Low Voltage Grid Control through Electrical Vehicles Charging Stations

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Abstract: - Electric mobility requires modern, reliable and efficient infrastructures in order to finally reach a wide diffusion. At the same time, these infrastructures have to be integrated with existing, and often aging, electric networks: this matching must face several technical challenges, mostly on urban scenarios, where many technical and operational constraints are present. Moreover, electric vehicles charging operations require very accurate control devices in order, not only to avoid causing further troubles to the low voltage distribution systems, but also to help ensuring network security and power quality. In this paper, a methodology for the optimization of EVs charging operations, that aims at optimizing EVs charge and discharge in response to violations of technical constraints of power networks, congestions and other security constrained issues at LV level, is presented.

Key-Words: - charging station, electric vehicles, low voltage distribution networks, smart grids, storage systems

1 Introduction

The number of electric and hybrid vehicles circulating on our city streets grows faster everyday [1-4]. EVs offer a significant advantage compared to self-contained hybrid electric vehicles (HEV) and traditional internal combustion engines (ICE) vehicles: their connection to the electric power grid, that makes them capable to act both as grid-to-vehicle (G2V) devices, when they are in charge mode, and vehicle-to-grid (V2G) devices, when at the contrary they are in discharge mode [5]. This means that EVs can be represented alternatively as dispatchable loads or generators.

The charging behavior of EVs is depends from many different factors, such as the type of connection (unidirectional or bidirectional), number of vehicles being charged in a given proximity, their charging voltage and current levels, geographical location, charging duration, battery status and capacity, and so on [6].

G2V includes conventional and fast battery charging systems, but fast charging in particular can really stress the grid distribution network because power request is high. Other effects on the amount of power taken from the electric grid can also be originated by the charging practices in different locations of a fleet of EVs. Daily charging at work in congested urban centers, for example, can provoke undesired peak loads and could require investments in expensive additional generation units. Power quality can also be affected by serious problems deriving from injected harmonics and low power factor, if the charger does not employ well-engineered converters [7].

On the other hand, V2G, allowing to share benefits among grid operators and vehicle owners, is a promising driver for EV deployment. Nevertheless, V2G control strategies and charging/discharging modes must deal with short-term and long-term impacts on battery life and energy grids. EVs can also be made able to act like stored energy resources and reserve against unexpected outages by advanced connections to the grid, realized through smart charging stations with adequate onboard power electronics devices and BES systems.

The optimization of time and power demand profiles can be reached through well-coordinated smart charging and discharging operation and could become the most beneficial and efficient strategy for both the grid operator and EV owners [8-11]: V2G-capable vehicles offer a possible backup for renewable energy sources (RES) such as wind and solar power, and support efficient integration of intermittent power production; V2G can also supply additional opportunities for grid operators, such as reactive power support, active power regulation, load balancing by valley filling, peak load shaving and current harmonic filtering [12-14]. In a future perspective, these systems will also perform ancillary services as frequency control and spinning reserves, improving global grid efficiency, stability, reliability and generation dispatch [15-19]. In this paper, the authors present a methodology to optimize EVs charge and discharge in response to violations of technical constraints of power networks, congestions and other security constrained issues at LV level, aiming at fulfilling the objectives of an urban level smart city project.

2 Charging Stations and Control Devices

The key-concept is focused on the development of smart EVs charging stations which can be used not just for their main original purpose, but also to control and improve LV distribution system security and power quality, without making expensive investments for the improvement of existing infrastructures.

The DC charge system of the proposed charging stations has a capability of 22kW; each device is able to supply electric power not only to EVs batteries but also to an auxiliary storage system placed under its pedestal. Charging columns are connected to the network through a front-end active rectifier; their power flows can be managed by means of two bidirectional DC/DC converters in order to use the auxiliary storage systems to shorten recharge times or to improve the number of charging operations that can be accomplished in a certain period. The auxiliary storage systems can even store the exceeding power, possibly generated from RES units installed on the same low voltage grid, and use it for peak shaving operations during the day. Figure 1 shows the technical scheme of the charging stations, while Figure 2 represents the diagram of the AC/DC converter control. Some operational parameters are indicated in Table 1.

TABLE 1 Technical parameters

Vn (grid)	400 V
fn (grid)	50 Hz
Icc (grid)	8 kA
cosϕcc	0,6
Pn (charging station)	22 kW
cosϕn (charging station)	1
Vdc	800 V
Switching frequency	10 kHz
E (storage)	500 V

The charging stations are also able to support voltage by injecting reactive power in the system. The set points of the injected reactive power can be automatically calculated by the charging station controller or even determined by a centralized LV network control system, in order to get a constant voltage profile on a specific node, or group of nodes, on the grid.

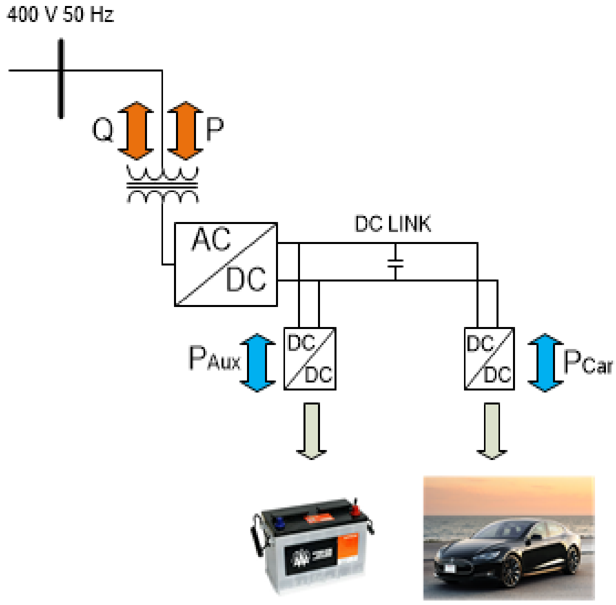

Fig.1 Technical scheme of the charging station

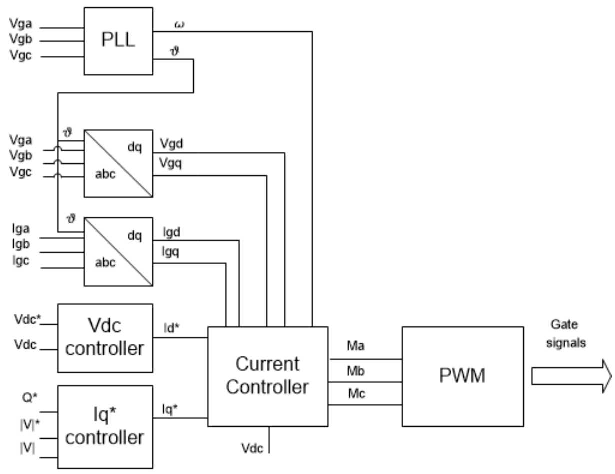

Fig.2 AC/DC converter control scheme

2.1 Mathematical Formulation

The converter control strategy has been developed through equations based on the *d,q* rotating coordinate system. The equations used for the design of the PI current controllers are:

$$V_d = RI_d + L\frac{dI_d}{dt} - \omega LI_q + E_d \qquad (1)$$

$$V_q = RI_q + L\frac{dI_q}{dt} + \omega LI_d + E_q \qquad (2)$$

where V_d, V_q are the values of voltages of the converter; I_d , I_q are the values of current exchanged (injected or absorbed) with the grid; R and L respectively represent the total resistance and inductance provided by the grid, the transformer and the filter; E_d, E_q are the voltage levels of the grid which the converter is connected to.

The d axis of the chosen coordinate system is aligned with the grid voltage vector, according the voltage oriented control technique (VOC). Therefore, active power P and reactive power Q exchanged with the network are formulated as:

$$P = \frac{3}{2}E_d I_d \qquad (3)$$

$$Q = -\frac{3}{2}E_d I_q \qquad (4)$$

As shown in Figure 2, current set point I_d* on d axis, is calculated controlling the DC link voltage level V_{dc}, whereas V_{dc}* is set to 800 V. Power exchanges on the DC link are described in Figure 3.

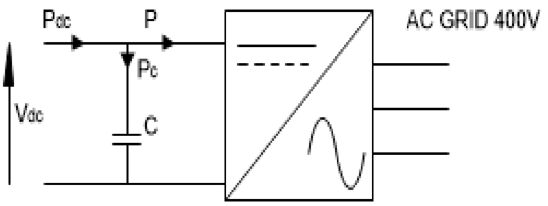

Fig.3 Power exchanges on DC link

P_{dc} indicates the power exchanged through DC/DC converters and the interface converter and is the sum of the power injected in the EV battery and in the auxiliary battery (power is assumed positive during charge and negative during discharge). P is the power exchanged with the AC/DC converter and is equal to active power exchanged with the grid (neglecting losses).

P_{dc} is formulated thorough the following equation:

$$P_{dc} = V_{dc}\cdot C\frac{dV_{dc}}{dt} + \frac{3}{2}E_d I_d \qquad (5)$$

Variations of P_{dc} value can also modify the behavior of V_{dc}: when P_{dc} increases, the capacitor start to charge itself and V_{dc} grows; on the contrary, when P_{dc} decreases, the capacitor will be discharging, causing the lowering of V_{dc} value. The V_{dc} controller detects these voltage variations and evaluate the I_d* setpoint in order to keep V_{dc} value as constant as possible and maintain an equilibrium between P and P_{dc} , (i.e. P=P_{dc}).

P_{aux} and P_{car} indicate the power levels of the auxiliary storage system and of a generic EV during its recharge

I_q* setpoint can be obtained by in two different ways. If the reactive power setpoint Q* is known, the controller can set I_q* by solving equation (4) (clearly in this case Q is equal to Q*). Q* is supposed to be an input received from a centralized grid control system. Alternatively, I_q* can be set through a control ring that keeps voltage constant at a setpoint level. This level is also determined by the main control system and is represented by |E*|.

Batteries are charged (and discharged) through the adoption of two current controlled DC/DC bidirectional boost converters, that are linked to the DC link. Figure 4 shows the DC/DC converter control scheme. The internal current control ring allows to manage charge/discharge currents by means of PWM modulation. For each controller, the charge/discharge power setpoint (P_{bat}*) allows to calculate the current setpoint I_{bat}* that is used in the current controller. P_{bat}* is set by the main control system, whereas the power controller block is constituted by a PI controller.

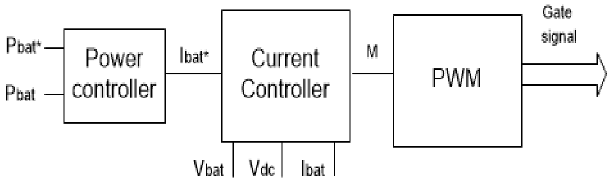

Fig.4 DC/DC converter control

Current controllers were designed considering the equation:

$$V_{boost} = R_{bat}I + L_{bat}\frac{dI}{dt} + E_{bat} \qquad (6)$$

This equation refers to the subsystem constituted by the storage system and the inductive filter for each DC/DC converter. V_{boost} is the voltage value applied from each converter on the plant, E_{bat} and R_{bat} are referred to the Thevenin equivalent model of the battery, L_{bat} is the filter inductance, I is the current value of a single battery.

3 Test Results

In order to evaluate the performances of the charging station, four test cases have been simulated. Each test is referred to different operating conditions.

3.1 Case 1

The simulation starts while the column is performing a 20 kW charge on a vehicle; the power is fully supplied the network. At t=0, due to a grid congestion, only a maximum amount of 10 kW can be supplied by the network. In order to keep unchanged the charging speed, the remaining 10 kW electric power must be supplied by the auxiliary battery.

In Figure 5, active and reactive power transients are shown. In all diagrams power imports are assumed always positive; power to/from the battery and the EV is positive during charge and negative during discharge. The charging station reacts very quickly to the effects of the congestion, activating the discharge of the auxiliary battery.

After few cycles, steady-state conditions are reached and the EV charging power is set again to 20 kW. Figure 6 shows the current transient.

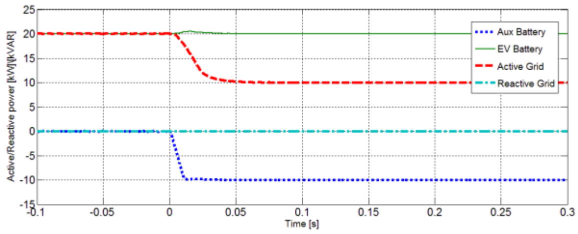

Fig.5 Power flows - case 1

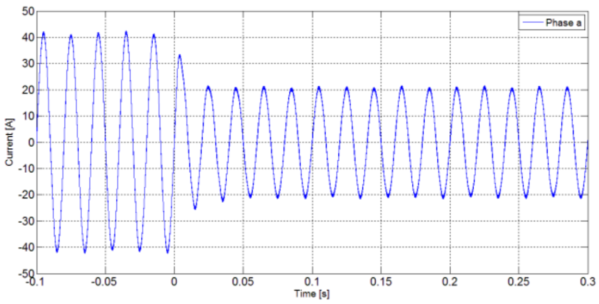

Fig.6 AC Current - case 1 (phase a)

3.2 Case 2

This scenario simulates a condition in which a sudden request of active power (10 kW) arises, due for example to an unexpected load peak that has to be balanced. In this case, it was hypothesized that, before the controlling action takes place, the column is supplying a 5 kW charge. In Figure 7, it is shown how the charging station is able to inject the requested amount of power (10 kW) within very few cycles, using the auxiliary storage system for supplying energy to both battery and grid.

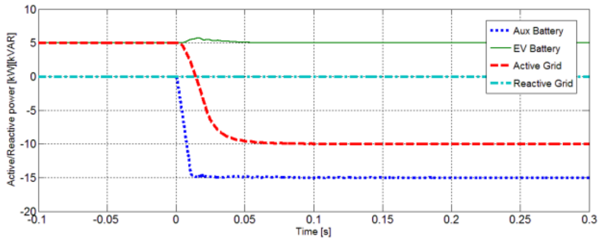

Fig.7 Power flows - case 2

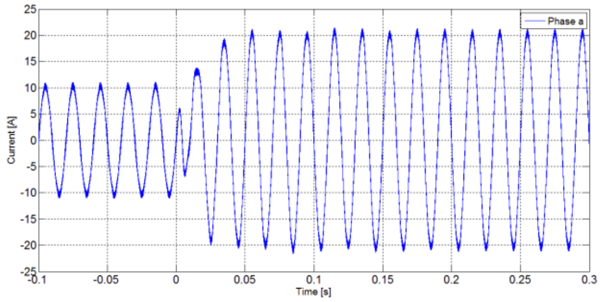

Fig.8 AC Current - case 2 (phase a)

3.3 Case 3

In Case 3, it is assumed that, due to the implementation of centralized control actions, an injection of 20 kVAr is requested. Moreover, it is hypothesized that before the implementation of such control action the charging station is absorbing 16 kW from the network.

In Figure 9 it is shown how the charging station is able to provide the requested reactive support within a very short amount of time. Moreover, the proposed control scheme is able to adjust active power flows in order to respect capability constraints on the AC/DC interface controller. This controller is rated 22 kVA, so the active power import is reduced to 9 kW.

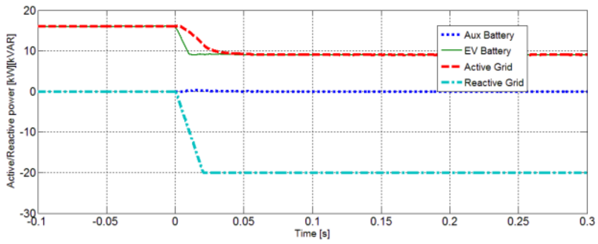

Fig.9 Power flows - case 3

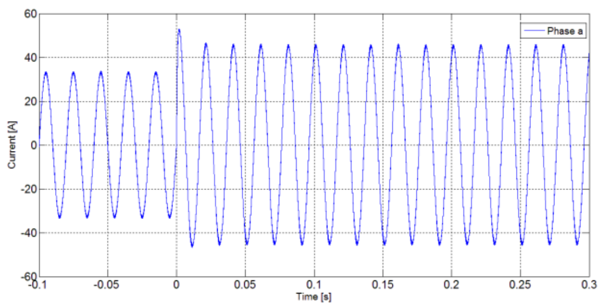

Fig.10 AC Current - case 3 (phase a)

3.4 Case 4

This final case proves the ability of developed charging stations to keep optimal voltage stability on the grid node to which they are connected.

At the beginning of the simulation, LV network is supplying 10 kW to the column for an EV charge and 10 kW (plus 15 kVAr) to another load with constant impedance. The maximum voltage module of the column is equal to 315 V, almost 10 V lower than its nominal level.

At t=0, the voltage controller is activated in order to adjust the voltage module of the charging station. This action also causes an automatic reactive power exchange with the grid, as shown in Figure 11. Consequently the reactive support of 15 kVAr is supplied by the column and not by the grid anymore.

Figure 12 shows the voltage module transient at the charging station. Differently from previous cases, in this simulation the current diagram reported in Figure 13, as long as the reactive grid plot showed in Figure 11, are related to the global performance of "column plus load" supply.

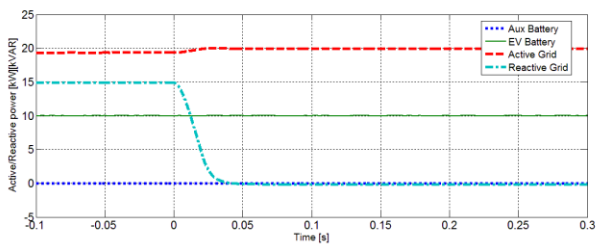

Fig.11 Power flows - case 4

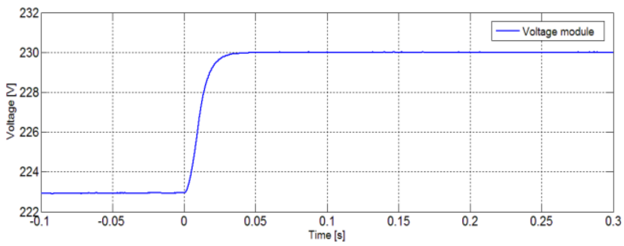

Fig.12 Vrms value

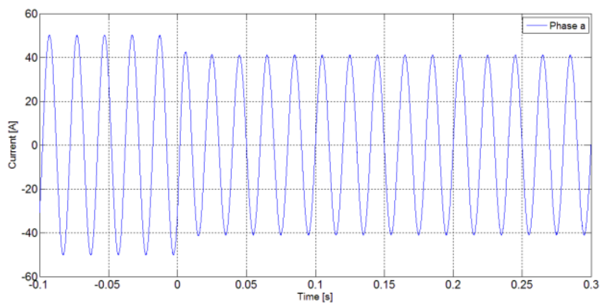

Fig.13 AC Current - case 4 (phase a)

4 Conclusions

In this paper, a methodology for the optimization of EVs charging operations, through the control of a smart charging station has been presented. The proposed approach aims at controlling active and reactive power resources in response to possible congestion events or other security constrained issues at low voltage distribution level.

The proposed scheme of an EV smart charging station is characterized by a 22 kW power capability, DC charging, and is able to supply electric power, not only to EVs batteries, but also to auxiliary storage systems placed under the pedestals. Test results showed how the control of such charging station can be used for power system operation, for LV grid congestion management, active and reactive power balancing, and voltage control.

Due to its flexibility, the proposed control scheme of the smart charging station can also be applied to a great number of different grid control and management operations that will be investigated in future works.

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