PV powered microgrid for electric vehicle applications

Prakash Kumar Sahoo
College of Engineering Bhubaneswar, Odisha, India

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Abstract

Several solutions to renewables dispatchability challenges are currently being proposed or employed such as storage and Demand Size Management. Also, electric vehicles represent a good opportunity to support renewables expansion thanks to the synergic possibility of offering a storage system and a demand management solution in connection with a control logic system. To this aim, this study investigates the feasibility to recharge electric vehicles, using solar energy from photovoltaic plants, into a "local microgrid" developed in a shopping centre parking area. In particular, an "integrated" control system will be proposed to manage simultaneous accesses to the electric charging stations for maximizing use of solar source (Microgrid module) and also evaluate impacts on microgrid stability (Powerflow module). The developed control logic, in particular, using deterministic model of queuing management, focuses the attention on computational simplicity to obtain a fast response system.

1 Introduction

The environmental damages caused by carbon dioxide emissions have forced worldwide governments to take steps to prevent serious consequences highlighted from the majority of researches on environmental issues [1,2]. According to this target, European government policies have allowed a rapid increase of Renewable Energy Sources (RES) generation capacity in recent years. But, some renewable resources, such as solar, are non-dispatchable; in other words, solar units cannot be controlled to increase or decrease output power, unlike fossil fuel units, and large not-adjustable volumes of renewable sources may cause reverse power flow problems, negative effects on power quality and increase fault levels on electrical grids [3]. Several solutions to RES dispatchability challenges are currently being proposed or employed such as RES storage and Demand Size Management (DMS) programs [4,5,6,7,8,9]. To support RES expansion, also, Electric vehicles (EV) represent a good opportunity thanks to the synergic possibility of offering a storage system and a DMS solution in connection with a control logic system [6].
To this goal, this study investigates the feasibility to recharge electric vehicles, using solar energy from photovoltaic plants (PV), into a "local microgrid" developed in a shopping centre parking area. In particular, a control logic and related function will be designed in order to govern the supply of electricity to charging stations under different operative conditions (generation/loads).

2 Solar microgrid characteristics and control logic

Methodology and literature

Due to high purchase cost and limited availability of charging stations, electric vehicles have a low penetration in Italian market. So, in order to maximize potential number of EV charging stations, in this study, it is considered the installation of a microgrid, at service of EV charging stations, in a shopping centre parking area.
The choice of shopping centres, is particularly interesting for many reasons: 1) high annual number of users/vehicles (75% of Italian people go to a shopping centre at least once a month) with significant turnover (average visit time: 68.8 minutes [10,11]; 2) a transformer substation is usually present in medium-large shopping centre; 3) parking areas are generally suitable for PV installation; 4) high shopping centre consumptions could absorb surplus production from RES minimizing negative impacts on distribution electric grid.
Though the opening hours of shopping centres are advantageous to the use of solar energy (closing hours coincide with time at which PV generating is not available), to make optimal use of renewable generating capacity and maximize convenience on behalf of consumers and producers, we need control mechanism of the microgrid to manage loads so that overlapping them, to times at which solar generating capacity is available.
Control function is not simple due to the simultaneous dependence on many stochastic and time-dependent variables, such as available actual PV power, number of incoming electric vehicles to the stations, charge level of incoming electric vehicles to the stations. Many scientific papers existing in literature evaluate algorithms and/or functions for an intelligent scheduling of electric vehicle storage capacity

in a parking lot or processing energy system models [12,13,14,15,16] that try to predict demand, incoming at charging stations, using various statistical prediction methods. The approach proposed in this study is different not requiring complex statistical methods for intelligent scheduling of EV charging operations. The developed control logic, in fact, is based on an algorithm that uses deterministic model of queuing management to define the supply order.

In particular, we have considered the actual behaviour of the customer that goes to a fuel station. As we can note, the user, usually, asks for fuel in money (equivalent to litres); using the same approach, the user at EV charging station could ask for energy, in money or in kWh. Therefore, in the control function, we do not need to know battery level of incoming vehicles such as with traditional vehicles, as well as we do not need to know filling level of the petrol tank for refuelling. So, main variables of our model are reduced to the followings: simultaneous accesses to recharging operation into the microgrid and forecasting data for photovoltaic producibility.

Starting from operative conditions (active loads/generation), the algorithm examines microgrid electrical characteristics to identify potential critical situations. Voltage and frequency analysis, in fact, is very important for the particular typology of turnout in a shopping centre. In particular in a certain hours/days of the week, such as the weekend days, are present great people flows in a relatively short time; this situation, could produce additional sudden loads, also greater than 10% of the available power, with potential critical situations in microgrid. Purpose of the control system, is to detect such situations and to flick switches, for example to isolate, even if temporarily, critical feeder lines.

That being so, in this paper, we propose an “integrated” control system aimed to: i) manage simultaneous accesses to the electric charging stations for maximizing use of solar source; ii) evaluate impacts of PV/loads on the voltage and frequency profile and stability within operation limits (e.g. voltage ±5% of 1 p.u.).

In order to obtain a single, integrated, solution for electric and EV traffic optimization, the control function was developed by internal programming language (DPL) of Digsilent Powerfactory software. Thanks to DPL programming blocks, associated with the physical microgrid components (e.g. breakers), Powerfactory, in addition to power flow studies, allows to manage the grid, in function of different operative conditions. In particular, Control Module, the proposed control function consists of two parts: Microgrid module and Powerflow module (see Figure 1).

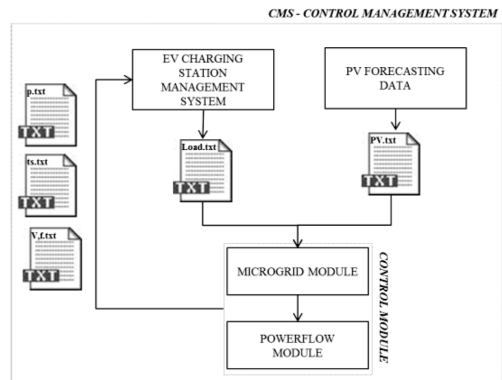

Figure 1: control management logic

At prefixed time step, the first module defines management parameters (e.g. energy source, service timing, price), in function of external measurement file (load and PV forecasting data) as detailed in the next section; later, automatically, the second module executes, in sequence, the stability analysis (RMS-Root Mean Square) of actual configuration [17].

Microgrid architecture

The microgrid architecture for charging parking area is composed of parts, which are called as sub-grids (see Figure 2). Each sub-grid, at prefixed level of power, contains many charging points (charging stations); both the sub-grid and each charging point could be connect/disconnect from the microgrid system following a command from central management system (CMS).

Connection between microgrid and distribution network (DSO) takes place into the MV/LV substation, owned and operated by the shopping center, in which are also situated supervision and control systems: remote (communication DSO - shopping center) and local (internal to the microgrid - CMS). The presence of supplementary storage is not considered in this work and will be considered at a later stage, therefore the surplus of RES production is sent to the shopping center (if it is connected with microgrid) otherwise to the DSO; also from DSO, is taken the energy to fuel stations, at times of solar source unavailability. These assumptions are the basis of control statements of the algorithm.

Charging stations (CS) are compatible with Mode 3 IEC 61851-1. Generating units are photovoltaic modules covering parking-spaces. PV plant is connected, with microgrid network, on the LV or MV side, mainly depending on the plant size.

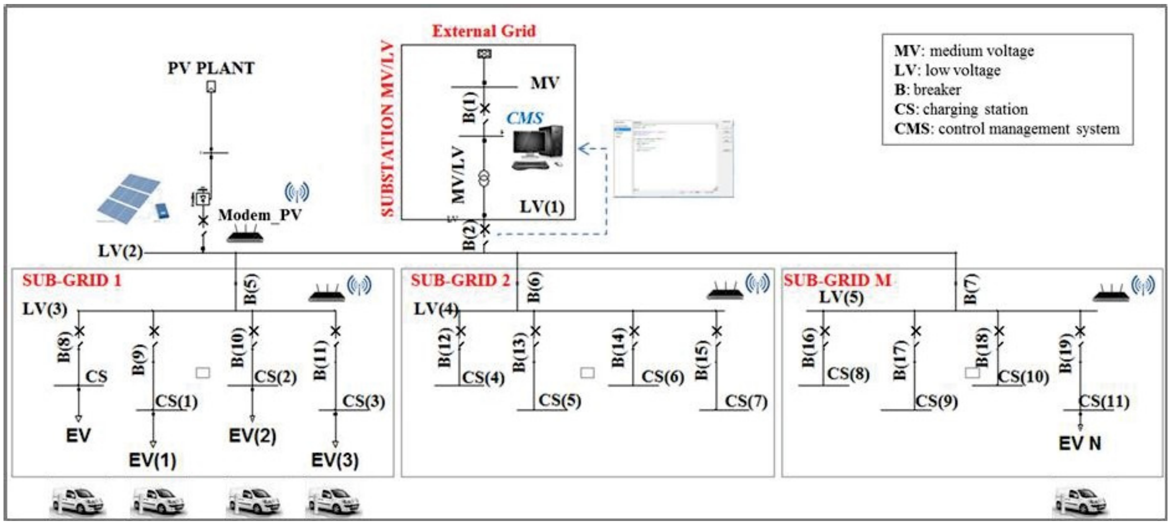

Figure 2: conceptual microgrid architecture

3 Control model design

Microgrid module

The first block of developed algorithm allows to managing the traffic within the microgrid.

In our hypothesis, all parking spaces, in the grid, are equipped for charging, but the effective operation is activated by CMS commands ("active" charging station), simulated in Powerfactory with open/close switching upstream the loads (EV). The service logic is FCFS type (First Come First Served).

As already said, the main aim of CMS is to maximize solar energy use for recharging. This objective, assuming a photovoltaic price less than purchase price from Power Company, means cost savings for microgrid manager and also for the final customer. So, for this purpose, at each access request, CMS proceeds to check operating conditions in order to identify the possibility to cover the loads with photovoltaic production in a certain waiting time. Actually, charging operation not necessarily starts at the connection of the vehicle with charging station but when the control system send close/open command to the suitable breaker. In particular, if N is the number of active stations at "arrival time" of *(N+1)-th* vehicle, as the following order, the algorithm:

- evaluates the availability of PV power, $P_{PV}(t)$, from forecasting data, in the interval [$a(N+1), \ldots, a(N+1)+T_R$] where *a(N+1)* where a(N+1) is the "arrival time" and T_R, correspond to "average residence time" in the shopping center;
- compares this value with total power needs from active stations (*N*) and *(N+1)-th* EV request, in the same temporal interval:

$$\Sigma_1^{N+1} P_{abs,h}(t) \qquad \textbf{(1)}$$

where $P_{abs,h}$ is the power absorbed from *h-th* active charging station;

- sets the breaker status (open/closed) per each microgrid component as a result of the relationship (1) so as enable the correct power sources;
- calculates unitary price for energy selling to the customer multiplying either the industrial price (PV source) or purchase price from power company (external grid source) for a markup factor (*m, m'*) defined by microgrid manager. In case of use combined PV/external grid, the price is assumed equal to the same applied for the use of external grid alone;
- calculates "service time", t_s, as the sum of charging time, t_c, and waiting time, t_w.

In presence of "total unavailability" or "total availability" of PV power for required charging, waiting time is equal zero and recharging starts at arrival time, *a(N+1)*, such as in cases 1. and 2. in Table 3. Waiting time is also equal zero when PV power is available only partially during T_R ("average residence time" in the shopping center) starting from arrival time *a(N+1)*; in this case, energy integration from external grid is necessary [case 3., condition (7)] and there is no reason to delay the charging.

Instead, if during T_R, starting from arrival time *a(N+1),* PV power, initially not sufficient, become able to cover the total additional *(N+1)* load, it is useful to delay the charging time [(case 3., condition (8)]. In particular, waiting time depends on the customers queuing for service. If *Q* is the number of customers queuing and *N* the number of active stations, "waiting time" corresponds to the "exit time" of the customer *(Q +1)-th* in the array of *(N + Q)* elements, sorted in ascending order of service timings; relative conceptual conditional statements are reported in relationship (6) - Table 1. Finally, in Table 3 are summarized, for each case: operative conditions, condition statements used for the algorithm, power source, service timing and unitary price for energy selling.

CASE	OPERATING CONDITIONS	CONDITIONAL STATEMENTS	SOURCE	TIMING/PRICE
1.	Total Absorbed Power greater than the total Power from PV Plant **or** No energy photovoltaic production available	$\Sigma_1^{N+1} P_{abs,h}(t)>P_{PV}(t)$ (2) $\forall t\in \{a(N+1),\dots, a(N+1)+T_R\}$	GRID	$t_S= t_c=kWh_{(N+1)}/P_{(abs,N+1)}$ $p=m\cdot p_{grid}$
2.	Total Absorbed Power **lower** than the total Power from PV Plant **and** PV Plant covering overall demand of (N+1)-th access	$\Sigma_{1_{N+1}} P^{abs,h}(t)\leq P^{PV}(t)$ (3) $\forall t\in \{a(N+1),\dots, a(N+1)+T_R\}$	PV	$t_S= t_c=kWh_{(N+1)}/P_{(abs,N+1)}$ $p=m'\cdot p_{PV}$
3.	Total Absorbed Power, from all active charging stations (*N*) **lower** than the total Power from PV Plant **and** PV Plant partially covering demand of (N+1)-th access	$P_{PV}(t)-\Sigma_1^N P_{abs,h}(t)\leq P_{abs,(N+1)}(t)$ (4) $\forall t\in \{a(N+1),\dots, a(N+1)+T_R\}$ $t_s=t_c+t_w=kWh_{(N+1)}/P_{(abs,N+1)}+t_w$ (5) Where t_w can be calculated by following equations: (6) [B]=array[e(N,Q] [A]=sort[B] t_w=extract[(Q+1), [A]]		
	Service time greater than average residence time T_R in the shopping center	$t_s>T_R$ (7) [t_s evaluated as (5)]	GRID/PV	$t_S= t_c=kWh_{(N+1)}/P_{(abs,N+1)}$ $p=m\cdot p_{grid}$
	Service time lower than average residence time T_R in the shopping center	$t_s\leq T_R$ (8) [t_s evaluated as (5)]	PV	$t_S= t_c+t_w=kWh_{(N+1)}/P_{(abs,N+1)}+t_w$ $p=m'\cdot p_{PV}$

$P_{abs,h}$: power absorbed from h-th charging station; P_{PV}: power from PV Plant; kWh_N: energy demand of N-th station
N: number of active stations; Q: queuing customers
t_s: service time; t_c: charging time; t_w: waiting time; T_R: average residence time in the shopping centre; a(i): arrival /request time of customer i
p_{grid}: purchase price from power company; p_{PV}: industrial price for PV production; m, m': mark-up factors

Table 3: algorithm conditional statements

Powerflow module

As clear from analysis of visitor behaviour in terms of shopping center traffic , weekend and non-working are peak days. Because the majority of customers reach the shopping center by car [18], non-working days are also those of higher turnout for the parking. So the correspondent traffic, if concentrated in a small number of hours, is a potential cause of voltage and frequency problems or critical situations into the microgrid, reason that Powerflow module is needed.

In order to consider the dynamic behaviour of system in the time domain, for the presence of loads and renewables, Powerflow module executes a steady-state simulation RMS type (Root Mean Square). The initial conditions for all power system elements are determined by a valid load flow that represents the steady-state operating point at the beginning of the simulation. Time interval for RMS Simulation is fixed equal at T_R. Load situation and PV generation are evaluated starting from measurement files. The PV.txt file, for example, contains irradiance data during analysis interval from which the algorithm obtains PV power.

Simulation results are sent, in text format, to EV charging station management system. In particular, txt file contains data about analysis results and eventual warning messages (e.g. over/under voltage condition: when the voltage exceeds/lags the nominal voltage by 10% for more than x seconds.). In presence of fault, Powerflow module should be able to:

- open the breakers to isolate critical feeder line;
- communicate to EV charging station management system the problem so as immediately interrupt the correspondent feeder;
- repeat the RMS simulation so as evaluate the effect of applied solution. Simulation analysis will be performed iteratively, per each time step; so, when the fault will be solved, the control function will provide to close the breakers for the reactivation of feeder lines.

4 Simulation and results

In order to evaluate the correct operation and efficacy of control module, a simulation model was run. As a case study, for the simulation, it was considered a large shopping center, localized in southern Italy, with 6000 parking spaces (area: about 12 m^2 for each car).

The simulation was run under 3 scenarios with different size of PV plant and consequent different number of active stations. Each scenario represents a different number of EV stations, evaluated by allocating to EV recharging stations a percentage of total parking spaces equal to the percentage of EV vehicles on total Italian car market. In particular, starting from present EV penetration value [19], in the first scenario we assumed a yearly level of sales such as to reach for Italian EV market, at 2020, the current maximum level reached in European EV market (Italian penetration level on total vehicle market: 0.5% at 2020). In the second scenario, more aggressive, we supposed a EV market penetration of 5% on total Italian vehicles market. Finally, the last scenario supposes a total PV covering of parking spaces in order to assess the possible problems in correspondence to maximum number of active charging stations. Simulation arguments are summarized in Table 4.

From the practical point of view, each scenario was constructed with 12 Powerfactory variations (1 variation per each month of the year), in which were loaded:

- PV measurement file with hourly radiation data in a typical day of the month (from forecasting data);

- 1 load measurement file with hourly EV turnout in a typical non-working day of the month. Average number of cars in non-working day is: 42.000.

Table 4: simulation scenarios

	SCENARIO 1	SCENARIO 2	SCENARIO 3
Number/percentage of parking spaces covered by PV modules	60 (1%)	600 (10%)	6000 (100%)
PV plant - kWp Photovoltaic module efficiency: 0,15 BOS efficiency: 0,85	108	1080	10800

Charging stations were chosen compatible with Mode 3 IEC 61851-1; Power CS: 22 kW with efficiency: 0.75. The chosen power allows obtaining a fast charge [20], minimizing potential stability problems at connection/disconnection instant.
In Table 5 are summarized:

- maximum number of 30 minutes-charging operations powered by solar source, per month;
- maximum annual number of recharges, $R_{max,year}$;
- average number of recharges per month, $R_{average,month}$.

Iteration time step is setted to 5 minutes.

Table 5: Monthly recharging

Recharge number (30 minutes each one)	**Scenario 1**	**Scenario 2**	**Scenario 3**
January	560	5595	55952
February	663	6633	66334
March	841	8411	84110
April	923	9232	92323
May	1129	11294	112936
June	1287	12870	128699
July	1439	14387	143875
August	1333	13325	133251
September	994	9941	99412
October	829	8294	82939
November	591	5912	59116
December	568	5677	56774
$R_{max,year}$	**11157**	**111572**	**1115720**
$R_{average,month}$	**930**	**9298**	**92977**

5. Conclusions and future works

Simulation analysis, in presence and in absence of control microgrid module, shows that the proposed queue management is able to manage simultaneous accesses optimizing use of solar source with a low computational effort.

In fact, during rush hours, thanks to proposed queue management, we obtain maximum number of vehicles charging with solar source in a total time lower than the average residence time in the shopping center.

Nevertheless, in absence of storage systems, 11% of PV production is not useful to charging operations and is sent to the distribution network. Therefore, future development will consider the integration in control module of an electric storage block modelled with Powerfactory.

Finally, to execute a good evaluation of function effectiveness, it would be also necessary to test the algorithm taking into account peak situations in correspondence of great atmospheric instability conditions. High variability of weather conditions, in fact, is more problematic than the adverse weather conditions; therefore, a PV measurement file with a level of variability upper than "running time" will be considered in future developments.

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