Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2021) 29: 1720 – 1735

doi:10.3906/elk-2006-149

Impact of hybrid power generation on voltage, losses, and electricity cost in distribution networks

Yavuz ATEŞ, Tayfur GÖKÇEK, Ahmet Yiğit ARABUL*
Department of Electrical Engineering, Faculty of Electric-Electronics, Yıldız Technical University, İstanbul, Turkey

Received: 28.06.2020 • **Accepted/Published Online:** 15.12.2020 • **Final Version:** 31.05.2021

Abstract: Energy and its capacity has emerged as one of the biggest distribution challenges all over the world. The existing grid becomes insufficient along with the expansion of the consumption. Therefore, the number of distributed generation (DG) in distribution networks increases and it allows us to sell back the extra energy. However, the efficiency of energy must be maintained into optimal values from the grid to the end-users. In spite of a lot of advantages of DG units, there are some disadvantages like fluctuations in voltage, increments of power losses, wrong protection coordination, harmonic and energy quality issues etc.. If the location, capacity, control mode, and type of DG resources cannot be designed optimally or the environment impacts such as wind speed and irradiation level cannot be considered before the integration in distribution networks, the integration results may lead to especially inefficiency of energy in terms of the voltage profile and the power losses. It is aimed to reduce the daily cost of an industrial area as well as improving the voltage profile and reducing the power losses by integrating DG units considering convenient location and dynamic price values. In this study, the impact of hybrid distributed power resources on voltage improvement, power losses, and electricity cost of the IEEE 13-bus test system are examined using Electrical Transient Analyzer Program software. In the simulation, the photovoltaic system and type 3 wind turbine generator are designed as 500 kW and integrated at bus 671 and bus 675 with four cases. Finally, the results obtained for voltage profiles and power losses of the entire system and total electricity cost of the industrial area are presented as comparative charts.

Key words: Hybrid distributed generation, wind energy, photovoltaic energy, voltage profile, power losses, electricity cost

1. Introduction

Along with the depletion of fossil fuels and the increase in energy consumption that change energy balances, the need for renewable energy sources and DG gain more interest. DG's integration allows distribution networks to turn into active distribution networks. Despite a lot of advantages of DG, some disadvantages emerge as operational and conditional challenges. Among the advantages, improving voltage profile and decreasing power losses and electricity cost play a major role in using the energy more efficiently. Diverse definitions of DG are available throughout the world. According to Ackermann et al. [1], although supplying active power, reactive power contribution is not anticipated. However, IEEE 1547TM [2] specifies that DG units shall provide voltage regulation capability by changes of reactive power if necessary. In this regard, reactive losses can be reduced by providing reactive power for voltage regulation[1]. Other standards of DG were given by Vaziri et al. [3]. DG

*Correspondence: arabul@yildiz.edu.tr

[1]Çetinkaya HB, Dumlu F (2013). Dağıtık üretim tesislerinin şebeke entegrasyonunda yaşanabilecek olası problemler ve entegrasyon analizleri (in Turkish) [online]. Website https://www.emo.org.tr/ekler/76bfae53cf6ecbd_ek.pdf

systems consist of wind power plant (WPP), solar power plant (SPP), hydropower, fuel cells (FC), microturbines, combined heat and power (CHP) etc. and generally have several classifications such as technology type, primary energy, and connection type [4]. As mentioned earlier, according to technology type, DGs can be classified as WPP, SPP, FC, microturbines, CHP, etc. Figure 1 shows the integration and management layers of DGs. In accordance with primary energy, while WPP and SPP are renewable energy sources, CHP are nonrenewable energy sources [4]. With respect to connection type, while synchronous generators and wind turbine generators can be connected directly, PVs and FCs have to be connected through power electronic interfaces [5]. While system characteristics can be classified as distribution network type, transformer connection, line impedance and loads, DG characteristics can be classified as type, size, location, and control method of DG [6]. Before DG integration, designing the system for losses and voltage profile is very important. Soni et al. [7] mentioned the design criteria of distribution networks. Thanks to the size and location of DG, voltage profile and system losses can be changed. Sailaja et al. [8] and Fengli et al. [9] performed an analysis by different location and DG capacity integrations.

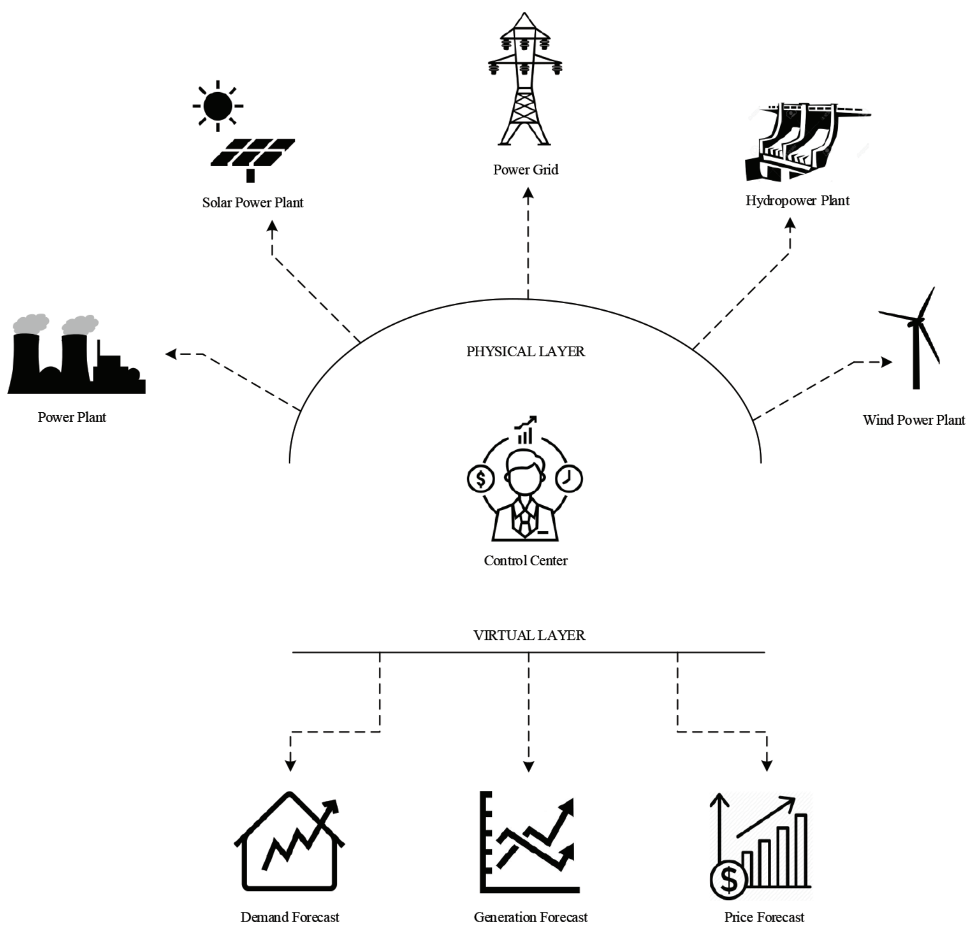

Figure 1. The integration, management layers, and types of DGs.

DGs have several benefits in terms of voltage support, reduction of losses, high power quality, and system reliability depending on both system and DG characteristics [10]. Moreover, customers' bills can be decreased by selling back the extra generated energy. On the other hand, DGs bring about bidirectional power flow, protection and safety issues, harmonic distortion, transient problems, and instability in voltage [11]. DG units used in this study are classified into two types. First of them, PV systems must be connected through inverters and contribute just active power to the system [12]. However, reactive power can be controlled by means of inverters [13]. Before designing a PV system, solar radiation with seasonal effects should be considered [14]. Different connection types of PV systems are shown in Figure 2 [15].

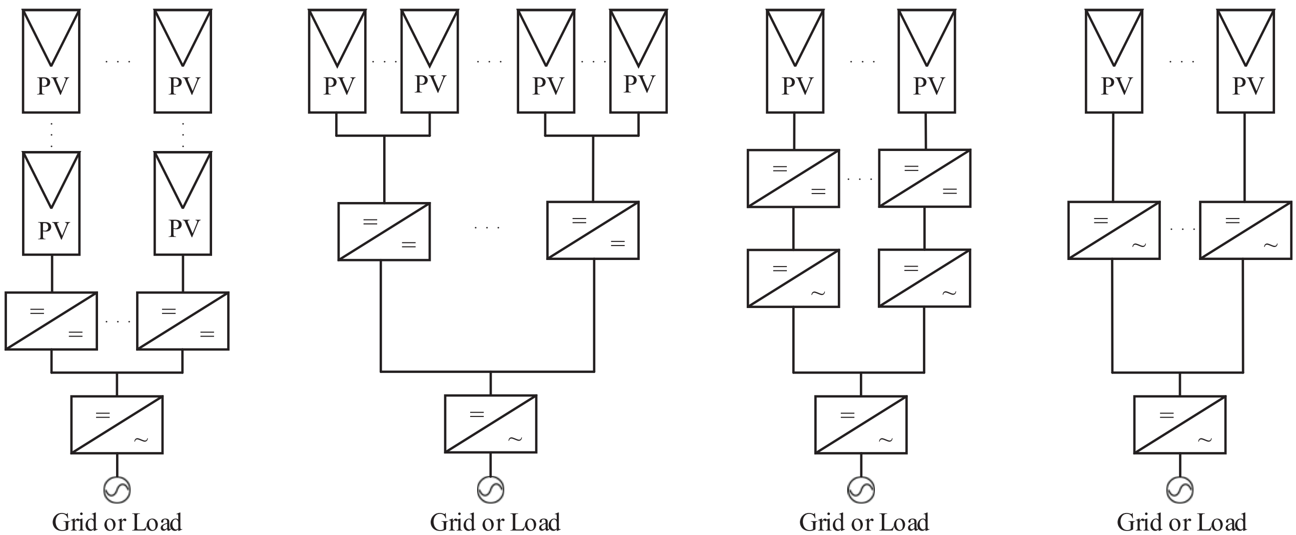

Figure 2. Classification of PV systems according to the connection types [17].

There are four types of WTG as fixed speed conventional induction generator, variable slip induction generator with variable rotor resistance, and variable speed doubly fed induction generators (DFIG) with rotor-side converter and variable speed asynchronous generators with full converter interface [16]. Induction generators included in wind energy systems inject active power but need to consume reactive power [17]. However, like PV systems, reactive power can be controlled via inverters as well as capacitor banks [18]. The connection scheme of the DFIG used in this paper is shown in Figure 3 [19].

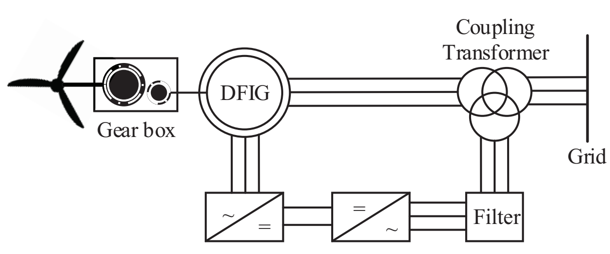

Figure 3. Integration of the DFIG consisting of wind power with full converter interface [21].

As well as a single DG source, the usage of hybrid DG systems which use two or more energy resources is widely growing. Diesel-wind integration which is the most widespread hybrid DG system also enables us to use the energy optimally. For instance, when the wind is insufficient in cloudy weather, a diesel or solar system can meet the lack of energy. Moreover, these systems can be classified as central grid connected and isolated hybrid systems [20]. They can provide more efficient energy by utilizing multiple sources such as solar, wind, and biomass compared to a single DG unit. The extra energy can be used as auxiliary resource thanks to storage systems. Servansing et al. also examined the configurations of hybrid DG connections [21].

Hybrid systems have almost the same advantages and disadvantages as a single DG source. In addition to the pros and cons mentioned above, they decrease the greenhouse gas emissions, they are harmless to the environment, renewable sources mean constant source, and they need less upkeep. However, since the system is complex, its initial cost higher and protection issues cannot be solved exactly [20]. Among the literature studies on hybrid DG systems, Afifi and Darwish [22] examined the short circuit levels of the WTG-PV hybrid system. Renani et al. [23] considered the effect of the PV-FC hybrid systems on total line losses and observed that losses changed according to loading conditions.

Three crucial subjects related to power systems including DG sources are voltage stability, power losses, and electricity cost. The voltages at buses must be kept within suitable limits, which is between 0.95 and 1 pu of the rated voltage, in a power system. As a result of voltage stability, power losses are influenced indirectly [17]. The impact of reactive power capability of wind turbines on voltage stability was investigated in [24]. Impact of the unpredictable profile of PV generation and electric vehicle on voltage magnitudes in radial distribution was examined in [25]. Deepa and Savier [26] obtained improvement in voltage profile and decrement in power losses considering smart grid scenarios. Zhang et al. [27] investigated the impact of PV energy on distribution systems with a proposed comprehensive control strategy based on PV grid connected inverter and obtained more stable voltage values at the nodes. The impact of the stochastic structure of PV generation on voltage magnitude and power flows was examined in [28]. Voltage regulation and reactive power allocation were investigated in DG integrated microgrid in [29]. The impact of reactive power capability of hydroelectric-based DGs on bus voltage and power factor was examined by Kesici et al. considering design limits [30]. In terms of power losses, the importance of capacity and location of DG was examined in [31]. Davda and Parekh [32] also studied the impact of the size and location of the DG on both voltage and losses. In [33], power losses in the case of sharing excess PV power in peer to peer energy transaction was investigated. Impact of the load scheduling of end users was also analyzed in terms of cost. Cost and power loss optimization strategy as well as selecting optimal size and location of DG was proposed by Ghanbari et al. [34]. Mahmoud et al. [35] proposed a new optimization technique by incorporating the efficient analytical method in the optimal power flow algorithm in order to minimize the losses considering size, location, and power factor of DG. Tutkun et al. [36] investigated the difference of operation cost between scheduled and unscheduled loading conditions in PV, WTG, and battery hybrid system, and achieved a decrement rate of 13% under scheduled loading compared to unscheduled loading. Bonthu et al. [37] proposed a particle swarm optimization method in order to reduce the electricity bills in PV, battery system considering time-of-use pricing. Maximizing usage of PV and minimizing electricity bill were considered simultaneously for PV and battery hybrid generation by Narimani et al. [38]. Energy management of hybrid energy storage and PV system was proposed in [39, 40]. Battery life time, profit of end user, and self consumption rate of PV were increased thanks to the proposed energy and frequency management model. Contribution of the renewable-energy-based DGs on short circuit cases was investigated considering location of integration in [41]. Impact of intermittent power output of a high-capacity DG in a microgrid on voltage and frequency was investigated by Kim et al. [42]. Moreover, they propose battery storage system instead of synchronous generator for steady state. In [43], an energy management system was proposed for commercial electric vehicles which benefit from PV. Moreover, it was aimed to cope with the uncertainty of PV generation. In [44], effects of the electric vehicle parking lot consisting of PV, battery storage, and diesel generator are investigated under island, grid connected, and diesel generator connected modes.

The electricity cost as well as the technical approaches is one of the most important issues in electrical engineering. Although wind and solar power plants have variable generations depending on weather conditions, they help to reduce both carbon emission and consumers' expense. Given this context, priority of contribution of the study is reducing daily cost under dynamic pricing. To assess the impact on voltage and power losses, several cases have also been carried out and presented. In this research paper, the impact of hybrid distributed power resources on voltage improvement, power losses, and electricity cost was examined using ETAP[2] software. IEEE 13-bus test system[3] was used as the test system. The stages of the study are as follows:

- The specifications of the test system are taken into account.
- Distributed generation resources used in the simulation are designed appropriately for the test system.
- The integration of the DG resources at bus 671 and bus 675 are realized.
- The results obtained from the simulations are assessed and compared.

This study was carried out considering industrial load profile under diverse DG integration. The main contribution of the paper is that evaluation of voltage magnitudes and power losses under different increment of load at each bus which has different distance to the main grid and different location of DGs. Besides, irradiance data of İstanbul was used for the cases in the study.

Following the introduction, Section 2 presents the system methodology and simulations. Obtained test results are discussed in Section 3. Finally, concluding remarks are presented in Section 4.

2. System methodology and simulations

In this section, parameters of designed DGs considering IEEE standards, specification of the test system and simulation cases are defined. In the simulation, PV and DFIG were integrated at bus 671 and bus 675 with four cases. The test system with DG integrated is shown in Figure 4.

The features of the system are listed in Table 1. For the test system, X/R ratio and 3-phase short circuit power of the grid are 2.744 and 71.072 MVA, respectively, and the frequency of the system is 60 Hz. This test system which is unbalanced consists of distributed and spot loads. The loads are also listed in Tables 2 and 3.

The parameters used in the WTG designing are indicated in Table 4. Assumed efficiency of all components of the turbine such as blades, gearbox, and transformer is considered 0.7 and also Betz constant is added to the calculations as 0.59.

Table 1. Specification of power grid and the 13-bus test system.

Type	X/R	Short circuit power (MVA)	Frequency (Hz)
Unbalanced	2.744	71.072	60

Daily power output of WTG can be calculated using Equation (1):

$$P_{wtg} = 1/2 * \rho * A * v^3 * \eta * C_p, \quad (1)$$

where P_{wtg} is the output power of wind turbine, ρ is the air density, A is the swept area of the turbine, v is the wind speed, η is the efficiency of the wind turbine components, and C_p is the Betz constant.

[2]ETAP (Electrical Transient Analyser Program). https://etap.com/

[3]IEEE 13 bus test feeder. https://site.ieee.org/pes-testfeeders/resources/

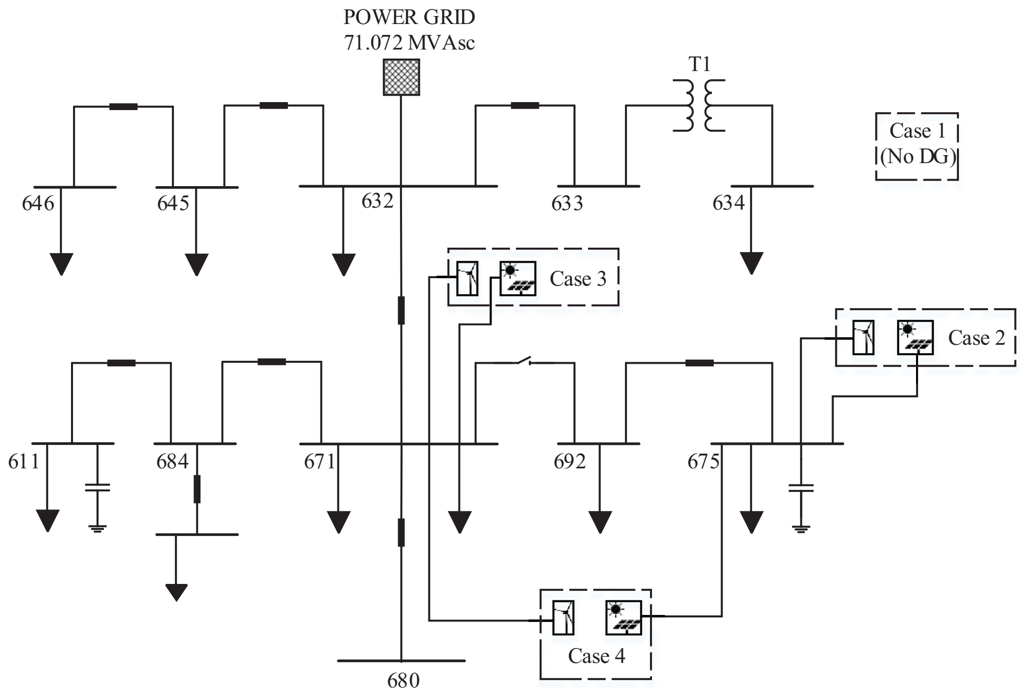

Figure 4. DG integrated 13-bus IEEE test system with variable loading conditions.

Table 2. Active and reactive power demand of spot loads data of 13-bus test system for each three-phase bus.

Node	Load (Model)	Ph-1 (kW)	Ph-12 (kVAr)	Ph-2 (kW)	Ph-23 (kVAr)	Ph-3 (kW)	Ph-34
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
TOTAL		1158	606	973	627	1135	753

Table 3. Active and reactive power demand of distributed loads data of 13-bus test system.

Node A	Node B	Load (Model)	Ph-1 (kW)	Ph-12 (kVAr)	Ph-2 (kW)	Ph-23 (kVAr)	Ph-3 (kW)	Ph-34 (kVAr)
632	671	Y-PQ	17	10	66	38	117	68

Table 4. The parameters of 500 kW wind turbine used for the simulation cases.

Power (kW)	Diameter (m)	Cut-in/cut-out (m/s)	n	Swept area (m2)
500	38	4-25	0.7	1144

The parameters of the PV module used in the PV designing are shown in Table 5. To reach the 500 kW installed power capacity, 2160 pieces (8 series*270 parallel) PV module are used. In the same way, daily power generation of PV is calculated considering average solar radiation.

Table 5. The parameters of a PV module used for the simulation cases.

Model	Power (W)	Efficiency (%)	Voltages (V_{dcmax})	Power tolerances (%)
KD235GX-LPB	232	14.5	600	11.8

Daily power output of PV can be calculated using Equation (2):

$$E_{pv} = A_{pv} * r * H * PR, \tag{2}$$

where E_{pv} is the daily produced energy by PV system, A_{pv} is total area of the panel, r is the solar panel efficiency, H is the average daily radiation, and PR is the performance ratio.

After designing the stage of DG resources, scenarios are carried out. In case 1, the results of IEEE 13 bus test system without any DG are obtained. In cases 2, 3, and 4, the results of hybrid DG integrated system are observed. Next, the simulation results are presented.

Cases of this study are listed as follows:

- Case 1: No DG
- Case 2: 500 kW WTG and 500 kW PV integrated at bus 675
- Case 3: 500 kW WTG and 500 kW PV integrated at bus 671
- Case 4: 500 kW PV integrated at bus 675 and 500 kW WTG integrated at bus 671

3. Test results

In this stage of the study, comparative results of the integrated test system are represented along with graphs. The results are evaluated in terms of voltage profile, power losses, and electricity cost of drawn power from the grid. While bus 671 and bus 675 are considered integration buses, the results are commented considering bus 634 and the integration buses so as to point out the impact of different short circuit power of buses. Firstly, load flow analysis was carried out using ETAP software and then the results were compared. The impact of voltage improvement is discussed firstly and the results are shown below in four parts. Demand powers and the values of each bus voltages for each case are indicated in Figures 5–8, respectively.

According to the results, it can be noticed that while voltages do not change at the bus 634 near the grid because of high short circuit power, it increases as move away from the grid and the contribution of the dispersed hybrid DG compared to single location integration on voltage improvement is greater. Moreover, it can be seen that although voltage drop is the highest at bus 675, this drop can be compensated thanks to hybrid DG systems. Moreover, PV system has no generation until reaching 06.00. Therefore, demand power is provided by WTG and the grid. The node voltages vary during the day for base case because of the production activity of industrial factory. It can be clearly seen that while demand power between 13.00 and 16.00 decreases, total generated power by hybrid DG increases. As a result of this, the voltage regulation rises. On the other hand, while demand power between 16.00 and 18.00 increases, total generated power by hybrid DG decreases and voltage regulation also decreases. In addition to the assessments, the total power demand for the entire system at 18.00 is 2370 kW. Thus, loading condition at each bus compared to previous hour increases. Since the load increment compared to nominal power demand in bus 634 is more than the increment of other buses, the voltage

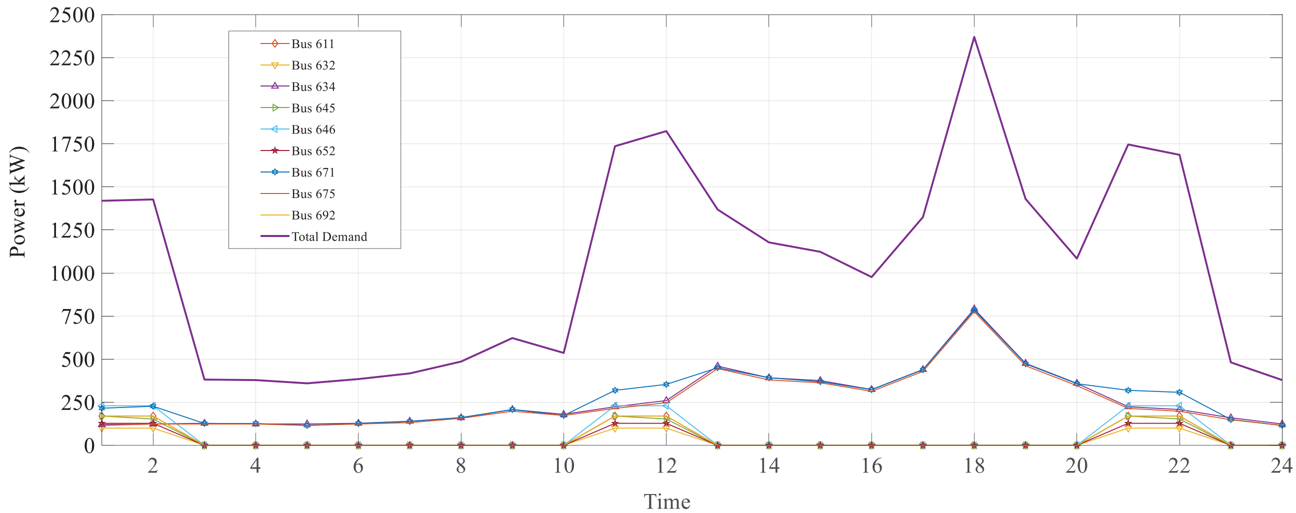

Figure 5. Power demand profile of each three-phase bus and total system for a daily time scale.

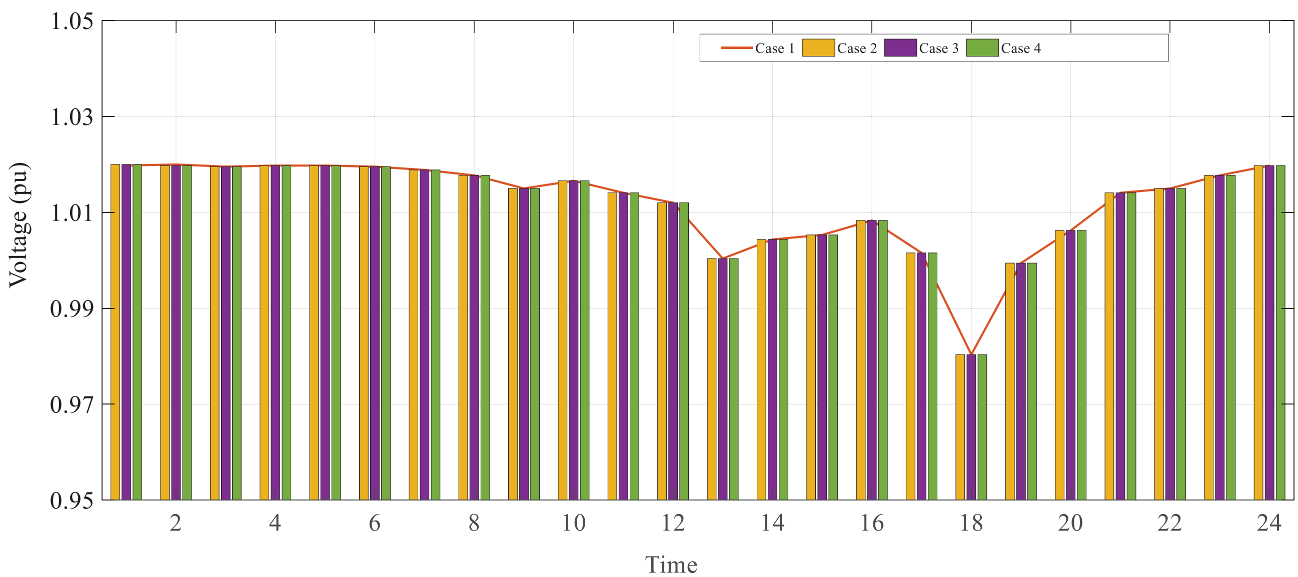

Figure 6. Voltage magnitude of bus 634 under cases consisting of different DG integration schemes and loading factors for a daily time scale.

magnitude on bus 634 decreases to 0.98 pu in the case 1. Although DG is integrated in the system, the value of 0.98 pu cannot be improved due to high short circuit power of bus 634 as mentioned earlier. Consequently, hybrid power generation influences the voltage regulation of the system by compensating node voltage drop.

Daily wind speed for 24 h and the power output of wind turbine according to Eq. (1) are shown in Figure 9.

Daily irradiation for 24 h and the power output of PV system according to Eq. (2) and variable loading conditions of the industrial factory are shown in Figure 10.

In addition, voltage magnitudes of the entire system at 12:00 and 18:00 are depicted in Figures 11 and 12, respectively. As we see, bus voltages especially at bus 634 and 633 compared to other buses are variable

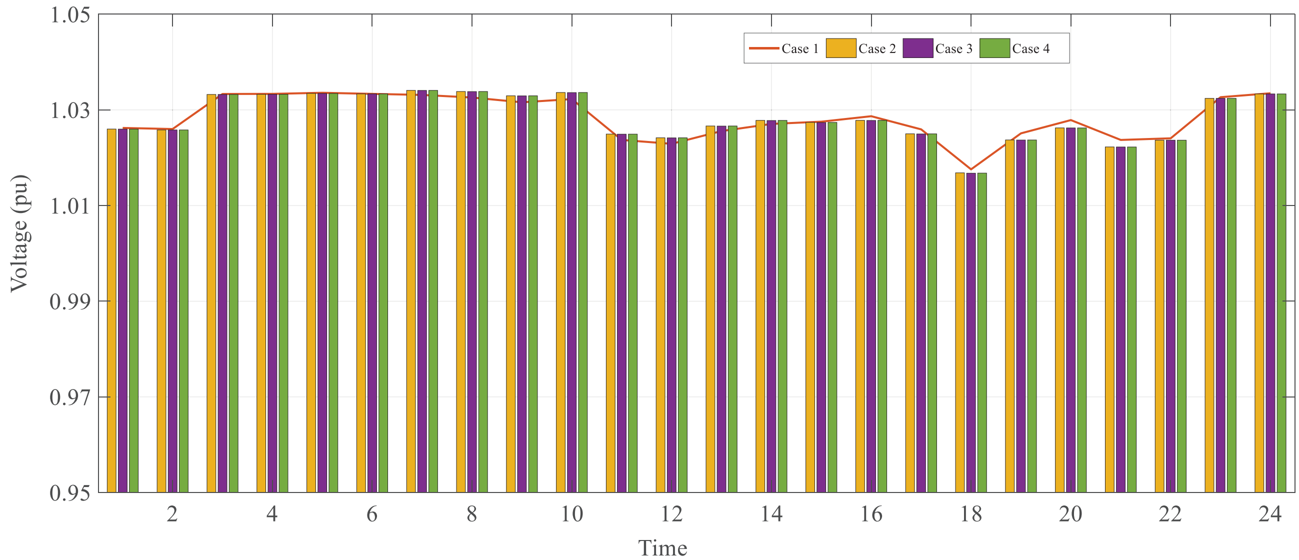

Figure 7. Voltage magnitude of bus 671 under cases consisting of different DG integration schemes and loading factors for a daily time scale.

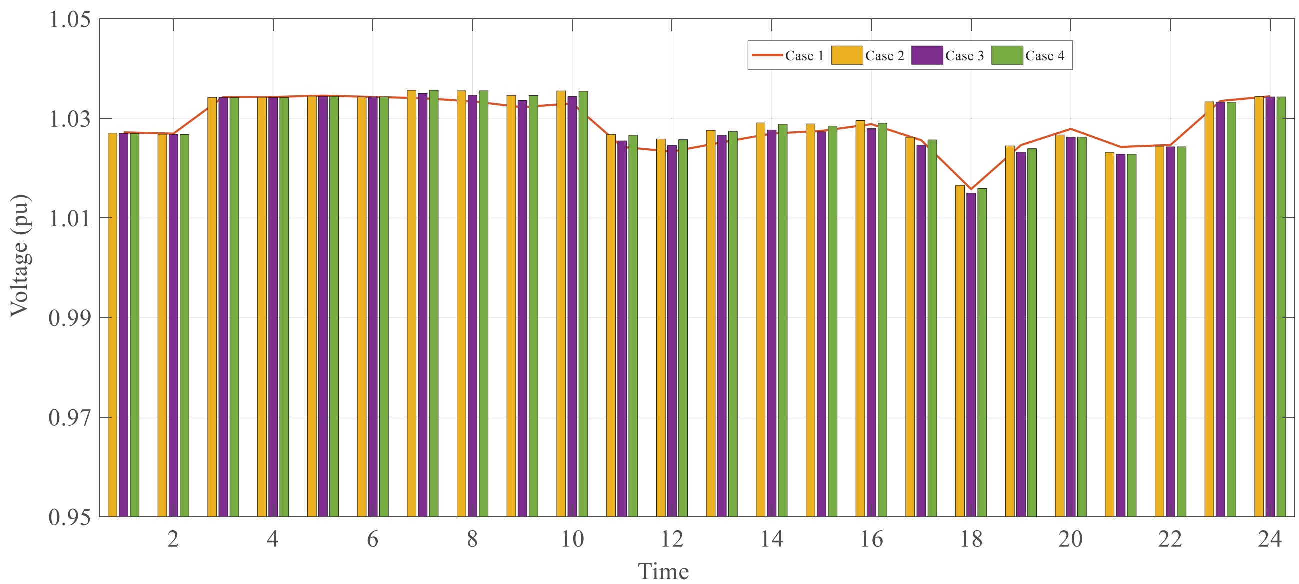

Figure 8. Voltage magnitude of bus 675 under cases consisting of different DG integration schemes and loading factors for a daily time scale.

due to the different loading factors.

Increasing in active and reactive power losses for each case during the day is observed because of the unbalanced condition between total demand and generation. Both for on peak and off peak hours, since consumption is low near the integrated DG location, excess power is deployed far from the consumption location. When the highest reduction in active power loss is 11.91% between 01:00 and 02:00. As we see, demand power is 1449 kW in this time interval. The results are indicated in Figures 13 and 14, respectively.

One more analysis was carried out considering full loading condition and average generated power by DG

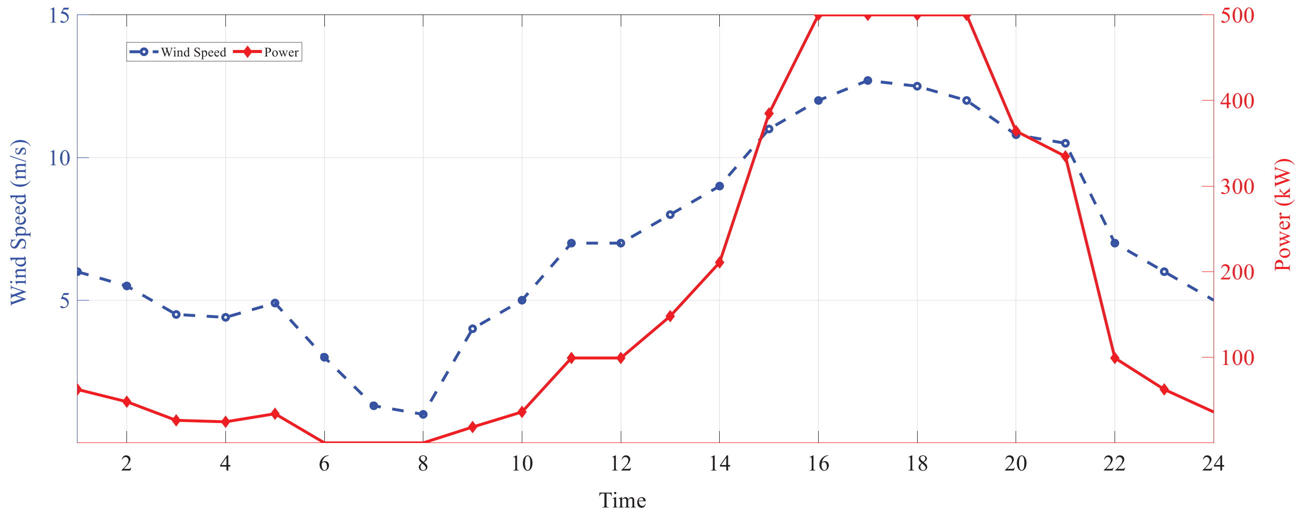

Figure 9. Daily variable wind speed (blue dotted line) and power output of 500 kW WTG (red line) used for the simulation cases.

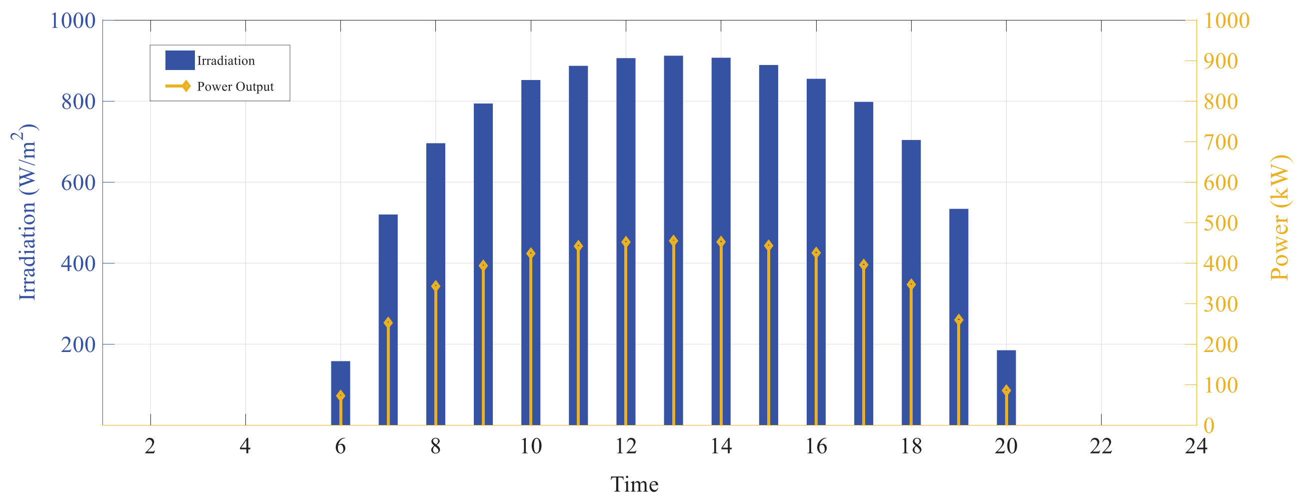

Figure 10. Daily variable solar irradiation (blue column) and power output of 500 kW PV system (yellow column) used for the simulation cases.

in order to realize the impact of loading factor on power losses. Figure 15 depicts variation in power losses for each case. Decrement in both active and reactive power losses is observed as expected because of the locational consumption with the DG generation.

According to the figures, while active power losses is reduced by 17.2%, 13.44%, and 15.86%, reactive power losses are reduced by 14.85%, 13.62%, and 14.38% considering the value of 3.5 MW and 1.5 MVAr demand and the value of 390 kW average daily power generation by DG for each case respectively. It can be clearly concluded that loading factor is a crucial issue as well as generation capacity.

The dynamic pricing shown in Figure 16 is used for the calculation of electricity cost from the grid via [45] and the total bill paid by the industrial area is calculated as the cost of drawn net power from grid. More clearly, deficit demand power after usage of the DG units is met by grid and equivalent total cost is obtained as the multiplication of drawn net power from grid and dynamic pricing. The total bill is also indicated in Figure

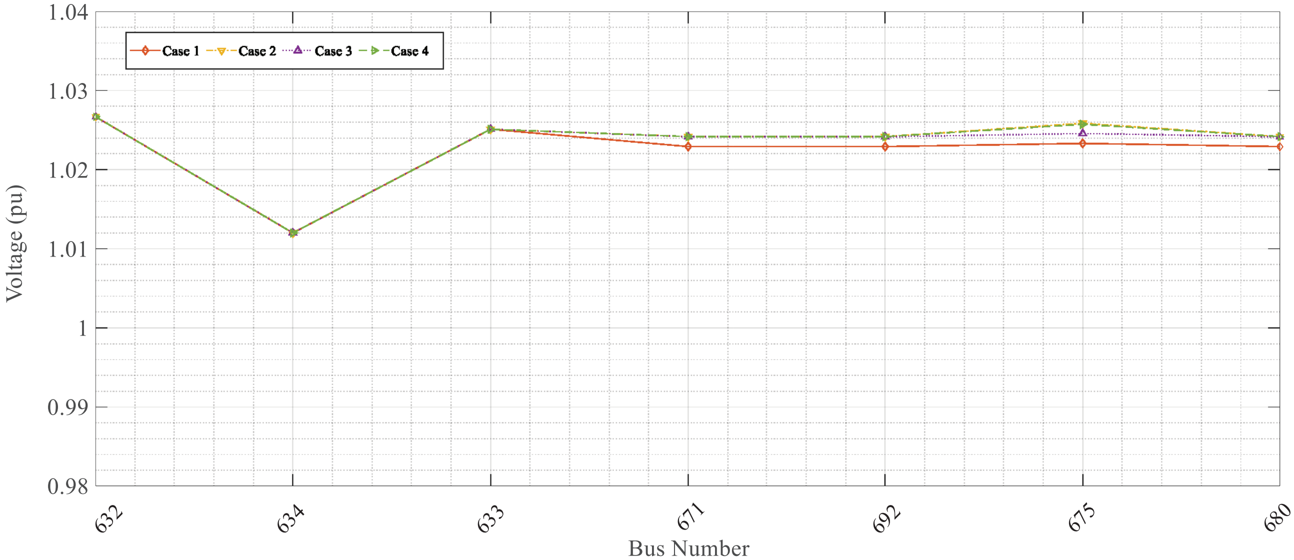

Figure 11. Voltage magnitudes of three-phase buses under cases consisting of different DG integration schemes and loading factors at 12.00 time interval.

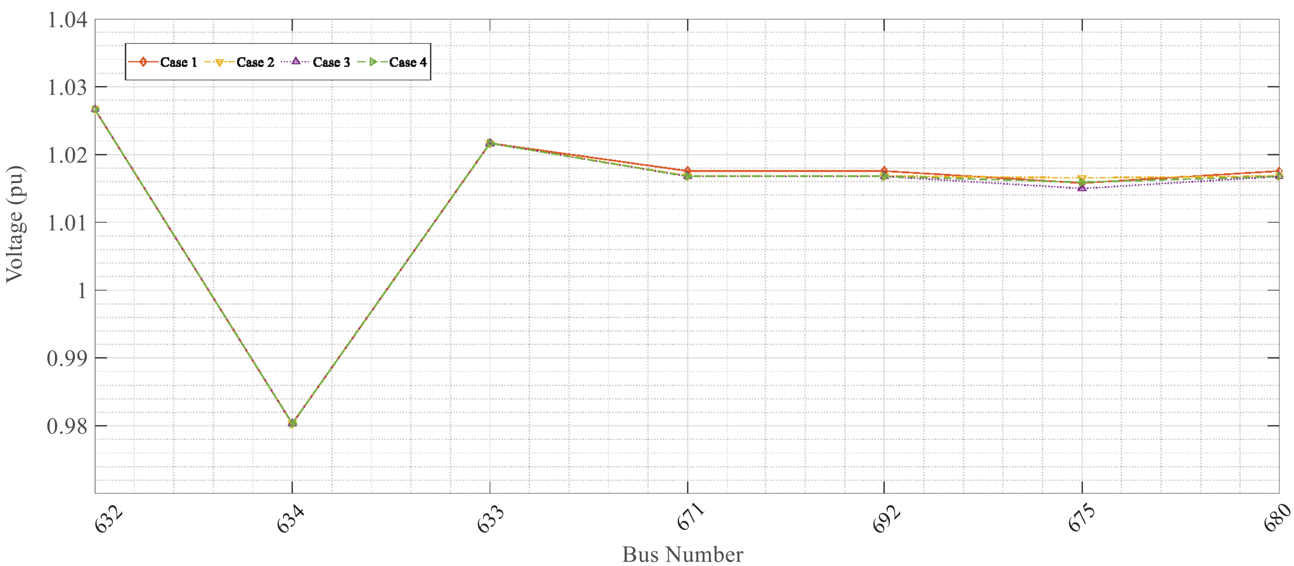

Figure 12. Voltage magnitudes of three-phase buses under cases consisting of different DG integration schemes and loading factors at 18.00 time interval.

16 for each case.

For the given load and generation by DG the highest electricity bill is observed to be 95.76 $ at between 18:00 and 19:00 because of the peak demand load for case 1. Moreover, no difference between the cases is observed until reaching 06.00 since the generation by DG is pretty low. With the DG integration, the highest decrement rate in the bill is obtained to be 94% at between 16:00 and 17:00 because power demand is low and generated power by DG is high at this time interval. Therefore, instantaneous cost is reduced due to the reduction of energy from the grid. While the average electricity bill is around 34.41 $ with no DG, it is decreased

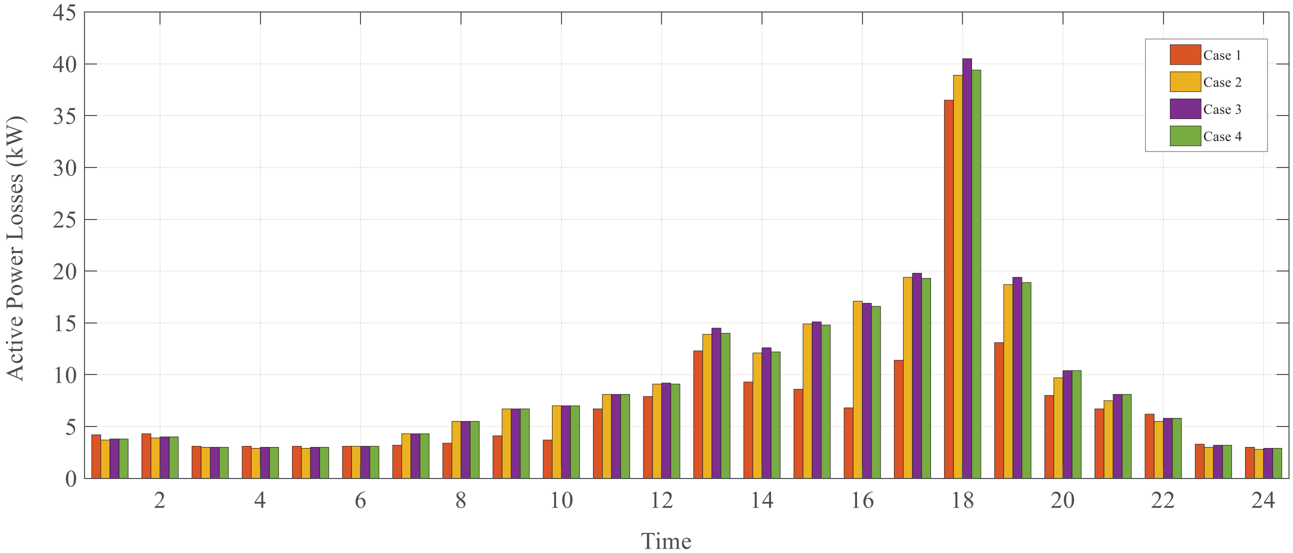

Figure 13. Active power losses of the entire 13-bus test system under cases consisting of different DG integration schemes and loading factors.

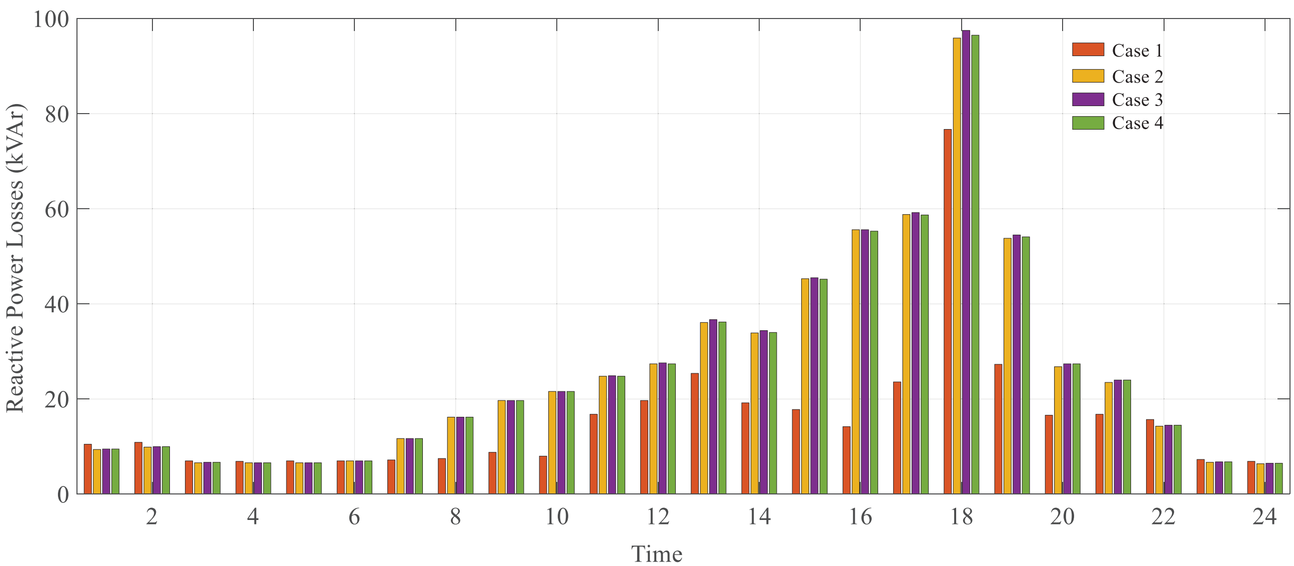

Figure 14. Reactive power losses of entire 13 bus test system under cases consisting different DG integration schemes and loading factors.

to the value of 21.13 $ for each case. The reason is that the total amount of active power demand is greater than the total generated power of DG for all time interval and for each case. Since all DG power is consumed in the industrial area, no extra power can be sold back to the grid. Thus, all the calculated bills state the cost of the net power drawn from the grid.

Figure 15. Active and reactive power losses of entire 13-bus test system under different cases and full loading condition.

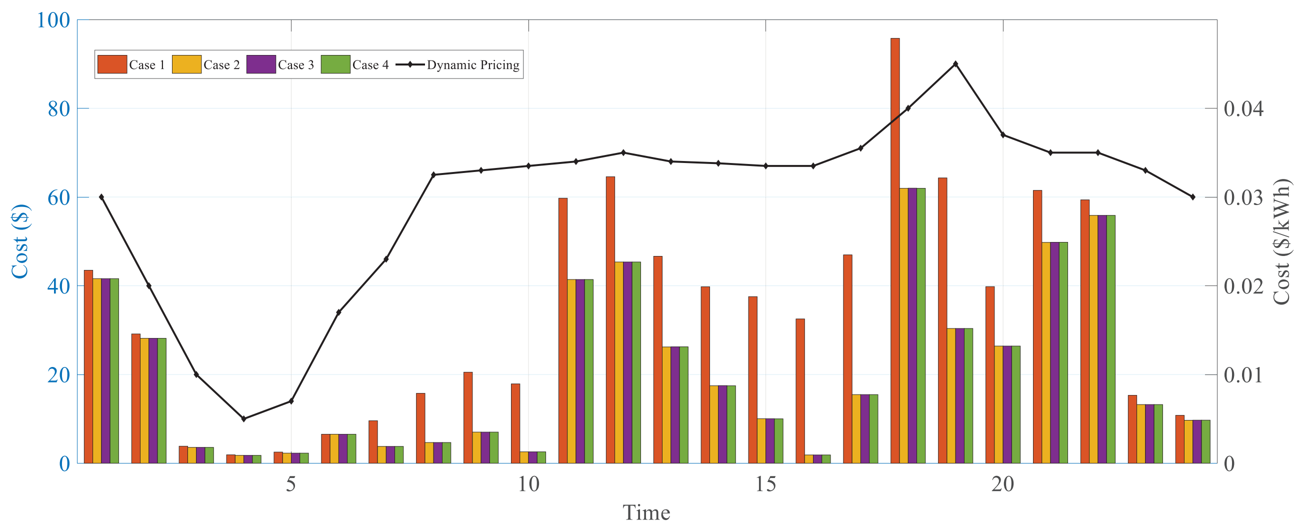

Figure 16. Daily costs of DG integrated test system for each case and dynamic pricing data.

4. Conclusions

In this study, the impact of hybrid DG resources on voltage improvement, power losses, and electricity bill in distribution network is examined in ETAP environment. Before the integration scenarios, DG resources with the total value of 1 MW consisting of PV and WTG are modeled according to the IEEE 13-bus test system and then integrated at bus 671, bus 675 with four cases. Loading factor is also considered as well as integrations of DGs. Even if DGs improve voltage magnitude of the integration or near buses under high increment in the load at these buses, it cannot affect voltage profile of the buses near the grid under the same increment rate. Moreover, it is observed that the contribution of the dispersed hybrid DG compared to single location integration on voltage improvement is greater in the study. Likewise, the location, DG capacity, and loading factor of an integration study should be considered in order to attain the optimal results for the power losses. However, when demand load near the location of DG integration is lower than the generated power by DG, the power losses may increase unexpectedly due to usage of the excess power from other loads. In terms of electricity cost, DGs can effectively reduce the electricity bill to the rate of 94% in the industrial areas considering dynamic pricing and load and generation varying. Moreover, since all DG power is consumed in the industrial area, no extra power can be sold back to the grid. Thus, the total cost of the industrial area is the same for each case. As a future study, massive storage systems for complex hybrid DG resources will be considered.

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