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Power quality of actual grids with plug-in electric vehicles in presence of renewables and micro-grids

R. Romo*, O. Micheloud

Department of Electrical Engineering, Tecnológico de Monterrey, Ave. Eugenio Garza Sada 2501 Sur, Monterrey 64849, NL, Mexico

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ABSTRACT

The penetration of plug-in electric and hybrid-electric vehicles (PEVs and PHEVs) will increase significantly in the next 20 years. The insertion of PEVs in households will facilitate the use of renewable sources and possibly create economic benefits to users, as shown in a Mexican example here presented, but also will introduce some challenges such as how the penetration of PEVs affect the quality of existing power grids. The contribution of this work is to review the literature in reference to the power quality problems and to test them in a real distribution system based on the Mueller community in Austin, Texas that has PEVs and photovoltaic panels (PVs). The results show that a coordinated delay charge mode reduces the loading on transformers at peak hours and improves voltage regulation. Additionally, it is shown that photovoltaic panels introduce a power factor reduction during daytime in the main feeder. Corrective measures should be considered for high levels of PV penetration, such as reactive power support, VAr compensators or community energy storage, which can be presented as one potential solution to most of the problems listed in current literature. However, more research needs to be done in a much broader scale because power systems differ from each other and between countries, but there is a consensus that high power demand by PEVs leads to voltage statutory violations at some points in the grid and smart charging is required to operate the system efficiently.

Contents

1. Introduction

In future years, the growth of the market of plug-in electric vehicles will trigger the rise in electric energy demand that can

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* Corresponding author: Tel.: +52 449 919 3550.
E-mail addresses: reneromo@ieee.org (R. Romo), osvaldo.micheloud@itesm.mx (O. Micheloud).

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lead to undesirable effects on the power system. The complexity of current grids will also grow because PEVs charging characteristics will vary from manufacturers, and also users have different needs.

PEVs may bring relevant benefits to the power systems, because they will facilitate the integration of renewable energy sources (RES), and will reduce contaminant emissions to the atmosphere, specially in large cities, as inefficient combustion engine cars are replaced with electric cars that are supplied by efficient generation stations or clean energy sources [1].

There are many difficulties that need to be taken into account with the addition of this technology such as transformer and line overloading if a fleet of PEVs is suddenly connected to the grid. If no corrective actions are done the transformers life could be significantly reduced and possibly the current capacity of the conductors could be dangerously exceeded. Harmonic distortion is another problem that power electronics, included in PEV's chargers and photovoltaic panel inverters may create in the grid. Some studies state that distortion is more relevant at low penetration because little to none harmonic cancelation takes place [2]. The impact PEVs have on the demand supply is significant at high penetration levels because the peak demand created by them could surpass the transformer capacity, and voltage deviations might even violate voltage constraints [3]. Transient stability is relevant in order to determine the systems behavior under faults and sudden load change. This is fundamental to be taken into account mainly when vehicle to grid operations occur. If a fleet of PEVs is charging and suddenly they start discharging to aid the system in covering the power demand, a transient state will appear that may affect the grid's voltage and frequency [4]. On long term, with a larger PEV population, smart metering, charge control, communication interfaces between user and operator will be necessary to maximize system's power quality without compromising users needs. Some of the stated problems have been previously addressed in a publication of this journal [5]. After three years of thorough research, some areas have considerably advanced, such as the vehicle to grid technology (V2G), the interaction of renewable sources with PEVs and micro-grids to balance demand, even with the high uncertainty related to the power output of distributed generation [6].

The contribution of this work is to review the literature in reference to the power quality problems mentioned above, and to study, in light of the above mentioned work, a real distribution system based on the Mueller community in Austin, Texas. The charge delay mode presented for the PEVs reduces considerably the transformer load during peak time, as this method defers the charging to later time, typically after midnight. The photovoltaic panels at homes bring an economic benefit to users in countries with sliding scale pricing but introduce a challenge as there is a reduction in the power factor of the main feeder because during the day, the PVs are producing an important part of the active energy consumed in the community.

The paper is structured with the following sequence. Section 2 reviews the most important topics related with PEVs and their impact on current power grids, including their interaction with renewable energy sources and micro-grids. Section 3 describes an economic analysis of photovoltaic generation implemented in Mexico that reduces the cost of electricity related to the PEVs. Section 4 defines the distribution system under study and presents the results shown in the simulations. Finally, Section 5 presents the main conclusions of this research work.

2. Literature review

2.1. PEVs charging and storage characteristics

Each electric vehicle has unique charging characteristics as manufacturers aim their presence to varying markets with different production costs. Up to date, some of the most known electric vehicles (EVs) are the Chevrolet Volt [7], the Ford Fusion Hybrid [8], and the Toyota Prius [9], which are hybrid-electric vehicles and the Nissan Leaf [10], the BMW i3 [11], and the Tesla Model S [12], which are fully electric. Table 1 presents the batteries storage capacity for these vehicles, but it has to be noted that none of these EVs can use the full extent of the capacity as batteries have a state of charge (SoC) limit, in order to extend their lives. For example, the Chevy Volt only uses 10.8 kWh of the 16.5 kWh available [13], about 65% of the SoC. Fig. 1 shows a generic Lithium-ion (Li-ion) battery curve modeled in Matlab Simulink [14]. The charge–discharge battery quasi-linear voltage region defines the SoC limits and most manufacturers establish an optimal working range with an upper limit of 85% and a lower limit of 20% of state of charge. The exponential regions should be avoided in order to increase the battery's life.

Table 1
PEVs and PHEVs storage capacity.

PEV and PHEV	Battery storage capacity (kWh)
Tesla Model S	85.0
Nissan Leaf	24.0
BMW i3	18.8
Chevrolet Volt	16.5
Ford Fusion Hybrid	7.6
Toyota Prius	4.4

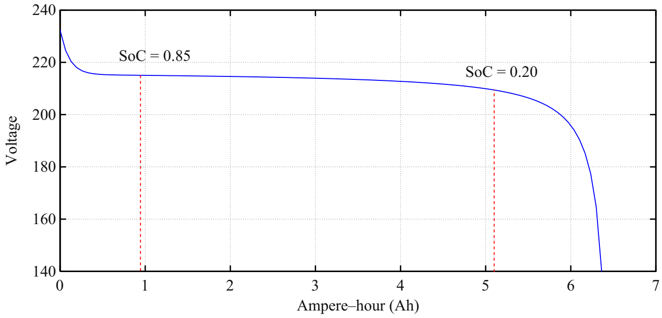

Fig. 1. Li-ion battery charge–discharge characteristic [14].

There is not a consensus on how many miles are driven everyday; it depends on the location where the measurement is done. According to the 2001 National Household Travel Survey (NHTS) the most common travelling range was 25–30 miles in the United States [15]. The Australian Bureau of Statistics car vehicle usage survey showed that a passenger vehicle travelled 23.4 miles per day [16]. Some other authors use a 60-mile range to establish the SoC [17,18]. A study done by ECOtality and the Idaho National Laboratory [19] collected information from "The EV Project" vehicles and charging units. The data analyzed belonged to 2903 PEVs, which travelled over 10 million driving miles in 2011. On average the vehicles drove 30.3 miles per day with a median of 26.8 miles, and the average and median number of times the vehicles were charged per day driven were 1.05, and 0.99, respectively. It is clear that countries have varying driving ranges, but even in cities users have diverse driving patterns, where some will require to charge their PEVs twice a day and some others every other day.

According to the previous study, [19], 82% of the PEV owners charged them at home. Fig. 2 shows that the range of SoC is wide during the start of the charging event. It could be implied that the data follows a normal distribution, with a mean value around 50% of SoC. At the end of the charging event, the distribution has a negative skewness, meaning that it is asymmetrical and owners

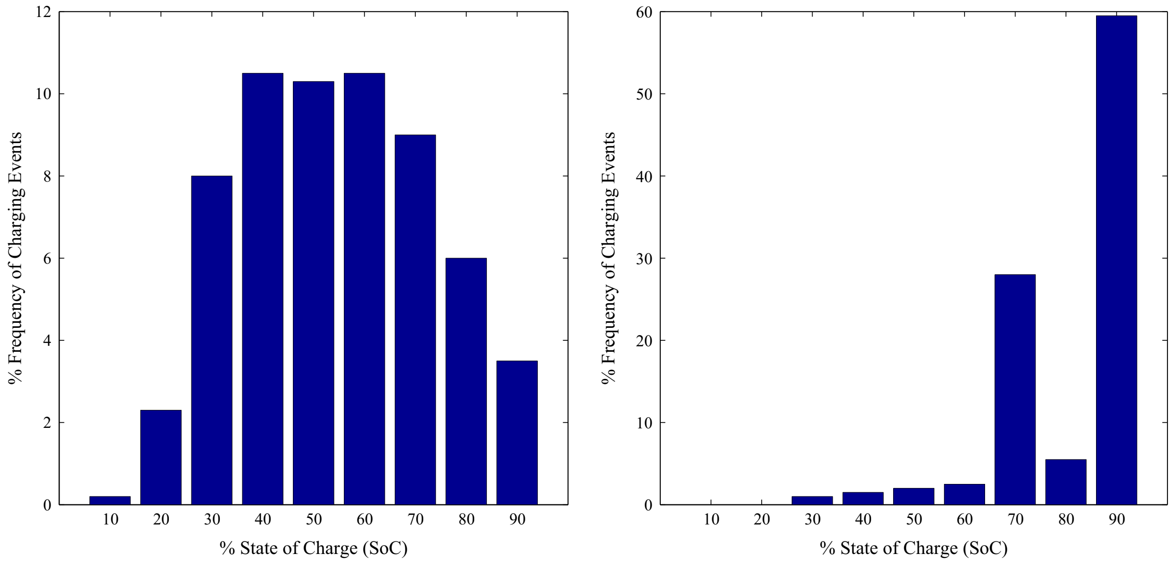

Fig. 2. Battery SoC during (a) the beginning, and (b) the end of the charging events [18].

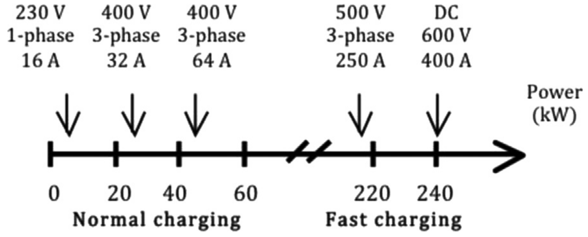

Fig. 3. Charging power rates for PEVs [2].

Table 2
Typical charging times for PEVs.

Average charging power	1.8 kW	3.7 kW	22.2 kW	240 kW
Driving distance/energy				
30 km/7.5 kWh	4.2 h	2.0 h	20 min	2 min
60 km/15 kWh	8.3 h	4.1 h	41 min	4 min
100 km/25 kWh	13.9 h	6.8 h	1.1 h	6 min
150 km/37.5 kWh	20.8 h	10.2 h	1.7 h	9 min

left the batteries to be charged to their maximum capacity for most of the PEVs. This can represent a future problem, as stated before a battery with a SoC higher than 85% for long periods of time reduces the battery life.

So, bearing in mind these aspects, the aggregated power demand to the grid is a function of users' driving patterns, battery capacity and chemistry, SoC and utility connection (supply voltage, allowable current and number of phases) [2]. Fig. 3 shows the power demand of a PEV load depending on the characteristics of the utility connection. PEVs focus primarily on normal charging done at home with the most common connection being a single phase at 230 V/16 A in some countries and 120 V/15 A in others.

Table 2 summarizes typical charging times depending on the average charging power, driving distance and energy that needs to be consumed from the utility. Most users will consider charging at 3.7 kW so the batteries could be recharged completely during the night.

2.2. Vehicle to grid

Vehicle to grid (V2G) technology allows some PEVs to reverse their power flow so they can contribute with power in peak times. This concept brings some benefits such as frequency and voltage control ensuring the vehicle reaches the desired SoC at its next reuse. One of the problems that arise from V2G is that batteries' life is considerable reduced because it depends on the amount and rate of energy withdrawn and is a function of depth of discharge and cycling frequency [20]. The cost of battery degradation is difficult to estimate, because technologies are still developing. Table 3 presents a comparison of the benefits and disadvantages of unidirectional and bidirectional charging [21]. It can be seen that V2G technology is expensive and more difficult to implement but it helps to distribute power demand in a more efficient way.

A Rule-Based Algorithm in a 400 kVA medium to low voltage distribution system was presented in [22]. The system fed 96 houses with a charging current varying from 5 to 32 A in steps of 5 A to determine the average power rating of the system. Authors established four study cases by changing the SoC, the arrival time, the type of PEV and the house power profile. For case 1 with an arrival time at 15:30 the household load increased from 0.2 kVA to a maximum of 7.9 kVA at a charging current of 32 A. Later they produced a Matlab/Simulink analysis that calculated the voltage profile of the distribution system. In this same case the house voltage went from 0.99 to 0.965 p.u., but the system voltage was reduced from 0.92 to 0.88 in winter. This voltage deviation was over the well-known 10% of several statutory limits. Finally, they proposed a linear voltage control plan based on the quasi-linear evolution of the voltage profile slope with the use of V2G ensuing the PEV has the needed charge at the time the user needs it.

An agent's optimization algorithm is developed in [23], where each agent tries to maximize its own profit. The EVs, according to the authors, can provide frequency regulation or serve as a spinning reserve. During each simulation step power distribution factors are calculated so the more suitable buses with EVs help to alleviate congestion in lines. The electric system, as stated by the authors, was composed of several loads in each bus, renewable and non-renewable generators among them a wind turbine, photovoltaic panels, a microturbine, a fuel cell generator, and one battery. Nine EVs were connected in different nodes depending on the hour of the day. Results show that the power given by the EVs, or simply by decreasing their charge rate reduce possible power congestion in feeders, but only in mild cases. They conclude that the reactive power control needs to be included in the algorithm in order to reduce high congestion levels.

Table 3
Unidirectional and bidirectional power flow comparison.

Power flow	Power flow and switches	Benefits	Handicaps
Unidirectional	One-way electrical energy flow. Diode Bridge plus unidirectional converter	• Simplifies interconnection issues • Supplies or absorbs reactive power, without having to discharge a battery, by means of current phase-angle control • Voltage and frequency control • Low cost • No discharging degradation	• No active power control • No peak shaving and valley filling
Bidirectional	Two-way electrical energy flow. MOSFET (low power) IGBT (medium power) GTO (high power)	• Ancillary services • Active power regulation and stabilization • Reactive power support • Peak shaving • Valley filling • Current harmonic filtering • Tracking the output of renewable energy sources	• Extra degradation due to frequent cycling • High investment costs • Extensive regulatory measures

2.3. *Harmonic distortion and transformer life reduction*

The nonlinear nature of electronic devices produces harmonic distortion on the distribution system, particularly in the current and voltage waveforms. This phenomenon can become more relevant depending on PEVs penetration level and power factor [1]. Harmonic distortion happens dynamically because household load changes during the day and PEVs are only charging at certain hours. One of the risks of delayed charging is that harmonic cancelation, a known phenomenon when a large number of PEVs are connected to the grid, may weaken at dawn when most PEVs are fully charged and no other domestic appliances are in operation.

Early studies, based on a Monte Carlo simulation [24], concluded that if the number of PEV chargers are more than 7, current THD_i remains constant around 49%. In [25], the authors analyzed, with the Central Limit Theorem, a local power supply network with 36 PEVs at a charging rate of 20 kWh for 5 h. The voltage distortion THD_v was 0.5%, but the current THD_i was in a range of 43.7–49.1%. Comparing with the previous analysis, results show that the current distortion would be considerable and might affect the operation of other electronic equipment close to this neighborhood.

A more recent work was presented in [26], which consisted in the use of derating *K*-Factors for load and power quality management. The derivation of the *K*-Factor was taken from [27]. The mathematical definition of *K*-Factor is expressed in Eq. (1), where I^h is the rms load current for harmonic order h, and I^1_{rms} is the rated rms load current of the transformer.

$$K = \sum_{h=1}^{H} \frac{\left(I^h\right)^2 h^2}{\left(I^1_{\text{rms}}\right)^2} \tag{1}$$

This *K*-Factor is relevant because it contributes to a reduction in apparent power the transformer can tolerate, and given the load current harmonic spectrum and rated eddy current loss coefficient P_{EC-R}, the *K*-Factor can be used to calculate transformer derating in per unit (p.u.), as expressed in Eq. (2).

$$I_{\text{derated}} = \sqrt{\frac{1+P_{EC-R}}{1+K\left(\left(I^1_{\text{rms}}\right)^2 / \sum_{h=1}^{H}\left(I^h\right)^2\right)(P_{EC-R})}} \tag{2}$$

The derated apparent power capability of the transformer can be estimated as in Eq. (3).

$$\text{kVA}_{\text{derated}} = \text{kVA}_{\text{rated}} \times I_{\text{derated}} \tag{3}$$

Finally, the percentage decrease in transformer kVA rating is calculated as Eq. (4).

$$\%\,Derating = (1 - I_{\text{derated}}) \times 100\,\% \tag{4}$$

Then, the authors proposed an IEEE 30-bus 23 kV distribution system that was modified to introduce a residential feeder with high penetration of PEVs and another serving an industrial area with nonlinear load. The transformer that fed the PEVs was 250 kVA 23 kV/415 V. The analysis was done for three cases with 1.3 kW chargers:

(1) Peak load with high penetration (120 PEVs).
(2) Charging with smart load management.
(3) Off-peak charge with high penetration of PEVs.

In case 1 current THD_i was 19.1% with a transformer derating of 4.9%, in case 2 and 3 THD_i was 17.9% and 29.9%, respectively, with no transformer derating.

The impact of overloading a power transformer is reflected in the transformer's “hot-spot” temperature inside the windings. So, based in this premise, a mathematical model to conduct this study was proposed in [17]. This work states that the transformer lifetime depends on insulation degradation, which is a function of winding temperature. The simulation was done with a transformer of 50 kVA that used oil natural air-cooling with an oil-time constant of 411.4 min and later conducted the same evaluation with a second less robust transformer with a time constant of 200 min. They used a common household profile of Austin, Texas, and the PEV contribution of the Chevy Volt and the Nissan Leaf. The results found show that transformer life is significantly reduced if uncontrolled charging takes place, mainly in the less robust transformer.

Later the same authors propose the use of transformer energy management systems (TEMS) in collaboration with home energy management systems (HEMS) in order to control the transformer's hot-spot temperature without compromising residential load. Results showed a significant rise in transformer's life when controlled charging takes place. Comparing results from the previous cited research work, it can be seen that the life increases from 24 to 47 years depending on the transformer and PEV considered. Another study [28], found a quadratic relationship between transformer life reduction and current THD_i, indicating that if THD_i is limited to 25–30% the transformer life will not be significantly affected.

A probabilistic model was presented in [29]. It was based on a binomial function to calculate the probability that a specific distribution transformer would experience excessive loading. The system evaluated, as stated by the authors, was “a distribution network in Denver, Colorado with 75,000 distribution transformers of varying capacities and 550,000 customers across 400 feeders. Two levels of charging were introduced (1.2 kW and 3.8 kW), and the penetration level varied from 10 to 30%”. The main constraint consisted that transformers could not be overloaded over 1.8 p.u., and if this happened it should be replaced. The results showed that a 3.64%, 8.58% and 15.8% of the transformers needed to be replaced for conservative, moderate, and aggressive scenarios, respectively. Finally the authors presented an optimization structure to reduce the costs involved in the replacement of the transformers.

An experimental test was conducted based on the aging transformer models (insulation aging, and hot-spot temperature) [30]. The household data used was based on a power load of the electric utility of Columbus, Ohio, and a 25 kVA transformer was loaded with the load ratio of 6 households with identical PEVs. The results displayed that the transformer could be overloaded to 150% when the 6 PEVs were simultaneously charging, and the authors concluded that an increase of 25% of the load might raise the temperature of the windings 10 °C.

Harmonic distortion in current PEVs has been radically reduced as modern power rectifiers have a unitary power factor while charging the PEV, the Nissan Leaf is an example of this [31]. Previous investigations used different methods to evaluate how PEVs affect transformers, but all of them conclude that uncontrolled charging can overload them and severely reduce the their life. So TEMS and HEMS are needed to maximize transformer’s life.

2.4. Impact on supply-demand balance

A research work done in [16] reported a simulation study in the city of Perth, Australia. Authors considered 800,000 PEVs allocating them to zone substations in proportion to the number of customer connections. The generation forecast (2010–2019) for the city goes from 4950 MW to 6600 MW with a spare capacity of 136 MW to 242 MW. They evaluated the impacts in the sub-transmission and transmission systems and generation capacity caused by the addition of the PEVs and found two relevant considerations.

1) An average day (80% of peak load) can have 1087 MW and 1473 MW available. This could service a fleet of 572,000 PEV or a 59% penetration.
2) On an average day, without new generation, 41% of PEVs load needs to be shifted to off peak times, and on the annual peak day 93% of this load should be shifted.

They concluded that a range of rate structures and load control systems are needed to encourage off-peak charging. If this doesn’t happen a 100% penetration of PEVs could exceed the forecasted generation capacity.

Another study [32] on a typical distribution network from a voltage level of 33 kV to 400/230 V. Each 33/11 kV substation had six outgoing feeders, supplying eight 11/0.4/0.23 kV substations. Only one of the four feeders of these last substations was modeled in detail. Each 400 V feeder supplied 100 domestic customers where they could have a PEV. The authors used domestic summer and winter UK load profiles with 3 charging scenarios. The uncontrolled charging produced an increase of 18% in maximum demand for every 10% increase in the penetration level, and a full penetration level could lead to exceeding the forecasted generation. The controlled charging scenarios showed a reduction of 25% of the peak demand compared to the previous case.

It is relevant that power operators consider the future increase of load related to PEVs if they do not plan to use control strategies to minimize the peak load; this situation would be very expensive for the company. A better strategy consists of creating an improved price regulation that benefits off-peak charging with conjunction of energy management systems, like TEMS and HEMS, so peak load is reduced. This would bring benefits to both, the power company and the user.

Power utilities need to ponder the addition of PEVs while planning the growth of the grid in the future. If no consideration is done, transformers, distribution and transmission lines could be severely overloaded creating blackouts, which would represent huge penalties for the utility.

2.5. Impact on voltage regulation

A comprehensive study [18] modeled the IEEE 34-node test feeder connected to each phase of a 100 kVA transformer. When no PEVs were present the maximum load registered was 69 kVA. Two different program simulations were used to optimize power losses considering 0%, 10%, 20% and 30% PEV penetration.

A deterministic program used a common load profile with a flat voltage profile where node voltages were computed using the backward-forward sweep method. Later a quadratic optimization was done to determine the optimum charging profile. Some constraints were applied so the batteries would be charged to the maximum capacity in an allotted time considering their initial SoC.

A stochastic program used random 2000 profiles that could be selected for each node. The voltages were computed the same way as stated in the deterministic program.

The differences between the two models were minimum, so they concluded that using a common load profile could be implemented for all households. According to the standard EN50160, mandatory in Belgium, a maximum of 10% voltage deviation is acceptable for 95% of the time, so with a 30% penetration with uncoordinated charging this standard would be violated on winter evenings (18–21 h) as a 10.3% voltage deviation would occur in one of the nodes.

An investigation done on the Ada County, Idaho electricity grid was modeled with an expected load increase of 18% by 2040 [33]. They found that a voltage drop below 0.96 p.u. would be present if load increases as proposed, so they concluded that the implementation of a time of day incentive plan in conjunction with the systematic replacement of underrated devices could reduce the strain placed on the power grid by the charging of PEV’s batteries.

An analysis [34] used a typical UK distribution system as mentioned in [32]. For each substation there were 384 users. They modeled the PEVs as a load with real and reactive power consumption to find the voltage drop that produced penetration levels of 50% to 100%. Even at a low penetration level, authors found that statutory voltage violations happened at the remote end of the network.

More research needs to be done in a much broader scale because power systems differ from each other between countries, but there is a consensus that high power demand by PEVs leads to voltage statutory violations at some points in the grid and smart charging is required to operate the system efficiently.

2.6. Transient stability impact

PEVs charging should be coordinated with the power grid in an efficient manner to avoid transient disturbance. While the system has a low demand, electricity prices will be also low, so PEVs will charge. At some point electricity demand will increase and the prices will rise. This would lead to a sudden load change as PEVs will start to discharge to the grid, creating a voltage and frequency transient that could be prejudicial to the system. A similar event would occur when vehicles that are discharging suddenly, due to the electricity price step variation, start to charge.

A small-signal stability analysis, where the PHEV was modeled as a constant power load (CPL) and constant impedance load (CIL), was done in [35] applied to the New England 39-bus system. The principal case consisted of 10 generation units with a normal production of 6140.75 MW to supply 6097.1 MW to the loads. When PEVs were modeled as CPL the generators could increase their generation to 7106.05 MW in a short time, while modeled as CIL they could tolerate a maximum penetration of 7138.16 MW. These results are relevant, as more PEVs examined as CIL could be optimally dispatched when electricity prices change.

Other researchers [36] considered a PEV fleet as a power source. They simulated the Short Term Voltage Stability Index (SVSI) in the Reliability Test System 96 (RTS-96), 24-bus system, after a three-phase fault and concluded that the SVSI improved when considering the PEVs as a source rather than a load. However, nothing was said about an increase in short circuit current that may impact circuit breakers. This assessment is important for V2G when the PEV has capability to deliver power to the grid.

A transient stability analysis of the power grid [37], was done to establish the benefit of integrating superconducting magnetic energy storage (SMES) with V2G operation. SMESs principal contribution is that the time delay during charge/discharge is short but they suffer from high cost and can only afford to store limited amount of energy.

The system studied by the authors included of the following elements “the main grid was connected with a synchronous generator (SG) that fed an infinite bus through a double circuit transmission line. The SMES unit was connected to the main grid at the generator terminal bus. The SMES unit consisted of a thyristor based SMES and a SMES controller. Each PEV was connected to the power grid through a DC/AC power converter. Both the SMES controller and PEV communicated with the main grid operator”.

They presented an active-reactive power control based on the speed deviation of the turbine generator for the active power and the voltage deviation for the reactive power. They considered three cases with 5000, 10,000 and 50,000 PEVs, respectively. A three phase to ground (3LG) and a single phase to ground (1LG) short circuits were applied to each case in order to examine the system's response at 0.05 s and cleared at 0.25 s. Results showed that under the three phase to ground fault, the use of SMESs stabilized the system after 1 s and only permitted a voltage reduction to 0.6 p.u. for the three cases. For the single phase to ground fault the voltage just reduced to 0.85 p.u. and stabilized in around 0.75 s for the same cases. Finally, they concluded that both SMESs and PEVs can enhance the transient stability of power grid, but SMESs provide a higher contribution to the grid than PEVs.

Other authors [4] also studied, with a real-time digital simulator (RTDS) model, the impact of PEVs on distribution grid stability on a 12 bus system with 8 parking lots that had 800 vehicles, each. As stated before, there are two severe cases where grid's transient stability could be compromised. First, when the demand is low, prices are low as only the efficient generation technologies contribute to the incremental cost of the system. If power demand suddenly increases at peak hours, inefficient power plants need to be turned on and the price of electricity rises. At this moment PEVs will start discharging to the grid producing a transient event that will have an impact depending on the penetration level or dispersion in the grid of PEVs. The second case is the opposite of the first one, when prices are high and are suddenly reduced. At this moment PEVs will start to charge and produce a similar transient event. They proposed a wide area controller (WAC) structure to improve the stability of the power system, optimized to damp oscillations caused by the load change. Results displayed that under a 3-phase fault for 10 cycles at one of the buses; the system's stability might be regained in about 5 s.

Transient stability may be critical if electricity prices vary within the day as sudden swings in power could appear while PEVs change their loading conditions. This demand response can be balanced with pay as bid pricing [38].

2.7. *Integration of renewable sources with PEVs*

A research study [39] was done for a German environment using stochastic driving patterns, an optimization model to reduce charging costs and an agent-based electricity market equilibrium model to estimate the variability of electricity prices. Authors explored a 2030 scenario with fluctuating renewable energy generation from wind and photovoltaic with PEVs that can balance this generation. An estimation of the installed capacity of onshore wind, offshore wind and photovoltaic was supposed as 37.8 GW, 25 GW and 63 GW, respectively, and 12 million PEVs in the roads. One of their main contributions is that an avalanche effect could be created with automated devices that detect price signals, leading to demand or generation peaks. To reduce this effect, they propose that price elastic demand bids could aid the system by allocating PEVs recharging during low demand times. Also, there is an expected utilization of power from German offshore wind parks during the night, so this supports the recharging of PEVs during these hours, integrating PEVs with intermittent renewables.

The same authors compare, in other research paper [40], the German 2030 scenario to a California similar case using an agent based simulation model. For Germany a fleet of 12 million PEVs were contemplated, while 6.8 million in California. Also, the power/energy ratio of the total fleet for California and Germany was considered as 0.44. The capacity factors for the wind and photovoltaic generation were supposed lower in Germany than in California, so the installed renewable energy sources (RES) capacity as a percentage of the system peak load was 162% for Germany and 97% for California, and both scenarios had a 47% of energy production based on RES. Results showed that PEVs are more effective in California, specially with photovoltaic generation if the adequate recharging infrastructure is available where vehicles are parked during the day.

The amount of PEVs modeled in the previous studies might be an optimistic approach as in Germany there are only 43 million registered vehicles in 2013, according to KBA [41], and with no population increase this number would not increase significantly by 2030. If 12 million PEVs are reached by 2030, this will represent a 28% penetration. With this penetration it is expected that the PEVs connected to the power grid will be able to provide the energy backup needed by the intermittency of the power generated by wind and solar sources. Should this happen it will decrease the investment in renewable sources.

A cyber-physical energy system (CPES) consists in the interaction of physical variables, such as solar irradiation, wind speed, SoC, and intelligent computations and decisions carried out based on them. A published work, combined by an electrical and a thermal infrastructure that interact with communication devices from utilities and markets, was used in [42] to efficiently integrate renewable energy sources with gridable vehicles. This model consisted in a communication between the power supply and users so their needs are met, reduce costs and contaminant emissions. The authors state that PEVs with V2G and RES with CPES could enable this purpose. They analyzed a sustainable integrated electricity and transportation infrastructure with 50,000 PEVs comparing standard generation to vehicles with RES and PEVs by particle-swarm optimization for recharging and CPES. Results showed that the marginal costs and emissions would be significantly reduced, although a serious investment is required to apply this smart grid model.

The introduction of PEVs will aid the allocation of renewable energy, but it would depend on the natural conditions of each country the way it should be done. Some regions have a higher solar irradiation, so the PEVs could absorb this energy during the day, but wind energy might be higher at night, so in other areas charging at night would be more adequate. More economic models need to be developed to predict and minimize the costs that the introduction of this technology can represent to the power grid. Current research work [38,43–46] have already started to consider these factors. Recent technological advances in liquid metal batteries [47] will be substantial for the storage of huge amounts of renewable energy and its usage when the power grid needs it the most.

2.8. *Micro-grid interaction with charging PEVs*

A study based on a British Distribution Network was presented in [48]. Authors analyzed, first, a deterministic model with snapshots of five loading conditions, and second, a probabilistic model, with the following uncertainty variables (1) residential load profiles, (2) EV types, (3) EV charging equipment power rating and location, (4) EV charging connection time and duration, and (5) micro-generation (mGen). The deterministic results showed that voltage violations would occur under minimum load with high PEV penetration (71%), the distribution transformer would be overloaded for minimum load with medium (33%) and high penetration levels, and with maximum load for all levels, and power losses could reach an 8% and 10% under minimum and maximum loading conditions, respectively.

The probabilistic model proposed several cases to upgrade the distribution network; the most important one is the integration of mGen in each household comprising of 1.1 kW of average power rating. Results showed that winter is more severe with the network, showing that voltage statutory violations would occur for medium and high penetration. A 100% of mGen might reduce the voltage violations for high penetration from 100% probability to 60%. mGen would not help for the transformer overloading in winter for high penetration, but it reduces the probability for low (12.5%) and medium penetration levels. Also, power losses with mGen can be reduced about 1%. The authors conclude that with high penetration of mGen sources, and smart control of battery charging would eliminate the probability of voltage violations at low level and the transformer overloading probability may be reduced from 85% to 5%.

Another study pondered the introduction of a micro-grid (MG) in a low voltage domestic system [49]. The MG considered by the authors consisted in a micro-turbine, a fuel cell, a wind turbine and five photovoltaic (PV) arrays. The network comprised three feeders: one serving a primarily residential area, one industrial feeder serving a small workshop and one feeder with commercial consumers. Three penetration levels were considered (2, 4 and 10 PEVs) with a battery capacity of 7.5 kWh and a SoC of 50% within departure, and a random charging duration profile was used to determine the uncertainty of each battery SoC while arriving at home. The charging scenarios of EVs that were considered are economical charging and uncontrolled charging.

In the uncontrolled charging scenario, PEVs load just increased the peak load, so the MG could not cope with all the demand at medium and high penetration levels, particularly in winter. During economical charging pattern, users charged during the night, encouraged by lower prices. This reduced the peak load for the MG for all levels, meaning that little to none energy was required from the utility at peak times for the charging.

Table 4
1 C rate cost structure.

Level	Range (kWh/month)	Unitary cost (USD/kWh)
Basic	1–150	0.0551
Intermediate low	151–300	0.0649
Intermediate high	301–450	0.0828
Excess	> 451	0.2214

Micro-grids will be relevant in the near future, as they would become an enhancement of current power grids. Voltage deviations, transformer overloading and power losses could be considerably reduced because local generation may help shave peaks generated by the charging of PEVs. Also, DC micro-grid can reduce power losses involved in the conversion of DC to AC from the photovoltaic panels, and later from AC to DC to charge PEVs or other household electronic equipment. The setback of distributed generation in micro-grids consist in the aggregated uncertainty on their power output, so new methods are being devised based on the simultaneous consideration possibilistic and probabilistic uncertainties [6].

3. Economic benefits of domestic photovoltaic generation

There are some countries, such as Mexico, where the introduction of photovoltaic domestic generation could help in the reduction of the grid's load while charging PEVs. This would be economically viable for some users since some cities have a significant solar irradiation that might lead to a lower investment; also, the prices of electricity are based on sliding scale rates for domestic users, so it is simple to calculate the savings and unitary cost of electricity.

One of the most common rates in Mexico is the 1C [50]. In summer there are four levels of pricing based on a range of energy consumption. The first one, called “basic”, has a range from 1 kWh to 150 kWh per month, the second is called “intermediate low”, which goes from 151 kWh to 300 kWh the third is named “intermediate high” and has a range from 301 kWh to 450 kWh, and finally the “excess”, which consist in the rest of the kWh. Table 4 presents the unitary costs of electricity for the month of August 2014 considering a rate of change of 13.05 Mexican Pesos per US dollar.

If any user exceeds 850 kWh/month average in a year the pricing automatically changes to a more expensive rate called DAC (Domestic High Consumption) [51], which has a fixed cost of 0.2700 USD for each kWh. It can be noted that each kWh is more expensive than in 1C where the cost is highly subsidized by the government.

For example if a user has a Chevy Volt that has a capacity of 16 kWh and recharges 50% of the battery everyday, it would consume 240 kWh per month. If this energy were added to the household load most users certainly will fall out of the subsidized rates, and forced to pay DAC prices.

Two cases were considered for analysis in the city of Monterrey:

1) A user that consumes 1000 kWh/month considering household loads and a single PEV.
2) A user that consumes 2000 kWh/month considering household loads and two PEVs.

The city has a solar irradiation of 5.1 kWh/m^2 [52] and a photovoltaic panel (PVP) with an area of 1.6 m^2 and 16% efficiency were selected. Under this condition each panel would generate 39.168 kWh/month. Also, the PVP has a nominal capacity of 250 W and it is sold in Monterrey at a cost of 4100 USD/kW in July 2014 (considering the PVP, the inverter, batteries and meter).

For the first case, the user needs to reduce his consumption in 150 kWh/month to return to 1C rate, so he/she needs 4 PVP to accomplish this task (Eq. (5)).

$$\#\ \mathrm{PVP} = \frac{1000(\mathrm{kWh/mo.}) - 850(\mathrm{kWh/mo.})}{39.168(\mathrm{kWh/mo.} - \mathrm{PVP})} \approx 4\mathrm{PVP} \tag{5}$$

The investment required would be of 4100 USD, as shown in Eq. (6).

$$P = (4100\ \mathrm{USD/kW})(0.25\ \ \mathrm{kW/PVP})(4\ \mathrm{PVP}) = 4100\ \ \mathrm{USD} \tag{6}$$

Considering an interest rate of 8% per year and a payment time of 120 months the monthly payment would be 49.74 USD/month (Eq. (7)).

$$A = (4100\ \ \mathrm{USD})\left[\frac{(0.08/12\ \ 1/\mathrm{mo.})(1+0.08/12)^{120}}{(1+0.08/12)^{120}-1}\right] = 49.74\ \mathrm{USD/mo.} \tag{7}$$

And the unitary cost of electricity would be 0.3175 USD/kWh (Eq. (8)).

$$\mathrm{UCE} = \frac{49.74(\mathrm{USD/mo.})}{(4\ \mathrm{PVP})(39.168\ (\mathrm{kWh/mo.}))} = 0.3175\ \ \mathrm{USD/kWh} \tag{8}$$

Certainly the price for the PV generation is more expensive than the DAC rate, but the rest of the energy could be cheaper. The new utility cost would be of 117.66 USD/month as shown in Table 5 compared to 270.00 USD/month if no PVP were installed. The savings would be of 152.34 USD/month and the simple payback period (SPP) of 2 years 3 months (Eq. (9)).

$$\mathrm{SPP} = \frac{4100\ \mathrm{USD}}{152.34(\mathrm{USD/mo.})} = 26.91\ \mathrm{mo.} \approx 2\ \mathrm{years,}\ 3\ \mathrm{mo.} \tag{9}$$

For the second case, the user needs to reduce his consumption in 1150 kW h/month to return to 1C pricing, so he/she needs 30 PVP to accomplish this task (Eq. (10)).

$$\#\ \mathrm{PVP} = \frac{2000(\mathrm{kWh/mo.}) - 850(\mathrm{kWh/mo.})}{39.168(\mathrm{kWh/mo.} - \mathrm{PVP})} \approx 30\ \mathrm{PVP} \tag{10}$$

The investment required would be 30,750 USD, as shown in Eq. (11).

$$P = (4100\ \ \mathrm{USD/kW})(0.25\ \ \mathrm{kW/PVP})(30\ \mathrm{PVP}) = 30,750\ \ \mathrm{USD} \tag{11}$$

Considering the same interest rate (8% per year) and payment time (120 months), the monthly payment would be 373.08 USD/month (Eq. (12)).

$$A = (30,750\ \mathrm{USD})\left[\frac{(0.08/12\ \ 1/\mathrm{mo.})(1+0.08/12)^{120}}{(1+0.08/12)^{120}-1}\right] = 373.08\ \mathrm{USD/mo.} \tag{12}$$

The unitary cost would be of 0.3175 USD/kWh as in case one. The new utility cost may be of 113.46 USD/month as shown in Table 6 compared to 540.00 USD/month if no PVP were installed. The savings would be of 426.54 USD/month and the simple payback period (SPP) of 6 years (Eq. (13)).

$$\mathrm{SPP} = \frac{30,750\ \mathrm{USD}}{426.54(\mathrm{USD/mo.})} = 72.09\ \mathrm{mo.} \approx 6\ \mathrm{years} \tag{13}$$

Comparing both cases, it can be seen that both users would benefit from the installation of PVP, but user one can recover his investment in a much shorter time. Also, user two needs a much larger area to install the PVP that maybe could make the project unfeasible.

To sum up, the installation of PVP can be beneficial to users in countries with sliding charging rates and have a medium to high solar irradiation. The utility could also benefit because little to none investment would be required by this users when they introduce PEVs and PVPs.

4. Analysis of a electric distribution system

A distribution system was examined in SimPower Systems from MATLAB based on a simplified design of the Mueller community in Austin, Texas. For this case, the frequency domain was chosen to simulate the sinusoidal steady state power flows as it enables the evaluation of large periods of time with much less computational requirements than time domain analysis. Also, a realistic study in time domain needs detailed models of the electric circuitry of the loads (Photovoltaic Arrays, PEVs charging infrastructure, etc.). The disadvantage of frequency domain analysis is that harmonic distortion cannot be assessed, and power electronic models cannot be introduced in the system.

4.1. Characteristics of the electric distribution system

The Electric Distribution System is connected to a main substation modeled as an infinite bus power source with an RMS voltage of 13,800 V, and by an overhead three-phase Pi line of 10 km of length with its parameters shown in Table 7. A 10 MVA maximum power flow was supposed for the system and at the end of the three phase overhead cable, groups of communities are connected but only one of them is modeled in detail and the rest are considered as a lumped load with a constant power demand of 1 MW and a power factor of 0.85 lagging.

Table 5
User one monthly payment.

Level	Energy (kWh/month)	Unitary cost (USD/kWh)	Cost (USD/month)
Basic	150	0.0551	8.27
Intermediate low	150	0.0649	9.74
Intermediate high	150	0.0828	12.42
Excess	394	0.2214	87.23
Total	844		117.66

Table 6
User two monthly payment.

Level	Energy (kWh/month)	Unitary cost (USD/kWh)	Cost (USD/month)
Basic	150	0.0551	8.27
Intermediate low	150	0.0649	9.74
Intermediate high	150	0.0828	12.42
Excess	375	0.2214	83.03
Total	825		113.46

Table 7
Positive and zero sequence resistance, inductance, and capacitance for the main feeder.

Parameter	Positive	Zero
Resistance (Ω/km)	0.23949	0.41274
Inductance (H/km)	1.0499×10^{-3}	4.9712×10^{-3}
Capacitance (F/km)	0.1115×10^{-9}	4.1778×10^{-9}

Table 8
Transformer equivalent circuit characteristics.

Capacity (kVA)	Loaded losses (W)	No load losses (W)	Series impedance (%) @ 85 °C
50	105	404	2.3
75	167	456	2.5
100	181	683	2.5

Three types of transformers are considered with a rating of 50 kVA, 75 kVA, and 100 kVA. All of them have a primary voltage of 13.8 kV, and the secondary is formed by two split 120 V windings that give a 240/120 V voltage with the parameters presented in Table 8 [53]. Each transformer is connected to a different number of homes with distinctive load profiles, as some of the households have photovoltaic arrays on the rooftops, and have different power demands for air conditioners (AC). The plug-in electric vehicles can be charged with the most typical electric installations in the United States, which are:

- A Level 1 slow charging at 960 W and 120 V single phase.
- A Level 1 medium charging at 1440 W and 120 V single phase.
- A Level 2 fast charging rate at 3600 W and 240 V single phase.

The slow charging power might be recommended for Plug-in Hybrid Electric Vehicles with batteries in the range of 5 to 8 kWh, the medium charging power for batteries ranging 10 to 15 kWh, and the fast charging for 20 to 25 kWh. Three phase chargers might be required for batteries with higher capacities like the Tesla Model S with a maximum capacity of 85 kWh.

The distribution system under study comprises of 100 homes with randomly allocated Chevy Volts and PVs. These houses are connected to 8 distribution transformers of different capacities, five of 50 kVA, two of 75 kVA, and one of 100 kVA transformers are connected to 10, 15, and 20 houses, respectively. Also each home has a range of air conditioner power demand, going from 1 to 3 kW and power factor between 0.9 and 0.94. Table 9 summarizes the charging power at unity power factor of the PEV (if any), and the photovoltaic maximum power (if any). All the PEVs have a battery capacity of 16.5 kWh, as the Chevy Volt, and alternate their charge with the use of air conditioner.

In total there are 33 PEVs and 35 PVs for these 100 homes. This kind of penetration levels might not be seen today in distribution systems, but in the next 10 years the use of these devices will increase, particularly in some segments of population where they will cluster at certain neighborhoods.

Table 9
House PEV and PV characteristics.

House	PEV (kW)	PV (kW)	AC (kW)	House	PEV (kW)	PV (kW)	AC (kW)
	Transformer 1 (50 kVA)				Transformer 2 (50 kVA)		
1	3.6	4	1.9	1	3.6	3	2.2
2	0	0	2.9	2	0	0	2.4
3	0.96	3	2.4	3	1.44	4	1.4
4	1.44	3	1.9	4	0.96	4	2.9
5	0	0	2.1	5	0	3	1.1
6	0	2	3.0	6	0	2	1.0
7	0	0	2.4	7	0	0	1.8
8	0	2.5	1.0	8	0	0	1.0
9	1.44	0	1.8	9	0	0	1.8
10	3.6	4	2.3	10	3.6	0	2.4
	Transformer 3 (75 kVA)				Transformer 4 (75 kVA)		
1	0	0	1.0	1	0	0	1.1
2	0	0	3.0	2	3.6	5	2.4
3	1.44	5	1.3	3	0	0	1.3
4	0	4	1.3	4	1.44	0	2.4
5	3.6	3	1.2	5	0	0	2.5
6	0	0	1.4	6	0	0	1.6
7	0	0	1.7	7	0	0	2.7
8	0	0	1.8	8	0	0	1.6
9	0	0	2.7	9	0	0	1.8
10	3.6	4	2.3	10	3.6	3	2.9
11	0	3	1.9	11	0	4	2.1
12	1.44	0	1.7	12	0	0	1.3
13	0	0	1.2	13	0	0	2.1
14	0	0	2.0	14	0	0	1.8
15	0	0	1.3	15	1.44	3	2.2
	Transformer 5 (50 kVA)				Transformer 6 (50 kVA)		
1	0	0	1.9	1	0	0	2.6
2	3.6	5	2.7	2	3.6	4	2.1
3	0	0	2.5	3	0	2	1.6
4	0	2	2.5	4	3.6	4	2.5
5	0.96	0	2.6	5	0	2	1.9
6	1.44	0	1.7	6	0	0	2.9
7	0	0	1.2	7	0.96	0	1.9
8	0	0	1.2	8	0	0	1.6
9	0	0	1.9	9	1.44	0	3.0
10	3.6	4	2.3	10	0	0	1.8
	Transformer 7 (50 kVA)				Transformer 8 (100 kVA)		
1	0	0	1.5	1	0	0	1.2
2	0	0	2.3	2	3.6	5	2.1
3	0	0	2.8	3	0	0	1.6
4	0	0	1.3	4	0	0	1.1
5	3.6	4	2.9	5	0	2	2.0
6	0	0	1.8	6	0	0	2.4
7	0	0	1.1	7	0	4	2.2
8	1.44	0	2.1	8	0	0	2.2
9	0	2	2.0	9	0	0	2.8
10	0.96	0	2.4	10	3.6	2.5	2.8
				11	0	0	2.0
				12	0	0	1.8
				13	0	0	1.8
				14	1.44	3	2.6
				15	0	0	2.8
				16	0	0	1.8
				17	0	0	2.5
				18	0.96	0	2.1
				19	3.6	5	3.0
				20	0	0	1.5

4.2. Controlled charge scenario

There are many forms of coordinating the PEV charge in order to reduce the system's power demand. One form is to monitor the transformer temperature with Transformer Energy Management Systems (TEMS) that send control signals to the Home Energy Management Systems (HEMS) to increase or reduce the power consumption. This type of coordination requires more complex systems but might be the best way to extend transformer life.

A simpler solution is to coordinate the charging of the PEV within the house. For example, interposing the charging of the vehicle with the air conditioner load cycles can reduce the peak load of a household. Meaning that the PEV charges when the air conditioner is off and stops charging when it turns on. The setback of this is that it might take longer to charge the electric vehicle, and at lower charging powers the battery might not charge completely.

The charging model designed considers this intercalation of the air conditioner with the PEV and also a charge delay mode. The delay mode means that the user establishes the time of the next departure, so the vehicle estimates the time it needs to be fully charged based on the arrival state of charge. For this case a random variable was used with estimated departure times from 7 to 9 am. Eq. (14) shows how the starting charging time is calculated with a 30-min correction if the user has to depart some minutes earlier.

$$t_{\text{start charge}} = t_{\text{depart}} - 30\ \text{min} - \frac{\Delta \text{SoC} \times \text{Battery Capacity (kWh)} \times 60\ \text{min}/\text{h}}{(1-\text{AC Duty Cycle}) \times \text{Power Charging Rate (kW)}} \tag{14}$$

To clarify this charging method (Fig. 4), consider a Chevy Volt, with SoC limits of 0.2 to 0.85, that arrives at home around 7 pm with a state of charge of 0.39. Since this is during the peak hours, the vehicle discharges the remaining energy until it reaches a SoC of 0.2. During this discharge period it can be noted that the power given is equal to the same of the air conditioner needs (1.9 kW). Then, the PEV is idle from 8:30 pm to 3:45 am; at this point it starts to charge at a rate of 3.6 kW, intercalating it with the air conditioner. The PEV acquires a SoC of 0.85 about 45 min before its departure at 8:50 am.

Fig. 5 shows the aggregated demand for 3 days of transformer no. 1 homes. The first plot depicts a voltage variation from 116.75 to 113.90 V, or a critical voltage regulation of 5.08%. The middle plot shows a reverse power flow during the day as the PVs are introducing to the grid a higher power than what the home consumes. The maximum load occurs around 7:30 to 8 pm with a peak of 40.8 kVA, so this transformer can be loaded an additional 18.4%. Also there is a slight increase in power due PEVs after midnight, but it is not near the maximum load, meaning that the control strategy used helps to reduce the impact of PEVs on transformer as the power demand of air conditioner and electric vehicles do not correlate. The third plot shows the power factor, which varies substantially when PVs are generating during the day. Previous works [54] have already explained this phenomenon. At certain moments, the home power consumption and the PVs power generation are almost equal, so the real power flowing

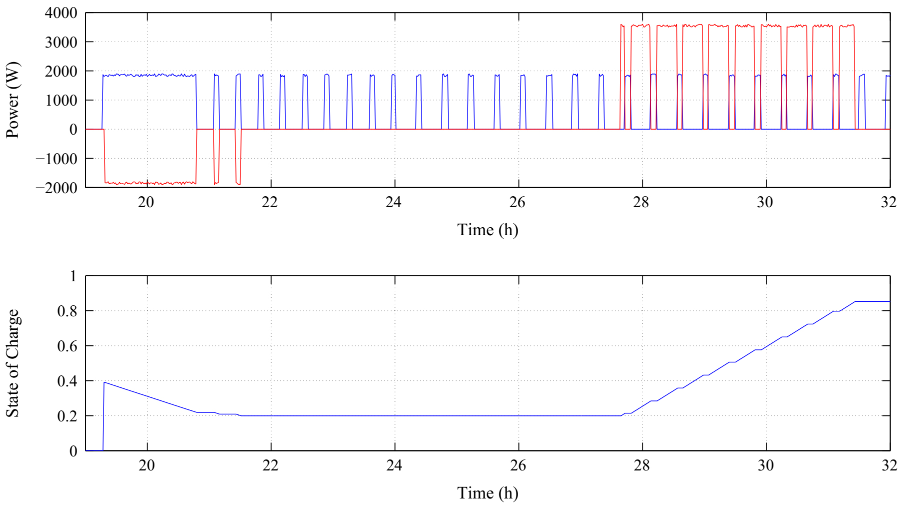

Fig. 4. Charge coordination with PEV with air conditioner for house 1 and SoC. (a) AC (blue) and PEV (red) power demand. (b) PEV's state of charge. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

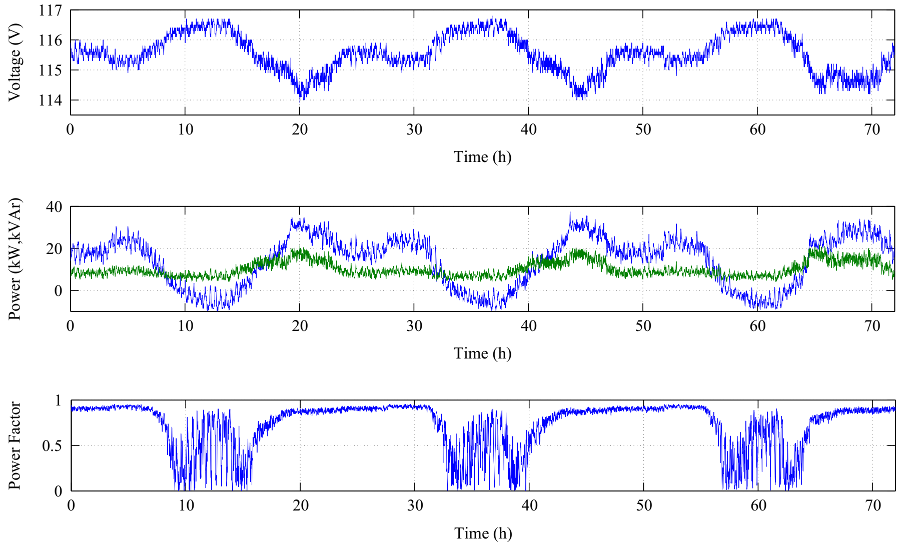

Fig. 5. Distribution transformer 1: (a) voltage, (b) real (blue) and reactive power (green), and (c) power factor. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 10
Controlled charge scenario main results.

Transformer	V_{max} (V)	V_{min} (V)	P_{max} (kW)	P_{min} (kW)	S_{max} (kVA)	S_{min} (kVA)	Average PF with PV	Average PF without PV
1	116.75	113.90	37.43	−9.83	40.76	4.57	0.585	0.907
2	116.68	114.19	37.66	−7.31	41.80	4.50	0.557	0.901
3	116.92	115.21	51.02	−5.69	58.88	6.23	0.561	0.896
4	116.78	115.18	51.04	−1.63	56.42	6.60	0.691	0.898
5	116.60	113.85	40.25	−2.87	44.36	4.23	0.650	0.902
6	116.69	114.06	41.03	−3.50	45.06	4.24	0.610	0.903
7	116.49	113.94	37.87	2.29	43.04	4.96	0.785	0.899
8	116.58	113.75	75.72	−4.88	87.00	8.79	0.633	0.895

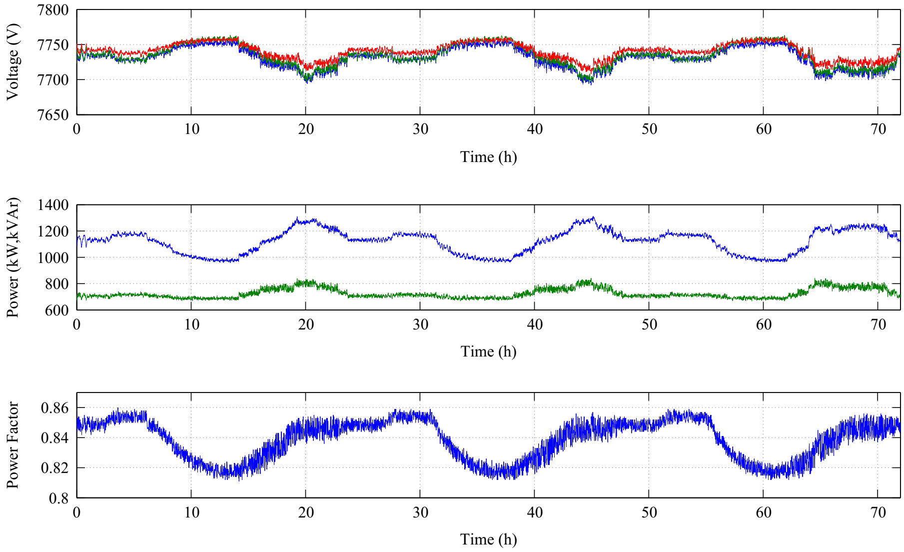

Fig. 6. (a) Phase to neutral voltages at feeder's end, substation, (b) real (blue) and reactive power (green) and (c) power factor. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

through the transformer is near zero. During the rest of the day the power factor is around 0.9.

Table 10 summarizes the maximum and minimum values for transformer voltages, real and apparent power, and power factor average value while PVs are generating and when they are not. None of the transformers have terrible voltage regulations as they only reach a maximum 5% regulation for some minutes a day. The real power varies significantly for every transformer as they have different capacities, and it should be noted that some transformers have little to none reverse power flow as they have a lower penetration of PVs. This can be directly related with an average power factor taken during the daytime hours, and its effect on the feeder's power factor.

With 100 houses, the main feeder is lightly loaded, as the maximum line current is 67.3 A for some minutes a day. Since house loads are single phase, there is a current unbalance for each of the phases that create a voltage unbalance in the feeder. For this scenario the current unbalance has a maximum value of 3.90%, which occurs at peak time. During low demand the current unbalance is below 2%. Fig. 6 shows the phase to neutral voltages at the end of the feeder. Between 7 and 8 pm a maximum voltage unbalance can be seen in Fig. 6(a), with a maximum value of 0.16% for the three days.

As stated above, PVs introduce in distribution systems is a reduction in power factor in the main feeder during daytime as real power flow is reduced, but the reactive power remains almost constant. Fig. 6(b) also illustrates the variation in the power flow through the feeder and this reduction in power factor with a minimum of 0.811 lagging (Fig. 6(c)).

5. Conclusions

This paper explores the main challenges electric vehicles will introduce to power grids in the near future. Even though, many variables are being measured, there is a high uncertainty related with the charging infrastructure at home, user mobility, battery technology and capacity, and market penetration. Micro-grids are a potential enhancement of distribution grids as local generation can help reduce peak loads as PEVs charge when users charge their cars while arriving at home. Also photovoltaic domestic generation for the micro-grid could present a potential benefit for users in countries with sliding scale energy pricing, and medium to high solar irradiation, such as Mexico.

Simulation results indicate that a coordinated charging for plug-in electric vehicles reduce the load at peak time, most of them where working under 80% during peak demand. The benefit of the controlled scenario allows a future allocation of PEVs to these transformers without the need of replacing them with others of higher rating. Voltage unbalance problems did not arise, as it should not be considered an intrinsic problem produced by PEVs or PVs. Voltage unbalances usually are produced by not having a correct distribution of the loads in each phase.

Photovoltaic panels reduce the transformer load during the day, as they supply most of the power needed by the homes. With the penetration level selected, most of the transformers produced a reverse power flow, so the homes were providing power to the grid. This change in power flow through the transformers reduces the feeder's power factor, so corrective measures should be considered for higher levels of PV penetration, such as reactive power support, VAr compensators or community energy storage.

Future work will be dedicated to improving the simulation analysis in time domain as to explore the importance of harmonics and transient events in the distribution system. Also a community energy storage model will be developed, which might enable a better use of the energy available throughout the year.

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