J Electr Eng Technol Vol. 9, No. 2: 452-460, 2014
http://dx.doi.org/10.5370/JEET.2014.9.2.452

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Evaluation of Voltage Sag and Unbalance due to the System Connection of Electric Vehicles on Distribution System

**Soon-Jeong Lee*, Jun-Hyeok Kim*, Doo-Ung Kim*, Hyo-Sang Go*,
Chul-Hwan Kim†, Eung-Sang Kim** and Seul-Ki Kim****

Abstract – Due to increased concerns for rising oil prices and environmental problems, various solutions have been proposed for solving energy problems through tightening environmental regulations such as those regarding CO_2 reduction. Among them, Electrical Vehicles (EVs) are evaluated to be the most realistic and effective approach. Accordingly, research and development on EVs and charging infrastructures are mainly proceeding in developed countries. Since EVs operate using electric energy form a battery, they must be connected to the power system to charge the battery. If many EVs are connected during a short time, power quality problems can occur such as voltage sag, voltage unbalance and harmonics which are generated from power electronics devices. Therefore, when EVs are charged, it is necessary to analyze the effect of power quality on the distribution system, because EVs will gradually replace gasoline vehicles, and the number of EVs will be increased. In this paper, a battery for EVs and a PWM converter are modeled using an ElectroMagnetic Transient Program (EMTP). The voltage sag and unbalance are evaluated when EVs are connected to the distribution system of the Korea Electric Power Corporation (KEPCO). The simulation results are compared with IEEE standards.

Keywords: Electric vehicle, Voltage sag, Voltage unbalance, System connection, Penetration level

1. Introduction

The Kyoto protocol of 2005 made CO_2 reduction compulsory for developed countries. The Republic of Korea has invested in R&D and the commercialization of EVs with aims for mass production in 2011, and for comprising 10% of the world green car market share by 2015, which would guarantee that green cars would comprise up to 10% of domestic compact vehicles by 2020 [1].

Since EVs are powered by batteries, charging is necessary. In order to charge the battery, EVs should be connected to the power system. However, EVs are charged randomly depending on driver's patterns, driving purposes, the time of days, the day of the week, the season, and so on. Consequently, various power quality problems such as voltage sag, harmonics, and voltage unbalance could occur in the power system. Among the power quality problems, voltage sag is the most frequent event. Hence, prior to the mass production of EVs, it is necessary to analyze the power quality problems and to make arrangements through simulations when EVs are connected to the power system.

Various studies have already been performed, including; the analysis of harmonics due to the connection of EVs [2], and of the impact of plug-in electric vehicle loading [3, 4], the impact of transformers [5], the active and reactive power demand [6-9], the power quality and voltage unbalance [10], loss reduction using charging control [11, 12], frequency control [13], and of EV chargers characteristics [14]. In these studies, however, EVs were not connected to an actual power system and numerical power quality analysis was not performed clearly. In this paper, voltage sag and unbalance occurs upon the connection of EVs are analyzed based on actual traffic volume and average driving time in distribution system of KEPCO. Simulations are performed on various penetration levels, and the results are compared with IEEE standards.

2. Connection of EV

EV charging can be divided into slow charging and rapid charging [15]. Generally, slow charging systems for households are operated at 230V on a single phase of the LV level. In contrast, rapid charging systems are operated at 350-400V on the three phase of MV level. This paper considers a slow charging system only. The single line diagram of a slow charging network is shown in Fig. 1.

---

† Corresponding Author: College of Information and Communication Engineering, Sungkyunkwan University, Korea. (hmwkim@hanmail.net)

* College of Information and Communication Engineering, Sungkyunkwan University, Korea. (kiraoov@gmail.com, kjh30309@naver.com, {krkic, ghs015}@hanamail.net)

** Korea Electrotechnology Research Institute. ({eskim, blksheep}@keri.re.kr)

Received: June 16, 2013; Accepted: November 13, 2013

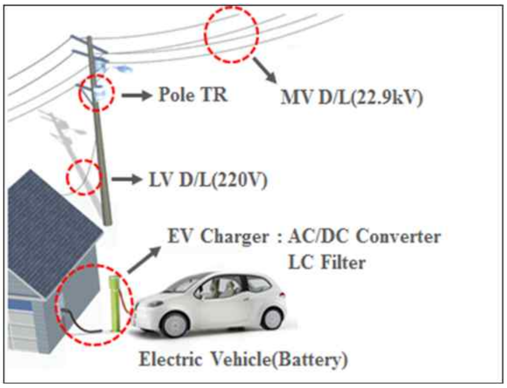


Fig. 1. Configuration of Slow Charging Network

2.1 Assumptions

In this paper, we make the following assumptions:

① The number of EVs connected to the power system is proportional to the load capacity.
② Charging is started promptly after driving is stopped.
③ While EVs are charging, other components of the power system do not affect power quality.
④ Characteristics of weekends and holidays are not considered.
⑤ A slow charging system will complete the battery charging within 2 hours.
⑥ All EVs are connected to phase A.
⑦ 1 hour is assumed as 0.1 second in the simulation.

We assume that the number of EVs is proportional to the load capacity because the load capacity is closely related to residential density. EVs will be charged promptly after driving is stopped. For this, we consider the actual traffic volume and average driving time. The average driving time in the Republic of Korea is 1 hour is applied in this paper [1]. Since this paper focuses on the impact of the EV charging, it is assumed that other components on the power system do not affect power quality. And, we consider only weekdays. EVs will be completely charged within 2 hours by considering the average driving distance, fuel efficiency and capacity of the charger. Next, in order to consider the worst case, all EVs are connected to phase A. Finally, we regard 1 hour as 0.1 second to reduce the simulation time.

2.2 Simulation system [16]

We model the distribution system in one part of Seoul, Republic of Korea, as shown in Fig. 16 of the Appendix. This system consists of “X S/S ~ Y D/L” and “X S/S ~ Z D/L”. The total length of this system is 1.5[km], and consists of two-step-type poles and a neutral line. Electric power is delivered to 13 loads in the upper portion and 11 loads in the bottom portion. The total active and reactive loads are 28.6[MW] and 13.9[Mvar], respectively. In this paper, only part 2 is considered. Because according to [1], actual traffic volume is surely required to estimate the number of EVs. However, it is very hard to get an actual traffic volume data in part 1. Because the part 2 only covers one certain area. On the other hand, part 1 covers two nearby areas. Therefore, if we consider part 1, it could cause uncertainties on analysis. It means when we regard part 1, it is obvious that certain amount of traffic volume have intersection between neighboring areas. Thus, uncertainties would occur. That is the main reason why we only consider part 2 area. For more detailed explanation, assume that the set A and B represents the actual traffic volume of each areas in part 1. To calculate the traffic volume of part 1 ($A \cup B$), we should know the number of actual traffic volume of A, B and its intersection ($A \cap B$, i.e. the number of EVs which drive from A to B and vice versa). However, if we do not know the exact number of traffic volume in intersection, the uncertainties would occur. On the other hand, part 2 include only one area. Therefore, there is no intersection and uncertainties. That is to say, more accurate analysis can be performed by considering only the part 2 area.

3. Case Study

3.1 Setting for the number of EVs

The number of EVs is an essential part of analyzing voltage sag and unbalance. In this paper, it is estimated according to the following process.

① Set the Penetration Level.
② Calculate the number of EVs on each load (L_1-L_{11}) based on the load capacity.
③ Analyze the system connection time based on actual traffic volume.
④ Estimate the number of EVs connected to the power system at each time by considering the load capacity and traffic volume.

The Republic of Korea established a scenario that EVs will comprise up to 10% of the total compact vehicles (about 65,000) by 2020 [1]. In 2012, the actual number of compact vehicles of the X S/S ~ Z D/L area is 8961 [17]. Thus, it is expected that there will be approximately 896 EVs in this area. The number of EVs on each load process could be calculated using Eqs. (1) and (2).

$$R_{Ln} = \frac{C_{Ln}}{C_t} \times 100(\%) \tag{1}$$

$$S_{Ln} = R_{Ln} \times S_t \tag{2}$$

where,

R_{Ln} : Rate of load capacity of Ln
C_{Ln} : Load capacity of Ln
C_t : Total load capacity
S_{Ln} : The number of EVs which are connected to Ln

Table 1. The number of EVs connected to each load

Location	Load capacity (kW)	Rate (%)	EVs
L1	1,189	8.574	77
L2	382	2.754	25
L3	843	6.079	54
L4	1,792	12.927	116
L5	565	4.074	37
L6	727	5.243	47
L7	1,194	8.610	77
L8	1,955	8.618	77
L9	1,282	9.245	83
L10	305	2.199	20
L11	4,392	31.674	284
Total	13,866	100	896

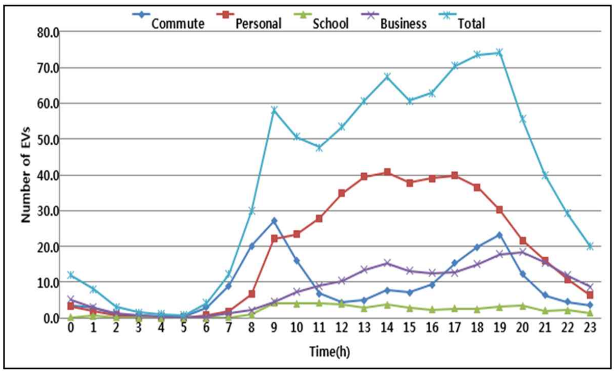


Fig. 2. Charging start time of EVs

S_t : Total number of EVs
n : 1~11

Based on these equations, the number of EVs connected to the power system for a day is shown in Table 1.

In order to set the charging start time of EVs at each load, the actual traffic volume of a simulation system [18] is used and depicted in Table 2. The traffic volume is highest during commute times (8h, 17h, and 18h) and noon.

According to the second assumption of section 2.1, EV charging would start 1 hour later than the actual traffic volume. Therefore, the number of EVs connected to the system at each time can be calculated using Eq. (4).

$$S_{Ln}^{h} = S_{Ln} \times R_h \tag{4}$$

where,

S_{Ln}^{h} : The number of EVs which are connected to Ln at each time
S_{Ln} : The number of EVs connectedto Ln
R_h : The rate of EVs at each time

Fig. 2 shows the charging start time of EVs in case of the 10% penetration level. From the Tables 1 and 2, the number of EVs connected to the system considering actual traffic volume and load capacity in the X S/S ~ Z D/L area is shown in Table 3. It should satisfy Eq. (5).

Table 2. Traffic volume and ratio of the simulation system

Time	Commute	Personal	School	Business	Total	Rate (%)
0	672	437	159	710	1,979	0.89
1	255	172	11	339	776	0.35
2	135	63	1	179	378	0.17
3	114	19	2	110	245	0.11
4	103	32	0	35	170	0.07
5	732	197	4	75	1,009	0.45
6	2,230	465	29	299	3,023	1.36
7	4,974	1,645	224	545	7,388	3.32
8	6,713	5,495	1,041	1,121	14,370	6.47
9	3,988	5,772	1,003	1,780	12,543	5.65
10	1,696	6,886	1,027	2,202	11,811	5.32
11	1,079	8,624	966	2,556	13,225	5.95
12	1,230	9,764	682	3,346	15,022	6.76
13	1,913	10,100	901	3,775	11,689	7.51
14	1,754	9,360	666	3,247	15,027	6.76
15	2,298	9,652	558	3,081	15,589	7.02
16	3,791	9,845	658	3,149	17,443	7.85
17	4,886	9,031	596	3,711	18,224	8.20
18	5,740	7,469	764	4,405	18,378	8.27
19	3,004	5,361	826	4,564	13,755	6.19
20	1,563	3,981	492	3,845	9,881	4.45
21	1,096	2,688	515	2,928	7,227	3.25
22	886	1,560	352	2,134	4,932	2.22
23	846	806	15	1,263	2,930	1.32
Total	51,699	10,9424	11,492	49,398	222,012	100

$$S_t = \sum_{n=1}^{11} S_{Ln} = \sum_{h=0}^{23} S_h \tag{5}$$

where,

S_t : Total EVs
S_h : The number of EVs which start charging at each time

3.2 Model of EVs using EMTP/ATPDraw

In this paper, the driving gear of vehicles is neglected, because we just focus on the case of EVs charging. The harmonics filter, PWM AC/DC converter [19], and Li-ion

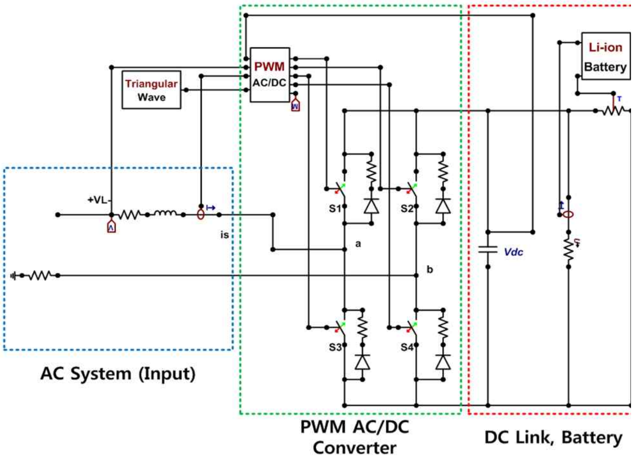


Fig. 3. EV charging interface

Table 3. The number of EVs connected to the power system considering time and load capacity (Penetration Level: 10%)

Time \ Load	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	Total
0	1	0	1	2	0	1	1	1	1	0	4	12
1	1	0	0	1	0	0	1	1	1	0	3	8
2	0	0	0	1	0	0	0	0	1	0	1	3
3	0	0	0	1	0	0	0	0	0	0	1	2
4	0	0	0	0	0	0	0	0	0	0	1	1
5	0	0	0	0	0	0	0	0	0	0	1	1
6	0	0	0	1	0	0	1	1	0	0	1	4
7	1	0	1	2	0	1	1	1	1	0	4	12
8	3	1	2	4	0	2	3	3	6	0	9	33
9	5	2	4	7	0	3	5	5	5	1	18	58
10	4	1	3	7	2	3	4	4	3	1	16	49
11	4	1	3	6	2	2	4	4	4	1	15	48
12	5	1	3	7	2	3	5	5	5	1	17	53
13	5	2	4	8	2	3	5	5	6	1	19	61
14	6	2	4	9	2	4	6	6	6	1	21	67
15	5	2	4	8	2	3	5	5	6	1	19	61
16	5	2	4	8	3	3	5	5	7	1	21	64
17	6	2	4	9	3	4	6	6	6	2	22	69
18	6	2	4	10	3	4	6	6	5	2	23	72
19	6	2	5	10	3	4	6	6	7	2	23	74
20	5	2	3	7	2	3	5	5	5	1	18	56
21	3	1	2	5	2	2	3	3	4	1	13	40
22	3	1	2	4	1	2	3	3	3	1	9	29
23	2	1	1	3	1	1	2	2	3	0	6	21
Total	77	25	54	116	37	47	77	77	83	20	284	896

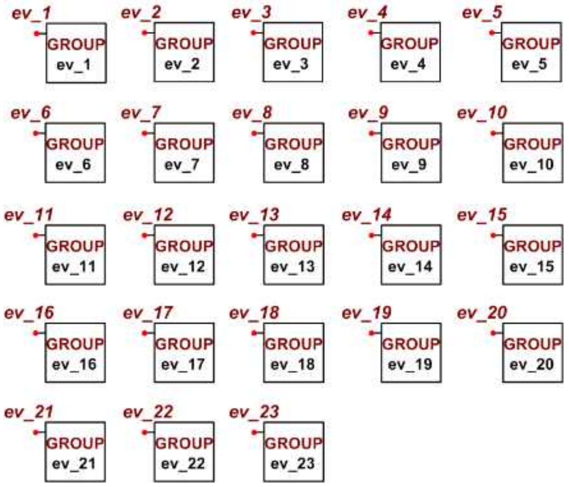


Fig. 4. EV models (Penetration level: 10%)

battery for EVs [20] are modeled using EMTP/ATPDraw. It is represented in Fig. 3.

If the penetration level is 10%, 23 models of EVs are required, and a "Time Controlled Switch" is used to connect to the power system. The name of the input node of each EV model shown in Fig. 4 should correspond to the name of a switch node. For example, according to the Table 3, 9 EVs are connected to L11 of the system at 8 AM. In order to simulate this case, the name of the switch operated at 8 AM on L11 should coincide with *ev*_9 as shown in Figs. 4 and 5.

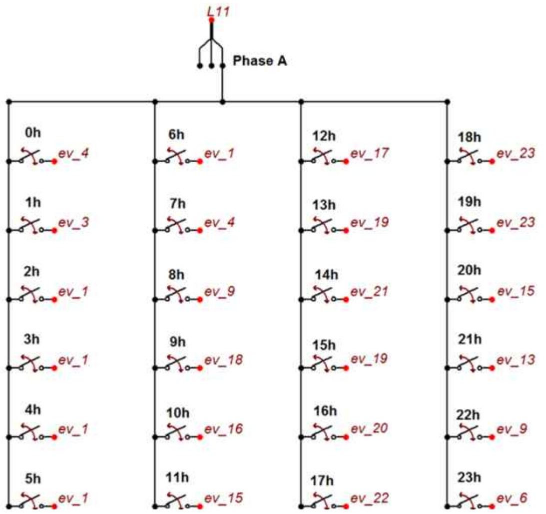


Fig. 5. Switch setting for system connection on L11 (Penetration level: 10%)

4. Simulation Results

4.1 Voltage sag

EVs could be regarded as a load and its charging point is concentrated. Hence, if many EVs are connected to the power system, voltage sag would occur. Voltage sag could be the most frequent power quality problem. IEEE standard 1159-1995 [21] define voltage sag as in Fig. 6.

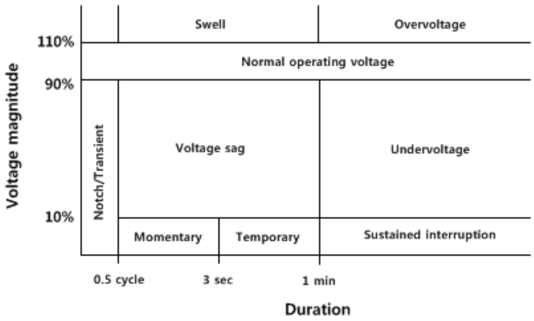


Fig. 6. Classification of voltage magnitude used in IEEE Std.1159-1995

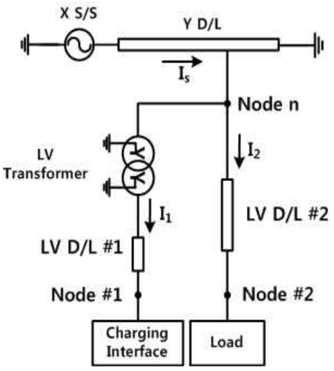


Fig. 7. Single line diagram on the simulation system

A simple diagram of the modeled system and charging interface is shown in Fig 7. In order to consider the voltage drops and losses of distribution lines, we calculate the complex power and voltage at node "n" as shown in Eqs. (6) and (7).

$$S_n = (S_{\#1} + Z_{LV\ \ D/L\,\#1} \times {I_1}^2) + (S_{\#2} + Z_{LV\ \ D/L\,\#2} \times {I_2}^2) \tag{6}$$

$$V_n = (V_{\#1} \times N) + (Z_{LV\ \ D/L\,\#1} \times I_1 \times N) \tag{7}$$

where,

S_n : Complex power at node n
$S_{\#1}$: Complex power at node #1
$S_{\#2}$: Complex power at node #2
$Z_{\text{LV D/L \#1}}$: Line impedance of LV D/L #1
$Z_{\text{LV D/L \#2}}$: Line impedance of LV D/L #2
I_1 : Current of node #1
I_2 : Current of node #2
V_n : Voltage at node n
$V_{\#1}$: Voltage at node #1
N : Turn ratio of LV Transformer

In the equation (6), $Z_{LV\ \ D/L\,\#1} \times {I_1}^2$ and $Z_{LV\ \ D/L\,\#2} \times {I_2}^2$ terms indicate the line losses by LV D/L #1 and #2, respectively. And the voltage drops on LV D/L #1 can be calculated by the latter term of Eq. (7). As shown in Eq. (7), $V_{\#1}$ is varied according to the connection of EVs. Therefore we measured the voltage V_1 on L1~L11. Fig. 8 shows the RMS voltage measured on L4 with the 10% of penetration level. If EVs are not connected the voltage is 244.63V. However, the voltage is rapidly reduced to 240.83V (0.964p.u.) when EVs are connected.

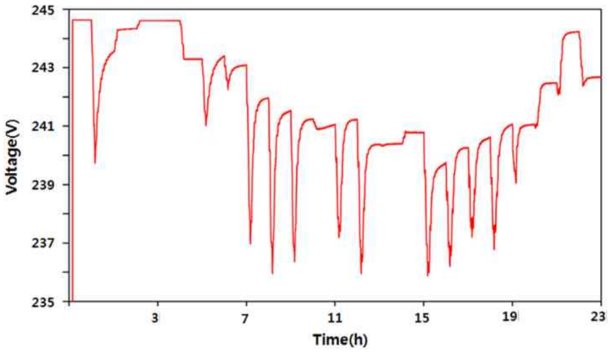


Fig. 8. RMS value of voltage measured on L4 (Penetration level: 10%)

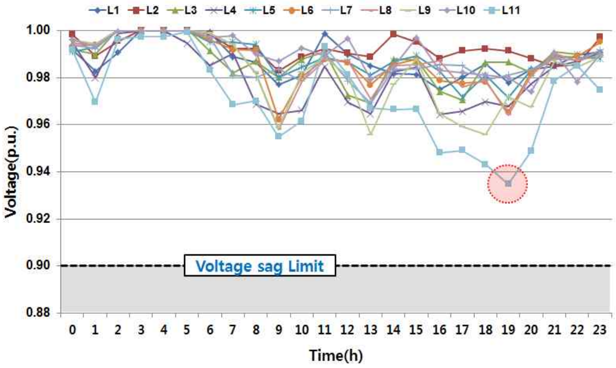


Fig. 9. RMS value of voltage measured on L1~L11 (Penetration level: 10%)

Fig. 9 represents the RMS voltage measured at L1~L11 expressed as a per-unit system. Generally, most cases show that voltage decreases expressly in commuting times and at noon. In other words, more EVs are stopped and connected to the system for charging at these times (i.e. 7~10 AM, 12 PM and 15~18 PM) than others. But voltage does not exceed the voltage sag limit when the penetration Level is 10% as shown in Fig. 9.

For more specific analysis, the minimum values from the results of Fig. 9 are depicted in Fig. 10. It is shown that the voltage decrease when EVs were connected to the power system and the decreasing rate was proportional to the number of connected EVs.

In this area, if the penetration level of EVs is 10% the voltage does not drop under the voltage sag limit defined by the IEEE standard. Thus, we simulate three cases of penetration levels and the results are shown in Fig. 11.

In Fig. 10, as the penetration level is increased by 5% intervals from 10% to 20%, the maximum and average decrements are 0.035 p.u. and 0.016 p.u., respectively. In the case of the 10% and 15% penetration levels, voltage does not drop under the voltage sag limit of IEEE standard.

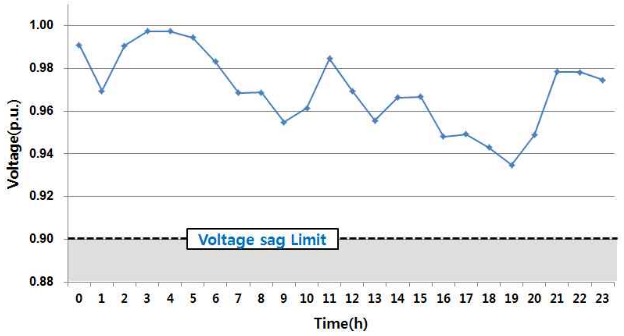


Fig. 10. The minimum value of voltage measured on L1~L11 (Penetration Level: 10%)

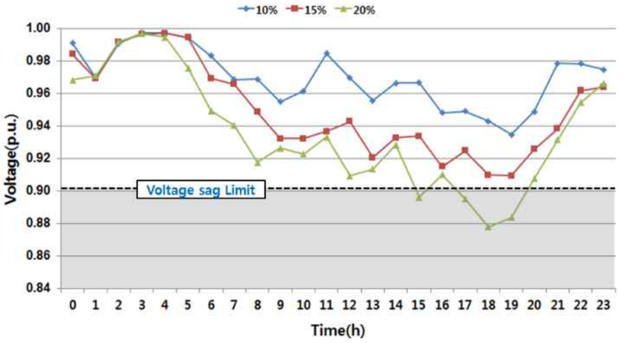


Fig. 11. The minimum voltage magnitude according to penetration levels

But, in the case of the 20% penetration level, the voltage decreases under 0.9p.u. at 15h and from 17h to 19h.

4.2 Voltage unbalance

Due to the long charging time and single phase connection, the slow charger for EVs leads to the voltage unbalance in the power system. Voltage unbalance can cause some power quality problems in the power system such as reverse torque and heating of a rotating machine, and irregular harmonics [22]. Therefore, it is necessary to analyze the voltage unbalance. Generally, voltage unbalance can be evaluated by using symmetrical transformations as shown in Eqs. (8~10).

$$V_0 = \frac{1}{3}(V_a + V_b + V_c) \tag{8}$$

$$V_1 = \frac{1}{3}(V_a + aV_b + a^2V_c) \tag{9}$$

$$V_2 = \frac{1}{3}(V_a + a^2V_b + aV_c) \tag{10}$$

where,

a : $1\angle 120^\circ = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$
V_0 : Zero sequence voltage
V_1 : Positive sequence voltage
V_2 : Negative sequence voltage

Voltage unbalance is also has a limitation according to the IEEE Standard [21]. u_f was the negative sequence unbalance factor represented by using the ratio of the positive sequence to the negative sequence. And it is limited to 2%. In this paper, to use the method applied in previous study [22], symmetrical transformation is performed through Eqs. (8) and (9) by measuring the 3 phase instantaneous voltage at L1~L11. Based on the calculated results, the negative sequence unbalance factor is analyzed. Fig. 12 shows the voltage waveform of the positive sequence, negative sequence, and u_f measured at L9 in the 10% penetration level.

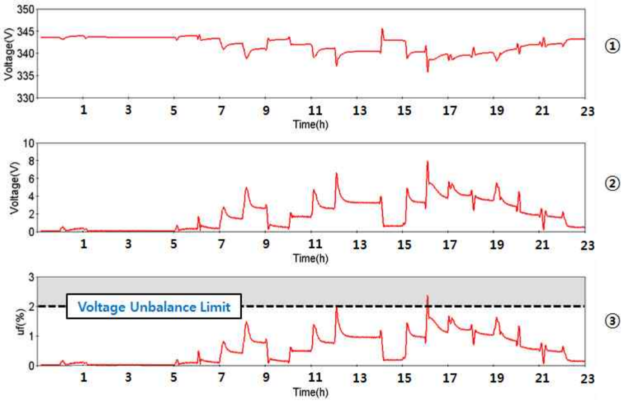


Fig. 12. Positive sequence(①), Negative sequence(②) voltage and u_f(③) wave according to the time on L9 (Penetration Level: 10%)

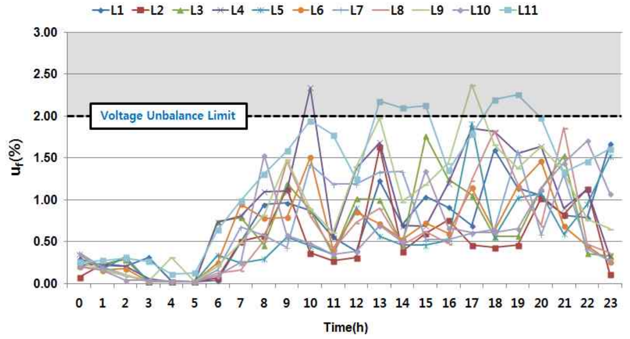


Fig. 13. u_f results measured on L1~L11 (Penetration Level: 10%)

$$u_f = \frac{V_2}{V_1} \times 100(\%) \tag{11}$$

In Fig. 12, the voltage unbalance occurred at L9 in the most time, but it exceeded the limit (2%) at 12 and 16h only. Therefore, in order to evaluate the voltage unbalance, the values of u_f calculated at L1 ~ L11 are represented in Fig. 13.

In Fig. 13, it is shown that the voltage unbalance exceeds the limit at L4, L9 and L11 which is connected with many vehicles compared with other load points.

In contrast to the case of voltage sag, the voltage unbalance exceeds the limit a total 8 times with a

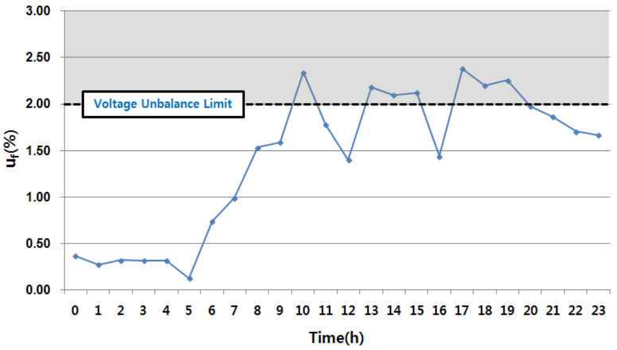


Fig. 14. The Maximum value of u_f measured on L1~L11

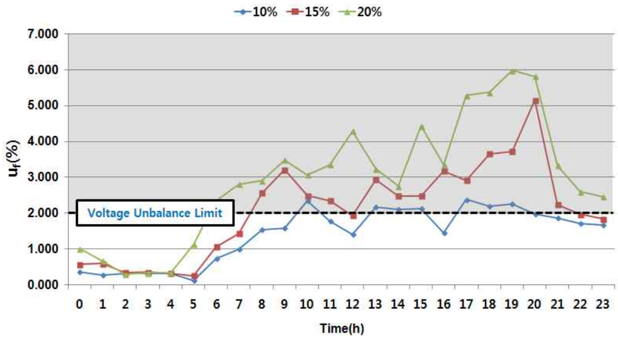


Fig. 15. u_f magnitude according to penetration levels

Appendix

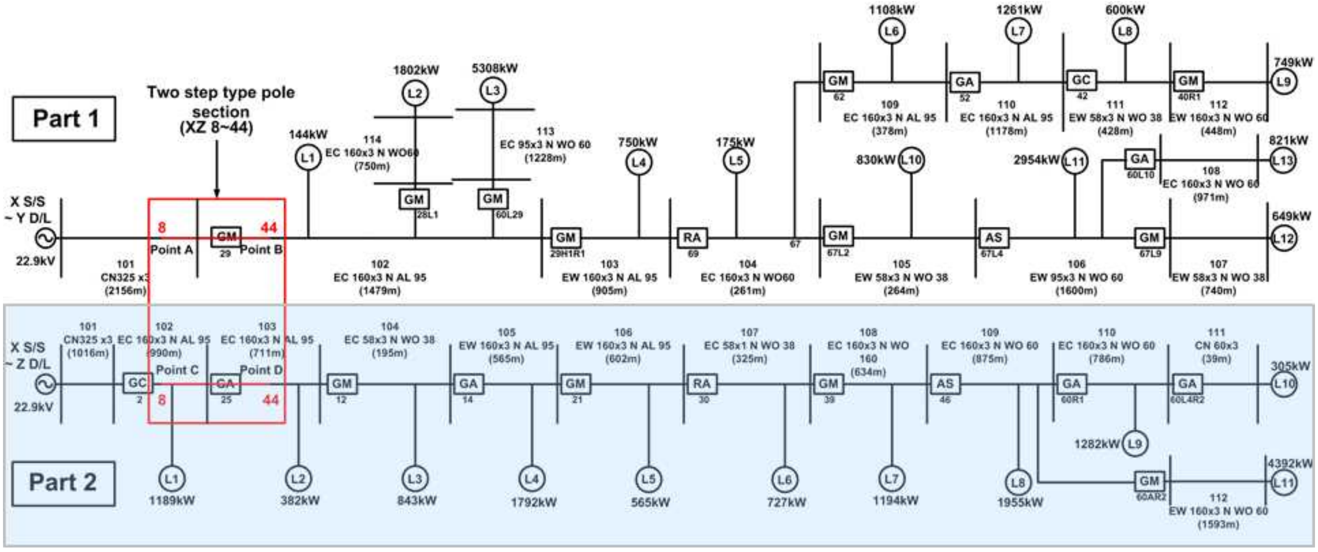


Fig. 16. One part of distribution system of KEPCO in Seoul

penetration level of 10%. Fig. 14 shows the maximum values of u_f at each time and Fig. 15 represents the simulation results with 10%, 15%, and 20% penetration levels.

Figs. 13 and 14 show that the voltage unbalance exceeds the limit at most times. On average, u_f is increased by 0.836% as the penetration level rises in 5% intervals from 10% to 20%.

5. Conclusion

The voltage sag and unbalance incurred by connecting EVs to actual distribution system of KEPCO in one part of Seoul, Republic of Korea were analyzed. EVs are connected to the power system at varying times 11 points. The number of EVs is estimated based on actual traffic volume and average driving time. Actual traffic volume data or the number of EVs should be investigated. EMTP/ATPDraw is used and the results are compared with IEEE standards. While voltage sag exceeds the limit at 20% penetration level, the voltage unbalance exceeds the limit at 10% penetration level. From the results of various penetration levels, it is also shown that voltage unbalance is more frequent than voltage sag. Accordingly, to maintain the supply reliability in the distribution system and to prepare the propagation of EVs, compensation devices and algorithms for reducing the voltage sag and unbalance should be applied.

Acknowledgements

This work was supported by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry and Energy (No. 20124010203300)

References

[1] Korea Smart Grid Institute, “A Research of Charging Infrastructure for Electric Vehicle,” 2010

[2] P. T. Staats, W. M. Grady, A. Arapostathis, R. S. Thallam, “A Statistical Analysis of the Effect of Electric Vehicle Battery Charging on Distribution System Harmonic Voltages,” IEEE Transactions on Power Delivery, Vol. 13, No. 2, April 1998

[3] L. Kelly, A. Rowe, P. Wild, “Analyzing the Impacts of Plug-in Electric Vehicles on Distribution Networks in British Columbia,” Electrical Power & Energy Conference, Otc, 2009

[4] J. Taylor, A. Maitra, M. Alexander, D. Brooks, M. Duvall, “Evaluation of the Impact of Plug-in Electric Vehicle Loading on Distribution System Operations,” Power & Energy Society General Meeting, July, 2009

[5] J. Carlos Gómez, Medhat M. Mocrcos, “Impact of EV Battery Chargers on the Power Quality of Distribution Systems,” IEEE Transactions on Power Delivery, Vol. 18, No. 3 July, 2003

[6] Shengnan Shao, Manisa Pipattanasomporn, Saifur Rahman, “Grid Integration of Electric Vehicles and Demand Response With Customer Choice,” IEEE Transactions on Smart Grid, Vol. 3, No. 1, March, 2012

[7] Arindam Maitra, Jason Taylor, Daniel Brooks, Mark Alexander, Mark Duvall, “Intergrating Plug-in-Electric Vehicles with the Distribution System,” International Conference on Electricity Distribution, June, 2009

[8] Martin Geske, Martin Stötzer, “Modeling and Simulation of Electric Car Penetration in the Distribution Power System-Case Study,” Modern Electric Power Systems, 2010

[9] Kejun Qian, Chengke Zhou, Malcolm Allan, Yue Yuan, “Modeling of Load Demand Due to EV Battery Charging in Distribution Systems,” IEEE Transactions on Power Systems, Vol. 26, No. 2, May, 2011

[10] Jason Taylor, Arindam Maitra, Mark Alexander, Daniel Brooks, Mark Duvall, “Evaluations of Plug-in Electric Vehicle Distribution System Impacts,” Power and Energy Society General Meeting, July, 2010

[11] Kristien Clement, Edwin Haesen, Johan Driesen, “Stochastic Analysis of the Impact of Plug-In Hybrid Electric Vehicles on the Distribution Grid,” International Conference on Electricity Distribution, June, 2009

[12] Kristien Clement-Nyns, Edwin Haesen, Johan Driesen, “The Impact of Charging Plug-In Hybrid Electric Vehicles on a Residential Distribution Grid,” IEEE Transactions on Power Systems, Vol. 25, No. 1, Feb, 2010

[13] Koichiro Shimizu, Taisuke Masuta, Yuyaka Ota, Akihiko Yokoyama, “Load Frequency Control in Power System Using Vehicle-to-Grid System Considering the Customer Convenience of Electric Vehicles,” International Conference on Power System Technology, 2010

[14] P. Papadopoulos, L. M. Cipcigan, N. Jenkins, I. Grau, “Distribution Networks with Electric, Electric Vehicles Chargers Characterization: Load Demand and Harmonic Distortion,” Electrical Power Quality and Utilisation, 2011

[15] João P. Trovão, Paulo G. Pereirinha, Leonor Trovão, Humberto M. Jorge, “Electric Vehicles Chargers Characterization: Load Demand and Harmonic Distortion,” Electrical Power Quality and Utilisation, 2011

[16] Keon-Woo Park, Hun-Chul Seo, Chul-Hwan Kim, Chang-soo Jung, Yeon-Pyo Yoo, Yong-Hoon Lim, “Analysis of the Neutral Current for Two-Step-Type Poles in Distribution Lines,” IEEE Transactions on Power Delivery, Vol. 24, pp1483～1489, 2009

[17] Statics Korea, “http://www.index.go.kr”

[18] Korea Transport Database, “http://www.ktdb.go.kr”

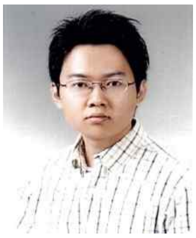
[19] Doo-Ung Kim, Jun-Hyeok Kim, Hyo-Sang Go, Hun-Chul Seo, Chul-Hwan Kim, Eung-sang Kim, “Modeling of Single Phase PWM AC/DC Converter for EV using EMTP/MODELS,” KIEE Summer Conference & General Meeting, July, 2012

[20] Jun-Hyeok Kim, Hyo-Sang Go, Doo-Ung Kim, Hun-Chul Seo, Chul-Hwan Kim, Eung-Sang Kim, “Modeling of Battery for Electric Vehicle Using EMTP/MODELS,” IEEE Vehicle Power and Propulsion Conference, Oct, 2012.

[21] IEEE Power & Energy Society, “IEEE Recommended Practice for Monitoring Electric Power Quality,” 2009

[22] Jan Meyer, Stephan Hahle, Peter Schegner, Carsten Wald, “Impact of electrical car charging on unbalance in public low voltage grids,” Electrical Power Quality and Utilization conference, 2011

Soon-Jeong Lee He received his B.S. degree in Depart ment of Electrical and Electronics Engineering from Kangwon National University, 2010 and M.S. dgree in College of Information and Communication Engineering from Sungkyunkwan University, South Korea, 2012 respectively. At present, he is working for his Ph.D. course in Sungkyunkwan University. His research interests are power quality, power system transient analysis, power system protection and electric vehicle.



Jun-Hyeok Kim He received B.S degree in School of Electrical an d Computer Engineering from Sungkyunkwan University, 2012. At present, he is working on his MS course in Sungkyunkwan University. His research interests include power system transients, protection and stability with electric vehicle.

Doo-Ung Kim He received B.S degree in School of Electrical and Computer Engineering from Sungkyunkwan University, 2012. At present, he is working on his MS course in Sungkyunkwan University. His research interests include power system transients, DC distribution system and electric vehicle.

Hyo-Sang Go He received his B.S in School of Department of Physics from Chungbuk National University, Korea, 20 10. At present, he is working on his MS course in Sungkyunkwan University. His main research interests are power system transients, protection and power quality.

Chul-Hwan Kim He received his B.S. and M.S. degrees in Electrical Engineering from Sungkyunkwan University, South Korea, 1982 and 1984, respectively. He received a Ph.D. degree in Electrical Engineering from Sungkyunkwan University in 1990. In 1990 he joined Cheju National University, Cheju, South Korea, as a full-time Lecturer. He has been a visiting academic at the University of BATH, UK, in 1996, 1998, and 1999. Since March 1992, he has been a professor in the College of Information and Communication Engineering, Sungkyunkwan University, South Korea. His research interests include power system protection, artificial intelligence application for protection and control, the modelling/protection of underground cable and EMTP software.

Eung-Sang Kim He received B.S degree in and M.S degrees in Electrical Engineering from Seoul National University of Science & Technology, 1988. He received his M.S and Ph.D. degree in Electrical Engineering from Soongsil University, 1991, 1997 respectively. At present, he is working at KERI. His research interests include modeling and analyzing of distributed generation system, design, control and analysis of micro-grid system.

Seul-Ki Kim He received B.S and M.S degrees in Electrical and Electronics Engineering from Korea University, 1998, 2000 respectively. He received his Ph.D. degree in Electrical and Electronics Engineering from Korea University, 2010. At present, he is working at KERI. His research interests include modeling and analyzing of distributed generation system, design, control and analysis of micro-grid system.