RESEARCH ARTICLE

Investigation of the effects of electric vehicle charging stations and solar energy integration on grid performance

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Abstract

In this study, the negative effects of electric vehicle charging stations, whose use has rapidly increased all over the world in the last few years, on the electricity network were analyzed. The charging station was purchased and installed in a suitable area. Measurements taken using the energy analyzer at this charging station were examined. An electrical network model has been prepared. IEEE 6-bus power test system data was used for this model. The model was built using Electrical Transient Analyzer Program (ETAP). In addition to the existing loads on the electricity grid, the loads that will occur with the increase in electric vehicle charging stations have also been added. In this case, this electrical network was analyzed using the Newton-Raphson load flow algorithm with the existing load data of the generators, buses and data of the added charging station loads in the IEEE 6-bus test system network. Considering that one thousand additional charging stations come as load for each load bus, 22 MW load was added. In order to reduce the power losses detected here, grid-connected solar power plants have been proposed. By adding these power plants, it is aimed to reduce the negative effects of the load increase caused by electric vehicle charging stations. For the case of adding solar power plants (SPP), the results were examined by making load flow and it was shown that the network losses decreased. As a result of the study, as a result of adding electric vehicle charging station loads (EVCS) to each load bus in addition to the existing loads, active power loss doubled and reactive power loss reached more than three times. In the buses with the recommended consumption, these losses, which increased with the energy production by load solar power plants, decreased by more than half.

Keywords: Electric Vehicles, Load Flow, Solar Power Plants, Charging Stations, Power Loss, Newton-Raphson Load Flow.

1. Introduction

Due to the limited lifespan of fossil fuels and their harmful effects such as greenhouse gases, the interest in electric vehicles (EV) in the automotive industry as an alternative fuel has been rapidly increasing in recent years [1,2]. For this reason, electric vehicles and their components have become an important research topic [3]. Reducing

greenhouse gas effects and using EVs that will have positive effects on climate change increases the incentives in this field. Because today, climate change is one of the leading situations that negatively affect living life [4,5,6]. It is thought that increasing EV use will significantly reduce these negative effects. Because when we look at the causes of carbon dioxide emissions in Europe, the automotive industry ranks second in terms of causing greenhouse gases when the sectors are compared [7]. For these reasons, EV technology, which can benefit from the energy production of alternative energy sources, is supported by governments due to its high efficiency, not causing CO_2 emissions and its positive contributions to energy sustainability, and their numbers are increasing day by day. [8,9,10]. In addition to the benefits of using electrical energy in electric vehicles, it also causes some problems. Especially negative situations that may arise on the electricity grid restrict the increase in the number of EVs. It is stated in academic studies that EV sales will constitute approximately 20% of total vehicle sales [11]. These vehicles, which consume electrical energy, will cause increased losses in the network, sudden load changes, changes in demand profiles, decreased energy quality as a result of harmonic distortions, shortened lifespans of transformers and conductors, network voltage losses and a significant decrease in network efficiency [12-15]. The resulting network effects will also increase the probability of failure. This is a situation that threatens energy supply demand.

This rapid promote in EVs shows that the number of electric vehicle charging stations (EVCS) will also increase [8,16]. These increases raise the infrastructure deficiency in the network. Therefore, understanding the effects of electric vehicle charging stations on energy networks and minimizing these effects has become an important research area. Olcay et al. [2] suggested the use of solar power plants to reduce the effects of electric vehicles on greenhouse gas emissions. In the study, a solar power plant (SPP) model was built in open parking lots and the emission effects of different vehicle brands were examined by EV charging with the resulting system. In addition, the emissions and SPPs caused by EVs according to the production raw material of the energy provided by the grid and their reduction amounts are shown here. In another study, the effects of EV charging in a 240-bus distribution network were investigated. An hourly demand profile data for EVs has been created. Along with this profile, the demand profile of the 240-bus distribution network was evaluated together. As a result, the degradation of energy demands arising from EV charging is shown. To reduce this degradation, three different charging scenarios have been proposed [11]. In another study, SPP was designed for EVs. In the study, the power plant was modeled and efficient use of space was aimed. Additionally, the use of a wind turbine and photovoltaic panels has been compared for EVCSs [17]. In another study, daily load curves were created using user feedback data to ensure power distribution optimization of EV charging in the electrical grid and a double-layer optimization strategy was created [18]. Other studies in the literature have examined the regulation of EV network usage times according to energy sales prices [19-21]. In another study that proposed an internet of things (IoT)-based system for EV users, EVCS usage optimization was created in multi-storey car parks. The created IoT system encourages EV users to charge during periods when the electricity grid load is less. In addition, the aim of the study is to direct EVs to charge by using solar energy in the afternoon, when solar energy is intense and the electricity grid load is less [22]. Himabindu et al. [23] proposes an alternative energy source EVCS system. The economic evaluation of this system and its improvement effect in terms of greenhouse gas emissions have been demonstrated. The effects of EVCS on the electricity grid also vary depending on their location. In a study conducted in this context, the criteria that determine EVCS locations in a certain geography were shown and optimum locations were determined [24]. In another study, it was studied to activate EVCS and smart photovoltaic inverters simultaneously to prevent or reduce the negative effects of EVCS such as voltage deviation, power losses and voltage imbalance. Pareto dominance based differential evolution algorithm is proposed and implemented to solve this optimization equation. The study results show that the electricity grid performance will raise significantly [25]. In another study, distributed generation was added to the distribution system to reduce the electrical grid power loss that would be increased by the EVCS effect [26]. Sigma Ray et al. [27], EVCS optimum location problem was created for different operators. Different objective functions were created by considering distribution system operators, charging station operators and EV user approaches. Different optimization techniques are discussed and the effects of EV-generated loads on the distribution network

are analyzed. Since EV charging and discharging schedules change the effects of EVCS on the electricity grid, studies have been conducted on various optimization techniques [28-30].

In this comprehensive study, the negative effects of electric vehicle charging stations on energy networks are analyzed in detail and innovative solution suggestions are offered. A charging station was installed in a suitable location and measurements taken using the energy analyzer were meticulously examined. For the electrical network model, a model was created using the ETAP (Electrical Transient Analyzer Program) program using IEEE 6-bus power test system data.

In addition to the existing loads, the analysis was also made to include the additional loads caused by electric vehicle charging stations. In this context, network analysis was carried out by combining the data of generators, buses, existing load data and added charging station loads in the electrical network using the Newton-Raphson load flow algorithm.

The main goal of this study is to reduce the detected power losses and optimize the performance of the energy grid. In this regard, it is recommended to add grid-connected solar power plants and a solution is offered to reduce the negative effects of the load increase caused by electric vehicle charging stations of these power plants. By examining the results of the load flow analysis for the addition of solar power plants (SPPs) in addition to electric vehicle charging stations, it is shown that network losses are reduced. In addition, using EVCS and SPP together, that is, charging EVs with energy produced by SPP, will provide a sustainable system [31-33].

This study contributes to the sustainable integration of electric vehicles and aims to improve grid performance. The proposed solutions offer a forward-looking approach to counter the growing importance of electric vehicles in our energy landscape, in line with the goals of smart grid development and sustainable energy management.

2. Materials and methods

In this section, the steps and methods of the study are explained. The network model is introduced in Section 2.1. Test Network model details are given. In Section 2.2, the infrastructure work for EVCS implementation and data collection is explained. In the last part, section 2.3, the load flow analysis performed with ETAP is shown.

2.1. IEEE 6 bus power grid test system information

IEEE 6 Bus power test system was used to analyze EVCS network effects. IEEE 6 bus power system is a standard test system used in power systems analysis, control and protection studies in the field of electrical engineering. This grid represents part of the American Electric Grid. This system is used as a reference model for power systems analyses, voltage drop calculations, short circuit analyses, frequency response evaluations and other power systems engineering applications. It is used to examine the energy flow between different buses and to evaluate the performance of each component in the system.

The 6-bus test model used in this study was created in the ETAP program. In this study, in the 6-bus network system, bus number 1 is the swing bus, buses 2 and 3 are voltage-controlled buses, and buses 4, 5 and 6 are the load buses. A single line diagram of the test system is shown in Figure 1.
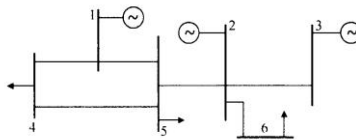

Fig. 1. IEEE 6-bus power test system.

While creating a network model, the values of production and loads are shown in Table 1.

Table 1. IEEE 6-bus test system load values (pu).

Bus number	Bus type	Bus voltage	P_{gen}	Q_{gen}	P_{load}	Q_{load}
1	Swing	1,05+j0	-	-	0	0
2	Generator	1	1,2	0,5	0	0
3	Generator	1	1,2	0,5	0	0
4	Load	-	-	-	0,7	0,7
5	Load	-	-	-	0,7	0,7
6	Load	-	-	-	0,7	0,7

While creating the model, the values of the lines between the buses were also determined. These data are shown in Table 2.

Table 2. IEEE 6-bus test system load values (pu).

Branch number	Branches		R	X	B
1	1	2	0,1	0,2	0,04
2	1	4	0,05	0,2	0,04
3	1	5	0,08	0,3	0,06
4	2	3	0,05	0,25	0,06
5	2	4	0,05	0,1	0,02
6	2	5	0,1	0,3	0,04
7	2	6	0,07	0,2	0,05
8	3	5	0,12	0,26	0,05
9	3	6	0,02	0,1	0,02
10	4	5	0,2	0,4	0,08
11	5	6	0,1	0,3	0,06

Using the data in Table 1 and Table 2, the nominal equivalent circuit of the electrical network system here was created. Equivalent circuits are created and these circuit models vary depending on the length of the transmission lines and the type of analysis to be performed. For short transmission lines, the capacitive reactance between the phase conductors and the ground and the leakage resistance here are neglected. However, since the model here is evaluated in the medium and long lines class, nominal equivalent circuits have been created. "π (pi) nominal" and "T nominal" circuits are used when creating equivalent circuits of transmission lines. These concepts represent two different approaches used in mathematical modeling and analysis of transmission lines. Pi nominal circuit will be used for the load flow analysis. This model includes inductance, capacitance, resistance and conductance values in the transmission line. These values are generally based on values measured at nominal frequency. The main reason for using this model is to evaluate power systems that are generally operated at nominal frequency (such as 50 Hz or 60 Hz) in load flow analysis. The π nominal circuit generally gives accurate results in load flow analysis and is widely used to evaluate operating conditions. The values in Table 1 and Table 2 are given per-unit. It was used in this way in the model. "Per Unit" (pu) is a unit of normalization used to compare a measurement or value to a standard reference value. It is widely used in electrical engineering and energy systems. This normalization makes it easier to compare and analyze values of different magnitudes. The expression "Per Unit" represents a ratio in which

a value is expressed as divided by a specific reference value (base value). Information on these base values is needed to obtain the real values in the system. S_{load} 100 MVA, V_{base} 230 kV and Z_{base} 529 ohms were used as base values.

2.2. EVCS field application and analysis

In the implementation phase of the study, a 22 kW AC type 3-phase charging station was used. The reason why the 22-kW station was chosen is that it is the EVCS type preferred by EV users and many commercial EVCS entrepreneurs. When industry research is done, it costs approximately 5% of the price of 120 kW DC EVCS. Since its power is much lower than DC types, it is also widely used in residences. It is much easier for 22 kW devices to integrate into existing electrical infrastructures. In addition, due to its lower price and ease of connection to existing infrastructures, their numbers are increasing much faster and becoming a collective burden. According to October data for commercially used ones, the number of AC EVCS in Turkey is approximately 3 times more than DC type

Fig. 2. Electric vehicle charging station panel assembly visual.

ones. When those that are not used commercially are added, it becomes a huge burden. Current, voltage and harmonic analysis measurement data are taken from this charging station. The infrastructure and installation works carried out for this purpose are explained in this section. First of all, a separate panel content was designed so that the charging station can receive energy from the existing electrical system and targeted measurements can be made. The point where this panel will receive energy from the existing electrical system was determined and the energy was received from the existing electrical panel through the overcurrent circuit breaker protection element, and the energy supply to the charging station panel was made with a 4x10 mm² copper cable. In addition, the protection grounding of the electric vehicle charging station panel was made with a 10 mm² single-core copper cable and connected to the existing grounding system. Energy intake from the existing electrical system and installation of the electric vehicle charging station panel are shown in Figure 2.

After the installation of the sheet metal panel and the installation of the power line from the existing system, the interior design of this panel was started. One 40/5 A current transformer for each electrical phase and three current transformers in total were used in the panel energy input. The current information that the charging station will draw

from these current transformers will be transferred to the energy analyzer. For this purpose, the connection between current transformers and energy analyzer is also made. The conductors passing through the current transformers are connected to the main input switch of the panel. With this switch, overcurrent protection is provided and the conductors are protected. From here, energy distribution was made within the panel and the energy analyzer was mounted to the relevant connection points on the energy analyzer using three single-phase circuit

breakers for electricity supply. Three-phase leakage current protection switch connections were made with the output taken from the panel input switch. In this way, user protection is provided against any leakage current fed from this panel or that may occur on the metal parts of the panel. The residual current protection switch cuts off the energy by opening the circuit at 30 mA level. In-panel installation is shown in Figure 3.

Electric vehicle charging station current, voltage and harmonic measurements will be provided through the energy analyzer mounted on the panel. The energy analyzer has RS485 communication connection and Ethernet connection. Instant remote monitoring of the data will be done using an ethernet connection. For this, an internet

Fig. 3. Electric vehicle charging station in-panel installation visual.

connection was made as seen in Figure 4. CAT6 cable was installed to connect the output from the relevant port of the energy analyzer to the free port of the data switch in the existing infrastructure. The energy analyzer connection is seen in Figure 4.

Fig. 4. Energy analyzer installation visual on the panel.

After these stages, the charging station energy cable was selected and an underground cable channel was opened from the energy receiving point to the charging station installation point. In this channel, energy cables were pulled through the plastic pipe and brought to the vehicle charging station installation point. A 4-core 10 mm² energy cable was pulled through the pipe and a connection was made between the charging station and the electrical panel from which it receives energy. In this way, the charging station power line installation has been completed. Following this

process, the metal body of the charging station was assembled and a 22 kW AC type 2-socket charging station was installed on this body. The installed charging station is seen in Figure 5.

Fig. 5. Installation image of 22 kW AC type 2-socket charging station.

2.3. Load flow analysis with ETAP

Electrical energy is of vital importance in every field in today's world. Therefore, the safety, efficiency and performance of electrical systems must be constantly monitored and analyzed. These systems may contain complex and dynamic variables due to their structure. At this point, ETAP program is a software that provides the opportunity to analyse and optimize electrical energy systems.

In this section, load flow analysis was performed with the Newton-Raphson method by adding the EVCS loads of the IEEE 6-bus power test system modelled in the ETAP program. As a result of the analysis, active power and reactive power losses in the lines were determined. Afterwards, active power and reactive power losses were reduced by connecting SPP to the production buses in the system. The most suitable production bus has also been determined.

There are many load flow analysis methods. It can be said that the most used ones are the Fast Decoupled method, Gauss-Seidel method and Newton-Raphson method. Studies in the literature [34] show that losses increase as the number of iterations of the Gauss-Seidel method increases. In the Fast Decoupled method, as the number of buses increases, it causes no results to be found in the calculation. The most appropriate results are obtained with the Newton Raphson method. For this reason, it was preferred as the load analysis method of this study.

First of all, the IEEE 6 bus power test system was modelled in the ETAP program. The model is shown in Figure 6.
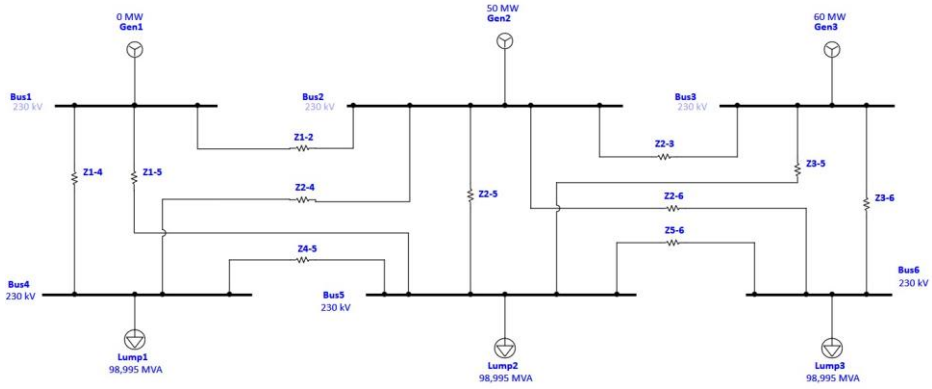
Fig. 6. Installation image of 22 kW AC type 2-socket charging station.

In this model, it was made with existing loads, lines and productions. It represents an existing grid system. The effects of electric vehicle charging stations (EVCS) to be integrated into existing systems on the network will be analysed through this model. This study will especially focus on power losses. Losses in the current system were determined by the Newton-Raphson load flow method. Afterwards, EVCSs were added to the load buses in the IEEE 6 bus network model. The added EVCS features are explained in section 2.2 and shown in Figure 5. It is considered that 1000 units of 22 kW AC type 2 charging stations are added to each load bus, individually and commercially. EVCS network effect is made according to the peak load scenario that will occur if all devices operate at the same time. The model with EVCS loads added is shown in Figure 7.
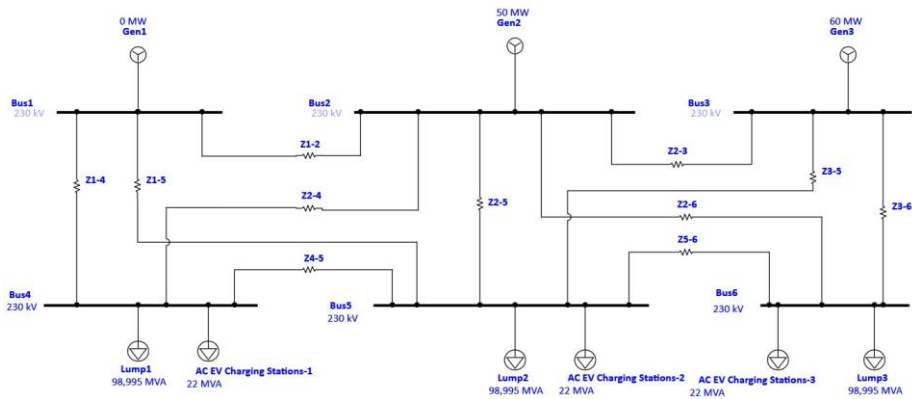

Fig. 7. ETAP model with IEEE 6 bus EVCS loads.

In order to reduce the impact of electric vehicles on the grid and ensure energy supply security, SPPs as well as EVCS consumption have been added to the system as distributed generation resources. The network model with SPPs added is shown in Figure 8.
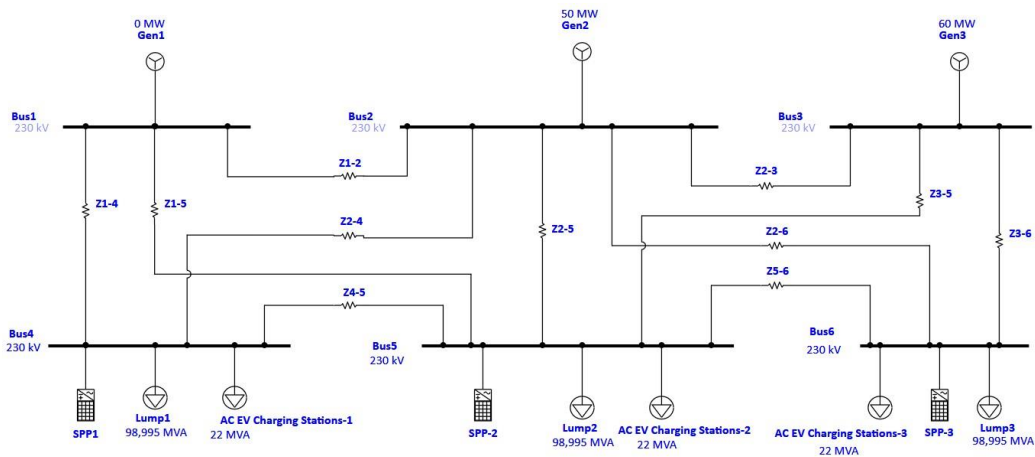

Fig. 8. IEEE 6 bus EVCS loads and SPP ETAP model.

3. Conclusion

The increase in the number of EVCS is predicted to be 1.5 million and 2.5 million in our country, according to different scenarios as medium growth and high growth. This situation will cause a significant infrastructure problem and negative effects for existing electricity grid systems. In this study, a real EVCS field installation was made and the values were read through the energy analyzer. It has been observed that no harmonics that will affect the network for AC devices occur due to EVCS energy consumption during charging. From this point on, focusing on other problems, their collective impact as a load on the network was investigated and a network model was created for this. The created network model consists of generators, existing transmission lines and existing loads. Relevant values are given in this study.

4. Results and discussion

First, load flow analysis was performed with the IEEE 6 bus power system model and data shown in Figure 6. The results are seen in Table 3.

As seen in Table 3, line losses in the current system show 23,832 kW active power loss and 34,450 kVAr reactive power loss. These losses are high for existing systems due to their own loads. As shown in Figure 7, load flow was made with these powers to analyze the line losses that would occur in the system with the addition of EVCS-sourced loads. The results are seen in Table 4.

As can be seen from the results in Table 4, by adding EVCS loads to the 4th bus, 5th bus and 6th bus in addition to the existing loads, line losses more than double. As a result of the analysis, 46,427 kW active power loss and 110,763 kVAr reactive power loss occurred.

Table 3. IEEE 6 bus Newton-Raphson load flow analysis line losses results.

Branch ID	From-to bus flow		To from bus flow		Loses		% Bus voltage	
	MW	MVAr	MW	MVAr	kW	kVAr	From	To
Z1-2	85,443	22,753	-77,539	-10,305	7.904,3	12.267,9	100	87,8
Z1-4	80,813	60,551	-75,592	-43,091	5.221,7	17.460,1	100	84,5
Z1-5	67,576	47,535	-61,880	-31,146	5.696,2	16.388,8	100	81,1
Z2-3	21,385	0,359	-21,083	-3,381	301,4	-3.022,4	87,8	86
Z2-4	4,206	26,220	-3,722	-26,735	484,3	-515,1	87,8	84,5
Z2-5	13,187	13,787	-12,657	-15,050	530,7	-1.263,1	87,8	81,1
Z2-6	38,760	22,117	-36,870	-20,222	1.890,4	1.895,3	87,8	79,5
Z3-5	-1,492	15,282	1,972	-17,734	479,8	-2.452,6	86	81,1
Z3-6	22,375	50,713	-21,721	-47,816	853,8	2.897,4	86	79,5
Z4-5	9,314	-0,174	-9,050	-4,782	263,3	-4.956,1	84,5	81,1
Z5-6	11,615	-1,288	-11,409	-1,963	206	-3.250,2	81,1	79,5

Table 4. IEEE 6 bus EVCS loads Newton-Raphson analysis line losses results.

Branch ID	From-to bus flow		To from bus flow		Loses		% Bus voltage	
	MW	MVAr	MW	MVAr	kW	kVAr	From	To
Z1-2	118,764	44,197	-102,525	-15,037	16.239	29.160,3	100	81,2
Z1-4	111,137	88,759	-100,843	-50,808	10.294	37.950,5	100	78,3
Z1-5	92,526	73,016	-81,055	-34,600	11.471	38.416,3	100	73,1
Z2-3	28,812	4,317	-28,152	-4,815	660	-498	81,2	77,9
Z2-4	4,145	20,484	-3,792	-21,052	352,3	-567,7	81,2	78,3
Z2-5	17,922	14,991	-17,031	-14,703	891,2	287,6	81,2	73,1
Z2-6	51,645	27,423	-47,914	-19,644	3.731	7.778,7	81,2	70,3
Z3-5	-2,685	14,457	3,203	-16,187	518	-1.729,5	77,9	73,1
Z3-6	30,837	52,972	-29,578	-47,779	1.258,8	5.192,7	77,9	70,3
Z4-5	12,635	1,860	-12,054	-5,287	581,3	-3.427,2	78,3	73,1
Z5-6	14,936	0,777	-14,508	-2,577	428,3	-1.800,1	73,1	70,3

These losses pose a serious problem for existing network infrastructures. These losses will cause energy loss in energy transmission and distribution lines, resulting in a decrease in energy efficiency. It may result in increased costs for consumers and companies as it will require more energy production, transmission and distribution. In addition, increasing line losses will increase voltage drops and reduce energy quality, creating the possibility of damaging devices in the system. It causes voltage regulation problems. It will cause electrical devices such as transmission lines and transformers to overheat, shortening their material life. Furthermore, it will increase the need for maintenance and the potential for failure. Excessive losses in electrical energy production and transmission can increase environmental impacts. In particular, increased consumption of fuels used for energy production and increased energy losses may increase environmental impacts. In order to reduce all these problems and support

sustainable energy, SPPs with a power of 22 MW were added to the 4th load bus, 5th load bus and 6th bus against EVCS consumption. To see the effect of this situation on line losses, load flow analysis was performed using the Newton-Raphson method and the results are shown in Table 5.

Table 5. IEEE 6 bus EVCS loads and Newton-Raphson analysis line losses results in SPP network.

Branch ID	From-to bus flow		To from bus flow		Loses		% Bus voltage	
	MW	MVAr	MW	MVAr	kW	kVAr	From	To
Z1-2	88,714	24,176	-80,159	-10,586	8,555	13.589,4	100	87,2
Z1-4	83,895	62,807	-78,276	-43,739	5,619	19.067,3	100	83,9
Z1-5	70,117	49,547	-63,975	-31,454	6,142	18.093,2	100	80,4
Z2-3	22,157	0,68	-21,829	-3,503	328,5	-2.823,4	87,2	85,3
Z2-4	4,225	25,720	-3,753	-26,240	472,7	-520	87,2	83,9
Z2-5	13,678	13,865	-13,120	-15,008	557,2	-1.142,8	87,2	80,4
Z2-6	40,099	22,500	-38,071	-20,158	2.027,7	2.341,9	87,2	78,7
Z3-5	-1,617	15,216	2,100	-17,607	482,7	-2.390,3	85,3	80,4
Z3-6	23,446	50,900	-22,562	-47,832	883,4	3.068,9	85,3	78,7
Z4-5	9,646	-0,021	-9,359	-4,811	286,3	-4.832,2	83,9	80,4
Z5-6	11,972	-1,120	-11,750	-2,011	222,7	-3.131,2	80,4	78,7

As can be seen from the results, the effects of EVCS-induced overloads on the network are quite large. The proposed addition of SPP to reduce line loss increases to the network has yielded beneficial results. Active power losses decreased by approximately 21 MW, falling to 25,577 kW. Reactive power losses decreased by approximately 70 MW, falling to 41,321 kW. As can be seen from the results, it is a useful method to reduce the effects of EVCS on existing networks. In addition, electricity generation from solar energy makes great environmental contributions since it does not cause carbon emissions. Using SPPs as distributed generation plants with EVCS also provides other advantages. These power plants will contribute to keeping the voltage stable by regulating voltage fluctuations at the points where they will be connected to the grid. In addition, having production close to consumption points, as in this study, is also an advantage and reduces line losses. It can diversify energy supply and increase energy security by locating power sources in various locations. Renewable resources such as solar panels, wind turbines or hydroelectric power plants can be used more effectively through distributed generation plants.

It should be noted that care should be taken when determining the connection points of distributed power plants. It is important that the network capacity is sufficient. Since these power plants will be connected to the grid above a certain voltage level, the grid voltage level should be analyzed when selecting connection points. Network topology, environmental and social impacts must be taken into account. Short circuit analyses, power flow analysis, voltage drop, reactive power balance, frequency, transformers and transmission lines, protection and coordination analyzes should be performed.

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