SCHEDULING OF OPERATION IN LOW VOLTAGE DISTRIBUTION NETWORKS WITH MULTIPLE DISTRIBUTED ENERGY RESOURCES

Konstantinos KOTSALOS
Efacec – Porto, Portugal
konstantinos.kotsalos@efacec.com

Nuno SILVA
Efacec – Porto, Portugal
nuno.silva@efacec.com

Ismael MIRANDA
Efacec – Porto, Portugal
ismael.miranda@efacec.com

Helder LEITE
University of Porto
hleite@fe.up.pt

ABSTRACT

The goal of this work is to propose a tool that optimizes the operational planning of the Low Voltage (LV) grid at the day-ahead stage. The multiple Distributed Energy Resources (DER) are incorporated within a three-phase Optimal Power Flow (OPF), which is executed sequentially considering future grid states, based on forecasted information for load and renewable generation. Relying on the fact that the DER units can provide a certain degree of flexibility for the operation of the grid, such assets are being coordinated within a top-level centralized approach. The scheme is assessed within an IEEE - LV benchmarked network, and compared with different scenarios of DER integration and local controls.

INTRODUCTION

The increasing integration of DER along the distribution network is driving it to be operated in a non-optimal way (i.e. techno-economic standpoint) as well as reaching near to its intrinsic limits. In order to address these technical challenges, the Distribution System Operators (DSOs) are currently increasing the observability and controllability of the grids, envisioning the active management of the DERs for ancillary services, through new operation stages (e.g. voltage regulation with ancillary service remuneration) [1]. The deployment of the smart grid concept has commenced not only through the ubiquitous deployment of advanced automation and metering apparatus along the LV grid, but also with the adoption of extensive monitoring and control functionalities, embedded in Advanced - Distribution Management System (A-DMS).

Recent studies have addressed the possibility of considering Low Voltage (LV) controllable assets beyond DSO assets, such as distributed Battery Storage System (BSS), controllable loads under demand response schemes and micro-generation units [2].

Particular focus has been given in aggregating flexible resources connected along the LV grid to support the operation of MV, by considering the LV grid as a flexible cluster [3]. Advanced methodologies need to be implemented to determine control actions related to controllable DER, which can improve the performance and operation of distribution networks delivering benefits to residential users. Several studies focus on the potential impacts and flexibility of DER -mainly Electric Vehicles (EV) and BSS-, implying their potential active management for operational purposes [3-6].

Optimal Power Flow (OPF) is widely used by DSOs for planning and operation purposes among numerous optimization problems, by manipulating the objective function and the respective control variables [1].
Recent seminal works [4-5], have proposed advanced schemes that address the operation of the grid by setting linear approximations to multi-period OPF, although focused on single-phase analysis of the distribution grid. This is not adequate, since LV grids are typically multi-phase (i.e. 3-phase with coupling among active conductors); facing unbalanced conditions due to the untransposed lines, single-phase loads and single-phase microgeneration.

In this work a conceptual secondary substation centered control approach will be proposed, which aims at coordinating DER in favor of the technical operation of the LV grid. The proposed tool relies on the exact formulation of three phase AC-OPF scheme, taking advantage of the availability of DER devices to improve the operation of the LV grid.

CONCEPTUAL FRAMEWORK

A conceptual framework is presented for settling an additional control layer at the level of the secondary substation, which essentially leverages control and management functionalities for the downstream LV distribution grid. Based on previous concept at [7], this work further focuses on the level of the advanced tools for the operation of the LV grid. In this approach presented in Fig. 1, the secondary substation -as a central entity, with a smart RTU, comprised by the DTC-, acquires and processes measurements from sensoring devices, IEDs and smart meters through heterogeneous communication. This data (i.e. incoming from upstream layer and downstream connected DER and end-users) will onwards feed control and management strategies, hosted on the DTC.

The upstream layer stands for the interface with upper control levels and corporate systems, as well as the communication with control centers of the DSO. Within this framework, an aggregator, possibly exists to bundle and further promote flexibilities provided by the end-users (i.e. any controllable resource) with the market procedures.

Furthermore, at the upstream layer a Forecast Provider transmits forecast profiles for short term periods (i.e. hourly based up to 24 hours) regarding the consumption of end consumers as well as the production of the micro-generation. In the frame of consumers smart metering devices provide load and generation profiles, interfacing them to the Data Aggregator (i.e. DTC). As it is illustrated on Fig. 1 some of the end-users are considered to include a Home Energy Management System (HEMS), which will be substantially in charge of managing the household smart appliances or Photovoltaic roof top panel and storage devices. The HEMS is basically interconnected with the Smart Meter to the DTC, releasing the capability to accept set-points in order to participate in Demand Response schemes.

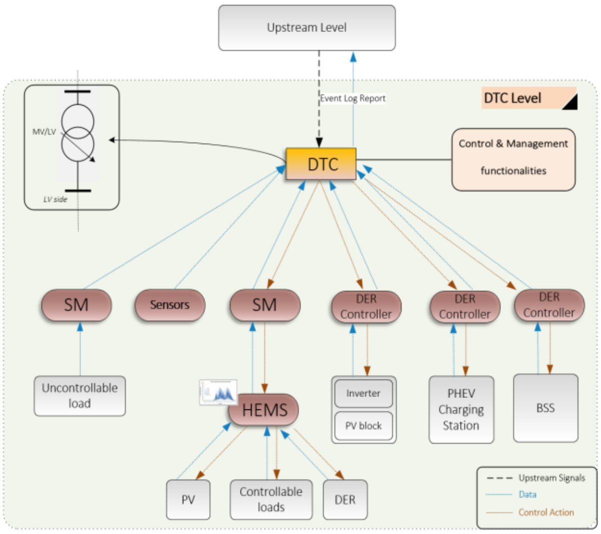

Fig. 1 Conceptual framework based on centralized management - substation centered approach.

METHODOLOGY

3 – phase Power flow

A three-phase Power Flow (PF) is implemented according to the main notions described in [8]. The PF tool is incorporated in the overall proposed scheme, as an algorithmic step, for the calculation of the initial point of the optimization, as well as the validation of the control set points.

The PF is based on Backward-Forward Sweep (BFS) technique, where in the Backward stage the branch current calculations occur, whilst in Forward Sweep stage the nodal voltage is calculated. This method, unlikely to classical power flow methods, copes with a branch-oriented technique rather than nodal relations.

It is quite interesting to stress that this PF algorithm present quick convergence, i.e. iterations do not exceed 4 for tolerance convergence ε_τ=*1e-4*. The performance can be further accelerated by the valid assertion that the angle displacement in LV distribution networks between adjacent nodes is fairly small [5], i.e. Δθ leads to zero which arise to the conception in equation (1), for the voltage drop.

$$\Delta V_{abc}^{(k+1)} \cong \mathrm{Re}\left\{ \mathrm{Z}_\ell \cdot J_{abc}^{(k)} \right\} \tag{1}$$

where Z_ℓ is the corresponding impedance among the connected branches and $J_{abc}^{(k)}$ is the vector for the line section currents at iteration k. Regarding the PF is structured in such way that each load might have different load model among constant PQ and constant I or constant Z model. Accordingly, the injection current at node j is given by equation (2).

$$I_{abc}^{j} = \left(S_{abc}\mathrm{diag}^{-1}(\mathrm{V}_{L-L}) \right)^{*} \cdot \left| \frac{V_j}{V} \right|^{\kappa} \tag{2}$$

where S_{abc} stands for the apparent power consumed at node j, V_{L-L} the line-to-line voltage. Hereby, diag(.) is settled as an operator that returns a diagonal vector and κ is considered the load model parameter, which is 0 for constant PQ load, 1 for constant current and 2 in case of constant impedance.

Optimal Power Flow and Scheduling

In this section, the proposed day ahead operational scheme is presented. In Fig. 2, a. Initially, the setup consists of providing an adequate initial point provided by an accelerated (i.e. Δθ=0) three phase BFS-PF performance. During the subsequent optimization steps, the previous acquired state vectors are provided as initial points.

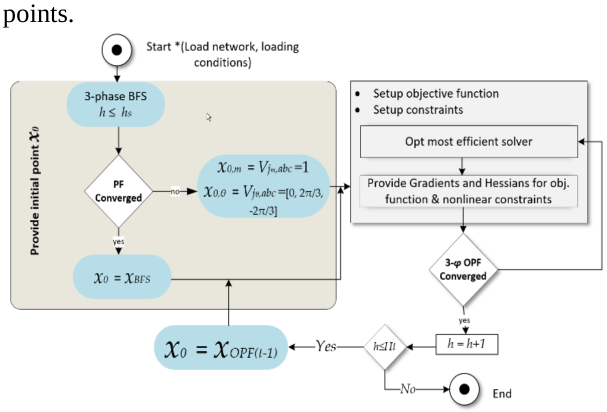

Fig. 2 Algorithm for the scheduling of operation, describing the important steps for the optimization stages.

The objective function targets to minimize the operating costs assigned with all the controllable assets providing their coordination according to their availability. Nevertheless, for the purpose of this work the objective function prioritizes or penalizes the controllable assets accordingly, since they are not assigned with reflecting remuneration prices; thus, this implies a merit order for the option of each asset.

For the sake of understanding, the scheduling tool is mathematically expressed, through at the initial step for *h=0*. The vector $[x_t]$ expresses to the state vector of the grid (i.e. voltage magnitude and angle -not critical for LV network- but included for completeness) at each time step t. Let us consider the set of controllable assets $\mathcal{U} := \{u_1, \dots, u_{ng}\}$, described by the control vector u, comprised by active and reactive power set points; Φ as the set phases, $\mathcal{J}$ the set of branches of the network and $\mathcal{N}$ the set of nodes. Therefore, in a single-run resolution the AC-OPF problem is posed by equation 3:

$$\min_{u} C_{obj}\left(x_t, u_t\right) = \min_{\mathrm{u_t}} \sum_{\mathrm{j=1}}^{\mathrm{n_g}} \left(c_{n_c}^T \cdot u_j\right) \tag{3}$$

subjected to

$$F_{j,\varphi}(x,u) = 0 \qquad \forall j, \varphi \in \mathcal{N}, \Phi \qquad \text{(a)}$$
$$h_{i,\varphi}(x,u) \leq 0 \qquad \forall j, \varphi \in \mathcal{J}, \Phi \qquad \text{(b)}$$
$$V_{\min} \leq V_{j,\varphi}(x,i) \leq V_{\max} \qquad \forall j, \varphi \in \mathcal{N} \qquad \text{(c)}$$
$$g_{\xi}(x,u) = 0 \qquad \text{(d)}$$
$$h_{\xi}(x,u) \leq 0 \qquad \forall \xi \in \mathcal{U} \qquad \text{(e)}$$

where the constraints in (3a) set the three-phase power balances at each bus of the network; (3b) constraint poses the nonlinear constraints for the constrained lines; (3c) to respect all nodal voltages that range strictly within the admissible bounds. The generalized equality and inequality constraints (3d-e), correspond to the operational limits of the controllable DER, which vary according to the type of DER. The gradient and Hessian matrix of the objective function and the nonlinear constraints are provided to the optimization solver, by expanding the calculations presented in [9]. The presented optimization problem corresponds to a non-linear optimization problem with convex objective function. The selected optimization solver, which addressed the optimization is the *fmincon* solver provided by MATLAB, which is based on an interior point algorithm.

DER Models

A brief discussion about the controlled DER modes follows.

Electrical Vehicle (EV)

The EV is structured following the same rationale a first order BSS model. In addition to incorporation of some behavioural statistical model data provided by [11]. The process of the statistical data to form the corresponding probability density function is followed as suggested in [12]. Concerning EV's availability, it expresses the periods that the end-user do not use the EV for any trip, but it is parked at the charging spot -which is considered to be only at home premises-. Consider p(t) as the power that EV consumes at time step *t*, then the energy stored at its battery is given from eq. (4).

$$e_{t+1} = a\, e_t + T_s\, \eta_{ch}\, p_{(t)} \tag{4}$$

Among this model, technical constraints have to be posed for EV's minimum and maximum State-of-Charge (SOC)-(5), the maximum power might be consumed (6) while the $\underline{p}$ is set to 0 since vehicle to grid operation mode is not concerned hereby. The technical constraint (7), poses that the charging power between two consecutive steps should not exceed the rated one.

$$\underline{SOC} \leq SOC_{e_t} \leq \overline{SOC} \tag{5}$$
$$\underline{p} \leq p(t) \leq \overline{p} \tag{6}$$
$$|p(t) - p(t-1)| \leq p_{rated} \tag{7}$$

These constraints are automatically incorporated in the OPF scheme as the set of equations (3d-e), whenever the availability of the EV allows it. The availability of the EV to charge, is considered along the day during their idle periods.

PV Installations

Regarding the microgeneration, all units are considered as single phase PV rooftops, with different installed power. In the presented scenario the local controls applied to microgeneration, refer to P-V and Q-V droop functions (with a deadband) proportional to the deviation from the nominal voltage with unitary gain. An additional case presented in the results section corresponds to the operation of the microgeneration with constant power factor equal to 0.9.

RESULTS

The network that was selected as a case study to perform the validation of the proposed scheme belongs to the IEEE benchmarked LV European network. The simulation results correspond to a daily analysis for a summer period.

Several different case scenarios were posed to identify possible technical bottlenecks resulting by the integration of PV installations and EVs owned by residential users. In Table 1, the results are collectively given, for different indexes such as maximum and minimum voltage met, the maximum voltage deviation, the voltage unbalances (VUF%) (i.e. the ratio of the negative to the positive sequence component) and the active network losses. According to the standards of EN50160, under normal operation conditions, at all nodes should kept below 2% for 95% of the week. The nodal voltages, should be limited within +10%, -15% for a 10min mean rms value. Therefore, since for the proposed scheme the data used correspond averaged 30min resolution, the voltage limits are set in [0.95, 1.05] p.u.values.

Applied Strategy	*Scenario Name*	*DER integration*	*min (Vphase)[p.u]*	*max (Vphase)*	*max(ΔV)[%]*	*max (VUF) [%]*	*Losses [kWh]*	*P curt [kW]*	*Q disp [kVA]*
No controls	No DER **(c1)**		0.937	*1*	6.22	1.09	11.3		
Uncontrolled DER	PV **(c2)**	20	0.958	1.053	5.25	0.78	14.61		
	EV **(c3)**	20	0.941	1	5.85	0.91	15.17		
	PV +EVs **(c4)**	20 + 20	0.942	1.022	5.74	0.87	12.73		
Local Controls	PV **(c5) (P-Q)**	20	0.958	1.05	5.05	0.71	13.5	1.4	17.3
	PV **(c6) (pf=0.9)**	20	0.958	1.056	5.65	0.72	14.3		
Proposed Scheduling	PV **(c6)**	20	0.951	1.049	4.9	0.74	12.3	0.9	0
	PV +EVs **(c7)**	20 + 20	0.95	1.029	5.01	0.93	12.9	0	0
	PV +EVs **(c8)**	20 + 20	0.952	1.019	4.9	0.95	12.1	0	0

Table 1 Simulation results for a daily analysis -seasonal data: Summer-

Scenarios (c1)-(c4) are obtained without any controls, whilst they represent different DER integration levels, according to the number of installations in the total of 55-residential users. The bus and phase connection as well as the load profiles of the consumers, are those published for the benchmarked network.

Scenario (c5), refers to a high integration of PV installation where droop based controls mitigate prevent overvoltages, while in (c6) constant power factor is set to 0.9. In both cases, there are increased active power losses due to the reactive power variations. The examined cases (c6)-(c8) were addressed by the proposed day-ahead scheduling. In particular, (c6) proposes the curtailments of active power. Most importantly, in (c7), the EV availability incorporated in the day ahead scheduling leads to more satisfying results than the conventional droop control. In this case scenario, available EVs for charging are being enabled avoiding unnecessary active power curtailments. In the last case scenario, an additional constraint was set for the scheduling of setting to the net-injected power (P_s≤10kW single-phase power) by the secondary substation to create a more extreme scenario. This scenario led to 0 active power curtailments.

CONCLUSIONS

The proposed methodology introduces the coordination of multiple DER, ensuring safe and cost-effective operation in LV distribution grids with high integration of DER. In this study, the proposed scheme targets mainly on assigning proper scheduling of the DER according to their availability in order to improve the performance of the LV grid. Nonetheless, the scheme can be deployed only by the subsequent communication technologies, together with forecasting data, power flow-state estimation tools. Future work encompasses the incorporation further assets, as well as to expand the scheme for quasi-real time operational purposes.

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