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A Novel Newton Raphson-Based Method for Integrating Electric Vehicle Charging Stations to Distribution Network

Mustafa Nurmuhammed[1], Ozan Akdağ[2], Teoman Karadağ[3]

[1]Department of Electric and Energy, Malatya OIZ Vocational School, İnönü University, Malatya, Turkey
[2]Turkish Electricity Transmission Inc., Malatya Regional Directorate, Malatya, Turkey
[3]Department of Electrical and Electronics Engineering, İnönü University, Malatya, Turkey

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ABSTRACT

Electric vehicle sales are rising due to numerous factors such as government policies, falling prices, advanced, and eco-friendly technology. Built-in battery packs are charged using the energy from the distribution network. When a large number of electric vehicles are simultaneously charged with high power, the distribution network can be adversely affected. Differences in electricity supply and demand on the distribution network, voltage imbalance, and power losses are among the examples of effects. In this study, a mathematical model has been proposed in order to properly handle the effects of charging stations on the distribution network. According to the model, the optimum placement of electric vehicle charging stations is achieved within the constraints of the distribution network. In order to prove the robustness and validity of this model, the proposed model is applied to IEEE 33-bus radial test system. Results are discussed in cases.

***Index Terms*—**Distribution network, electric vehicles, electric vehicle charging stations, load flow analysis, power analysis modeling

I. INTRODUCTION

In recent years, electric vehicles (EVs) have been gaining popularity as sales figures are increasing in most countries. Almost all new trend vehicles include some form of electric drivetrain. A forecast shows that the ratio of EVs will be more than 25% of all vehicles in the next 10 years [1]. Electric vehicles generally provide drivers faster acceleration, less cost per mile, less maintenance costs, environment awareness, and other innovative technological advantages such as autonomous driving and remote access features. These advantages contribute to an inevitable rise in popularity and sales in numerous countries. Electric vehicle sales have increased at a rate of 46–69% between 2014 and 2019 [2].

There are many types of EVs depending on the drivetrain and charging architecture. A hybrid EV (HEV) is manufactured with both an internal combustion engine (ICE) and an electric motor. On the other hand, an HEV that can be charged through the distribution network is called a plug-in HEV (PHEV). Plug-in hybrid electric vehicles and all electric vehicles are charged using power distribution network and this charging can be an unpredictable source of load that can impact the power grid. The impact resulting from differences in electricity supply and demand on the power grid can be voltage imbalance and power losses on the distribution network. This study presents modeling and load flow analysis in order to further analyze the integration of EV charging stations (EVCSs) into a power distribution network. Based on the effects of this integration, supplementary procedures can be executed in order to mitigate the adverse effects on the distribution network.

When the literature studies in this field are examined in detail, it is seen that many studies on the integration of EVs into the distribution network are handled with different aspects. In some studies, load uncertainty and future predictions are considered. For instance, in [3], load uncertainty along with using renewable energy sources (RES) in EVCSs is studied in nine scenarios. According to the study, before the place of EVCS is determined, RES and demand for charging should be studied in order to lower the cost of EVCS installation and the power instability in the network. Planning of EVCSs is performed based on charging demand prediction, minimization of cost, and

Corresponding author:
Mustafa Nurmuhammed

E-mail:
mustafa.nurmuhammed@inonu.edu.tr

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load variance of power grid [4]. Charging/discharging schedules and energy management schemes are also utilized in studies in order to reduce power loss and voltage deviation and improve reliability [5–8]. In addition, some studies include social aspects such as travel characteristics and EV drivers' habits. In research, EVCS planning is studied considering the transportation and electrical network interactions [9]. On the other hand, numerous studies use power-related parameters such as power loss and voltage profile. In research study [10], power loss, charging power, and cost parameters are used in EVCS placement. Another study uses voltage stability, power loss, cost, and reliability along with accessibility to optimally locate EVCSs [11]. Voltage deviation, operational cost, and power loss parameters are also used in [12] to rank candidate sites as optimal, midst, or unfit. In [13], solar-powered EVCSs are optimally placed considering power loss, voltage deviation, and Voltage Stability Index (VSI) using improved chicken swarm optimization. In addition, there are other studies focusing on the effect of charging EVs on the grid such as studies in references [14–18].

In current studies, it is seen that EVs are generally limited to their internal structure or their basic effects on the existing grid. In addition, in order to further evaluate the possible problems, there are still deficiencies that need to be studied in terms of the effects of EV charging stations on voltage stability, effects on nominal operation, and modern integration. In order to analyze the above problems in detail, in this study, a Newton Raphson-based mathematical model is proposed for the optimum integration of EVs into the distribution network. In this context, the model proposed by the study was implemented as a state network model using the DIgSILENT Power Factory program. By applying this model to the existing IEEE 33-bus radial test system, the optimum number and location of EVCSs are determined. Thus, after the integration of EVCSs into the relevant distribution network, the continuity of the nominal operation of these networks has been ensured.

In summary, the contribution of this study to the literature can be summarized as:

1. A new mathematical model has been proposed to see the effects of EVCSs on existing distribution networks and to ensure the optimum integration of EVCS to these networks.
2. The proposed mathematical model has been applied efficiently in IEEE 33-bus distribution system.

A. Electric Vehicles

The term "electric vehicle" covers many vehicles from electric bicycles to electric buses. In order to increase the focus on the subject and normalize the data, the term "electric vehicle" in this study refers to the electric cars that can be charged through the EVCS.

B. Electric Cars Impacts on Low Voltage (LV) Grids

There are many types of EVs depending on the drivetrain and charging architecture. A HEV contains both an ICE and an electric motor. On the other hand, an HEV that can be charged through the distribution network is called PHEV. Plug-in hybrid electric vehicles and all EVs are charged using the distribution network and this charging can be an unpredictable source of load that can affect the network. The impact resulting from differences in electricity supply and demand on the power grid could have adverse effects.

With the increase in the number of EVs every year, the charging process will bring additional loads to the network in the near future and will cause an increase in the losses caused by the density and harmonics in the transformers/lines [19]. Because of these effects, undesired interruptions or equipment failures may occur. Thus, voltage quality in the relevant distribution networks will be a problem that needs to be solved. For this reason, it is important to integrate EVCSs into the system within a plan.

C. Voltage Stability Index

The integration of EVCSs into distribution networks has significant effects on the voltage stability of the network. Voltage stability is the capability of a power system to sustain an acceptable and stable operating condition and to return to its normal equilibrium position after a disturbance. Under normal operating conditions, the voltage of a distribution network is within certain limits, but when disturbance occurs in the system, voltage imbalance and an uncontrollable voltage drop may take place. The bus voltage stability index is utilized to determine the bus that may cause such stability problems and to keep the system stable [20]. The index can be found using the active and reactive power equations. In this study, the VSI formula (1) presented in [16] was used to calculate the VSI values.

$$2V_k^2V_{k+1}^2 - 2V_{k+1}^2\left(P_{k+1}r + Q_{k+1}x\right) - \left|Z\right|^2\left(P_{k+1}^2 + Q_{k+1}^2\right) \geq 0 \quad (1)$$

II. MATERIALS AND METHODS

A. Model Developed for Integrating Electric Vehicle Charging Stations

In order to accurately address the effects of charging stations on distribution networks, a mathematical model has been proposed to place charging stations within the scope of the determined scale model. According to this mathematical model, the number of EVCS that can be integrated into the distribution system is calculated while the constraints in the distribution system are fulfilled. This model is based on a simple mathematical approach. In this model, Newton Raphson and VSI methods are integrated into the mathematical approach. With this model, the number of EVCS that can be integrated into the distribution buses in distribution systems can be determined with a simple and effective method. The steps of this model are as listed below: The constraints in the proposed model are as follows:

$$\textit{Active power}\ P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad i = 1,2,\ldots Ng \quad (2)$$

$$\textit{Reactive power}\ Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \quad i = 1,2,\ldots Ng \quad (3)$$

$$\textit{Bus voltage}\ V_i^{min} \leq \left|V_i\right| \leq V_i^{max} \quad i = 1,2,\ldots Nb \quad (4)$$

where P_G: active power generations of *ith* generator; Q_G: reactive power generations of *ith* generator; *Nc* is the number of nominated buses for reactive compensation, *Nt* is the number of tap transformers. where *Gx* is the slack buses, Q_C: shunt capacitor of *ith* bus; *T*: tap setting of *ith* bus; S_L: line flow limits of *ith* bus; V_L: voltage of *ith* bus (load buses); V_G: voltage of *ith* bus (generation), *NPQ*, *NG, and NL* are number of load buses, generator buses, and transmission lines, respectively.

Step 1: In the first step, load flow is performed based on the Newton Raphson method, and the line losses in the distribution system, the loading of the distribution transformers, the current values drawn by the relevant lines, and the voltage values of the buses are determined.

Step 2: In this step, considering the data of the relevant distribution transformers and the losses of the current distribution line, the amount of power demand that this distribution transformer can meet (here, line losses are calculated in Step 1) is calculated. The mathematical model of this situation is given in (5).

$$dt_iml\left(MW\right)-lineloss_k\left(MW\right)-maxload_i\left(MW\right)=remainload_i\left(MW\right) \quad (5)$$

dt_iml , i. the maximum load (label value) of the distribution transformer, $lineloss_k$, total loss (MW) of all lines connected to the distribution transformer, $maxload_i\left(MW\right)$ i. maximum load drawn by current consumers connected to the distribution transformer.

Step 3: In this step, the number of EVCS is calculated using the remaining load of the relevant distribution transformer calculated in Step 2. The mathematical equivalent of Step 3 is given in (6).

$$\frac{remainload_i\left(MW\right)}{cload\left(MW\right)}=n \quad (6)$$

$cload$ is the total load capacity of EVCS, while n is the number of EVCS.

If the number of connected buses beyond the relevant distribution transformer is more than two, step 4b, if not, step 4a is executed.

Step 4a: Depending on the capacity of the charging stations to be added to each distribution transformer, the capacity of the line, which will provide the connection between this distribution transformer and the EVCS, is calculated. Line capacities are determined by (7). Afterward, charging stations are integrated into the relevant lines. If integration is planned directly on the distribution line, (7) is executed. Otherwise, a charging station is integrated into the relevant bus.

$$\sqrt{\frac{remainload_i}{R}}=I_{Ch,i} \quad (7)$$

R indicates the resistance value of the relevant line, $I_{Ch,i}$ indicates the carrying capacity of the transmission line between the bus with the charging stations to be added to the *ith* distribution transformer and this distribution transformer.

Step 4b: Charging stations calculated in step 3 are added to the buses with voltage of the distribution bus close to 1 p.u. (preferably above 0.97 p.u. and below 1.03 p.u.) according to the bus voltage values calculated in step 1 and the VSI calculated in this step (VSI is calculated before adding charging stations) with a value above 0.9.

Step 5: After adding EVCSs to the relevant buses in step 4a or 4b, load flow analysis is performed by applying the Newton Raphson method. Based on the results of the load flow analysis, the transformer and line loads are checked whether they are within the desired limits. If the results are within the limits, proceeded to step 6. If not, go to step 5a. Step 5a: in this step, the buses in the distribution system are examined according to the load flow performed after step 5. If the voltage level of the buses is close to or outside the desired constraint limits, the number or capacity of EVCSs can be reduced to attain desired range of p.u. values. However, if the number and/or capacity of EVCSs is planned to be constant (depending on the desired application), then shunt capacitors can be used to keep the p.u. levels in the desired range. Furthermore, the Newton Raphson method is applied again and if the limits are met, the system moves on to execute step 6. If not, the same step is repeated. Step 5b: if the shunt capacitor is not added, the number of EVCS near the distribution transformer is decreased/increased. Next, load flow is executed again and if the constraints are met, the system moves on to execute step 6. If not, the same step is repeated.

Step 6: According to the data obtained from Newton Raphson and the data of the power system, the VSI data of this power system are determined (VSI for all buses is calculated by (1)). If the VSI is greater than zero for all buses, the system moves on to execute step 7, otherwise, goes back to step 5.

Step 7: End. Figure 1 shows the flowchart of the proposed method.

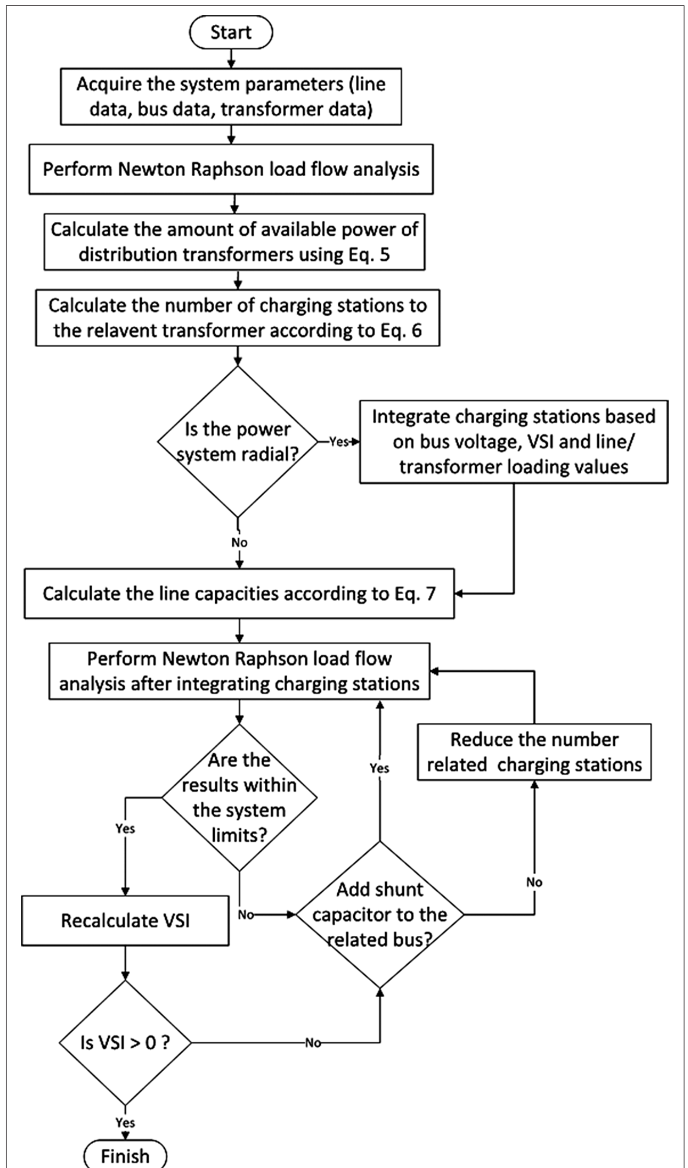

Fig. 1. Flowchart of the proposed method.

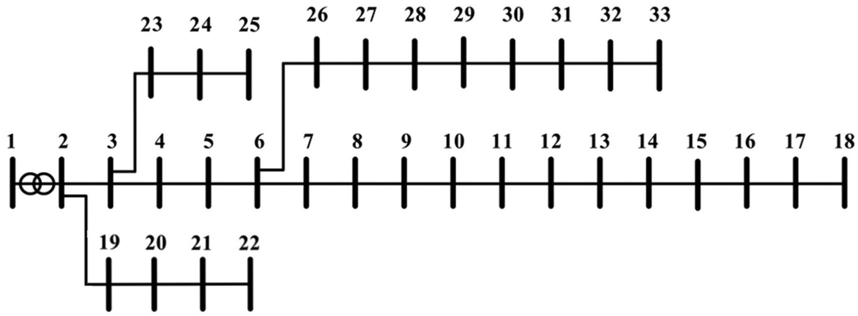

Fig. 2. IEEE 33-bus test system diagram.

IV. SIMULATIONS AND RESULTS

A. The IEEE 33-Bus Radial Distribution System

The IEEE 33-bus distribution system includes 33 buses and 32 lines. All buses are at 12.66 kV level. Voltage limits are assumed to be ±10%. The total load demand of this distribution system is 3175 MW and 2.3 MVAR. Distribution line data and load data of this power system values are taken from [16] and IEEE 33-bus test system diagram is shown in Fig. 2. Distribution system was modeled using DIgSILENT software. In this study, a distribution transformer has been added to Bus 1. This transformer has a power of 20/12.66 kV, 6.5 MVA. Most AC charging stations are designed to supply 22 kW and small-size DC stations 24–25 kW. In this study, to cover both charging possibilities, each EV is modeled as a load with an average of 25 kW. The IEEE 33-bus test system will be used in case 1 and case 2.

Case 1: in case 1, a load flow analysis was carried out according to the Newton Raphson method in IEEE 33-bus distribution network before commissioning the EVCSs. The results are given in Tables I and II.

Bus voltages in Table I and distribution line data in Table II are within normal limits. In this power system, the synchronous generator produced 3.91 MW/2.51MVAR active/reactive power. Line losses in this distribution system are 0.2 MW/0.21 MVAR.

Case 2: in case 2, the number of EVCS that will be integrated into the relevant buses of IEEE 33-bus system is determined by the model

TABLE I. RESULTS OF LOAD FLOW ANALYSIS OF IEEE 33-BUS DISTRIBUTION SYSTEM

Bus Name	Vpu/deg	Bus Name	Vpu/deg
Bus1	0.991/−0.66	Bus18	0.9/−1.57
Bus2	0.99/−0.65	Bus19	0.99/−0.66
Bus3	0.976/−0.57	Bus20	0.98/−0.73
Bus4	0.97/−0.5	Bus21	0.985/−0.75
Bus5	0.961/−0.45	Bus22	0.984/−0.77
Bus6	0.942/−0.52	Bus23	0.972/−0.6
Bus7	0.94/−0.76	Bus24	0.965/−0.69
Bus8	0.925/−0.91	Bus25	0.962/−0.73
Bus9	0.923/−1.11	Bus26	0.94/−0.48
Bus10	0.917/−1.17	Bus27	0.94/−0.42
Bus11	0.916/−1.16	Bus28	0.931/−0.69
Bus12	0.915/−1.15	Bus29	0.923/−0.62
Bus13	0.91/−1.25	Bus30	0.92/−0.62
Bus14	0.906/−1.33	Bus31	0.916/−0.6
Bus15	0.905/−1.37	Bus32	0.914/−0.64
Bus16	0.903/−1.39	Bus33	0.914/−0.64
Bus17	0.901/−1.48	Ploss	0.2 MW
Pg	3.91 MW	Qloss	0.21 MVAR
Qg	2.51 MVAR	TRload	77

TABLE II. LINE LOADINGS OF IEEE 33-BUS TEST DISTRIBUTION SYSTEM

Line Name	From Bus	To Bus	Line Charging %	Line Name	From Bus	To Bus	Line Charging %
1	1	2	23	17	17	18	1.1
2	2	3	41	18	2	19	4
3	3	4	29.5	19	19	20	3
4	4	5	28	20	20	21	2
5	5	6	27.5	21	21	22	1
6	6	7	12.9	22	3	23	10.6
7	7	8	10.5	23	23	24	9.6
8	8	9	8.1	24	24	25	4.8
9	9	10	7.4	25	6	26	14.6
10	10	11	6.7	26	26	27	13.6
11	11	12	6.2	27	27	28	13
12	12	13	5.4	28	28	29	12.4
13	13	14	4.7	29	29	30	11
14	14	15	3.1	30	30	31	5.1
15	15	16	2.5	31	31	32	3.3
16	16	17	1.8	32	32	33	0.8

TABLE III. RESULTS OF LOAD FLOW ANALYSIS OF IEEE 33-BUS TEST SYSTEM

Bus Name	Vpu/deg	Bus Name	Vpu/deg	Bus Name	Vpu/deg
Bus1	0.99/−0.97	Bus10	0.911/−1.55	Bus22	0.976/−1.32
Bus2	0.988/−1.21	Bus11	0.91/−1.54	Bus23	0.966/−0.98
Bus3	0.971/−0.93	Bus12	0.909/−1.53	Bus24	0.959/−1.1
Bus4	0.964/−0.87	Bus13	0.904/−1.63	Bus25	0.955/−1.14
Bus5	0.956/−0.8	Bus14	0.902/−1.63	Bus26	0.935/−0.85
Bus6	0.937/−0.89	Bus15	0.901/−1.75	Bus27	0.932/−0.8
Bus7	0.933/−1.13	Bus16	0.901/−1.77	Bus28	0.926/−1.07
Bus8	0.92/−1.29	Bus17	0.90/−1.85	Bus29	0.919/−0.99
Bus9	0.918/−1.5	Bus18	0.9/−1.86	Bus30	0.915/−0.88
Pg	5.71 MW	Bus19	0.987/−1	Bus31	0.909/−1.62
Qg	2.98 MVAR	Bus20	0.978/−1.21	Bus32	0.909/−1.01
Ploss	0.24 MW	Qloss	0.29 MVAR	Bus33	0.909/−1.62
TRload	99%				

proposed in this study. Each EVCS is assumed to have a power of 0.125 MW (each EVCS is considered to charge five vehicles). According to the proposed model, load flow analysis was performed in step 1. The results obtained are given in Tables I and II. According to (5) given in step 2, the remaining power of the distribution transformer is calculated. Based on calculations, the remaining power of the transformer is 1.77 MW. Next, in step 3, the number of EVCS that can be integrated is calculated to be 14. Next, step 4b is executed for the distribution of these charging stations to the buses. According to step 4b, Tables III, and V (VSI values were calculated before and after EVCS integration), it can be concluded that charging stations can be integrated into Buses 1,2,3,4,19,20,21,22,23, and 24. Afterward, these 14 EVCS are distributed to these buses. Two EVCSs are integrated into buses 1,2,3, and 4 with high bus voltage and a single EVCS to the others. After the charging stations are integrated, a load flow is performed again in step 5. The results are given in Tables III and IV. After verifying whether all the data are within the desired limits, the voltage quality of the power system is measured (VSI) by proceeding to step 6. When this value is at the desired range, the study is concluded in step 7. The VSI values obtained are given in Table V. All VSI values are higher than zero. With the proposed model, a total of 14 EVCS (70 EVs) have been successfully integrated into the relevant buses.

B. Recommendations for Integrating Electric Vehicle Charging Stations into the Distribution System

It is important to foresee the impact of EVCSs on the existing distribution networks. The effects of controlled and uncontrolled charging conditions on the network can be examined by developing a virtual model of the distribution system to be integrated, similar to the model presented in this study. Thus, the number of EVCSs that can be safely integrated into the distribution system can be determined. Scheduling EVs in charging stations is a research topic in mitigating the possible effects. Investing in system components with higher capacities is another way of keeping the distribution network system stable and safe; however, required component costs are very high. Furthermore, using renewable energy resources can help reduce the adverse effects of charging stations on the distribution network.

TABLE IV. LINE LOADINGS OF 33 BUS TEST SYSTEMS

Line name	From bus	To bus	Line Charging %	Line name	From bus	To bus	Line Charging %
1	1	2	30.7	17	17	18	1.1
2	2	3	48.6	18	2	19	9.2
3	3	4	32.1	19	19	20	6.9
4	4	5	28.2	20	20	21	5.6
5	5	6	27.6	21	21	22	2.3
6	6	7	12.9	22	3	23	13.3
7	7	8	10.6	23	23	24	10.9
8	8	9	8.2	24	24	25	4.8
9	9	10	7.5	25	6	26	14.3
10	10	11	6.8	26	26	27	13.7
11	11	12	5.5	27	27	28	13.1
12	12	13	5.5	28	28	29	12.5
13	13	14	4.7	29	29	30	11.1
14	14	15	3.1	30	30	31	5.1
15	15	16	2.5	31	31	32	3.3
16	16	17	1.8	32	32	33	0.8

TABLE V. VSI VALUES OF IEEE 33-BUS TEST SYSTEM

Bus Name	VSI/initial	Bus Name	VSI/initial	Bus Name	VSI/later	Bus Name	VSI/later
Bus1	0.999	Bus18	0.67	Bus1	0.998	Bus18	0.665
Bus2	0.999	Bus19	0.988	Bus2	0.995	Bus19	0.975
Bus3	0.987	Bus20	0.984	Bus3	0.982	Bus20	0.974
Bus4	0.933	Bus21	0.975	Bus4	0.931	Bus21	0.970
Bus5	0.9052	Bus22	0.967	Bus5	0.9012	Bus22	0.965
Bus6	0.88	Bus23	0.935	Bus6	0.877	Bus23	0.93
Bus7	0.82	Bus24	0.912	Bus7	0.815	Bus24	0.902
Bus8	0.76	Bus25	0.89	Bus8	0.745	Bus25	0.888
Bus9	0.755	Bus26	0.82	Bus9	0.75	Bus26	0.814
Bus10	0.74	Bus27	0.81	Bus10	0.735	Bus27	0.804
Bus11	0.72	Bus28	0.8	Bus11	0.715	Bus28	0.799
Bus12	0.719	Bus29	0.76	Bus12	0.710	Bus29	0.755
Bus13	0.712	Bus30	0.74	Bus13	0.706	Bus30	0.735
Bus14	0.7	Bus31	0.72	Bus14	0.685	Bus31	0.711
Bus15	0.69	Bus32	0.71	Bus15	0.680	Bus32	0.705
Bus16	0.685	Bus33	0.7	Bus16	0.675	Bus33	0.685
Bus17	0.68			Bus17	0.677		

VSI, Voltage Stability Index.

V. CONCLUSION

In this publication, a new mathematical model is presented to place EVCSs in the distribution network. Moreover, IEEE 33-bus system was modeled using DIgSILENT software. The proposed model was successfully implemented while meeting operational constraints. In this study, two cases were evaluated. In the first case, IEEE 33-bus system is used to test the effectiveness of the model. Initially, a load flow analysis is performed without charging stations being active. In the second case, a load flow analysis is performed with all charging stations in an operational state. Based on load flow analysis, charging stations capable of charging 70 EVs at the same time are connected to the relevant buses.

This simulation study can help in planning the integration of EVs as a mobile load to the distribution network in the coming years. The simulation output ensures optimum integration of EVs into the existing distribution networks. In addition, enabling more EVs on the distribution network helps the environment by reducing CO_2 emissions. According to the European environment agency, in 2019, the average emission rate of newly registered vehicles is 122 g CO_2/km [21]. This means that if an EV travels 12 000 km per year, nearly 1.4 tons of CO_2 can be avoided. 70 EVs were integrated into the second case, which can lead to approximately 100 tons of CO_2 per year. Similar studies can help countries meet their carbon emission reduction targets by minimizing the effect of EVs on the distribution network. Future studies can be performed using DC networks and renewable energy sources and tested on various distribution test systems.

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Mustafa Nurmuhammed received his B.Sc. degree in Computer Engineering from University of Michigan-Dearborn in 2004. He has over 10 years of experience in the I.T industry. He received his master's degree in Computer Engineering from Inonu University in 2015. He is a candidate for Ph.D. degree in Department of Computer Engineering at Inonu University. He is currently a lecturer at Inonu University, Malatya OIZ Vocational School in Malatya, Türkiye. His research interests include hybrid and electric vehicles, charging systems, renewable energy, analysis of power systems, optimization algorithms, and metaheuristic algorithms.

Ozan Akdağ received his B.Sc. degree in Electrical and Electronics Engineering from Inonu University in 2010. He received his master's degree in Electrical and Electronics Engineering from Kahramanmaras Sutcu Imam University in 2013. He received his Ph.D. degree in Computer Engineering from Inonu University in 2020. His research interests include analysis of power systems, modeling of power systems, energy efficiency, electric vehicle, distributed generation system, smart networks, wind power, heuristic algorithms, relay coordination, greenhouse control.

Teoman Karadağ (Member, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical and electronics engineering. He is currently a Lecturer and a Researcher with the Electrical and Electronics Engineering Department, Engineering Faculty, Inonu University. He worked as an Engineer in the telecommunications industry for more than seven years. His research interests include extremely high and low frequency electromagnetic fields and applications, electric vehicles, and battery management systems.