LTC AND SHUNT CAPACITOR SWITCHING IN SMART GRID: SENSITIVITY TO PLUG-IN ELECTRIC VEHICLE FORECASTS

SARA DEILAMI

Member, IEEE, Department of Electrical and Computer Engineering, Curtin University, Perth, WA, Australia
E-mail: s.deilami@curtin.edu.au

Abstract- Optimal scheduling of transformer load tap changer (LTC) and switched shunt capacitors (SSCs) in smart grid (SG) with plug-in electric vehicles (PEVs) and nonlinear loads can be performed to reduce system losses, node voltage fluctuations and total harmonic distortion (THD). This paper investigates the effects of vehicles' plug-in time forecast errors on performance of LTC and SSCs switching. First, a genetic algorithm (GA) is used to determine the optimal switching schedules within the 24 hours based on forecasted daily load curves of residential feeders with random PEV charging activities. Then, system performance without and with forecasting errors are presented and compared. Simulations are performed for a 449 node SG test system with nonlinear loads and PEVs.

Keywords- Smart Grid, Forecasted PEVs, LTC and Switched Shunt Capacitor Scheduling.

I. INTRODUCTION

Smart grid (SG) performance can be improved by real time monitoring and online control of apparatuses and loads while incorporating high penetrations of renewable distributed generations (DGs). The main challenges are stochastic nature of renewable energy resources such as wind and PV generators and the nonlinear time-variant behaviors of loads such as switching devices, smart appliances and plug-in electric vehicles (PEVs).

The performance of SG can be improved by mitigating voltage and current harmonic distortions due to the nonlinear v-i characteristics of large industrial loads and power electronic devices incorporated in DGs as well as preventing potential issues associated with PEV charging activities in distribution and residential networks such as high system losses and poor voltage profiles. Possible approaches to improve SG performance are:

- Customer demand side management through optimal coordination of loads, smart appliances, PEVs and renewable DGs.
- Power quality improvement through optimal siting and sizing of power filters (e.g., passive, active and hybrid) and custom power devices (e.g., unified power quality conditioner (UPQC)).
- Allocation of distributed flexible AC transmission systems (DFACTS) and distributed energy storage units to compensate renewable DG output fluctuations.
- Simultaneous control of voltage, reactive power and total harmonic distortion (THD) by incorporating harmonics and PEVs in the optimal scheduling of transformer load tap changer (LTC) and switched shunt capacitors (SSCs). This will require accurate forecasted information for PEVs (e.g., locations, random plug-in times charge durations), nonlinear loads (e.g., ratings, harmonic orders, types and magnitudes) and renewable DGs (e.g., wind and weather conditions) which are not always available.

This paper investigates the sensitivity of optimal LTC and SSCs scheduling to PEV forecast errors (e.g., vehicles' plug-in times). First, a recently developed genetic algorithm (GA) [6] is used to determine the optimal LTC/SSCs switching schedules within the 24 hours based on the forecasted daily load curves of residential feeders with random PEV charging activities. SG performance is presented before and after optimal LTC/SSCs switching. Then, simulations are repeated with various PEV forecasting errors to investigate their impacts on the overall SG performance. Simulation results without and with forecasting errors are presented, compared and analysed for a 449 node SG test system with nonlinear loads and PEVs.

II. PROBLEM FORMULATION

Problem formulation includes harmonic power flow (HPF) calculations, scheduling of LTC/SSCs and PEV coordination.

A. Decoupled Harmonic Power Flow Calculation

To model the SG under non-sinusoidal operating conditions with nonlinear loads, the decoupled harmonic power flow (DHPF) algorithm of is used. At the fundamental frequency, the conventional formulation with slag and PQ nodes is used while at harmonic frequencies, the system is modeled as a combination of passive elements and harmonic current sources representing nonlinear loads. The general model of linear load as resistance in parallel

with a reactance is utilized while nonlinear loads are modeled as current sources that inject harmonic current into the system. Two types of nonlinear industrial loads are considered; variable frequency drives (VFDs) and PWM based adjustable speed drives (ASDs). Typical current harmonic spectra for these loads are shown in Table I.

B. Formulation of Optimal Dispatch Problem

The objective function of LTC/SSCs scheduling problem is minimization of energy loss over a 24-hour period:

$$\min \sum_{t=1}^{24} P_{loss}(Q_t, T_t)\,\Delta t =$$

$$\min \sum_{t-1}^{24}\left(\sum_{h=1}^{H}\sum_{i=0}^{m-1} R_{i,i+1}\left(\left|V_{i,i+1}^{h} - V_i^{h}\right|\left|y_{i,i+1}^{h}\right|\right)\right)\Delta t.$$

Subject to the following constraints:

$$\begin{cases} V_{i\min} \le \quad V_{irms} = \left(\sum_{h=1}^{H}\left|V_i^h\right|^2\right)^{1/2} \le V_{i\max} \\ THD_{vi} = \left[\left(\sum_{h\ne 1}^{H}\left|V_i^h\right|^2\right)^{1/2} / \left|V_i^1\right|\right]\times 100\% \le THD_v^{\max} \\ \sum_{t=1}^{24}\left|TAP_t - TAP_{t-1}\right| \le K_T \\ \sum_{t=1}^{24}\left(C_{nt} \oplus C_{nt-1}\right) \le K_c; \quad n = 1, 2, ..., nc \end{cases}$$

(2)

where P_{loss} is total power loss at hour t as a function of Q_t (status of SSCs) and T_t (LTC tap position); Δt= 1 hour is the time interval; H, m, i and $R_{i,i+1}$ are highest harmonic order considered, total number of nodes, node number and line resistance between nodes i and i+1; $V_{i\ min}$ and $V_{i\ max}$ are the minimum and maximum limits of rms voltage at bus i (V_{irms}); THD_{vi} and THD_v^{max} are the distortion at bus i and the maximum distortion allowed; TAP_t and K_T are LTC tap position at hour t and maximum LTC switching; C_{nt} and K_C are the status of capacitor n at hour t and maximum switching allowed; and nc is the number of shunt capacitors.

C. Formulation of PEV Charging Coordination Problem

The PEV charging coordination problem is formulated with a cost objective function subjected to two system constraints:

$$\min F_{cost} = F_{cost-loss} + F_{cost-gen}$$

$$= \sum_{\Delta t} K_E\ P_{\Delta t}^{total\ loss} + \sum_{\Delta t} K_{\Delta t,G}\ P_{\Delta t}^{total\ demand}$$

(3)

Subject to the following constraints:

$$\begin{cases} 0.9\,pu = V^{\min} \le V_k \le V^{\max} = 1.1\,pu \quad for\ \ k = 1, ..., n. \\ P_{\Delta t}^{total\ demand} = \sum_k P_{\Delta t,k}^{load} \le D_{\Delta t,\max} \end{cases}$$

(4)

where $F_{cost\text{-}loss}$ and $F_{costlges}$ are the costs corresponding to total system losses and total generation; Δt is the time interval (e.g., Δt =5 min); K_E is the cost per MWh of losses (e.g., K_E =50 $/MWh,); $K_{\Delta t,G}$ is the cost per MWh of generation at time interval Δt based on the variable price of purchasing or producing the energy (e.g., Fig. 1,); $P_{\Delta t}^{total\ loss} = P_{loss,\Delta t}^{h=1}$ (Eq. 2) is the total power losses of distribution system for time interval Δt; k and n are the node number and total number of nodes; $P_{\Delta t}^{\text{total demand}}$ is total power consumption at time interval Δt within the 24 hours, $P_{\Delta t,k}^{load}$ is the power consumption of node k at Δt; and $D_{\Delta t,max}$ is the maximum demand level at Δt that would normally occur without any PEVs.

TABLE I
TYPICAL HARMONIC CURRENT CONTENTS OF INDUSTRIAL LOADS

Harm. Order	Six-Pulse VFD		PWM-ASD	
	Mag. [%]	Phase [deg]	Mag. [%]	Phase [deg]
1	100	0	100	0
5	23.52	111	23.52	111
7	6.08	109	6.08	109
11	4.57	-158	4.57	-158
13	4.20	-178	4.20	-178
THDi	25.2 %		7.1 %	

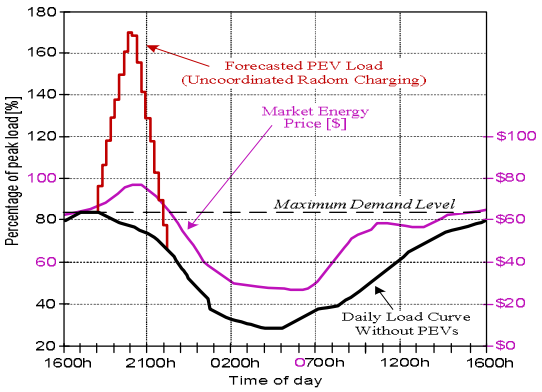


Fig. 1. Daily load curve (without PEVs), forecasted PEV load (random charging) and variable short term market energy pricing.

III. SIMULATION RESULTS

To perform optimal dispatch of LTC/SSCs with random PEV charging, the 449 node smart grid

topology of Fig. 2 is considered. It consist of the IEEE 31 node 23 kV system with 7 nonlinear loads and 22 low voltage 19 node 415 V residential feeders. System parameters are provided in.

The online PEV charging coordination algorithm of is used to calculate (forecast) daily load curves of the 22 low voltage residential feeders of Fig. 2. The residential networks are assumed to have identical forecast daily load curves. The forecasted daily load curve is shown in Fig. 1.

Cases A-B: Optimal Scheduling of LTC/SSCs with Random PEV Charging Considering Harmonics

The forecasted daily load curve with random PEV charging of Fig. 1 is used to perform optimal scheduling of LTC/SSCs using GA for the 449 node SG of Fig. 2. Simulation results before and after optimization including system losses, worse node voltage profile, THD and transformer loading for random PEV charging at 63% penetration are provided in Table II (rows 1-5) and Figs. 3(a) to (d), respectively.

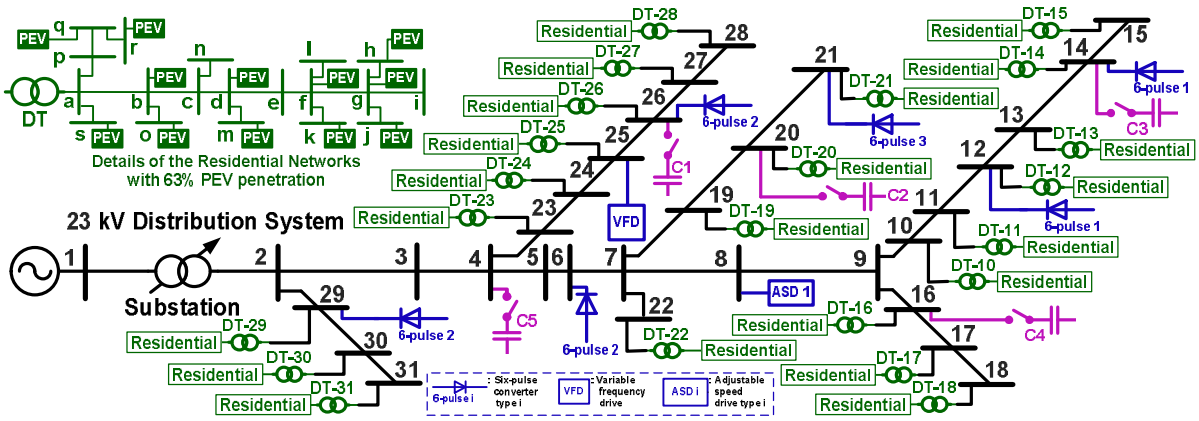


Fig. 2. The 449 node smart grid system consisting of the IEEE 31 node 23 kV system with 7 nonlinear loads and 22 low voltage 415 V residential feeders.

The top left had side diagram presents details of one residential feeder with 63% PEV penetration showing high, medium and low priority consumers in red, blue and green colours paying very high, moderate and very cheap tariff rates, respectively (Fig. 1).

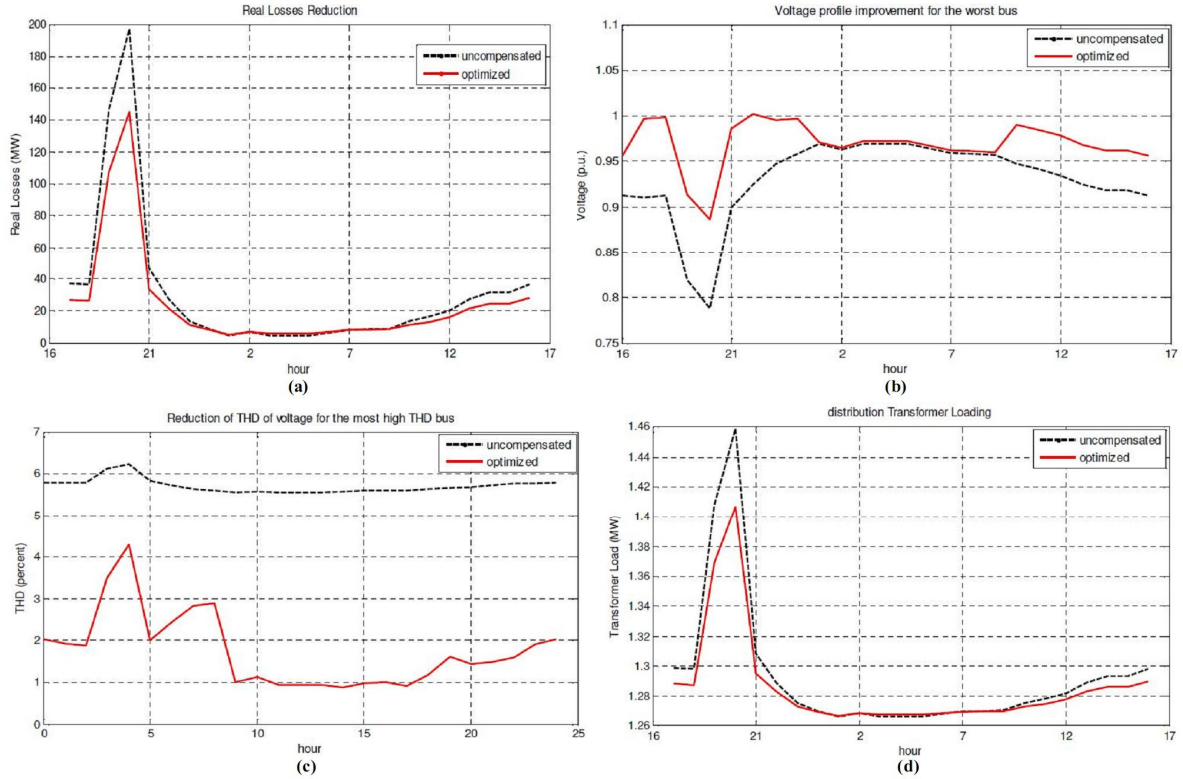


Fig. 3. Simulation results for Cases A-B: Optimal scheduling of LTC and SSCs using GA for the 449 node smart grid of Fig. 2 with forecasted random PEV charging (Fig. 1); (a) total system losses, (b) worst node voltage profile, (c) THDv, (d) distribution transformer load.

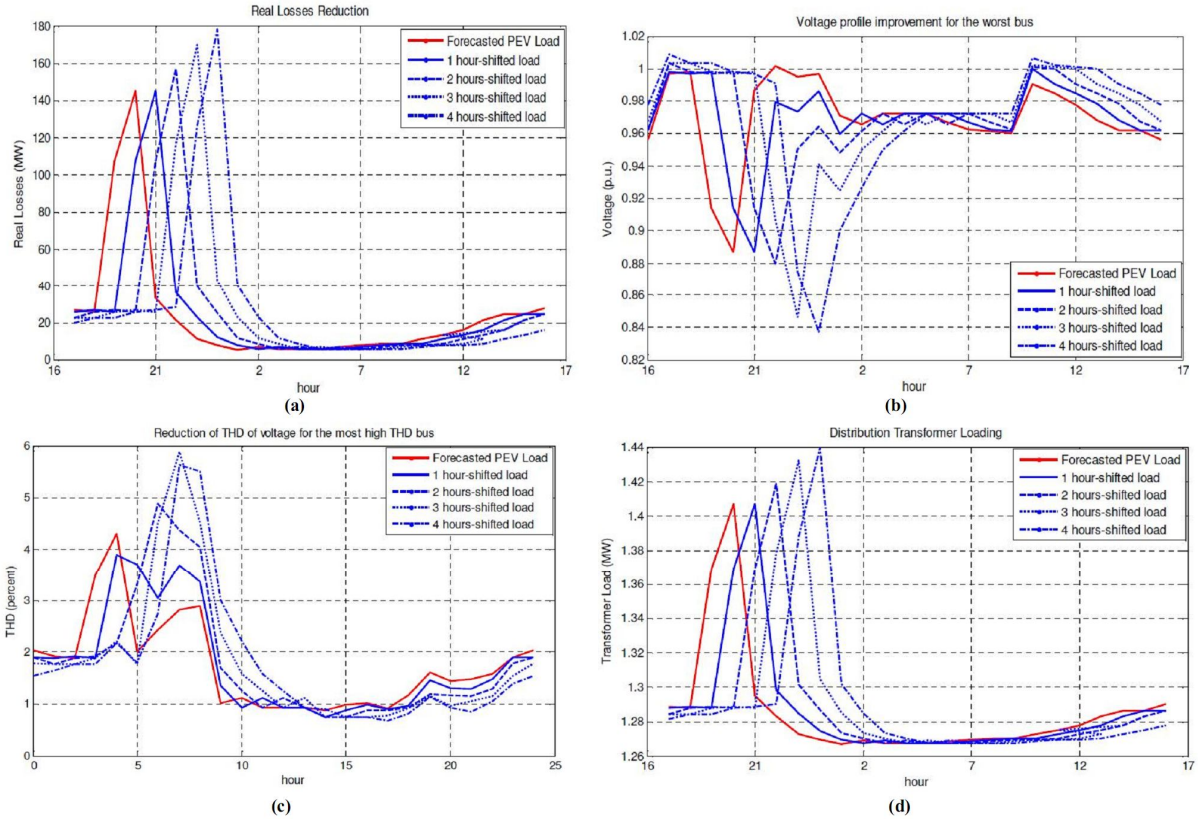


Fig. 4. Simulation results for Case C: Impact of error in the forecasted PEV load of Fig. 2; (a) total system losses, (b) worst node voltage profile, (c) THDv, (d) distribution transformer load.

TABLE II
IMPACT OF PEV FORECASTS ERROR ON OPTIMAL LTC/SSCS SWITCHING PERFORMANCE

PEV FORECASTS ERROR [HOURS]*	MINIMUM VOLTAGE (AT WORST BUS)		SYSTEM LOSSES		TRANSFORMER LOADING		THD	
	MAGNITUDE [PU]	INCREASE [%]**	TOTAL [MW]	INCREASE [%]**	MAGNITUDE [PU]	INCREASE [%]**	MAGNITUDE [PU]	INCREASE [%]**
CASE A: BASE CASE WITHOUT LTC/SSCS SCHEDULING (FIG. 3)								
0	0.883	--	200	--	1.464	--	6.327	--
CASE B: OPTIMAL LTC/SSCS SCHEDULING WITHOUT FORECASTING ERROR (FIG. 3)								
0	0.918	--	141	--	1.412	--	3.555	--
CASE C:OPTIMAL LTC/SSCS SCHEDULES OF CASE B WITH FORECASTING ERROR (FIG. 4)								
1	0.883	-3.8	141	0	1.414	+0.141	3.541	-0.39
2	0.879	-4.2	158	+12.1	1.422	+0.708	4.987	+40.3
3	0.846	-7.8	170	+20.6	1.436	+1.700	5.469	+53.8
4	0.835	-9.1	180	+27.7	1.456	+3.116	5.637	+58.6

*) Shift of forecasted PEV load (random forecasted plug-in times).
**) Increase in magnitude with respect to Case B.

To investigate the impact of error in the forecasted PEV plug-in times, simulations are repeated with the same LTC/SSCs schedules of Case B; however, some error is included in the forecasted PEV load curve of Fig. 1. This is done by shifting the PEV forecasts of Fig. 1 by 1-3 hours. That is all PEVs are assumed to be plugged-in a couple of hours after the forecasted periods. Simulations results without/with forecast errors are compared in Table II (rows 6-10) and Figs. 4.

IV. ANALYSES

As expected and according to Table II (rows 4 and 6), optimal LTC/SSCs scheduling has greatly improved SG performance by significantly reducing total losses (by 29.5%), transformer loading (by 3.6%) and THD (by 43.8%).

However, simulation results of Figs. 3-4 and Table II also indicate that the performance of optimal LTC/SSCs schedules is sensitive to large errors in the forecasted PEV information (plug-in times).

For example, for PEV load shifting of 2 and 4 hours (Fig. 4 and Table II, rows 9 and 11), there will be significant increases in system losses (12.1% and 27.7%), transformer loading (0.708% and 3.116%) and THD (40.3% and 58.6%). The worst impact is on the THD since the PEV load shifting will change the tuning of the passive filters shaped by the switching capacitors and system line impedances.

CONCLUSION

This paper investigates the effects of PEV forecasts error on performance of optimal LTC/SSCs switching. This is done by using the optimal schedules while deliberately introducing errors (shifting) in the forecasted PEV plug-in times. Based on detailed simulations, main conclusions are:

- As expected, optimal LTC/SSCs scheduling will greatly improve SG performance by reducing total losses, transformer loading and THD.
- Performance of optimal LTC/SSCs schedules is sensitive to errors in the forecasted PEV information.
- While small forecasted errors will not have substantial impacts on the SG performance with optimal LTC/SSCs schedules, large errors can result in significant increases in total system losses, distribution transformer loading and voltage harmonic distortion.

REFERENCES

[1] S. Massoud Amin, B.F. Wollenberg, "Toward a smart grid: power delivery for the 21st century," IEEE Power Energy Mag., vol. 3, no. 5, pp. 34-41, Sept.-Oct. 2005.

[2] G. Mauri, D. Moneta, C. Bettoni, "Energy conservation and smart grids: New challenge for multimetering infrastructures," in Proc. IEEE Bucharest PowerTech, Jun. 2009, pp. 1-7.

[3] S. Bruno, S. Lamonaca, M.L. Scala, G. Rotondo, U. Stecchi, "Load control through smart-metering on distribution networks," in Proc. IEEE Bucharest PowerTech, 2009, pp. 1-8.

[4] E.F. Fuchs, M.A.S. Masoum, Power Quality in Electrical Machines and Power Systems. New York: Academic, 2008.

[5] M. Ladjevardi, M.A.S. Masoum, "Genetically optimized fuzzy placement and sizing of capacitor banks in distorted distribution networks," IEEE Trans. Power Delivery, vol. 23, pp. 449-456, 2008.

[6] A. Ulinuha, M.A.S. Masoum, S.M. Islam, "Optimal scheduling of LTC and shunt capacitors in large distorted distribution systems using genetic algorithms", IEEE Trans. on Power Delivery, vol. 23, no. 1, pp. 434-441, Jan 2008.

[7] S. Deilami, A.S. Masoum, P.S. Moses, M.A.S. Masoum, "Real-time coordination of PEV charging in smart grids to minimize power losses and improve voltage profile", IEEE Trans. on Smart Grid, vol.2, no.3, pp.456-467, 2011.

[8] Amir S. Masoum, S. Deilami, A. Abu-Siada, M.A.S. Masoum, "Fuzzy Logic Approach for Online Coordination of Charging Plug-In Electric Vehicles in Smart Grids," Special issue of IEEE Transactions on Sustainable Energy, vol.PP, no.99, pp.1-10, 2014.

[9] A.S. Masoum, S. Deilami, P.S. Moses, M.A.S. Masoum, A. Abu-Siada, "Smart Load Management of Plug-In Electric Vehicles in Distribution and Residential Networks with Charging Stations for Peak Shaving and Loss Minimization Considering Voltage Regulation", IET Proceedings on Generation, Transmission and Distribution, Vol.5, No.8, pp.877-888, 2011.

[10] S. Deilami, M.A.S. Masoum, "Optimal Dispatch of LTC and Switched Shunt Capacitors in Smart Grid with Plug-In Electric Vehicles," IEEE Power Engineering Society General Meeting PES GM, Vancouver, British Columbia, Canada, pp. 1-7, 21-25 July, 2013.

Sara Deilami received the B.S. degree in Electrical Engineering from Islamic Azad University, Tehran, Iran in 2000 and the M.S. and Ph.D. in Electrical and Computer engineering from Curtin University, Perth, Australia, in 2011 and 2014, respectively.

Currently, she is a Faculty Member with the Electrical and Computer Engineering Department, Curtin University. She has 9 years of industry experience. Dr Deilami was awarded the Curtin University Postgraduate Scholarship (CUPS) and an Australian Postgraduate Award (APA) scholarship in 2010 and 2011, respectively.

★★★