POWER QUALITY ASSESSMENT IN DISTRIBUTION SYSTEMS EMBEDDED WITH ELECTRIC VEHICLES AND ITS ENHANCEMENT BY OPTIMAL CHARGING

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ABSTRACT

In this paper, the impact of electric vehicles (EVs) on power quality in distribution networks is analyzed. The impacts of EVs on power quality indices such as undervoltage or overvoltage are discussed. As the EVs do not follow a deterministic pattern for their charge/discharge duties, hence a probabilistic analysis is applied to quantify their impacts on power quality. Moreover, the overload and unbalance of distribution transformers are assessed for different EV types and penetration level. It is indicated that the limits for undervoltage/overvoltage is not the same for different countries, so the impact of EVs on voltage quality depends on the set values. Hosting capacity is a term used for the acceptable amount of Distributed Generation (DG) in distribution feeders; this definition is extended for taking into account the fleet of EVs that could be connected to a feeder without violating the power quality indices.

INTRODUCTION

The interaction between the electrical grid and the connected consumers is interpreted as power quality with two main categories: voltage quality and current quality. Voltage quality is referred to the effects that the supply voltage have on the electrical components that connected to the grid, while current quality concerns with the impact of the electric components on the supply grid [1]. Voltage sags and interruptions are the most salient features in power quality. New power electronic devices made it possible to have a bilateral flow between the consumers and the producers, sometimes referred to as consumer/prosumers. Electric Vehicles (EVs) with the V2G functionality establishes a two-way power flow between the grid and the EV. So, the impact of this technology with its progressive penetration level on the power quality is of main concern. Although power quality is a mature concept in conventional power systems, it becomes somewhat more complicated when considering the EVs. It is worth mentioning that power quality was previously divided into two main classes: voltage quality and current quality. Another aspect could be added when considering EVs, that is the impact of connection/disconnection of a fleet of EVs using the V2G functionality. In other words, the charging/discharging of a fleet of EVs could be affected by the voltage disturbances.

Ref. [2] is a good work analyzing the impact of EVs on power quality in distribution systems. Under/overvoltage and voltage imbalance are investigated in [2] by probabilistic methods using Monte Carlo. It is assumed that the EVs are randomly connected or disconnected; so their impacts on the power quality indices are evaluated. Moreover, the overload and unbalance of distribution transformers that supply the feeders with the EVs are studied. The effect of EV types and penetration level is analyzed. In this paper, we investigate on the following cases:

- The study in [2] is based on American National Standard Institute (ANSI) C84.1 standard, which defines the voltage deviations of the service voltage to be ±5% of the nominal voltage. These limits are mainly applicable in North America. However, there are different limits in other countries, for example in Europe the EN50160 standard [3] sets the supply voltage within ±10% of the nominal voltage. It means that the impact of EVs on voltage quality especially undervoltage/overvoltage is substantially correlated with the set limits.
- Distribution structure is of great importance when evaluating the power quality of consumers. For example, the study in [2] is based on center-tapped distribution transformers when the load unbalance on distribution system is analyzed; this is according to the American distribution system topology, while the European distribution configuration is different.
- It is indicated that probabilistically extracting the driving patterns of the drivers would help to manage the charging of EVs in a controlled manner, so prohibiting the unwanted deviations of the voltage from the permissive limits.
- Optimal charging is proposed as an efficient strategy to cope with the degradation of power quality. As charge upon arrival would lead to an uncontrolled charging, it means that the aggregator charges each connected EV with maximum possible charging rate as soon as EV arrives, but in the optimization process the desired constraints such as keeping the voltage magnitudes within the specified range and alleviating the unbalance operation of the distribution transformers are satisfied. In other words, a kind of adaptive optimal charging is applied in order to enhance the power quality indices.
- As stochastic nature of EVs may have detrimental impacts on power quality indices and even loss of life of the distribution transformers; optimal charging

of EVs using communication infrastructure could mitigate the undesired operation of the distribution feeder and would enhance the power quality of the distribution system.

- Hosting capacity as explained in [4] is used for the permissible value of Distributed Generation (DG) in a distribution feeder without any improvement and extra investment. In this paper, this concept is extended for taking into account a fleet of EVs that could be connected to a feeder without violating the power quality indices

VOLTAGE QUALITY

The European standard EN 51060 defines the voltage characteristics of the customers under normal operating conditions at low-voltage (LV) or medium-voltage (MV) levels. It is indicated that the supply voltage should not exceed ±10% of the nominal voltage. This definition is further complemented by specifying some measurement hints. Firstly, 99% of the 10 min mean rms values of the supply voltage shall be within the limits as a minimum requirement; and secondly none of the 10 min mean rms values of the supply voltage shall be outside the limits ±15% of the nominal voltage. It is worth noting that some other European countries have set more strict regulations for the supply voltage of the LV and MV customers [4].

France

In France, the LV and MV customers should be supplied by a voltage within 10% of the nominal voltage. However, the MV customers can sign a contract to have a voltage within 5% of a declared voltage, which should be within 5% of the nominal voltage. The design limits for LV networks used by EDF are 90% and 106% [5].

Hungary

In Hungary, LV customers should be supplied with a voltage that 95% of its 10 min rms should be within 7.5% of the nominal voltage. Moreover, 100% of the 10 min rms voltages should be within 10% and also 100% of the 1 min rms voltages should be within 15%.

Norway

In Norway, it is required to have 100% of the 1 min rms voltages to be within 10% of the nominal voltage.

Spain

In Spain, it is stated that 95% of the 10 min rms voltages should be within 7% of the nominal voltage.

Japan

In Japan, the voltage should be 101±6V at LV level, because LV feeders are very short. It is worth saying that the MV voltage range is even more narrow than LV voltage.

Canada

In Canada the lower band is 94% and the higher is106% of the nominal voltage [6].

USA

In USA, the MV supply voltage should be within 95–105% [7], meanwhile, the network operators use their own regulations provided that not to violate these limits. For example, some set the difference between the highest and the lowest voltage to 8%; while some other set to a lower band say ±6% [4] and [8]. According to some investigation as explained in [9], the upper voltage limit is 104 to 106% and the lower limit is from 93 to 102%. The wide range in the lower limit is mainly due to the different lengths of the LV feeders.

UK

In UK, the voltage limits for MV feeders are set as 94–106% [7].

Brazil

In Brazil, the LV customers should be supplied by a voltage within 86–106% with the preferred range of 91–105%. For MV customers, the acceptable range is 90–105% with the preferred range 93–105% [10].

Sweden

In Sweden, the limits for voltage levels up to 24 kV are set as 95–105% of nominal voltage and for more than 24 kV up to 145 kV the limits are 90–110% [4]. These values should not be violated in 95% of times at minimum.

HOSTING CAPACITY WITH EVS

Power quality indices are affected by introduction of EVs, due to their charging as a sink and their V2G functionality as a source. Improvement or deterioration of voltage quality indices depends on the performance of the distribution system after connection of a fleet of EVs. As mentioned in the previous section, a degradation of the power quality is not a great issue as long as the resulting quality is within the permissible range. In other words, the deterioration of the power quality indices greatly depends on the set limits of the supply voltage. Hence, the power quality may be preserved in one country, while with exact the same conditions would be deteriorated in another one. Needless to say, the power quality performance is degraded with the increasing of the penetration level of EVs. When the number of EVs is small on a specified node, the voltage quality indices are kept within limits; but for larger number of EVs the indices tend to violate the limits.

The hosting capacity approach explained in [4] is extended to consider the penetration of EVs as follows:

- Voltage quality limits are selected at first based on the values mentioned in the previous section;

- The power quality indices are calculated based on the penetration level of the EVs,
- The hosting capacity is determined by calculating the amount of EVs that could be connected without violating the permissible voltage limits.

SIMULATION RESULTS

In order to simulate the hosting capacity approach, a sample power system is selected as in [11]-[12]. The IEEE 30 node system is selected as the MV distribution system, which its nominal voltage is 23 kV. Then according to [11], several LV residential feeders are set on the selected feeders. Each LV feeder has 19 nodes to simulate the customers with EVs; so the number of nodes is increased to 448. Then EVs with different types and charging/discharging rates are connected to selected nodes in order to check the voltage deviation from the determined rates. In this way, the hosting capacity of the EVs on a selected feeder could be determined.
Figure 1 shows the one-line diagram of the MV grid and Figure 2 shows the corresponding LV grid. LV grids are inserted on 22 MV nodes. The MV sample system is a 23 kV distribution system with 30 sections and six laterals. The charging modes of EVs are considered as a load, while the EVs in V2G mode are considered as negative loads to simulate the discharging mode.
The LV grids are considered on nodes: 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29 and 30.

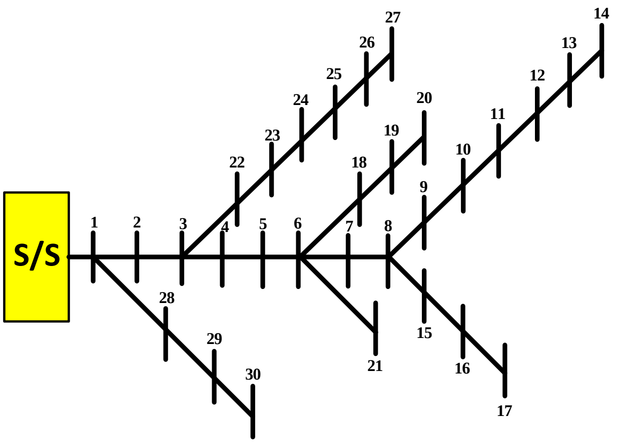

Figure 1: Sample system used for Simulations (IEEE 30 bus)

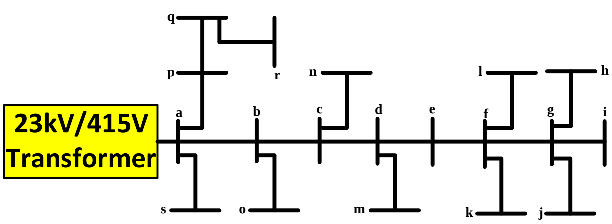

Figure 2: LV feeder with the connected EVs

Each EV is considered as a 4 kW load that should be connected for 2 hours to the grid in order to be fully charged starting at a moderate SOC, i.e., 40%.
Table 1 shows the deterioration of the voltage quality by increasing the penetration level of the EVs. The concept of hosting capacity can be best understood by the specified limits.

Table 1: Voltage Quality Preservation Based on Hosting Capacity Approach for bus 9

Bus Name	No EV P /kW	No EV Q /kvar	No EV |V| /p.u.	With EV P /kW	With EV Q /kvar	With EV |V| /p.u.	With EV EV No.
a	2	1	0.94	2	1	0.94	
b	2	1	0.93	6	1	0.93	2
c	2	1	0.93	2	1	0.92	
d	2	1	0.92	2	1	0.91	
e	2	1	0.91	2	1	0.91	
f	2	1	0.91	2	1	0.90	
g	2	1	0.90	2	1	0.90	
h	2	1	0.90	2	1	0.90	
i	2	1	0.90	2	1	0.90	
j	2	1	0.90	2	1	0.90	
k	2	1	0.90	2	1	0.90	
l	2	1	0.91	2	1	0.90	
m	2	1	0.92	2	1	0.91	
n	2	1	0.92	2	1	0.91	
o	2	1	0.93	6	1	0.91	1
p	2	1	0.94	2	1	0.93	
q	2	1	0.93	6	1	0.91	2
r	2	1	0.93	2	1	0.91	
s	2	1	0.94	2	1	0.94	

If two EVs are connected to bus *o*, then the voltage drops to 0.88 p.u., which means that the permissible hosting capacity is violated by the existing structure. It is clear if we strengthen the feeder, the hosting capacity would be increased. It is worth saying that the lower limit for voltage is -10% in the case studied in Table 1. If the undervoltage limit is set at -5%, it means that the sample grid is out of range even without any EV. The distribution transformer is 23 kV/0.415 kV and 200 kVA. With the data of Table 1 and with the indicated number of EVs, its loading is 37%. Needless to say that the normal loading of the sample feeder is not constant and it follows a consumption pattern with the determined peak and trough, so the selected case in Table 1 is for the peak load as the voltages are stressed.
Table 2 shows the same scenario as in Table 1 but with other number of EVs. In this case, the hosting capacity is not of main concern, and the analysis is solely concentrated on the amount of voltage deviation from the permissible ranges. As can be deduced from Table 2, when high penetration of EVs is selected, then most of the buses fall outside the undervoltage range. Meanwhile by using a moderate penetration level, the status is relatively improved and only one bus has the voltage magnitude less than 0.8 p.u. However, this number is 7 for the previous case.

Table 2: Voltage Quality Deterioration by Increasing the Penetration Level of EVs

Bus Name	High Penetration Level				Medium Penetration Level		
	P /kW	Q /kvar	|V| /p.u.	EV No.	P /kW	|V| /p.u.	EV No.
a	2	1	0.94		2	0.94	
b	12	1	0.90	3	10	0.91	2
c	2	1	0.87		2	0.88	
d	12	1	0.84	3	10	0.85	2
e	2	1	0.82		2	0.84	
f	12	1	0.79	3	10	0.82	2
g	12	1	0.78	3	10	0.80	2
h	12	1	0.78	3	10	0.80	2
i	2	1	0.77		2	0.80	
j	12	1	0.76	3	10	0.79	2
k	12	1	0.77	3	10	0.80	2
l	2	1	0.79		2	0.82	
m	12	1	0.83	3	10	0.84	2
n	12	1	0.86	3	10	0.87	2
o	12	1	0.88	3	10	0.92	2
p	2	1	0.91		2	0.92	
q	12	1	0.90	3	10	0.91	2
r	12	1	0.87	3	10	0.88	2
s	12	1	0.93	3	10	0.94	2

CONCLUSIONS

In this paper we have shown the impact of EVs on the voltage quality. An approach that is applicable to the penetration level of DGs is extended here for taking into account the number of EVs that could be connected to a distribution feeder without violating the voltage quality performance indices. It is shown that a limited number of EVs could be connected to the distribution system during peak hours, as the performance index is violated very fast. However, during low-load periods, the hosting capacity could be increased, because the nodes have more potential to accept new loads as EVs without stressing the power quality indices. This analysis indicate that for keeping the power quality within the specified limits, it is necessary to consider optimal charging and manage the load inserted by the EVs, otherwise, the voltage quality is compensated. Another point that could be beneficial in this regard is the V2G functionality, as the EVs could be considered as negative loads, so they help to reduce the load on the related nodes, hence the voltage drop is mitigated accordingly.

REFERENCES

[1] M. H. J. Bollen, 2000, *Understanding Power Quality Problems: Voltage Sags and Interruptions*, IEEE Press, New York, 2000.

[2] M. K. Gray, W. G. Morsi, 2014, "Power Quality Assessment in Distribution Systems Embedded With Plug-In Hybrid and Battery Electric Vehicles," *IEEE Trans. on Power Systems*, Early Access.

[3] *Voltage Characteristics of Electricity Supplied by Public Distribution Systems*, 1999, EN50160, CENELEC: European Committee for Electro Technical Standardization, Brussels, Belgium.

[4] M. Bollen, F. Hassan, 2011, "*Integration of Distributed Generation in the Power System*," IEEE Press, USA.

[5] P. Bousseau, E. Monnot, G. Malarange, and O. Gonbeau, 2007, "Distributed generation contribution to voltage control," In *International Conference on Electricity Distribution (CIRED)*, Vienna.

[6] J. Wong, P. Baroutis, R. Chadha, R. Iravani, M. Graovac, and X. Wang, 2008, "A methodology for evaluation of permissible depth of penetration of distributed generation in urban distribution systems," In *IEEE Power Engineering Society General Meeting*, Pittsburgh, PA, USA.

[7] M. R. Patel, 2002, "*Wind and Solar Power Systems*," CRC Press, Boca Rotan, FL, USA.

[8] J. J. Burke, 1994, "*Power Distribution Engineering: Fundamentals and Applications*," Marcel Dekker, New York.

[9] H. L. Willis. *Power Distribution Planning Reference Book*, Marcel Dekker, New York, 1997.

[10] A. Barin, L.F. Pozzatti, C.G. Carvalho, L.N. Canha, R.Q. Machado, A.R. Abaide, C. Fernandes, and F.A. Farett, 2007, "Analysis of the impact of distributed generation sources on the operational characteristics of the distribution systems for planning studies," In *International Conference on Electricity Distribution (CIRED)*, Vienna.

[11] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. S. Masoum, 2011, "Real-Time Coordination of Plug-In Electric Vehicle Charging in Smart Grids to Minimize Power Losses and Improve Voltage Profile," *IEEE Trans. on Smart Grid*, vol. 2, no. 3, pp. 456-467.

[12] C. Civanlar, J. J. Grainger, 1985, "Volt/Var Control on Distribution Systems with Lateral Branches Using Shunt Capacitors and Voltage Regulators, Part III: The Numerical Results," *IEEE Trans. on PAS*, vol. PAS-104, no. 11, pp. 3291-3297.