Impact of Electric Vehicle on Power System Operation: Technical Overview

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Abstract

Nowadays many sector promote electric vehicles' (EV) use in light of declining fossil fuels and increasing greenhouse gases, however there are many concerns about the reliability, security and stability issues in the power grid. Will the infrastructure be able to handle that mobile and no constant demand? What are the major concerns about equipment life span? Is the power grid smart enough to deal with this transition?

This paper seeks to show, through a literature review, the most important issues regarding EVs penetration in the medium and long term.

***Index Terms*—Electric vehicle, state of charge,batteries, distribution networks, renewable energies, electric mobility**

I. INTRODUCTION

The research and in-depth analysis of all diverse topics associated with EV are product of not only the need to reduce greenhouse gases but also the need to look for tools and alternatives that help to develop a more dynamic and integrated network. This integration can benefit load curve's control, the energy market and improve the application of smart metering systems. Trying to cover in a comprehensive manner the entire group of conceptual elements that are part of the study of EV within our electrical system is not an easy task; however this paper presents, in a general way, the state of the art of all the elements that play a significant role during the interaction between the network and the EV.

This paper presents the current status for EVs integration and shows the problems related to its implementation in the distribution network. The paper is divided in 5 chapters; chapter II covers all the different available models of chargers and batteries for EVs. Chapter III presents the impact that EVs cause on the distribution networks and identify the problems related to peak demand, transformers and power quality. Chapter IV identifies the problems related to voltage and frequency stability on transmission networks. Finally, the conclusions are shown in chapter V.

II. MODELS BATTERIES AND CHARGERS

The models use to analyze EVs performance have been different in both application and complexity. Those models describe two main elements in the EV: The charger and battery.

Early studies regarding charger's model included potential problems analysis while the EV was connected with the network. [1] mentions a series of requirements to satisfy design optimization and solve future drawbacks related with signal conversion during EV plug-in.

Today most of the studies focus on developing a simulation tool that reflects batteries behavior using physicochemical characteristics. Many authors have grouped them into three types of batteries, the models are defined based on simulation needs and number of known and un-known variables.

[2] identifies three models: experimental, analyticaland electric. Other studies consider the experimental modelthe sameelectromechanicaland the analyticalmodelequal to themathematical. Nevertheless, the electric model doesn't have any change [3].

The experimental model uses different equations to simulate the electro-chemical process in the battery and involves intensive computation to solve complex equations [2]. Electromechanical models are used to optimize batteries physical designs, describe the fundamental mechanism of energy generation and bridge the simulation gap between macroscopic (current and voltage) and microscopic (concentration distribution) parameters [4].

Analytical or mathematical models simulate an approximated response in the batteries behavior using mathematical representation and ignoring all electrical characteristics[2]. Those models only work for specific applications and provide results with errors between 5% and 20%.

Electric models are used to represent the electrical characteristics of the batteries. They use a combination of voltage sources, resistors and capacitors for simulation purposes. The use of these models in conjunction with other systems and circuits reduce complexity during batteries design process.

To sum up, the electric model can be divided into three categories: Thevenin, impedance and discharge time model as seen in Fig.1 (a), (b) and (c) respectively.

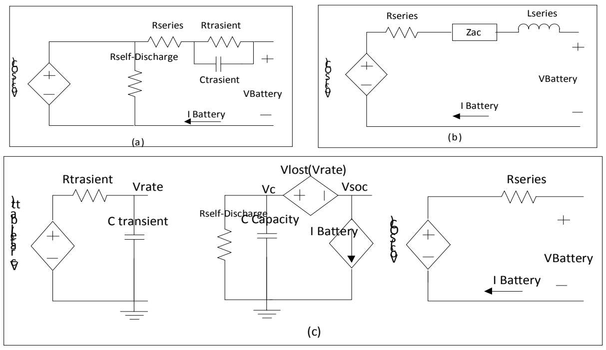

Fig.1Electric Models (a) Thévenin. (b) Electric Impedance (c) Discharge Time Model [4].

III. IMPACTS ON THE DISTRIBUTION GRID

Nowadays the distribution grid is represented as a passive network [5] that transfers energy without any kind of control mechanism. However, the new modifications that EVs produce and the introduction of more intelligent grids change this old statement. These modifications have a strong impact in the system and promote uses of advance solutions from all kind of engineering.

These new network changes are reflected in: elevated demand consumes through the low voltage (LV) grid, high load peaks in the daily load curve, adverse impacts on certain circuit elements, e.g. transformers, protection elements, etc. and adverse impacts in power quality during the early stage of the incorporation.

A. PEAK DEMAND

One of the most significant factors whileplugging EVs is the increase of peak loaddemands, which is reflected in high current flows through lines, transformers, protective devices, and evidently in currents and energies generated inside all the rotating machines. From this point [6, 7] focus their studies on different load demand curve variations during diverse years.

This scenario attracts attention because there is a significant number of EVs with power magnitudes greater than those of traditional loads in residential areas (1kW) [8, 9]. The authors talk about vehicles with an average power ranging between (1.4kW-6.6kW) [10] for systems connected to 120V 60Hz single phase and an average range of (4.4kW-6.8kW) for those plug-in with single phase connectors to 240V 50Hz [10]. The result of these studies [7-9, 11-13], provide possible scenarios before connecting a large number of EVs. From the above, [7, 14]define the existence of two types of patterns for EVs charging:

1) Uncontrolled Charge

This scenario provides an uncontroled EV plugging as desired by the customer. [15]states that the vehicles will be connected following the classic patterns of user mobility. E.g. the owner or driver will connect the EV while is not in operation and most commonly during night hours or "off-peak" hours. Featuring two main problems: First, the increase in the energy price during peak hours. Second, reducing cables and transmission lines life. All this reflected in constant and excessive machine utilization and leading to constant updating and replacement of circuit elements.Fig.2 shows an example of an expected load curve

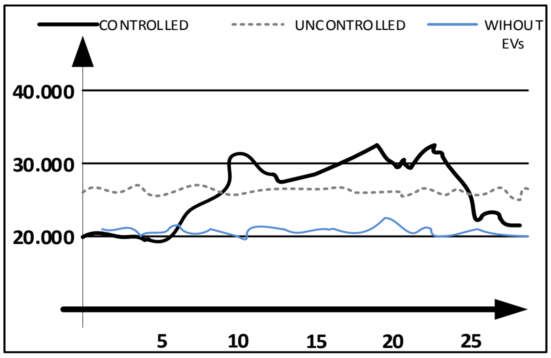

Fig.2 Example of a load curve for different controlled and uncontrolled EV plugging patterns [7]

2) Controlled Charging

On the other side, a controlled charging scenario presents conditions such as economic incentives for the user. So that the EVs owner chooses to connect the vehicle when the energy price is not high[1][16, 17].This produces a flattening on the load curve and reduce, as already mentioned, electrical stress in the distribution lines. This behavior avoids the constant infrastructure updating and increases prices in both contracts and spot prices, in the electricity market.

This charging method proposes two types of smart charging (SmartGrid) [7]:

<u>Step Charging:</u> is a charging pattern in which the EVs are connected in stages, e.g. there is no any possibility for simultaneous network connection for all the vehicles. Some vehicles are connected during night time when the peak load curve present a negative slope and another in the early morning hours when previously connected aggregates have already been charged.

<u>Proportional Charging:</u> this is a charging pattern where EVs are connected inversely to the load curve, e.g. there will be more vehicles in areas where the curve appears flat and vice versa. It provides a connection between 00:00 -08:00

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[1] This can be achieved because EVs are constantly connected to the network so the battery chargers can program their control algorithms to connect the EV in those zones with low-energy prices

and 14:00 and 18:00. Fig. 3 show how these factors can influence the load curve [16].

B. TRANSFORMERS UNDER EV PLUGGING

The proliferation of EV chargers connected to the transformer terminals, Fig. 4, plays a relevant role on power losses increase and at the same time decreases the transformer's life expectancy. In particular[12] shows a system of 1200 nodes, which represent a modified IEEE 31 nodes (23kV) and a series of low voltage busbars with real distribution loads on the Western Australia. The study assess losses within transformers. Other studies show decreases on transformers life span for residentialareas [7, 15].

1) Transformer losses

[12, 15]perform a transformers analysis when different percentages of electric vehicle are integrated in the grid. For this, the authors propose studies comparing the current load status of the system before EVs connection. The studytakes record of the losses and current flows in the machine, and then evaluates all the changes due toEVs penetration increased[7, 12, 15, 18, 19].

These studies take typical load curves for distribution systems and compared them with future load profiles after EVs insertion, Fig.2 [16, 17].

As expected, with the merge of EVs in the grid, a noticeable demand increasedappears in the transformers. Such an increased is higher than the normal, resulting in undesired currents that overload the machine and produce higher losses in the transformer and the network.

In[7, 20] a study case shows how with different EV penetration levels between 2% and 42% the transformer may reach winding losses increases up to 390% and total losses increases approximately of 300%. These models of current sources for the inclusion of EVs includes a complete description that merge not only the main current magnitude but also includes the main harmonics in the battery [20].

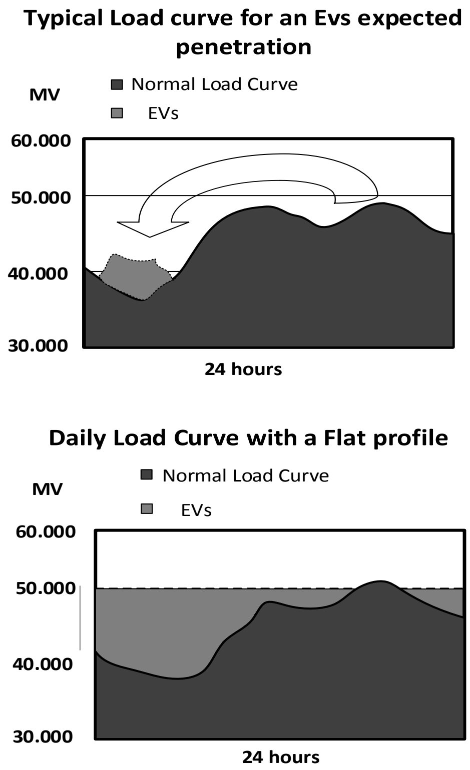

Fig.2Comportamiento de la curva de carga bajo el escenario de incorporación controlada deEVs[16, 17].

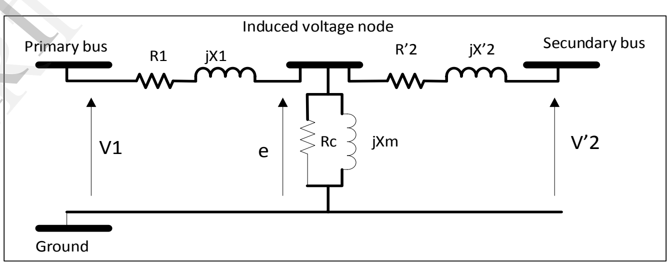

Fig. 4 Transformer model for losses calculation[12]

In these scenarios, [7, 12, 19]show that although the transformers are well designed for other types of demand, different from the EV, these can be overloaded with EV introduction,overreaching the thermal limits and decreasing the life span for the machine.

[12]also shows the absence of voltage variations in the transformer's secondary because their magnitudes are given for an upper transmission voltage level. As a result, only the low voltage terminal appears as the most impacted terminal because the voltage dip has a direct relation with the distance to the main feeder, the voltage drop increases as the distance to the common point to the transformer increases (in this case, customers are considered far away from the main feeder in the distribution network). Finally, the study showed that when penetration of electric cars becomes 30% voltage regulation exceeds tolerable limits of 10% variation, a commonly undesired limit.

2) Thermal overloading and life span reduction

Another crucial characteristic evaluated in transformers during EVs penetration is the transformer's temperature analysis[2], this is an important feature to assess the transformer's life span.

A key point in the transformers design is the study of the hot spots inside the machine. Because the entire temperature in the machine is not constant the designer only focuses on those specific points which are commonly overheated during transformer's operation. This temperature value is calculated from two variables, the load in the transformer and the temperature on the environment, facts that deteriorate the insulation inside the machine.

[15, 20]shows a direct relation between the temperature and the load in the transformer. These studies determine the life per unit, the aging acceleration factor in the machine and the percentage of life span reduction due to increased temperature of the hot spots. As a result, the index show a considerable life span reduction with a large among of plug in EVs.

C. POWER QUALITY

In this area studies have developed analysis related to long-term electromagnetic phenomenon, especially on issues related to the waveform distortion.

The main problems associated with this phenomenon are generally: Additional Losses (additional transformers heating), increased resonance risk for capacitor banks, decreased motor rated torque and mechanical oscillations.

In the three phase transformers case the losses due to wave's deformation are generated mainly in the copper [18]andare 6% greater than those withoutthepresence of harmonics.

Recent studies suggest some solutions to reduce harmonic losses such as the possibility of using active rectifiers (filter rectifier) which replace the rectifier diodes and produce a sinusoidal line current with unity power factor, or placing compensating units parallel to the loading station to cancel harmonics originated in the rectification process[18]. Fig. 5 [21] illustrates the current flow directions in the presence of a nonlinear load (power harmonics). As observed in the Fig., harmonics are injected to other loads and the source.

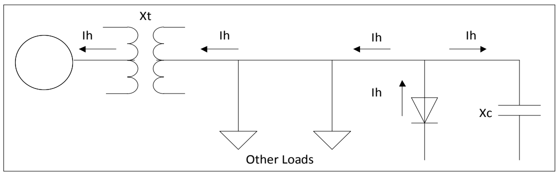

Fig.3Current harmonics flow

To control the harmonics network injection or the harmonics network demand, some studies suggest control strategies as the BSSC (Balanced Sinusoidal Current Source)[2].

In the presence of EVcharging malfunctioning, an inside system failure condition can causedistortioninthe waveformthat may be spread out intothe network[22]. This type of failure is not normally detected by the protection over current system, so a substantial EV increase could significantly increase the fault current magnitudes in the local network[22].

Other authors focused their studies on software development. Programs that relate the transformer life span with battery characteristics and charging algorithms. Those studies found direct quadratic relationship between transformer life span and the THD for battery charging current. The same study concludes that is necessary to limit the maximum THD for currents between 25% and 30% in order to preserve transformer life[19].

On the other hand, the latest power electronics advances provide the possibility of constant voltage level independent of load variations control, removing small interruptions, manage demand (e.g.the load can be controlled using voltage control), etc. Additionally, there are other studies which applied power electronics to protection systems, allowing quick answers to fault conditions [23].

D. PROTECTIONS

When EVs are considered to be small generators connected (V2G)[3]in times of need, an inherent fact is the recalculation of elements such as the protections for transmission and distribution systems.

The EVs are a special type of distributed generators(GD)[24].Unlike synchronous (SG) and induction generators (IG), the most of these devices are coupled to the grid by power converters and inverters[25]. A result of this is thatin the presence of a fault the GS and GI have a greater impact, because they can feed electrical failure longer thanEVs Chargers (0.02 to 0.25 cycles), this characteristic causes heating in the conductors, damage to electrical machines, loss of synchronism among the generators, etc. On the other hand, the reference [4] shows that the current magnitudes produced during a fault with EVs plugged in are about 2-4 times the rated current, allowing easy control. All this factors are reflected in low currents supplied under fault scenarios.

However, [26] considers that although these values were presented as non-dangerous for the protection systems andconductors, it is necessary to observe the EVs not only individually but also as aggregate groupswith rising penetration, this penetration will be high in 2020 [4].These groups will present problems similar to those expected with DG. For that reason, it is necessary to see how theEVs

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[2] At this point it is noticeable that combination of various parameters such as humidity, temperature and oxygen mixtures are the most relevant that reduce transformer's life span. However, advances in transformers oil reduce equipment damage and make the moisture and oxygen mixtures not considerable. For that reason, temperature is a determinant factor in transformer's life span.

[3] Concepto introducido por el profesor WilletKempton de la Universidad de Delaware.

[4] An estimated value of more than 40% penetration has much more drastic changes than expected with values under this reference.

lotsconnected to the network can lead to different problems[21, 27, 28]:

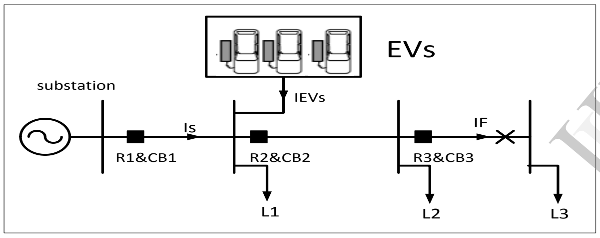
- ✓ False feeders opening(Sympathetic tripping)
- ✓ False generator tripping.
- ✓ Relay miss-operation
- ✓ Fault currents increase or decrease
- ✓ Poor coordination of protective devices.
- ✓ Inability of automatic reclosing.
- ✓ Creating of unwanted isolated areas.

A detailed description for each of the preceding impacted factors in DG is explained in [28]. For this paper,only one of the most outstanding cases is explained:

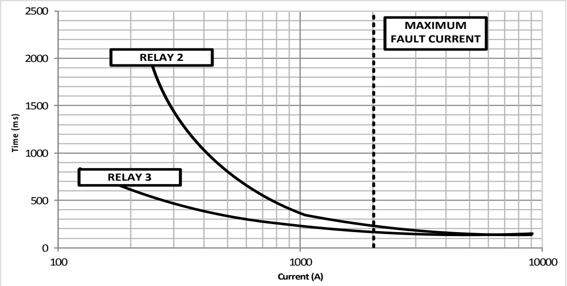
Fault currents Increase-Protective devices miss-operation

Fig. 6 illustrates the protection system response when a radial feeder supplies an EV aggregate. The diagram shows a network composed of a substation and three lines, each line has an overcurrent protection, this is activated by having a current greater than an already set up threshold.

In this case an increase in fault currents (IF) is capture through the relay 2 (R2). Initially,$IF = I_S$, however with the use of EVs$IF = I_s + \mathbf{IEVs}$. This fact generates the necessity of protective equipment parameters recalculation, since protection devices were not previously designed for those larger currents e.g.causing relays miss-operation and miss-coordination, factor that may become dangerous for relays, circuit breakers, fuses, reclosers and transformer currents.



a) *Radial system under EV aggregates*



b) *Curves for relays coordination*

Fig.4Fault current under presence of EV aggregates

E. ANCILLARY SERVICES

In addition to the well-known traditional services that EVS provide while are considered as mobile cars, they can also provide different services that some authors recognize as ancillary services (AS)[9, 11, 22, 23, 29-32]. Among the examples of ASone remarkable service is the use of the EV to provide energy in an specific zone, this case has been recognize as *dynamic islanding*,which refer to the creation of small distribution areas provide energy in an independent form.Those areas are integrated by battery storage systemsthat provide support during emergency situations[11, 33]. The AS are shown as possible incentives that may counteract the largepeak demand increases in the electric power network and can offer an improvement respectreliability and stability for distribution systems[9, 11, 34]. Those alternatives may be incentives to promote the introduction of EV for energy markets in transmission networks [[35]].

Other functions show the EVs as: *possible reactive compensators* [36, 37],that may be charged or discharged with power factorsdifferent to the unity; *active powergenerators* [38-40], that actas spinning reserves or reserve electric power able to supply an entire home; and finally as controlled loads that can offer demand response services[39].

1) Peak power supply

With EVs introduction,[11] demonstrates that future variations in the system load are considerable not only in the load curvebut also in the peak of the curve[41] while using uncontrolled charging patterns[7, 15] (Section III).

Under those aspects the EVs energy storage for future supply is a motivated solution that capture the interest of multiple engineers(*V2G orVehicletoGrid*) [9, 11, 29, 42]. To illustrate the idea, the EV could discharge its battery in zones with low load factors[5], in other words the EV would supply energy in on–peak times. E.g. [11] describes a case study in the state of California, where with a progressive insertion EVs the state could reach power reserve in the order of 424MW in 2004 and 1GW in 2008[6][7].

In [9, 11, 29, 42]the authors also performed the same type of study, and mentioned three important factors when using the EVs:

- ✓ Time spent for the vehicleplugged into the grid. This will determine the battery aging.
- ✓ The minimum electric power that must be stored in the vehicle for both local travel and for emergency scenarios like travel to hospitals, etc.
- ✓ The profitability to the power distribution company.

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[5] Load Factor (LF)Being an important index that relatesthe average power of the load curve and the peak power. So that a LF close to 1 shows a flat load curve; on the other hand, one LF close to 0 or away to 1 describes a system with many peaks demand.

[6] In this case the author makes an estimate with all the EDVs (Electric Drive Vehicles) of the California State.

2) Spinning reserve

The energy reserved by some units for quick responsein cases where power variations require additional electric power is identified as spinning reserve[43, 44].

This type of service is paid in interconnected power systems (IPS), based on two main factors[9]:

- ✓ Thecapacity for spinning reserve.
- ✓ The total time that the generator can provide those reserves

For example a unit that can provide a reserved power of 1 MW for 1 h, it is said that offers a spinning reserve of 1 MWh, which as mentioned will be paid according to the regulations.This type of incentive is not paid only for the time that the unit feeds the power grid, but also is paid by the time that the unit is available to support contingencies such as the failure of a unit, considerable load variations, or power supply during on-peak moments, etc.

In this sense the EVs could have a large field of action being used as elements constantly connected to the grid, elements that individually have reduced energy, but in groups of "aggregates" may supply considerable electric power to the IPS[11, 30, 45]. In response, the users of EVs can get a great benefit for only maintain your vehicle connected to the charger, without being constantly discharged , which avoids battery damage and motivatesthe owners for ancillary service provision.

3) Supply of reactive compensators

Among the most important forms of compensation we have the shunt and series, but the more conventional for EVs and the system reliability is the shunt compensation, because this is a simple way to connectand allows local compensation. So, the distribution systems are most benefited, this is because they are the closest to the chargers of EVs [46]. This same type of compensation allows distribution companies to maintain the voltage within permissible limits.

According to [36, 37] the compensation in the loading state is the most attractive because it has the lowest requirement for battery.

IV. IMPACT ONTRANSMISSION NETWORKS

Although[6, 9-11, 28, 39, 47] do not perform a deep study on EV'stransmission networks (TN) impacts, those mention some possible remarkable problems as: increasing peak load(**Error! Reference source not found.**), reflected in new line current magnitudes;leading to a transformers life span reduction(**Error! Reference source not found.**) and problems associated with the protection response (0), in the last case it is emphasized that although the transmission networks are not radial, they will have thesame problem respect coordination and selectivity in protection systems due to power flow variation when charging the EV lots.

Additionally, [6, 48] perform a frequency and voltage stability analysis.

A. FREQUENCY STABILITY

Frequency stability is defined in [49]as the system capacity to maintain a stable frequency after suffering a significant imbalance between generation and load. WithEV insertion the relationship between power generated and power consumed will be affected [6, 9, 47]. This means that the traditional power consumes at homes will increase by over 100%, the studies consider home power consumes in the ranges of 0.8-1kW while EVs around 4.4kW [6, 9, 32, 39].For this reason, uncontrolled load increments would present considerable frequency variations[7].

Some authors [6, 9, 23, 50,51]propose potentialstrategies to controlthese phenomena, for example frequency control using EVs(**Error! Reference source not found.**). Basically,whenthe system reach states belowthe required limit, the system operator could make alert oneof the EV aggregatesand requestthemto disconnect,

in such a waythat reduces systempower consumptionandthe frequencyis restoredto its nominal value. In the opposite case, whenthere exist powerexcess, the system operatorcould makea request forEVs plug-in. All thisis done so thatthe system frequency recovers acceptable values.

From this picture EVaggregatescanbe observedas possiblesystem reserves, offering frequency regulation[9, 11]. The differenttypes ofregulationcouldbe affected bytheEV's in the following way:

1) ***Primaryregulation*** *(reply (0-10s), power supplied time (30s)):* This scenario is the most suitable for implementation [6, 9, 52], because the EVs can supply electric energy in short frame times. Those times can beachieved withcontrolcharger mechanism.

2) ***Secondary regulation****:* [9] This type of regulation requires long times EV plug in, thereforethis scenario is not viable because of the cars batteries cannot supply the power that for long terms.

3) ***Tertiary regulation:*** [52-54]:This scenario proposes controlled EVs connection and disconnection to achieve optimal system power flows, however this is dependent on variables such as the time that EV's will be connected to the grid, the geographic positioning and the amount of power to be delivered. These factors are summarized in the battery storage capacity.

B. VOLTAGE STABILITY

Voltage stability is an important aspect for reliable and secure power system operation, although not many authors mention the problem, some others [40-42] consider possible voltage stability issues in transmission and distribution grids [50] with a representative increase of EV's. The main problems are related with uncontrolled phase angles between current and voltage in the chargers the can finish in unstable voltage profiles.

V. CONCLUSIONS

- Although current studies demonstrate that EVs connected to the network provide great benefits to their owners through the provision of ancillary services, the lack of incentives to batteries’ producers and chargers manufacturers do not allow easy implementation due to associated cost.
- While ancillary services contribute to the power system dynamics and provide benefits to EVs’ owners and demand in general, it is necessary to make a complete study of the impact of massive entrance of these vehicles in protection devices and their coordination.
- Although there are a variety of methodologies to evaluate EVs connection to the network, typically the algorithms are based on parameters such as voltage and losses in lines; therefore it is necessary to extend the field of research to take into account parameters such as estimation of representative aging factors or the permissible power quality limits of the network.
- There is a great expectation over the future of flexible loads like electric vehicles. However, several more studies have to be done in order to avoid any inconvenient related to the network.

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