting in a voltage profile of 1.04 pu. In instances of optimal penetration, 70% of the generated energy is consumed on site, thereby reducing line losses. The contribution to reactive power ranges from 5% to 7.5%. In the time-series analysis, with the inclusion of BESS, it has been demonstrated that 93% of the energy demand can be met by DERs at certain times of the day, and that it functions satisfactorily to provide energy to the load.

I. INTRODUCTION

The advent of industrialization, population growth, and improvements in living standards have precipitated a precipitous rise in global energy demand in recent years. This increase has precipitated a series of challenges, including energy shortages and environmental degradation. The Paris Climate Agreement stipulates that to achieve the objective of limiting the increase in global temperature to 1.5°C, it is necessary to achieve a 45% reduction in emissions by the year 2030 and to reach net zero emissions by the mid-century. An analysis of the greenhouse gas inventory reveals that the energy sector is the primary source of anthropogenic greenhouse gas emissions [1]. A critical step in addressing this issue is the generation of electricity from renewable energy sources (RES).

From 2016 to 2024, the growth rate of renewable energy will exceed that of fossil fuels by a factor of three. Among these energy sources, solar energy has the most advanced technology and the widest application [2]. This growth is increasing worldwide, primarily due to heightened awareness among energy users, advancements in technology, government support, incentives, policies, and the declining costs of green energy as its use rises. Energy production in the world and in Turkey is still largely dependent on fossil fuels (oil, gas, and coal) [3]. However, the utilization of nuclear energy persists in certain nations. As renewable energy continues to expand due to concerns regarding climate change and technological advancements that reduce production costs, there is a shift in the energy sources utilized [4].

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The accelerated development of energy production from renewable sources is profoundly altering energy systems and markets worldwide. For instance, it is emphasized that policy uncertainties in climate can significantly affect institutional investments in the energy sector and thus affect market dynamics. Energy markets, which have historically been designed for predictable and controllable load patterns, are now confronted with the challenge of accommodating the intermittent output of RES. This dynamic environment poses a significant challenge, namely the need to maintain equilibrium between supply and demand in real time while ensuring the efficient allocation of production resources [5].

The contemporary electricity systems are characterized by a centralized structure, whereby high-voltage transmission networks facilitate the transmission of energy from interconnected large power plants, and low-voltage distribution networks ensure the delivery of energy to consumers. The overarching objective of this centralized framework is to deliver energy to energy loads in an economical and reliable manner [6].

However, as the future of electricity generation is increasingly shifting toward a decentralized, distributed structure (the primary reason being the connection of smaller-scale production facilities to the system), decentralized distribution is replacing the traditional centralized power source. This shift is leading system operators to have less control over DERs [7].

Distributed RES, which are sustainable and clean energy sources, have been shown to reduce the carbon footprint and power losses caused by long-distance transmission. Consequently, there is a prevalent interest in establishing a grid that facilitates integration, thereby reducing the burden on the electricity grid for local power suppliers utilizing RES. Distributed energy resources (DERs) integrated into the system can provide energy for load demand as a microgrid, and excess DERs power can be transferred to the grid with a feed-in tariff (FiT) [8].

The generation of electricity from photovoltaic (PV) and wind energy is contingent upon meteorological conditions that are inherently unstable and difficult to predict. This inherent variability leads to deficiencies in these energy sources, including intermittent operation and a misalignment between energy production and energy demand [8].

It has been established that energy production is abundant in locations exhibiting elevated levels of irradiation. The impact of DERs on technical losses in the distribution system has been a subject of numerous investigations, which have concluded that local production can lead to a reduction in losses. However, in scenarios characterized by high penetration of DERs, the energy production from these sources can lead to an augmentation in distribution losses [9].

The integration of DERs has the potential to disrupt the operation of existing electricity grids, often resulting in saturated load levels and elevated power flows within the electricity distribution system [9]. DERs have been shown to have several positive effects, including the reduction of power loss, the enhancement of hosting capacity, the facilitation of fault management, the support of both voltage and frequency variations, the improvement of voltage profiles, particularly during periods of peak demand, and the augmentation of the resilience of the electricity grid. However, DERs have the potential to induce voltage and frequency instability, sags and swells, voltage imbalances, increased reactive power, and power quality issues (e.g., signal voltage and current distortion). Furthermore, DERs can lead to increased power losses due to electrical protection failures, reduced hosting capacity, and disconnection of distributed generation (both active power outages and active power reductions) [10].

Within the broader context of low-carbon technologies in electrical grids, grid operators have integrated smart solutions to ensure supply security, stability, and reliability while effectively managing electrical grids. Battery energy storage systems (BESS) are regarded as a sophisticated solution for providing a variety of ancillary services that have recently been adopted by grid operators [6].

Although distributed BESSs were initially designed to increase the self-consumption of RES producers connected to low voltage (LV) or medium voltage (MV) grids [4], they are also recommended to ensure the efficient and secure operation of distribution grids by providing numerous functions, such as ancillary services and active/reactive power control [11].

BESSs are regarded as one of the most effective and efficient measures for increasing the operational flexibility of energy systems. Additionally, they have been identified as a potential solution to the problem of global warming [6].

BESSs play a vital role in addressing grid problems caused by DERs, contributing significantly to grid stability by responding quickly to changes in supply and demand and stabilizing short-term fluctuations in renewable energy generation capacity. Storage facilitates the shifting of peak loads to periods of low demand. Consequently, energy not utilized by customers during periods of high demand is stored and accumulated for subsequent use in situations necessitating load shifting and peak shaving [12]. The optimization of capital resources can be achieved through the augmentation of BESS systems. This augmentation in online renewable energy is accompanied by the pivotal role of energy storage in ensuring system reliability. The capacity lost during peak periods can be recuperated subsequently, a process facilitated by stored energy [4]. While storage systems incur certain initial expenses, they can ultimately yield a net benefit through the reduction of individual unit and infrastructure investments over time. In essence, BESSs furnish electrical systems with flexibility and power, thereby facilitating more efficient allocation and addressing unexpected problems. By leveraging these features, energy storage is steering the world toward a cleaner, more reliable energy future [13].

The integration of DERs into the electricity grid is a recent development that has introduced a new level of complexity. To address the challenges posed by this integration, particularly in the context of utilizing existing grid infrastructure, the practice of combining batteries with DERs has emerged. This combination, often referred to as DER-BESS (distributed energy resources-battery energy storage systems), represents a significant development in the field of energy storage and management. Ongoing technical advancements and cost reductions are expected to strongly encourage and implement the connection of DER-BESS systems to the grid [8]. In this context, Turkey has approved the installation of 30,000 MW of DER-BESS systems by 2024.

Appropriate DER system, energy management between batteries and the grid, and end users are of great importance to system operators to achieve the desired performance.

In practice, different stakeholders have their own concerns about different aspects of DER-BESS performance. For instance, end users prioritize economic efficiency, TOU pricing, SPT, real-time pricing, and minimizing operating costs. Conversely, the electricity grid operator prioritizes grid stability, that is, ensuring the smooth exchange of power with the grid. Specifically, this entails minimizing power losses, enhancing voltage profiles, adjusting short-circuit levels, and alleviating grid line capacity utilization [14].

Consequently, it is imperative to investigate the impact of DER integration on the grid's operational capacity and to identify potential beneficial configurations [15].

Consequently, a multitude of technical considerations must be considered when evaluating the advantages and disadvantages of such penetration [2]. A substantial body of research has been dedicated to examining the impact of DER penetration. However, a significant proportion of these studies have been analyzed under steady-state conditions.

The present study focuses on the quasi-dynamic analysis of parameters affecting energy quality based on 24-hour generation and consumption values of DERs and DER-BESS integration. The analysis considers all outputs of the distribution grid (7 feeder outputs) supplied by a substation (154/33 kV). The energy infrastructure comprises four PV power plants, one wind power plant, and one BESS system. The results of the load flow analysis were then compared and interpreted in relation to grid stability, voltage profile, short-circuit contribution, active/reactive power, and losses for all medium-voltage feeders in the distribution grid with DER-BESS integration. The present study was conducted using DIGSILENT-Power Factory, a software that provides comprehensive modeling and simulation for power systems.

II. EXPERIMENTAL METHOD / TEORETICAL METHOD

2.1 Distributed Generation Technology

The architecture of the electricity grid is undergoing a major transformation, with efforts to phase out generators that produce greenhouse gases and replace them with RES [16]. Consequently, this substantial modification necessitates the implementation of novel functionalities within distribution feeders, allowing for the assessment of an expanded array of variables that were not previously measurable within the conventional framework. Furthermore, the integration of additional controllable devices and resources within distribution feeders is imperative.

Distributed generation is defined as small or medium-scale power generation sources located near load centers [17]. Distributed generation sources encompass a range of RES, including solar, wind, hydro turbines, geothermal, and biomass, as well as diverse energy sources such as fuel cells, gas turbines, diesel generators, and energy storage devices [7].

Distributed generation sources encompass a wide array of energy sources, including RES such as solar, wind, and hydro turbines; geothermal energy; biomass; and energy storage devices, as well as fuel cells, gas turbines, and diesel generators [17]. However, numerous studies in the extant literature have addressed the fact that DERs included in the system without the necessary technical analyses can cause power quality parameter degradation and even long-term outages in the system.

In the context of power quality issues, the sizing and location of DERs, the hosting capacity of the grid to be connected, the balancing problems in the grid to which DERs are connected, changes in grid voltage, short circuit contribution, line losses, reactive power contribution, and the effect on harmonics are considered. Numerous methods and techniques have been proposed in the literature to optimize these effects [7]. n this study, steady-state and hourly analyses were conducted on the effects of DER connection on voltage, short-circuit contribution, line losses, and reactive power contribution [18, 19].

2.2 System Methodology

The configuration of the grid in the DIgSLIENT PowerFactory program comprises a 154/33 kV main substation and seven medium voltage feeders, as illustrated in the single-line diagram presented in Figure 1. The two feeders in question are ring grids. Bus 6 is directly connected to the DM and has a ring via buses 3 and 4. The system comprises four photovoltaic (PV) power plants and one wind power plant. Additionally, a DER-BESS energy storage system is in place. The battery-based energy storage system is connected to the PV power plant.

DERs are integrated into the system and placed considering the load and generation relationship to comprehensively examine their impact on the grid. The consumption profile of the modeled distribution grid encompasses users such as villages, agricultural irrigation, residences, small businesses, government offices, and mines. The distribution grid supplies an area of approximately 1500 square kilometers. The medium voltage distribution grid is comprised of a 161.3-kilometer distribution network. Of the total length, 0.3 km consists of XLPE cable, while 161 km is designated for energy transmission. According to data obtained from the Photovoltaic Geographical Information System (PVGIS) program, the annual average irradiation is approximately 1582.26 kWh/m²/year. According to data from the Meteorology Directorate collected in 2021, the average wind speed is estimated to be approximately 7.8 meters per second. The transformer's installed power is measured at 50/62.5 MVA, with an occupancy rate of 72.6% (equivalent to 36.3 MVA).

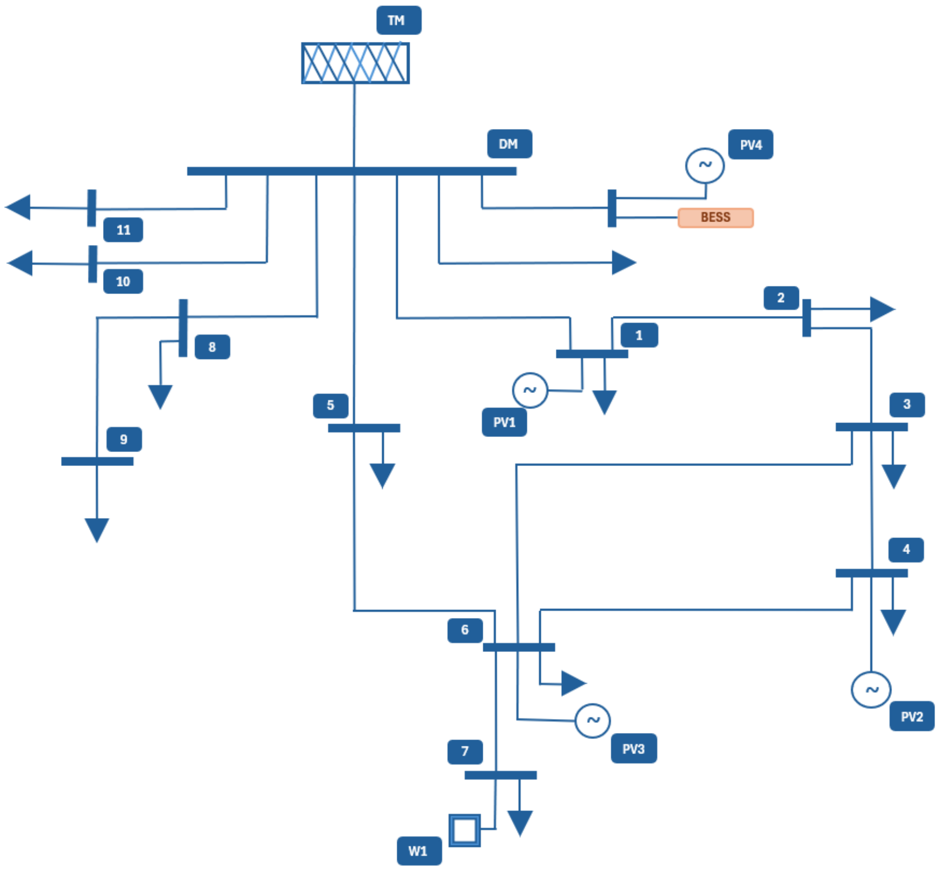

Figure 1. Single line diagram

The initial status of the system was ascertained through the execution of analyses grounded in steady-state principles for the electricity distribution grid.

In the second scenario, the full-time effects of the relationship between generation and consumption were examined. To this end, quasi-dynamic analyses were performed based on average values for each hour between 00:00 and 24:00. The hourly data on generated energy, consumed energy, and storage for all assets in the electricity distribution grid were considered.

2.3 System Parameters

The analyses were calculated using the DIgSLIENT PowerFactory program for both steady state and 24-hour time series. In the steady state, the analysis results were compared between a scenario where DERs were not included in the system and were supplied from a single substation and a scenario where DERs were included in the system.

Table 1 presents the characteristic data of the substation. The substation is 154/33 kV, 50/62.5 MVA. The total power drawn from the transformer is 36.3 MVA. The total power of the DERs added to the system is selected as 32 MVA. As illustrated in Table 2, the distances and line types of the medium voltage feeders emanating from the substation are delineated. A mere 0.3 km of XLPE underground cable is utilized between the substation and the distribution center, while the remainder of the distribution grid comprises overhead lines. As illustrated in Table 3, the line distances and conductor cross-sections employed for the interconnection of DERs to the grid are delineated. Typically, 3x3/0 AWG conductors were selected for DER connections; however, at the point where the DER-BESS connection is to be made, 3x477 MCM conductors were selected, considering the PV power. Table 4 presents the aggregate grid loads for each user at each bus point. The total network load is 36.3 MVA. Table 5 presents the connection powers for each DER. The grid comprises one wind power plant with a capacity of 10 MW, four PV power plants with a total capacity of 22 MW connected at different points, and one BESS connected with the same power as the PV. Load flow analyses were conducted using the DIgSLIENT PowerFactory program, with the relevant data specified in the following tables.

Table 1. Substation technical specifications

TM	
U	154/33 kV
S	50/62.5 MVA
Connection Group	YNyn0

Table 2. Feeder distances and lines characteristics in grid

Node		**Line**	**Distance *(km)***
TM	DM	3x(1x240/25) XLPE	0.3
DM	BUS_1	2x(3x3/0) AWG	19.2
BUS_1	BUS_2	2x(3x3/0) AWG	3.8
BUS_2	BUS_3	3x3/0 AWG	3.1
BUS_3	BUS_4	3x3/0 AWG	12.0
BUS_4	BUS_6	3x3/0 AWG	19.6
BUS_3	BUS_6	3x1/0 AWG	31.4
DM	BUS_5	3x3/0 AWG	7.0
BUS_5	BUS_6	3x3/0 AWG	8.2
BUS_6	BUS_7	3x3/0 AWG	12.0
DM	BUS_8	2x(3x3/0) AWG	9.5
BUS_8	BUS_9	3x477 MCM	6.0
DM	BUS_10	2x(3x477) MCM	21.0
DM	BUS_11	3x3/0 AWG	8.2

Table 3. Grid connection parameters of DERs distance and line cross-section

Node		**Line**	**Distance *(km)***
DM	PV_4 +BESS	3x477 MCM	10.3
BUS_1	PV_1	3x3/0 AWG	5.0
BUS_4	PV_2	3x3/0 AWG	5.4
BUS_6	PV_3	3x3/0 AWG	4.0
BUS_7	W_1	3x3/0 AWG	2.1

Table 4. Loads on the feeders at the point of common coupling

Node	**Load *(MW)***
DM	2.5
BUS_1	1.2
BUS_2	11.67
BUS_3	0.63
BUS_4	1.5
BUS_5	2.7
BUS_6	2.5
BUS_7	1.5
BUS_8	3.2
BUS_9	0.5
BUS_10	0.4
BUS_11	8.0
Total	***36.3***

Table 5. Active power of DERs connected to the grid

Busbar	**P *(MW)***
PV_1	1
PV_2	6
PV_3	5
PV_4	10
W_1	10
BESS	10
Total	***42***

III. RESULTS AND DISCUSSIONS

3.1 Steady-State Case Analysis Results

3.1.1. Voltage profile

The impact of DERs on the voltage stability of the local electricity grid is subject to variation [10]. In an electrical grid with high DER penetration, voltage stability issues are compounded by the integration of renewable energy, which alters the original power flow distribution, line transmission power, and inertia of the entire system [20]. However, the transient stability of the power system is not undergoing significant changes.

In the steady-state analysis, separate load flow analyses were performed for two conditions in the system: with and without DERs. The operating voltage was designated as 31.5 kV, 1 pu. The results of the analysis, as presented in Table 6 and Figure 2, indicate a substantial increase in voltage in the buses (8, 9, 10, 11) where DERs are not directly connected. The observed increase in power output of 0.01 pu in these buses is attributable to the fact that not all the energy generated by buses 1, 4, and 7 (to which DERs are connected via the DM) is consumed. This results in a power flow back to DM.

Legislation pertaining to the voltage variation range at medium voltage levels is not in effect in Turkey. Many international standards pertaining to the interconnection of DERs permit a voltage variation of ±5%. Therefore, voltage levels ranging from 0.95 pu to 1.05 pu are considered acceptable. Pursuant to the aforementioned baseline values, voltage drops due to distance are presently occurring on buses 1, 2, 3, and 4. The voltages present on these buses are 29.7, 29.4, 29.3, and 28.9 V, in that order. As illustrated in Table 6, the values in question are expressed in pu units. However, the integration of DERs into the system has led to an observed increase in voltage values on buses 1, 2, 3, and 4. These values, ranging from 30.1 to 29.9 to 29.9 to 30.4 V, respectively, signify an enhancement in voltage levels within the system. The integration of DERs has been demonstrated to positively contribute to buses with low voltage, resulting in voltage values within an acceptable range of 0.95 pu to 1.05 pu. In bus 7, where DERs are densely connected, the voltage increase rises from 0.96 pu to 1.04 pu (from 30.2 to 32.7 V), approaching the risky threshold value. This will cause the material in the system to overheat and endanger the distribution equipment. The observed voltage increases on bus 7 underscores the significance of optimal sizing and strategic placement of DERs.

Table 6. Voltage variation at grid point of common coupling with and without DERs (pu)

Node	Without DERs *(pu)*	With DERs *(pu)*
TM	1.00	1.00
DM	1.00	1.00
Bus_1	0.94	0.96
Bus_2	0.93	0.95
Bus_3	0.93	0.95
Bus_4	0.92	0.97
Bus_5	0.98	1.00
Bus_6	0.97	1.02
Bus_7	0.96	1.04
Bus_8	0.98	0.99
Bus_9	0.98	0.99
Bus_10	0.99	1.00
Bus_11	0.96	0.97

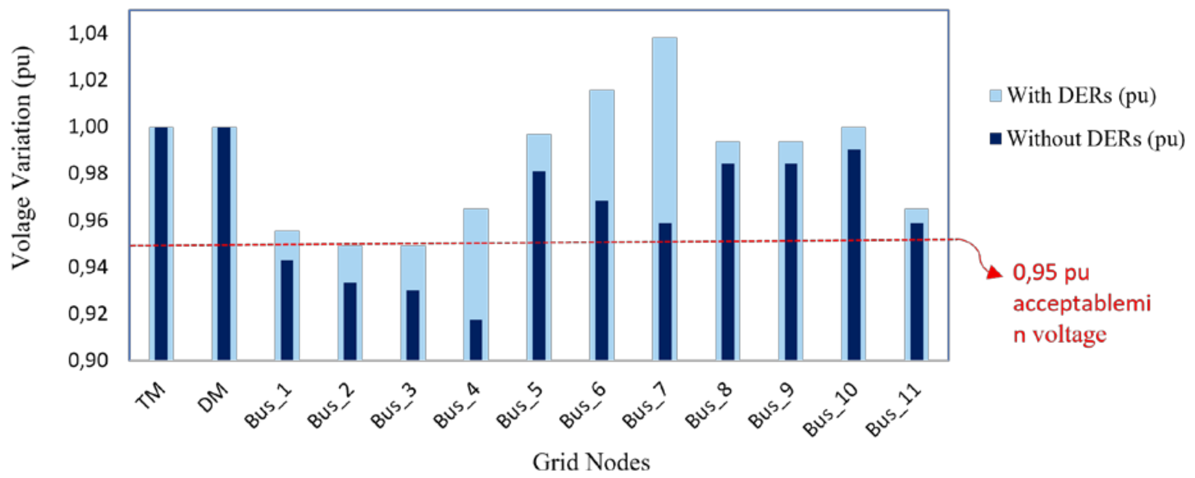

Figure 2. Voltage variation at grid point of common coupling with and without DERs (pu)

3.1.2. Short circuit fault

The integration of DERs within distribution systems has been observed to result in a notable augmentation of fault currents. This phenomenon can potentially compromise the functionality of protective relays, thereby raising operational concerns [2]. However, PV-DERs operating in current control mode exhibit a reduced contribution to fault current when compared to synchronous machine DERs. The results of various simulations conducted for the purpose of testing indicate that fault currents caused by PV-DERs range from 1.5 to 2 times the nominal current.

In the context of synchronous machine DERs, an increase ranging from 2% to 24% has been documented, contingent upon the voltage level [21].

The magnitude of fault currents caused by PV-DERs is largely dependent on the maximum power output, which refers to the number of PV strings or energy sources. Conventional fault calculations, such as the Z-bus matrix, do not apply to systems incorporating inverter-based DERs [22]. Furthermore, the short-circuit power at the point of connection between DERs has been shown to impact the flicker power of the system, while the short-circuit current has been demonstrated to affect the harmonics of the system [2].

The three-phase short-circuit power analysis of the grid reveals the results when DERs are not connected to the system in Table 7 and the results when DERs are integrated into the system in Table 8. According to the findings of this study, in busbars exhibiting high DER penetration, the short-circuit power (Sb), peak short-circuit current (ip), and thermal short-circuit current (Ith) values are elevated, while in busbars demonstrating low DER penetration, these values are diminished. This finding suggests a direct correlation between DER penetration and short-circuits power. Bus 1 has a 1 MW PV plant connected to it, with a short-circuit contribution of 0.035%, while bus 6 has a DER penetration of 3.5% due to the high penetration and diversity of sources. This figure stands in stark contrast to the rates observed in other bus services. This scenario demonstrates that solitary DER penetration does not exert a substantial influence on the short-circuit contribution; however, it will be more pronounced in buses exhibiting high penetration.

Table 7: Three-phase short circuit analysis results without DERs

	ip *(kA)*	**Ik** *(kA)*	**Sb** *(MVA)*	**Ith** *(kA)*
DM	20.9	7.22	394.18	8.58
Bus_1	4.62	2.58	140.99	2.59
Bus_2	4.00	2.28	124.35	2.29
Bus_3	3.29	1.91	104.18	1.92
Bus_4	1.72	1.04	56.81	1.04
Bus_5	5.85	3.16	172.28	3.17
Bus_6	3.21	1.87	102.03	1.88
Bus_7	1.92	1.15	62.99	1.16
Bus_8	7.61	3.89	212.46	3.89
Bus_9	5.32	2.74	149.22	2.75
Bus_10	4.07	1.95	106.16	1.96
Bus_11	5.21	2.87	156.32	2.88

Table 8: Three-phase short circuit analysis results with DERs

	ip *(kA)*	**Ik** *(kA)*	**Sb** *(MVA)*	**Ith** *(kA)*
DM	21.24	7.42	395.36	8.72
Bus_1	4.64	2.60	141.04	2.63
Bus_2	4.06	2.31	125.59	2.34
Bus_3	3.37	1.95	106.34	1.96
Bus_4	1.75	1.06	57.80	1.07
Bus_5	6.01	3.26	177.20	3.27
Bus_6	3.32	1.92	105.80	1.93
Bus_7	1.99	1.20	65.10	1.20
Bus_8	7.61	3.89	212.46	3.90
Bus_9	5.32	2.74	149.22	2.75
Bus_10	4.07	1.95	106.16	1.96
Bus_11	5.21	2.87	156.32	2.88

3.1.3. Reactive power effect

DERs have the capacity to either support or disrupt the functioning of protective equipment on the grid. These systems possess the capacity to draw reactive power from the grid; however, they are also capable of supplying reactive power to the grid. The provision or withdrawal of reactive power to the power system exerts a direct influence on the grid voltage [23]. The absence of reactive power support has been identified as a contributing factor to the outage. The utilization of distributed static synchronous compensator (D-STATCOM) is advocated for the purpose of reactive power support [24]. In instances where the load voltage exceeds the desired voltage, the D-STATCOM has the capacity to absorb reactive power from the grid. In instances where the load voltage falls below the desired voltage, the D-STATCOM has the capacity to inject reactive power, thereby enhancing the voltage level [25].

Table 9: Active and reactive powers of the grid

	Without DERs		**With DERs**	
	P ***(MW)***	**Q** ***(Mvar)***	**P** ***(MW)***	**Q** ***(Mvar)***
DM	37.7	7.1	6.4	10.0
Bus_1	15.2	0.7	8.4	1.7
Bus_2	13.8	0.3	8.1	1.4
Bus_3	2.1	0.3	-3.6	1.4
Bus_4	1.5	0.2	-4.4	1.1
Bus_5	6.8	1.0	-7.5	3.6
Bus_6	4.0	0.6	-10.5	2.9
Bus_7	1.5	0.2	-8.4	1.5
Bus_8	3.7	0.5	3.7	0.5
Bus_9	0.5	0.1	0.5	0.1
Bus_10	0.4	0.1	0.4	0.1
Bus_11	8.0	2.9	8.0	2.9

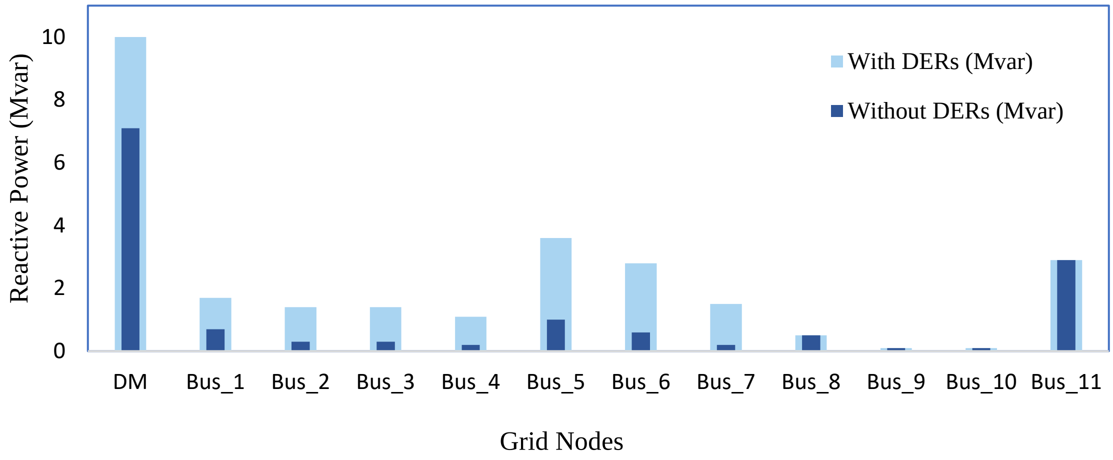

Figure 3. Graph of reactive powers of the grid

Table 9 presents a comparison of the active and reactive power of the system with and without DERs, illustrated in bars. During the analysis, calculations were conducted under the assumption that grid operators prefer DERs to operate at a fixed power factor. The negative values displayed in Table 9 denote the power supplied to the grid by DERs. DERs have been shown to increase reactive power by 1.5 to 7.5 times in buses connected to the system. This phenomenon is particularly pronounced in bus 6 and 7, where DER penetration is substantial. With respect to active power, the power drawn from the primary substation is in decline, and the energy generated is being consumed at the local level. However, in buses with high penetration, reverse energy is fed into the grid. As illustrated in Figure 3, the graph displays the reactive power before and after the integration of DER for all buses in the grid. Consequently, reactive power levels experience an increase in all buses connected to DERs.

Specifically, at bus 7, where a 10 MW wind power plant with high generation is connected, reactive power has increased 7.5 times, rising from 0.2 to 1.5 Mvar. Despite their capacity to both receive and distribute reactive power to the grid, this functionality of DERs remains underutilized by grid operators in Turkey. In general, distribution companies require DERs to maintain a constant power factor, which modifies the reactive power according to the generated power. This method of operation enables the distribution company to oversee the voltage of DERs while concurrently constraining the impact of DERs on the grid.

3.1.4. Losses

Energy losses, categorized into technical and non-technical categories, occur during the process of supplying electricity to consumers. [26]. The dissipation of energy in conductors, equipment utilized for energy transmission (e.g., transformers, circuit breakers, insulators), and the distribution of power to consumer facilities are the primary causes of technical losses. These technical losses are inherent in the system and can be reduced to an optimal level. The minimization of power loss within a system has the potential to result in cost savings with respect to energy consumption [27, 28].

Table 10 presents a comprehensive overview of the total active and reactive losses experienced by the power system. Conductor losses of the system were considered during the calculation of losses. It should be noted that other technical losses of the system were not considered in the calculations. According to the findings of the analysis, the integration of DERs has resulted in a substantial reduction in both active and reactive losses. This reduction will prevent wear and tears, overheating, and/or corrosion of the equipment in the power system. Consequently, this will contribute to the system's lifespan and potentially lead to investment delays.

Table 10. System total active and reactive losses

	P ***(MW)***	**Q** ***(Mvar)***
With DERs	0,43	1,95
Without DERs	2,40	9,89

In general, the number and location of DERs connections have a significant impact on distribution system losses and voltage profile. This highlights the importance of optimizing the size and placement of DER units to ensure efficient and reliable operation of the distribution grid [20, 29].

3.2. Time-Series Case Analysis Results

While the DERs were connected to the system, a feeder-based quasi-dynamic analysis was performed based on estimated 24-hour generation and consumption data. As illustrated in Figure 4, the hourly analysis results are derived from the 24-hour generation and consumption values for feeder 1. It has been determined that the feeder 1 is connected to buses 1, 2, 3, and 4. A ring grid has been established, with connections between Bus 4 and Bus 5. However, with respect to distance and load distribution, the energy derived from feeder 1 is stored at bus 5. Two power plants, designated as PV_1 and PV_2, are located on feeder 1. The energy consumed by this feeder exceeds the energy produced. A total of 30% of the energy consumed is supplied by DERs. During periods of peak production, approximately 70% of the energy consumed is generated within the local community. However, due to the inherent characteristics of PV power plants, consumption typically experiences an increase after evening hours, contingent on prevailing weather conditions. In the absence of generation, the energy is supplied from the grid.

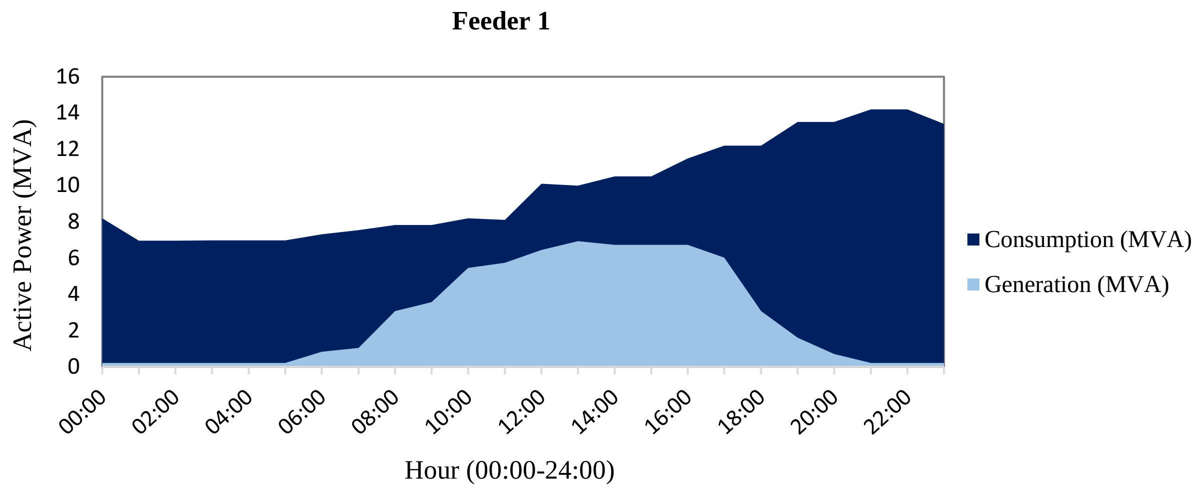

Figure 4. Time-series analysis of hourly generation and consumption profiles in Feeder 1

As illustrated in Figure 5, the hourly analysis results are derived from the 24-hour generation and consumption values for feeder 2. It is important to note that bus bars 5, 6, and 7 are connected to feeder 2. The PV_3 and W_1 power plants are located on feeder 2. The energy generated on this feeder exceeds the energy consumed. The entirety of the energy consumed is met by DERs. Given that the number of DERs in the feeder is greater than the energy consumed, approximately ±40% of the energy generated is consumed on site, with the remainder being transferred to the grid. Throughout the entire time period under consideration, a reverse energy flow to the grid is observed.

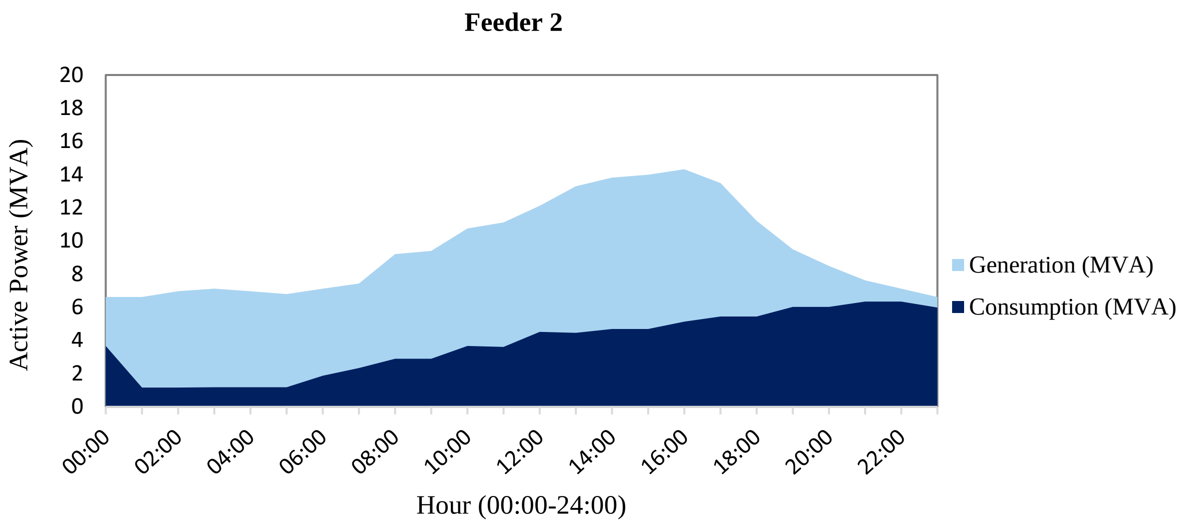

Figure 5. Time-series analysis of hourly generation and consumption profiles in Feeder 2

As illustrated in Figures 6a, 6b, and 6c, the hourly graphs are based on the 24-hour energy consumption values for feeders 3, 4, and 5. It has been determined that feeder 3 is connected to bus bars 8 and 9; feeder 4 is connected to bus bar 10; and feeder 5 is connected to bus bar 11. Given the absence of DERs connected to these feeders, the energy utilized in this location is entirely reliant on the grid.

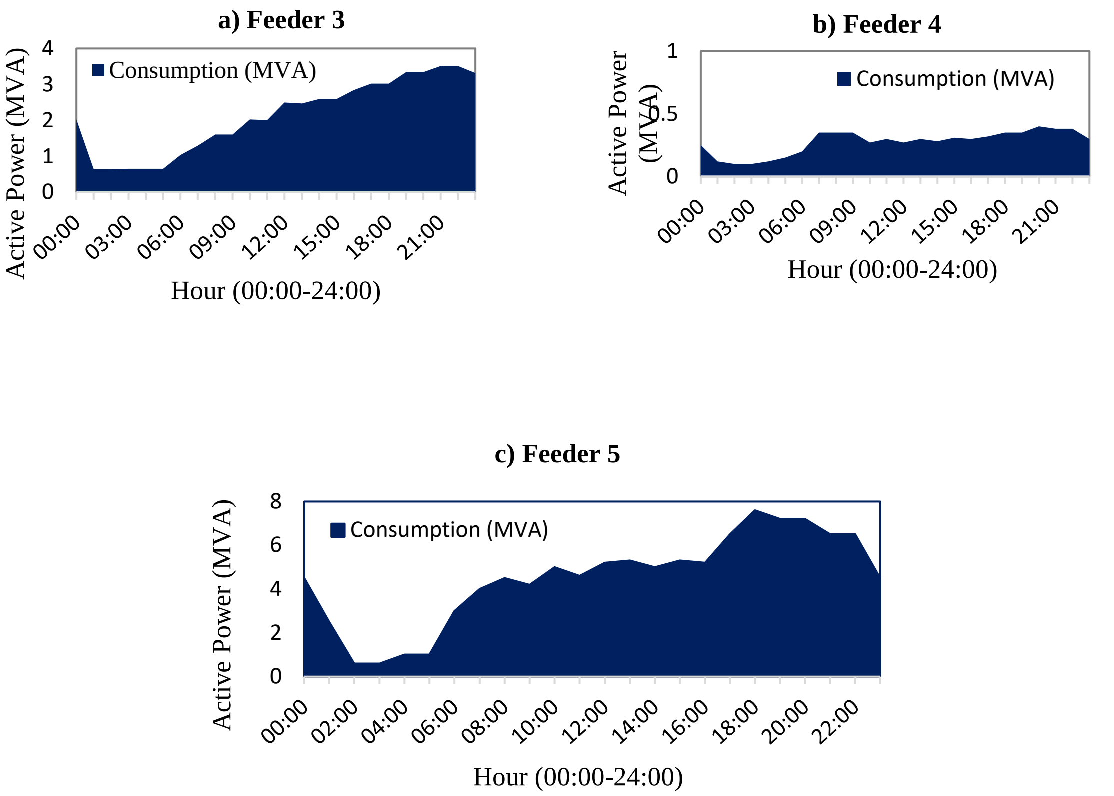

Figure 6 . Time-series analysis of hourly consumption profiles in **a)** Feeder 3, **b)** Feeder 4, **c)** Feeder 5

Figure 7 presents a graphical representation of the aggregate hourly production and consumption data for the substation over a 24-hour period. It has been determined that 72% of the energy consumed is produced by DERs. During peak production hours, all energy needs are met by DERs, and there is even a reverse energy flow to the TM between 10:00 and 17:00. However, during periods of reduced generation and elevated consumption, the substation diverts energy to the distribution grid.

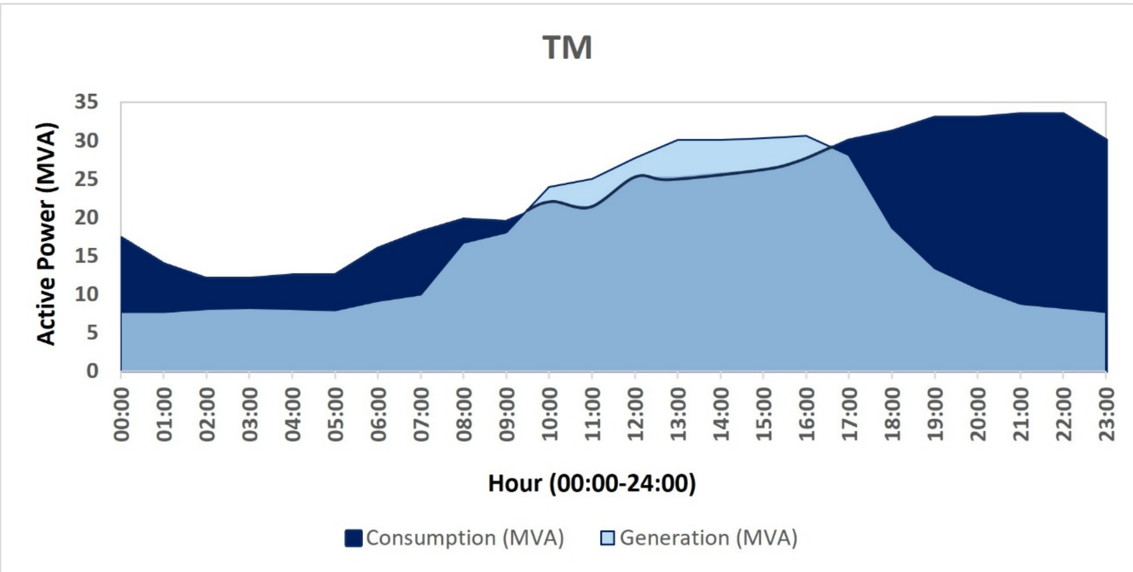

Figure 7. 24-hour total generation and consumption graph of the substation.

Figure 8 presents a graphical representation of DERs, and PV-BESS incorporated within the system. A substantial proportion of the energy utilized by PV-BESS is derived from DERs, accounting for 93% of the total consumption. It has been determined that 7% of the total energy consumed between 5:00 p.m. and midnight is supplied by the transformer station. The incorporation of BESS within the system has led to a significant reduction in energy consumption from the grid. In this scenario, BESS employs two critical strategies, load balancing and shaving, to mitigate fluctuations in energy requirements. Load balancing serves to reduce the energy expenditure during periods of peak demand and to minimize energy consumption during off-peak hours. Conversely, peak shaving involves the strategic storage of energy during periods of low demand and its subsequent utilization during periods of high demand. To ensure the stability and flexibility of the grid, as well as to facilitate the expeditious release of energy during supply, the implementation of electrical energy storage units is imperative. In this study, peak shaving was employed during periods of peak demand using BESS. In the hourly analysis conducted with BESS integrated into the system, 93% of the energy was supplied by RES.

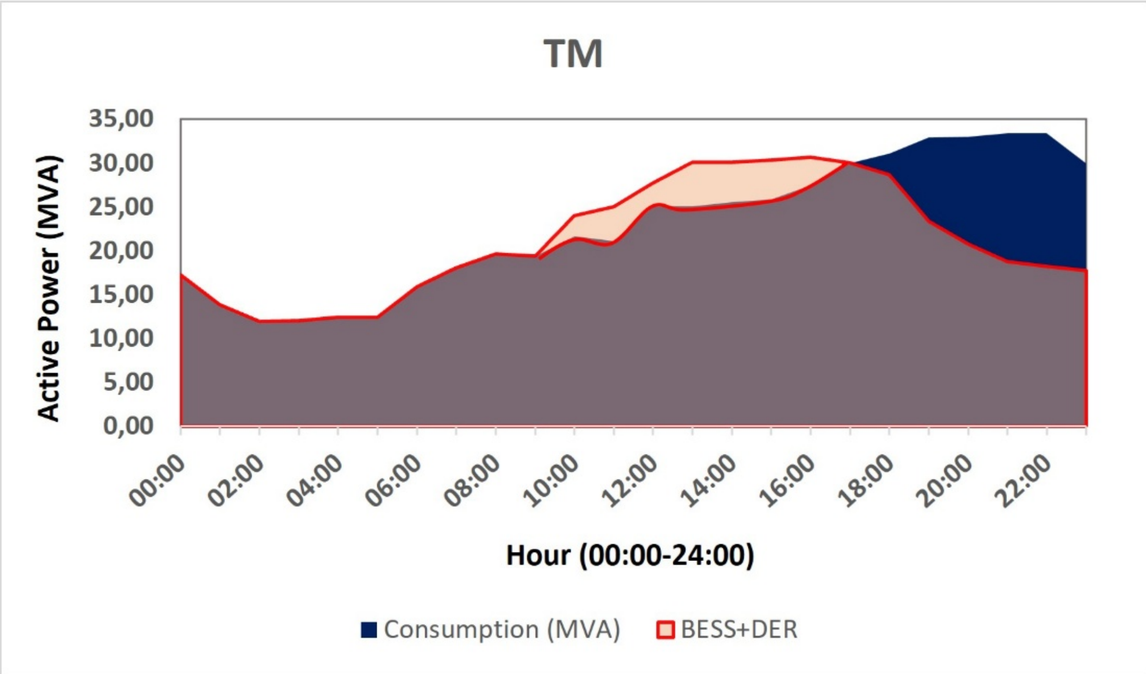

Figure 8. Time-series analysis of 24-hour aggregate generation, consumption, and BESS operation at the substation

As illustrated in Figure 9, the graph depicts the energy utilization metrics from the 10 MW BESS system. During the period of peak production, which occurs between 10:00 and 16:00, the demand for energy is met by DERs. Consequently, there is no energy usage from the BESS system during this time. Between 6:00 p.m. and 12:00 a.m., the BESS supplies energy to the grid at maximum capacity.

The benefits of BESS are manifold. These include the ability to balance the variability of RES, increase the stability and flexibility of the power system, delay transmission upgrades, and ensure environmental friendliness. However, proper sizing and placement of BESS is imperative to reduce investment costs, minimize losses, and enhance power quality [30]. The BESS stores excess power to maintain system frequency, voltage, and load power during periods of low solar radiation. As demonstrated by time-series analysis, the BESS has the capacity to store excess power for subsequent use when the power generated in grid-connected mode exceeds the demand. Conversely, stored energy can be utilized to offset load during periods of insufficient power generation [31].

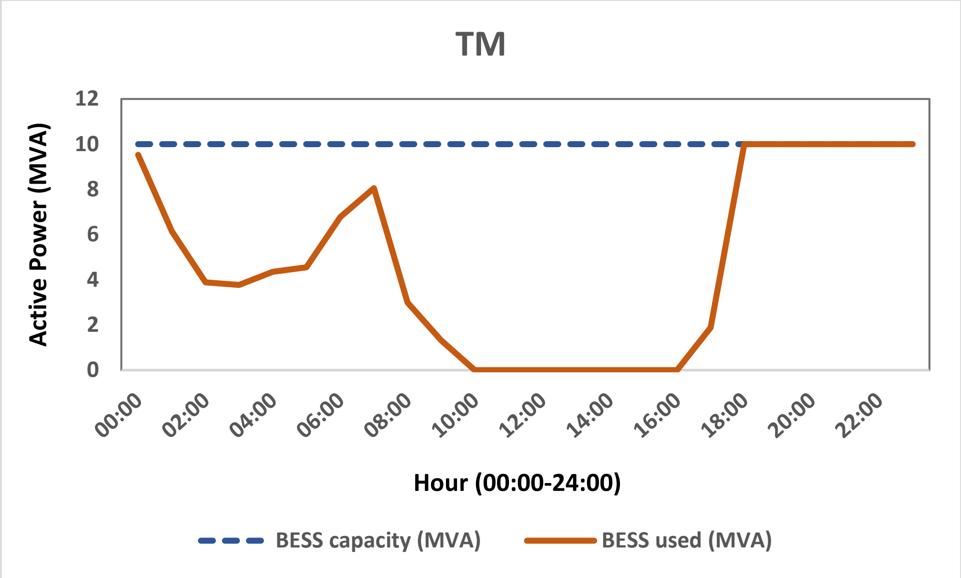

Figure 9. Energy graph utilized from TM's 24-hour BESS

The BESS is utilized for the purpose of regulating excess grid energy, in addition to renewable energy. The viability of the grid hinges on effective battery management in relation to peak power requirements. [32]. During periods of peak demand, the capacity of power generation is decreased by leveraging storage technology in power systems that utilize battery energy. BESS offers numerous advantages, including enhanced power system stability and flexibility, as well as mitigated effects of fluctuations resulting from wind and solar energy [30, 33].

The interest in BESS is increasing due to its apparent advantages, including geographical independence, controllability, and rapid response. Moreover, BESS boasts a variety of applications, including the enhancement of power quality in the short term, the optimization of energy management and reliability in the long term, and the deferral of transmission upgrades.

IV. CONCLUSIONS

This study evaluated the effects of integrating DERs, such as PV power plants, wind turbines, and BESS, into an existing electricity distribution grid on power quality parameters. Steady-state and 24-hour dynamic analyses were conducted under high and low DER penetration scenarios to reveal the effects of DERs on grid performance.

Numerous studies have been conducted on the integration of DERs into the grid, and these studies collectively signal a significant and promising era for the global impact of new generation electricity grids on energy and climate relations. However, it is important to note that every innovation is accompanied by inherent challenges and vulnerabilities. The potential integration of DERs is a significant issue that requires further research to address the existing challenges.

Under typical operating conditions, DERs do not contribute to system active power (frequency) regulation, and grid frequency adjustment is exclusively executed by conventional power plants. Conversely, as the proportion of DERs rises, the proportion of power capacity available for system active power regulation experiences a substantial decline. Consequently, DERs must also engage in active power regulation within the system.

The control of reactive power and voltage is contingent upon the topology of the grid, its operational mode, and the characteristics of both generators and loads. The implementation of reactive power regulation at the point of DER integration facilitates the provision of dynamic VAR support to the system. The configuration and coordination of flexible reactive power compensation equipment on transmission lines is also imperative. A notable concern is the potential for an increase in the number of D-STATCOMs recommended for reactive power regulation, which may introduce unforeseen complications to the grid. A comprehensive investigation is imperative to ascertain the effects of these phenomena and the optimal placement of D-STATCOMs, along with the methodologies for their monitoring and operation.

Moreover, given that the transmission and distribution sides are only able to regulate switching and settings in the pertinent grid, a reconfiguration of the system topology is necessary.

Time-series analysis has demonstrated that 24-hour data reveal the critical role of battery storage systems in balancing the variability of RES and increasing system efficiency by reducing peak load demands. Additionally, the findings indicate that BESS contributes to the flexibility of the grid. When the generation-consumption relationship is evaluated on an hourly basis and the right combination of DER is provided, it has been demonstrated that the grid's entire energy can be met from RES. Furthermore, it has been shown that the negative effects of energy generation on the environment can be mitigated by considering greenhouse gas emissions and generating clean renewable energy in the most efficient way.

In subsequent studies, these findings can be expanded by focusing on shorter time intervals, considering the depth of discharge and efficiency values of BESS with different grid topologies and advanced control algorithms.

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