DISPERSED ENERGY RESOURCES SCHEDULING FOR THE INTENTIONAL ISLANDING OPERATION OF DISTRIBUTION SYSTEMS

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Abstract – The paper presents an algorithm for the automatic optimal scheduling of dispersed energy resources (DERs) and of under-load tap changers (ULTCs) position. The aim of the scheduling problem consists in the minimization of the voltage deviations with respect the rated value, of the DERs production deviation with respect the maximum efficiency point, and of the network losses. The system incorporates also a procedure to facilitate the intentional islanding maneuver of the distribution network. The adopted approach is based on iterative solution of linear-constrained multi-objective optimization problems. The nonlinear power flow relationships are linearized by means of the calculation of sensitivity coefficients to small variations of the control variables (namely, controllable DERs power outputs and ULTCs positions). The algorithm is implemented in Matlab environment to exploit different solvers and suitably interfaced with EMTP-RV for three-phase power flow detailed calculations. In particular, two optimization solvers are adopted: the least square method and the goal attainment approach. The relevant results are compared using the IEEE 34-node distribution feeder as test case.

Keywords: Dispersed generation, active distribution networks, islanding operation.

1 INTRODUCTION

The increasing penetration of dispersed energy resources (DER) in distribution systems calls for a substantial evolution of the operational practice of these networks [1]. Distribution system operators (DSO) are expected to schedule DERs during their normal operation and to manage unpredictable transient dynamics. Within this context, the presence of DERs can indeed provide a significant improvement of system reliability, in case the distribution network has the capability of performing the islanding maneuver and of operating in islanded mode (e.g. [2-4]). In this respect, several studies have been carried out to investigate the optimal control strategies of DERs during intentional and unintentional islanding of microgrids and distribution systems (e.g. [5-10]). The intentional islanding capability may provide also an improved DERs participation in local electricity markets (e.g. [11-13]).

This paper deals with an algorithm for the short-term automatic DERs scheduling (e.g. 15 minutes) coordinated with transformers under-load tap changers (ULTCs) positions. The algorithm has been developed to be included in a centralized Energy Management System (EMS) of a DSO. The general characteristics of the DSO EMS, whose prototype is currently under test at the Microgrid test facility developed at CESI Laboratories, has been presented in [14-15].

The proposed approach is based on iterative solution of a linear-constrained multi-objective optimization problem. The multi-objective function of the scheduling problem consists in the minimization of the voltage deviations with respect the rated value, of the DERs production deviation with respect the maximum efficiency point and of the network losses.

The nonlinear power flow relationships are linearized by means of the calculation of sensitivity coefficients to small variations of the control variables, namely controllable DERs outputs and ULTCs positions.

Two optimization approaches are applied: a least square optimization solver and a goal attainment method. The algorithms have been implemented in the Matlab environment suitably interfaced with the EMTP-RV software that calculates the detailed three-phase power flows.

A specific procedure has been also implemented to facilitate the intentional islanding maneuver and the subsequent operation of the islanded distribution network. The aim of the islanding procedure is to adapt the DERs scheduling in order to minimize the impact of the islanding maneuver on the power flows and on node voltage profile, taking into account all the system constraints and the reserve requirements. For this purpose a two steps approach is followed. The first step solves the optimization problem still assuming the distribution system connected to the primary network but with the value of the transmission capability of the connecting link constrained to be negligible. In this phase, the connecting link is the slack bus for the required power flow calculations. In the second step the connection to the primary network is completely excluded and the slack bus is then associated to the DER characterized by the largest reserve capability. The linear constrained optimization routine is finally applied to the islanded system.

The outline of the paper is the following: Section 2 reviews the objectives and constraints of the DER and ULTC scheduling system based on linear constrained optimization. Section 3 presents the two steps approach for intentional islanding. Section 4 describes the implementation of the scheduling algorithm by using the interface between Matlab and EMTP-RV software. Section 5 presents some test results and Section 6 reports some conclusive remarks.

2 DER AND ULTC SHORT-TERM SCHEDULING BASED ON LINEAR-CONSTRAINED OPTIMIZATION

2.1 General assumptions

We consider an N-bus distribution network with

- N_{fix} load or generation nodes in which fixed forecasted PQ demands or injections are assumed;
- N_{DER} controllable PQ nodes where controllable DERs are located.

Other control devices in the network are in general present. In particular, we consider the presence of N_{ULTC} transformers equipped with ULTCs.

The problem is to find the operating point $\mathbf{x} = [\mathbf{P}_{\text{DER}}\ \mathbf{Q}_{\text{DER}}\ \mathbf{n}_{\text{ULTC}}]$ − being $\mathbf{P}_{\text{DER}}$ and $\mathbf{Q}_{\text{DER}}$ the vectors of the active and reactive power set points of controllable DERs, respectively, and $\mathbf{n}_{\text{ULTC}}$ the vector of the ULTC positions − that meets the following objectives:

- minimization of the voltage deviations with respect to the rated value $\overline{V}$

$$\min_{\mathbf{P}_{\text{DER}},\mathbf{Q}_{\text{DER}},\mathbf{n}_{\text{ULTC}}} \sum_{i=1}^{N} \left| V_i - \overline{V} \right| \tag{1}$$

- minimization of power production cost C at every period t, taking into account production cost $C_{\text{P},j}$ of the j-th DER at output level P_j, considered constant in time interval Δt, and price C_{net} of energy $P_{\text{net}}\Delta t$ imported from the feeding network

$$\min_{\mathbf{P}_{\text{DER}},\mathbf{Q}_{\text{DER}},\mathbf{n}_{\text{ULTC}}} C = C_{\text{net}} P_{\text{net}} \Delta t + \sum_{j=1}^{N_{\text{DER}}} C_{\text{P},j} P_j \Delta t \tag{2}$$

- minimization of the losses P_{loss} in the system

$$\min_{\mathbf{P}_{\text{DER}},\mathbf{Q}_{\text{DER}},\mathbf{n}_{\text{ULTC}}} P_{\text{loss}} = \min_{\mathbf{P}_{\text{DER}},\mathbf{Q}_{\text{DER}},\mathbf{n}_{\text{ULTC}}} \sum_{l=1}^{n_{\text{br}}} R_l I_l^2 \tag{3}$$

  where n_{br} is the number of branches, R_l is the l-th branch resistance and I_l is the l-th branch current.

The constraints are:

- upper and lower limits of the values of the controlled variables, namely the DERs power outputs and ULTCs positions, taking into account the required power reserves;
- voltage limits in all the nodes and power transfer limits in the network branches and from the primary network.

Objective (2) should be extended to all the intervals of a considered horizon, taking into account inter-temporal constraints and energy storage. For this reason in [14,15] a two stage approach has been proposed: a day-ahead economic scheduler that calculates the active power set points during the following day in order to minimize the overall costs and an intra-day scheduler that, every 15 minutes, updates the DERs outputs and ULTCs positions taking into account the results of the day-ahead scheduler. In the intra-day scheduler, subject of this paper, objective (2) is therefore replaced with the minimization of the deviation of the DERs active power output with respect to the vector of their predefined maximum efficiency values $\overline{\mathbf{P}}$.

For the solution of the multi-objective problem, we have applied two different optimization approaches, namely

- a least square optimization solver
- a goal attainment method.

2.2 Least square optimization solution

The objective function is the minimization of the square norm of the linear combination of three components: (i) the square deviations of each j-th DER active power output with respect the corresponding predefined maximum efficiency value $\overline{P}_j$, (ii) the square value of network losses, and (iii) the square value of voltage deviations at each i-th network bus with respect rated value $\overline{V}$:

$$\min_{\mathbf{P}_{\text{DER}},\mathbf{Q}_{\text{DER}},\mathbf{n}_{\text{ULTC}}} \left\{ \sum_{j=1}^{N_{\text{DER}}} \alpha^2 \left(P_j - \overline{P}_j \right)^2 + \beta^2 P_{\text{loss}}{}^2 + \sum_{i=1}^{N} \gamma^2 \left(V_i - \overline{V} \right)^2 \right\} \tag{4}$$

where coefficients α, β, and γ are the weights of the multiobjective optimization function.

The equality constraints of the problem are given by the power flow equations. The inequality constraints are given by the operating constraints of the distribution resources and network branches.

The problem should be solved by a reliable and automatic fast procedure. For this reason we apply a linear-constrained optimization approach. The problem is therefore solved with an iterative procedure.

At the beginning of every iteration k, the deviations of DERs active power outputs $\Delta\overline{P}_j = \overline{P}_j - P_j^{k-1}$, the value of P_{loss} and the deviations of the voltages at each bus $\Delta\overline{V}_i = \overline{V}_i - V_i^{k-1}$ are known as a result of a three-phase power flow calculation.

Voltages and power loss linearized functions of control variables variations $\Delta\mathbf{x}$ are

$$\begin{aligned} \left|\Delta V_i\right| &= \mathbf{K}_{i\mathbf{P}}\Delta\mathbf{P} + \mathbf{K}_{i\mathbf{Q}}\Delta\mathbf{Q} + \mathbf{K}_{i\mathbf{n}}\Delta\mathbf{n} \qquad \forall \text{ bus } i \\ \Delta P_{loss} &= \mathbf{H}_{P_{\text{loss}}\mathbf{P}}\Delta\mathbf{P} + \mathbf{H}_{P_{\text{loss}}\mathbf{Q}}\Delta\mathbf{Q} + \mathbf{H}_{P_{\text{loss}}\mathbf{n}}\Delta\mathbf{n} \end{aligned} \tag{5}$$

where

- $\Delta\mathbf{P}$, $\Delta\mathbf{Q}$ and $\Delta\mathbf{n}$ are the vectors of the variations of P and Q operating levels as well as of tap-changer positions considered as continuous variables;
- $\mathbf{K}_{i\mathbf{P}}$, $\mathbf{K}_{i\mathbf{Q}}$, and $\mathbf{K}_{i\mathbf{n}}$ are the vectors of sensitivity coefficients of voltage deviations at the various buses;
- $\mathbf{H}_{P_{\text{loss}}\mathbf{P}}$, $\mathbf{H}_{P_{\text{loss}}\mathbf{Q}}$, and $\mathbf{H}_{P_{\text{loss}}\mathbf{n}}$ are the vectors of sensitivity coefficients of active network losses.

The sensitivity coefficients are estimated by a series of load flow calculations each performed for a small variation of a different control variable.

Equations (5) are included in the objective of the least square optimization problem as

$$\min_{\Delta\mathbf{x}} \left\| \mathbf{C} \cdot \Delta\mathbf{x} - \mathbf{d} \right\|^2 \tag{6}$$

where

$$C=\begin{bmatrix} \alpha\cdot\mathbf{I}_{N_{\mathrm{DER}}} & 0 & 0 \\ \beta\cdot\mathbf{H_P} & \beta\cdot\mathbf{H_Q} & \beta\cdot\mathbf{H_n} \\ \gamma\cdot\mathbf{K_{1P}} & \gamma\cdot\mathbf{K_{1Q}} & \gamma\cdot\mathbf{K_{1n}} \\ \cdots & \cdots & \cdots \\ \gamma\cdot\mathbf{K}_{N\mathbf{P}} & \gamma\cdot\mathbf{K}_{N\mathbf{Q}} & \gamma\cdot\mathbf{K}_{N\mathbf{n}} \end{bmatrix} \tag{7}$$

and

$$\Delta\mathbf{x}=\begin{bmatrix}\Delta\mathbf{P}\\ \Delta\mathbf{Q}\\ \Delta\mathbf{n}\end{bmatrix} \qquad \mathbf{d}=\begin{bmatrix}\alpha\cdot\Delta\overline{\mathbf{P}}\\ -\beta\cdot P_{loss}\\ \gamma\cdot\Delta\overline{V}_1\\ \vdots\\ \gamma\cdot\Delta\overline{V}_N\end{bmatrix} \tag{8}$$

with $\mathbf{I}_{N_{\mathrm{DER}}}$ is the unit matrix of size N_{DER}.

The problem is subject to the DERs capability constraints. Also the minimum power factor $pf_{\min}$ constraints at the DERs buses, as well as at the slack bus, are taken into account as inequality constraints.

For each DER j, the following constraints are considered

$$\begin{aligned} &\Delta Q_j-\tan\varphi_{\min,j}\Delta P_j\le -Q_{\mathrm{ini},j}+\tan\varphi_{\min,j}P_{\mathrm{ini},j}\\ &-\Delta Q_j-\tan\varphi_{\min,j}\Delta P_j\le Q_{\mathrm{ini}j}+\tan\varphi_{\min,j}P_{\mathrm{ini},j}\end{aligned} \tag{9}$$

where P_{ini} and Q_{ini} are the active and reactive power outputs at the previous iterations and $\tan\varphi_{\min,j}=\tan\left(\cos^{-1}pf_{\min,j}\right)$.

For the slack bus, the inequality constraints are

$$\begin{aligned} &(\Delta Q_{\mathrm{loss}}-\sum_{j=1}^{N_{\mathrm{DER}}}\Delta Q_j)-\tan\varphi_{\min,slack}(\Delta P_{\mathrm{loss}}-\sum_{j=1}^{N_{\mathrm{DER}}}\Delta P_j)\le\\ &\qquad -Q_{\mathrm{ini},slack}+\tan\varphi_{\min,slack}P_{\mathrm{ini},slack}\\ &-(\Delta Q_{\mathrm{loss}}-\sum_{j=1}^{N_{\mathrm{DER}}}\Delta Q_j)-\tan\varphi_{\min,slack}(\Delta P_{\mathrm{loss}}-\sum_{j=1}^{N_{\mathrm{DER}}}\Delta P_j)\le\\ &\qquad Q_{\mathrm{ini},slack}+\tan\varphi_{\min,slack}P_{\mathrm{ini},slack}\end{aligned} \tag{10}$$

where ΔP_{loss} is given by (5) and, similarly, ΔQ_{loss} is provided by

$$\Delta Q_{\mathrm{loss}}=\mathbf{H}_{Q_{\mathrm{loss}}\mathbf{P}}\Delta\mathbf{P}+\mathbf{H}_{Q_{\mathrm{loss}}\mathbf{Q}}\Delta\mathbf{Q}+\mathbf{H}_{Q_{\mathrm{loss}}\mathbf{n}}\Delta\mathbf{n} \tag{11}$$

being $\mathbf{H}_{Q_{\mathrm{loss}}\mathbf{P}}$, $\mathbf{H}_{Q_{\mathrm{loss}}\mathbf{Q}}$, and $\mathbf{H}_{Q_{\mathrm{loss}}\mathbf{n}}$ the vectors of sensitivity coefficients of reactive network losses.

Moreover, the iterative optimization procedure includes also the limits on the maximum power that can be exchanged with the primary network. The excess of active and reactive power exchange at the slack bus is reallocated among the other DERs:

$$\begin{aligned} &\sum_{j=1}^{N_{\mathrm{DER}}}\Delta P_j-\Delta P_{\mathrm{loss}}\le -P_{\min,slack}+P_{\mathrm{ini},slack}\\ &\Delta P_{\mathrm{loss}}-\sum_{j=1}^{N_{\mathrm{DER}}}\Delta P_j\le P_{\max,slack}-P_{\mathrm{ini},slack}\end{aligned} \tag{12}$$

$$\begin{aligned} &\sum_{j=1}^{N_{\mathrm{DER}}}\Delta Q_j-\Delta Q_{\mathrm{loss}}\le -Q_{\min,slack}+Q_{\mathrm{ini},slack}\\ &\Delta Q_{\mathrm{loss}}-\sum_{j=1}^{N_{\mathrm{DER}}}\Delta Q_j\le Q_{\max,slack}-Q_{\mathrm{ini},slack}\end{aligned} \tag{13}$$

Because the problem being solved is always convex, a global solution of the linear-constrained least square is found, although not necessarily a unique one, by using, standard quadratic programming solvers, such as an active set projection method [16].

At each iteration, after obtaining solution $\Delta\mathbf{x}$ of the linearized optimization problem, the initial values of the control variables are modified by $\xi\,\Delta\mathbf{x}$, where coefficient $\xi\in[0,1]$ is calculated so to minimize the value of objective function (4), taking into account the limits on the slack-bus maximum power. We have applied the golden section method for the solution of this nonlinear one-dimensional problem.

The iterative procedure stops when the difference between the values of objective function (4) at two subsequent iterations is lower than a predefined value (objective function not changing) or when the variations of the control variables are smaller than a predefined value (control variables not changing). A maximum number of iterations is also enforced.

2.3 Goal attainment method

Similarly to the least square approach, the linear constrained multi-objective problem can be addressed by using the goal attainment method [17], which has been proposed in the literature as an effective strategy for the problem of interest (e.g. [18]).

The goal attainment method solves the multi-object optimization problem by defining a set of control goals together with a set of under- or over-attainment weighting coefficients, which allow the relative degree γ of under- or over-achievement of the goals to be minimized.

The problem formulation is

$$\min_{\mathbf{P}_{\mathrm{DER}},\mathbf{Q}_{\mathrm{DER}},\mathbf{n}_{\mathrm{ULTC}}}\gamma \tag{14}$$

such that

$$\left|\mathbf{C}\cdot\Delta\mathbf{x}-\mathbf{d}\right|-\mathbf{weight}\cdot\gamma\le\mathbf{goal} \tag{15}$$

where

$$C=\begin{bmatrix} I_{N_{\mathrm{DER}}} & 0 & 0\\ \mathbf{H_P} & \mathbf{H_Q} & \mathbf{H_n}\\ \mathbf{K_{1P}} & \mathbf{K_{1Q}} & \mathbf{K_{1n}}\\ \cdots & \cdots & \cdots\\ \mathbf{K}_{N\mathbf{P}} & \mathbf{K}_{N\mathbf{Q}} & \mathbf{K}_{N\mathbf{n}}\end{bmatrix} \qquad \mathbf{d}=\begin{bmatrix}\Delta\overline{\mathbf{P}}\\ -P_{loss}\\ \Delta\overline{V}_1\\ \vdots\\ \Delta\overline{V}_N\end{bmatrix} \tag{16}$$

and

- **weight**=[$\mathbf{weight_V}$, $\mathbf{weight_P}$, $weight_{\mathrm{loss}}$], being $\mathbf{weight_V}$ the bus voltages weighting vector, $\mathbf{weight_P}$ the weighting vector of the DERs active power outputs and $weight_{\mathrm{loss}}$ the losses weight;
- **goal**=[$\mathbf{goal_V}$, $\mathbf{goal_P}$, $goal_{\mathrm{loss}}$], being $\mathbf{goal_V}$ the

vector of maximum voltage deviations that the objectives attempt to attain and assumed equal to 1% of the rated voltage value, whilst $\mathbf{goal_P}$ and $goal_{\text{loss}}$ are chosen equal to 0.

The remaining constraints are the same as those already described for the least square approach.

At each iteration, the initial values of the control variables are modified by $\xi\,\Delta\mathbf{x}$, where coefficient $\xi \in [0,1]$ is calculated so to minimize the maximum relative degree of under- or over-achievement of the goals by means the application of the golden section method.

As for the application of the least square approach, the iterative procedure may stop both when objective function is not changing or when the control variables are not changing between two subsequent iterations.

3 TWO STEPS APPROACH FOR INTENTIONAL ISLANDING

Intentional islanding requires, in general, an adequate adjustment of DERs outputs and ULTC positions. Also this maneuver can be facilitated by the action of the centralized scheduler that solves an optimization problem in order to allocate the active and reactive power flow originally provided by the feeding network among the available DERs.

After the islanding maneuver, the algorithm should automatically reallocate the slack bus for the load flow calculations. When the distribution network is connected to the main grid, it appears in general convenient to assign the slack bus role to such a grid. However, in islanded operating conditions, also the choice of the slack node can be considered as an additional optimization variable [19].

Starting from an optimized configuration in which the slack bus is the connection bus to the main grid, the proposed islanding procedure is arranged in the following two steps.

1. The first step is the solution of an optimization problem that considers the system still connected to the feeding network (considered as slack bus), formulated as described in the previous section, with the difference that inequality constraints (10)-(13) are replaced by two following equality constraints:

$$\sum_{j=1}^{N_{\text{DER}}} \Delta P_j - \Delta P_{loss} = P_{\text{ini},slack}$$
$$-\tan\varphi_{\min,slack}(\Delta P_{\text{loss}} - \sum_{j=1}^{N_{\text{DER}}} \Delta P_j) - (\sum_{j=1}^{N_{\text{DER}}} \Delta Q_j - \Delta Q_{loss}) = \tan\varphi_{\min,slack} P_{\text{ini},slack} - Q_{\text{ini},slack} \quad (17)$$

which constrain the value of the transmission capability through the connecting link to be negligible.

2. The second step consists on an optimization problem that considers the system actually disconnected from the feeding network formulated in the same way as described in the previous section. The new slack bus is assumed to be the one connected to j'-th DER characterized by an adequate production margins:

$$j' = \arg \max_{j\in\{1,\ldots,N_{\text{DER}}\}} \frac{\left(P_{\max,j} - P_{\min,j}\right) - (\Delta P_{\max,j}^2 + \Delta P_{\min,j}^2)}{\Delta P_{\max,\text{tot}} - \Delta P_{\min,\text{tot}}} + \frac{\left(Q_{\max,j} - Q_{\min,j}\right) - (\Delta Q_{\max,j}^2 + \Delta Q_{\min,j}^2)}{\Delta Q_{\max,\text{tot}} - \Delta Q_{\min,\text{tot}}} \quad (18)$$

being

- $P_{\min,j}$, $P_{\max,j}$, $Q_{\min,j}$, $Q_{\max,j}$ the minimum and maximum output limits of DER j;
- $\Delta P_{\min,j}$, $\Delta P_{\max,j}$, $\Delta Q_{\min,j}$, $\Delta Q_{\max,j}$ the margins between output values and minimum and maximum limits;
- $\Delta P_{\min,\text{tot}}$, $\Delta P_{\max,\text{tot}}$, $\Delta Q_{\min,\text{tot}}$, $\Delta Q_{\max,\text{tot}}$ the summation of all the previous mentioned margins of each DER.

4 IMPLEMENTATION OF THE PROPOSED ALGORITHMS

The optimization problems are solved by computer programs implemented by using the interface between Matlab scripts and the EMTP-RV software package [20].

The interface between Matlab and EMTP-RV is realized by means of scripts specifically developed in the JavaScript modelling programming environment that is part of the EMTP-RV resources. For that purpose the Matlab code that solves the constrained minimization problem described in the previous sections (by using the `lsqlin` and `fgoalattain` solvers of the Matlab optimization toolbox) has been compiled as a COM (Component Object Model) object and included as ActiveX (Active eXtension) control inside the developed JavaScript code, as described in [15].

5 RESULTS AND COMPARISONS

5.1 Description of the distribution test system

An extensive analysis has been carried out to investigate the proposed optimization strategies. In particular, we show here the results obtained on a test network adapted on the basis of the 34-nodes IEEE radial distribution test feeder [21]. Further details on the system are reported in [15].

Three different dispatchable power production units are assumed to be connected to the network in correspondence of nodes 802, 818 and 856 (see Fig. 1). The relevant power limits are $P_{\max,802}$=4000 kW, $P_{\min,802}$=1600 kW, $P_{\max,818}$=1800 kW, $P_{\min,818}$=720 kW, $P_{\max,856}$=2000 kW, $P_{\min,856}$=800 kW. Two not-dispatchable electric power production units (fixed forecasted *PQ* injections) are also connected to the network, namely a photovoltaic (PV) array for a total peak power equal to 50 kW connected to the node 844 and a 750 kW wind generator connected to the node 826. Three ULTCs are present at transformers Tr_1, V_reg_1 and V_reg_2.

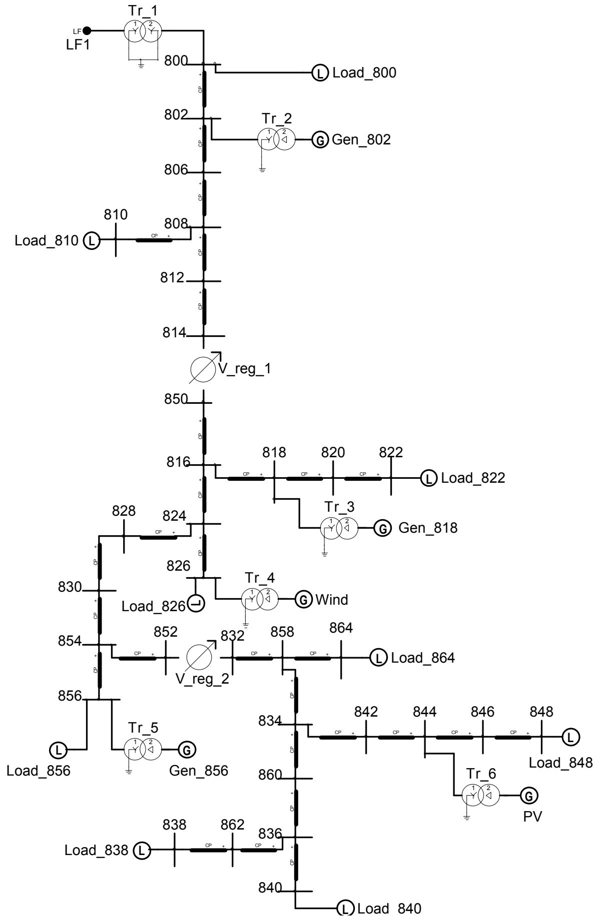

Fig. 1 Test network implemented in EMTP-RV, based on the IEEE 34-node 24.9 kV test distribution feeder.

The DER outputs before the scheduler action are assumed equal to: 4000 kW and 1937.3 kvar for generator 802, 1800 kW and 871.8 kvar for generator 818, 1646.7 kW and 797.6 kvar for generator 856. The initial values of the active power outputs are assumed as the predefined maximum efficiency values $\overline{\mathbf{P}}$ for the considered period, whilst $\bar{V}$ =24.9 kV.

The initial ULTC positions are $n_{\mathrm{Tr\_1}}$=6.024, $n_{\mathrm{V\_reg\_1}}$=1, $n_{\mathrm{V\_reg\_2}}$=1.

5.2 Distribution system connected to the 150 kV feeding network

This section shows the results obtained by applying the proposed scheduler to the case of the distribution network connected to the 150 kV feeding network. As mentioned, bus LF1, the high voltage terminal of transformer Tr_1, is the slack bus, whose voltage is assumed equal to 1 p.u..

Fig. 2 shows the comparison between the initial voltage profile and the ones obtained after the action of the scheduler on the controllable DERs outputs with reference to the following cases:

(i) 1 ULTC (Tr_1);
(ii) 2 ULTCs (Tr_1 and V_reg_1)
(iii) all the 3 available ULTCs

The single optimization objective of the scheduler is the minimization of voltage profile deviations. The results are obtained by means the least square optimization solution with α=0, β=0, and γ=1.

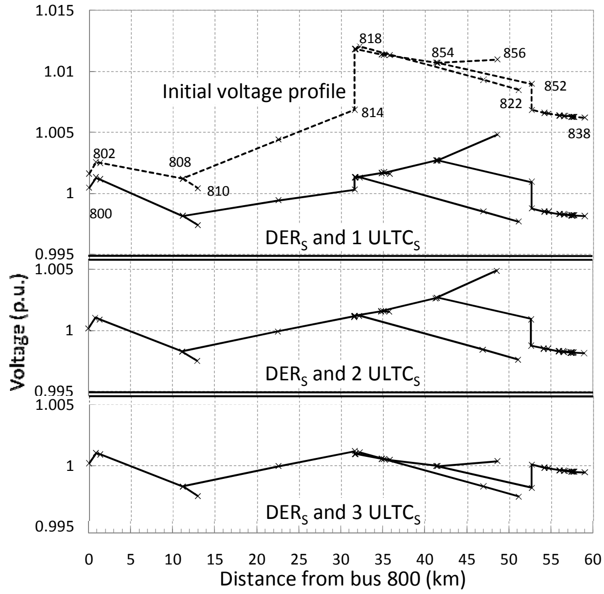

Fig. 2. Influence of the ULTC actions on the voltage profile as function of the distance from the bus 800.

The comparison between the original configuration and the results obtained for the three considered cases after the scheduler action is shown in Table I.

TABLE I. INFLUENCE OF THE ULTC ACTION.

	initial condition	1 ULTC	2 ULTCs	3 ULTCs
voltage mean absolute deviation (V)	152.3	29.78	29.34	12.23
DERs output deviations (kW)	$\Delta P_{802}=0$ $\Delta P_{818}=0$ $\Delta P_{856}=0$	$\Delta P_{802}=-883.5$ $\Delta P_{818}=0$ $\Delta P_{856}=353.2$	$\Delta P_{802}=-943.1$ $\Delta P_{818}=0$ $\Delta P_{856}=353.2$	$\Delta P_{802}=-940.1$ $\Delta P_{818}=0$ $\Delta P_{856}=353.2$
losses (kW)	32.40	28.90	28.48	26.80
ULTC optimal positions	$n_{\mathrm{Tr\_1}}=6.024$ $n_{\mathrm{V\_reg\_1}}=1$ $n_{\mathrm{V\_reg\_2}}=1$	$n_{\mathrm{Tr\_1}}=6.028$ $n_{\mathrm{V\_reg\_1}}=1$ $n_{\mathrm{V\_reg\_2}}=1$	$n_{\mathrm{Tr\_1}}=6.03$ $n_{\mathrm{V\_reg\_1}}=1.002$ $n_{\mathrm{V\_reg\_2}}=1$	$n_{\mathrm{Tr\_1}}=6.03$ $n_{\mathrm{V\_reg\_1}}=1.002$ $n_{\mathrm{V\_reg\_2}}=0.996$

We consider now the case in which all the three ULTCs are available and we compare the results obtained by applying both the least square method and the goal attainment method. Such comparison makes reference to different sets of weights and goals values, being the initial condition of the network the same as considered in the previous calculations of Fig. 2 and Table I.

In particular, for the case that refers to the application of the least square optimization solver, Fig. 3 and Table II shows the comparison between the results obtained for the following different sets of the α-β-γ values:

(lsq0) α=0, β=0, and γ=1, i.e. corresponding to the already considered case (iii);
(lsq1) α=50, β=0, and γ=1;
(lsq2) α=0, β=1, and γ=1;
(lsq3) α=50, β=1, and γ=1.

Case (lsq1) selects as single optimization objective the minimization of voltage profile deviations. Case (lsq2) takes into account also the minimization of network losses. Case (lsq3) tends to keep DERs active power outputs close to their $\overline{\mathbf{P}}$ values by means the high value of the α-coefficient. Case (lsq4) minimizes both the voltage deviations and the losses by keeping, as for the case (lsq3), DERs active power outputs at their $\overline{\mathbf{P}}$ values.

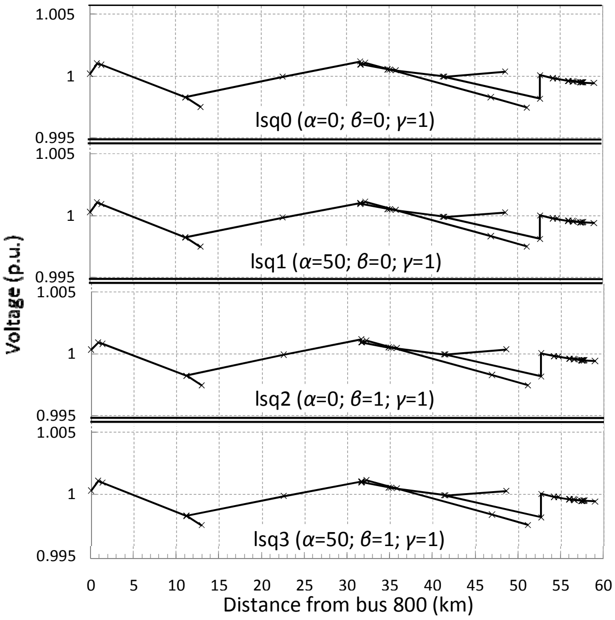

Fig. 3. Comparison between the voltage profiles obtained by applying the least-square solution method for different sets of the α-β-γ values.

TABLE II. COMPARISON BETWEEN THE RESULTS OBTAINED BY APPLYING THE LEAS-SQUARE METHOD FOR DIFFERENT SETS OF α-β-γ VALUES.

	lsq0	lsq1	lsq2	lsq3
voltage mean absolute deviation (V)	12.23	12.6	12.32	12.6
DERs output deviations (kW)	ΔP_{802} = -940.1 ΔP_{818} = 0 ΔP_{856} = 353.2	ΔP_{802} = 0 ΔP_{818} = 0 ΔP_{856} = 0	ΔP_{802} = 1702.5 ΔP_{818} = 0 ΔP_{856} = 353.2	ΔP_{802} = 0 ΔP_{818} = 0 ΔP_{856} = 0
losses (kW)	26.8	30.69	20.85	30.64
ULTC optimal positions	n_{Tr_1} = 6.03 $n_{V\_reg\_1}$ = 1.002 $n_{V\_reg\_2}$ = 0.996	n_{Tr_1} = 6.023 $n_{V\_reg\_1}$ = 1.002 $n_{V\_reg\_2}$ = 0.996	n_{Tr_1} = 6.017 $n_{V\_reg\_1}$ = 1.002 $n_{V\_reg\_2}$ = 0.996	n_{Tr_1} = 6.022 $n_{V\_reg\_1}$ = 1.002 $n_{V\_reg\_2}$ = 0.996
objective function	25819	26254	26460	27197
stopping criterion	both	control variable not changing	both	control variable not changing
iterations	3	2	3	2
ξ values	1,1,1	1,1	1,1,1	1,1

For the case that refers to the use of the goal attainment method, Fig. 4 and Table III compare the results obtained for the following sets of weighting coefficients:

(goal1) $\mathbf{weight_P} = 0.1\,\overline{\mathbf{P}}$ and $weight_{\text{loss}}$ = infinity;

(goal2) $\mathbf{weight_P}$ = infinity and $weight_{\text{loss}} = 10$;

(goal3) $\mathbf{weight_P} = 0.1\,\overline{\mathbf{P}}$ and $weight_{\text{loss}} = 10$;

whilst $\mathbf{weight_V}$ is always assumed equal to $\mathbf{goal_V}$, i.e. equal to 1% of the rated voltage value $\overline{V}$.

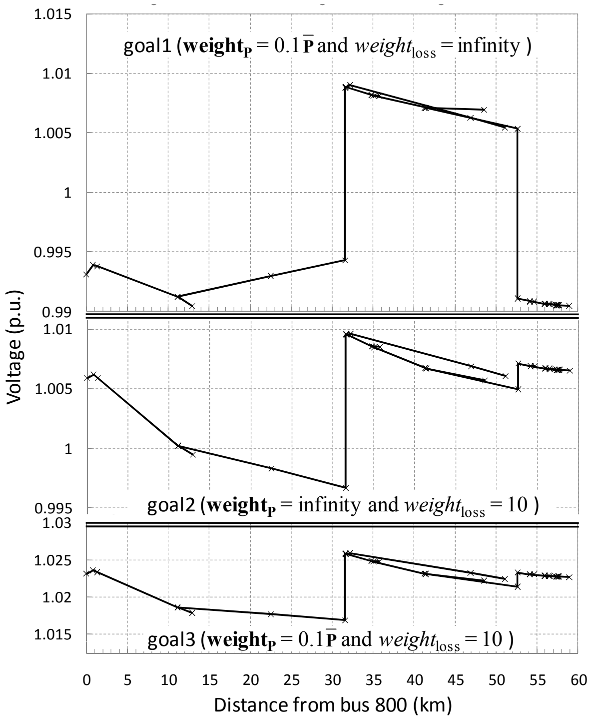

Fig. 4. Comparison between the voltage profiles obtained by applying the goal attainment method for different sets of weighting coefficients.

TABLE III. COMPARISON BETWEEN THE RESULTS OBTAINED BY APPLYING THE GOAL ATTAINMENT METHOD FOR DIFFERENT SETS OF WEIGHTING COEFFICIENTS.

	goal1	goal2	goal3
voltage mean absolute deviation (V)	163.04	133.88	468.31
DERs output deviations (kW)	ΔP_{802} = 0 ΔP_{818} = 0 ΔP_{856} = 0	ΔP_{802}=-1104.4 ΔP_{818}= -618.6 ΔP_{856}= 99.8	ΔP_{802}=-373.7 ΔP_{818}= -292.4 ΔP_{856}= -267.5
losses (kW)	30.83	23.40	26.63
ULTC optimal positions	n_{Tr_1} = 6.067 $n_{V\_reg\_1}$ = 0.988 $n_{V\_reg\_2}$ = 1.012	n_{Tr_1}= 5.967 $n_{V\_reg\_1}$= 0.984 $n_{V\_reg\_2}$= 0.996	n_{Tr_1}= 5.873 $n_{V\_reg\_1}$= 0.990 $n_{V\_reg\_2}$= 0.996
objective function	0	2.34	2.66
stopping criterion	objective fun. not changing	objective fun. not changing	objective fun. not changing
iterations	2	2	2
ξ values	1,0	0.6, 0	0.9,0

As expected, the voltage profiles obtained by applying the least square optimization method are similar to each other, since, for the considered DERs reactive capability limits, the action on the reactive power set points is sufficient to provide an adequate voltage control on the considered test distribution system.

The voltage profiles obtained with the goal attainment method respect the maximum 1% variation goal for the weighting coefficient sets (goal1) and (goal2). For the case of set (goal3), the higher variations are obtained because both the goals of null active power deviations and losses are searched.

The results obtained by using both the least square and the goal attainment method show that the minimum losses are in general associated with operating conditions characterized by lower voltage deviations. On the contrary, higher voltage deviations are obtained when DERs active output deviations are forced to be zero.

5.3 *Intentional islanding*

This section presents an illustrative example of the use of the proposed procedure for the intentional islanding maneuver. The results are obtained by means the least square optimization solution with α=0, β=0, and γ=1.

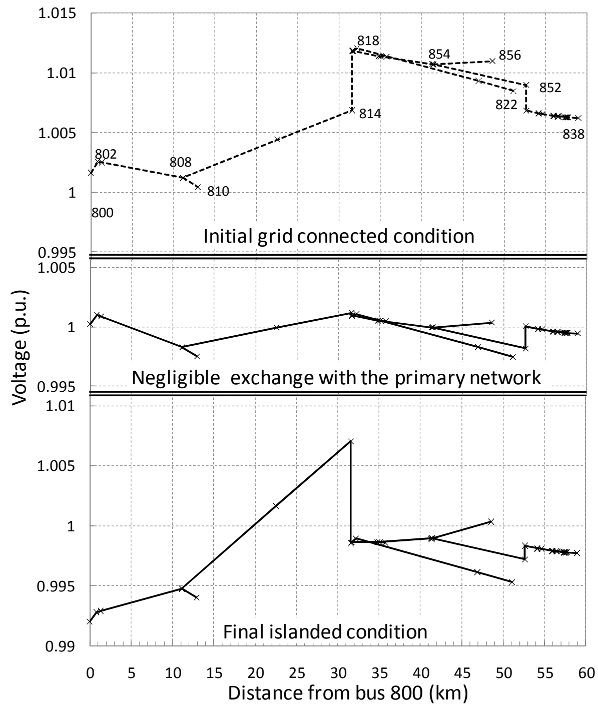

Fig. 5. Voltage profile during the intentional islanding transition.

Fig. 5 shows first the voltage profiles before the islanding maneuver, then the voltage profile resulting after the solution of the optimization problem subject to the constrain that limits the exchange with the primary network to a negligible value, and finally the voltage profile obtained for the islanded network.

In the islanded condition, the role of the slack bus is assumed by bus 802. It is indeed characterized by the largest production margin value given by (18) and equal to 5120.26. The corresponding values relevant to Gen_818 and to Gen_856 are 959.89 and 1266.78, respectively. These values are calculated when the exchange with the primary network is constrained to a negligible value.

The final DER active and reactive outputs, after the islanding procedure, are: 3965 kW and 619 kvar for generator 802, 1800 kW and 1323.3 kvar for generator 818, 1718.4 kW and 1172.5 kvar for generator 856. The final ULTCs positions are $n_{\mathrm{Tr\_1}}$=6.022, $n_{\mathrm{V\_reg\_1}}$=1.02, $n_{\mathrm{V\_reg\_2}}$=0.997.

6 CONCLUSIONS

The paper has presented a multi-objective linear constrained optimization approach implemented in an automatic intra-day scheduler of controllable DERs and ULTCs available in active distribution networks.

The developed intra-day scheduler, suitably integrated with local control systems to ensure system security during fast transients (e.g. due to random load or configuration changes), appears to be adequate for the optimal management of active networks during the slow modifications (e.g. 15 minutes) due to daily load variations.

The same approach is used also to implement a procedure able to facilitate the intentional islanding maneuver and the following operation of the islanded distribution network.

Two different multi-objective optimization solvers have been applied and compared. In both cases, the optimization variables have been assumed to be continuous, deliberately disregarding, in a first approximation, the non-continuous behavior of the variations of the ULTCs; an assumption that deserves further investigation.

The network representation by means the EMTP-RV software environment allows to incorporate distributed resources different from those present in the assumed test system, such as power electronic components (SVC, DFACTS, etc.). Another advantage of such a network modeling consists in the possibility of performing time-domain transient studies suitably initialized from the calculated operating points. Such a transient studies allows more accurate evaluation of the appropriate security margins.

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