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Stochastic Approach to Assess Impacts of Electric Vehicles on the Distribution Network

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Abstract-- **With the rapid growth of electric vehicles connected to the distribution network, which are in general low voltage network, the development of a simulation tool becomes necessary in order to determine the limit EV penetration level, to assess impacts of EV integration on a distribution network and opportunities contributed by EV. In this paper, a simulation tool based on a probabilistic three phase Load Flow (PLF) program has been developed and combined with EV usage scenarios simulated by using Monte Carlo techniques. By using this tool, technical and economic impacts of EV integration on the distribution network are assessed. Studies of the potential opportunities of ancillary services provided by EV are also carried out. Low voltage rural and urban networks are used for these studies.**

Index Terms-- **Electric vehicle, LV network, stochastic approach, impact, services**

I. INTRODUCTION

RECENTLY, there has been a rapid growth of electric vehicles (EV) connected to the grid. Electric vehicles (EVs) play an important role in the transition towards a cleaner energy future. The intersection of energy and automotive sectors and the Smart Grid potential given by electric mobility is followed with great interest [1]. In France in 2020, this enthusiasm for electric vehicles will result in the consumption of 4 to 5 TWh of electricity per year - for 2 million electric vehicles [2].

The connection of a large number of electric vehicles to the grid can raise several technical problems or can have significant impacts on power systems such as mentioned in [3-13]:

- Changing the load profile of the network with an increase in peak demand
- Increasing the risk of congestion (overload)
- Changing the voltage profile
- Increasing the voltage unbalance between phases
- Increasing losses
- Increasing harmonics on the network…

Marketing of electric vehicles will be accompanied by energy services to be offered to customers. These energy services are based on the battery of electric vehicles that offers an opportunity for energy storage to the power grid. Studies are needed to understand the constraints and technical and economic opportunities provided by electric vehicles.

The purpose of studying EV penetration to the network is to:

- Assess technical and economic impacts of EV charging on power systems
- Study the ancillary services with the help of a simulation tool to measure the impacts and opportunities for the network, users, and vehicle manufacturers
- Evaluate the intelligent management of charging and services such as V2H (Vehicle to Home) or V2G (Vehicle to Grid).

To accomplish these tasks, in our work a simulation tool with a probabilistic three phase Load Flow (PLF) program has been developed and coupled with a simulation of EV usage using Monte Carlo techniques.

A better knowledge of the induced constraints becomes necessary in order to determine the EV penetration level and to assess impacts of EV integration on the distribution network. This simulation tool can be used to estimate technical and economic constraints and opportunities associated with power flow passing between electric vehicles and power grids. The model integrates the physical modeling of electrical networks, taking into account technical and economic criteria.

Loads in distribution grids are highly unbalanced. This is why in the developed simulation tool, modeling of all three phases is carried out in order to provide a good estimation of feasible EV integration, in particular to assess the allowed EV penetration level for a given network by maintaining voltage and current within limits.

Considering the probabilistic nature of the EV charging combined with the one of loads, a probabilistic approach is therefore used by using Monte Carlo techniques. By using the developed tool, studies to assess impacts and opportunities of EV integration on the LV (Low Voltage) distribution networks are carried out.

II. DEVELOPMENT OF THE SIMULATION TOOL

From random variables of EV charging such as the battery SOC (state of charge), the starting time of charging, then location of VE, a probabilistic three phase Load Flow (PLF) is

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developed by using Monte Carlo techniques as shown in Fig. 1.

Two modes of simulation can be realized with this tool:

- Deterministic simulation: all parameters are fixed (including the location, EV SOC and starting time of charging)
- Monte-Carlo simulation: set of simulations are performed, some parameters are defined as random variables such as SOC, starting time of charging, location of EV…

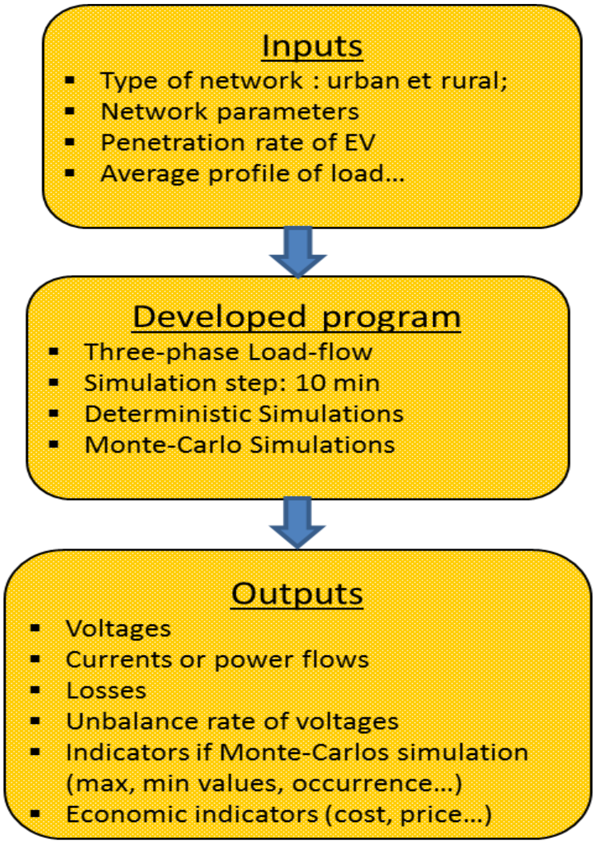


Fig. 1: Description of the methodology

In order to assess impacts of EV on the distribution network, the following indicators are proposed:

- Indicators related to power flow in lines, cables or transformer (S/Sn: actual power/rated power)
- Indicators related to the minimal voltage (V_{min} = 0.9 pu) and the maximal voltage (V_{max}=1.1 pu)
- Indicators related to unbalance voltage rate (V_2/V_1: Inserve voltage / Direct voltage)
- Indicators related to variation of losses
- Indicators related to economic criteria (charging cost).

In particularly, the neutral currents and losses in neutral conductors are also calculated. The program also shows:

- Max or min values of these quantities and their occurrences ;
- Distribution of over-voltage, under-voltage or overcurrent (overload)
- .Critical instants and locations (buses) in the network.

The developed tool based on the Monte Carlo simulation has the following advantages:

- A three-phase load flow program with a fast calculation
- A simulation which takes into account the unbalance between phases (single or three-phase loads)
- An ability to determine the voltage unbalance and losses in neutral conductors
- The identification of critical time, locations (buses) and occurrence probability of EV charging
- A simple analysis of results with the help of proposed indicators.

There were several papers written about this topic, but most of them use MV networks this is why several hypotheses are used. Only a few papers studied this problem on LV network but the unbalance and losses in neutral are ignored [7; 13 and 14]. The proposed program allows an assessment of the impacts of EV on distribution network and also the determination of critical EV penetration rate. This tool can be used for education to see the real behavior of EV charging procedure and to propose smart interaction mechanisms between EV and the network.

After identifying the critical cases by using the developed tool, solutions can be developed end re-evaluated in particular to avoid the congestion, to maintain voltage within standard limits…

III. MODELING

A. LV Distribution Networks

Most EVs are connected to the LV network, either in single phase (normal charge) or three phase (fast charge). Therefore modeling of a three-phase low voltage network is necessary. With the different characteristics of the two types of LV distribution network (rural and urban network), impacts can be different. In order to study impacts of EV on LV distribution network, in this paper two networks are used:

- Rural network as shown in Fig. 2
- Urban network as shown in Fig. 3.

LV rural network

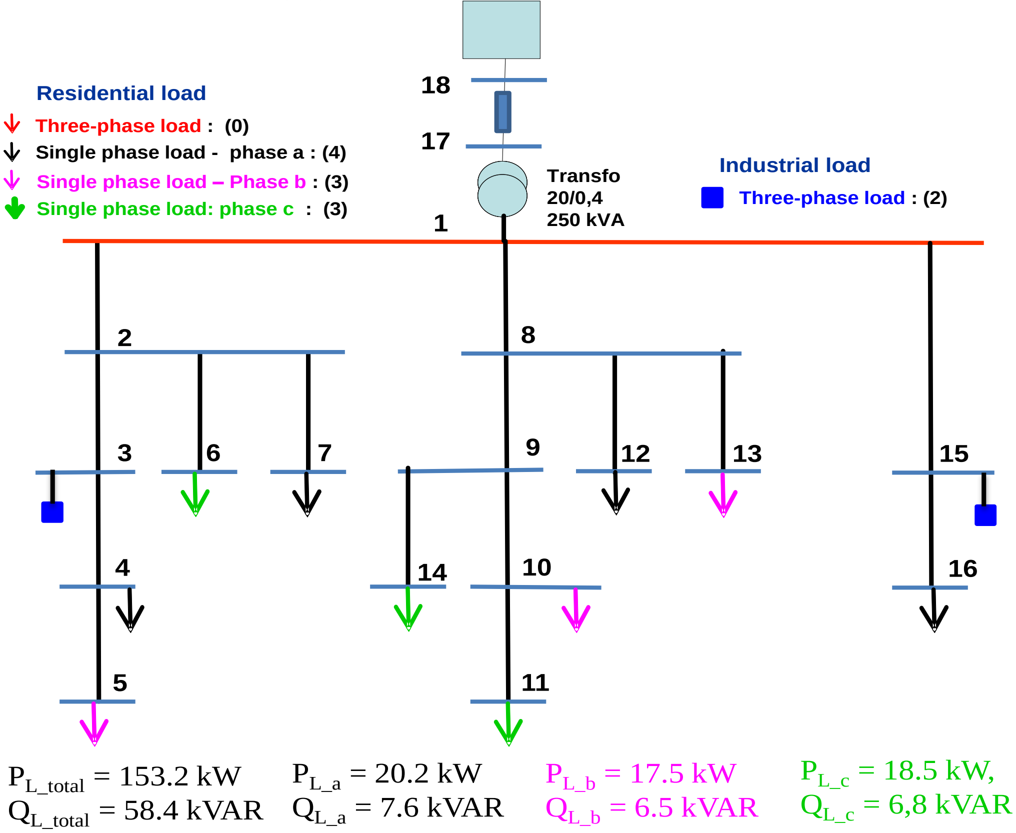
The LV rural network is supplied by a 20/0.4kV, 250 kVA transformer with a total power of 153.2 kW and 58.4 kVAR. This network consists of 18 buses, 10 single phase residential loads and 2 three-phase commercial loads. Three-phase commercial loads are connected to bus 3 and bus 15. Single-phase loads are connected to other buses. These loads and EV are distributed as following:

- 20.2 kW, 7.6 kVAR and 4 EV on phase a (buses 4, 7, 12 and 16)
- 17.5 kW, 6.5 kVAR and 3 EV on phase b (5, 10 and 13)
- 18.5 kW, 6.8 kVAR and 3EV on phase c (6, 11 and 14)
- EVs with fast charging (buses 3 and 15).

LV urban network

The LV urban network is supplied by a 20/0.4kV, 630 kVA transformer with a total power of 532.5 kW and 213 kVAR. This network consists of 85 buses, 71 single-phase and 7 three-phase residential loads and one three-phase industrial load. Three-phase industrial loads are connected to bus 83. Single-phase loads are connected to other buses. These loads and EV are distributed as following:

- 145 kW, 58 kVAR and 26 EV (slow charging) on phase a
- 128 kW, 51.2 kVAR and 23 EV (slow charging) on phase b
- 122.5 kW, 49 kVAR and 22 EV (slow charging) on phase c
- 7 EV with fast charging (bus 83).



P_{L_total} = 153.2 kW, Q_{L_total} = 58.4 kVAR

P_{L_a} = 20.2 kW, Q_{L_a} = 7.6 kVAR

P_{L_b} = 17.5 kW, Q_{L_b} = 6.5 kVAR

P_{L_c} = 18.5 kW, Q_{L_c} = 6,8 kVAR

Fig. 2. LV rural network with VE

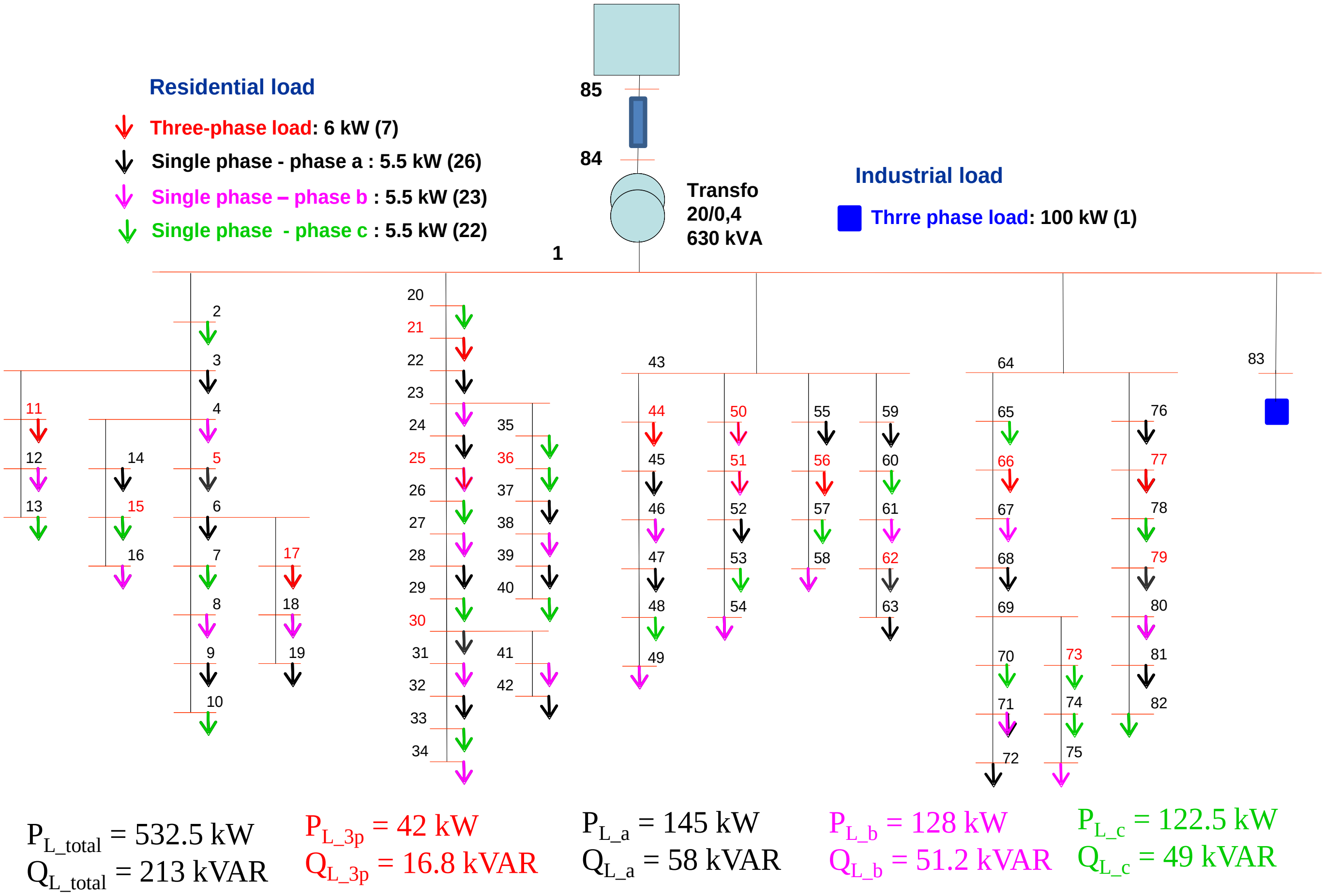


Fig. 3. LV urban network with VE

B. *Load Modeling*

Two kinds of load are concerned by this simulation: residential and industrial (commercial) load (Fig. 4). These load curves are almost the same for different countries. The residential load reaches peak values between 17 and 20 H. The industrial load reaches peak value at 7H and varies slowly between 7 and 18 H.

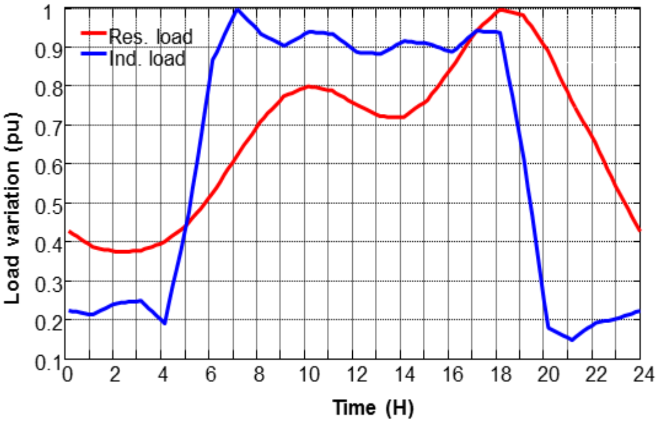


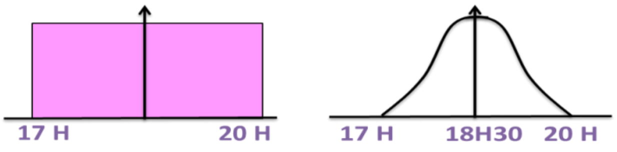
Fig. 4: Daily load curve for residential and industrial loads

C. *Electric Vehicle Load Modeling*

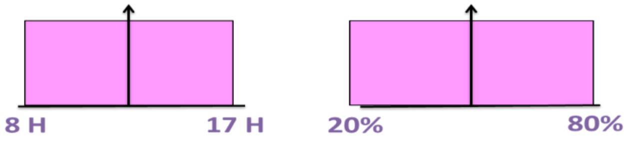
In our study, two types of charging are considered: slow (3 kW) and fast charging (43 kW). It is assumed that the process of electric vehicle recharging is randomly determined by two variables:

- The charging start times
- The EV battery state of charge at the charging start time.

For slow charging, it is assumed that the power is constant during the charging time (3 kW or 2.1 kW). The charging start time of the EV follows a uniform distribution (Fig. 5.a) or a normal distribution (Fig. 5.b) between 17 and 20 h (or 22-24 H) with a charging time as a function of the state of charge at the instant of charging. The initial state of charge is a random variable described by a uniform distribution (Fig. 5.d). The SoC at the instant of charging is assumed to be independent from the charging time. The slow charging corresponds to the EV charging at home (residential).



(a) (b)



(c) (d)

Fig. 5: Distribution of charging start time and EV SOC

For a fast charging, it is assumed that the power is constant during the charging time and about 43 kW. The charging start time of the EV is a uniform distribution (Fig. 5.c) between 8 and 17 h. The fast charging corresponds to the EV charging in parking.

D. *Tariff model*

To economically evaluate these different solutions, two tariff models are proposed (Fig. 6):

- Peak/off-peak tariff
- Dynamic tariff.

The peak/off-peak tariffs are fares currently in use in France. The dynamic tariff is built from the tariff of RTE (transmission system operator in France) by taking into account the distribution tariff.

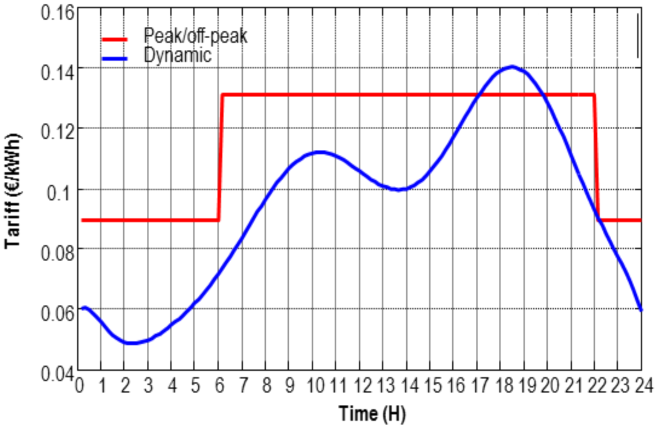


Fig. 6: Dynamic and peak/off-peak tariff

IV. SIMULATION RESULTS

By using the developed tool, several scenarios are carried out to assess impacts of EV on the distribution network. In this part, we present only two cases: a deterministic simulation for the rural network (Fig. 2) and Monte-Carlo simulations for the urban network.

A. *Deterministic simulation for the rural network*

For this case, 10 EV with residential slow charging (3 kW, 25 kWh) and 6 EV (buses 3 and 15) with fast charging in parking (43 kW, 25kWh) are connected to the rural network (Fig. 2).

The distribution of EV, the instant of charging and the charging time are shown in Table I. After simulation, the EV charging energy, the costs for dynamic and peak/off-peak tariffs are obtained in Table I. For example, the EV connected at bus 4 in phase a starts charging at 18h40 with a charging time of 1h20. This EV consumes 5 kWh corresponding to 0.68 € for dynamic tariff or 0.66 € for peak/off-peak tariff.

Fig. 7 shows active and reactive power of total load and those of transformer. Fig. 8 shows losses on three phases and neutral. Voltages in the network for phase c are presented in Fig. 9. The distribution of violation of the minimal voltage (0.9 pu) of buses and the distribution for critical time are shown in Fig. 10.

TABLE I
SCENARIOS OF EV CHARGING, ENERGY AND COST

	Mode	Bus	Instant (H)	Duration (H)	Energy (kWh)	Cost(€) Dyn	Cost (€) Peak/off Peak
Phase a	**Slow**	4	18H40	1H20	5.00	0.68	0.66
		7	17H00	4H20	13.50	1.74	1.77
		12	17H20	1H50	5.50	0.76	0.72
		16	17H00	2H40	8.00	1.10	1.05
Phase b	**Slow**	5	19H20	2H20	7.00	0.82	0.92
		10	17H30	4H40	14.00	1.77	1.84
		13	17H30	2H40	8.00	1.09	1.05
Phase c	**Slow**	6	18H20	2H10	6.50	0.88	0.85
		11	17H30	5H20	16.00	1.92	2.01
		14	17H30	6H00	18.00	2.08	2.19
Ph. abc	**Fast**	3	15H30	0H20	14.33	1.65	1.88
		3	13H00	0H30	21.50	2.15	2.82
		3	15H40	0H20	14.33	1.58	1.88
		15	11H10	0H20	14.33	1.58	1.88
		15	11H40	0H30	21.50	2.37	2.82
		15	10H10	0H30	21.50	2.37	2.82

The results obtained by simulations show that:

- The occurrence of overload is small (only in case of two EV with fast charging at the same time at 15h40 as shown in Fig. 7)
- There are problems of voltage (Fig. 9) during the peak load (17-20H), see also Fig. 10b;
- Losses in neutral are increased (Fig. 8), in particular during a large number of single-phase EV connected to the network;
- Critical buses for voltage are identified at buses 10, 11 and 14 (Fig. 10a)
- Heavy load period (17-20H) is critical for voltage (Fig. 10b). For 1000 simulations, the number of voltage violations (< 0.9 pu) are 12, 19 and 11 at bus 10, 11 and 14, respectively. It shows that the maximal occurrence is observed in bus 11 between 17H00 and 18H30.

The same deterministic simulations are carried out for the urban network.

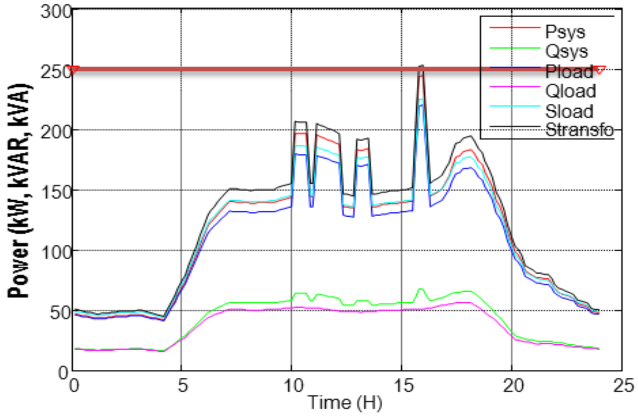


Fig. 7. Power flows of transformer, total load and provided from source

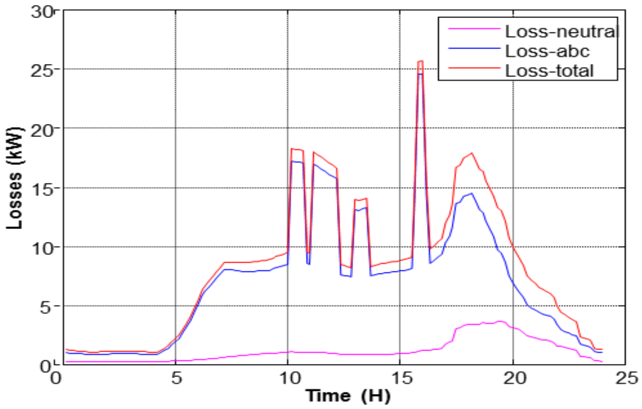


Fig. 8. Losses on three phases, the neutral and total losses

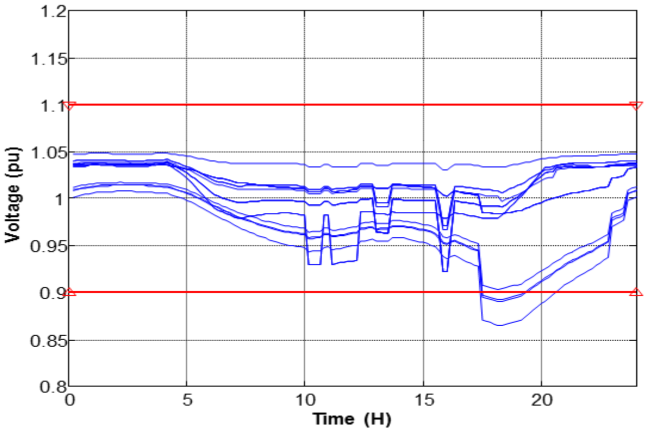
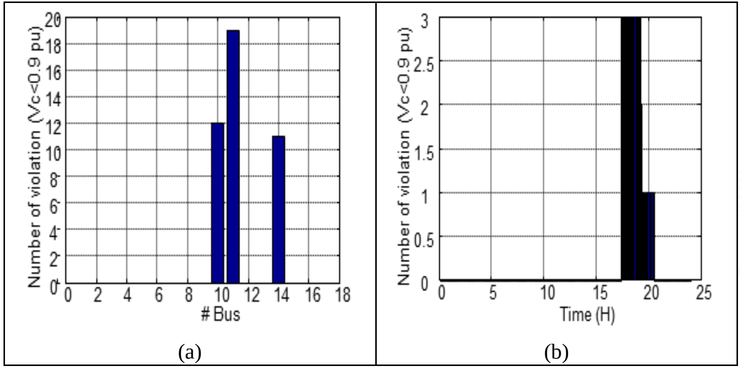


Fig. 9: Voltages in phase C



(a)

(b)

Fig. 10. Distribution of violation in voltage (<0.9 pu)

B. Monte-Carlo simulation for the urban network

In this case, the initial load of system is 600 kVA (S_transfo=630 kVA). In case with 100% VE penetration rate, 71 EV slow charging (26 EV in phase a, 23 EV in phase b and 22 EV in phase c) are used for the simulation. The power of EV is 3 kW. The Monte-Carlo simulation with 1000 simulations is carried out by using the developed tool for each scenario. There are four scenarios:

- 0% EV: no EV
- 30% EV: (30%*71=21 EV randomly distributed)
- 60% EV: (60%*71=43 EV randomly distributed)
- 100% EV: (100%*71=71 EV).

The three random variables considered here are the charging starting time, the SOC at this time and the location of EV (for cases of 30% and 60% EV penetration rates).

The results obtained by simulations show that:

- There are overloads with EV penetration rate superior to 20% EV (Fig. 11) – 20% correspond to 20%*71EV=14EV;
- There is no problem of voltage (Fig. 12) in all cases;
- Fig. 13 shows the variation of voltage in three phases and the variation of transformer power transformer is presented in Fig. 14. It shows that from 500 simulations the variation of voltage and power of transformer is stable.

Several solutions to prevent the congestion and voltage problems have been carried out. In order to compare the performances of different solutions, the following cases are simulated by Monte-Carlo simulation (1000 simulations):

1) Ref. case: Reference case with an initial load of 600kW (100% EV)
2) 40%S case: 40% EV accept to shift the charging after 22H00 instead of between 17 and 20H00;
3) 100%S case: 100% EV accept to shift the charging after 22H00
4) 50%Q case: EV participation to reactive compensation – The maximal reactive power of EV can be 50% of EV rated power (each EV of 3 kW can provide up to 1.5 kVAR)
5) 40%S+50%Q case: 40% EV accept to shift the charging after 22H00 and provide reactive compensation
6) 2.1 kW case: Power of EV is decreased to 2.1 kW (instead of 3 kW).

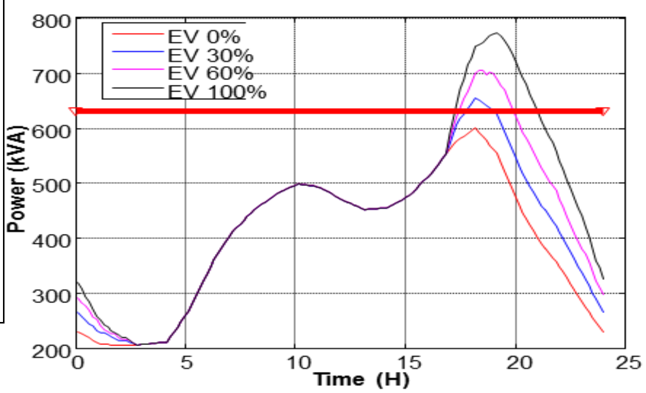


Fig. 11. Power flows of transformer, total load and provided from source

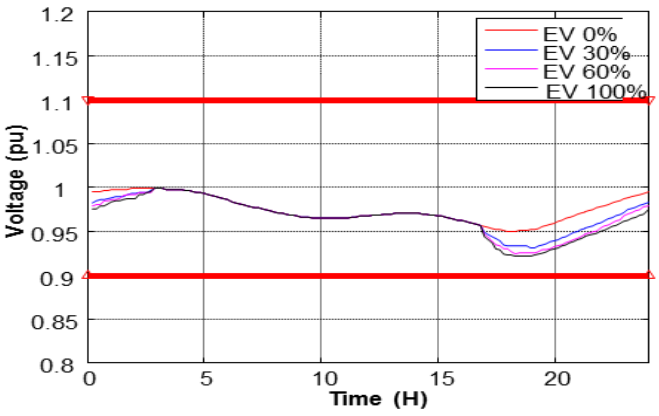


Fig. 12. Minimal voltages

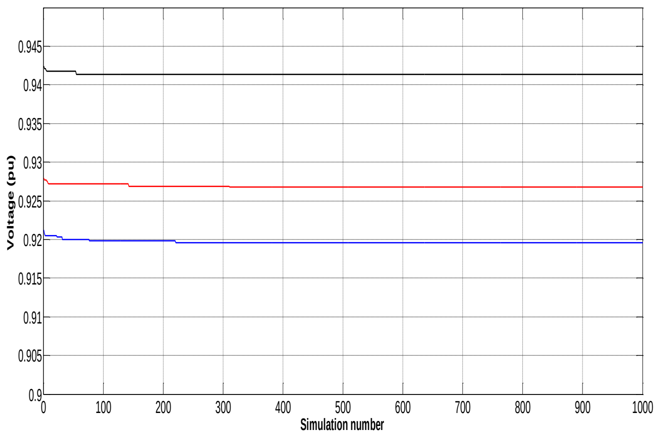


Fig. 13. Voltage variation for 1000 simulations

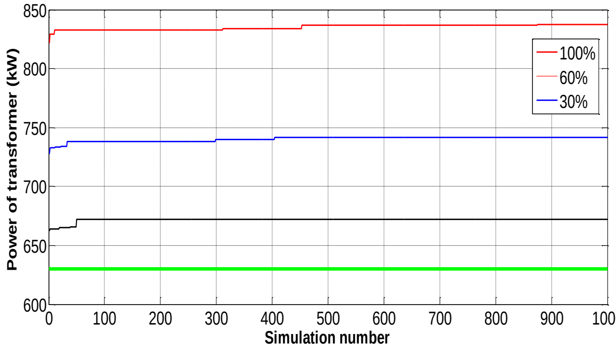


Fig. 14. Power of transformer variation for 1000 simulation (case of 100%, 60 and 30% EV)

Fig. 15 shows the variation of power of the transformer in function of total power of EV connected to the network for 6 cases. For example, the rate of P_EV/S_transfo=10% corresponds to 10%*630=63 kW, ie 21 EV of 3 kW). Fig. 16 shows the variation of minimal voltage in function of total power of EV connected to the network for 6 cases. It shows that there is no problem of voltage, because all voltages are maintained within limits ($1.1 \leq V \leq 0.9$ pu).

To avoid the congestion, it shows that the solution with 100% of EV (case 6) participating to the energy management is the best solution. For this case, there is no problem of overload with 37% EV penetration (about 37%*630=233 kW can be connected to the network, which corresponds to about 77 EV).

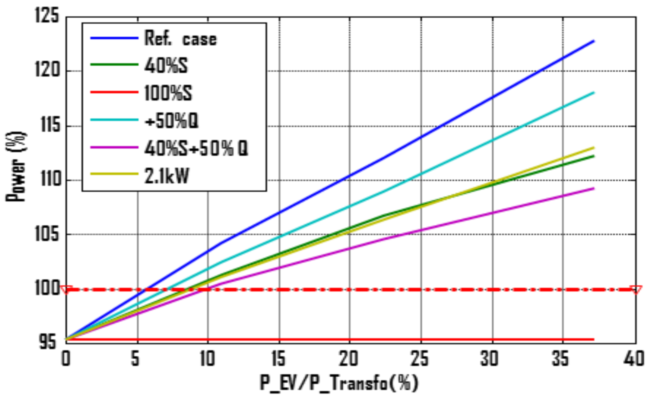


Fig. 15: Power of transformer for 6 cases

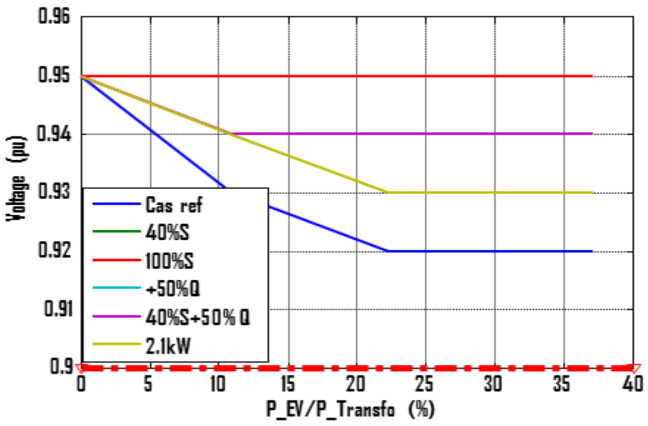


Fig. 16: Minimal voltage for 6 cases

The case 5 is interesting, because the EV penetration rate to the network can reach 10% of rated power of transformer (10%*630=63 kW, i.e. 21 EV).

The same probabilistic simulations are carried out for the rural network.

C. *Synthesis*

From the studies carried out in both the studied networks and with the assumptions presented above, we can see:

- There are risks of voltage problem (essentiallyunder voltage) on rural network because it has a long distance and a low section lines. Without fast charging, the risk for congestion problem dimishes because rural networks are generally light loaded and will have a small number of EV;
- There is less risk of voltage problems on urban network because it has a short length and a big cross section of underground cables. But this network incurs more risks of congestion problems because it has generally an important load and a great number of EV;
- In general, with an EV penetration rate less than 30%, there is no problem of voltage or congestion
- There are problems of voltage unbalance between phases for the rural network but no problem for the urban network
- Additional losses due to voltage unbalance are high (up to 18% of total losses for the rural network and 8% for the urban network).

- Distribution of EV on the phases has also an influence on impacts, particularly on blood. Some times, a penetration of 10 EVs on the same phase is more critical than the penetration of 20 EV well distributed between the three phases
- The solution of shifting the charge of EV in period between 22 and 24H is more effective because it allows
  - The increase of the EV penetration rate up to 100% for the rural network and 30% for the urban network
  - A smoothing effect of the load curve
  - A significant economic gain (241 € / year for the dynamic tariff and 146 € / year for the price peak / peak)
- A reduction of the charging power (2.1 kW instead of 3 kW) also has a significant positive impact (both from the technical and economic viewpoint).

V. CONCLUSIONS

In this paper, a simulation tool based on the probabilistic three phase Load Flow (PLF) program has been developed and used with Monte Carlo techniques in order to determine the influence of an EV penetration rate, assessing impacts on the distribution network and opportunities provided by EV. Impacts of EV integration on the distribution network are easy to assess by technical and economic indicators proposed in this paper.

Starting from critical problems identified in the simulations, solutions have been proposed and evaluated.

The future work will focus on the EV participation in ancillary services such as:

- EV coupling with renewable energy
- EV participation in voltage control
- EV participation in congestion management
- EV participation to reduce losses …

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VII. BIOGRAPHIES

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