Volt-Var Support in Distribution Systems by controlling Electric Vehicles Charging

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***Abstract*— This paper investigates the potential benefits provided by plug-in electric vehicles charging with reactive power support for voltage regulation in low voltage distribution systems. The reactive power support is provided by a Volt-Var control scheme at the inverter. Vehicles inject reactive power only when voltage at the connection point is below the established values according to inverter capability limits. The results are analyzed in a low-voltage distribution feeder developed by CIGRE with real residential load data. Electric vehicles charge at Level 1 with single-phase connection. Simulations are performed using OpenDSS software and evaluate voltage quality aspects. Results show the proposed Volt-Var control helps improve system voltage profile and reduce unbalance condition, minimizing negative effects caused by electric vehicles themselves while charging.**

***Index Terms*— distribution system, plug-in electric vehicles, reactive power control, volt-var control, voltage unbalance.**

I. INTRODUCTION

The massive penetration of plug-in electric vehicles (PEVs) presents challenging technical issues in distribution systems. PEVs charging demand introduces an extra load and can increase energy losses, cause undervoltage situations and transformer overload condition in the case of uncoordinated charging [1]. Several papers proposed different approaches attempting to reduce the negative impacts introduced by PEVs. Most studies focus on developing PEV smart charging algorithms to control charging power and time, PEV tariff schemes to shift vehicles demand, and methods to provide frequency regulation through centralized or distributed strategies [2,3,4]. Most of the proposed solutions require the presence of an aggregator with advanced communication technology to coordinate a large amount of PEVs, following strict protocols and standards to avoid cyber-attacks, which is still under development [5]. Besides, strategies which optimize vehicles charging power and duration may affect user comfort, not having much consumer acceptance.

Generally, PEVs inverter operate close to unity power factor, controlling only the active power used to charge vehicle battery. However, there are already commercially available photovoltaic generation (PV) inverters, namely smart inverters, capable of providing reactive power support. The revised IEEE 1547-2018 standard requires that every distributed energy resource (DER) must have reactive power support capability, which may be used when requested by electric power system operators [6]. Moreover, with the California interconnection Rule 21, PV power inverters are now required to use Volt-Var control (VVC) to assist system voltage regulation [7]. Recent wholesale market regulations encourage DER participation in ancillary service products [8].

With the emergence of smart inverters, PEVs could also provide ancillary services for voltage support injecting or absorbing the grid's reactive power, similarly to the available PV inverters. Few papers have been published addressing this issue. Reference [9] proposes PEVs active and reactive power management to minimize system losses. A single-phase medium voltage distribution feeder is used, and PEVs are charged at Level 2. Reference [10] proposes a centralized VVC strategy through smart inverters of PVs and PEV charging stations. Simulations are performed using medium voltage IEEE-34 node system, and PEVs charge at Level 2 with charging power of 6 kW. In [11], authors propose a Genetic Algorithm to perform centralized PEV charging and decentralized Var discharging strategy in a real unbalanced distribution network. Authors in [12] analyze the effect of PEVs to provide reactive power in low voltage distribution feeders when using fast charging stations, charging with 12.5 kW and constant capacitive power factor of 0.9. Reference [13] proposes a peak-shaving strategy controlling reactive power injection from PEVs in fast charging stations to avoid undervoltage events in a medium voltage system.

Though some work has been done, a deep analysis exploring the use of PEVs to provide reactive power support in three-phase low voltage distribution grids is still lacking. This paper analyzes the potential benefits of VVC strategy provided by PEVs chargers offering reactive power support in a residential distribution system. PEVs inverter provide reactive power when the voltage at the connection point is below specified values. Vehicles have single-phase connection and charge at Level 1, thus voltage unbalance conditions in addition to voltage violation need to be evaluated. Results are verified using OpenDSS software with quasi-static time series simulations. The main contribution of this paper is to investigate the effectiveness of VVC that allows PEVs to inject reactive power in a three-phase low voltage distribution system.

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The remainder of the paper is organized as follows. Section II describes the Volt-Var control method. Section III shows the test approach. Simulations results are presented in Sections IV, and main conclusions are addressed in Section V.

II. VOLT-VAR CONTROL STRATEGY

Consider a typical distribution system as shown in Fig. 1, where R_L and X_L are the line parameters, $\bar{E}_1$ and $\bar{E}_2$ are the voltages at the two terminals, P_L and Q_L are the costumer active and reactive load, and P_{PEV} and Q_{PEV} are electric vehicles active and reactive demand while charging.

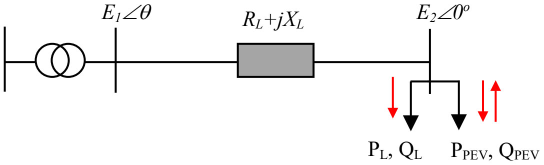

Figure 1. Typical distribution system.

The current at the end of the feeder is expressed by (1) [14]:

$$\bar{I}_c = \frac{\bar{S}_c}{\bar{E}_2^*} = \frac{P-jQ}{\bar{E}_2^*} = \frac{(P_L+P_{PEV})-j(Q_L+Q_{PEV})}{\bar{E}_2^*} \tag{1}$$

The voltage drop along the feeder can be expressed by:

$$\Delta V = [\bar{E}_2 - \bar{E}_1] = |\bar{I}_c(R_L + jX_L)| \tag{2}$$

$$\Delta V = \frac{|(R_L P + X_L Q) + j(X_L P - R_L Q)|}{E_2} \tag{3}$$

In (3), the imaginary part of the equation can be neglected due to the small angle between E_1 and E_2 obtaining (4).

$$\Delta V \approx \frac{R_L(P_L+P_{PEV}) + X_L(Q_L+Q_{PEV})}{E_2} \tag{4}$$

Assuming there is no reactive power provision from vehicles, as PEV active power increases, the voltage drop increases as well. However, the voltage drop along the feeder will be slightly reduced in case PEV injects reactive power into the grid while charging (positive P_{PEV} and negative Q_{PEV}).

Electric vehicles are connected to the grid through inverters, and with the evolution of power electronic, smart inverters have advance control functions. One of them is the Volt-Var functionality, which dynamically changes the reactive power injected or absorbed by inverter depending on the voltage level at the point of connection. Fig. 2 shows the characteristic of the VVC implemented in each PEV.

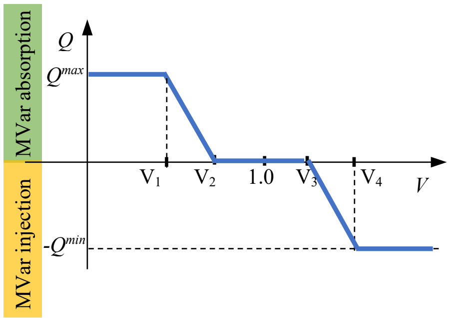

Figure 2. Volt-Var control characteristic.

For voltage levels between V_2 and V_3 the inverter neither injects nor absorbs reactive power, which is called a dead-band. The absorption/provision of the maximum available reactive power occurs for voltage levels under V_1 and above V_4, respectively. For voltage levels between V_1 and V_2 and between V_3 and V_4, the reactive power absorption/injection is calculated linearly. Eq. (5) evaluates the reactive power injected/absorbed by the inverter according to the voltage level at the connection point $V(t)$ for each range in VVC curve.

$$Q\big(V(t)\big) = \begin{cases} Q^{max} & ,V(t) \le V_1 \\ \frac{-Q^{max}(V(t)-V_2)}{(V_2-V_1)} & ,V_1 < V(t) \le V_2 \\ 0 & ,V_2 < V(t) \le V_3 \\ \frac{-Q^{min}(V(t)-V_3)}{(V_4-V_3)} & ,V_3 < V(t) \le V_4 \\ -Q^{min} & ,V(t) > V_4 \end{cases} \tag{5}$$

The reactive power injected by PEVs is limited by inverter rating (S_{inv}) and PEV charging power (P_{PEV}) as shown (6), where PF is the maximum allowable power factor. In this paper, the VVC parameters has been defined as $V_1 = 0.95$, $V_4 = 1.05$, and the dead-band range has been set to ±0.02 pu from nominal voltage ($V_2 = 0.98$ pu, $V_3 = 1.02$ pu). Since the system under analysis is a residential feeder, vehicles are assumed to charge at Level 1 with single-phase connection at 16A, 120V and charging power of 1.92 kW. Inverter rating was adjusted to obtain maximum power factor of 0.85 (injecting/absorbing 1.19 kVar), avoiding inverter excessive over-sizing and degradation.

$$Q_{PEV}^{max} = \sqrt{S_{inv}^2 - P_{PEV}^2} = S_{inv}\sqrt{1 - PF^2} \tag{6}$$

System modeling and VVC functionality were implemented using OpenDSS software to perform quasi-static time series (QSTS) simulations [15]. Fig. 3 shows the control strategy applied. First, PEVs demand are randomly allocated in the distribution system. Then, the power flow is solved to each half-hour time interval considering a 48-h simulation period. Based on power flow results, the VVC verifies the voltage at PEVs connection point, and check the necessity to perform a control action. In positive case, the reactive power injected by PEVs is calculated following the proposed VVC curve using software's built-in object *invcontrol*. The control loop converges when the variation in the monitored voltage from one iteration to another is lower than a pre-specified tolerance.

The analysis includes transformer load and power factor, steady state voltages and voltage unbalance factor (VUF). In this paper, the acceptable voltage limits considered are 0.95 pu to 1.05 pu according to ANSI standard C84.1 [16]. The voltage unbalance factor is defined as the ratio of the negative sequence voltage (V^-) to the positive sequence voltage (V^+) as in (7) [17]. It is a condition in which the three-phase voltages differ in amplitude and/or are displaced from their normal 120° phase relationship. Most standards require a 2% limit for voltage unbalance, which is adopted in this work [17].

$$VUF = \frac{V^-}{V^+} \times 100 \tag{7}$$

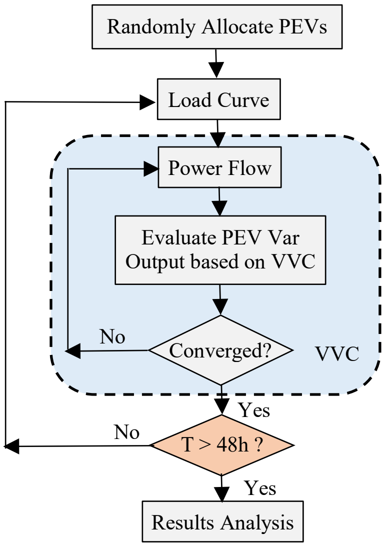

Figure 3. Proposed control strategy.

III. TEST SYSTEM

The test system adopted to perform simulations is the North American low-voltage distribution feeder developed by CIGRE as shown in Fig. 4. The detailed data concerning bus bars, cables/lines and transformer is given in [18]. The demand profiles for each house are based on real hourly measurement data from Midwest region of the United States [19]. A total of 20 households is modeled with individual peak demand varying from 1.1 kVA to 2.0 kVA distributed between phases 1 and 2. The system total peak demand is 21.6 kW and 9.48 kVar.

Simulations consider the randomly connected PEVs at several locations of the residential feeder. Based on a total of 20 houses, 15 electric vehicles are connected, resulting in 75% of local penetration rate. Each vehicle is modelled individually with initial SOC randomly varying between 40% and 58% and start charging time between 16h and 17h, which is reasonable in a residential area where most users start charging after arriving home at the end of the day. PEVs are assumed to have 40 kWh of battery capacity, and charge at Level 1 with a single-phase connection at 16A, 120V and charging power of 1.92 kW, as shown in Fig. 5.

IV. SIMULATION RESULTS AND ANALYSIS

In this section, the Volt-Var control strategy presented in Section II is applied. Simulations analyze transformer load and power factor, system voltage deviation, and voltage unbalance considering the following scenarios:

- Case 1: PEVs is charged with unity power factor and inverter reactive power output is zero;
- Case 2: PEVs is charged by controlling inverter reactive power output to meet the desired Volt-Var requirement.

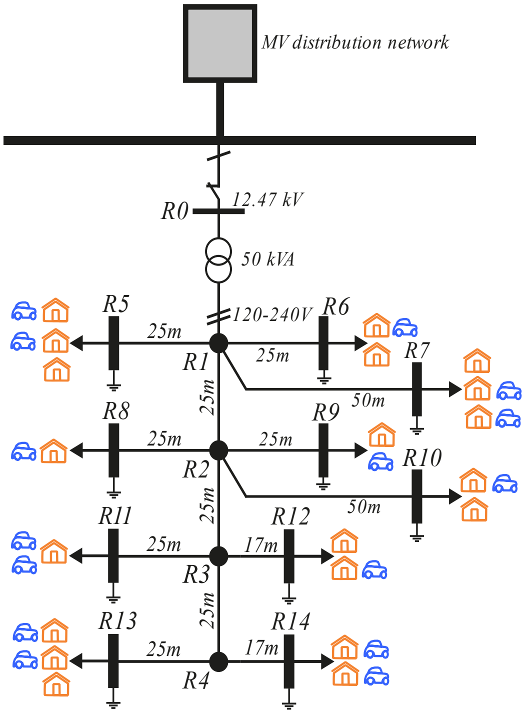

Figure 4. CIGRE low voltage distribution system.

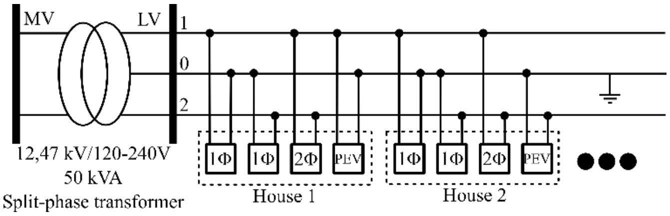

Figure 5. Connection of electric vehicles and household load in the system.

A. Transformer Load and Power Factor

Fig. 6 shows the aggregated load at the distribution transformer with and without the connection of PEVs. The results show transformer exceeds its nominal capacity for 2 hours and 30 minutes when PEVs are connected. Electric vehicles demand coincides with residential peak demand, which is in the evening, exacerbating peak load condition. Fig. 7 shows the power factor at the transformer secondary during the simulation period. Results show power factor remains almost constant at 0.93 when electric vehicles are not considered in simulation. When PEVs charge with unity power factor, the active power demand at the transformer considerably increases. Since the reactive power demand at the transformer is maintained, the power factor angle is reduced increasing the power factor from 0.92 to almost 1.0. In case 2, since a small amount of reactive power is injected, the power factor is slightly increased, without significant impacts.

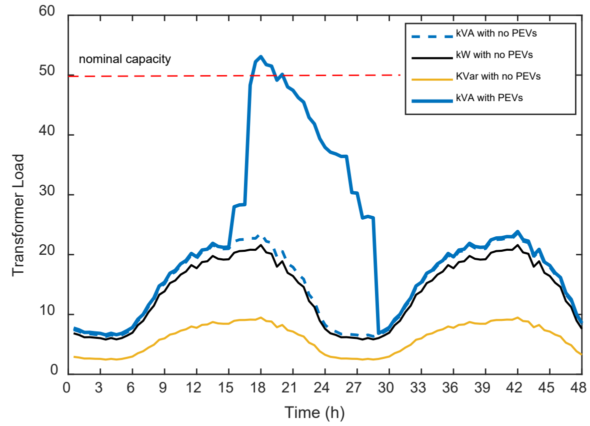

Figure 6. Distribution transformer load with PEVs.

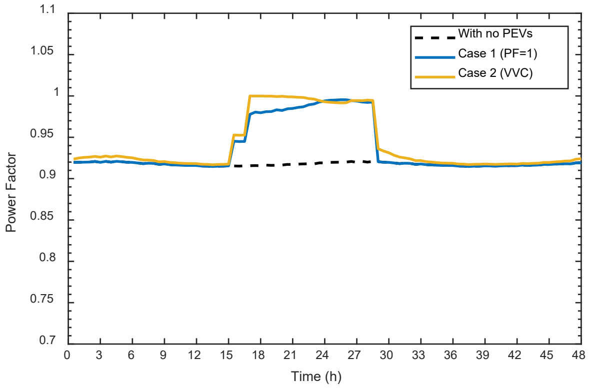

Figure 7. Power factor of distribution transformer for Cases 1 and 2.

B. *Voltage Deviation*

Fig. 8 presents the voltage profile along the feeder at 18:00h, when the system reaches the lowest voltage level. The electric vehicles demand will reduce system voltage levels. As expected, households that are farther away from the beginning of the feeder are most affected by PEVs connection. The minimum voltage limit of 0.95 pu is violated at buses R10, R11, R13, and R14 when PEVs charge with unity power factor. When VVC is applied, inverters inject reactive power only when needed and according to their maximum capacity. Voltage increases along the feeder and only 2 buses (R13 and R14) continue violating the voltage limit. The voltage increase achieved with VVC at 18:00 h varies from 0.31% to 1.73%.

Fig. 9 shows system voltage profiles during the simulation period for cases 1 and 2. Inverter reactive power support reduces the negative impact of PEVs while they charge and reduce voltage deviation. It is important to mention that reactive power support is provided only when the car is charging, aiming to reduce the potential undervoltage issues caused by the vehicles themselves.

Voltage profile on phase 1 of bus R12 and PEVs active/reactive power are presented in Fig. 10. It is possible to note that when voltage reaches values below 0.98 pu, PEV's inverter starts to inject reactive power, and continues to provide reactive power support until necessary. The reactive power injected by the inverter is recalculated for each load flow iteration.

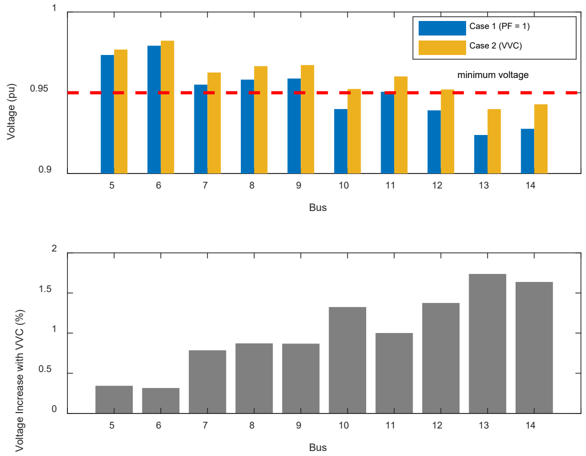

Figure 8. Voltage profile and increase along the feeder at 18:00 h.

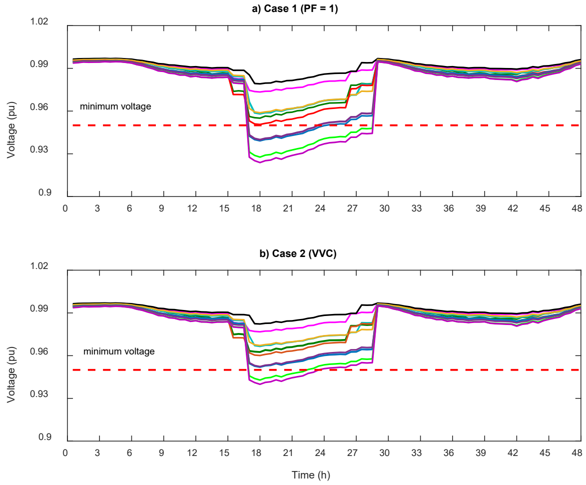

Figure 9. System voltage profile. a) Case 1 (PF = 1). b) Case 2 (VVC).

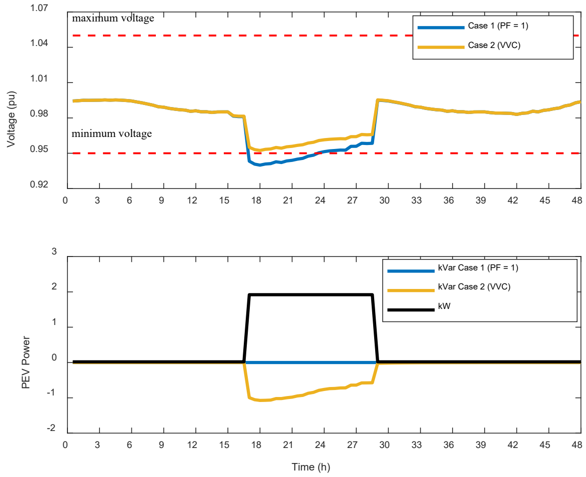

Figure 10. Voltage in phase 1 at R12 and reactive power provided by PEVs.

Fig. 11 shows the voltage profile in phase 1 of bus R13 and active/reactive power of both PEVs connected at this bus. In this case, the reactive power injected by PEVs inverter is not enough to bring the voltage to the acceptable operating range. In this case, the violation level is reduced when PEVs charge under VVC, but more reactive power would be required to eliminate voltage violations.

C. *Voltage Unbalance Factor*

The connection of PEVs at distribution feeder operating at unity power factor largely increases voltage unbalance factor due their single-phase connection, and the minimum required limit is violated at buses R11, R12, R3, and R14 as shown in Fig. 12. The implementation of VVC reduces VUF. However, the reactive power support provided by the inverter is not enough and VUF at bus R13 and R14 remains above 2%.

Fig. 13 shows voltage unbalance factor in all buses and its variation with VVC. The VUF variations are more significant at buses with VUF close to the limit and above it, which need the most reactive power support. At bus R13, VUF decreased from 3.46% to 2.48%, and at bus R14 VUF decreased from 3.7% to 2.64%, an absolute reduction of 1%.

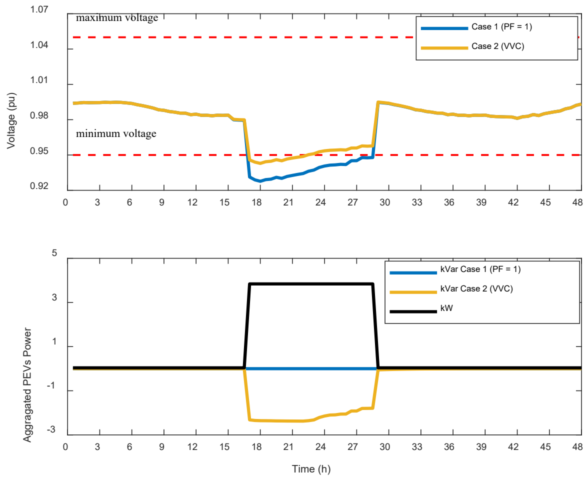

Figure 11. Voltage in phase 1 at R13 and reactive power provided by PEVs.

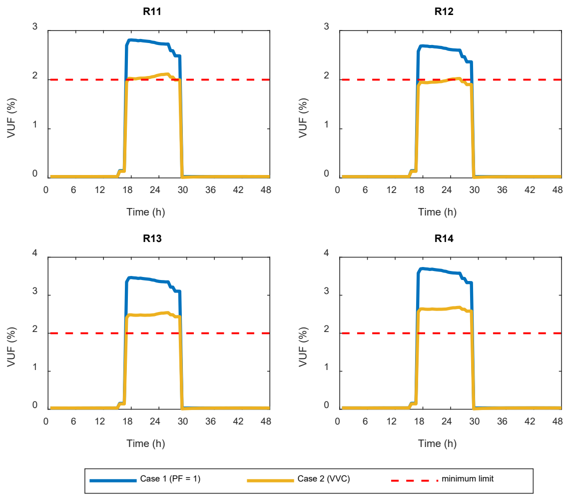

Figure 12. Voltage unbalance factor at R11, R12, R13 and R14.

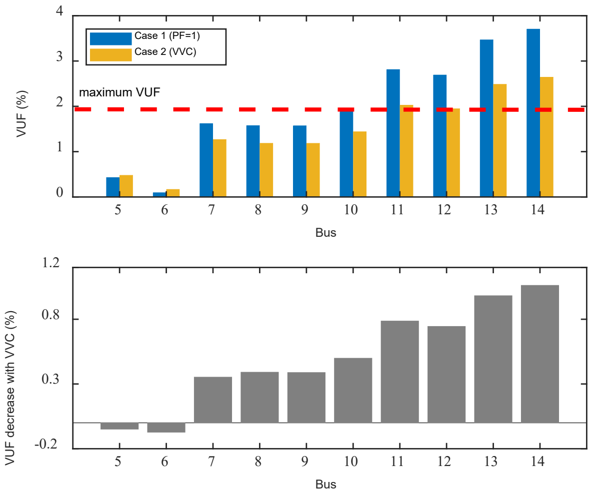

Figure 13. VUF and its decrease for cases 1 and 2 at 18:00 h.

The proposed VVC can minimize the negative effects caused by electric vehicles charging. However, in some cases, it is not enough to assure compliance with power quality standards. A possible solution to overcome this issue is to increase inverter capacity, allowing more reactive power injection when necessary. Other strategies can be combined to prevent unacceptable undervoltage and unbalance conditions, such as applying smart charging and implementing demand response strategies such as load shifting and load curtailment.

V. CONCLUSIONS

The conclusions based on testing using CIGRE low voltage distribution system with real residential load data, with three-phase modeling in OpenDSS software are:

- The Volt-Var control helps improve system voltage profile. A maximum power factor of 0.85 at the inverter improves system minimum voltage by 0.31% to 1.73% compared to the case PEVs operate at unity power factor;
- The Volt-Var control decreases voltage unbalance factor at buses that need the most reactive power support, and maximum absolute decrease of 1% was achieved with VVC;
- There is no excess of reactive power injected by PEVs inverters since they provide reactive power only when voltage at the connection point violates the specified limit;
- Volt-Var control does not affect driver comfort since it does not affect active power charging, hence does not require longer charging time;
- Volt-Var control at vehicles inverter can help regulate local voltage levels and unbalance conditions, and minimize negative effects caused by electric vehicles while charging.
- When VVC does not assure compliance with the power quality standards, other strategies should be combined to avoid unacceptable undervoltage and unbalance conditions;

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