EFFECTS OF PHEVs IN POWER DISTRIBUTION SYSTEMS: REVIEWS AND ANALYSES

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ABSTRACT

This paper deals with the analysis of the impacts of plug-in hybrid electric vehicles (PHEVs) on the power system, with focus on the low voltage power distribution system. First a review of the technical challenges in the power system due to the mass introduction of PHEVs in the transporation sector is given. Then the paper shows on an analysis of the overloading effects of PHEVs on the distribution system with normal charging and quick charging of PHEVs for an IEEE 13-node distribution test system using power flow analysis. The results of the study show that introduction of PHEVs in the transportation sector will lead to overloading of distribution system and cause voltage problems at the end-users. The paper also analyzes the effects of PHEVs in the transmission system, using the Nordic 32-bus test system. The study results showed that the overloading problem is not prominent. However, one interesting and important result is that PHEVs may lead to overvoltages in some buses in the transmission system which requires the voltage control measures. PHEVs would also lead to increased number of network violations in the contingency analysis.

INTRODUCTION

High penetration of plug-in hybrid electric vehicles (PHEVs) in the transportation sector will likely be envisioned by the transportation authority as well as energy authority in many parts of the world, e.g., European countries, Japan, and the USA. The benefits from replacing the conventional internal combustion vehicles by the PHEVs are the subjects of many current research and mass-media because the transport sector is one of the largest and fastest growing contributors to energy demand, urban air pollution, and greenhouse gases (GHGs) [1]. The possibility to reduce the dependency on oil consumption by the transportation sector and the possibility to reduce harmful environmental emissions, e.g., CO_2, SO_x, and NO_x by ways of improved conversion efficiency through PHEVs are the key socio-economical and environmental benefits. Given the said benefits, critics have warned that the vehicles could put too much pressure on already strained power grids. The concern is that plug-ins may not appear to be a good way to reduce gasoline consumption, because if they become popular, and millions of car owners recharged their cars at three in the afternoon on a hot day, it would crash the grid. Specially, uncontrolled charging can lead to grid problem on the local scale [2].

The organization of the paper is as follows: The next section will provide a brief overview and discussions on the effects of PHEVs on the power system with focus on the low voltage power distribution system. The power flow analysis in the IEEE test distribution system when assuming certain levels of PHEVs penetration levels is presented in the following section. The effects on PHEVs on the meshed transmission network are shown in the following section. The grid support effects of PHEVs are also analyzed through the contingency analysis of the transmission system. Finally, conclusions and remarks are made in the last section.

PHEVS IN THE POWER DISTRIBUTION SYTEM: A BRIEF REVIEW

As highlighted in the previous section, PHEVs have the potentials to contribute to reduce the environmental emissions from the transportation sector. However, it will likely pose new challenges in the power system, especially in the power distribution system where the vehicles are directly connected to. This section will highlight those challenges and effects. Other detailed information about the current technology and charging requirement of PHEVs will be presented in the next Section.

Fig. 1 shows the effects of PHEVs on the power systems, and categorizes the problems at different levels, i.e., at system level, distribution system level, and transmission system level. The key question being asked today is how the power system sees the increase in its total loads when high level of PHEVs will be used in the near future. This is largely dependent on the charging habits which will be practiced by the users of PHEVs. As shown in Fig. 1, even though the PHEVs are connected in low voltage distribution system, they also have large effects on the generation system and transmission system levels.

If the vehicle users are free to charge their cars anytime they want (uncontrolled charging), one can easily say that they will plug in at the end of the day, which corresponds with peak loads. In this case, PHEV increases the system peak loads which require additional generation (and transmission) capacity. A new dimension of peak load capacity for the power system might be required if the charging of PHEV is left uncontrolled. On the other hand, if controlled charging is used, which means that the utility controls charging between, for example, 10:00 pm and 07:00 am. In this case the system load profile will be improved in a way similar to the effect of "valley filling" demand-side management measure, meaning that the system utilization can be improved.

PHEVs would result in the changes in the system load shapes which in turn would result in changes in power generation mixes, changes in electricity prices as well as the CO_2 emission level from power production.

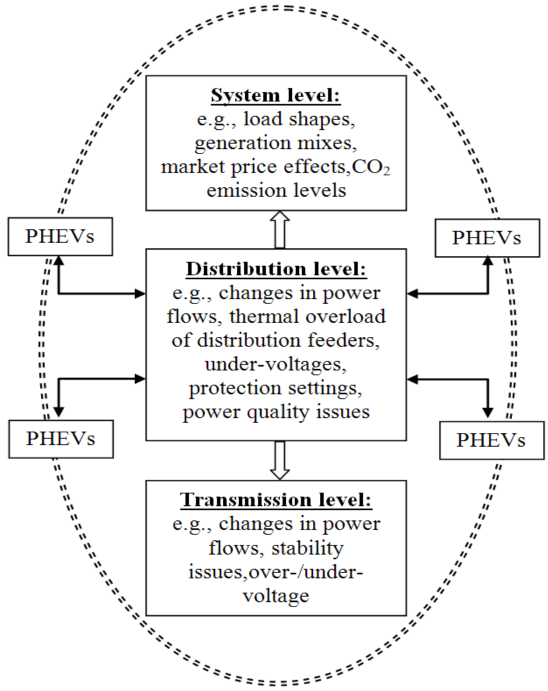

Fig. 1: Overview of possible effects of PHEVs on power systems

PHEVs are connected to the power systems at low voltage power distribution system level, *i.e.,* at the end-user sides. Potential problems with distribution system include the overloading of distribution feeders when many PHEVs charge at the same time and at the same area. Overloading of feeders are normally associated also with the large voltage drop over the feeders which makes the voltage at end-users lower than minimum acceptable voltage. This will lead to necessity to upgrade substations earlier than expected because of charging, but there could also be the need to change or modify the existing protection systems. Normally, in distribution system, the power flow is normally uni-directional from medium voltage (MV) grid to low voltage (LV) grid. However, when PHEVs functions as the energy storage and inject the current into the grid, which is known as vehicle-to-grid (V2G) [3], bidirectional power flow would take place within a certain area. Therefore, setting of relays in the LV and MV level may have to be changed because they might trip under normal working conditions when power should be provided from the LV to the MV level. Depending on the design of charging system, either it is one-phase charging or three-phase charging, the load unbalance might occur with the one-phase charging if the distributions of PHEVs between the phases are unequal. A more comprehensive review of the effects of PHEVs on the power systems can be found in [4].

The above mentioned problems, however, are dependent on the characteristics of the grid in question, number of PHEVs in the areas, types of charging, time of charging, and so on. More specific research would have to be done in order to answer specific questions related to each grid. The next section will provide a specific analysis of the effects of PHEVs on the IEEE Test Distribution System. The effects will be focused on the overloadings of the distribution feeders and the voltage problems at the customers' positions.

ANALYSIS OF PHEVS IN THE DISTRIBUTION SYSTEM

Description of the IEEE 13-Node Test Distribution System

Fig. 1 shows the single line diagram of the IEEE 13-node distribution test system [5].

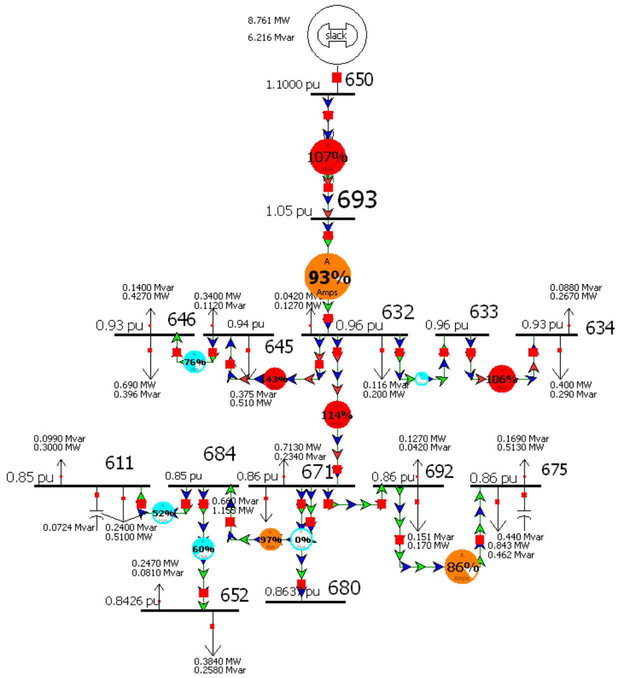

Fig. 2: IEEE 13-node distribution test system

The system is appropriately modified to represent the power distribution system for a small residential area. The power flow analysis for this system is done using the PowerWorld Simulator [6]. To model PHEVs, 9 loads have been added to the system, showing with the up arrows in Fig. 2. In this network, the maximum load is 4.82 MW at 6:00 PM and minimum load is 3.02 MW at 3:00 AM. It is assumed that this network for the residential area. According to [7] and [8], each 25 kVA distribution feeder can approximately serve 4 houses and it can be assumed that every 4 houses will own 2 PHEVs. From this assumption, the number of PHEVs at each bus will be calculated as in (1):

$$N_{PHEV} = \frac{S_{max}}{25} \times 2 \qquad (1)$$

where,

N_{PHEV}: Estimated number of PHEVs at each bus

S_{max}: Maximum supplied kVA at each bus

Chevy Volt is taken as the model of PHEVs used in this study. Chevy Volt is equipped with a Lithium-Ion battery [8]-[9]. In principle, there are two methods of charging: *normal charging* and *quick charging*. According to [8], the Lithium-Ion battery of a Chevy Volt car draws 1.45 kW in 6 to 6.5 hours for normal charging and draws 5.8 kW in 1.7 hours for quick charging. The efficiency of 87% is assumed for the whole charging process [7]. The following four different cases have been considered in this study:

1. *Business as usual (BAU):* System at peak load without PHEVs.
2. *Normal charging, peak load:* BAU with PHEVs normal charging
3. *Quick charging, peak load:* BAU with PHEVs quick charging
4. *Quick charging, min load:* System at min load with PHEVs quick charging

Case study results and discussions

Tables 1 shows the bus voltages of four different scenarios described above. In the BAU case, all the bus voltages are within the acceptable limits of ±10% of nominal voltage. In the normal charging case, there were no violations in voltages at all the buses. However, in the quick charging at peak load scenarios, there are 50% of buses with voltage below the minimum acceptable level (shown with underlined numbers in Table 1). It is because that quick charging draws much higher current/power than the normal charging. The voltages at different buses in the case of quick charging at max load are also shown in Fig. 2 above. If quick charging can be controlled and done during the min load period, there were no problem of voltage violations in the system as shown in Table 1.

Table 1: Buses voltages in per unit for different scenarios

Bus #	BAU	Normal charging, peak load	Quick charging, peak load	Quick charging, min load
611	0.97	0.95	**0.85**	0.96
632	1.03	1.01	0.96	1.02
633	1.03	1.01	0.96	1.02
634	1.00	0.99	0.93	1.00
645	1.01	1.00	0.94	1.00
646	1.01	0.99	0.93	1.00
650	1.10	1.10	1.10	1.10
652	0.96	0.94	**0.84**	0.95
671	0.97	0.95	**0.86**	0.97
675	0.97	0.95	**0.86**	0.96
680	0.97	0.95	**0.86**	0.97
684	0.97	0.95	**0.85**	0.96
692	0.97	0.95	**0.86**	0.97
693	1.07	1.07	1.05	1.07

Table 2 shows the line loadings in percentage of rated line capacity. In the BAU and normal charging scenarios, the line loadings are within the maximum limits.

Table 2: Loading of lines as percentage of rated power

From bus	To bus	BAU	Normal charging, peak load	Quick charging, peak load	Quick charging, min load
684	611	32.20	37.10	51.80	39.00
632	633	20.70	23.60	32.60	25.00
632	645	87.50	99.80	**137.80**	**106.00**
632	671	66.20	75.90	**113.70**	80.90
693	632	56.20	64.90	97.50	68.80
633	634	67.20	76.60	**105.80**	81.20
645	646	48.40	55.20	75.70	58.60
650	693	60.50	70.10	**107.40**	74.20
684	652	38.80	44.10	60.40	45.70
671	680	0.00	0.00	0.00	0.00
671	684	60.00	69.00	96.60	72.30
671	692	0.00	0.00	0.00	0.00
675	692	45.60	52.20	73.90	57.50

When PHEVs are charged with quick charging during peak load period, there are four lines (i.e., lines *632-645, 632-671, 633-634, and 650-693*) overloaded as can be seen with the red circles in Fig. 2, meaning that the network is under the stress condition. With quick charging but under the min load condition, the stress condition for the line overloading is reduced with only one line overloading (i.e., line *632-645*).

Fig. 3 shows total system active power losses for different scenarios. System loss increases dramatically when PHEVs have been connected for quick charging at peak load as compared to the BAU scenario. Total system losses at normal charging at peak load and quick charging at minimum load are found to be the same.

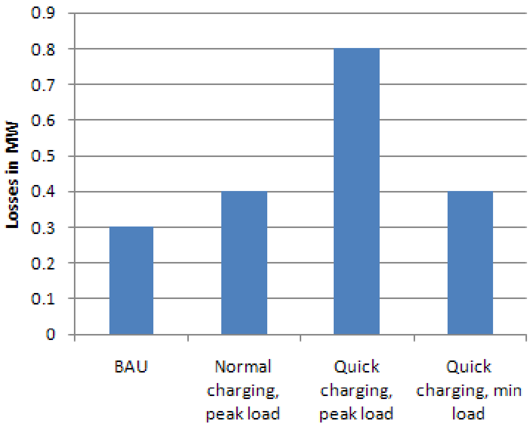

Fig. 3: Total system active power losses

As shown in Fig. 1 and discussed in previous section, PHEVs are connected directly in the distribution network but they will have potential effects in the meshed transmission network. The following section will present the power flow analysis for the effects of PHEVs on the Nordic 32-bus test system.

ANALYSIS OF PHEVS IN THE MESHED TRANSMISSION NETWORK

The Description of Nordic 32-Bus System

Nordic 32-bus system is used in this study to represent different scenarios with PHEVs. The single-line diagram of this system is shown in Fig. 4. The detailed information about the system can be found in [10]. In this study, 22 loads have been added to the network to represent PHEVs load. The PHEVs penetration has been considered as percent of total load of each bus with load connected in the system. Batteries have been modelled with negative loads when they are injecting power into the grid (i.e, in V2G mode). To analyse the effect of the PHEVs on the network, the following 3 cases have been considered:

1. *Business as usual (BAU):* The system without PHEVs
2. *10% penetration:* The BAU with 10% load as PHEVs at each bus with load.
3. *10% penetration V2G:* The BAU with 10% load as V2G at each bus with load.

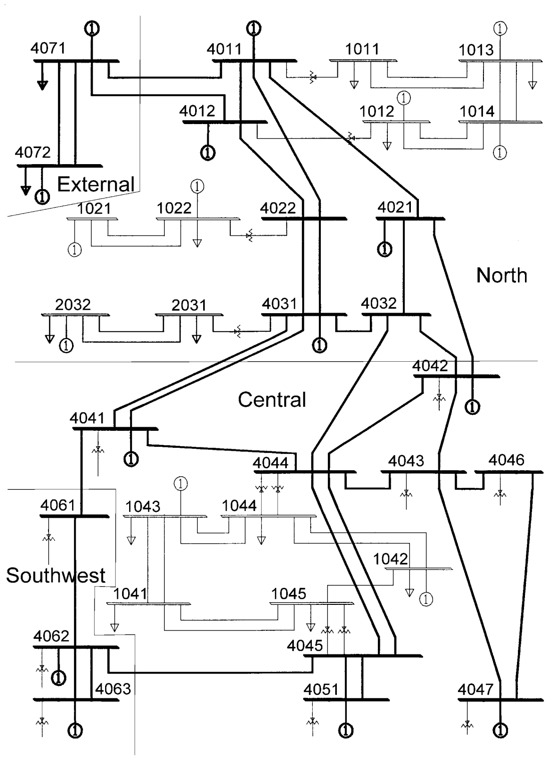

Fig. 4: Single line diagram of Nordic 32-bus system

Case study results and discussions

Introducing the penetration of 10 percent will dramatically change the voltage profile of the transmission network. As shown in Table 3, when adding PHEVs penetration of 10% to the system, there would be 26 buses in the system with voltages level over the maximum allowable limit. This is quite interesting since it is normally expected that the voltage is decreased when the load is increased. However, this can always be true with the radial system like in the distribution network. In the meshed network like the Nordic 32-bus system, when PHEVs loads are added, the power flows over the system have changed quite significantly, especially the reactive power flow. This makes the voltages magnitudes in southern part of the system increased. In this simulation study, the increase in PHEVs load can be managed by existing generators for both active and reactive power.

Table 3: Case study results for 3 cases

	No of over voltage buses	No of under voltage buses	No of violations in N-1 contingency analysis
BAU	0	0	307 violations and 9 unsolvable contingencies
10% penetration of PHEVs	26	1	1257 violations and 16 unsolvable contingencies
with 10% penetration of V2G	1	6	587 violations and 15 unsolvable contingencies

Another important result from this study is that the number of violations (mainly in bus voltages) in N-1 contingency analysis of the system increases dramatically with 10% penetration of PHEVs, indicating that power system security must be properly studied with mass introduction of PHEVs. With V2G, the number of violations is reduced as compared to the 10% peneration of PHEVs case.

CONCLUSIONS

This paper summarizes possible key effects of introduction of PHEVs in the power system. Results from the studies show that problems with low voltage distribution networks with PHEVs are mainly related to overloadings of distribution feeders, and under voltages in end-users' locations in the case of quick charging during peak load period. If normal charging is to be used, the system would be able to support the PHEVs without overloading and under voltage problems. In the transmission level, an interesting phenomena with regard to the bus voltage level is observed for the Nordic 32-bus system. That is when PHEVs equally distributed in the system, the voltage in the system might increase, showing the need for voltage regulation measures. However, this could not be concluded for every system since this is system-dependent. An other problem with meshed transmission networks is typically that the level of security could be affected when more PHEVs are plugged into the network.

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