Assessing the Impact of Plug-in Hybrid Electric Vehicles on Distribution Network Operations Using Time-Series Distribution Power Flow Analysis

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***Abstract*— Plug-in Hybrid Electric Vehicles (PGEVs) are fast becoming an effective alternative to the fossil-fuel based vehicles and its penetration in the consumer market is poised to increase at a faster rate in the coming decades. However, the uncontrolled charging-discharging of PHEVs – given its increasing use – will pose a formidable challenge to the Distribution System Operators (DSOs). It can both be seen as an opportunity in terms of dispatchable energy storage as well as a threat in the form of uncontrolled factor raising the maximum real power demand. DSOs' other concerns may include the impact of PHEVs on overall feeder voltage profile, energy losses, power factor – reactive power management and switching operations of Voltage Regulators (VRs), transformers with Line Tap Changers (LTCs) and Shunt Capacitors (SCs). In order to account for seasonal and diurnal variability and to undertake time-integral studies for losses and switching operations of controllable devices, Time-Series Distribution Power Flow (TS-DPF) analysis is used in this paper for IEEE37 node underground cable-fed network to assess the impact of PHEVs. The results show the realistic annualized effect of PHEVs on voltage profile, energy losses, peak demand at source node and tap changing operations of VRs in a low voltage distribution network.**

Keywords*— Distribution Network Operations; Plug-in Hybrid Electric Vehicle; Time-Series Analysis; Time-Series Distribution Power Flow;

I. INTRODUCTION

It is apparent by now that the shift towards Plug-in Hybrid Electric Vehicles (PHEVs) and Plug-in Electric Vehicles (PEVs) from conventional combustion based vehicles has already began and as per a survey by EPRI, [1], the overall share of PHEVs in US markets may go beyond 60% by 2050 considering only moderate penetration scenario. Along with the technological challenges of developing efficient energy storage systems, emergence of PHEVs and their interactions with electric power distribution networks will also raise concerns regarding the quality and stability of the overall power system, [2]. A typical issue of increasing peak demand with increasing PHEV penetration is analyzed and predicted in [3] with different PHEV penetration levels. The rise in peak demand is analyzed in [3] with IEEE34 node test network where the feeders are assumed to cater to residential loads. The analysis predicts sharp rise in peak demand in winter season when average load is high – due to heating requirements. Urban residential area with high density of loads and rural area with dispersed load are studied for impact investigation of PHEVs on distribution networks in [4]. The results quantify the required investments due to given penetration level of PHEVs. A system level analysis is presented in [5] to estimate the load profiling with PHEVs. This analysis has shown the change and rise in overall demand profile due to different penetration scenarios considered for PHEVs; whereas effect of randomized charging is analyzed in [6] with a proposal for coordinated charging for inclusion of more number of PHEVs.

It should be noted that (a) all these attempts have considered several different scenarios including different penetration levels for PHEVs and seasonal variations in load profiles, (b) typically residential networks are considered and (c) the analysis has been restricted to single line equivalent models. However, analyses with sequential time simulations over a period of one or more year with time-integral studies for losses, switching operations, real and reactive power management etc. are not found in published literature. Also, the community level low voltage distribution networks in university campuses, institutional premise, hospitals – where PHEV density can be justifiably much higher than elsewhere – are not considered.

In this paper, attempt is made to summarize the effect of increasing PHEV penetration on low voltage urban distribution networks by applying TS-DPF approach over a period of one year with actual load profiles and hypothetical PHEV penetration and their charging cycles. The parameters analyzed include feeder voltage profile, voltage limit violations, frequency of such occurrences, effect on number of Tap Changing Operations (TCOs) of Voltage Regulator (VR) and/or LTCs, energy losses, and peak demand. The exercise is undertaken with all the system components modeled in 3-phase domain to represent the real life unbalance distribution network.

Rest of the paper is organized as follows: next section elaborates the need of TS-DPF approach and its application in the present exercise, details of modeling and data sets are given

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in section III which is followed by exhaustive results in section IV. Section V is the last section with conclusion, limitations of this analysis and further scope for future work

II. TS-DPF APPROACH

Need and significance of Sequential Time Simulations (STS) is elaborated in [7] by R F Arritt and R C Duggan. The STS approach is essential to analyze the diurnal variations over a period of one year in order to estimate the impact of highly intermittent and atmosphere dependent Renewable Energy Sources (RES). The time-interval at which the simulations are iterated depends on the applications. Certain protection and control related applications may need simulations at every second whereas steady state operations may go with per-minute to per-hour simulation intervals, [7]. In the present case, the effect of PHEVs on steady state operations of distribution networks is under consideration and thus a time interval of 15 minutes is selected. However, it should be noted that with this time interval, the results of TCOs are always conservative. Nonetheless, with availability of high resolution data, the same approach would produce all the more reliable results. Need to sensibly use the intelligent techniques in solving the problems associated with active distribution networks is emphasized in [8] where judicious selection of time-intervals for STS is also considered a crucial decision.

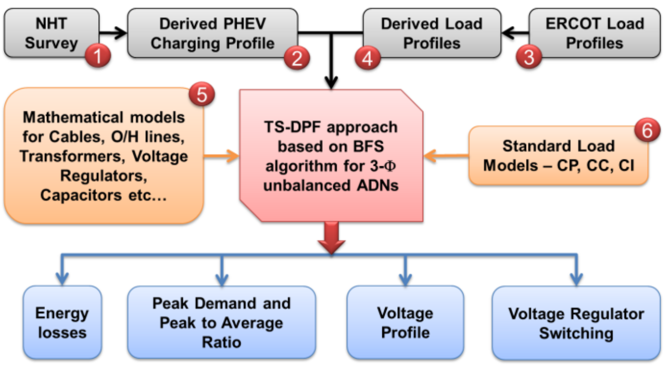

Fig. 1 TS-DPF approach with data-sets and modeling details

The details of TS-DPF approach are shown in the block diagram of Fig. 1. Block-1 is the data sets available from [9] in raw form. The same is used to derive the PHEV charging profiles (block-2, Fig. 1) for the year 2012 at three nodes in IEEE 37 node network. The ERCOT annual load profiles available in [10] are used to derive node-wise demand at the interval of 15 minutes for the year 2012 – shown by blocks 3 and 4 in Fig. 1. Modeling details are provided in the following section.

III. TEST NETWORK – MODELING & DATA SETS

IEEE37 node network is a highly unbalanced but moderately loaded network with underground cables. The network, with longest cable section of 1850 ft, is spread in a relatively small geographical area. Its operating voltage level is 4.8 kV and has one voltage regulator near substation node. This network can easily be assumed to be serving a small community with mixed type of loads – commercial and residential. It can also represent a university campus or institute premise with residential blocks. In this paper, the network is assumed to be a campus with in-house fleet of PHEVs and 2 charging stations. Modeling of network components – such as cables, transformer and VR - is done based on 3-phase modeling given in [11], represented by block 5 in Fig. 1. The Backward-Forward Sweep (BFS) algorithm is used for distribution power flow for 3-phase unbalance network, [11]. Standard load modes such as Constant Power CP), Constant Current (CC) and Constant Impedance (CI) are used as per the feeder load specifications in [12].

The public charging stations are listed with details given in Table-1. The 32A charging current is not too high for a dedicated charging station working at 240V, single-phase. However, in this study, Tesla Superchargers, [13] with 120 kW rating are considered at three charging stations. The type of PHEV based on its All Electric Range (AER) is selected as PHEV-20 and PHEV-40 considering the small geographical spread of the network and the fact that the PHEVs of this networks are assumed to be operative in the given restricted campus area. The corresponding charging time are given in Table 2.

TABLE I LEVELS OF CHARGING

	Level-1	Level-2	Level-3
Voltage (V)	120	208/240	240
Current (Amp)	12	32	70
Power (kVA)	1.44	6.7/7.7	16.8

TABLE II CHARGING TIME FOR BATTERIES

	PHEV-10	PHEV-20	PHEV-40
Battery Size	4 kWh	8 kWh	16 kWh
Level-1	3 h 5 m	6 h 10 m	12 h 20 m
Level-2	35 m	1 h 10 m	2 h 20 m

The data in Table 1 and Table 2 is based on the details given in [2]. The NHTC database, [9] is used to extract the travelling patterns for PHEVs thereby to determine the State of Charge (SOC) – based on equation (1) – for each PHEV at a given time.

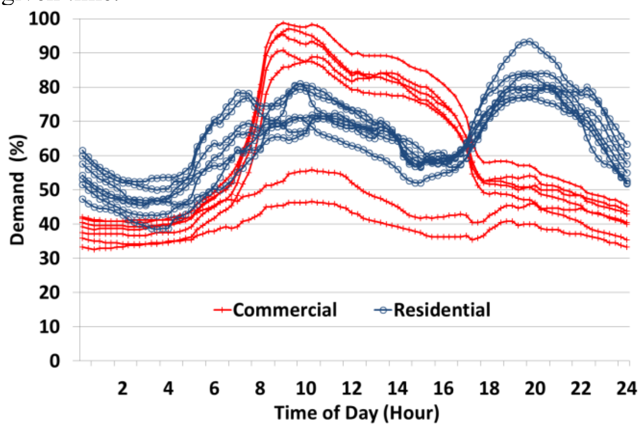

Fig. 2 Daily load profiles - commercial and residential - for one week

In (1), λ is the factor that determines the usage of electrical energy to drive the vehicle. This factor when multiplied by total travelled distance gives the SOC. Thus, SOC is obtained from the randomly generated travelling profile for a particular PHEV. The randomization is applied to avoid repeating trends over a period of time.

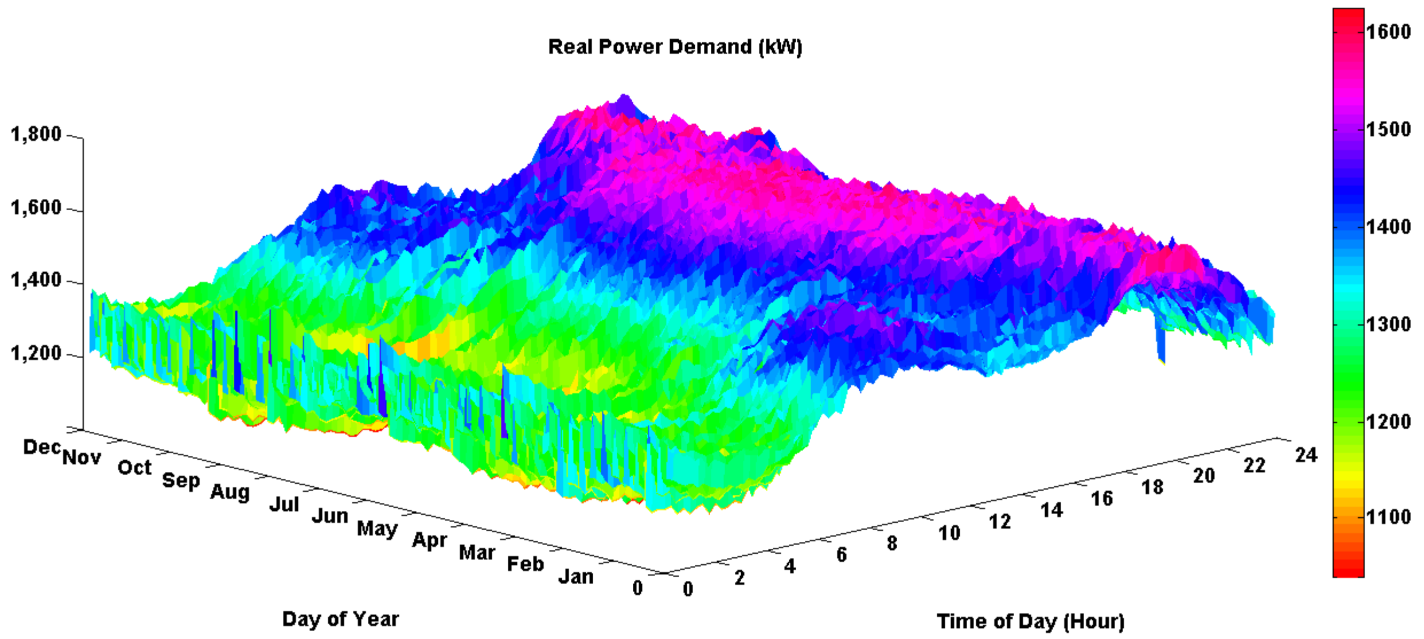

Fig. 3 Annual load profile for IEEE 37 node network for the year 2012

$$SOC = \begin{cases} 0 & \text{for } \lambda \cdot d \geq AER \\ \left(1 - \dfrac{\lambda \cdot d}{AER}\right) & \text{for } \lambda \cdot d < AER \end{cases} \quad (1)$$

The annual load profiles for the IEEE37 node network are used from the website of Electric Reliability Council of Texas, Inc., [10]. Two types of load profiles – residential consumer profile and commercial consumer profiles – are used to obtain the overall annual load profile for the selected network. Two types of load profiles derived from the available set of profiles in [11] are shown in Fig. 2. Note that the residential user group has similar shape for all days in week whereas commercial user groups show sharp decline in peak demand during weekend days. These load profiles are modified by charging and discharging of PHEVs at two charging stations. The aggregate Annual Load Profile (ALP) is thus obtained for the year 2012 at source node which is shown in Fig. 3. It can be observed from Fig. 3 that the daily maximum demand occurs at late evening hours in winter and during noon to late evening hours in summer months. The ALP shown in Fig. 3 is without the additional load current drawn by PHEV charging stations located at three nodes in the IEEE 37 node network.

IV. Simulation Results

STS approach is applied for the year 2012 with annual load profile and PHEV charging data generated based on the NHT survey, [9]. The obtained results are exhaustive and therefore results of two representative days are provided for different parameters such as feeder voltage profile, real power loss and real power demand, VR tap positions, and daily maximum demand. However, cumulative results are included with discussion in following subsections and annual trends are also presented wherever possible.

Two typical days' results are presented. Day of Year (DoY) 40 represents a typical winter day and DoY 178 is selected to represent the typical summer day. This selection is based on the typical Daily Load Profile (DLP) that the two days have. DLPs of DoY 40 and 178 are shown in Fig. 4 below.

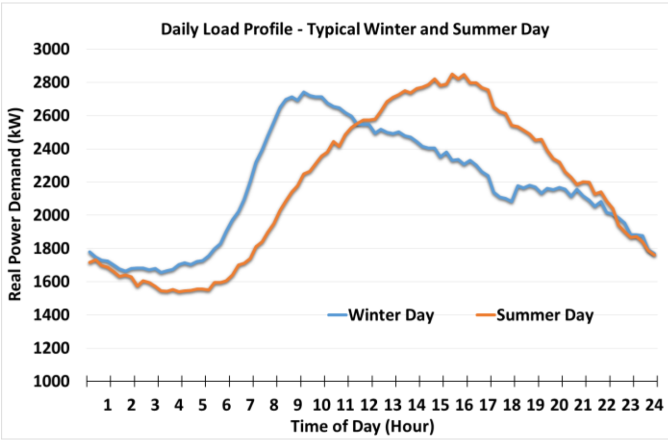

Fig. 4 DLP for DoY 40 and 178 - typical Winter and Summer day respectively

A. Feeder Voltage Profile

The foremost concern of the Distribution System Operator (DSO) is the feeder voltage profile. The node voltages should be maintained within the limit of ±5% of the nominal voltage level. PHEV charging poses a temporary increase in load – from few minutes to several hours – based on the charging profile. It should be noted here that the charging stations considered here are superfast chargers which charge the batteries up to 80% within first 15 to 20 minutes. Therefore the PHEV charging load appears as a 15 minute at the source node. IEEE 37 node feeder's base-case voltage profile is very healthy with 2.5 MW of load. The node voltages remain well within the 0.97 to 1.02 p.u. of voltage range. However, number of minimum node voltage limit violations observed with PHEV charging is 30. But it should be noted that over 8700 occurrences are observed when minimum node voltage is lesser than 0.955 p.u – which is close to the minimum node voltage limit of 0.95 p.u. Expectedly, with PHEV charging there is no effect on maximum node voltage violations.

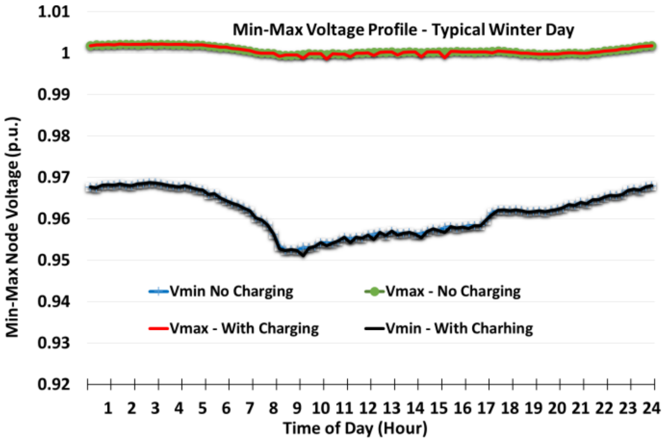

Fig. 5 Feeder voltage profile for a typical winter day - with and without PHEV charging

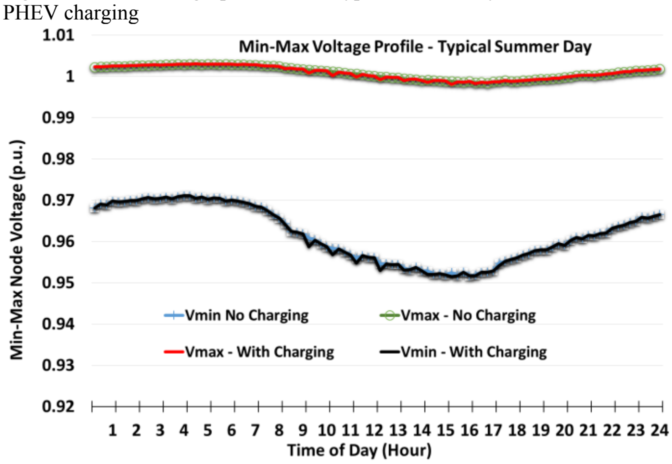

Fig. 6 Feeder voltage profile for a typical summer day - with and without PHEV charging

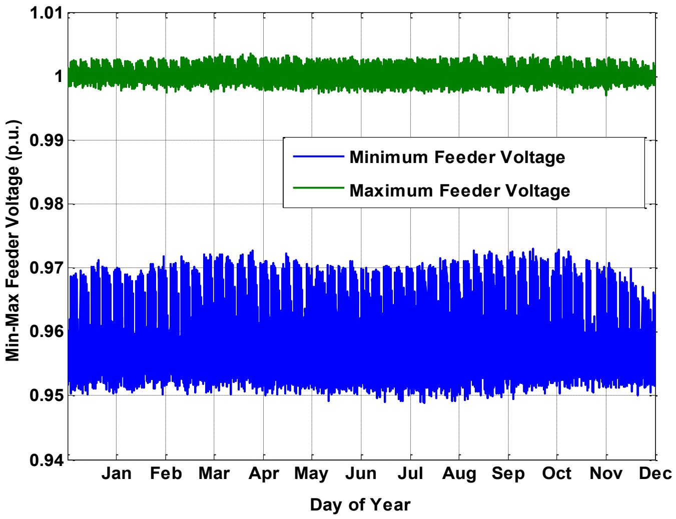

Fig. 7 Annual feeder voltage profile with minimum and maximum node voltages

The daily feeder voltage profile of a typical winter day as shown in Fig. 5 shows the possibility of minimum node voltage violations due to PHEV charging in early morning hours. Whereas, Fig. 6 shows the similar probability during afternoon to evening hours. It is also observed that the PHEV charging marginally augments the possibility of minimum node voltage limit violation. It however does not pose a serious risk. Annual feeder voltage profile with maximum and minimum node voltages is shown in Fig. 7 which clearly shows the proximity of minimum node voltages to the minimum node voltage limit of 0.95 p.u.

B. Real Power Loss

IEEE 37 node test network is relatively small with cable sections. The base-case power loss is merely 2.4% of its real power demand. Therefore, the PHEV charging does not add substantially to this low real power loss. Effect of PHEV charging can be observed in Fig. 8 and 9 respectively for Winter and Summer day. The temporary increase in real power demand which is to the tune of 2 to 8% of maximum demand does not cause substantial rise in real power losses.

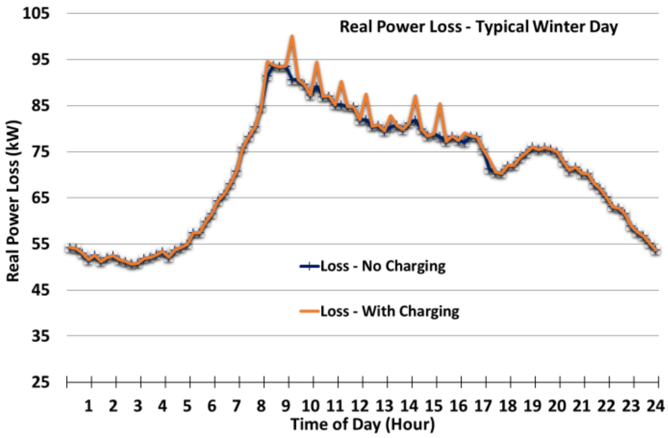

Fig. 8 Real power loss for a typical winter day

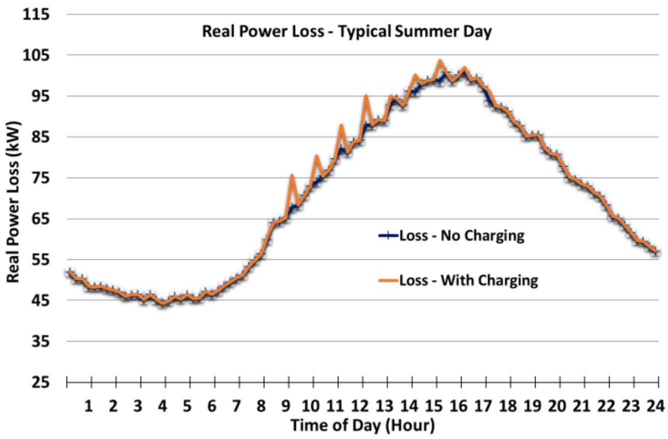

Fig. 9 Real Power loss for a typical summer day

C. Real Power Demand

Base case real power loss of IEEE 37 node network is 60.563 kW against the demand of 2521.83 kW. With the network being subjected to 20% overload, the energy loss for the simulated year (2012) stands at 0.6467 Million Units (MUs) against the annual demand of 22.8 MUs. The energy losses increase to 0.6512 MUs with PHEV charging which is complimented by proportional increase in annual energy demand at 22.9 MUs. However, it should be noted that the ratio of energy loss to energy demand – annually – remains constant as expected. Effect of PHEV charging on real power demand is shown in Fig. 10 and 11 respectively for Winter and Summer day. This result is again not a serious concern for either the DSO or the bulk power consumer.

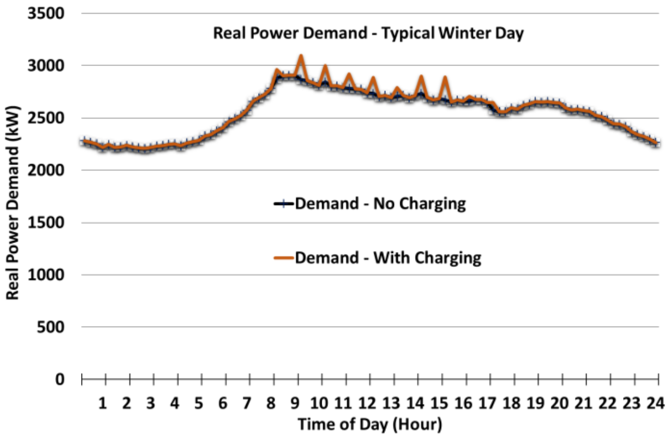

Fig. 10 Real power demand for a typical winter day

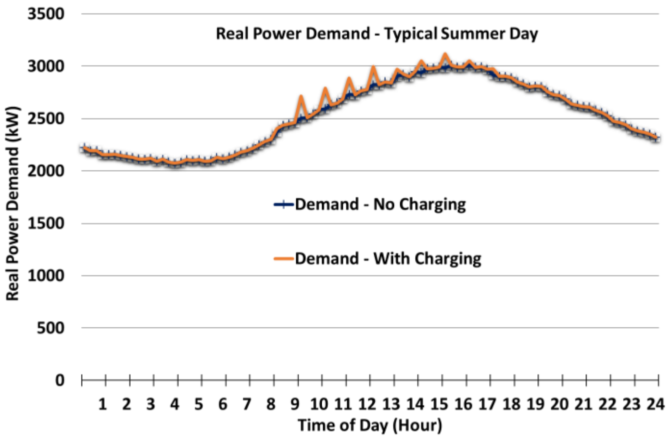

Fig. 11 Real power demand for a typical summer day

D. *VR Tap Positions*

VRs are used to maintain voltage at a remote node based on the measurement of current at the node where the VR is placed. The fluctuations in real power demand can cause the movement of VR taps to maintain the voltage within desired limits. The temporary increase in real power demand by PHEV charging stations can cause frequent operations of tap position change which may lead to rise in total number of TCOs annually. This is one of the concerns for the mechanically operated tap changers. VR is places at the source node in IEEE 37 node network in phase-A and phase-B connected in line-to-line mode to control voltage in all the phases at node 701. The daily tap positions with and without PHEV charging are shown in Fig. 12 and 13 respectively for a typical winter and a summer day. It is observed that the TCOs increase with PHEV charging load in both the typical days. This leads to increased TCOs with PHEV charging by 1,241 in A-phase and 1,315 in B-phase annually. Collectively, it is an increase of 7 TCOs daily on average. The tap positon occupancy also shifts with PHEV charging which is shown phase-wise in Fig. 14 on annual bases. It is a histogram showing total number of timeslots (15 minutes each) for which the particular tap position was occupied by the VR in presence and absence of PHEV charging.

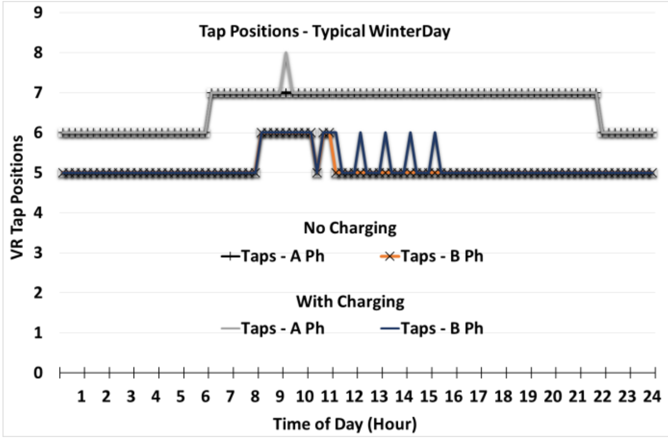

Fig. 12 VR tap positions for a typical winter day

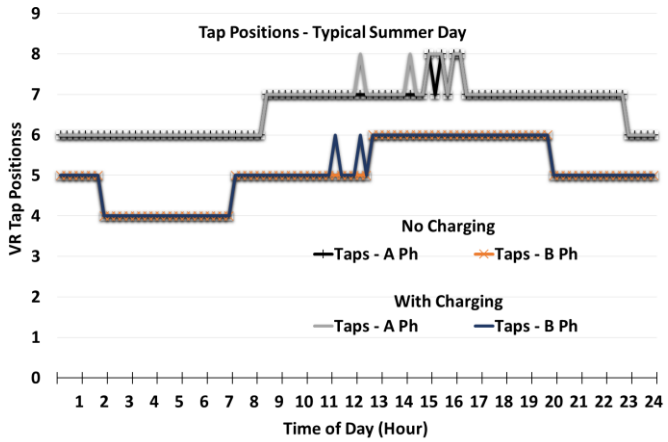

Fig. 13 VR tap positions for a typical summer day

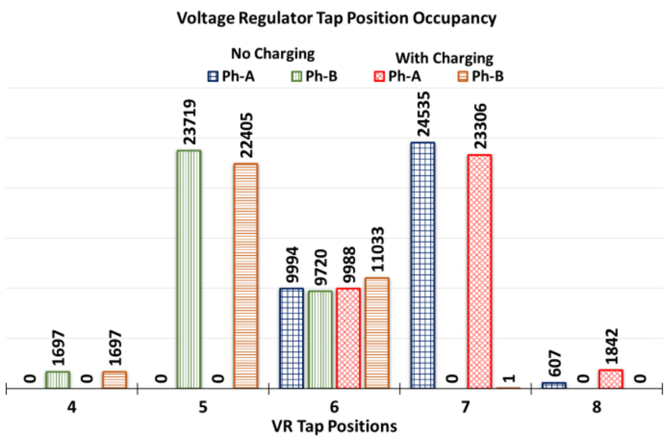

Fig. 14 Histogram for annual VR tap position occupancy

Further increase in PHEV charging will shift the tap positions more. However, given the healthy voltage profile of the network, risk of extreme taps being occupied by the VR is meagre. But the increase in TCOs is close to double the average number of TCOs per day which accelerates the wear and tear of the moving parts in VR. The maintenance schedule needs to be altered with this effect.

E. Daily Maximum Demand

Daily maximum demand of the network is second important concern of the DSO, and it is also equally important concern of a bulk power consumer. The annual maximum demand of the network is found to be 3.11 MW whereas the same in the presence of PHEV charging increases to 3.30 MW. The time of occurrence of this maximum demand also shifts from evening to noon hours. The daily maximum demand with and without PV charging for the simulated year is shown in Fig. 14. Except few occurrences, it can be observed from Fig. 14 that the daily maximum demand remains above the earlier maximum demand i.e. 3.1 MW.

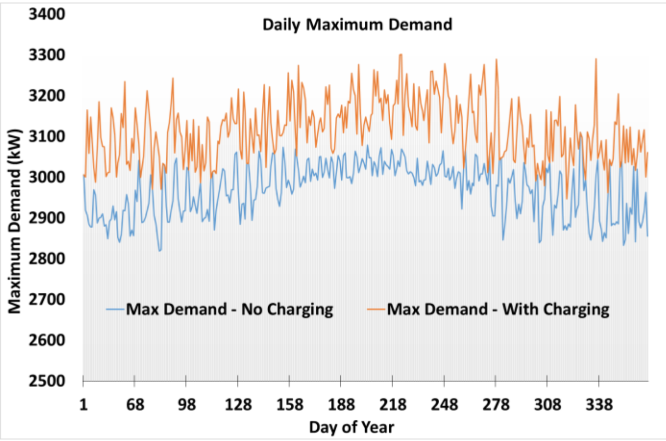

Fig. 15 Effect of PHEV charging on daily maximum demand

V. CONCLUSION

STS approach is applied to summarize the effect of PHEV charging in a low voltage unbalance distribution network. The parameters such as feeder voltage profile, minimum and maximum node voltage violations, peak demand, TCOs of VR, energy losses and energy demand are analyzed with a detailed modeling of IEEE 37 node test network. The 3-phase distribution power flow based on BFS algorithm is used to simulate quarterly annual load profile along with PHEV charging profiles.

The results provide an insight to the effects of PHEV charging in a small community level distribution feeder. It is observed that the PHEV charging may lead to increased minimum node voltage violations along with significant rise in TCOs of VRs and considerable increase in peak demand. However, effect of PHEV charging on real power losses and energy losses remains less of a concern for both DSOs and bulk power consumers.

The STS approach in this exercise used 15-miutes interval for sequential simulations which produces conservative results for TCOs of VRs. More accurate results can be obtained by quasi-static time-series power flow simulations at 1-minute or smaller time intervals. Based on availability of high resolution data, the same analysis can produce better results. Further research can also be directed towards using the PHEVs as energy storage mechanism with bidirectional flow of energy which can be used for flattening of load profiles with peak load shaving.

REFERENCES

[1] M. Duvall and E. Knipping, "Environmental assessment of plug-in hybrid electric vehicles," Elect. Power Res. Inst.. Charlotte, NC, Jul. 2007.

[2] Wencong Su; Eichi, H.; Wente Zeng; Mo-Yuen Chow, "A Survey on the Electrification of Transportation in a Smart Grid Environment," Industrial Informatics, IEEE Transactions on , vol.8, no.1, pp.1,10, Feb. 2012

[3] Shafiee, S.; Fotuhi-Firuzabad, M.; Rastegar, M., "Investigating the Impacts of Plug-in Hybrid Electric Vehicles on Power Distribution Systems," Smart Grid, IEEE Transactions on , vol.4, no.3, pp.1351,1360, Sept. 2013

[4] Pieltain Fernández, L.; Román, T.G.S.; Cossent, R.; Domingo, C.M.; Frías, P., "Assessment of the Impact of Plug-in Electric Vehicles on Distribution Networks," Power Systems, IEEE Transactions on , vol.26, no.1, pp.206,213, Feb. 2011

[5] Darabi, Z.; Ferdowsi, M., "Aggregated Impact of Plug-in Hybrid Electric Vehicles on Electricity Demand Profile," Sustainable Energy, IEEE Transactions on , vol.2, no.4, pp.501,508, Oct. 2011

[6] Kan Zhou; Lin Cai, "Randomized PHEV Charging Under Distribution Grid Constraints," Smart Grid, IEEE Transactions on , vol.5, no.2, pp.879,887, March 2014

[7] Arritt, R.F.; Dugan, R.C., "Value of sequential-time simulations in distribution planning," Rural Electric Power Conference (REPC), 2013 IEEE , vol., no., pp.C2-1,C2-5, April 28 2013-May 1 2013

[8] Heydt, G.T., "The Next Generation of Power Distribution Systems," Smart Grid, IEEE Transactions on , vol.1, no.3, pp.225,235, Dec. 2010

[9] U.S. Department of Transportation, Federal Highway Administration, 2009 National Household Travel Survey. URL: http://nhts.ornl.gov.

[10] Electric Reliability Council of Texas, Inc. – annual load profiles available online at http://www.ercot.com /mktinfo/loadprofile, accessed April, 2014

[11] W. H. Kersting, Distribution System Modeling and Analysis, London: CRC Press, First Edition 2002, p. 83-85

[12] W. H. Kersting,"Radial distribution test feeders," IEEE Trans. Power Syst, vol.6, no.3, pp.975,985, Aug 1991.

[13] Tesla Superchargers, Charging Station Network [Online]. Available: http://www.teslamotors.com/supercharger

[14] K. A. Joshi and N. M. Pindoriya, "Impact investigation of rooftop Solar PV system: A case study in India," in Innovative Smart Grid Technologies (ISGT Europe), 2012 3rd IEEE PES International Conference and Exhibition on, 2012, pp. 1-8.

[15] C. S. Cheng and D. Shirmohammadi, "A three-phase power flow method for real-time distribution system analysis," *IEEE Trans. Power Syst.*, vol.10, no.2, pp.671,679, May 1995.

[16] K. Joshi, "On some aspects of Distribution System Analysis and Optimization," M.Tech. Thesis, Dept. of Electrical Engineering, Indian Institute of Technology Delhi, New Delhi, 2008.