TECHNICAL AND ECONOMIC IMPACT OF INTEGRATING EV IN AN INSULAR DISTRIBUTION GRID

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ABSTRACT

Global warming, added to security of supply concerns in insular grids has attracted the development of electric vehicles (EVs) as a more efficient source of transportation and also as an storage option. In this context, the motivation of this paper is to investigate the impact of integrating EV in the operation of a real distribution network in La Graciosa, which is interconnected with Lanzarote (Canary Islands) including diesel and wind generation. Consequently, a Mixed Integer Linear Programming (MILP) including Alternative Current (AC) power flow is formulated with the goal of minimizing the overall operation costs. Finally, results are shown by in technical (power losses, voltage behaviour, EV behaviour) and economic (generation cost, substation price signals) terms.

NOTATION

Indexes:

i,j,k	Node index
r	Block index for the linearization
t	Time period (h)
ω	Scenario index

Sets:

Ω_l	Set of branches in the network
Ω_n	Set of nodes in the network
Ω_r	Set of blocks of the linearization
Ω_t	Set of real-time periods
Ω_ω	Set of scenarios

Parameters:

C^{ens}	Non-served demand cost [$/MWh]
C^{w_curt}	Wind curtailment cost [$/MWh]
C^{conv}	Variable cost of the diesel engine [$/MWh]
C^{sub}	Cost of injected power from substation [$/MWh]
C^{wind}	Operation and maintenance (O&M) cost of wind generation [$/MWh]
$d_{it\omega}$	Active power demand at node *i* in period *t* and scenario *ω* [MW]
$q_{it\omega}$	Reactive power demand at node *i* in period *t* and scenario *ω* [MVAr]
$EffGtB^{ev}$	Efficiency of the charging process of EVs
$EffBtG^{ev}$	Efficiency of the discharging process of EVs
$EffBtW^{ev}$	Efficiency of the energy to move the EVs
$\overline{EV}$	Maximum charging/discharging capacity of EVs
f^{loss}	Power losses penalization weight factor
f^{v_dev}	Voltage deviation penalization weight factor
$\bar{I}_{ij}$	Maximum current flow in branch *ij* [A]
$m_{ijrt\omega}$	Slope of the *r*-th block of the piecewise linearization for branch *ij* in period *t* and scenario *ω*
$P_{it\omega}^{fore}$	Wind real power forecast at node *i* in period *t* and scenario *ω* [MW]
PF^{conv}	Power factor of diesel engine
PF^{wind}	Power factor of wind turbines
R^{tot}	Total number of blocks of the piecewise linearization
RC^{conv}	Maximum up/down ramp of diesel engine
RC^{ev}	Maximum charge/discharge ramp for EVs
R_{ij}	Resistance of branch *ij* [Ω]
X_{ij}	Reactance of branch *ij* [Ω]
Z_{ij}	Impedance of branch *ij* [Ω]
V_{nom}	Nominal voltage of the distribution network [kV]
$\underline{V_i}$, $\overline{V_i}$	Minimum/maximum voltage at node *i* [kV]
$\Delta S_{ijrt\omega}$	Power flow upper bound for *r*-th block at branch *ij* in period *t* and scenario *ω*
π_ω	Probability of scenario *ω*

Non-negative Variables:

$ch_{it\omega}^{ev}$	Power charged by the EV at node *i* in period *t* and scenario *ω* [MW]
$disch_{it\omega}^{ev}$	Power discharged by the EV at node *i* in period *t* and scenario *ω* [MW]
$EV_{it\omega}^{ev}$	State-of-charge (SOC) of the batteries of the EVs in period *t* and scenario *ω* [MWh]
$I_{ijt\omega}^{sqr}$	Square of the current flow of branch *ij* in period *t* and scenario *ω* [A^2]
$P_{it\omega}^{conv}$	Active power diesel generation at node *i*, in period *t* and scenario *ω* [MW]
$P_{it\omega}^{wind}$	Active power wind generation at node *i*, in period *t* and scenario *ω* [MW]
$P_{it\omega}^{w\_curt}$	Active power wind curtailment at node *i* in period *t* and scenario *ω* [MW]
$P_{it\omega}^{ens}$	Active non-served demand at node *i* in period *t* and scenario *ω* [MW]
$P_{ijt\omega}^{2}$	Square of the real power in branch *ij* in period *t* and scenario *ω* [MW]
$Q_{ijt\omega}^{2}$	Square of the reactive power in branch *ij* in period *t* and scenario *ω* [MW]
$P_{ijt\omega}^{+}$	Active power flow in branch *ij* in period *t* and scenario *ω*, downstream [MW]
$P_{ijt\omega}^{-}$	Active power flow in branch *ij* in period *t* and scenario *ω*, upstream [MW]
$Q_{ijt\omega}^{+}$	Reactive power flow in branch *ij* in period *t* and

scenario ω, downstream [MVAr]

$Q^{-}_{ijt\omega}$ Reactive power flow in branch ij in period t and scenario ω, upstream [MVAr]

$TR^{ev}_{t\omega}$ Power of the battery of EVs used in transportation [MW] in period t and scenario ω

$V^{sqr}_{it\omega}$ Square of the voltage magnitude of branch ij in period t and scenario ω [kV^2]

$\Delta P_{ijrt\omega}$ Value of the r-th block associated with real power through branch ij in period t and scenario ω [MWh]

$\Delta Q_{ijrt\omega}$ Value of the r-th block associated with reactive power through branch ij in period t and scenario ω [MVAr]

Free Variables:

$P^{sub}_{it\omega}$ Active power of substation located at node i in period t and scenario ω [MW]

$Q^{sub}_{it\omega}$ Reactive power of substation located at node i in period t and scenario ω [MVAr]

$Q^{wind}_{it\omega}$ Reactive power of wind generation at node i in period t and scenario ω [MW]

$Q^{dcurt}_{it\omega}$ Curtailed reactive power of demand at node i in period t and scenario ω [MVAr]

$Q^{conv}_{it\omega}$ Curtailed reactive power of demand at node i in period t and scenario ω [MVAr]

Binary Variables:

$v^{P+}_{ijt\omega}$ Variable related to real power (upstream) through branch ij in period t and scenario ω

$v^{P-}_{ijt\omega}$ Variable related to real power (downstream) through branch ij in period t and scenario ω

$v^{Q+}_{ijt\omega}$ Variable related to reactive power (upstream) through branch ij in period t and scenario ω

$v^{Q-}_{ijt\omega}$ Variable related to reactive power (downstream) through branch ij in period t and scenario ω

$v\_ch^{ev}_{it\omega}$ Variable related to EVs charging process

$v\_disch^{ev}_{it\omega}$ Variable related to EVs discharging process

INTRODUCTION

Diesel and heavy fuel oil generation units currently dominate small islands generation mix, incurring in higher costs than mainland systems, thus, incrementing the total costs of the system. Islands will face considerable challenges in the future in order to meet their needs in a sustainable, affordable and reliable way. For that, policy makers have promoted renewable energy and electric vehicles (EVs) [1]. To serve this purpose, several European projects have been launched in the last years (e.g. MERGE [2], G4V [3]).

Moreover, In order to cope with the Kyoto Protocol, the European target 20-20-20 implies reductions in greenhouse emissions, primary energy use and energy consumption. In this context, the motivation is to investigate the impact of the integration of Electric Vehicles (EV) in the operation of a real distribution network in an island, La Graciosa, coexisting with conventional energy (diesel engine, in this case) and renewable energy (wind power).

Different studies have been developed to analyse the effects of EVs on distribution networks [4][5]. The authors in [6] focus on the impact of EV on power system costs. In deliverable 2.2 in [2] a short-term operation model allows determining the technical and economic impact of EVs. Others are related to the analysis of voltage variation [7] and power loss [4].

Furthermore, the impact of EV has been studied for mainland systems [6][8]. Most studies are based on the Unit Commitment (UC) problem without taking into account the distribution grid [9].

In literature, the presence of EVs in the distribution grid of an island interconnected to another one and the analysis of its impact has not been presented yet. The main contribution of this paper is to show how EV can improve distribution systems by reducing the operation cost of the system and giving a price signal for the interconnection of La Graciosa with Lanzarote, including AC power flow in the formulation.

FORMULATION OF THE PROBLEM

The following assumptions are defined to represent the operation of a distribution network in an insular system including diesel generation, wind generation and EVs:

- EDS are balanced three-phase systems and can be represented by an equivalent single-phase circuit.
- Wind turbines are located at node with high wind speed.
- A centralized distribution operator optimizes the charging/discharging process of the EVs.
- The possibility of renting electric vehicles of the type Vehicle-to-grid (V2G) for tourism, implying they have the capability for charging and injecting energy into the grid.
- The maximum charging/discharging capacities of the batteries of the EV are the same and equal to $\overline{EV}$.
- The maximum charge/discharge ramps of the batteries between two consecutive hours are the same and equal to RC^{ev}.
- An EV charging station is used in one of the buses of the network.

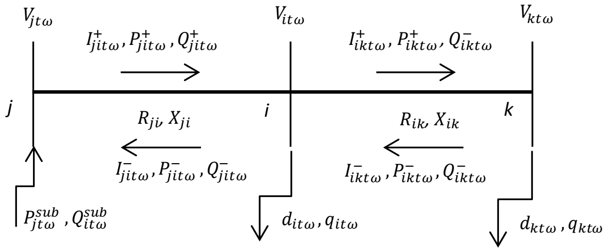

Fig. 1.: Illustrative radial distribution system.

In order to distinguish the direction (sense) of the current and power flow (forward or backward), two positive separate variables are shown in Fig. 1.

Objective function

The objective function is related to the minimization of the total operational costs, considering both technical and economic aspects. Regarding the technical terms (2), the active power losses and voltage deviation are penalized. Regarding the economic terms (3), the operation cost of the generation includes the cost of the power injected from the substation, which is interconnected to another system, the variable cost of the diesel engine, the O&M cost of wind and, both wind curtailment cost and non-served energy.

$$\text{Min } \{E[\emptyset(\omega)] + E[\gamma(\omega)]\} \quad (1)$$

$$\emptyset(\omega) = \left[\sum_t \sum_{ij} R_{ij}\, I_{ijt\omega}^{sqr}\, f^{loss} + \sum_t \sum_i \left|V_{it\omega}^{sqr} - V_{inom}^2\right| f^{v\_dev}\right] \quad (2)$$

$$\gamma(\omega) = \sum_t \sum_i \left(P_{it\omega}^{sub}\, C_t^{sub} + P_{it\omega}^{conv}\, C^{conv} + P_{it\omega}^{wind}\, C^{wind} + P_{it\omega}^{w\_curt}\, C^{w\_curt} + P_{it\omega}^{ens}\, C^{ens}\right) \quad (3)$$

Constraints

Various constraints are established in the following mathematical statements to assure optimal operation conditions.

Power flow equations

The MILP including AC power flow is formulated below:

$$P_{it\omega}^{sub} + P_{it\omega}^{conv} + P_{it\omega}^{wind} + \sum_j \left(P_{jit\omega}^{+} - P_{jit\omega}^{-}\right) - \sum_k \left[\left(P_{ikt\omega}^{+} - P_{ikt\omega}^{-}\right) + R_{ij}\, I_{ijt\omega}^{sqr}\right] = d_{it\omega} - P_{it\omega}^{d_{curt}} + ch_{it\omega}^{ev} - disch_{it\omega}^{ev} \quad (4)$$

$$Q_{it\omega}^{sub} + Q_{it\omega}^{conv} + Q_{it\omega}^{wind} + \sum_j \left(Q_{jit\omega}^{+} - Q_{jit\omega}^{-}\right) - \sum_k \left[\left(Q_{ikt\omega}^{+} - Q_{ikt\omega}^{-}\right) + X_{ij}\, I_{ijt\omega}^{sqr}\right] = q_{it\omega} - Q_{it\omega}^{d_{curt}} \quad (5)$$

$$V_{it\omega}^{sqr} - 2\left(R_{ij}\left(P_{ijt\omega}^{+} - P_{ijt\omega}^{-}\right) + X_{ij}\left(Q_{ijt\omega}^{+} - Q_{ijt\omega}^{-}\right)\right) - Z_{ij}^2\, I_{ijt\omega}^{sqr} - V_{jt\omega}^{sqr} = 0 \quad (6)$$

$$\underline{V}^2 \le V_{it\omega}^{sqr} \le \overline{V}^2 \quad (7)$$

$$0 \le I_{ijt\omega}^{sqr} \le \bar{I}_{ij}^2 \quad (8)$$

$$P_{ijt\omega}^{+} \le V_{nom}\, \bar{I}_{ij}\, v_{ijt\omega}^{P+} \quad (9)$$

$$P_{ijt\omega}^{-} \le V_{nom}\, \bar{I}_{ij}\, v_{ijt\omega}^{P-} \quad (10)$$

$$Q_{ijt\omega}^{+} \le V_{nom}\, \bar{I}_{ij}\, v_{ijt\omega}^{Q+} \quad (11)$$

$$Q_{ijt\omega}^{-} \le V_{nom}\, \bar{I}_{ij}\, v_{ijt\omega}^{Q-} \quad (12)$$

$$v_{ijt\omega}^{P+} + v_{ijt\omega}^{P-} \le 1 \quad (13)$$

$$v_{ijt\omega}^{Q+} + v_{ijt\omega}^{Q-} \le 1 \quad (14)$$

$$P_{ijt\omega}^2 + Q_{ijt\omega}^2 = \sum_r \left(m_{ijrt\omega}\, \Delta P_{ijrt\omega}\right) + \sum_r \left(m_{ijrt\omega}\, \Delta Q_{ijrt\omega}\right) \quad (15)$$

$$P_{jit\omega}^{+} + P_{jit\omega}^{-} = \sum_r \Delta P_{ijrt\omega} \quad (16)$$

$$Q_{jit\omega}^{+} + Q_{jit\omega}^{-} = \sum_r \Delta Q_{ijrt\omega} \quad (17)$$

$$0 \le \Delta P_{ijrt\omega} \le \Delta S_{ijrt\omega} \quad (18)$$

$$0 \le \Delta Q_{ijrt\omega} \le \Delta S_{ijrt\omega} \quad (19)$$

$$m_{ijrt\omega} = (2r-1)\Delta S_{ijrt\omega} \quad (20)$$

$$\Delta S_{ijrt\omega} = \left(V_{nom}\, \bar{I}_{ij}\right)/R^{tot} \quad (21)$$

$$V_{nom}^2 I_{ijt\omega}^{sqr} = \sum_r \left(m_{ijrt\omega}\, \Delta P_{ijrt\omega}\right) + \sum_r \left(m_{ijrt\omega}\, \Delta P_{ijrt\omega}\right) \quad (22)$$

$$\forall\, ij \in \Omega_l;\ \forall\, t \in \Omega_t;\ \forall\, \omega \in \Omega_\omega$$

Constraints (4) and (5) represent the active and reactive power balance equations, respectively. The EV charge/discharging process affects to increase of demand or generation. Constraint (6) represents the voltage drop in branch *ij*. Voltage, current and active and reactive power limits are defined in (7)-(12). Moreover, (13) and (14) are allocated to avoid considering forward and backward power flows simultaneously. The linearization procedure is defined in (15)-(21) by a piecewise linear approximation in the same manner as in [10]. Since the voltage magnitude is within a small range in distribution systems, a constant value, V_{nom}^2, is selected and substitutes $V_{it\omega}^{sqr}$ (22).

Diesel engine constraints

In order to coordinate active and reactive power, limits for the reactive power for the diesel engine are defined in (23). Constraint (24) the variation in production is limited by the maximum up/down ramps.

$$P_{it\omega}^{conv}\left(tan(arccos(-PF_i^{conv})\right) \le Q_{it\omega}^{conv} \le P_{it\omega}^{conv}\left(tan(arccos(PF_i^{conv})\right) \quad (23)$$

$$\left|P_{it\omega}^{conv} - P_{it-1\omega}^{conv}\right| \le RC^{conv} \quad (24)$$

$$\forall\, ij \in \Omega_l;\ \forall\, t \in \Omega_t;\ \forall\, \omega \in \Omega_\omega$$

Wind production modelling

Active wind generation is declared in (25), including curtailment, if necessary. The reactive power is related to the active generation by the power factor (26).

$$P_{it\omega}^{wind} = P_{it\omega}^{fore} - P_{it\omega}^{w\_curt} \quad (25)$$

$$P_{it\omega}^{wind}\left(tan(arccos(-PF_i^{wind})\right) \le Q_{it\omega}^{wind} \le P_{it\omega}^{wind}\left(tan(arccos(PF_i^{wind})\right) \quad (26)$$

$$\forall\, ij \in \Omega_l;\ \forall\, t \in \Omega_t;\ \forall\, \omega \in \Omega_\omega$$

EV modelling

The mathematical constraints that represent EV are presented in equations (27)-(32). The state-of-charge (SOC) of the batteries of the EV is governed by (27). Only the EVs that are connected to the grid can charge/discharge their batteries and only the EVs that are in motion can use the energy of the battery in transportation. When the EVs are connected to the grid, they can only charge or discharge (30). The maximum power charged/discharged by the EVs is bounded by the maximum charging/discharging capacity of the batteries (28)(29).

$$EV_{it\omega}^{ev} - EV_{it-1\omega}^{ev} = ch_{it\omega}^{ev}\ EffGtB^{ev} - TR_{t\omega}^{ev}/\ EffBtW^{ev} - disch_{it\omega}^{ev}/\ EffBtG^{ev} \quad (27)$$

$$ch_{it\omega}^{ev} \le \overline{EV}\ v\_ch_{it\omega}^{ev} \quad (28)$$

$$disch_{it\omega}^{ev} \le \overline{EV}\ v\_disch_{it\omega}^{ev} \quad (29)$$

$$v\_ch_{it\omega}^{ev} + v\_disch_{it\omega}^{ev} \le 1 \quad (30)$$

$$|ch_{it\omega}^{ev} - ch_{it-1\omega}^{ev}| \le RC^{ev} \quad (31)$$

$$|disch_{it\omega}^{ev} - disch_{it-1\omega}^{ev}| \le RC^{ev} \quad (32)$$

$$\forall\ ij \in \Omega_l; \forall\ t \in \Omega_t;\ \forall\ \omega \in \Omega_\omega$$

Finally, the variation in charge/discharge between two consecutive hours is limited by the maximum charge/discharge ramps of the batteries, as stated in (31)(32).

CASE STUDY

La Graciosa Island

Fig. 2 shows the one-line diagram distribution network of La Graciosa overlapping a drawing of the island. La Graciosa is a small island located 2 km north of Lanzarote by a submarine cable (20 kV, 1.5 MW capacity). The substation, diesel engine, wind turbines and EVs charging station are located at nodes 1, 2, 12 and 4, respectively.

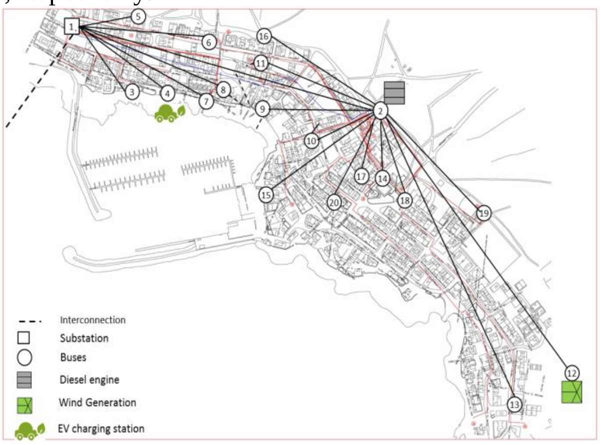

Fig. 2. One-line distribution network of La Graciosa.

The base power and base voltage of the system are 1 MVA and 20 kV, respectively. Network costs and losses and voltage deviation penalization are shown in Table II.. The cost of the energy injected into the substation is obtained for the system Lanzarote-Fuerteventura per hour, as seen in Fig. 3. The maximum current limit is 100 A and the upper and lower voltage limits are 1.1 and 0.9 pu, respectively. The total time horizon is 24 hours divided into 1 hour period. The demand data considered is the average of year 2013 and also an optimistic and pessimistic demand scenario, taking into account the standard deviation of the real data (see Fig. 4). The diesel engine is 650 KVA with a PF_i^{conv} equal to 0.77. In addition, the total wind generation capacity factor is 40% over the average demand and PF_i^{wind} equal to 0.95. Wind scenarios have been generated randomly by Monte Carlo, covering the standard deviation for real data of 2013 (see Fig. 5). The probability is the same for all scenarios. The EVs is assumed to be used for transportation during hours 8-19. For the remaining periods, they are assumed to be connected to the grid with the possibility of charge, discharge or just remain parked.

Some data about the technical characteristics of the EV, and the mobility patterns of the commuters are necessary: distance travelled, energy storage of the batteries, minimum and maximum state-of-charge (SOC), specific EV consumption, and efficiencies (grid-to-battery, battery-to-wheel, battery-to-grid).

TABLE I
EV AVERAGE CHARACTERISTICS

Distance travelled	44 km
Energy specific consumption	0.4 kWh/km
Battery capacity	30 kWh
Grid-to-battery efficiency	0.95%
Battery-to-wheel efficiency	0.95%
Battery-to-grid efficiency	0.95%
Maximum charge/discharge ramp	0.005

TABLE II
COST AND WEIGHTING FACTOR DATA

f^{loss}	f^{v_dev}	C^{conv}	C^{wind}	C^{w_curt}	C^{ens}
5	5	220	17	250	1000

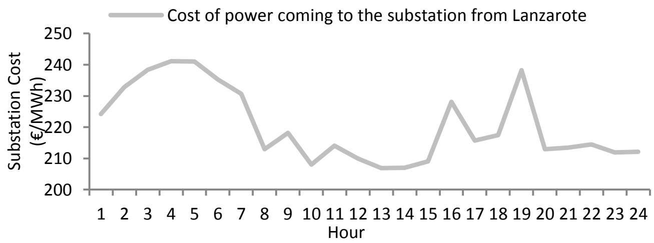

Fig. 3. Cost of active substation power injected from Lanzarote.

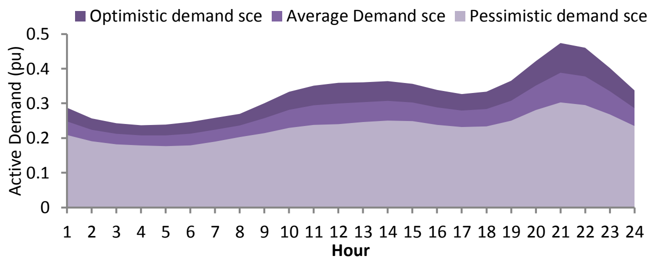

Fig. 4. Demand scenarios.

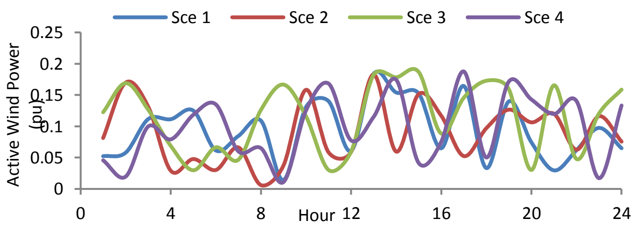

Fig. 5. Wind scenarios.

Results and Analysis

Generation costs

The results showing the benefits in the overall operation costs are shown for 1, 2, 3, 4 and 5 EVs (Table III), representing 8%, 16%, 24%, 31% and 40% over the average daily demand. In this case, there is no demand and wind curtailment.

TABLE III
GENERATION COSTS RESULTS (€)

EVs	No EV	1	2	3	4	5
C^{sub}	1011	1009.5	1007.9	1006.4	1004.8	1003.3
C^{conv}	770.0	770.0	770.0	770.0	770.00	770.0
C^{wind}	40.6	40.6	40.6	40.6	40.6	40.6

The operation costs from wind and diesel engine are the same for all cases. However, the cost of the power coming from the substation is decreased with EV penetration. This is due to the fact EVs inject power to the grid instead of it coming from the substation.

Substation Active Power

In Fig. 6, the behaviour of the substation for wind scenarios is represented under an average demand scenario. As the price of the energy coming from Lanzarote is high at night, La Graciosa starts-up the diesel engine and injects power to Lanzarote. On the other hand, during the day the power comes from the substation with a profile similar to the one of the demand.

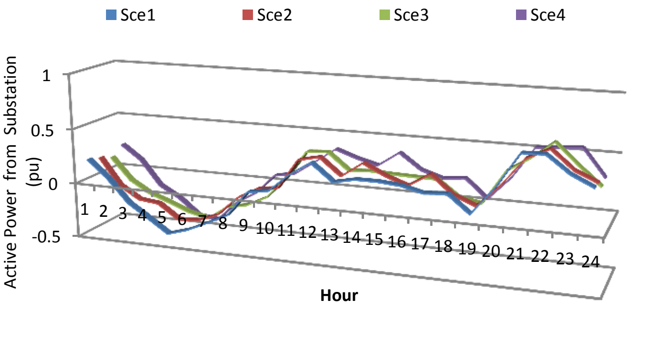

Fig. 6. Substation active power.

EV behaviour

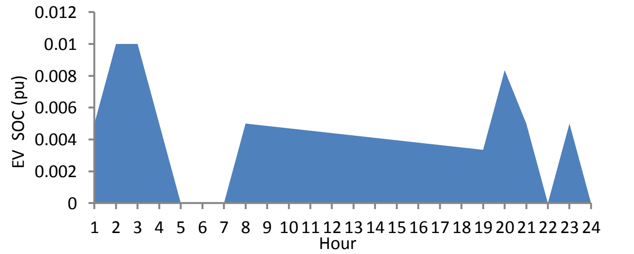

Fig. 7: State of charge of the EV.

The EV charges in hours 1 and 2 for all levels of penetration, as the cost of the energy coming from the substation is not as high as in hours 4 and 5. In these hours, the EV discharges and injects power into the grid. From hours 8-19 onwards, the EV is used for transportation without the possibility of connection to the network. During peak hours the EVs charges when the substation cost decreases.

Technical behaviour

TABLE IV
LOSSES (KW) AND VOLTAGE DEVIATION (x10^{-3})

EVs	0	1	2	3	4	5
Loss	0.72839	0.72832	0.72824	0.72821	0.72832	0.72848
V Dev.	116.808	116.800	116.793	116.777	116.779	116.786

Power losses are maximum decreased when there are 3 EVs in the network, though the number is increased to 5 (the maximum battery capacity is 0.15 pu) power losses are higher than without EV. The same occurs with the voltage deviation. For this reason, EV penetration affects the technical requirements of the grid.

CONCLUSION

This paper analyses the effects of introducing EV in an insular grid. This is of special interest due to decrease in operation costs. However, a big penetration of EV into the network has a drawback: the increase of power losses and lack of voltage stability and security.

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