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Determining the Optimum Location for Charging Stations Based on Voltage Stability in the Microgrid

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ABSTRACT

The paper presents the investigation into determining suitable locations for electric vehicle charging stations within the Microgrid 16-Bus system based on the objective of considering voltage stability using the FVSI and RVS indices. This study examines the impact of charging stations on the electrical grid at each bus during charging power mode by evaluating the FVSI and RVS parameters of the Microgrid when varying charging power respectively at each bus. Consequently, this research draws conclusions regarding optimal charging station placements or recommendations for locations where charging stations should not be placed. Simulation results demonstrate the effectiveness of voltage stability indices in identifying nodes with significant voltage loss. Hence, identifying buses to avoid installing charging stations and determining stable buses where charging stations can be installed. Specifically, the system frequency only recovers with charging levels below 50%. Bus 5 is identified as advantageous in terms of voltage, with the lowest FVSI of 0.185 among load buses. The simulation process and testing the effectiveness of the proposed method are evaluated using PowerWorld software. Simulation results demonstrate that the proposed locations provide voltage stability. The voltage drop at Bus 5 is only 1.52%, which is 5% lower than the normal allowable value of national power grids.

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1. Introduction

The integration of solar energy systems and electric vehicle (EV) charging stations can enhance effectively the on-site renewable energy consumption and reduce indirectly the carbon emissions of EV users. Today, the rapid development of electric vehicle systems, especially electric cars, has driven the construction of charging stations. The challenge lies in economically and technically rational placement of these stations, a concern shared by many researchers. The cost and operating range of electric vehicles can only be optimally addressed when a well-developed charging infrastructure is in place.

The essential task is to ensure that charging stations satisfy economic, technical, and minimal grid impact criteria. Research [1] presents a model for selecting the location of solar-powered charging stations combined with a Geographic Information Systems (GIS). Multi-criteria decision-making methods are applied in this case, utilizing the AHP and FUZZY AHP algorithms. This paper demonstrates rational placement of solar-powered charging stations. In the AHP method employed by this paper, criteria include: firstly, natural conditions (population density, average annual environmental temperature); secondly, economic conditions (construction costs and payback period); thirdly, technical factors (impact on the grid and future scalability); fourthly, social factors including government recognition and community acceptance.

Similarly, Dogus Guler & Tahsin Yomralioglu [2] proposed a solution to determine charging station locations based on the integration of GIS and Analytical Hierarchy Process (AHP) and fuzzy AHP algorithms. In this study, the authors used three criteria of the AHP method to determine charging station locations: accessibility, environmental, and economic factors.

Figure 1 provides an overview of the criteria considered within the three categories. Specifically, for the convenience criterion, it includes Income rates, Transportation stations, Petrol stations,...; for the environmental aspect, only Green areas are considered; and finally, for the economic criterion, it involves slope and land values.

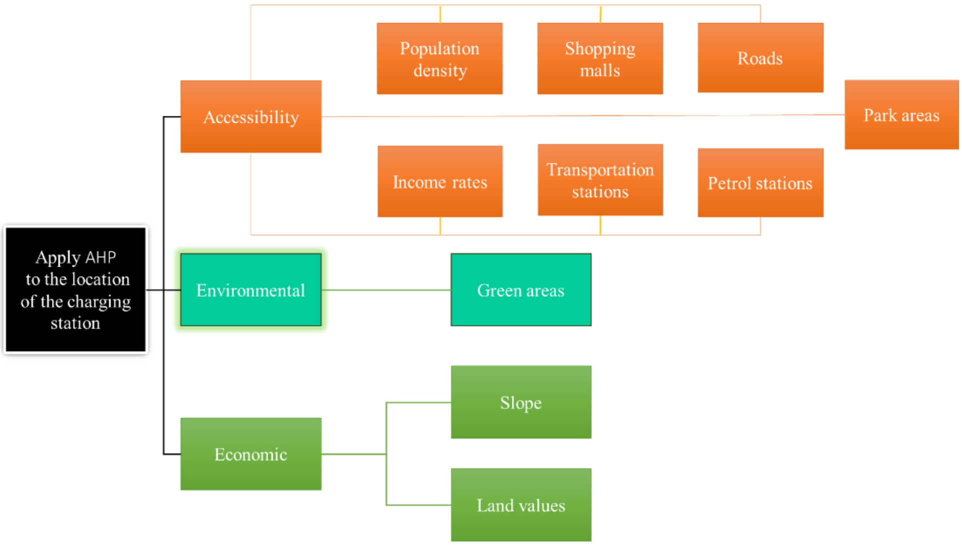


Figure 1. *Application of AHP integrating geographic information system (GIS) to determine charging station location*.

In addition, the authors also utilized ten criteria, including population density, park areas, shopping malls, roads, green areas, income rates, slope, transportation stations, land values, and petrol stations, when applying the Fuzzy AHP algorithm to determine charging station locations, as depicted in Figure 2 as follows:

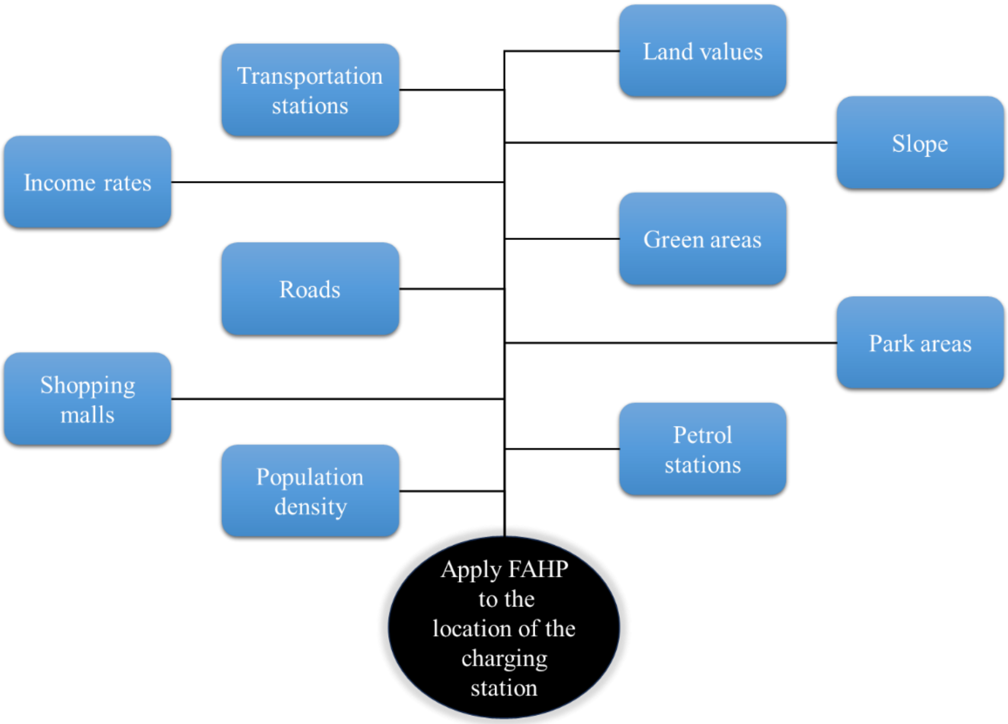


Figure 2. *Applying FAHP to locate charging stations in the power grid*.

Ali Karas¸an and colleagues [3] proposed a decision-making process for selecting charging station locations based on fuzzy sets. The study applied fuzzy sets utilizing AHP, TOPSIS, DEMATEL to evaluate criteria including cost, geographic location, reliability and safety, and social factors to determine optimal charging station locations. While this approach allows for both quantitative and qualitative data consideration, it relies on subjective manager opinions for its inference and may not address technical power grid issues such as voltage and frequency stability during charging. Tugce Uslua and colleagues [4] introduced a mixed-integer linear programming model for determining the location and capacity of electric vehicle charging stations, incorporating economic factors and parking lot locations to optimize convenience and pricing. However, this model lacks consideration for power grid technical aspects like voltage stability. Zhuo Sun and colleagues [5] developed a model for charging station location based on urban residents' travel behavior, utilizing slow and fast charging systems. Despite its focus on user behavior, the study overlooks technical grid impacts and the development of energy storage solutions in electric vehicles. Research by [6] explored fast charging and fleet charging optimization, improving charging time but neglecting power grid technical parameters and customer satisfaction factors. Mouna Kchaou-Boujelben [7] synthesized optimal charging station placement solutions considering decision variables and constraints, yet overlooked voltage stability and charging time optimization. Authors in [8] proposed a method to enhance electric vehicle resource utilization, emphasizing online booking and charging session wait times, though fixed user behavior assumptions limit its practicality.

Fareed Ahmad et al. [9] presented a metaheuristic algorithm-based approach for large-scale charging station placement, considering various stakeholders' perspectives. However, the study fails to address voltage stability concerns. Research in [10] aimed to minimize missed trips with fixed charging stations, using Genetic Algorithm. Though effective, its computational speed and susceptibility to local optima are drawbacks. In [11], assisted grid operators in fast charging station placement, optimizing with the Analytic Hierarchy Process but overlooking technical grid issues. Mohd Bilal et al. [12] discussed fast charging station placement but didn't deeply analyze voltage stability effects. In [13], developed a model to calculate charging station costs but did not address grid stability concerns. Vishnu Suresh et al. [14] surveyed optimal charging station locations but overlooked voltage stability. In [15] explored the impact of charging stations integrated with renewable energy but didn't address voltage stability. In [16], Krishnamurthy discussed EV charging infrastructure optimization, focusing on multi-objective optimization, but didn't consider economic factors. Musirin et al. [17] introduced the Fast Voltage Stability Index but lacked clear application objectives for grid improvement.

In this paper, we present the determination of charging station locations based on the criteria of the Fast Voltage Stability Index (FVSI) and RVS (Reliability Voltage Stability). Additionally, we analyze the voltage impacts of charging stations in the Microgrid grid. The following content in section 2.1 provide an overview of the impacts of charging stations on the power grid. Subsequently, section 2.2 focus on evaluating factors of voltage stability to determine suitable charging station locations through FVSI and RVS assessment. Moreover, section 2.3 verifies the effectiveness of the proposed method by evaluating the charging station state's impact on the Microgrid, including assessments of system performance regarding frequency and voltage. Finally, section 2.4 concludes by assessing the feasibility of FVSI and RVS in determining charging station locations.

2. Materials and Methods

2.1. Impact of Charging Stations on the Power Grid

The integration of renewable energy sources and charging stations for application in infrastructure and superstructure architecture is a top concern for many countries, including the smart electric charging station system, which is receiving significant attention [18]. However, numerous studies have raised concerns about cybersecurity in managing and operating electrical devices. Consequently, authors have highlighted the risks of adverse impacts of charging stations on the power grid. According to [19], in various forms of attacks on the power grid, an attack can cause an imbalance between supply and demand of power by suddenly increasing (or decreasing) power demand, leading to abrupt decreases in system frequency and voltage. If this imbalance exceeds the system threshold, it can lead to tripping of generators and even cause a collapse of the power system. As mentioned in [20], a method hes been proposed to generate the impact of electric vehicle charging stations on the power grid through charging/discharging. In Figure 3, there is an illustration depicting the sudden increase/decrease in grid frequency when charging/discharging at charging stations unexpectedly. According to North America’s standards, the allowable frequency range is between 59.5Hz and 61.5Hz. If the frequency exceeds this range, the system will experience an imbalance between supply and demand. Simulation results at t=20s show that in the case of charging, the frequency drops below 59.5Hz, and in the case of discharging, the frequency increases close to 61.6Hz, causing an imbalance in the system.

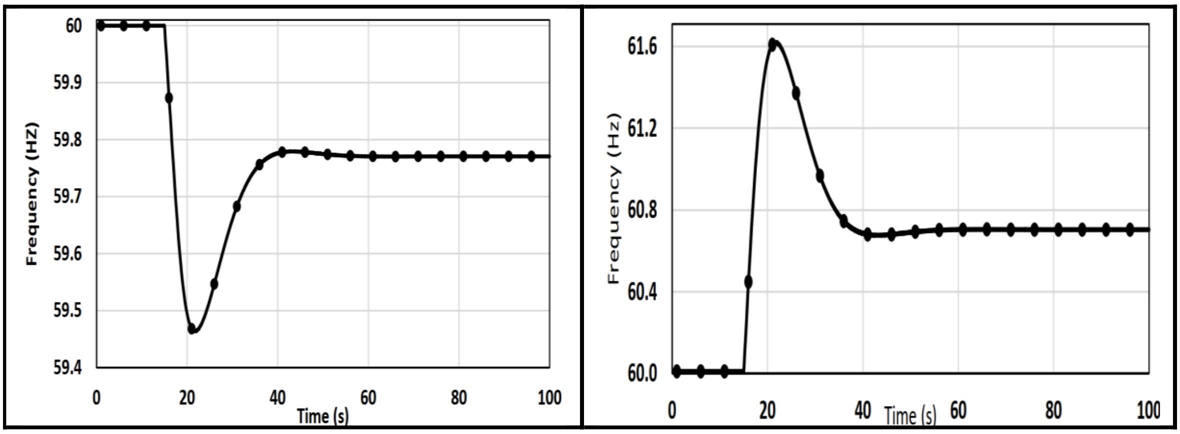


Figure 3. *Impact on grid frequency when subjected to charging/discharging*.

In addition to frequency fluctuations, voltage is also affected by the magnitude of oscillations. In the simulated scenario of the research problem, when discharging power at the charging station, the maximum voltage fluctuation values at Bus 4 are 0.1pu, Bus 5 is 0.04pu, Bus 7 is 0.03pu, and Bus 9 is 0.025pu. Thus, it can be observed that determining the location of charging stations is necessary to consider the impact on frequency and voltage stability of the power grid. Additionally, based on the data provided, Bus 4 is experiencing voltage oscillations beyond the permissible value (0.1pu > 0.05pu), exceeding 5% of the allowable voltage deviation according to section 5.5.3 of IEEE 1159-1995 standard.

2.2. Power System Voltage Stability-Related Indices

Voltage collapse is a process whereby a sequence of events related to voltage instability leads to the breakdown of the power system or abnormal low voltage in most areas of the power system. At load nodes, small disturbances cause voltage variations. These voltage variations can violate the principles of P and Q balance, leading to the collapse of the grid, loads, and asynchronous motors ceasing to operate. The ability of the power system to withstand these disturbances without disrupting operation is called voltage stability.

2.2.1. The Fast Voltage Stability Index - FVSI

The Fast Voltage Stability Index (*FVSI*) is utilized to identify vulnerable or critical nodes capable of bearing maximum load in power systems. *FVSI* is employed in detecting crucial interconnecting lines during online voltage stability assessment. This index provides a selection criterion to be used as an alert for a system operator before the system reaches its bifurcation point. The mathematical equation is described as follows [17].

$$FVSI_{ij} = \frac{4Z_{ij}^2 Q_j}{V_i^2 X_{ij}} \tag{1}$$

Where, Z_{ij} is the line impedance between bus i and j. V_i, V_j represent the voltage at the sending and receiving power, respectively. Q_i, Q_j represent the reactive power, X_{ij} represents the reactance value between node *i* and *j*.

According to [17], the *FVSI* value is used to assess the overall voltage collapse condition in the power system. Specifically, when the *FVSI* value of a line approaches 1.00, the line tends towards instability point. Therefore, to maintain the operational state of the system, the *FVSI* index of the lines in the system must be kept below 1.00.

2.2.2. The Reciprocal Voltage Sensitivity - RVS

The charging/discharging of Electrical Vehicles is similar to increasing/decreasing the load power at the buses. To examine the voltage impact during charging/discharging, based on $\partial V/\partial Q$ at the bars with the largest magnitude of $\partial V/\partial Q$, they are brought to the top of the list and sorted in descending order. The voltage sensitivity index of i^{th} Bus [21] is presented as follows:

$$RVS_i = \frac{\dfrac{\partial V_i}{\partial Q_i}}{\left(\dfrac{\partial V_1}{\partial Q_1} + \dfrac{\partial V_2}{\partial Q_2} + \ldots + \dfrac{\partial V_n}{\partial Q_n}\right)} \tag{2}$$

2.3. Simulation and validation on the Microgrid diagram

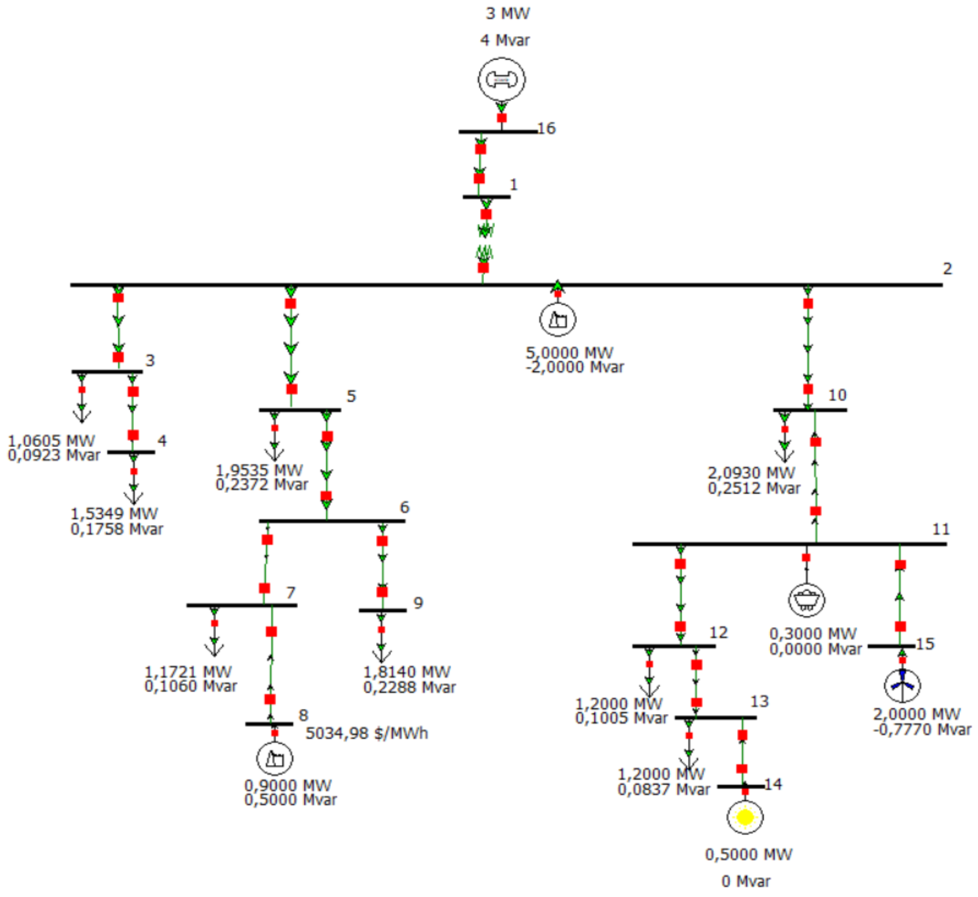


Figure 4. *The Microgrid 16-Bus IEEE diagram*.

The Microgrid Diagram in Figure 4 has been developed and widely used in various works related to Microgrid power systems [22], [23]. The procedure for operating and calculating the voltage quality assessment indices *FVSI* and *RVS* is presented as follows.

The process of calculating the FVSI index is as follows:

Figure 5 illustrates the data collection and calculation process in the Microgrid diagram. Specifically, starting from a power level of 30%, gradually increasing to values of 50-80-100%, the charging station locations at load buses {3, 4, 5, 7, 9, 10, 12, 13} are altered. In the project, the charging state is considered akin to the power consumption of a load. Additionally, to construct a charging station, the factor of load demand needs to be considered because nodes with loads will have the capacity to consume electricity. Based on these considerations, the simulation only examines the installation of electric vehicle charging stations at load buses. The charging level is activated for observation, and the parameters of the Microgrid are recorded. After iterating through these steps, the FVSI index calculation is presented in section 2.4.

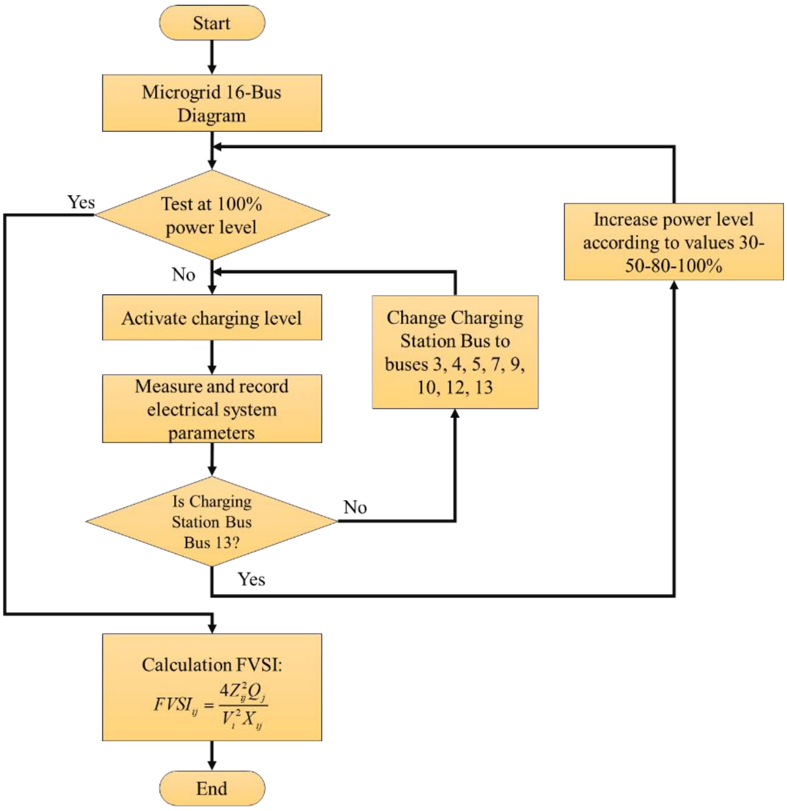


Figure 5. *The Flowchart of the FVSI Calculation Process*.

The process of calculating *RVS* index:

Step 1: From the Jacobian matrix in the power system diagram, extract matrix J_4, which is the matrix of reactive power sensitivity to voltage. Where, *(k)* represents the number of iterations in power distribution calculation, and n represents the order of nodes in the grid system.

$$J_4 = \begin{bmatrix} \frac{dQ_2^{(k)}}{d|V|_2} & \cdots & \frac{dQ_2^{(k)}}{d|V|_n} \\ \cdots & \cdots & \cdots \\ \frac{dQ_n^{(k)}}{d|V|_2} & \cdots & \frac{dQ_n^{(k)}}{d|V|_n} \end{bmatrix} \quad (3)$$

Step 2: Invert the elements of the Jacobian matrix J4.

$$J_4^{-1} = \begin{bmatrix} \frac{d|V|_2}{dQ_2^{(k)}} & \cdots & \frac{d|V|_n}{dQ_2^{(k)}} \\ \cdots & \cdots & \cdots \\ \frac{d|V|_2}{dQ_n^{(k)}} & \cdots & \frac{d|V|_n}{dQ_n^{(k)}} \end{bmatrix} \quad (4)$$

Step 3: Calculate the RVS index.

The *RVS* at each bus is the ratio of the partial derivative of *dV/dQ* at that bus to the total computed amount above. To assess the impact on voltage, based on *dV/dQ*, the bars with the largest *dV/dQ* magnitude are prioritized and arranged in descending order to assess the level of influence. The voltage sensitivity of ith Bus [21] is presented as follows:

$$RVS_i = \frac{\dfrac{dV_i}{dQ_i}}{\left(\dfrac{dV_1}{dQ_1} + \dfrac{dV_2}{dQ_2} + \ldots + \dfrac{dV_n}{dQ_n}\right)} \text{ with } i^{th} \text{ bus} \quad (5)$$

The *RVS* index indicates the voltage sensitivity of Bus i with respect to other buses in the power system when charging/discharging occurs.

2.4. Comparison and evaluation of efficiency among methods

From the experimental process, the computed results yield a table of data regarding the *FVSI* and *RVS* indices at the load buses where it is desired to place the charging stations.

Table 1. *FVSI indices corresponding to different cases of placing charging stations at load buses*

Charging level	Line Number	Bus 3	Bus 4	Bus 5	Bus 7	Bus 9	Bus 10	Bus 12	Bus 13
30%	**1**	0.1030	0.1030	0.1029	0.1028	0.1029	0.1030	0.1030	0.1030
	2	0.1714	0.1714	0.1713	0.1712	0.1712	0.1714	0.1714	0.1714
	3	0.2860	0.2861	0.2859	0.2857	0.2857	0.2861	0.2860	0.2860
	5	0.3676	0.3677	0.3639	0.3634	0.3635	0.3639	0.3639	0.3639
	6	0.1854	0.1889	0.1835	0.1833	0.1833	0.1836	0.1835	0.1835
	9	0.5952	0.5952	0.5964	0.5995	0.6006	0.5952	0.5952	0.5952
	10	0.0240	0.0240	0.0241	0.0242	0.0242	0.0240	0.0240	0.0240
	11	0.1340	0.1340	0.1343	0.1349	0.1352	0.1340	0.1340	0.1340
	13	0.0957	0.0957	0.0958	0.0959	0.0960	0.0957	0.0957	0.0957
	16	0.3432	0.3432	0.3431	0.3427	0.3427	0.3468	0.3507	0.3506
	17	0.0216	0.0216	0.0216	0.0216	0.0216	0.0219	0.0221	0.0221
	19	0.1099	0.1099	0.1099	0.1098	0.1098	0.1111	0.1125	0.1125
	20	0.1377	0.1377	0.1377	0.1375	0.1376	0.1391	0.1410	0.1426
	22	0.0116	0.0116	0.0116	0.0116	0.0116	0.0117	0.0119	0.0120
	AVERAGE	0.1847	0.1850	0.1844	0.1846	0.1847	0.1848	0.1853	0.1855
50%	**1**	0.1030	0.1031	0.1030	0.1028	0.1029	0.1031	0.1030	0.1030
	2	0.1715	0.1715	0.1715	0.1711	0.1712	0.1715	0.1715	0.1715
	3	0.2862	0.2863	0.2862	0.2856	0.2857	0.2863	0.2862	0.2862
	5	0.3703	0.3706	0.3641	0.3634	0.3635	0.3642	0.3641	0.3641
	6	0.1868	0.1927	0.1836	0.1833	0.1833	0.1837	0.1837	0.1837
	9	0.5951	0.5952	0.5972	0.6024	0.6042	0.5952	0.5952	0.5951
	10	0.0240	0.0240	0.0241	0.0243	0.0244	0.0240	0.0240	0.0240
	11	0.1340	0.1340	0.1344	0.1356	0.1360	0.1340	0.1340	0.1340
	13	0.0957	0.0957	0.0958	0.0960	0.0961	0.0957	0.0957	0.0957

	16	0.3434	0.3435	0.3433	0.3427	0.3427	0.3494	0.3560	0.3559
	17	0.0217	0.0217	0.0217	0.0216	0.0216	0.0220	0.0225	0.0224
	19	0.1100	0.1100	0.1100	0.1098	0.1098	0.1119	0.1144	0.1143
	20	0.1378	0.1379	0.1378	0.1375	0.1376	0.1402	0.1433	0.1461
	22	0.0116	0.0116	0.0116	0.0116	0.0116	0.0118	0.0121	0.0123
	AVERAGE	0.1851	0.1856	0.1846	0.1848	0.1850	0.1852	0.1861	0.1863
80%	**1**	0.1032	0.1033	0.1031	0.1028	0.1029	0.1032	0.1032	0.1032
	2	0.1717	0.1718	0.1716	0.1711	0.1712	0.1718	0.1717	0.1717
	3	0.2866	0.2868	0.2865	0.2856	0.2857	0.2867	0.2866	0.2866
	5	0.3753	0.3757	0.3645	0.3633	0.3635	0.3648	0.3647	0.3647
	6	0.1893	0.1996	0.1838	0.1832	0.1834	0.1840	0.1839	0.1839
	9	0.5951	0.5952	0.5986	0.6074	0.6106	0.5952	0.5951	0.5951
	10	0.0240	0.0240	0.0241	0.0245	0.0246	0.0240	0.0240	0.0240
	11	0.1340	0.1340	0.1347	0.1367	0.1374	0.1340	0.1340	0.1340
	13	0.0956	0.0956	0.0958	0.0963	0.0963	0.0956	0.0956	0.0956
	16	0.3438	0.3440	0.3437	0.3426	0.3428	0.3542	0.3658	0.3655
	17	0.0217	0.0217	0.0217	0.0216	0.0216	0.0223	0.0231	0.0230
	19	0.1101	0.1102	0.1101	0.1097	0.1098	0.1135	0.1178	0.1177
	20	0.1380	0.1381	0.1379	0.1375	0.1376	0.1421	0.1476	0.1525
	22	0.0116	0.0116	0.0116	0.0116	0.0116	0.0120	0.0124	0.0128
	AVERAGE	0.1857	0.1866	0.1848	0.1853	0.1856	0.1860	0.1875	0.1879
100%	**1**	0.1033	0.1034	0.1032	0.1028	0.1029	0.1033	0.1033	0.1033
	2	0.1718	0.1720	0.1718	0.1711	0.1712	0.1719	0.1719	0.1719
	3	0.2868	0.2871	0.2867	0.2856	0.2857	0.2870	0.2869	0.2869
	5	0.3782	0.3789	0.3647	0.3633	0.3635	0.3652	0.3649	0.3649
	6	0.1908	0.2039	0.1839	0.1832	0.1834	0.1842	0.1841	0.1841
	9	0.5951	0.5954	0.5993	0.6105	0.6145	0.5952	0.5951	0.5951
	10	0.0240	0.0240	0.0242	0.0246	0.0248	0.0240	0.0240	0.0240
	11	0.1340	0.1340	0.1349	0.1374	0.1383	0.1340	0.1340	0.1340
	13	0.0956	0.0956	0.0958	0.0964	0.0965	0.0956	0.0956	0.0956
	16	0.3441	0.3445	0.3439	0.3426	0.3428	0.3572	0.3718	0.3713
	17	0.0217	0.0217	0.0217	0.0216	0.0216	0.0225	0.0234	0.0234
	19	0.1102	0.1103	0.1102	0.1097	0.1098	0.1144	0.1199	0.1197
	20	0.1381	0.1382	0.1380	0.1375	0.1376	0.1433	0.1502	0.1565
	22	0.0116	0.0116	0.0116	0.0116	0.0116	0.0121	0.0126	0.0132
	AVERAGE	0.1861	0.1872	0.1850	0.1856	0.1860	0.1864	0.1884	0.1888

Table 2. *RVS indices at load buses*

Name Bus	Bus 3	Bus 4	Bus 5	Bus 7	Bus 9	Bus 10	Bus 12	Bus 13
RVSI	0.0118	0.0158	0.0169	0.0504	0.0526	0.0567	0.0664	0.1841

From Table 1, the comparison data regarding the *FVSI* index among the buses can be observed. Bus 5 has the lowest index, indicating that it is prioritized for charging station installation. Additionally, Bus 13 is evaluated as having the potential for significant voltage loss. Conducting experiments using PowerWorld software to examine voltage oscillation is depicted in Figure 4. Similarly to Table 1, the *RVS* evaluation results from Table 2 also identify Bus 13 and Bus 4, with the lowest and highest indices, respectively, as buses where charging stations should not be placed. From the simulation results, it can be understood that when the *RVS* value of Bus "*i*" lies between the Max-Min range, that bus exhibits high stability and minimal oscillation.

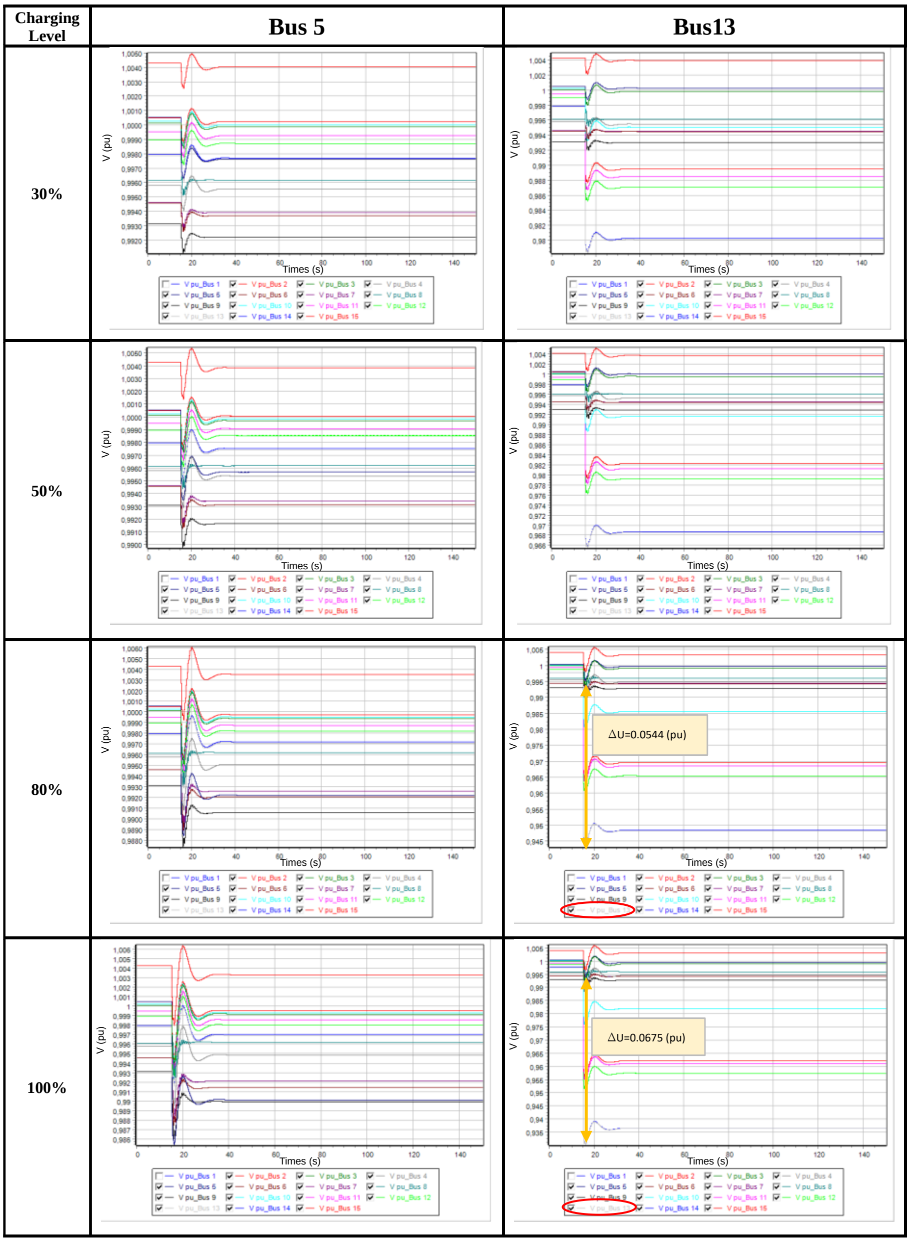


Figure 6. *Voltage oscillation at Bus 5 and Bus 13 with different power charging levels*.

The voltage oscillation data across different charging levels demonstrates the accuracy of the *FVSI* index in predicting the voltage collapse of the system when charging stations are placed at buses with higher *FVSI* values approaching 1.00. From Figure 6, it is evident that at 100% charging level, the voltage drop at Bus 5 is only 1.52%, while at Bus 13, it reaches 6.75%, exceeding the allowable threshold of 5%. The voltage drop also decreases with specific charging levels: at 80% charging, Bus 5 experiences a voltage drop of 1.21%, and Bus 13 experiences 5.44%. At 50% charging, Bus 5 experiences a voltage drop of 0.71%, and Bus 13 experiences 3.22%, both within the acceptable range.

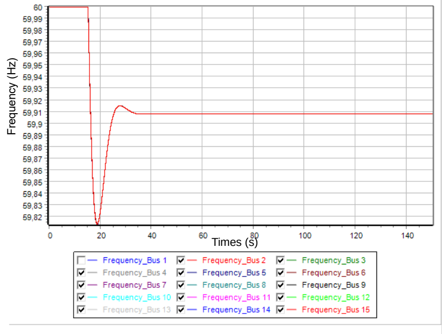
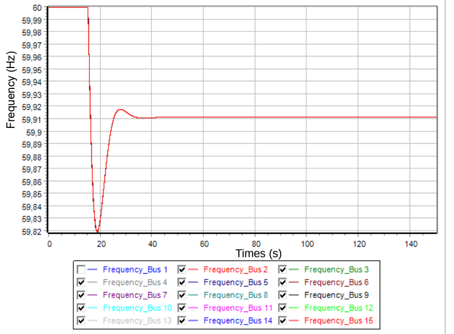
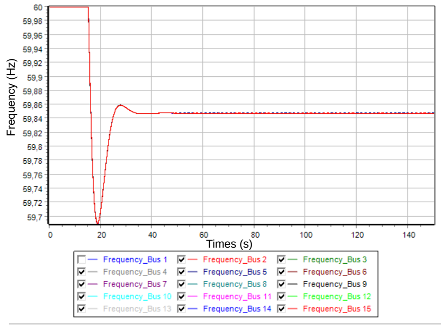
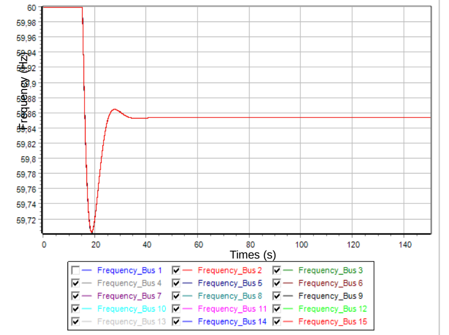
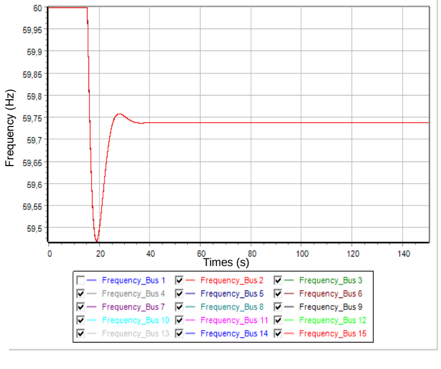
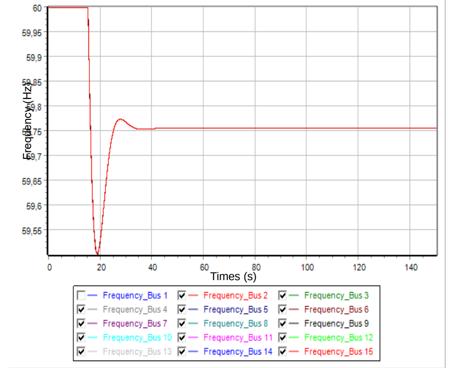
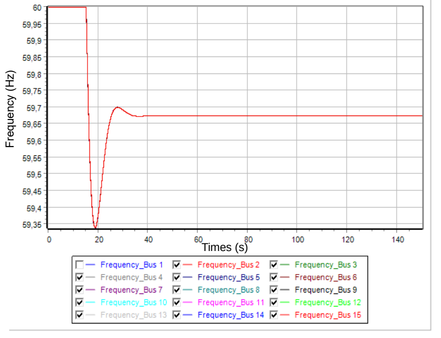
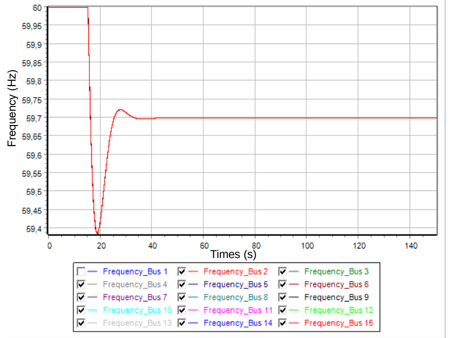
Charging Level	Bus 5	Bus13
30%		
50%		
80%		
100%		

Figure 7. *Frequency oscillation at Bus 5 and Bus 13 with different power charging levels*.

Furthermore, the method of determining the charging station location proposed by evaluating voltage stability indices has a limitation in that it is one-dimensional. This means that it only considers the voltage variations of buses in the system without considering other parameters such as frequency or phase angle. This leads to suboptimal system stability overall. In Figure 7, the frequency oscillation of the grid under different charging levels (30%, 50%, 80%, 100%) is depicted. Simulation results show that the frequency returns within the permissible range at charging levels of 50% and below. In summary, to determine the optimal charging station locations, it is necessary to conduct multidimensional evaluations considering both power optimization and system stability under varying conditions.

4. Conclusions

The paper has achieved its objective of determining the optimal locations for placing charging stations to benefit the voltage stability of the Microgrid power system. The results obtained from simulations on the 16-Bus Microgrid diagram, using parameters derived from *FVSI* and *RVS*, clearly indicate which buses are suitable and unsuitable for installing charging stations. However, it is important to note that the determination of station locations still has shortcomings due to the frequency deviation of the system, which exceeds the permissible range. Only when the charging level decreases to 50% does both the frequency and voltage meet the permissible conditions. Therefore, the process of determining station locations needs to integrate considerations of capacity limits to optimize the goal of stabilizing the power system. In the future work, we will study the construction of the transfer function to evaluate the stability of frequency, voltage and rotor angle. In addition, considering charging stations combined with renewable energy sources is one of the development directions that the research team is exploring for future projects.

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Conflict of Interest

The authors declare no conflict of interest.

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