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Modelling and Analysing of Electricity Transmission Infrastructure of Ankara, Turkey: A Case Study on the Critical Line Scenarios

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ABSTRACT

The use of electricity has been increasing constantly from past to now and there is a need of reliable transmission and distribution systems in order to provide continuous and balanced energy. Besides, traditional energy management systems have been forced to change as a result of increases in the usage of renewable energy resources and the efficiency of demand-side on the market. In this respect, power systems should be planned and operated, properly and the balance of generation-consumption should be ensured within the nominal voltage limits. In this study, initially, the current status of electricity infrastructure in Turkey is evaluated. Afterwards, the electricity transmission infrastructure of Ankara that is the capital city of Turkey is modelled by Digsilent program. The critical line scenarios are implemented on the electricity transmission infrastructure model developed. These scenarios are based on the period of maximum and minimum electricity demand and the effects of demand response in this period. As a result of grid analyses performed, several findings has been obtained about the impacts of different line scenarios on the transmission system, the optimization of grid voltage profile and the role of demand response on voltage regulation.

Keywords: Electricity transmission system, modelling, critical line scenarios, demand response, power flow, voltage regulation.

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1. INTRODUCTION

Electricity which is one of the most fundamental necessities of our life is currently used in every field from transportation to health. Despite the electricity demand increases day by day, traditional energy production sources are depleted and it becomes more difficult to supply of electricity energy. On the other hand, although the use of renewable energy resources like wind, solar, etc. is a solution on the generation side, it causes several problems for a reliable and sustainable power system [1]. For these reasons, new solutions are being sought to ensure security of supply in electricity energy.

Contrary to the past, electricity can be produced not only in great powerful plants but also in medium and low voltage levels though new generation technologies of production and storage. It provides efficiency to customers by means of producing their own energy needed and they can sell more electricity. In addition to these, customers are able to save their money by controlling electricity consumption according to the market price or to shift electricity consumption to cheaper tariff time. However, numerous generation-consumption integrations and two-way energy flows causes complex grid structure and energy management becomes more difficult [2-3]. Therefore, the process of planning and operating of power systems gain more importance for meeting growing needs of electricity energy reliably along with constantly expanding grid infrastructure.

Installation of power systems takes a long time and investment costs of them are high. For this reason, power flow, restriction and short-circuit analyses are carried out before the installation of a power plant in order to determine the capacity of new transmission lines and the effects of existing grid [4]. In the literature, the determination of connection points of distributed generation plants and its effects on voltage profile and grid losses were examined [5-6]. In addition, several analyses were done for previously assessing the reaction of grid in the cases of failures, outages etc. occurred in transmission and distribution grids. As a result of these analyses, possible future problems and system reliability were examined [7-9].

In the literature, there are many studies that examine the effects of renewable energy integration into the power system without immediate load variation on the source-based load flow stability. *Kaygusuz et al.* studied the additivity and the impacts of discontinuous distributed generation sources on the basis of daily and hourly [10]. *Meegahapola et al.* compared the optimal power flow in a normal condition of 39-busbar power system with the optimal power flow in wind-based generation. The impacts of wind-based generation on voltage limits, reactive power variations and active power losses were investigated and voltage safety of the grid was reviewed [11]. *Li et al.* carried out risk assessments of a wind-based power system that was affected by variable weather conditions. In different weather conditions, overloading situations of transmission lines were analyzed and grid conditions were evaluated on the basis of daily and hourly [12]. *Elliott et al.* for North West America [13], *Nair et al.* for New Zealand [14] and *You et al.* for Denmark [15] made grid models of their power systems and surveyed the integration impacts of wind and solar energy-based generation, their voltage profile and power quality. *Singhn et. al.* realized the optimal power flow analysis of the transmission system in Switzerland for a long-term capacity planning. The regional availability of wind power and its effects on transmission lines were examined and grid constraints were determined for 2020 [16]. *Celli et al.* foresaw the status of generation and consumption cases in 2030 by making the continuous state analysis of the transmission grid of Sardinian in Italy. In addition, power flow analyses of the related grid were evaluated according to the regional generation estimates of wind and solar energy [17].

In addition to these studies in literature, the effects of demand response cannot be ignored in modern grid management. Since, the demand response increases the consumer's activities, directs the grid profile to the point where energy is consumed, enhances the voltage control and reduces the grid losses. In this way, the flexibility structure can be achieved for the supply-demand balance of electricity system through micro- grid generation or direct load control on consumer side. There are works about demand response and its grid effects in literature. *Wang et al.* implemented the demand side management that includes direct load control and energy storage systems along with real- time pricing and measuring systems [18]. *Cha et al.* monitored the instant electricity prices by means of the developed micro-grid management system and implemented smart load management systems (it is based on load shifting) [19]. *Fan et al.* and *Petinrin et al.* controlled the voltage levels and optimized the power losses by means of the demand response modelled for a distribution system [20, 21]. Besides, the working performance, lifetime, power flow analysis and risk assessment of devices such as transformers, circuit breakers etc. in a grid were surveyed through smart grid management approaches used in transmission and distribution systems [22].

Unlike the existing studies in literature, in this study, the grid infrastructure of Ankara that is a part of the interconnected transmission system in Turkey is initially modelled. Afterwards, the critical line scenarios are implemented on the electricity transmission model developed. Maximum and minimum demand situations in 2013, the effects of demand response on the grid and the comparison of voltage levels are made efficiently.

2. CURRENT STATUS OF TURKEY'S ELECTRICITY INFRASTRUCTURE

Turkey has the installed power of 71429 MW as of May 2015. 60% of electricity demand is provided by thermal energy resources such as natural gas, coal, etc., while 40% of it is supplied from renewable energy resources such as hydraulic, wind, solar, geothermal, etc. [23]. The existing installed power is able to meet the need of annual average electricity energy, but the grid capacity is inadequate in the time of instant peak demand. In this case, the required electricity is imported from neighbouring countries. In opposite cases, the more electricity can be sold to neighbouring countries.

The electricity transmission infrastructure represents the third largest grid of Europe and it consists of the line length of exceeding 53000 km and the total substations of 686. So, the energy losses and the energy quality have a great importance in such a large grid. Therefore, all power system is monitored in real time by National Power Quality Monitoring Centre of Turkey and the problems occurred are resolved. The electricity transmission infrastructure is managed by the national and regional load dispatch centres. The existing transmission system consists of 66 kV, 154 kV and 400 kV grids, while the existing distribution system consists of 34.5 kV and lower voltage levels. Transmission and distribution systems are governed and operated by different companies [24-26].

3. ANALYSIS AND CONTROL IN AN ELECTRICITY TRANSMISSION SYSTEM

Some analyses are done in the existing power system for the installation of new lines and substations, the integration of new generation stations and the synchronization of protection-control devices. These analyses are based on the power flow analysis in order to determine active-reactive power cases of the related system and loading capacity of the related lines and transformers. Short-circuit, harmonic, stability, constraint and coordination analyses are used for deciding the limit values of switching equipments on a grid [27]. On the other hand, transmission system operators situated in the international synchronization area should ensure the national and international standards in order to carry out their electricity market activities taking into consideration of supply-demand balance. For these reasons, primer and secondary frequency control, tertiary control, active-reactive power control and voltage control are realized for controlling the active power and the load frequency [28, 29].

In interconnected systems, the electricity consumption is met from great powerful plants which are generally situated away from residential areas. The transportation of electricity energy for a long distance causes voltage dropping in lines and so, different voltage levels occur in the power system according to the different usage cases. Moreover, voltage variations also arise depending on the load demand in an electricity system. While the voltage drops in the time of high electricity consumption, it is high in the time of low electricity consumption. However, it is required that the grid should be within the voltage limits in its nominal operating state [4, 30]. On the other hand, the voltage is also affected by the active and reactive energy consumption. Inductive and capacitive reactance is equal in the nominal load capacity of transmission lines. If the transmission line is loaded below the nominal transportation capacity, the voltage increases, otherwise it decreases above the nominal transportation capacity. Generally, inductive consumers reduce the voltage, while capacitive consumers enhance the voltage [29].

4. MODELLING OF THE ELECTRICITY TRANSMISSION INFRASTRUCTURE OF ANKARA

In an interconnected electricity system, it will be enough to know the substation capacities and the grid parameters for a regional analysis [31]. In this study, the grid modelling of a 154 kV electricity transmission system in Ankara is made in a city-wide manner. The electricity transmission system modelled consists of 28 substations and 48 transmission lines between these substations. In addition, there are 24 generation plants. 8 of them are medium- and large-sized (the installed power > 10 MV) and the other ones are small-sized. The small-sized plants are the micro-grids which are generally established by costumers.

The single-line diagram of the electricity transmission infrastructure of Ankara is shown in Fig. 1. It is performed by means of using real grid, line, transformer and plant data in *Digsilent Program*. Electricity transmission lines have physically single- or double-circuit structure. However, they are modelled as separate lines in the single-line diagram because of the different bus connections. In addition, the tie-lines with outer regions are defined as external grids. G3, G4, G6, G9, G12, G15, G19 and G23 among generation plants are medium and large-sized plants. Through the electricity transmission system model developed, voltage, phase angle, directions of active-reactive power flow and line loading are examined according to the generation, load and line situations in maximum and minimum demand periods in 2013. Particularly, the effect of demand response on the grid voltage profile is focused with different scenarios in both periods. The amount of power generation and load for each grid scenario implemented in single-line diagram is given in Table 1 and Table 2, respectively.

In 154 kV electricity transmission systems, the maximum and the minimum operating voltage limits should be 170 kV and 140 kV, respectively. However, it is required that the voltage limit should be in the range of ±5 % at substations [4, 26]. In addition, base values are generally used instead of actual values belong to system components such as voltage, current and active-reactive power. So, the base voltage value has been defined as 154 kV in the performed analyses in this study. In this respect, the voltage limits are assigned as follows:

The operating voltage limits: $0.90 < U\ (pu) < 1.1$

The bus voltage limits: 0.95 < U(pu) < 1.05

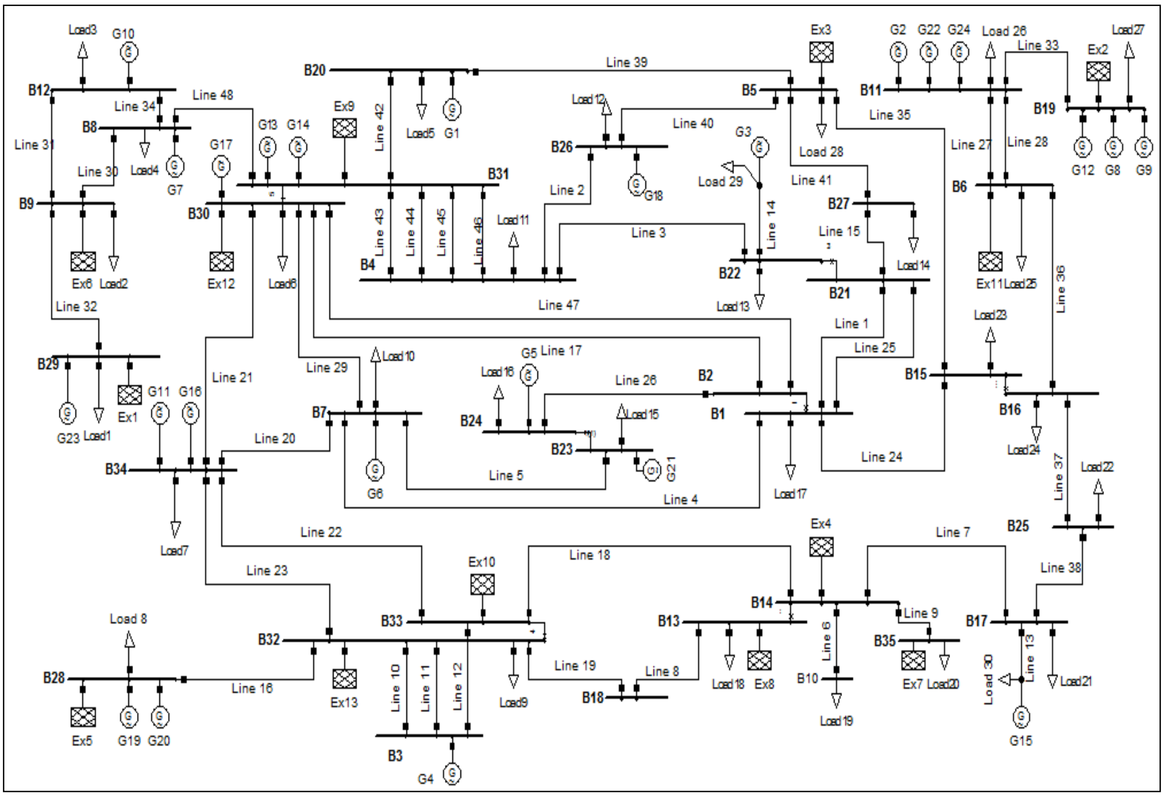

Fig. 1. Single-line diagram of electricity transmission infrastructure for Ankara

Table 1. The amount of power generation for each grid scenario implemented in single-line diagram

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	AP	**RP**	**AP**	**RP**	**AP**	**RP**	**AP**	**RP**	**AP**	**RP**
G1	0	0	0	0	3.84	0	3.84	0	3.84	0
G2	0	0	0	0	1.81	0	1.81	0	1.81	0
G3	33	1	0	0	33	1	33	1	33	1
G4	200	32.1	360	-50.6	200	32.1	360	-50.6	360	-50.6
	163	31	265	-67.4	163	31	265	-67.4	265	-67.4
G5	0	0	0	0	3.2	0	3.2	0	3.2	0
G6	23	8.5	0	0	23	8.5	0	0	0	0
G7	0	0	0	0	0.79	0	0.79	0	0.79	0
G8	8.2	0	0	0	8.2	0	8.2	0	8.2	0
G9	0	0	0	0	19.1	0	19.1	0	19.1	0
G10	0	0	0	0	6.2	0	6.2	0	6.2	0
G11	0	0	0	0	2.04	0	2.04	0	2.04	0
G12	16.7	2	0	0	16.7	0	0	0	0	0
G13	0	0	0	0	14.16	0	14.16	0	14.16	0
G14	0	0	0	0	5.425	0	5.425	0	5.425	0
G15	16.5	2.20	15	-3.5	16.5	2.20	15	-3.5	15	-3.5
G16	0	0	0	0	3.558	0	3.558	0	3.558	0
G17	0	0	0	0	0.514	0	0.514	0	0.514	0
G18	0	0	0	0	2.05	0	2.05	0	2.05	0
G19	11.7	2.2	0	0	11.7	2.2	0	0	0	0
G20	0	0	0	0	0.834	0	0.834	0	0.834	0
G21	0	0	0	0	2	0	2	0	2	0

G22	0	0	0	0	4.3	0	4.3	0	4.3	0
G23	160	2.8	0	0	160	2.4	0	0	0	0
G24	0	0	0	0	3.89	0	3.89	0	3.89	0

AP: Active Power (MW), **RP:** Reactive Power (MVAr)

Table 2. The amount of load for each scenario implemented in single-line diagram

	Scenario 1		**Scenario 2**		**Scenario 3**		**Scenario 4**		**Scenario 5**	
	AP	**RP**	**AP**	**RP**	**AP**	**RP**	**AP**	**RP**	**AP**	**RP**
Load1	12	1	4	1	12	1	12	1	12	1
Load2	11	5	14	7	11	5	11	5	11	5
Load3	31	1	0	0	31	1	31	1	31	1
Load4	14	2	10	1	14	2	14	2	14	2
Load5	66	11	15	5	66	11	66	11	66	11
Load6	176	12	35	-5	176	12	176	12	167.2	11.4
Load7	165	-8	61	-14	165	-8	165	-8	165	-8
Load8	56	4	20	4	56	4	56	4	56	4
Load9	18	2	1	3	18	2	18	2	18	2
Load10	195	6	62.6	-12	195	6	195	6	195	6
Load11	38	2	28	0	38	2	38	2	36.1	1.9
Load12	84	14	5	-5	84	14	84	14	84	14
Load13	38	2	12	4	38	2	38	2	38	2
Load14	96	3	36	1	96	3	96	3	96	3
Load15	79	9	24	4	79	9	79	9	79	9
Load16	47	7	14	1	47	7	47	7	44.65	6.65
Load17	132	12	50	3	132	12	132	12	132	12
Load18	89	9	30	1	89	9	89	9	89	9
Load19	8	0.2	3	0	8	0.2	8	0.2	8	0.2
Load20	156	15	60	2	156	15	156	15	156	15
Load21	33	3	17	1	33	3	33	3	33	3
Load22	118	5	34	1	118	5	118	5	118	5
Load23	22	3	23	2	22	3	22	3	22	3
Load24	68	6	8	0	68	6	68	6	68	6
Load25	22	1	0	0	22	1	0	0	22	1
Load26	74	3	24	-6	74	3	74	3	74	3
Load27	8	1	1	1	8	1	8	1	8	1
Load28	0	0	8	0	0	0	8	0	0	0
Load29	53	1	20	3	53	1	53	1	53	1
Load30	71	0	15	-3.5	71	0	71	0	71	0

AP: Active Power (MW), **RP:** Reactive Power (MVAr)

5. ASSESSMENT OF CRITICAL LINE SCENARIOS

In this study, five different line scenarios are created in order to evaluate the electricity transmission infrastructure of Ankara. Scenarios 1 and 2 investigate the power grid constraints in the cases of maximum and minimum electricity demand, respectively. The impact of demand-side participation in the cases of maximum and minimum electricity demand are also analyzed in Scenarios 3 and 4, respectively, Finally, Scenario 5 reduces the contribution of large-scale power plants in the case of minimum electricity demand. Many detailed comparisons and assessments about all scenarios are made in the following subsections.

5.1. Comparison of Scenario 1 and Scenario 2

Scenario 1 and Scenario 2 represent the periods of maximum and minimum demands, respectively. In the analysis of these two periods, the transmission system includes only medium- and large-sized generation plants. The most important difference between these scenarios is the variation in generation and consumption values. In addition, there are physical differences on the grid at the time of analysis performed. The bus voltage values and the voltage variations in both scenarios are shown in Fig. 2. The average values of voltages in Scenario 1 and Scenario 2 are found as 0.99 pu and 0.95 pu, respectively. Besides, the voltage values of 16 buses are below the lower limit in Scenario 2. It should be noticed that the system voltage is more stable in peak demand period.

Moreover, the direction of power flow depends on the voltage magnitude and the phase angle of buses in power flow analysis. While the larger positive phase angles represent the injection of production to the system, the negative phase angles or lower phase angles represent the consumption buses. Also, the active power flow towards from the bus having larger voltage phase angle to the one having lower voltage phase angle. On the other hand, the reactive power flows from the bus having higher voltage to the bus having lower voltage. In this context, the voltage phase angles of Scenario 1 and Scenario 2 are shown in Fig. 3. In case of giving an instance for this figure; B29 has a positive phase angle due to the injection of production to the system in Scenario 1. However, the related phase angle is negative in Scenario 2 due to the lack of production.

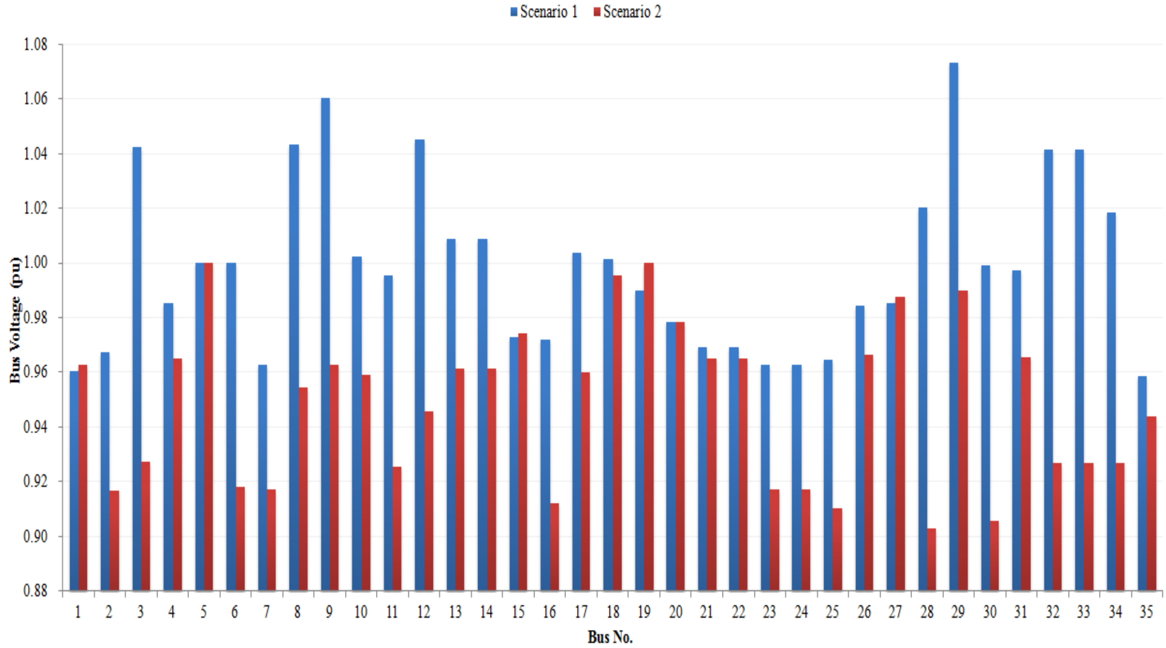

Fig. 2. Bus voltages of Scenario 1 and Scenario 2

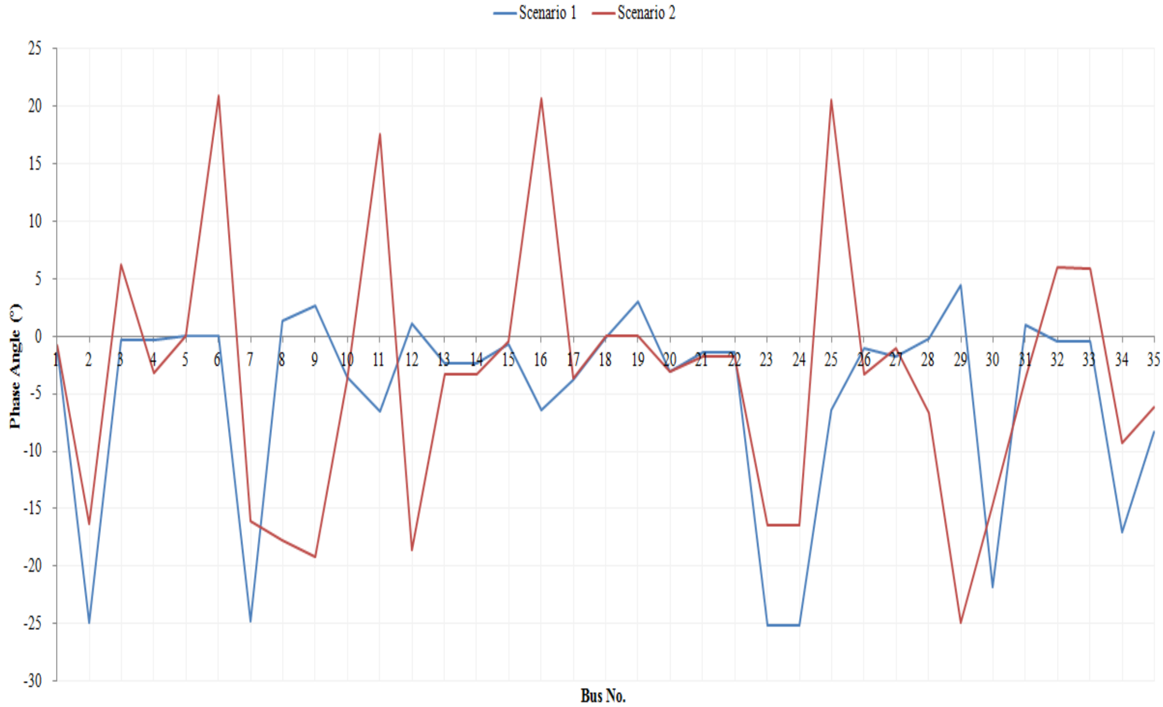

Fig. 3. Phase angles of Scenario 1 and Scenario 2

5.2. Comparison of Scenario 1 and Scenario 3

In Scenario 3, the effects of small-sized micro generation plants on the grid are analyzed in the period of maximum demand (This period means Scenario 1). The buses numbered as 8, 11, 12, 19, 20, 23, 24, 26, 28, 30, 31 and 34 are included for the micro-grid generation. The active power participation is increased approximately 11% in the power system.

The bus voltage values belong to Scenario 3 and the voltage differences according to Scenario 1 are given in Fig. 4. The average value of voltage is 1.00 pu in Scenario 3. So, the system voltage has become more stable in the peak demand period. In addition, the voltage phase angles of buses are given in Fig. 5. As seen in this figure, the voltage phase angles of buses that increase their electricity generation have risen in Scenario 3.

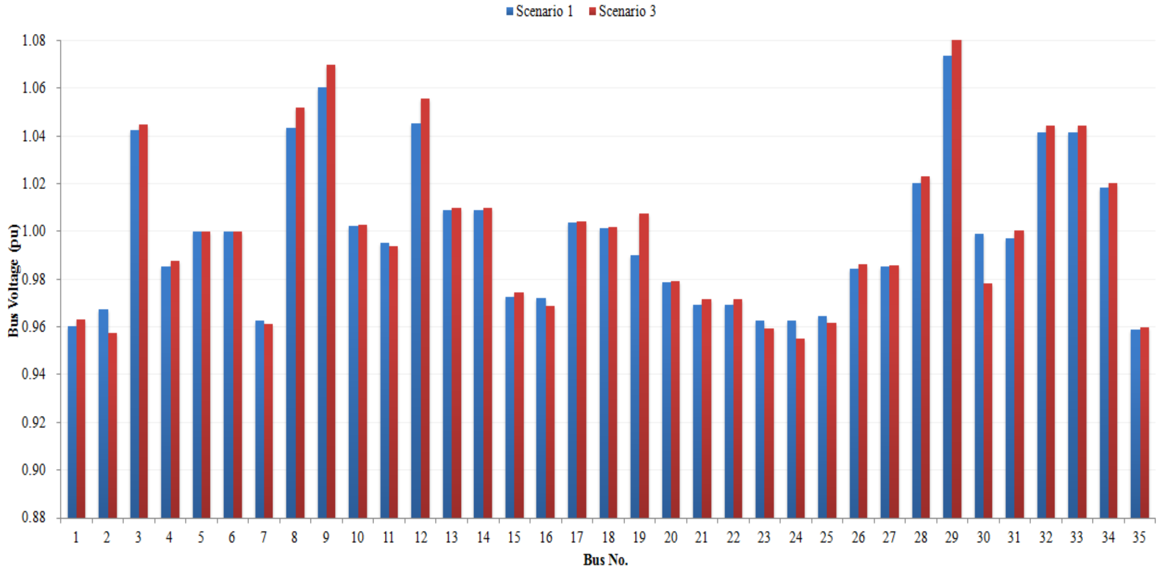

Fig. 4. Bus voltages of Scenario 1 and Scenario 3

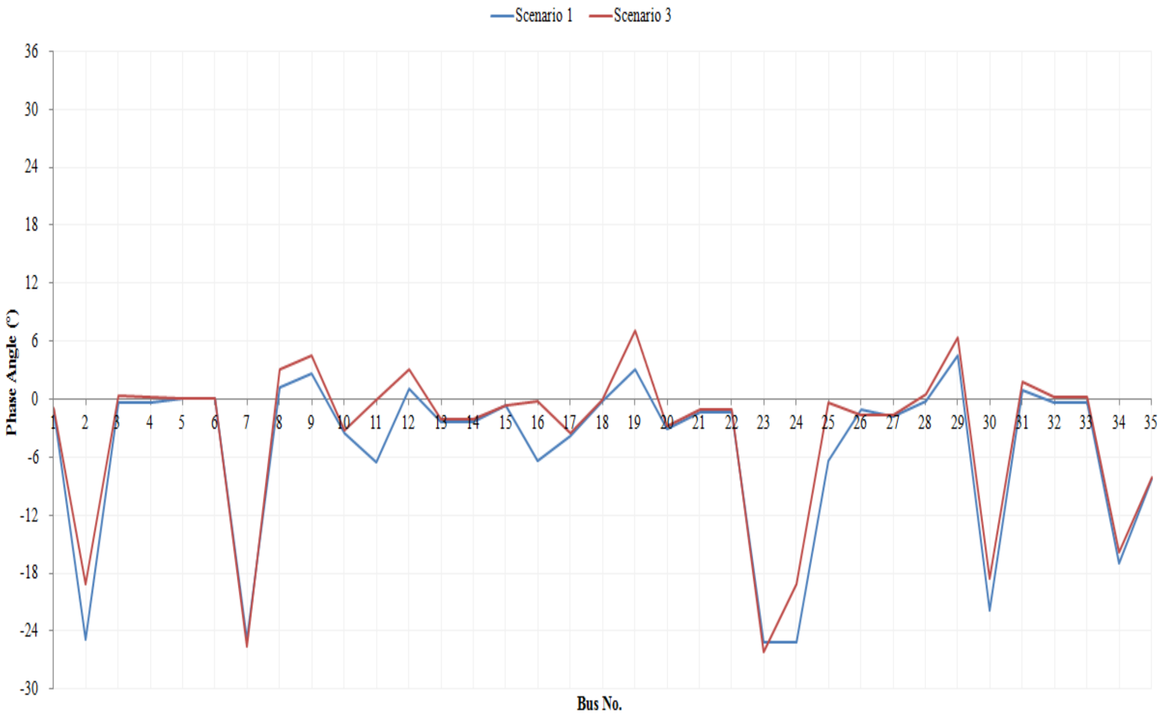

Fig. 5. Phase angles of Scenario 1 and Scenario 3

5.3. Comparison of Scenario 2 and Scenario 4

In Scenario 4, the effects of small-sized micro generation plants on the grid are analyzed in the period of minimum demand (This period means Scenario 2). The buses numbered as 8, 11, 12, 19, 20, 23, 24, 26, 28, 30, 31 and 34 are included for the micro-grid generation. The active power participation is increased about 17% in the power system. The bus voltage variations and the voltage phase angles belong to Scenario 2 and Scenario 4 are illustrated in Fig. 6 and Fig. 7, respectively. The voltage in 45% of buses has remained below the lower limit in Scenario 2. This rate is reduced to 11% through the demand response implemented. In addition, the average voltage of grid has risen to 0.97 pu in Scenario 4 and the voltage profile has become more stable according to Scenario 2.

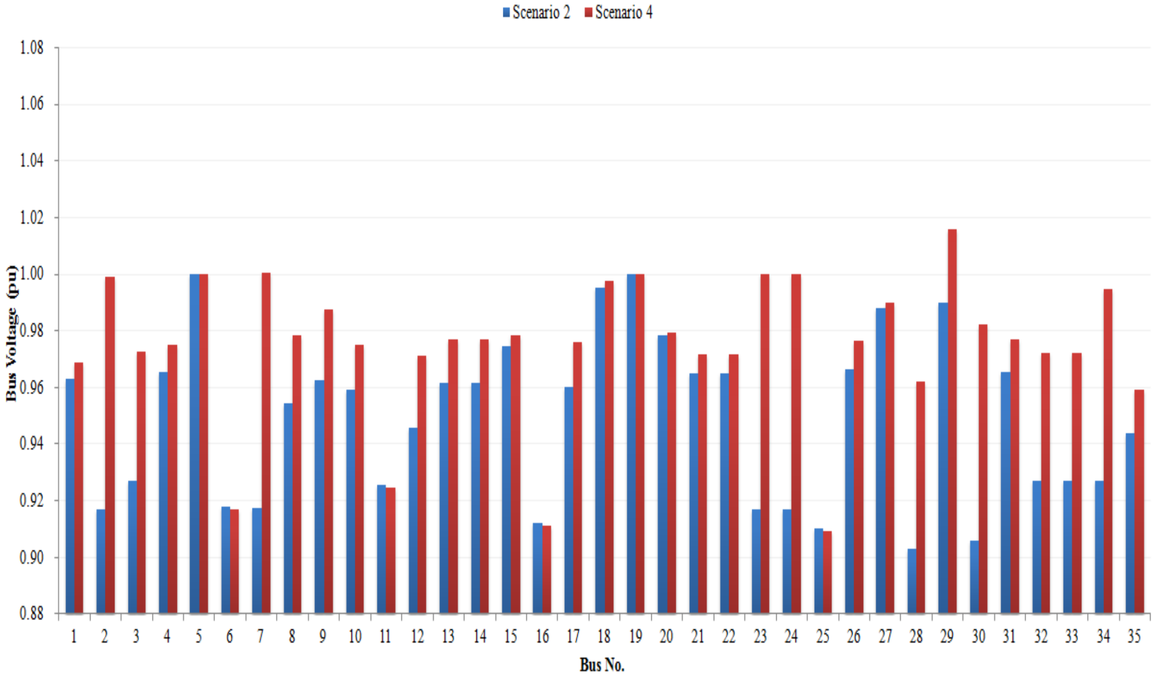

Fig. 6. Bus voltages of Scenario 2 and Scenario 4

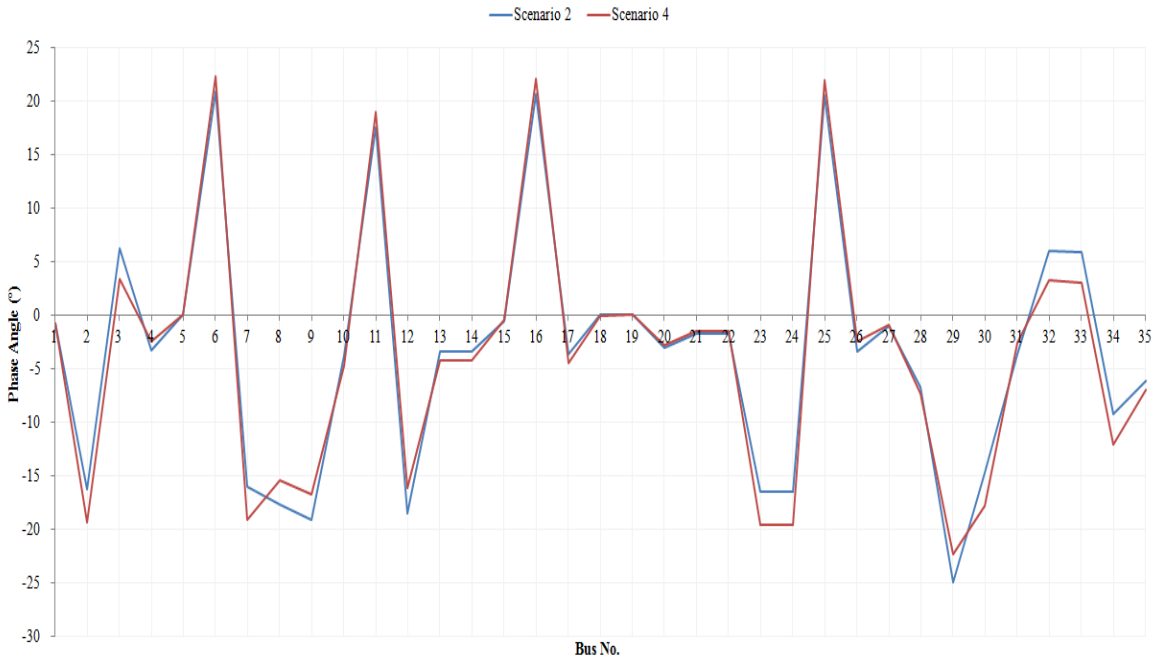

Fig. 7. Phase angles of Scenario 2 and Scenario 4

5.4. Comparison of Scenario 4 and Scenario 5

In Scenario 4, the voltage levels have remained below the lower limit in the buses of 6, 11, 16 and 25. For this reason, in Scenario 5, the voltage variations in the mentioned buses are analyzed by changing the consumption and the reactive power rates of these buses. The consumption values in these buses are decreased in the rate of 5%. The bus voltage values belong to Scenario 5 and the voltage differences according to Scenario 4 are depicted in Fig. 8. It has been seen that the voltages in the buses of 6, 11, 16 and 25 have increased and the average voltage of grid has risen to 0.994 pu. The variations of voltage phase angles in Scenario 4 and Scenario 5 are also depicted in Fig. 9. The voltage phase angles are closer to the reference values as a result of the voltage increase in the buses of 6, 11, 16 and 25.

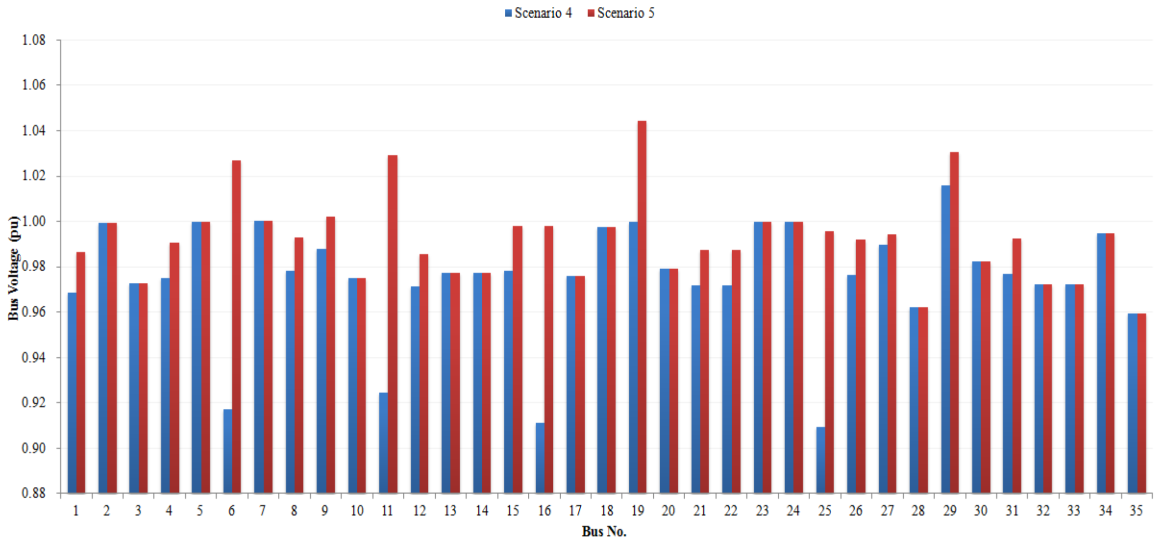

Fig. 8. Bus voltages of Scenario 4 and Scenario 5

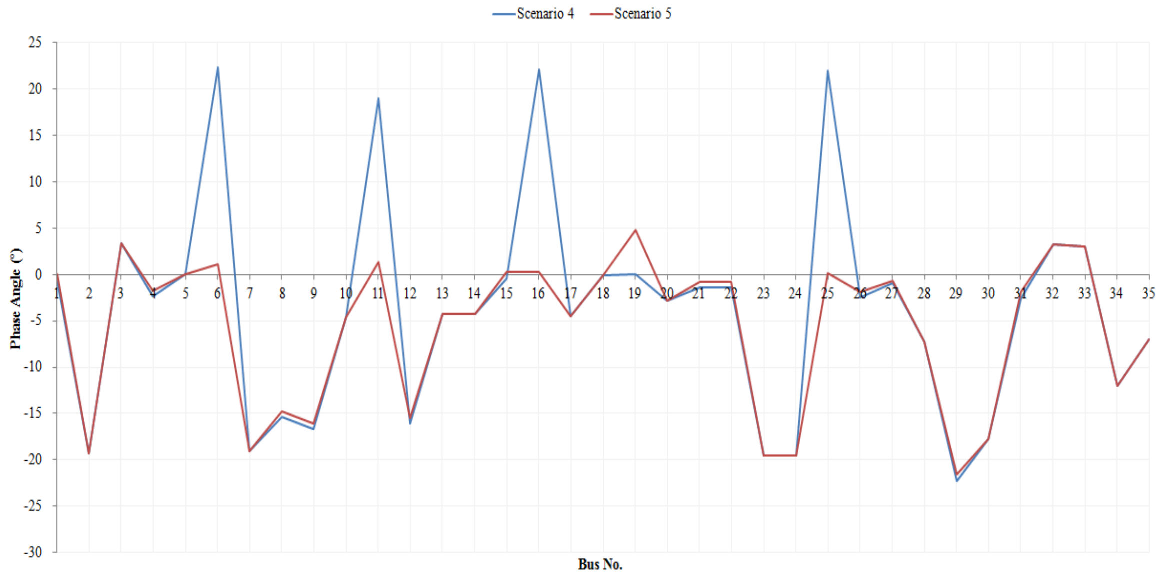

Fig. 9. Phase angles of Scenario 4 and Scenario 5

6. CONCLUSIONS

In this study, the grid infrastructure of Ankara that is a part of the interconnected transmission system in Turkey is modelled and some critical line scenarios are analyzed on the grid model developed. Firstly, the voltage levels in the cases of maximum and minimum electricity consumption are compared in the grid analyses made. In this comparison, it is shown that the voltage profile is more stable due to the maximum generation in the peak demand period. Furthermore, the grid voltage is closer to the nominal level when the demand response is included into the transmission system in both scenarios. Particularly, the contribution of demand response to the grid voltage is more in the minimum consumption period. In addition, the voltage control is carried out exactly by means of controlling the electricity consumption in the demand side.

As a result of the critical line scenarios performed, many reasonable and significant outcomes are achieved as follows: It is foreseen that the demand response will play a key role in the control of transmission systems. It is obvious that the demand response consideration will provide the crucial contributions to grid security and energy market in the stages of planning and operating of power systems. The overloading cases in transmission lines will be prevented and the system voltage will be more stable by meeting the electricity demand on the consumer side. Thus, the capacity investments of transmission systems and the grid losses will be reduced.

In future works, more large-scale grid analyses can be done in the existing interconnected transmission system. The effects of different generation resources or variable loads on the grid can be analyzed in detail. Especially, the long-term capacity planning and the grid steady analyses can be realized by considering a regional demand response.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

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