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Advanced DMS to Manage Active Distribution Networks

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***Abstract* — The paper presents an advanced Distribution Management System capable to manage an active distribution network economically and safely. The DMS optimizes the power flows in the network, regulates the voltage profiles, acting on reactive flows and tap changers in substation, minimizes the energy losses, reconfigures the network, exploits storage devices and responsive loads in an integrated way. The optimization algorithm finds the optimal combination of such operation options to minimize system costs without causing violations of the technical constraints. The system costs include the energy losses, the cost of generation curtailment, the cost of reactive power, the cost of load shedding, and the cost of storages. The proposed method has been applied on a model test network to verify the validity of the approach.**

***Keywords*— Active Networks, Distribution Management System, Distributed Energy Resources, Responsive Loads, Generation Curtailment.**

I. Introduction

THE concepts of Smart Grids, self-healing networks, or Active Networks are commonly used in the Literature [1]-[2]. The most comprehensive definition to describe what such an active approach was recently approved by the CIGRE SC C6: "Active Distribution Networks (ADNs) are distribution networks that have systems in place to control a combination of distributed energy resources (generators, loads and storage). DSOs have the possibility of managing the electricity flows using a flexible network topology. DERs (Distributed Energy Resources) take some degree of responsibility for system support, which will depend on a suitable regulatory environment and connection agreement." The most innovative concept is that DERs are active subjects of the system with new business opportunities from the active management (e.g., selling of ancillary services) but with the responsibility to assure a proper work of the system working in coordination with DSOs. ADNs need new flexible network topology, protection, communication, and integration into existing systems. The most common ADNs applications are power flow congestion management, voltage regulation, DG and load control, and fast reconfiguration. The expected benefits are improved reliability, increased asset utilization, improved access for DER, alternative to network reinforcement and network stability. Currently, there are few examples of pilot installations of ADNs in Australia, Denmark, Spain and the UK. In the scientific Literature, some contributions highlight the factors that would help facilitate future deployment of active distribution networks. These include (in level of priority, from highest to lowest): new investment remuneration/regulatory frameworks to foster utility adoption; research and development (including publicly funded demonstration projects), standardization, whereas demand growth and environmental factors were deemed to slightly impact the adoption of ADN. The lack of experience, the increased complexity, and the use of novel communication systems are perceived weaknesses of ADNs and potential threats to the ADNs development. In any case, among these fundamental issues, the Literature has been mainly focused on designing efficient Distribution Management Systems (DMS) to abandon the classical paradigm of passive power distribution systems. Indeed, many DMS algorithms have been recently proposed in the Literature to operate the system by interacting with the OLTC (On Load Tap Changer) and DERs to solve voltage regulation problems or power congestions. The main options proposed to relieve such contingencies are flexible network topologies, DG generation curtailment, the use of ancillary services from DG, and demand side response. Algorithms for voltage regulation have been proposed that resort to generation curtailment whether all other possible operation settings are unsuccessful. Sensitivity indexes to identify the most convenient DG units to be controlled have been often used with the aim to minimize the amount of curtailed power. Other DMS algorithms optimize objective functions that consider energy losses, line ampacity and the contribution of responsive loads.

In previous papers the authors proposed an algorithm to be implemented in a DMS that allows operating a distribution network with high DG share without violations of the constraints on nodal voltages and line currents [3]-[4]. This goal was achieved by minimizing the cost of system operation, which is expressed in terms of cost of energy losses, cost of curtailed energy, cost of reactive support, and cost of shed energy. The DMS makes the system comply with the constraints by optimizing the use of DG generation curtailment, DG ancillary services, and demand side response. The objective function and the constraints have been linearized to reduce the computing burden so that the algorithm can be used in real time applications.

In this paper, the algorithm supporting the DMS to optimally operating the network has been further improved and it helps not only solve contingencies, but also in the

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ordinary operation of the system. Voltage profile, energy losses and power flows are continuously monitored and controlled to minimize the overall cost of the system.

Significant examples are provided to show the effectiveness of the algorithm.

II. Distribution Management System

The DMS is the core of active management where all the control decisions are made. Basic DMSs simply decide to disconnect DERs in case of severe network conditions. Advanced DMSs can control the OLTC and DER, and change in real time the network topology to minimize energy losses, improve voltage regulation and exploit existing assets. In Fig. 1, a scheme of an advanced control system is shown, with a central controller, the DMS. The DMS inputs are the status of the network, technical constraints, as well as market prices and information on energy trades. The DMS outputs are typically the followings:

- DG generation curtailment;
- ancillary services from DG;
- exploitation of storages;
- load shedding;
- network reconfiguration.

The simplest DMS does not have a complicated control algorithm but only reduces the DG production in case of severe network conditions. More complex DMSs are able to manage contingencies and emergency conditions occurring in the network by regulating more control variables. They may be tripped by constraint violations like voltage regulation problems (typically over-voltages caused by DG and voltage drops caused by high load) and line over-currents both in standard and emergency configurations. The goal in this case is to minimize the reduction of DG production, particularly the one from renewable sources. The DMS can use the DG generation curtailment, the reactive power dispatch, and the load shedding. More elaborate algorithms for DMS can also allow minimizing energy losses. To reduce energy losses, the DMS optimizes power production (active and reactive) and load demand by considering sensitivity of losses with respect to power injections; the integrated use of network reconfiguration and distribution FACTS may be another option to be considered to redirect power flows and reduce energy losses.

Advanced DMSs are based on algorithms that find the optimal combination of all the available operation options to minimize system operation costs and comply with technical constraints and contractual ties with the customers. The costs that have to be taken into account include the energy losses,

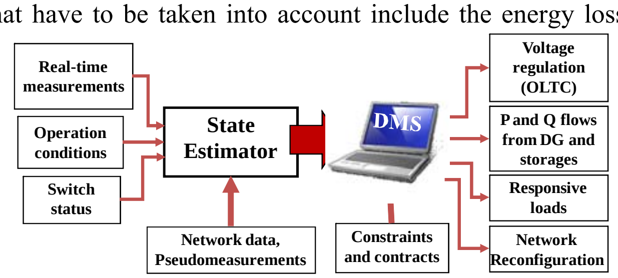

Fig. 1. Advanced DMS layout.

the cost of generation curtailment, the cost of reactive power and ancillary services, the cost of load shedding, and the cost of storage.

Various DMS algorithms have been recently proposed in the literature. Some of them are focused on voltage regulation that can be severely affected by DG, especially in long overhead lines. Algorithms for voltage regulation are proposed in [5]-[6]. In [5] the DMS improves voltage regulation by resorting to generation curtailment whether all other possible operation setting were unsuccessful. In [6] the optimization algorithm is based on sensitivity indexes to identify the most convenient DG units to inject active and/or reactive power. The objective of the algorithm is to minimize the amount of curtailed power. In [3], [4] and [7] the DMS is based on the optimization of an objective function that considers energy losses, line ampacity and the contribution of responsive loads. The algorithm is very fast and well suited for real time applications. As stated before, the DMS may be triggered by the violation of technical constraints or it can continuously optimize the use of the system. In both cases, the decision-making process needs an accurate knowledge on the state of the network. For this reason, ad hoc state estimators are usually integrated in the DMS in order to provide the real-time status of a network by exploiting data gathered from distributed measurement system (insufficient at distribution level) and other available information retrieved from historical and available data (pseudo-measurements) [8].

A. *Proposed algorithm*

The novel algorithm proposed in this paper is able to deal with all the operational options mentioned in the previous section. The problem to find the optimal combination of operation options can be considered as a classical OPF (Optimal Power Flow) problem. It can be formulated as a constrained minimization, where the overall costs of the system are the terms of the objective function, and the constraints concern the maximum allowable variations in voltages and currents during normal and emergency conditions, the technical limits of DG generators, the dynamics of the storage energy sources, etc.. Obviously, the Load Flow (LF) equations (for a given topology) as well as the contractual ties between DSOs and customers have to be complied with in each time interval. The active network management aims at minimizing energy losses and solving critical contingencies by modifying nodal power injections or by making use of flexible network topologies. In such a system, power producers or responsive loads are get paid for the services they provide, and for that reason, from the DSO point of view a cost is associated to active or reactive power changes with respect to the scheduled power pattern. Eq. (1) summarizes the objective function to be minimized in the active network management.

$$\min \sum_{i=1}^{N_{branches}} \alpha_i P_i^{loss} + \sum_{j=1}^{N_{DG\_gc}} \beta_j P_j^{gc} + \sum_{j=1}^{N_{DG\_gc}} \psi_j Q_j^{gc} + \sum_{k=1}^{N_{DSR}} \gamma_k P_k^{DSR} \quad (1)$$

With some approximation, the objective function (1) can be expressed as linear combinations of line flows [9], curtailed active power [7], reactive power from DG, and shed power [4]. The first summation in (1) represents the cost of the energy losses. Being F_i the active power flow through the i^{th} branch of the network and δ_i a coefficient that allows estimating the cost of energy losses, (2) gives the approximated value of the cost of energy losses in the network, C^{loss}.

$$C^{loss} = \sum_{i=1}^{N_{branches}} \left(\frac{c_l \cdot \Delta t \cdot r_i \cdot F_{avg}}{3 \cdot V_n^2} \right) \cdot \left| F_i \right| = \sum_{i=1}^{N_{branches}} \delta_i \left| F_i \right| \quad (2)$$

where c_l is the unitary cost of the energy lost, V_n is the nominal voltage, r_i is the resistance of the i^{th} branch, Δt is the time interval between two successive DMS runs. The average value of the estimated power, F_{avg}, equal for each network branch is used to obtain an estimate of the average losses. The idea of this calculation is to optimize the power flows penalising paths with high resistance and favouring those that have small resistance, using the coefficient δ_i (that is proportional to r_i).

The second summation in (1) takes into account that by dispatching the active power from each DG units, the DMS can modify the line power flows with positive effects on the system. In the paper it has been assumed that DG owners have to be compensated for any power curtailment so that the resort to this control action is justified only if the cost of the losses becomes greater than the cost of power curtailment. The cost of generation curtailment, C^{gc}, can be calculated with (3).

$$C^{gc} = \sum_{j=1}^{N_{DG\_gc}} c_j^{DG} \Delta t \left(P_{gj}^* - P_{gj} \right) = \sum_{j=1}^{N_{DG\_gc}} \beta_j P_{gj} - \sum_{j=1}^{N_{DG\_gc}} \beta_j P_{gj}^* \quad (3)$$

$$\beta_j = -c_j^{DG} \Delta t$$

where c_j^{DG} is the cost for reducing 1 kWh of the j^{th} DG unit production, Δt is the interval between two successive real-time network calculations, N_{DG_gc} is the number of the controllable generators connected to the distribution network, P_{gj} is the real power output of the j^{th} DG unit and $P_{gj}{}^*$ is the rated power production in the time interval. By considering that the second term of (3) is invariant in the optimization process it has been disregarded in (4).

The third summation in (1) represents the cost for purchasing reactive power from DG; ψ_j is the cost that the DSO has to pay for the kVARh produced by the DG units.

Finally, the last summation takes into account the cost for shedding the responsive loads in the network. P_k^{DSR} is the power shed from the k^{th} load, N_{DSR} is the number of the responsive loads, γ_k is proportional to the cost of power shedding.

In order to linearize the optimization problem, the power flow F_i is expressed by means of two non-negative quantities, X_i and Y_i, that cannot be both nonzero at the same time (the quantity X_i assumes a nonzero value if the power flows in the positive direction of the oriented graph, otherwise it is Y_i to be nonzero) [9]. The same is for the reactive power flows that may assume positive or negative values (depending on the generator supplies inductive or capacitive reactive power).

Definitely, the linear model of the optimization problem can be formalized as in (4).

$$\min \sum_{i=1}^{N_{branches}} \delta_i (X_i + Y_i) + \sum_{j=1}^{N_{DG\_gc}} \beta_j P_j^{gc} + \sum_{j=1}^{N_{DG\_gc}} \psi_j \left(X_{Qj}^{gc} + Y_{Qj}^{gc} \right) + \sum_{k=1}^{N_{DSR}} \gamma_k P_k^{DSR} \quad (4)$$

subject to (5) and (6).

$$\left[A \right] \cdot x = B \quad (5)$$

$$[X_P],[Y_P],[X_Q],[Y_Q],[S] \geq 0 \quad (6)$$

Assuming $s_k^{P_g} = \frac{dv_i}{dP_{g,k}}$, $s_k^{Q_g} = \frac{dv_i}{dQ_{g,k}}$, $s_j^{P_L} = \frac{dv_i}{dP_{L,j}}$, $s_j^{Q_L} = \frac{dv_i}{dQ_{L,j}}$ (the sensitivity indexes), the (5) can be represented by (7).

$$\begin{bmatrix} A_1 & -A_1 & B_g & B_{DSR} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & tg\varphi_L & A_1 & -A_1 & B_g & -B_g & 0 \\ 0 & 0 & -s_k^{P_g} & \left(s_j^{P_L} + s_j^{Q_L} tg\varphi_L \right) & 0 & 0 & s_k^{Q_g} & -s_k^{Q_g} & I \\ 0 & 0 & -s_k^{P_g} & \left(s_j^{P_L} + s_j^{Q_L} tg\varphi_L \right) & 0 & 0 & s_k^{Q_g} & -s_k^{Q_g} & I \\ I & -I & 0 & 0 & m^B & -m^B & 0 & 0 & I \\ 0 & 0 & I & 0 & 0 & 0 & m^g & -m^g & I \end{bmatrix} \begin{bmatrix} X_P \\ Y_P \\ \Delta P^{gc} \\ \Delta P^{DSR} \\ X_Q \\ Y_Q \\ X_Q^{gc} \\ Y_Q^{gc} \\ S \end{bmatrix} = \begin{bmatrix} P \\ Q \\ \Delta V_{\lim}^{over} \\ \Delta V_{\lim}^{under} \\ q^B \\ q^g \end{bmatrix} \quad (7)$$

where I is the identity matrix, A_1 is the node to branch incidence matrix, B_g and B_{DSR} are binary matrixes introduced to insert DSR and GC into power flow equations, $tg\varphi_L$ is referred to DSR loads (the DSR loads are considered with a constant power factor), S is a non-negative vector of slack variables to transform inequality constraints into equality constraints, ΔP^{DSR} is the vector of the shedding powers, ΔP^{gc} is the vector of the curtailed powers, P and Q are the nodal powers, and $\Delta V_{\lim}^{over} = V_{ref}^{over} - V^*$, and $\Delta V_{\lim}^{under} = V_{ref}^{under} - V^*$ are the maximum allowable deviations of the bus voltages vector V^*, with V_{ref}^{over} =1.05 p.u. and V_{ref}^{under} =0.95 p.u..

The first two blocks of equations ($2 \cdot N_{bus}$ equations) in (7) represent the balance of powers, active and reactive respectively, in each node of the network. The third and the fourth groups of equations represent the voltage constraints. In particular, using these equations the DG and the DSR loads can be exploited, by curtailing active power and/or by injecting reactive power, to relieve contingencies or simply for economic reasons, without causing violations of the technical constraints. The $2 \cdot N_{bus}$ equations of these blocks can be expressed in the equality form as in (8).

$$\begin{aligned} &\sum_{k=1}^{N_{DG\_gc}} \left[-s_k^{P_g} P_k^{gc} + s_k^{Q_g} \left(X_{Q,k}^{gc} + Y_{Q,k}^{gc} \right) \right] + \sum_{j=1}^{N_{DSR}} -\left(s_j^{P_L} + s_j^{Q_L} tg\varphi_j \right) P_j^{DSR} + S_i = \Delta V_{\lim,i}^{over} \\ &\sum_{k=1}^{N_{DG\_gc}} \left[-s_k^{P_g} P_k^{gc} + s_k^{Q_g} \left(X_{Q,k}^{gc} + Y_{Q,k}^{gc} \right) \right] + \sum_{j=1}^{N_{DSR}} -\left(s_j^{P_L} + s_j^{Q_L} tg\varphi_j \right) P_j^{DSR} + S_i = \Delta V_{\lim,i}^{under} \end{aligned} \quad (8)$$

where i=1…N_{bus}. The non-negative slack variable S_i has been introduced in order to transform the inequality constraints fixed by the voltage bounds.

Finally, the active and reactive powers generated by the k^{th} generator have to comply with the capability curve of the generator (for synchronous machines). The capability curve is approximated with a piecewise linear to maintain the linear formulation. Assuming that N_{seg} is the number of straight lines used to approximate the generator capability curve, for each generator 2*N_{seg} inequality constraints have to be considered (in order to take into account both inductive and capacitive reactive power). Eq. (9) gives a general formulation of the constraint in the equality form.

$$P_k + m_{jk}^g Q_k + S_{jk} = q_{jk}^g \quad j = 1 \ldots N_{seg}, \quad k = 1 \ldots N^{DG\_gc} \tag{9}$$

m_{jk} and q_{jk} are the slope and the intercept of the j^{th} line used to approximate the capability curve of the k^{th} generator.

A similar approach is also used to take into account the constraints caused by the rated ampacity of the lines. In fact, since in (7) the active and the reactive power flows are decoupled, it is necessary to bound the operation point of each line (in terms of P and Q) with a piecewise linearized circle that has the rated apparent power of such line as radius.

Obviously, besides the mentioned constraints, the minimization problem is subject to the upper and lower bounds of the unknown variables x, as in (6) and (10).

$$\begin{aligned} &0 \le \Delta P_i^{gc} \le \Delta P_{\max,i}^{gc} \quad i = 1 \ldots N_{DG\_gc} \\ &0 \le \Delta P_j^{DSR} \le \Delta P_{\max,j}^{DSR} \quad j = 1 \ldots N_{DSM} \end{aligned} \tag{10}$$

DMS can curtail i^{th} generator power production of $\Delta P_{\max,i}^{gc}$ or shed j^{th} DSR load of $\Delta P_{\max,j}^{DSR}$ at maximum.

B. ADNs optimal operation

The DMS with dedicated DSP (Digital Signal Processor) or industrial computers solves the optimization algorithm running in real-time, gathering input data from field measurements. The optimal solutions are the set points to be sent to the local controllers of DERs.

Once the time horizon is divided into intervals (in the presented studies the duration of the time interval is set to 1 hour, but such time interval would be even shorter), the whole on-line procedure may be described with the following steps:

1. at the beginning of the time interval the DMS gathers data from the network and from the distribution state estimator, that could be essential whether the number of measurement devices was too small;
2. the DMS finds the optimal combination of the available operation options and gives the set points to the DERs that participate at the active management. Generators might be committed to curtail active power and/or modify the production of reactive power. Loads might be requested to reduce power demand. Storage devices might be used to compensate excessive power production or insufficient power. Furthermore, if technically necessary or economically convenient, the DMS can command network reconfiguration;
3. the new set points are hold until the end of the time interval, when new data are gathered from the network and used for a new optimization.

The main novelty of this paper is that the DMS continuously controls and optimizes the network: it acts not only whether some constraints were not complied with, but also in some normal conditions that may be improved, in terms of costs and technical exploitation of the existing assets. Indeed the DMS has the goal to reduce the costs of the active operation of the system.

III. Case study

The described whole procedure has been implemented in a composite digital tool to test the validity of the proposed approach. This tool makes use of the commercial software package DIgSILENT Power Factory® to simulate the network subjected to the DMS control. In particular in the DIgSILENT® environment has been implemented an MV distribution network model that is used as benchmark in the SMARTGRID Research Project that involves the Italian distribution company ENEL and 8 Italian Universities [10]. The data useful for the optimization, that in the on-line procedure are gathered from the field (or from the DSE), in the simulation are obtained as results of DIgSILENT® calculation, i.e. Load Flow (LF) calculation, through a user-defined command written in the DIgSILENT® Programming Language (DPL). This program commands the LF calculation and collects the data for the optimizer. Then, the optimization is performed by solving the algorithm and finally, the results of the optimization are sent again to the model network in DIgSILENT® and hold until the end of the time interval.

A. Test network

Figure 2 shows the network scheme used for the tests. One primary substation feeds 118 MV substations (52 trunk nodes and 66 lateral nodes) that deliver about 26.3 MW to the MV

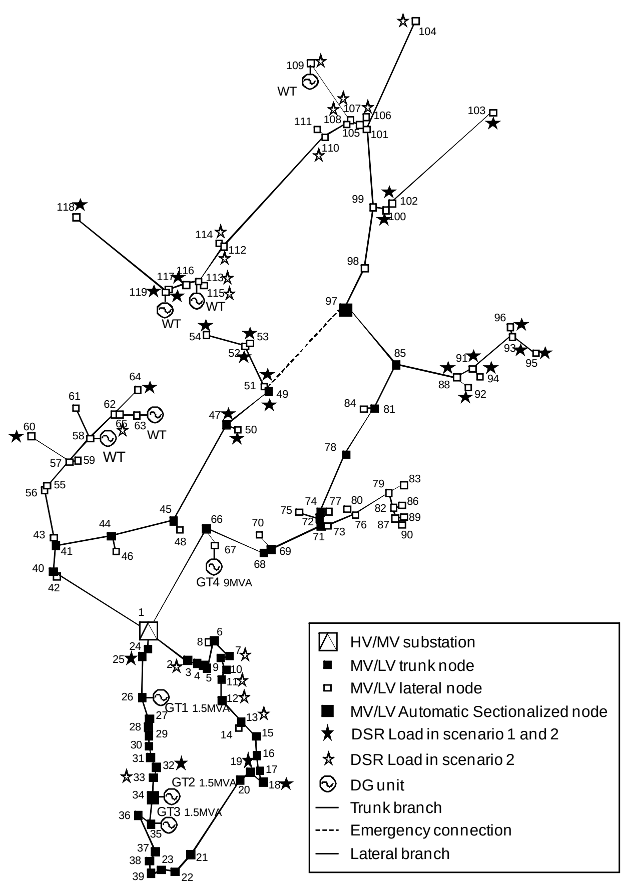

Fig. 2. Test Network

and LV customers. The network is radially operated but is weakly meshed to increase network reliability.

The network may be subdivided in two areas, the rural one (upper part of Fig. 2) where there are long overhead lines, with small cross section, feeding small loads, and the urban one (lower part of Fig. 2) where underground cables with bigger cross section supply urban/industrial high density loads. The rated power capacity and position of DG can severely affect voltage regulation causing over-voltages and line overloads. In particular, two typologies of generators have been taken into account: wind turbine (WT) and gas turbine (GT). Three 1.5 MVA GTs are installed in the urban area and one bigger GT (9 MVA) is connected to the rural portion of the network. The WTs installed in the rural part can generate about 3.6 MVA; they are connected at five busses of the network as it is shown in Fig. 2. Five typologies of loads, with their own daily curves, have been considered: residential, industrial, tertiary, agricultural, and public lighting. Each load is modelled with the appropriate load curve considering the combination of several low voltage customers. In Fig. 3 the daily curves of the total load demand and of the loads in the rural feeder and in the urban one where GTs are connected are reported. Some loads of the network are assumed to be involved in DSR policies and they offer the load shedding service to the DSO according to the two following scenarios:

1. <u>DSR 1 scenario</u>: about 6.6 MW equal to 25% of the total demand;
2. <u>DSR 2 scenario</u>: about 12.6 MW equal to 48% of the total demand.

The loads that participate to the DSR program are pointed out in Fig. 2.

Each scenario may be further split in two ones, if the loads that participate at the DSR program offer a total shedding service (100% of their load demand) or a maximum percentage of 50% of shedding power for the single load. In the last case the maximum amount of power to be shed will be equal to 3.3 MW (DSR 1) or 6.3 MW (DSR 2). The shed power can be used by the DSO to solve critical network conditions.

In order to show the positive role of the DMS in the network operation with high share of DG, the adoption of three operation policies has been simulated:

- the "fit and forget" policy,
- the basic DMS operation, only to relieve contingencies acting on the set points of dispatchable DG (the four TG in the network of Fig. 2), and
- the advanced DMS operation, that continuously manage the network by purchasing network services from DERs (DG and interruptible loads) to improve energy efficiency and relieve expected contingencies.

In the fit and forget policy no central control of generation and load has been used and only local voltage controls are available to disconnect DG in case of high over-voltages or network faults. Local voltage controls should be only seldom used because, according to such a policy, the operation problem is solved at the planning stage, by limiting the integration of renewable energy sources and DG.

The basic DMS dispatches both active and reactive powers from DG for voltage regulation by means of a control law more sophisticated than a simple on-off approach. In this case the algorithm is able to find the optimal reduction of active production. The control of reactive power allows reducing the voltage in some nodes with a smaller generation curtailment. Load shedding is not available with this policy.

Advanced DMS continuously strives to maintain the network close to the optimal operation point that means minimum energy losses at the minimum expenditures for energy services and it is not triggered by incoming contingencies as the basic DMS. In this case, the DMS can resort also to DSR policies. Both advanced and basic DMS are also integrated with delayed local voltage controls on the not dispatchable DG units (e.g. wind turbines). Whether the DMS was not able to eliminate an overvoltage in one node, the DG local control commands the disconnection of one or more than one generator.

Without any active control, the voltage profile of one rural passive feeder (that one with the biggest GT connected) is shown in Fig. 4, for a critical hour (4:00 am) of the day and for two position of the tap changer at the HV side of the transformer in the primary substation. The upper profile corresponds to an increase of 6% of the nominal voltage at the LV side of the transformer. The voltage at the sending end is

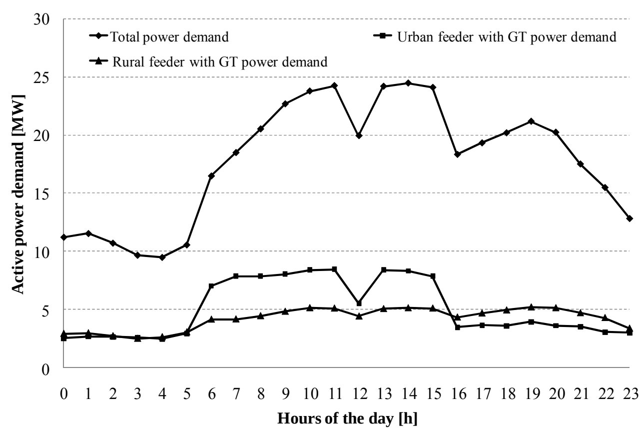

Fig. 3. Nominal power demand

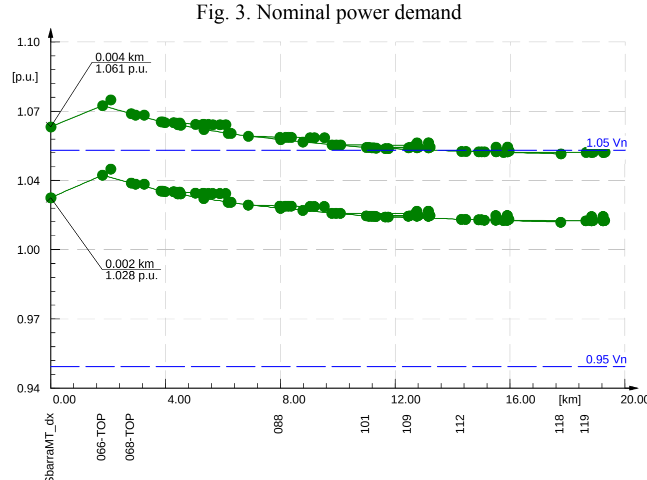

Fig. 4. Voltage profiles of the rural feeder in the fourth hour of the day (corresponding to two different positions of the tap changer).

1.061 p.u. so that voltage drops in the feeders not depicted in Fig. 2 are kept within the prefixed limit.

B. Results and discussion

The fit and forget means that connection problems caused by DG are solved at the planning stage with network upgrades.

Without any change in the network, the connection of 4 MVA GT at node 67 is allowable only if the voltage at the sending end is kept close or below 1 p.u.. By considering that the primary substation has to supply more loads than those depicted in Fig. 2 that assumption is not feasible and the OLTC will try to increase the voltage to compensate the voltage drops. For that reason, in the proposed example, it has been assumed that no generator could be connected at bus 67 without any network upgrade. Without any active control, in order to allow the connection, a dedicated line from the generator to the primary substation is necessary and the related costs are generally high. Those costs are totally or partially paid by the DG owner but, in any case, they cause a barrier to the integration and discourage investments even if they could be economically and environmentally sound.

A basic DMS is capable to avoid any network upgrade even with voltage at the sending busbar at the maximum required value. The reduction of power production from 10:00 pm to 6:00 am allows keeping voltages and line power flows within their respective limits. ADNs are more attractive to DG investors and to DSO because bigger generators may be connected at the same node without any network improvement. Figures 5-7 show the scheduled and the actual power production from 4, 7, and 9 MVA GT installed at the node 67 of Fig. 2 (power production curves refer to dispatchable DG in the network). The surface below the graphs is proportional to the energy sold to the system. The difference between the scheduled and the actual production is due to the active management of the network that, by reducing the power production and controlling the reactive power injection, allows the network to comply with the technical constraints.

Connecting a GT with a rated power of 9 MVA in the considered network is absolutely unprofitable as showed in Fig. 7. Such a big generator can never run at its nominal power and, as a consequence, the DG owner suffers an unacceptable income reduction that cannot lead to the payback of the investment in reasonable times. It can be also observed that the 7 MVA GT is the optimum choice since the scheduled production of DG can be followed for many hours of the day with small reductions (Fig. 6). As showed in Fig. 6, the dispatchable DG energy production is roughly 233 MWh whereas, with the 4 MVA GT installed, the production is 182 MWh (Fig. 5). In the most critical hour of the day the reduction of active power production with the smallest DG set is 21 % (with reference to the scheduled power) and 13 % with the 7 MVA GT. This positive effect is achieved by exploiting the inductive reactive power generation capability of the biggest generator.

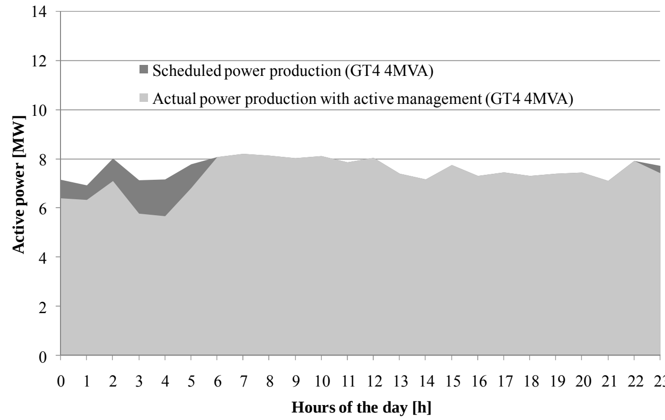

Fig. 5. The energy curtailed by the DMS with reference to 4 MVA gas turbine connected at node 67 in the network of Fig. 2

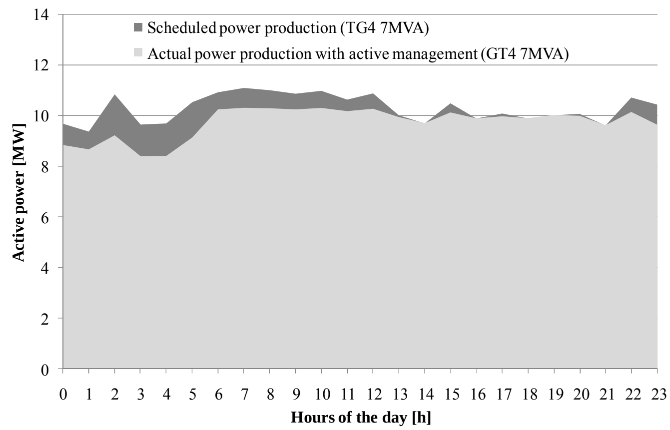

Fig. 6. The energy curtailed by the DMS with reference to 7 MVA gas turbine connected at node 67 in the network of Fig. 2

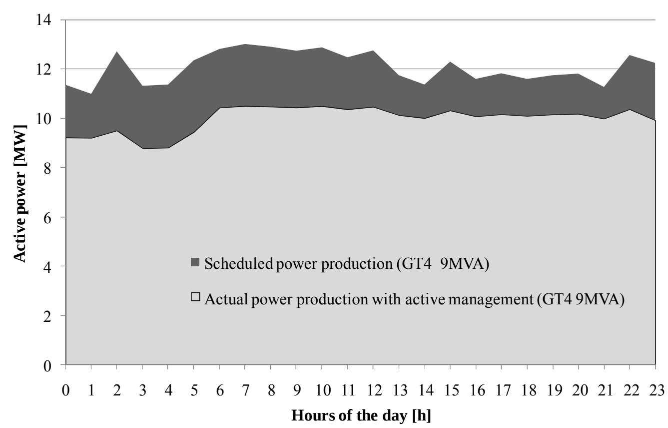

Fig. 7. The energy curtailed by the DMS with reference to 9 MVA gas turbine connected at node 67 in the network of Fig. 2

From the DSO point of view, the ADN may be less convenient because the curtailment of active power production and the reactive power generation are services that have to be purchased from the producers, depending on the regulatory environment. The DMS minimizes the resort to ancillary services and increases the benefit to DSO by minimizing energy losses. The energy losses with the 4 MVA, 7 MVA and 9 MVA GTs are depicted in Fig. 8. It is worth to noticing that the DMS allows connecting DG concentrated on generators with bigger rated power capacity without a significant increasing of losses. With the fit and forget policy,

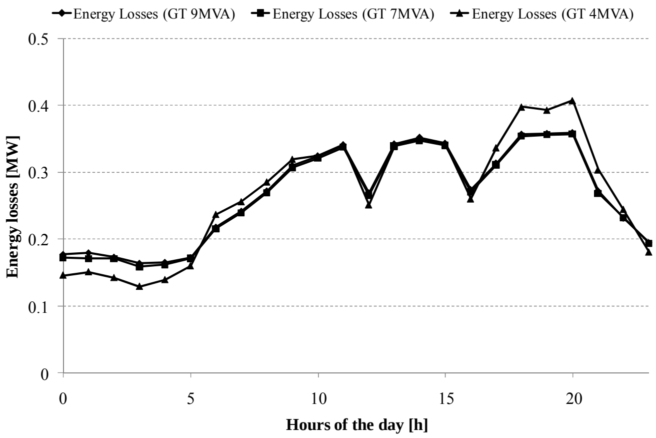

Fig. 8. Energy losses with the 4 MVA, 7 MVA and 9 MVA gas turbines.

DSO does not like that DG is concentrated on few generators because that situation generally causes an worsening in the energy efficiency and, in some countries, penalties to be paid. On the other side, DG investors strive to minimize the payback time of the investment and they do prefer to choose the size of generator considering the availability of renewable energy sources or the heat demand. The DMS allows big dispatchable units being installed without an increasing of energy losses. In the proposed example energy losses are roughly 6.4 MWh with the three examined GTs. The DMS is then a way to solve the tensions between DSOs and DG owners caused by the opposite objective of integrating generation as big as it is economically convenient and the obligation to reduce energy losses [11].

Whether some loads of the network are involved in DSR policies and offer load shedding services to the DSO, the DMS is able to solve voltage regulation problems in the peak hours by integrating the DG capabilities with the willingness of some customers to differ the energy demand. In order to show that features, the network of the case study has been modified so that during the peak hours voltage drops exist that could be eliminated only with high cost network upgrades. By reducing the voltage at the sending bus, the voltage profile has been modified so that there are some nodes in the network with the voltage below the minimum allowable bound. In this situation, the network, even with the 7 MVA GT connected at the node 67, suffers voltage drops and overloads in the peak hours (from 6:00 am to 10:00 pm).

The basic DMS by dispatching the active power, regulating the reactive power injections, without acting on the load demand, optimizes the power production from the GTs. The advanced DMS uses the DSR option and reduces power demand. That action is taken looking also at the DG scheduled production and energy losses. Indeed, an excessive use of DSR can cause overvoltage, excessive curtailment of power production, and the increasing of the demand in other hours of the day. The proposed optimization algorithm avoids that risk by considering all the options simultaneously.

Fig. 9 shows the actual power productions in the hypothesized scenarios. The production curves a) – Basic DMS, b) – Advanced DMS in DSR1 50%, c) Advanced DMS in DSR1 100% are well separated and readable. Areas d) and e) in Fig. 9 are almost completely superimposed to b). The basic DMS uses active and reactive power support to relieve voltage regulation problems and overloads. It is worth noticing that in this particular example the sharing of responsibilities between DSO and DG causes a significant reduction of active power production and the increasing of reactive power generation. By so doing, the technical constraints are complied with, but the price in terms of energy efficiency and pollution may be high and the cost for ancillary services may be high too. In the proposed example, the power generated with DG is 227 MWh/day if the basic optimization algorithm is used for the active management. The advanced DSR is capable to keep the DG scheduled production at a higher level by resorting to DSR. With only a small part of loads integrated in the DMS (25 % in DSR 1) the demand is reduced in the most critical hours of the day and the DG can produce 237 MWh/day. Increasing the load participation to DSR is less profitable from DG point of view. Indeed the increasing of power production is only 2 MWh/day and generally speaking it is not enough to justify the greater complexity of the ADN to allow almost 50 % of responsive loads.

IV. Conclusions

The integration of distributed generation and renewable energy sources has been favored with the incentives and

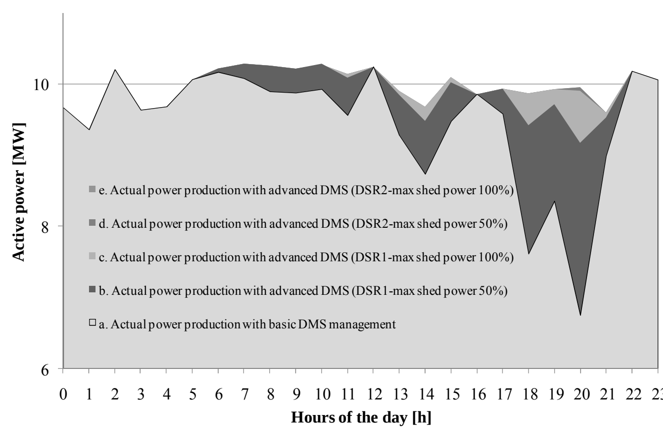

Fig. 9. Actual power production of gas turbines in different scenarios.

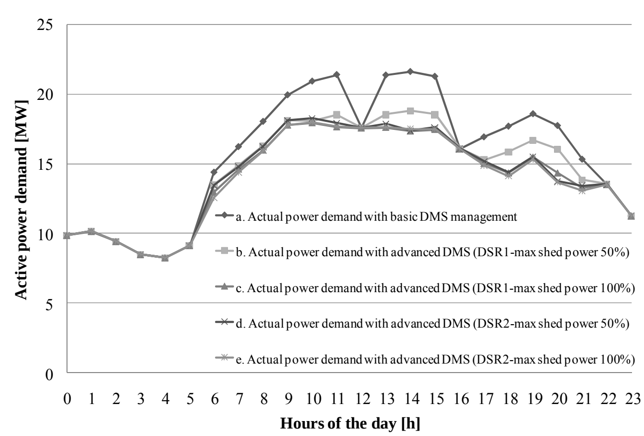

Fig. 10. Load power demand in different scenarios.

penalties established by EU and national governments that are concerned about climate change and carbon dioxide emission. As a result, the distribution system in many industrialized countries is rapidly approaching the critical point beyond that the passive operation is no longer feasible and economic. The active distribution network aims at allowing producers and consumers to actively playing in the energy market being a stimulus to increase energy efficiency and renewable penetration. The DMS can operate the system in several ways according to the regulatory environment, but its kernel is represented by the optimization algorithm used. In this paper, an algorithm for the active distribution network operation with different level of complexity is proposed. The general remark is that the proposed optimization algorithm allows connecting at lowest costs high quantities of DG. Most important, generators of big size can be integrated without an increasing of the network Joule losses.

Secondly, demand side policies can be very helpful but they are expensive and difficult to implement. DSR is useful to limit the curtailment of active power from DG but an excessive use of demand participation does not give significant benefits. Future research will try to better storage capabilities in the optimization process used by the DMS.

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VI. Biographies

Fabrizio Pilo (M’ 1998) was born in Sassari, Italy, in 1966. He graduated in Electrical Engineering at the University of Cagliari in 1992 (magna cum laude) and earned the Ph.D. from the University of Pisa in 1998. Since 2001 he is Associate Professor of Power Systems at the University of Cagliari. His research activity is focused on power systems, electric power distribution, distribution planning, and distributed generation. He is author of more than 90 papers published in international journals or presented in national and international conferences. He is an IEEE and AEIT member, CIGRE SC C6 invited expert and member of the CIRED TC.

Giuditta Pisano (M’ 2004) graduated in Electrical Engineering at the University of Cagliari in 2001. In 2006 she received the Ph.D. in Industrial Engineering from the same University, and currently is post doc. Research interests are in the field of power quality, distribution planning and optimization, distributed generation, state estimation, active distribution networks and MicroGrids. She is IEEE and AEIT member, and member of the CIGRE WG SC6-11.

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