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RESEARCH ARTICLE

Impact of Rising Number of Electric Vehicle Charging Points on Electrical Utility

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ABSTRACT This paper presents an investigation of the impact of a rising number of electric-vehicle charging points on an interconnected distribution system. Using the PSCAD 4.6 software, this study simulates an electric-vehicle charging station consisting of a charging unit with 2 DC charging and a maximum power of 100 kW. The station receives power from a 23 kV substation through a step-down transformer at 400 V and provides power through the charging unit. The unit regulates the voltage level at 500 V and has a maximum charging capacity of 50 kW each. In addition, the study replicates an actual distribution system of the Provincial Electricity Authority (PEA) in the section spanning the Si Samrong to Sawankhalok substations in Sukhothai Province, Thailand. The effects of the following study conditions on the power quality are observed in the simulation: 1) variable location of charging panels, 2) variable number of charging panels, and 3) additional sets of charging panels in the distribution system. The results show that the charging-panel installation location and number of charging panels are significant factors that affect the power quality, including the voltage level. Therefore, optimizing the design of EV charging stations should consider the location and number of charging panels as important factors.

INDEX TERMS Charging stations, electric vehicles, power distribution, power demand, PSCAD.

I. INTRODUCTION

Over the past decade, the world has paid more attention to the problems of global warming and air pollution. On average, a typical car emits approximately 4.6 tons of carbon dioxide per year, which is quite a large amount. Therefore, several companies have invented and developed car technologies to be more environmentally friendly. For example, in 1997, the world's first gasoline–electric hybrid car was launched, marking the beginning of the development of electric cars in the world market.

According to global car sales statistics collected by the International Energy Agency for 2021–2023, as shown in Fig. 1, people in many countries are starting to use more electric cars. They can choose to buy cars from both domestically produced and foreign brands. With regard to the statistics for Thailand, in particular, it was found that Thai people buy their electric cars mainly from Chinese brands. However, there may be many factors involved in this choice, such as appearance and price, among others.

From Fig. 2(a), which shows the increase in number of each type of electric vehicle (EV) in 2019–2023, as collected by the Energy Policy and Planning Office, it can be observed that in 2019–2021, the number of EVs did not increase by much. This may have been due to the COVID-19 outbreak, when the population had to be quarantined and did not need to travel as much as they normally did. Therefore, there was a relatively low demand for EVs at that time. However, after the pandemic had finished, and life returned to normal, it can be seen that in 2022–2023, the number of EVs in

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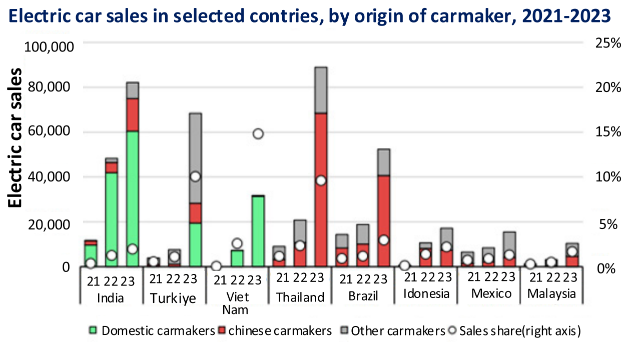
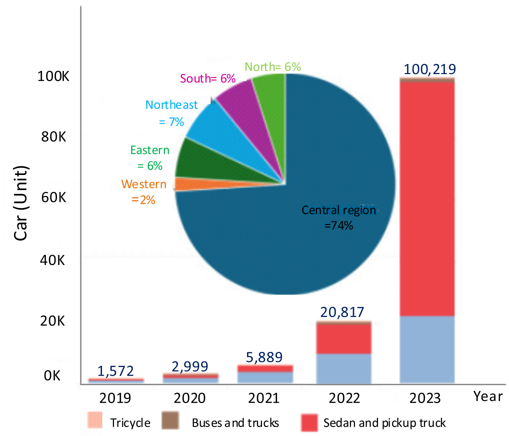
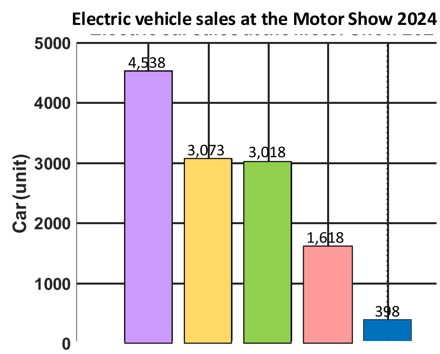


FIGURE 1. **Electric-car sales in several countries.**



(a) Increase in number of each type of electric vehicle (EV)



(b) Electric-car bookings at motor shows in Thailand

FIGURE 2. **EV growth rate in Thailand.**

Thailand increased significantly, with most of them being used in the central region. Moreover, the Thai government has implemented a policy to support electric cars by providing a subsidy of 20,000–100,000 baht and reducing import taxes and excise taxes, which has made electric cars less expensive. The data in Fig. 2(b), recorded by Motor Show 2024 in Thailand, show that the event had a total of 53,438 bookings, an increase of 24.6% from last year. Furthermore, these bookings comprised 35,921 regular-combustion-engine cars, accounting for 67.7%, and 17,517 electric cars, accounting for 32.8%. The top 5 electric car brands with the highest bookings in Thailand were BYD, ChangAn, Aion, Neta, and Zeekr. Therefore, the trend of EV use in Thailand is expected to increase continuously.

Based on the increase in the number of EVs, the number of EV charging stations (EVCSs) must increase to cover all areas of Thailand and meet the demand. Fig. 3 shows the number of EV charging stations in the country as of 2023. Most charging stations are located in the densely populated central region, such as in Bangkok, Nonthaburi, and Pathum Thani. However, other regions and provinces have begun to establish more charging stations to meet the demand of users. Power engineers are facing considerable challenges due to the growing demand for EV charging. EVCSs need to be strategically distributed to successfully serve users in highly populated areas with high charging demand, but this requires careful planning. Power losses need to be prevented, while the voltage variation of the power grid needs to be kept within acceptable regulatory parameters. Moreover, the price of the land is one of the significant factors that should be considered in setting up charging stations. Strategically planning the placement of charging stations is complicated by the need to manage the unknowns that come with EVs. Therefore, several research studies have been conducted on various aspects of the problem, such as the reliability of the power system [1], [2], [3], [4], [5], [6], [7], investment in building charging stations [1], [2], [3], optimal capacity for the charging stations [4], [5], [6], and optimal location for establishing charging stations [7], [8], [9], among others.

With regard specifically to the reliability of the power system, EV charging can have a negative impact on the

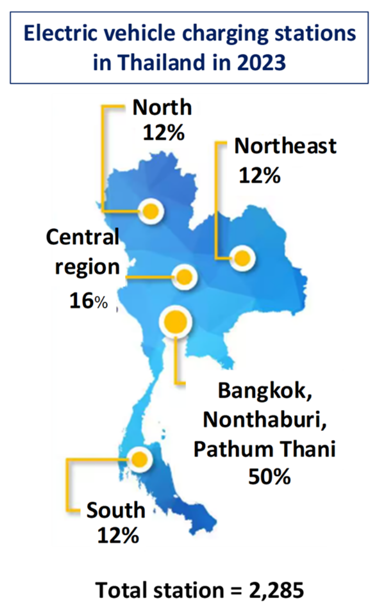


FIGURE 3. **Number of EV charging stations (EVCSs) in Thailand.**

distribution system, and system failures lead to the unavailability of power needed to charge EVs. To solve this problem, vehicle-to-grid (V2G) technologies [1], [2] have been used with charging stations to improve system reliability. Solar rooftop photovoltaic (PV) units [3] are integrated with charging stations to overcome the negative impacts of EV charging and further enhance the reliability of the system. However, it is not sufficient that charging-station companies are already building stations that follow the requirements of the distribution system; the charging port also has to be changed to prevent failure. Therefore, the research [4] proposed a novel charging-port design based on the binomial distribution method. The failure rate [5] and voltage stability [6] have been related to the system reliability.

The capacity and location of the charging station are also significant factors that should be considered. First, EV charging stations have to be of an appropriate size to prevent the power system from having to store an unnecessarily large amount of energy, to help reduce energy waste. Several methods for estimating the appropriate size of an EV charging station have been proposed, such as deterministic power flow (DPF), stochastic power flow (SPF) [7], and optimal power flow (OPF) algorithms [8]. Moreover, artificial intelligence (AI) [9], [10], [11] techniques such as fuzzy logic and artificial neural network (ANN)-based methods can be applied to increase the accuracy of the assessments.

Another significant factor that should be considered in establishing new charging stations, apart from the sizing of the charging, is location. The fine-grained charging situation [12] and distributed consensus-based optimization algorithm (DCBOA) [13] are among the methods that have been proposed to use for optimizing the locations of new charging stations [14], [15], [16]. The research [16] also accounted for V2G technologies, as has been done in other research studies. However, novel road and power grid models are considering minimizing the total cost [17], [18], [19], which includes the operator cost, user charging cost, and power grid loss, among others. Applying a renewable energy source [20], [21], [22] to be used to charge EVs or incorporating battery technologies such as battery management systems (BMS) and energy storage systems (ESS) [23], [24] can help reduce the cost of charging EVs.

From a comprehensive literature review, it was found that although there have been a variety of research studies on EVCSs and their impact on power systems, most share a common characteristic: their use of simulations in their investigations. Therefore, following this apparently reliable tactic, this research study simulated EV charging stations by analyzing real electrical systems and parameters used in practice to obtain conclusions that can be applied for practical use. At present, a car battery can run for about 500 kilometers. The behavior of the car user is to charge the car battery when the battery is about 10% (driving 450 kilometers) or may stop to charge every 45%-50% of the battery, which means that if traveling from Bangkok, they will stop to charge the battery in Sukhothai Province. That province uses the Si Samrong-Sawankhalok transmission line to distribute electricity. Therefore, the actual electrical system used in this research study is set at the Si Samrong-Sawankhalok electrical system. Thus, a simulation prototype is a 23 kV distribution system under the Provincial Electricity Authority (PEA). The sending and receiving stations were determined to be Sri Samrong and Sawankhalok, respectively. The distance between the stations is 43.5 km. Three parameters, i.e., active power (P), reactive power (Q), and voltage (V), were observed. The results are deemed satisfactory and can be used in future practical applications.

The contributions of this study are as follows:

1. The observed system was based on a real-world system: a 23 kV distribution system of the Provincial Electricity Authority (PEA), located at the Sri Samrong and Sawankhalok stations.
2. In addition to the simulation circuit referring to a real electrical system, this study also used real EVs in the market (BMWi3) to obtain more accurate and precise values.
3. This paper provides a graph of how the parameters change as the charging-station conditions change, to help the readers see the changing trends more clearly and easily understand them.

The remainder of this paper is organized as follows: the observed system and the measurement of power quality for a number of study cases are illustrated in Section II, an analysis of the effects of adding a new charging station to an already existing EV charging system is shown in Section III, the results are presented and discussed in Section IV, and finally, the paper is concluded in Section V.

II. MODEL OF CHARGING STATIONS USED IN PUBLIC UTILITIES

The study model of a charging station is shown in Fig. 4; a single-line diagram is depicted in Fig. 4(a), whereas the equivalent system used for simulation in the PSCAD software program is shown in Fig. 4(b)–(c).

The study model consists of four parts, i.e., (1) power-source part, (2) EV part, (3) electrical-load part, and (4) charging-station part, as shown in Table 1.

The power-source part consists of two 23 kV power sources, which are distributed from the PEA. The voltage is stepped down using a transformer. The next part is the electric-vehicle part, and for this study, it was decided that the EV to be used was the BMWi3 car model. The third part is the electrical-load part, which has the charging station connected to the system. For this study, the location of the charging station was variable. Finally, the fourth part is the charging-station part. For this study, the number of charging panels installed in the charging station was also variable.

The power quality, which was the main property observed in this study, was measured in terms of the active power (P), reactive power (Q), and voltage (V). The behaviors of the parameters with respect to the variable study conditions were observed. The base case for this study is under the condition that no EVs are charging at the charging station. The power quality of the study case was measured. The measurement

TABLE 1. System conditions used for simulation.

No.	Section		Description
1.	Power source	23 kV PEA system voltage	- Power source 1 is SRI SAMRONG - Power source 2 is SAWANKHALOK
		Transformer	- Step down 23 kV / 400 V
2.	Electric vehicle (EV)	Car model: BMWi3	
3.	Load usage	9 locations	- Distance from each location to power source was variable, ranging from 5.5 km to 38 km
4.	Charging station	Charging panel with fast charging (DC). Maximum power: 100 kW. Number of electrical power heads: 2	4.1 When location of charging panel was variable (Number of panels was fixed) - Location varied from location no. 1 to location no. 8
			4.2 When number of charging panels was variable (Location was fixed) - Number of charging panels varied between 4, 5, and 6 (Number of charging heads varied between 8, 10, and 12, respectively)
			4.3 When another set of charging panels was added at a variable location (Number of charging panels and location of charging station no. 1 were fixed) - Location of first station was fixed at location no. 1 - Location of second station varied from location no. 2 to location no. 8

points were assigned to 12 locations, as shown in Fig. 4(b), and the details are as follows:

- Measurement point 1: installed at S1 point or the post of power source 1
- Measurement point 2: installed at S2 point or the post of power source 2
- Measurement point 3: installed at L1 point or the front of load no. 1
- Measurement point 4: installed at L2 point or the front of load no. 2
- Measurement point 5: installed at L3 point or the front of load no. 3
- Measurement point 6: installed at L4 point or the front of load no. 4
- Measurement point 7: installed at L5 point or the front of load no. 5
- Measurement point 8: installed at L6 point or the front of load no. 6
- Measurement point 9: installed at L7 point or the front of load no. 7
- Measurement point 10: installed at L8 point or the front of load no. 8
- Measurement point 11: installed at L9 point or the front of load no. 9
- Measurement point 12: installed at EV point, which was the point in front of the EV charger

After the condition and simulation model were set up, as mentioned in the previous section, the power quality in terms of the (1) active power: P, (2) reactive power: Q, and (3) voltage: V was analyzed.

A. BASE CASE: (NO EVS CHARGING AT THE CHARGING STATION)

According to the simulation model of the base case is shown in Fig. 5 which it referred from real-world system. It was sending (S1) substation supplies power to and receiving (S2) substation. The distance between the two stations is 9 transformer positions, each position is designated as L1 to L9. The distance, reference from S1 position.

The condition for this case is that no EVs are charging at the charging station. Three observed parameters (active power, reactive power, and voltage) were measured; their values are shown in Table 2.

When considering the data in Table.2, the active power at source 1 and source 2 was 7.032 MW and 5.777 MW, respectively, whereas the active power at the loads was approximately 0.1 to 3 MW. In the same way, the reactive power at the sources was approximately 1.9 to 2.4 MW, whereas the reactive power value at the loads was less. The voltage measured at the sources was approximately 23 kV, whereas the voltage measured at the loads was approximately 22 kV.

Therefore, from the data in Table 2, it can be concluded that the magnitudes of active and reactive power decrease as the measurement point becomes farther away from S1 station, whereas the voltage is slightly lower at the midpoint of the transmission line or at positions L3–L6. However, based on voltage drop requirement, the voltage drop must not exceed 5% of the voltage level. The voltage level of this distribution system is equal to 22 kV, so the voltage at L3-L6 is not lower than the specified criteria.

B. STUDY CASE 1: LOCATION OF CHARGING PANEL WAS VARIABLE (NUMBER OF PANELS WAS FIXED)

Fig. 6 shows the simulation model used for this study case. This model has 3 units of charging panels installed in the station. This system can charge a maximum of 6 EV cars at the same time.

This study case was under the condition that 6 EV cars are charging at the same time at location no. 1. All EV cars were set to be of the BMWi3 model. The value of power quality was measured.

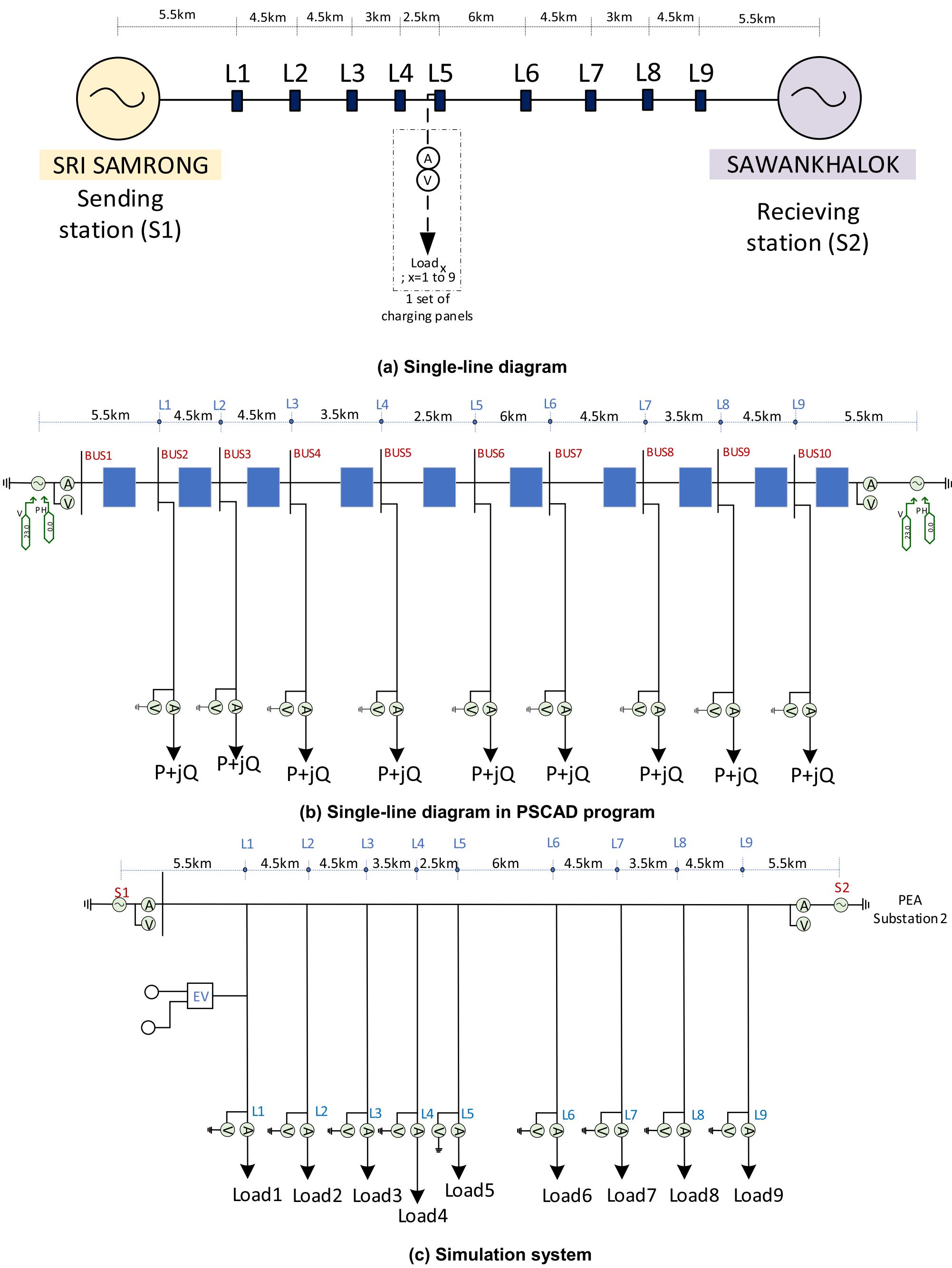


FIGURE 4. **Model of charging station.**

Moreover, the effects of the location variable on the three observed parameters were analyzed. In this case, the location to which the EV car was connected was varied to any one of the location numbers from location no. 1 to location no. 9. The values of the observed parameters were analyzed as follows.

1) ACTIVE POWER: P (MW)

The data in Table 3 and Fig 7 illustrate the active power measured under the condition that the number of EV cars charging at the station at the same time is at its maximum value, i.e., the station is at its full capacity in terms of the number of concurrently charging EV cars. At the same time, all EV cars are connected to the same location. For this analysis, the behavior of active power with respect to the connected bus variable, i.e., the bus to which the EV cars were connected, was observed. The location was varied to any one of the location numbers from location no. 1 to location no. 9.

For the case wherein the EV cars are connected to location no. 1, it can be observed that the active power at the sources was approximately 5–7 MW, whereas the active power at each load was approximately 0.1–3 MW. Moreover, when

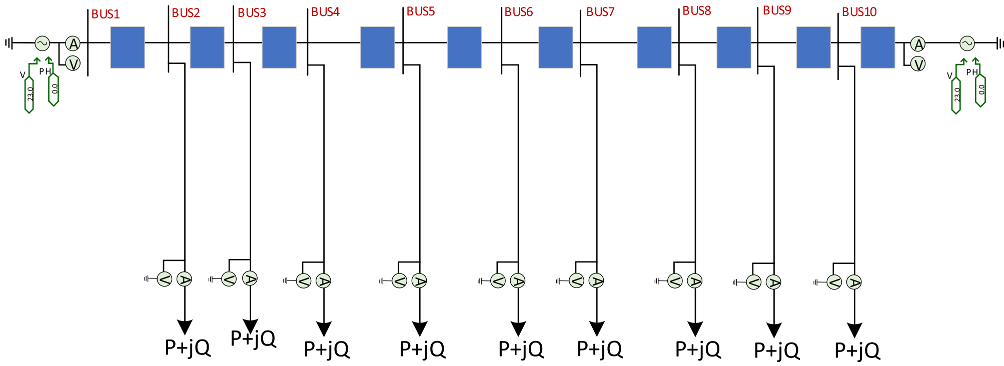


FIGURE 5. Simulation model for base case.

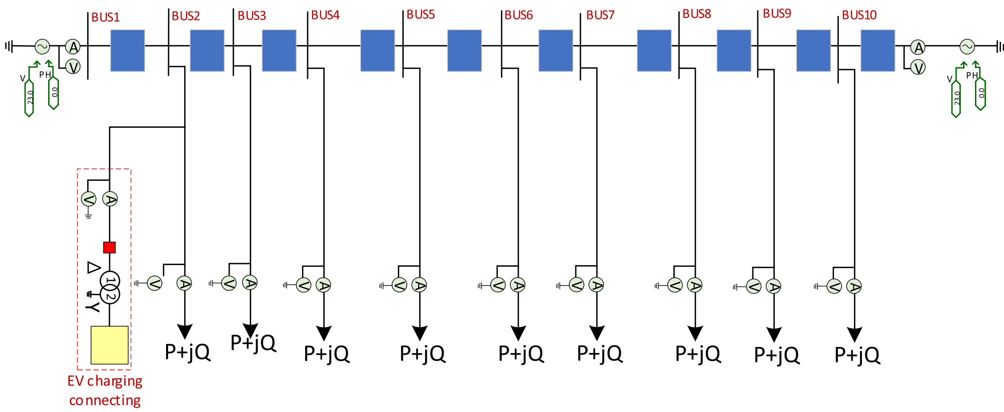


FIGURE 6. Simulation model for study case 1.

TABLE 2. Values of observed parameters for base case.

Measurement		Active power (MW)	Reactive power (MVAR)	Voltage (kV)
point	Distance(kM)			
S1	0	7.032	2.428	23.000
S2	43.5	5.777	1.975	23.000
L1	5.5	0.471	0.154	22.500
L2	10	2.492	0.817	22.120
L3	14.5	1.321	0.433	21.900
L4	17.5	3.091	1.013	21.800
L5	20	1.528	0.501	21.820
L6	26	0.507	0.166	21.990
L7	30.5	1.251	0.410	22.150
L8	33.5	1.591	0.521	22.300
L9	38	0.105	0.034	22.590

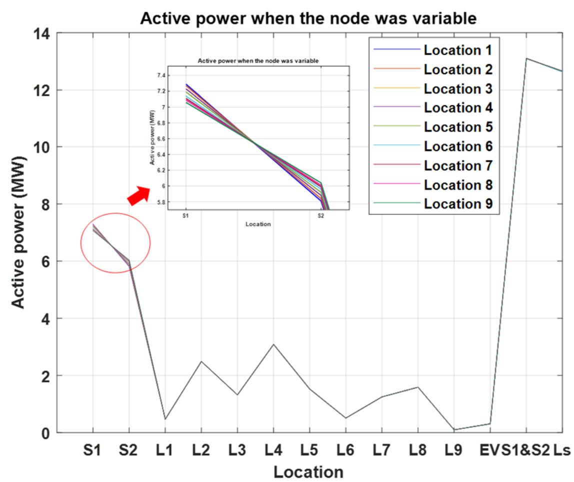


FIGURE 7. Active power when location of charging panels was variable.

these data were compared to those for the base case, shown in Table 2, it can be observed that adding the charging panel to the system caused the active power at the sources to slightly increase, whereas the active power at location no. 1, where the charging panel was installed, maintained a value of 0.47 MW.

When all EV cars were charging at location no. 2, the active power at the source and loads maintained similar values. Meanwhile, when the location to which the EV cars were connected was varied from location no. 2 to location no. 9, the data indicated that the change in location did not affect the active power at the sources and loads. The total active power at the sources was approximately 13 MW, whereas the total active power for all loads (loads L1–L9 and load EV) was approximately 12 MW.

2) REACTIVE POWER: Q (MVAR)

The reactive power was measured under the condition that the number of EV cars charging in the system at the same

TABLE 3. Active power for system with 3 units of charging panels, with variable charging location.

Measurement point	Location1 (MW)	Location 2 (MW)	Location 3 (MW)	Location4 (MW)	Location5 (MW)	Location6 (MW)	Location7 (MW)	Location8 (MW)	Location9 (MW)
S1	7.29	7.27	7.23	7.23	7.19	7.14	7.11	7.09	7.06
S2	5.81	5.84	5.88	5.88	5.92	5.96	5.99	6.01	6.04
L1	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
L2	2.49	2.49	2.49	2.49	2.49	2.49	2.49	2.49	2.49
L3	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
L4	3.09	3.09	3.08	3.08	3.08	3.08	3.09	3.09	3.09
L5	1.53	1.53	1.52	1.52	1.52	1.52	1.53	1.53	1.53
L6	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
L7	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
L8	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59
L9	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
EV	0.31	0.31	0.31	0.31	0.31	0.30	0.31	0.31	0.31
Total S1 & S2	13.10	13.11	13.11	13.11	13.11	13.10	13.10	13.10	13.10
Total all Lx to EV	12.66	12.66	12.64	12.64	12.64	12.63	12.66	12.66	12.66

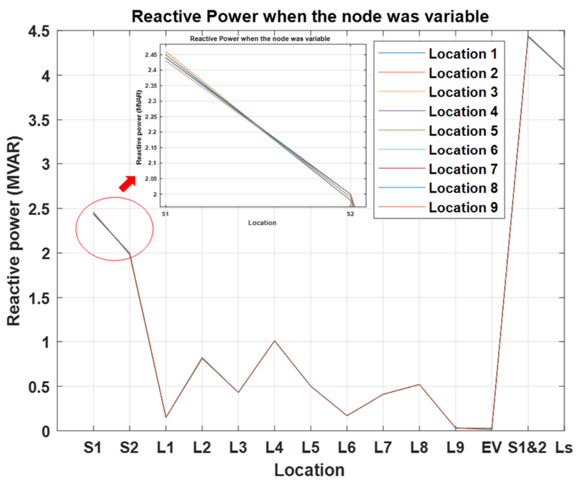


FIGURE 8. Reactive power when location of charging panels was variable.

time is at its maximum value, i.e., the system is at its full capacity in terms of the number of concurrently charging EV cars, while the location to which the EV cars were connected was variable. The values of the measured reactive power are shown in Table 4.

For the case wherein the EV cars are connected to location no. 1, it can be observed that the reactive power measured at the sources was approximately 2 MVAR, whereas the reactive power measured at the loads was approximately 1 MVAR. On the other hand, with regard to the influence of the location variable on the reactive power, it was found that changing the location to which the EV cars were connected apparently did not affect the reactive power, which maintained similar values.

The total reactive power at the sources and loads were 4.4 MVAR and 4 MVAR, respectively. In addition, when these data are compared to those for the base case, it can be observed that the trend of the reactive power was similar to that of the active power, which was that the reactive power increased only at the sources, and only by a slight amount. By contrast, the reactive power at load location no. 1 maintained the same value. To more clearly illustrate the characteristics of reactive power, the relationship of the location variable with reactive power is shown in Fig. 8, where it can be observed that the trend of reactive power was similar to that of active power, except that the value of the reactive power was lower than that of the active power. The reason was control of the power factor.

Moreover, for both reactive and active power, the values measured at points L1–L9 show interesting commonalities: the value at L4 was the highest, those at L2 and L8 were the second and third highest, respectively, and that at L9 was the lowest. The variation of the reactive power was a result of the electrical load (exiting load) mentioned in Table 1. Therefore, if it is necessary to install a charging panel, it is recommended to install it in a low-value location, such as L6 or L9.

3) VOLTAGE: V (KV)

The voltage data are shown in Table 5 and Fig. 9. For the case wherein the EVs are connected to location no. 1, it was found that the voltage at the sources was 23 kV, whereas the voltage at load no. 1 (measurement point L1) was slightly lower, at 22.49 kV. An interesting observation was that the voltage level decreased as the distance from the measurement point to the source increased, and in this case, point L4 was the furthest from sources 1 and 2, and thus, its voltage level was the lowest compared to the voltage levels at the other measurement points. The decrease in voltage was due to the line impedance. Similarly, with regard to the voltage at EV point, it was found that the voltages measured at location no. 3 to location no. 6 were lower than those measured at the other points. Moreover, when the voltage data for the case wherein the charging panel was installed at location no. 1 were compared with the voltage data for the base case, it was found that only the voltage at location no. 1 slightly decreased. Similarly, for the case wherein the charging panel was installed at location no. 2, the same behavior was observed, which was that the voltage level at the location was slightly lower than

TABLE 4. Reactive power for system with 3 units of charging panels, with variable charging location.

Measurement point	Location1 (MVAR)	Location 2 (MVAR)	Location 3 (MVAR)	Location4 (MVAR)	Location5 (MVAR)	Location6 (MVAR)	Location7 (MVAR)	Location8 (MVAR)	Location9 (MVAR)
S1	2.45	2.46	2.45	2.45	2.45	2.44	2.44	2.44	2.43
S2	1.98	1.98	1.99	1.99	1.99	1.99	2.00	2.00	2.00
L1	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
L2	0.82	0.82	0.81	0.81	0.81	0.82	0.82	0.82	0.82
L3	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43
L4	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
L5	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
L6	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
L7	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
L8	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
L9	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
EV	0.02	0.02	0.03	0.03	0.03	0.01	0.02	0.02	0.02
Total S1 & S2	4.43	4.44	4.44	4.44	4.44	4.43	4.44	4.44	4.43
Total all Lx to EV	4.06	4.06	4.06	4.06	4.06	4.05	4.06	4.06	4.06

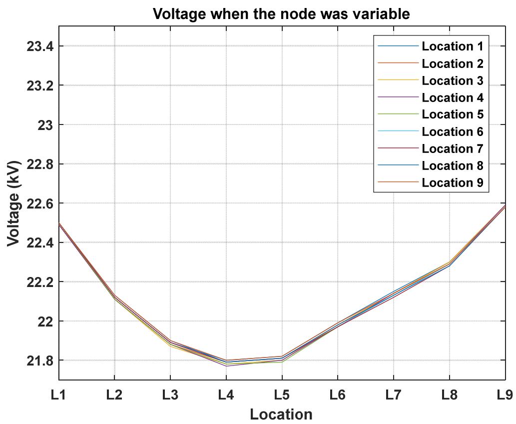


FIGURE 9. Voltage when location of charging panels was variable.

that for the base case. The reason for this decreasing voltage was that the charging panel was a load, and load affects the voltage.

Moreover, when considering on the effect of voltage drop, referring to the electricity regulation that voltage drop must not exceed 5% of voltage level, the voltage at L4 and L5 point are a tendency for voltage drop problems. Therefore, the solution usually avoid installing a large charging load or installs more capacitor banks, but in this research focuses on the charging cabinet. The installation of Capacitor banks was not taken to consider. However, we has been studied the developed power quality by using capacitor bank in the previous research [29], [30].

In concluding, owing to the observations described in this sub-section, it was inferred that the load directly affects the voltage. In the next sub-section, the influence of load (charging panels) on the power quality is considered.

C. STUDY CASE 2: NUMBER OF CHARGING PANELS WAS VARIABLE (LOCATION WAS FIXED)

In this case, the number of charging panels was increased from 3 panels to 4, 5, and 6 panels. Meanwhile, the charging-panel location was fixed at location no. 5.

According to the results of the previous cases, the voltage measured at location no. 5 was lower than those measured at the other measurement points. The reason for this was that location no. 5 was at the middle of the transmission line, and thus, the impedance of the transmission line was the significant factor that affected the voltage at the location and made it lower than those at the other locations. Therefore, in this case, the behaviors of the power-quality parameters were observed at the location where the voltage was the lowest.

Fig. 10 illustrates the model for when 4 units of charging panels are connected to location no. 5. The power-quality parameters were observed, and the values are shown in Table 6. Moreover, the behaviors of the power-quality parameters when the number of charging panels was varied from 4 to 6 were also observed, and the results were as follows.

1) ACTIVE POWER: P (MW)

The active power was one of the observed power-quality parameters. The active-power data for this study case are shown in Table 6 and Fig. 11. For the case wherein 4 units of charging panels are connected to the study system, the data in Table 6 show that the active power at the sources was approximately 13 MW, of which that at power source 1 was 7.25 MW and that at power source 2 was 5.97 MW, whereas the total active power of the loads (measurement points L1 to L9, and EV point) was approximately 12 MW. Thus, it can be observed that the active power at the loads was lower than at the power sources.

When the data for the case involving 4 charging panels were compared to the data for the case involving 3 charging panels, it was found that when the number of charging panels (loads) increases, the active power at both sources and at EV point slightly increase. Similar trends were observed for the active power when the number of charging panels was increased to 5 units, and then to 6 units. The data clearly show that increasing the number of charging panels affects the active power at both the power sources and the loads.

TABLE 5. Voltage for system with 3 units of charging panels, with variable charging location.

Measurement point	Location1 (kV)	Location 2 (kV)	Location 3 (kV)	Location 4 (kV)	Location 5 (kV)	Location 6 (kV)	Location 7 (kV)	Location 8 (kV)	Location 9 (kV)
S1	23.00	23.00	23.00	23.00	23.00	23.00	23.00	23.00	23.00
S2	23.00	23.00	23.00	23.00	23.00	23.00	23.00	23.00	23.00
L1	22.49	22.49	22.49	22.49	22.50	22.50	22.50	22.50	22.50
L2	22.12	22.11	22.11	22.11	22.11	22.12	22.12	22.13	22.13
L3	21.89	21.88	21.87	21.88	21.88	21.89	21.89	21.90	21.90
L4	21.80	21.79	21.78	21.77	21.78	21.79	21.79	21.79	21.80
L5	21.82	21.81	21.80	21.80	21.79	21.81	21.81	21.81	21.82
L6	21.99	21.98	21.98	21.97	21.97	21.97	21.97	21.98	21.99
L7	22.15	22.14	22.14	22.14	22.13	22.13	22.12	22.13	22.14
L8	22.30	22.30	22.30	22.29	22.29	22.29	22.28	22.28	22.29
L9	22.59	22.59	22.59	22.59	22.58	22.58	22.58	22.58	22.58
EV	22.49	22.11	21.87	21.87	21.79	21.97	22.12	22.28	22.58

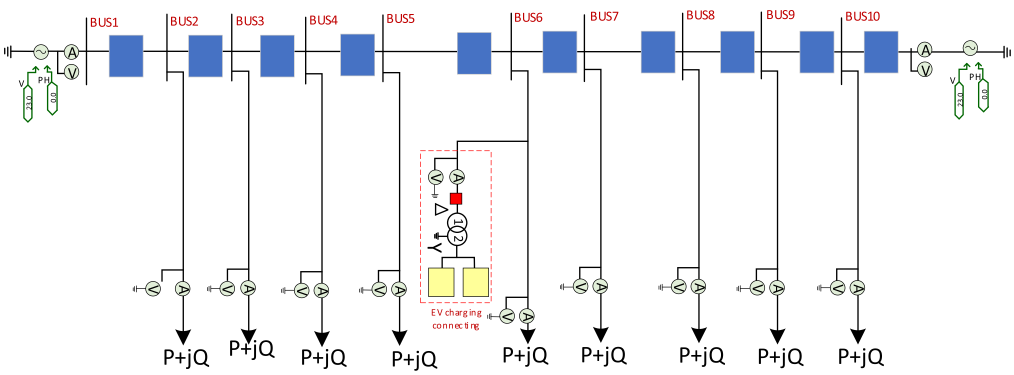


FIGURE 10. Simulation model for study case 2.

TABLE 6. Power-quality parameters for system with charging panels connected at location no. 5, with variable number of charging panels.

Measurement point	4 charging panels			5 charging panels			6 charging panels		
	P (MW)	Q (MVAR)	V (kV)	P (MW)	Q (MVAR)	V (kV)	P (MW)	Q (MVAR)	V (kV)
S1	7.25	2.46	23.00	7.30	2.49	23.00	7.36	2.50	23.00
S2	5.97	2.00	23.00	6.01	2.03	23.00	6.06	2.04	23.00
L1	0.47	0.15	22.49	0.47	0.16	22.49	0.47	0.15	22.48
L2	2.49	0.81	22.11	2.48	0.82	22.10	2.48	0.82	22.09
L3	1.32	0.43	21.87	1.32	0.43	21.86	1.32	0.43	21.85
L4	3.08	1.01	21.76	3.08	1.01	21.75	3.07	1.01	21.74
L5	1.52	0.50	21.78	1.52	0.50	21.77	1.52	0.50	21.75
L6	0.51	0.17	21.96	0.50	0.17	21.95	0.50	0.17	21.94
L7	1.25	0.41	22.13	1.25	0.41	22.12	1.25	0.41	22.11
L8	1.59	0.52	22.29	1.59	0.52	22.28	1.59	0.52	22.27
L9	0.11	0.03	22.58	0.10	0.03	22.58	0.10	0.03	22.57
EV	0.41	0.05	21.78	0.52	0.07	21.77	0.62	0.10	21.75
Total S1 & S2	13.22	4.46	-	13.31	4.52	-	13.42	4.54	-
Total all Lx to EV	12.75	4.08	-	12.83	4.12	-	12.92	4.14	-

Specifically, the active power for both is slightly increased as the number of charging panels is increased.

2) REACTIVE POWER: Q (MVAR)

The data for the reactive power, shown in Table 6, indicate that the trends for the reactive power were similar to those for the active power. The reactive power at sources S1 and S2 for the system with 3 charging panels was 2.45 and 1.99 MVAR, respectively. However, when the number of charging panels was increased to 4, 5, and 6 panels, the reactive power at both sources exhibited increasing trends, as illustrated in Fig. 12. Moreover, increasing the load of the charging panels affected the reactive power not only at the sources but at EV point, where the reactive power was observed to increase.

3) VOLTAGE: V (KV)

For the system with 4 charging panels connected, it was found that the voltage at both power sources maintained the

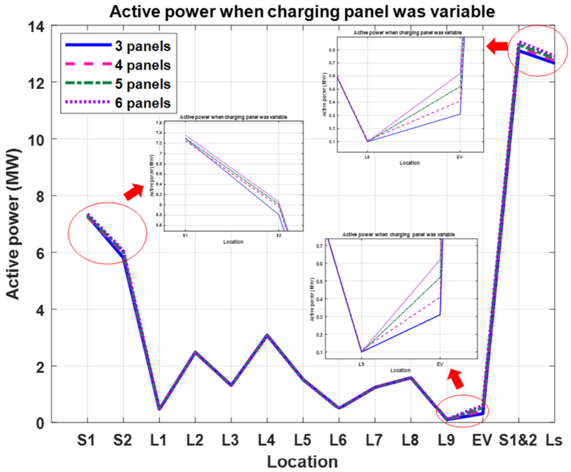


FIGURE 11. Active power when number of charging panels was variable.

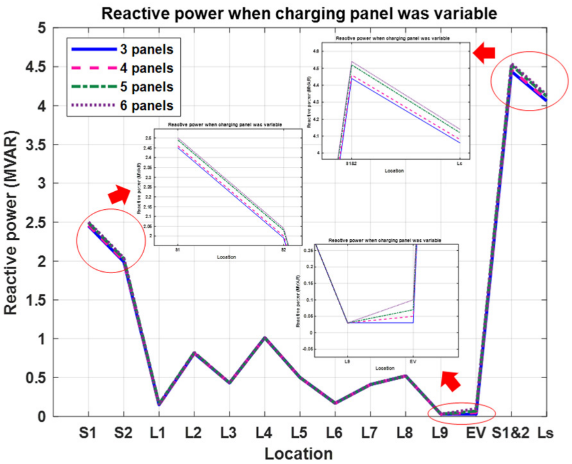


FIGURE 12. Reactive power when number of charging panels was variable.

same value, which was 23 kV. However, the voltage levels at the loads decreased with respect to the distance of the measurement point. In particular, the voltage levels at points L3 to L6 were lower than those measured at the other points. This decrease was due to the line impedance, which was already explained in the discussions of the previous cases.

In addition, when the voltage data for this case were compared to those for the base case, it was found that the voltages at points L1–L9 in the base case were higher than those for case study 2. Similar trends can be observed when the data for study case 2 were compared to those for study case 1. Fig. 13 shows the behaviors exhibited when the number of charging panels was varied, from which two generalizations were observed: (1) increasing the number of charging panels affects the active and reactive power at the sources and increases the load, and (2) the observed parameters (P, Q and V) maintained the same values even when the measurement point was varied.

From these investigations into the effects of changing the location and number of charging panels on the power quality, it was determined that the number of loads (which, in these

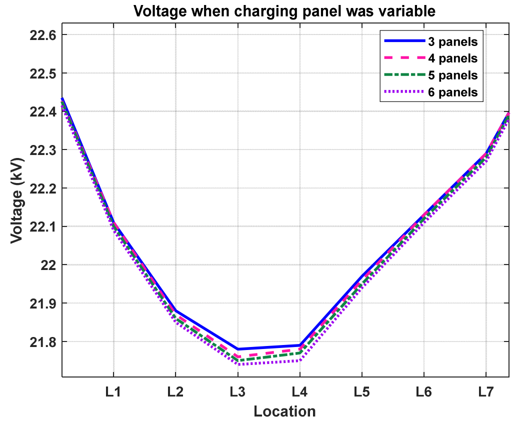


FIGURE 13. Voltage when number of charging panels was variable.

cases, is also the number of charging panels) is a significant factor that affects the power quality. Therefore, in the next part of the study, a more detailed investigation of load changes was conducted to obtain conclusions that can be applied in designing and analyzing the optimal locations of EVCSs.

III. TWO SETS OF CHARGING PANEL IN THE SYSTEM

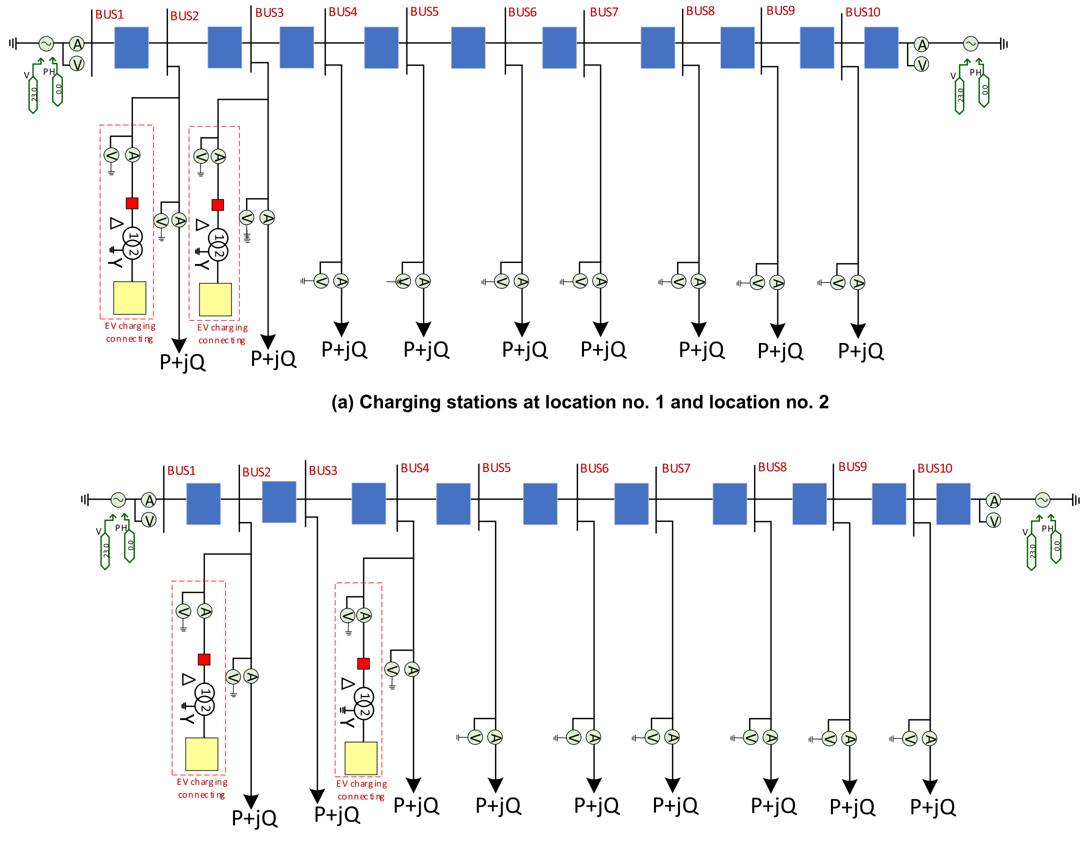
Study case 3 is for a future scenario in which another set of charging panels, i.e., station no. 2, is added to the system at a variable location (number of charging panels and location of charging station no. 1 are fixed).

For this case, a study is conducted to accommodate setups wherein the system already has a charging station but there is a desire to add a new charging station. This case study will explore the impact of the location of the second charging station on the power-quality parameters.

The conditions of this case are as follows: Charging station no. 1 has 3 units of charging panels connected at location no. 1. At this station, 6 EV cars can be charged simultaneously. Charging station no. 2 is to be added to the system. This new charging station also has 3 units of charging panels. However, the location of station no. 2 is variable. Its location can be changed to any location number from location no. 1 to location no. 8. The simulation system is shown in Fig. 14, and the values of the power-quality parameters are shown in Tables 7–9.

Fig. 14(a) depicts the simulation model, in which the power system has charging station no.1 installed at location no. 1 and station no. 2 installed at location no. 2. Because the effect of changing the location of station no. 2 is being studied, the model changes to that shown in Fig. 14(b). In this model, the location of charging station no. 1 is fixed, whereas the location of charging station no. 2 is changed to location no. 3. The model continues to change the location of charging station no. 2 until all locations have been exhausted. However, because of the limitation of the paper, only an example model is shown.

The power-quality parameters are then analyzed as follows. Table 7 shows the active-power data measured for study



(a) Charging stations at location no. 1 and location no. 2

(b) Charging stations at location no. 1 and location no. 3

FIGURE 14. Simulation model for study case 3.

TABLE 7. Active power for system with 3 units of charging panels, with variable charging-station location.

Measurement point	Location 1&2 (MW)	Location 1&3 (MW)	Location 1&4 (MW)	Location 1&5 (MW)	Location 1&6 (MW)	Location 1&7 (MW)	Location 1&8 (MW)	Location 1&9 (MW)
S1	7.53	7.50	7.48	7.46	7.42	7.38	7.36	7.33
S2	5.88	5.91	5.94	5.96	6.00	6.03	6.05	6.08
L1	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
L2	2.48	2.49	2.48	2.48	2.48	2.49	2.49	2.49
L3	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
L4	3.08	3.09	3.08	3.08	3.08	3.08	3.08	3.09
L5	1.52	1.53	1.52	1.52	1.52	1.52	1.52	1.53
L6	0.51	0.51	0.51	0.51	0.50	0.51	0.51	0.51
L7	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
L8	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59
L9	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
EV station 1	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
EV station 2	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Total S1 & S2	13.41	13.41	13.42	13.42	13.42	13.41	13.41	13.41
Total all Lx to EV	12.94	12.97	12.94	12.94	12.93	12.95	12.95	12.97

case 3. Changing the location of station no. 2 had a slight effect on the active power at both power sources. However, even though the active power measured at each power source changed, the total active power at the sources remained approximately the same. Thus, this change was inferred to be an effect of the impedance. In the same way, and for same reason, the active power measured at each load maintained the same value. Therefore, changing the charging-station location did not affect the total active power. The total active power at the sources was approximately 13.4 MW, whereas the active power at the loads was approximately 12.9 MW, slightly lower than that at the sources.

In addition, when the data for one scenario of this case (for example, 2 sets of charging panels installed at locations no.

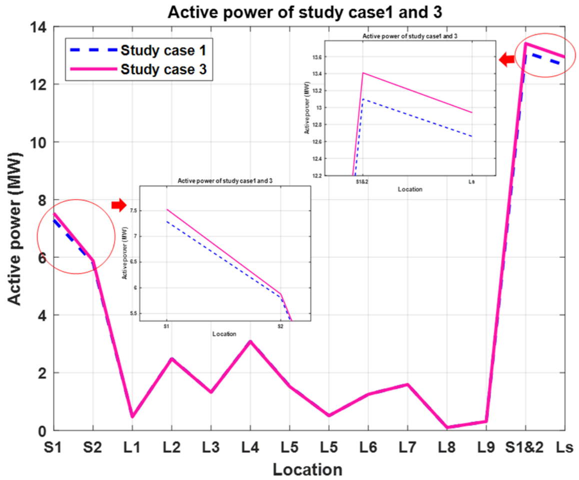


FIGURE 15. Active power when location of additional set of charging panels was variable.

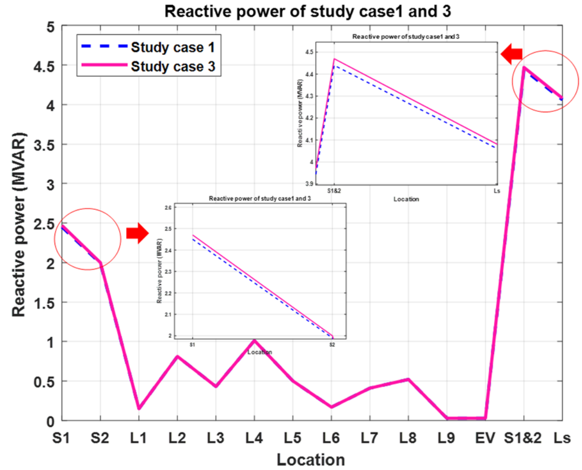


FIGURE 16. Reactive power when location of additional set of charging panels was variable.

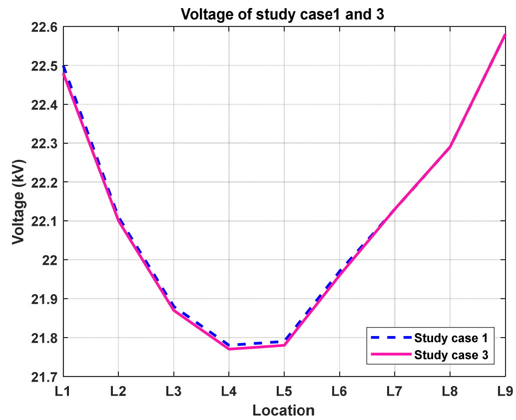


FIGURE 17. Voltage when location of additional set of charging panels was variable.

1 and no. 2) were compared to data for study case 1 (1 set charging panels installed at location no. 1), as illustrated in Fig. 15, it can be observed that the active power at S1 and S2 for study case 1 was lower than that measured for study case 3. Similarly, when the data for another scenario of study case 3 (for example, charging stations at locations no. 1 and no. 3) were compared to those for study case 1 (charging station at location no. 1), it was found that the location wherein the sets of charging panels were installed affected the active power at S1 and S2. As the number of charging panels (loads) increases, the active-power rating at the power supply tends to increase. At the same time, for measurement points L1–L9, it was found that increasing the number of charging panels did not affect the active power at the loads.

Similarly, the reactive-power data are shown in Table 8, from which it can be observed that the trends of the values were similar to those observed for the active power. Specifically, the location of the charging station had a slight effect on the reactive power measured at the power sources. However, even when the location of charging station no. 2 was changed, the total reactive power measured at the power sources or at the loads maintained the same value. The reason behind this behavior was the influence of impedance. Therefore, the distance between the load and bus affects the active and reactive power; specifically, the active and reactive power decrease as the distance becomes shorter. If the charging station is near the bus, the active and reactive power exhibit an increasing trend. In other words, if the charging stations are evenly distributed across the system, both active and reactive power will have similar values.

Moreover, when the data for this study case were compared to those for study case 1, the behavior of the reactive power, as shown in Fig. 16, was found to be similar to that of the active power, in that the location of the charging station affects only the power at the sources. For the case wherein one set of charging panels was installed at location no. 1, the reactive power at the sources was 2.45 and 1.98 MVAR, respectively. However, when another set of charging panels was added at location no. 2, the reactive power at S1 and S2 slightly increased to 2.48 and 1.99 MVAR, respectively. Similarly, when the additional set of charging panels was installed at location no. 3 instead, the reactive power at both sources increased to 2.47 and 1.99 MVAR, respectively.

The voltage levels outlined in Table 9 show that the voltages measured at the sources were higher than those measured at the loads. Furthermore, varying the charging-station location did not affect the voltage levels. Rather, the voltage level was affected by the impedance. Therefore, at the midpoint between power source 1 and power source 2 (measurement point L4), where the distance was the longest, the voltage was higher than at the others. In addition, interesting trends were observed when the voltage data for this case were compared to those for study case 3. Fig. 17 shows that changing the location of the charging-panels installation affected the voltages at the loads but apparently not the voltages at both sources, which maintained the same values. Therefore,

TABLE 8. Reactive power for system with 3 units of charging panels, with variable charging-station location.

Measurement point	Location 1&2 (MVAR)	Location 1&3 (MVAR)	Location 1&4 (MVAR)	Location 1&5 (MVAR)	Location 1&6 (MVAR)	Location 1&7 (MVAR)	Location 1&8 (MVAR)	Location 1&9 (MVAR)
S1	2.48	2.47	2.47	2.47	2.46	2.46	2.46	2.45
S2	1.99	1.99	1.99	2.00	2.00	2.01	2.00	2.00
L1	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
L2	0.81	0.81	0.81	0.81	0.81	0.82	0.81	0.82
L3	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43
L4	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
L5	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
L6	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
L7	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
L8	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
L9	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
EV station 1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
EV station 2	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.02
Total S1 & S2	4.47	4.46	4.46	4.47	4.46	4.47	4.46	4.45
Total all Lx to EV	4.07	4.08	4.08	4.08	4.08	4.08	4.07	4.08

TABLE 9. Voltage for system with 3 units of charging panels, with variable charging-station location.

Measurement point	Location 1&2 (kV)	Location 1&3 (kV)	Location 1&4 (kV)	Location 1&5 (kV)	Location 1&6 (kV)	Location 1&7 (kV)	Location 1&8 (kV)	Location 1&9 (kV)
S1	23.00	23.00	23.00	23.00	23.00	23.00	23.00	23.00
S2	23.00	23.00	23.00	23.00	23.00	23.00	23.00	23.00
L1	22.48	22.48	22.48	22.48	22.48	22.48	22.49	22.49
L2	22.09	22.10	22.10	22.10	22.10	22.11	22.11	22.11
L3	21.88	21.86	21.87	21.87	21.88	21.88	21.88	21.89
L4	21.78	21.77	21.76	21.77	21.77	21.78	21.78	21.79
L5	21.80	21.79	21.79	21.78	21.79	21.80	21.80	21.81
L6	21.98	21.97	21.97	21.96	21.96	21.97	21.97	21.98
L7	22.14	22.13	22.13	22.13	22.12	22.12	22.13	22.14
L8	22.30	22.29	22.29	22.29	22.28	22.28	22.28	22.29
L9	22.59	22.58	22.58	22.58	22.58	22.58	22.58	22.58
EV station 1	22.48	22.48	22.48	22.48	22.48	22.48	22.49	22.49
EV station 2	22.09	21.86	21.76	21.78	21.96	22.12	22.28	22.58

the results of study case 3 proved that the power and voltage at the sources vary with the load. At the same time, if the load quantity changes, the voltage drops across the load and changes accordingly.

IV. RESULT AND DISCUSSION

In this study, an EV charging station was simulated. The simulated system was based on a 23 kV power system. The voltage was stepped down by a transformer. At the low-voltage side, an EV was connected to the charging battery. The EV that was used in the simulation was the BMWi3 car model. The observed parameters were the active power (P), reactive power (Q), and voltage (V). The study cases were as follows:

Study case 1: The location of the charging station was varied to any location number from location no. 1 to location no. 9, whereas the number of charging panels was fixed at three.

For this case, three main findings were derived: (1) The active power at power source 2 (receiving station) was lower than that at power source 1 (sending station), owing to the effect of voltage drop. (2) Even when the location was varied to anywhere from 1 to 9, the active power maintained the same value. The reason for this trend was that the number of charging panels was the same. Therefore, the impedance load was unchanged. However, (3) the active-power measure at each measuring location was varied. The reason for this behavior of the active-power variable was the influence of voltage and line impedance.

Study case 2: The number of charging panels was varied from 3 panels to 6 panels, whereas the location of the panels was fixed at location no. 5.

For this case, because of finding no. 2 from study case 1, the influence of the number of charging panels on the active power was considered. The trends exhibited in Fig. 11–12 show that increasing the number of charging panels affected the active power at EV point and that the loads at all measurement locations (EV, Ls) increased. This is because if the number of charging panels is increased, the number of EV cars connecting to the system also increases. However, the active power measured at each location was maintained, exhibiting the same behavior as that observed in Fig. 7.

Lastly, the distribution of the charging panels was considered. Generally, the charging panels are in a distributed installation in the power system to cover the electricity needs of users in all areas. Therefore, the conditions in study case 3 were studied to be consistent with actual usage.

Study case 3: Additional set of charging panels (station no. 2) in the system with a variable location, with the first set of panels (station no. 1) fixed at location no. 1.

From the trends and behaviors observed from the two previous study cases, it was found that the active power was unchanged even when the location of the charging station was variable. Fig. 15 shows the trends and behaviors for these two conditions. In the first graph, the blue line shows the measured data for when one set of charging panels is installed in the power system at location no. 5 (3 charging panels/set). On the other hand, the pink line shows the data for when two sets of charging panels are installed in the power system at location no. 1 and location no. 5, respectively. The results reveal findings similar to those obtained for study case 2, i.e., increasing the number of charging panels increases the active power at all measurement locations for the EV and loads (EV and Ls).

The behavior of reactive power was also examined. The curves in Fig. 16 show that the trends for the reactive power were similar to those for the active power, except that the value of reactive power was lower than that of active power. The reason for this behavior was control of the power factor. Moreover, for both reactive and active power, the values measured at points L1–L9 show an interesting commonality: Among the values measured at points L1–L9, it can be observed that the value measured at L4 was the highest, those at L2 and L8 were the second and third highest, respectively, and that at L9 was the lowest. The variation of the reactive power was a result of the electrical load (exiting load), which is mentioned in Table 1. Therefore, if a charging panel is to be installed, it is recommended to install it in a low-value location, such as L6 or L9. Moreover, when the number of charging panels was variable, it can be observed that increasing the number of charging panels affected the reactive power at the sources and at the EV measurement point. The trend of the reactive power was in line with that of the active power. This is due to the power triangle theory.

When the data for study case 1 and study case 3 were compared, the relationship between the set of charging panels and the power was clarified. The results show that when the number of charging-panel sets is increased, the active and reactive power increase accordingly. This increasing behavior was in line with the observations for study case 2 (in which the number of charging panels was variable). Thus, increasing the number of charging-panel sets yields the same results as that of increasing the number of charging panels.

The parameter of voltage was the last factor that was examined. Its behaviors and trends when the location, number of charging panels, or number of charging-panel sets was varied were subjected to sequential analysis.

First, it was found that the voltage is at its highest at both terminals. After that, the voltage level exhibits a decreasing trend. It decreases until the middle of the transmission line. At the middle point, the voltage level is at its lowest. This result is an effect the impedance and voltage drop, which has already been indicated in previous sections of this paper.

Second, with regard to the behavior of the voltage level when the number of charging panels was varied between 3, 4, 5, and 6 panels, the graph shows that the voltage decreases as the number of charging panels increases. This is because increasing the number of charging panels signifies increasing the load, and when the loads increase, the voltage decreases. Moreover, owing to the impedance effect, the voltage levels at L4 and L5 were lower than at the other points. However, as indicated earlier, increasing the number of charging panels decreases the voltage. Therefore, the voltage for that case, in which the charging panels are installed at points L4 and L5, is the point where you should be most careful about voltage drops. In the regulations of the Electricity Generating Authority of Thailand (EGAT), it is specified that the voltage drop value should not be lower than 5% (for the case presented herein, the voltage must not be lower than 21.85 kV). However, in this case, the voltage at points L4–L5 was approximately 21.74 kV, which is lower than the value mandated by the EGAT regulations. Therefore, the installation of charging panels should avoid this point.

Third, the effect of the number of charging-panel sets on the voltage level was examined. When the number of charging-panel sets is increased, it signifies that the load increases. The load for study case 3 was greater than that for study case 1, and thus, the voltage level for study case 3 was lower than that for study case 1.

V. CONCLUSION

A power system with an EVCS installation was analyzed in this study. The topology of this system was based on a real-world system, specifically, a 23 kV distribution system of the Provincial Electricity Authority (PEA). The sending and receiving stations were determined to be Sri Samrong and Sawankhalok, respectively. The distance between the stations is 43.5 km, and there are 9 locations of tap points connected to the load usage. The charging station can be installed at any of these locations. The objective of this study was to elucidate the influence of charging EV cars on the fundamental parameters of the power system. The fundamental parameters observed in this study were active power (P), reactive power (Q), and voltage (V). The EV cars used in this study were of a BMWi3 model. The simulation was run in the PSCAD software program, and the observations have yielded four main findings.

1. The location of the tap point does not affect the active and reactive power. The active and reactive power depend on the loads.

2. Increasing the loads increases the active and reactive power at the stations by a slight amount.

3. The location of the tap point is related to the distance from the sending station, and the distance directly affects the impedance. Therefore, the voltage measured at the middle of the transmission line (at L4–L5 location of tap point) was lower than those measured at the other locations.

4. Therefore, based on the finding that the voltage at the middle of transmission is lower than those at the other locations, when a designer is deciding on suitable locations to establish charging stations, it is recommended that they avoid installing at such points. However, if this is unavoidable, the effect of voltage drop should always be considered in the design. If it does not satisfy the requirements, additional correction devices such as capacitor banks should be installed.

In the future, we will study 2 additional aspects of the EVCS topic: First, we will study different load sizes because in real electrical systems, the load sizes in different areas are different. Second, we will study different brands and models of EV cars to be able to accommodate their needs, because there are many types of cars on the road that are expected to use the services of the EVCSs.

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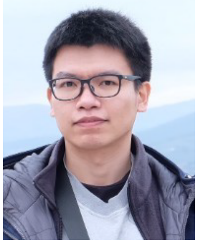

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