Digital model of a Distribution Management System for the optimal operation of active distribution systems

Fabrizio PILO
University of Cagliari – Italy
pilo@diee.unica.it

Giuditta PISANO
University of Cagliari – Italy
giuditta.pisano@diee.unica.it

Gian Giuseppe SOMA
University of Cagliari – Italy
ggsoma@diee.unica.it

ABSTRACT

The growing interest on environmental issues and the increasing cost of fossil fuels have determined the conditions for high shares of Distributed Generation in the distribution system. Nowadays distribution networks are approaching a critical point whereby the connection of DG will require an active approach. The paper presents a Distribution Management System to manage an active distribution network economically and safely.

INTRODUCTION

Deployment of Distributed Generation (DG) into the existing passive distribution networks is reaching a critical point whereby it can no longer be installed in the typical “fit and forget” fashion without impacting network operation and stability. Connection and management of DG in the network is the first challenge facing Distribution System Operators (DSOs) in making the transition to active, integrated networks.

Issues such as voltage rise effect and increased fault levels caused by DG represent a problem for DSOs. Without proper management, such problems require network reinforcement, thus increasing the cost of connection for DG [1]-[2]. This finally impacts the amount of additional DG that can penetrate the distribution system. Active management of distribution networks enables the DSO to maximize the use of the existing circuits by taking full advantage of generator dispatch, control of transformer taps, voltage regulators, reactive power management and system reconfiguration in an integrated way. This active approach to system operation is reducing the negative impact of DG on the network, minimizing requirements for reinforcement and reducing the cost of connection. Although an accurate and unique definition of active network has not been yet established, a distribution network can be defined active when the DSO can control loads, generators, node voltages and power flows. The Distribution Management System (DMS) is necessary to control the system by interacting with the OLTC (On Load Tap Changer) and Distributed Energy Resources. 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, specially in long overhead lines. Algorithms for voltage regulation are proposed in [3]-[4]. In [3] the DMS improves voltage regulation by resorting to generation curtailment whether all other possible operation setting are unsuccessful. In [4] 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 minimise the amount of curtailed power. In [5] and [6] 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. In this paper the optimization algorithm for the DMS has been improved so that it can continuously optimize the voltage profile, minimize losses and optimize power flows. The paper presents the DMS and its software realization in the DIgSilent Power Factory® software. Examples derived from real cases are provided to show some of the features of the algorithm.

ACTIVE DISTRIBUTION NETWORK

The aim of active networks is to increase the share of DG in existing distribution networks and keep the system stable and reliable at the same time [1]. An example of an active network is presented in Fig. 1. Active network can be defined as network with arbitrary power flow along the network feeders, where voltages are measured or estimated, and controlled in real time, using management of the various devices (DG units, FACTS devices, OLTC, storage devices, etc.). The central control system represents an intelligent system able to decide and operate the distribution network, taking into account the present network conditions. To determine the network conditions state estimation or real time measurements are required [7]. However, to operate the distribution system safely, the central control system would need backup scenarios in case of failure in the control or communication systems.

Parts of active network management are:

- real time measurements or distribution network state estimation,
- communication technology,
- distribution management system,

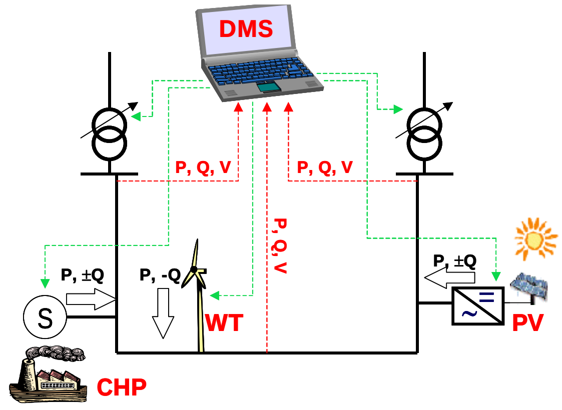

Figure 1: Main features of active distribution networks.

- local DG control systems,
- demand response,
- energy storage.

DISTRIBUTION MANAGEMENT SYSTEM

The DMS helps solve the following contingencies:

- voltage regulation problems (typically overvoltages caused by DG and voltage drops caused by high load),
- line overcurrents in both standard or emergency configurations,
- loss minimization.

The options to relieve the above mentioned contingencies are:

- network reconfiguration, if permitted by the automation level,
- DG generation curtailment and DG ancillary services,
- demand side response.

The optimization algorithm in the DMS has to find the optimal combination of such operation options to minimize system costs without causing violations of the constraints. The objective function (1) takes into consideration the energy losses, the cost of generation curtailment, the cost of reactive power, and the cost of load shedding.

$$\min \sum_{i=1}^{N_{branches}} \delta_i \left|F_i\right| + \sum_{j=1}^{N_{DG\_gc}} \beta_j P_j^{gc} + \sum_{j=1}^{N_{DG\_gc}} \psi_j Q_j^{gc} + \sum_{k=1}^{N_{DSR}} \gamma_k P_k^{DSR} \quad (1)$$

With some approximation, the objective function can be expressed as a linear combinations line flows [8], curtailed power [5], and shed power [6]. In this paper the optimization algorithm has been modified to take into consideration nodal voltage violations and the effect of reactive power injections.

The first summation in (1) is proportional to the cost of the energy losses. F_i is the active power flow through the i^{th} branch of the network. δ_I is a coefficient that allows estimating the cost of energy losses. Eq. (2) gives the approximated value of the cost of energy losses in the network, C_{loss}.

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

c_l is the unitary cost of the energy lost, V_n is the nominal voltage, r_i is the resistance of the i branch, Δt is the time interval between two successive DMS run. The average value of the estimated power, F_{avg}, equal for each network branch in order not to penalise specific paths in the optimisation process, is used to obtain an estimate of the average losses.

The second summation in (1) takes into account the role of active power dispatch to reduce energy losses and relieve network congestions. By dispatching the power from each generator, the DMS can modify the line power flows with positive effects on the systems. In the paper it has been assumed that DG owners should be compensated for any power curtailment so that the resort to this control action can be reasonable only if the cost of losses becomes greater than the cost of power curtailment. The cost of generation curtailment, C_{GC}, can be calculated with (3).

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

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

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_D} 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 power production in the time interval. Not dispatchable DG, e.g. wind generators, have to be included in the nodal power balance equations. Eq. (3) is the second term of (1); the invariant summation is neglected in the objective function (1) because it does not modify the solution of the optimization problem.

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 [8]. The optimization problem can be stated as follows:

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

subject to:

$$\begin{bmatrix} A & -A & 0 & 0 & B_g & B_{DSR} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & tg\varphi & A & -A & 0 & B_g \\ 0 & 0 & 0 & \frac{dv}{dP} & 0 & 0 & 0 & 0 & \frac{dv}{dQ} \\ 1 & -1 & 1 & 0 & 0 & m^B & -m^B & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & m^g & 1 \end{bmatrix} \begin{bmatrix} X_P \\ Y_P \\ S_P \\ P^{gc} \\ P^{DSR} \\ X_Q \\ Y_Q \\ S_Q \\ Q^{gc} \\ S^{PW} \end{bmatrix} = \begin{bmatrix} P \\ Q \\ \Delta V \\ q^B \\ q^g \end{bmatrix} \quad (5)$$

$$\left[X_P\right], \left[Y_P\right], \left[S_P\right], \left[X_Q\right], \left[Y_Q\right], \left[S_Q\right], \left[S^{PW}\right] \geq 0 \quad (6)$$

[A] 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, $tg\varphi$ is referred to DSR loads (the DSR loads are considered with a constant power factor), [S_P] and [S_Q] are the vectors of slack variables (for active and reactive flow, respectively) containing the residual power for each branches, P^{DSR} is the vector of the shedding powers, P^{gc} is the vector of the curtailed powers, P and Q

are the nodal power.

The main novelty introduced in the paper is that DG can help regulate voltage by injecting reactive power. For this reason the optimization problem is subject to constraints on voltage that are expressed according to (9).

$$\Delta V = \sum_{k=1}^{nbus\_GD} \left(\left.\frac{dv}{dP}\right|_k \Delta P_k + \left.\frac{dv}{dQ}\right|_k \Delta Q_k \right) \qquad (7)$$

where *ΔV* is the sum of the voltage deviations with reference to the nominal voltage, $\left.\frac{dv}{dP}\right|_k$ and $\left.\frac{dv}{dQ}\right|_k$ are the sensitivity indexes calculated according to [4].

Finally, the active and reactive powers generated from 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 N_{seg} inequality constraints have to be considered as in (10).

$$P_k + m_{jk}^g Q_k + S_{jk}^{PW} = q_{jk}^g \quad j = 1 \ldots N_{seg}, \quad k = 1 \ldots N^{DG\_GC} \qquad (8)$$

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; S_{jk}^{PW} is a non-negative slack variable to transform the inequality constraint into an equality one.

A similar approach is also used to take into account the transport capability of lines.

SIMULATION STUDIES

The simulation studies of method used for the active management of distribution systems with high DG share was performed in the DIgSILENT PowerFactory® simulation software. The active management was tested on an MV distribution network model that is used as benchmark in the SMARTGRID Research Project that involves ENEL and 8 Italian Universities. The test network has been created by merging two portions of real Italian distribution networks (Fig. 2). One primary substation feeds 118 MV substations (52 trunk nodes and 66 lateral nodes) that deliver power to the MV and LV customers. The network is radial with emergency tie connections. Two areas can be identified in the picture. In the upper part of the network there are long overhead lines feeding small loads. The cross section of the conductors is relatively small because of the low load density; as a consequence of the load growth voltage drop problems have to be expected. The DG in this area may severely affect voltage regulation causing overvoltages. In the lower part of the picture, urban/industrial loads have to be supplied. Here underground cables with bigger cross section are used due to the high load density. The increase of the energy demand in this area may easily lead to overloads and major investments might be necessary. Typically DG in such networks determines an increasing of the short circuit level and can contribute to sharpen voltage regulation problems in the rural area. In both areas DG may or not contribute to loss reduction depending on position, production, and load demand.

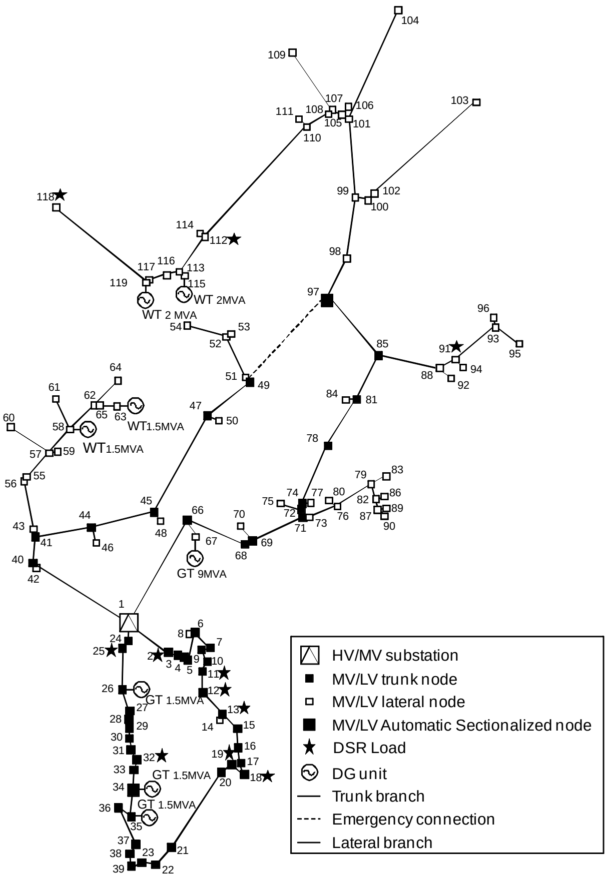

Figure 2: The benchmark network

Five typologies of loads have been considered: residential, industrial, tertiary, agricultural, and public lighting. The loads in the nodes 2, 11, 12, 13, 18, 19, 25, and 32 participate to the DSR offering a total or partial load shedding service that can be used by the DSO to solve critical network conditions. Moreover, three typologies of generators have been taken into account: wind turbine (WT), cogeneration (CHP) and gas turbine (GT). The annual medium active power delivered to the MV nodes is about 16.4 MW, divided in 11.9 MW for the urban feeder and 4.5 MW for the rural one. The unitary cost of Joule losses is 0.22 €/kWh. Two 1.5 MVA CHPs and 1 MVA gas turbine are installed in the urban area; three 2 MVA and two 1.5 MVA WTs are connected to the rural part of the network. A dispatchable 9 MVA biomass gas turbine is also connected to the rural portion of the network.

In the simulation model the DMS interacts with the distribution systems through the DIgSILENT Power Factory® that is used to perform the load flow calculations. The whole procedure may be described with the following steps:

1. the time horizon is divided into intervals (in the paper the duration of the time interval is set to 1

hour);

2. 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. In this paper, the network data are the electrical quantities as they are calculated by the load flow;
3. whether some constraints were not complied with, the DMS calculates the set point for generators, which might be committed to curtail active power and/or modify the production of reactive power, and loads, which might be requested to reduce power demand. Network reconfiguration is not allowed in the application proposed in the paper.
4. 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 central control is also integrated with delayed local voltage controls on the not dispatchable DG units (e.g. wind turbines). When the DMS was not able to eliminate an overvoltage in one node, the DG local control command the disconnection of the generator.

In order to show the positive role of the DMS in the network operation with high share of DG, the results of three simulations are presented in the following subsections:

Connect and Forget Simulation

In this study the current worldwide accepted practice, the connect and forget policy, has been analysed. No central control of generation and load has been used and only local voltage controls are available to disconnect DG in case of high overvoltages or network faults. Local voltage controls should be only seldom used because, according to the connect and forget policy, the operation problem is solved at the planning stage, by limiting the integration of renewable energy sources and DG.

In a typical day, the test network experiences some overvoltage. In particular, whether all the above described generators run according to their daily production curves, the rural portion of the network need a voltage regulation during the off peak hours (from 10:00 pm to 7:00 am). Because of the high overvoltage, the 9 MVA GT installed in the rural area has to be disconnected during all the off peak hours. Normally, the DSO does not allow the connection of a DG unit in such conditions because of the connect and forget rule. It requires that the DG owner pay very high connection costs to reinforce the network and eliminate voltage regulation problems. From the same simulation it can be argued that the maximum allowable GT in the node 67 should have a rated power of 3 MVA. The first conclusion is that even a drastic generation curtailment has the potentiality to be convenient for a DG owner because the switch off time very often will fall in the less convenient hours.

Generation Curtailment Simulation

The second simulation assumed that the DMS was able to control the active power produced by the generator 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. Furthermore, should more curtailment option be available, the optimization finds the optimal curtailment share among different generators with the final goal of minimizing losses and costs. In this case the overvoltage caused by excessive power generation during the off-peak hours would be reduced by imposing a set-point to GT according to the hourly demand and the status of the network. Fig. 3 shows the amount of active power curtailed to avoid voltage regulation problems. The total energy curtailed is 37 MWh/day.

Active and Reactive Power Dispatch Simulation

The third simulation study simulates a fully functioning DMS that dispatches both active and reactive power to resolve voltage regulation. In Fig. 3 the amount of the active power curtailment is reported. The reactive power injection allows reducing the voltage in some nodes with a smaller generation curtailment. The reduction of the energy production for the generator is 6 MWh/day. The general remark is that such a control might be very attractive for DG owners. In fact, a 3 MVA GT connected to the network can produce 65 MWh/day running at the nominal power (8.1 MW with unitary power factor). That power represents the maximum power that can be accepted by the DSO without charging the DG owner with high connection costs caused by the major network reinforcements imposed by the application of the connect and forget rule. The application of an on-off generation curtailment allows integrating a 9 MVA GT into the system. With a true control of the active power production the GT can run at nominal power during the most remunerative hours of the day; the generation curtailment imposed by the DMS causes a 16% reduction of energy in the less remunerative hours of the day (with reference to a nominal power production of 194 MWh/day). The control of reactive power allows a smaller reduction of the active power generated. The reduction with reference to

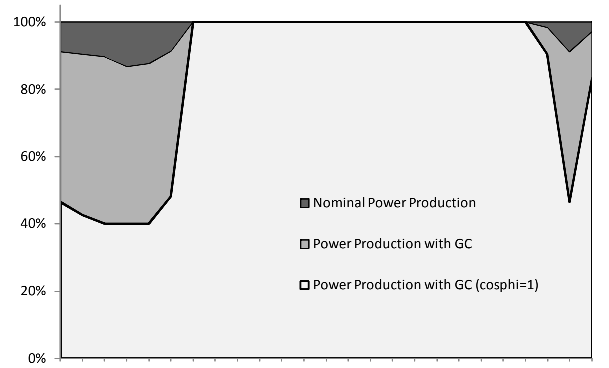

Figure 3: The energy curtailed by the DMS with reference to 9 MVA GT unit connected at node 67 in Fig. 2

the maximum producible energy is now only 3%, that means that about 188 MWh/day could be generated and injected in the network without network reinforcements. Fig. 3 reports the energy curtailed by the DMS during the day. In Fig. 4 the improvement of the voltage profile in the critical area of the network depicted in Fig. 2 is shown. The voltage profile refers to the first hour of the day, that is characterised by low load and possible high production.

Relieve of overloads during emergency network configurations

The benchmark network does not experience in the examined day line overloads. Anyway, in order to validate the capability of DMS of reducing overloads, some emergency network configurations originated by line faults have been also simulated. Faults in the underground cables close to the primary substation 1 in the benchmark network (Fig. 2) are particularly dangerous and, if they happened in the peak hours of the day, serious overloads can cause the intervention of the protections and the enlargement of the faulty area. The most severe fault condition is represented by a line fault in the line between the primary substation and node 2. In that situation, the lines 31-32, 20-21, 22-23, and 23-39 would be overloaded because the emergency connection is used to supply the loads downstream the faulty line. The most critical overloads would be caused by a fault at 12 pm. The only solution is to reduce power demand by using the load responsive loads in the area. In that case, the majority of responsive loads in the network (node 2, 11,12,13, 18, 32) were shed by the DMS. The amount of shed power was equal to 50% for those nodes; node 32 reduced power demand by 13.6%. Globally, the DSR policy shed 1.1 MWh in the examined day. At the same time, the active power generated by the big 9MVA GT in the rural area is curtailed by 7% so that it produces 7.535 MWh at unitary power factor (voltage regulation is not necessary).

CONCLUSIONS

The passive operation of distribution networks poses intolerable barriers to the integration of DG. Voltage regulation, energy losses and line overloads are the most common problems that arise from the integration of DG in a passive operated network. Active management of distribution networks allows postponing massive network reinforcement by controlling the power injected or drawn by generators or loads. In this paper a Distribution Management System for active distribution networks is presented. The optimization algorithm implemented in the DMS allows operating a distribution network with high DG share without violations of the constraints on nodal voltages and line currents. This goal is 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 use of linear programming allows reducing the computing burden so that the algorithm can be used in real time applications. The case studies presented in the paper confirm the effectiveness of the active approach in distribution systems.

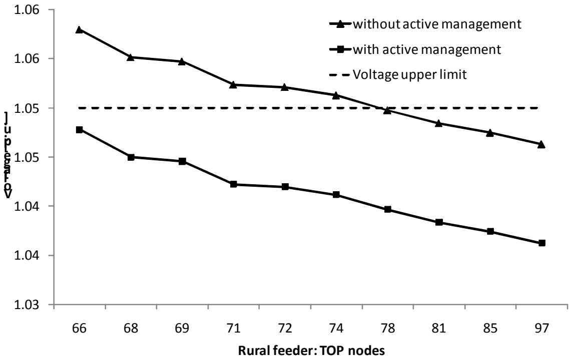

Figure 4: Voltage profile improvement in a critical hour of the day (the numbers in the x axis correspond to the node numbering used in Fig. 2)

REFERENCES

[1] S. N. Liew, G. Strbac, *"Maximising penetration of wind generation in existing distribution networks"*, IEE Proc. Generation, Transmission and Distribution, vol. 149, no. 3, 256-262, 2002.

[2] P. Djapic, C. Ramsay, et al., *"Taking an active approach"*, IEEE power & energy magazine, Vol. Vol. 5, Issue 4, July/August 2007.

[3] F. Kupzog, H. Brunner, W. Pruggler T. Pfajfarm, A. Lugmaier, *"DGDemoNet Concept – A new algorithm for active Distribution Grid Operation facilitating high DG penetration"*, 2007.

[4] Q. Zhou, J.W. Bialek, *"Generation curtailment to manage voltage constraints in distribution networks"*, IET Generation, Transmission and Distribution, 2007.

[5] G. Celli, M. Loddo, F. Pilo, *"Distribution Network Planning with Active Management"*, in Proc. of 6th World Energy System Conf., Torino (Italy), July 2006.

[6] G. Celli, F. Pilo, G. Pisano, G. G. Soma, *"Optimal planning of active networks"*, accepted for 16th Power Systems Computation Conference, 2008.

[7] C. Muscas, F. Pilo, G. Pisano, S. Sulis, *"Optimal Placement of Measurement Devices in Electric Distribution Systems"*, IEEE IMTC 2006, 2006.

[8] A. Abur, G. Celli, M. Loddo, F. Pilo, *"On-line network reconfiguration for loss reduction in distribution networks with Distributed Generation"*, CIRED 2005.