21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

C6-304

CIGRE 2006

Management of Low Voltage Grids with High Penetration of Distributed Generation: concepts, implementations and experiments

A.BERTANI[*], A.BORGHETTI[+], C.BOSSI[§], L.DE BIASE[°], O.LAMQUET[*], S.MASSUCCO[^], A.MORINI[^], C.A.NUCCI[+], M.PAOLONE[+], E.QUAIA[°], F.SILVESTRO[^]
[*]CESI, [+]University of Bologna, [§]CESI Ricerca, [°]University of Milan, [^]University of Genoa
Italy

SUMMARY

The interconnection of distributed generators in low voltage (LV) networks, together with storage systems, could cause a substantial change in grid operational practice: currently a rising idea proposes to treat generators, storage systems and even loads as distributed energy resources (DER), able to supply services to the grid and accept on-line requests.
To emphasise the advantages of Distributed Generation (DG) it is necessary to face the problem with a system approach. In this work both type of services, namely those provided by each generator and those deriving from the co-ordination of different resources, have been investigated. The option represented by a complex master-slave configuration has been discarded in order to avoid its fast communication and control requirements. Instead a prototype based on a centralised resource management solution and a somewhat plug-and-play functionality for each generator has been developed.
For this purpose, different control systems have been implemented in order to act during fast transient dynamics due to random load or configuration changes, or to manage the slow modifications of the system conditions due to daily, weekly and seasonal load variations. The regulators of every distributed resource are requested to give response to fast and unpredictable transient dynamics, i.e. to participate to voltage and frequency regulations, harmonic compensations and phase balancing, while a central dispatcher has been conceived as to periodically update the regulators set-points in order to exploit the capabilities of each distributed resource either for present and foreseen grid operating conditions.
For voltage and frequency regulations, a specific droop control algorithm has been designed so to be implemented on board of generators connected to the LV grid by an inverter device. In the conceived scenario, each machine, working in parallel with the others, takes on part of the regulation according to its capabilities.
For the optimal update of the distributed resources' operating conditions, the developed central dispatcher incorporates the following main functions: short-term forecast of the power produced by renewable energy sources (RES), short-term load forecast and day-ahead load profile prediction, distribution system state estimation, day-ahead economic dispatching and on-line scheduling of the optimal distributed resources' operating conditions.
The developed regulators and central dispatcher prototypes have been installed in a test facility set up at Cesi, where several distributed generators of different technologies, storage devices and loads have been interconnected with secondary LV network that can be arranged in different configurations.

alessandro.bertani@cesi.it

Some preliminary experiments have been carried out in order to assess the system performances. In particular, according to the view that the high penetration of DG could become an opportunity rather than a problem, as it is frequently considered, the results of this experimental activity show that distributed resources could be suitably used in order to control grid voltage profiles, power flows, and to handling intentional and unintentional islanding condition after separation of the LV grid from the MV distribution grid.
The research activity described in this paper was supported in the framework of a National Research Project named GENDIS 21 - Distributed Generation for the Improvement of Power Quality and Environment.

KEYWORDS

Distributed Generation – Renewable Energy Sources – Low Voltage Distribution Systems – Load Forecast – Renewable Energy Forecast – State Estimation – Test Facility – Dispatcher

1 INTRODUCTION

In order to avoid that the introduction of distributed generation (DG) causes a total re-engineering of electrical distribution systems, it is necessary to standardise generators' interfaces and their co-ordinated control.
The uncertainness of load requests and generator productions for renewable energy sources (RES) is a problem for system operation and control, thus statistic considerations have to be applied in network component sizing and design, and moreover also the use of predictive controls is often required. In fact network component sizing by on the basis of a maximum/minimum power values criterion (relevant to load requests and DG production levels) is nonsense, as it would requires unsustainable costs to face few occasional situations.
Moreover it is necessary to take into consideration the today's technical possibilities in the field of measurements, calculations and communications that make it viable to increase the information coming from the field and to centralise and hierarchically arrange the data, in order to set up a system able to optimise normal operating conditions and to face potentially dangerous sporadic events.
This paper describes a central dispatcher system, whose structure and main functions are illustrated in *Figure 1*. The central dispatcher has been designed and implemented, at prototypal stage, in a test facility representing a low voltage (LV) network that interconnects several distributed energy resources (DER), such as distributed generators of different technologies, storage devices and loads.
The dispatcher is devised not only to avoid the worsening of the system operating conditions at the increasing of the DG penetration, but also to exploit the capabilities of distributed resources in order to increase the system reliability, also by the islanding operation of some parts of the LV network at the occurrence of fault events that cause the partial or total unavailability of the interconnection with the MV distribution grid. In those occasions, the sub-network dispatcher assumes the role of the main coordinator and controller of the portion of the network in islanding conditions.

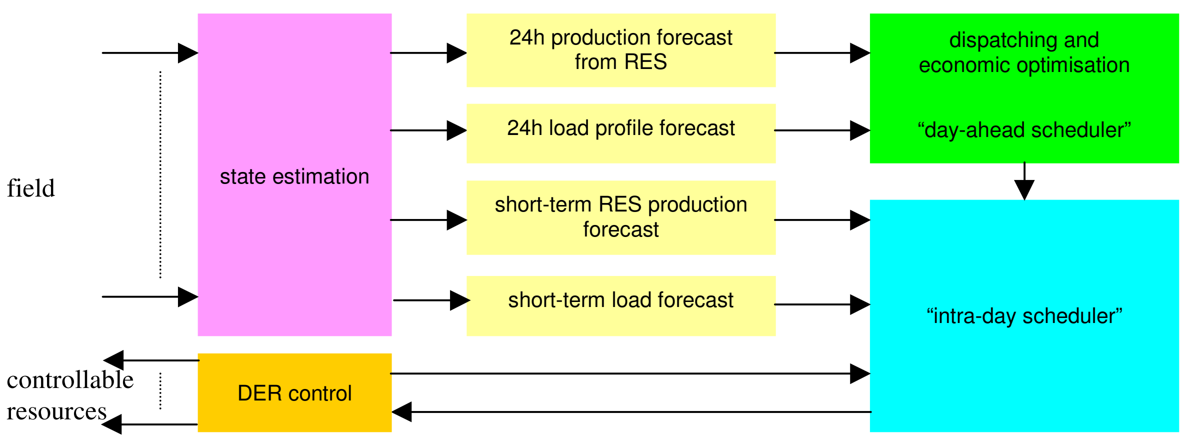

Figure 1 - Scheme of the sub-network controller and dispatcher.

2 STATE ESTIMATION

The term State Estimation (SE) is used in electric power engineering to refer to a broad class of techniques used for the calculation and/or approximation of system bus voltage magnitudes, phase angles and other related quantities. The aims of SE can be expressed as: (a) providing an estimate for all metered and unmetered quantities, (b) filtering out small errors due to model approximations and measurement inaccuracies and (c) detecting and identifying discordant measurements, the so-called bad data. If the system has an appropriate redundancy level (ratio between the number of measurements and the number of variables to estimate) SE can reduce the effect of bad data. Furthermore, in these conditions the SE allows the temporary loss of some measurements without significantly affecting the quality of the estimated values.

The quality of the solution obtained by the real-time SE has an important influence in functions like contingency analysis, optimal power flow, dispatcher training simulator, as well as in the new functions needed by the emerging electricity markets. This quality depends directly of the quantity and quality of information available as input of the process. SE software is generally located within EMS (Energy Management System).

The SE technique was developed to be used in transmission systems, while it is not commonly adopted in distribution systems.

The major differences between transmission and distribution systems can be summarized in: (a) the network topology, meshed against radial, (b) balanced systems against unbalanced systems, (c) low resistance to reactance ratio against high resistance to reactance ratio and (d) great number against low number of real-time measurements.

In order to solve these difficulties, pseudo-measurements have been introduced in the presented approach. The pseudo-measurements for the analyzed LV distribution network have been the forecasted loads and the field measurements that were available from the historical database.

An algorithm has been developed in Fortran 90 language using a Weighted Least Squares Method (WLS) adapted with piece-wise linear segments. This non-quadratic approach was adopted to minimize bad data influence on state estimation solutions as terms characterized by larger weighted residuals can greatly affect the solution. Different non-quadratic solutions have been tested and the piece-wise linear segment proved to be a good approximation to the problem.

One of the main features of the proposed algorithm is the ability to make a precise estimation even in presence of roughly wrong measures, detecting them in rigorous manner, or even in case of absence of measurements. Instead of using the Jacobian matrix of measurement derivatives with respect to system state, an alternative method has been adopted.

Observability analysis can also be carried out by using a topological method. The decision concerning observability is based on logical operation and therefore requires the information about network connectivity, measurement type and their location. If the network under analysis is not completely observable, pseudo-measurements are used in re-building the system observability, so that bad measurements can be detected and cancelled.

Considering the limited dimension of the type of networks analyzed, the preliminary placement of pseudo-measurements, selected in order to have an entire observable system, has been identified on the basis of network topology rather than on optimization techniques.

The input information for the developed state estimation algorithm corresponds to all values in the related static database for the test facility network at Cesi site (see section 6).

The output of the state estimator is a complete description of the current network model for all the observable areas of the analyzed network. This also means that the unobservable areas are identified. The consistency between the solution obtained for observable and initially declared unobservable areas of the network have been obtained.

The outputs of the developed state estimation algorithm are: (a) voltage magnitudes and angle values for each bus; (b) active and reactive power injected at each bus; (c) active and reactive power absorbed by each load; (d) normalized residuals for all the used measurements.

3 FORECAST TOOLS BASED ON NEURAL NETWORKS

A number of forecasting methods based on complex systems of differential equations have been proposed. Their main drawbacks are very long computational time and the need of a large enough computational domain, with the relative boundary conditions.

Neural networks, instead, represent a very powerful tool when a rich set of measures is available: their performance is of great value especially when the variables exhibit very sudden changes, when short term predictions are required and when the forecast must describe conditions at a specific geographic position, instead than on a wide area.

After checking the effective forecast of all variables in several different training conditions, it can be stated that the prediction of several variables together yields worse previsions than that of one variable at a time. Moreover, it is important the availability of the whole data set in the training phase.

Aim of this part of the work is a reliable prevision of renewable energy sources (RES) power production and load requests.

3.1 RES forecasting

An effective management of wind and photo-voltaic plants, especially when they want to contribute to the establishment of islands within a distribution grid, requires a reliable prediction of air temperature, direct and global solar radiation and wind intensity. Therefore a long enough time series of meteorological data must be collected, so that a proper combination of parameters can lead to a forecast of the power produced by the plants. At the test site, which is the Cesi test facility (see section 6), a number of data are collected with a frequency ranging from a few seconds to 5 minutes.

The most relevant data when computing wind and photo-voltaic power are the wind velocity and the solar radiation, but their behavior is influenced by many parameters. The database used in this work contains the values of air temperature, global and direct solar radiation, humidity, wind velocity and direction. It could even be helpful to provide further information (atmospheric pressure, cloudiness, wind direction), since the difficulty with atmospheric variables is their frequent sudden changes, often apparently unpredictable. For instance an isolated small cloud in spring or summer can produce a drop in solar radiation of up to 50% of its neighbouring values.

Discussing the behavior of the variables used in the work for several time intervals, we can say that:

- the air temperature is reasonably smooth and this implies very good predicted values;
- the solar radiation, both global and direct, on the contrary, is very irregular; this shows by comparing couples of consecutive values and by examining its range of variation (around 1000 W/m^2 in spring and summer). Moreover it is null between sunset and sunrise but reaches high values as soon as the day begins. This implies that prediction is a little less effective;
- wind velocity at the test site is extremely irregular and has very small values, so that sudden changes and range of values are very similar in magnitude. A prediction in this condition is unreliable enough. It should be noticed that the geographical position of the site is far from ideal for installing a wind power plant. For the case of some data collected in Southern Italy, at a spot where wind velocities are higher, in particular higher than pointwise variations, very good predictions have been obtained.

Among the relevant choices to be made, the time interval elapsing between the last measured value and the first predicted value is particularly interesting. As a first step we have computed previsions on an interval of 5 minutes (i.e. the same time interval separating the measured data), with very good results (an example is shown in *Figure 2*), although some error percentage has to be recorded. Whenever a longer term prediction is required, the longer interval can be covered by a single step or by a sequence of consecutive sub-intervals. In both cases the error propagation is rather discouraging.

After trying a few different strategies, we conclude that the best choice is keeping a prediction interval of the same size as the one separating the measured data. This means that when it is required to forecast the value of a quantity, e.g. a temperature value, at one-hour intervals, the training set must be defined on the basis of hourly values. This may be simply obtained by averaging the available data.

The variables considered in this work behave rather differently. Therefore each of them requires the choice of an adequate architecture for the neural network. The best results for air temperature are obtained by means of linear networks, while for the other variables multi-layer perceptron (MLP) lead to smaller errors.

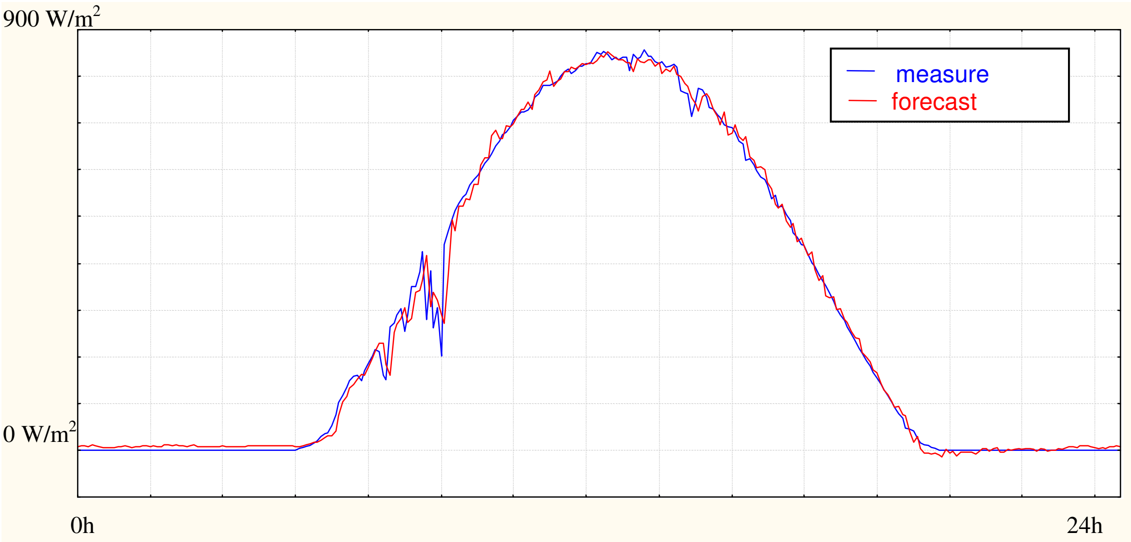

Figure 2 – Example of forecasted vs. measured global radiation.

During the research some analytic model of solar, wind and photo-voltaic generators were developed: the predicted meteorological variables are used as inputs for these models, which give back the power produced by mean the relating plants.

3.2 Load forecasting

For the development of a system for the co-ordination of the distributed resources in a micro-grid the adequate forecasting of the main characteristics of the load, is of utmost importance. To accomplish that one has to take into account that the load profiles in a low voltage distribution system are significantly different from those observed at high voltage substations.

Two different procedures have been implemented: one for forecast of the 24-hours power profile of the following day, and the other for the short-term forecast of the active power consumption in the following 15-min time interval. A similar approach is also implemented for the forecast of load power factors. The 24-hours power profile forecasts are used for a day-ahead economic scheduling of distribution resources, whereas the short-term forecast is used as input of an intra-day scheduler, which every 15 minutes updates the set points of the distributed resources regulators in order to achieve predefined security and power quality objectives.

As proposed in several works (e.g. [1], [2], [3]), the developed procedures are based on the combined use of wavelet transforms (in particular, the specific version known as the *à trous* algorithm has been used, in which decimation is not carried out) and MLP (multi-layer perceptron) feed-forward neural networks with three layers (with the classical Sigmoid hidden units). The wavelet transform is used as pre-processor in order to decompose the input time series in different components, namely approximation and details. Each component is then predicted by a separate neural network. The neural network outputs are then combined in order to obtain the load forecast.

The applicability and performance of the proposed approach has been assessed by using some sets of one-year data. Each set is composed by the mean values over 15-min time intervals of active and reactive load consumption, recorded at distribution transformers feeding different types of urban or rural low voltage distribution systems.

For both the short-term and 24-hours profile forecasting, different forecasting tools have been implemented: one for summer months (June, July and August) and another for all the other months of the year. The reason is that summer months are characterised by a different load composition, much affected by weather conditions which, note, are not implemented in this preliminary version of the tool. The training data set is composed by the load recordings of a week per month for summer forecasts and 8 weeks for the forecasts in the other months. The remaining set of data has been used for to verify the forecasting accuracy.

The inputs of the short-term forecasting procedure are the mean load levels at the 96 previous 15-min time intervals and the binary code that identifies the following 15-min time interval. The output is the forecasted mean load level in the following 15-min time interval. *Figure 3* shows an example of the results obtained for one day and the scatter graph of the comparison between forecasted and actual load levels for an entire week for the case of an urban distribution system. *Table I* shows the mean absolute percentage error (MAPE) values obtained in the various months, for the same case.

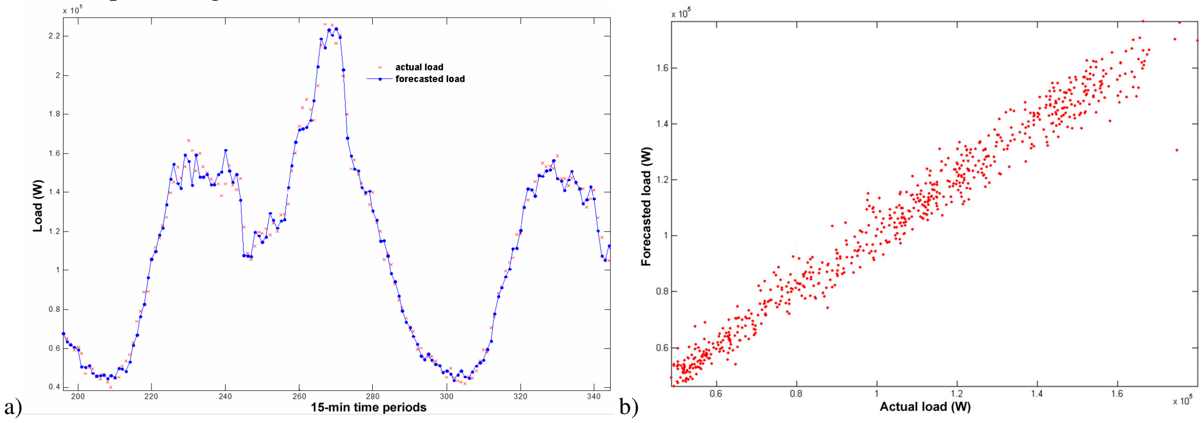

Figure 3 - Example of the results obtained with the short-term load forecasting tool: a) comparison between forecasted and actual loads in one day of June and b) scatter graph comparing the forecasted and actual load values for a week in June.

Table I - MAPE values obtained for the short-term load forecasts.

	January	February	March	April	May	June
MAPE (%)	3.75	4	3.6	3.9	4	3.8
	July	August	September	October	November	December
MAPE (%)	3.8	4	4.3	4.2	4.2	3.7

The inputs of the 24-hours load profile forecasting procedure are the mean load levels at the day-ahead 96 15-min time intervals and the binary code that identifies the following day, to be predicted. The outputs are all the 96 forecasted mean load levels of the following day. As an example of the obtained results, *Table II* shows the MAPE values and the daily energy percentage error (DEPE) values of the load profile forecasts in the various months, for the same low voltage distribution system of *Figure 3*.

Table II - MAPE values obtained for 24-hours load profile forecasts.

	January	February	March	April	May	June
MAPE (%)	7.09	6.97	6.92	7.33	7.03	6.17
DEPE (%)	5.11	2.49	2.65	4.70	3.28	3.59
	July	August	September	October	November	December
MAPE (%)	6.40	7.16	6.65	6	6.66	10.85
DEPE (%)	3.17	4.49	3.04	3.36	2.87	8.17

As the load measurements are in general available only at the MV-LV transformer, a method has been also developed in order to estimate the load distribution at the various buses of the LV system. The method is based on an bottom-up load model [4] that provides daily load diagrams through a process of synthesis starting from the knowledge of the most relevant socio-economic and demographic characteristics of the residential area, combined with the knowledge of the typical consumption of the most common appliances. The model is used to calculate – for the day of interest and for each LV bus – a number of daily load profiles, from which the average load requests, as well as the relevant standard deviations, are identified. The allocation of the forecasted total load to the various LV buses is then assumed to be proportional to these average loads.

4 MANAGEMENT OF LV GRIDS AND OPTIMISATION FUNCTIONS

The leading idea is to optimally manage LV active grids with significant presence of small size distributed generators, storage and controllable loads, matching technical and economical constraints and objectives posed by co-generation and energy storage.

The centralised dispatcher system is conceived to update the set points of the distributed energy resources' regulators in order to achieve some economic, reliability and power quality objectives, on the basis of the above mentioned forecasts and on system state information.
The implemented procedure is composed by two main parts: a day-ahead economic scheduler that calculates the active power set points during the following day in order to minimise the overall costs, and an intra-day scheduler that, every 15 minutes, updates the DERs' set points for the optimisation of the voltage profile in the feeders and laterals, on the basis of the measurements, the system state estimation and the short-term forecasts.

4.1 Day-ahead scheduler: dispatcher and economic optimiser

The defined and implemented algorithms aim at better exploiting the generation units on the basis of their availability, production costs and constraints.
The dispatcher performs the set point definition by operating on the day-ahead forecasts, i.e. utilizing thermal and electrical load previsions provided by properly set-up modules (see section 3).
Different scenarios have been analyzed according to possible load profiles, size of transformers that connect the LV network to the rest of the grid and different tariffs of electricity supply.
An overview of the day-ahead scheduler is shown in *Figure 4*. Its inputs are composed by: (a) electrical and thermal load forecasts, (b) prevision of energy supplied by renewable source, (c) costs for production units, (d) constraints (upper and lower limits) for generating units and (e) status of storage units. The day-ahead scheduler elaborates the set-points for each distributed resource in terms of required energy (power for the assigned time interval) production.

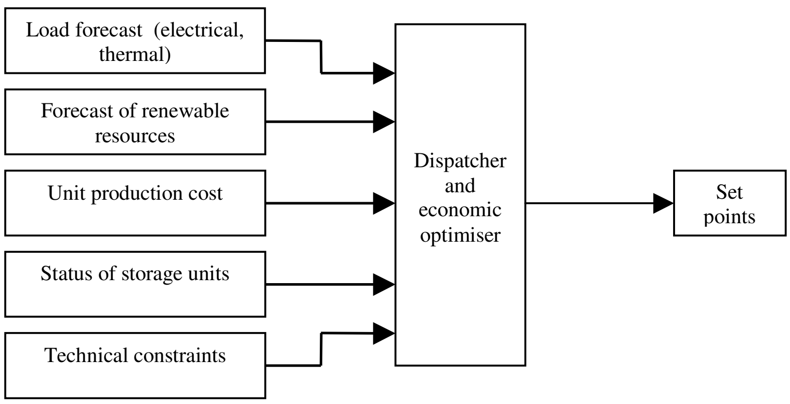

Figure 4 - Overall scheme for the day-ahead scheduler.

The optimisation problem can be defined as follows:

$$\min_{P_j^r} \left(\sum_{r=1}^{R} \sum_{j=1}^{N} c_{j,r} \Delta t P_j^r \right), \tag{1}$$

where the horizon time T is sub-divived into R intervals and the individual interval is defined *as* $\Delta t = T/R$, N are the programmable generating units, P_j^r is the output power for the j-th unit at instant r, $c_{j,r}$ is the cost of the j-th unit at time r in €/kWh.
Assuming that:

- S are the units that generate electric energy;
- M have no storage capability;
- C are of the co-generative type;
- $(M - C)$ are <u>not</u> in the co-generation mode;
- L have storage facility;
- $(N - S)$ are the production units for thermal energy;

the $\mathbf{P}$ vector of the power produced is $\mathbf{P}^t = \left[\mathbf{P}^{S^t} \middle| \mathbf{P}^{(N-S)^t} \right]$, with $\mathbf{P}^{S^t} = \left[\mathbf{P}^{C^t} \middle| \mathbf{P}^{(M-C)^t} \middle| \mathbf{P}^{L^t} \right]$. Further the vector of the j-th unit belonging to the group of generating units $h = \{C, (M-C), L, (N-S)\}$

can be defined as $\mathbf{P}_{j_h}^{t}=\left[P_j^1\cdots P_j^R\right]^t$. If V are the non-programmable generation units (np) and E_j^r is the level of the energy stored at time r for the j-th unit belonging to a storage unit, thus the technical constrains can be expressed as:

- electrical load balance

$$\sum_{j=1}^{N}P_j^r=P_{load_e}^r-\sum_{k=1}^{V}P_{np_k}^r,\qquad r=1,\dots,R; \tag{2}$$

- integral constrains for storage units

$$\begin{aligned}&E_j^r=E_j^{r-1}-\Delta tP_j^{r-1}, && r=2,\dots,R;\ j=M+1,\dots,M+L;\\&E_j^{R+1}=E_j^R-\Delta tP_j^R\\&E_j^1=E_j^0.\end{aligned} \tag{3}$$

- upper and lower limits

$$\begin{aligned}&P_j^{\min}\le P_j^r\le P_j^{\max} && \forall r,j\\&E_j\le E_j^{\max} && j=M+1,\dots,M+L.\end{aligned} \tag{4}$$

- thermal load balance

$$\sum_{j=S+1}^{N}P_j^r+\sum_{j=1}^{C}\left(a_jP_j^r+b_j\right)\ge P_{load_{th}}^r,\qquad r=1,\dots,R; \tag{5}$$

where the second term, $\sum_{j=1}^{C}\left(a_jP_j^r+b_j\right)$, represents the coupling function between electrical power and thermal production for co-generation units.

Some extensive analysis has been carried out to investigate the proposed optimisation strategies. In *Figure 5* a typical solution of the algorithm over a week period with seven consecutive 24-hour optimisations is presented. The scenario illustrated in *Figure 5* includes the use of a set of generators available in the test facility for DG that will be described in the following (see section 6): a micro-turbine for co-generation (maximum 100kW$_{el}$ and 167 kW$_{th}$), an electrical storage unit (42kW$_{el}$ / 2 hours) and a boiler (up to 500 kW$_{th}$).

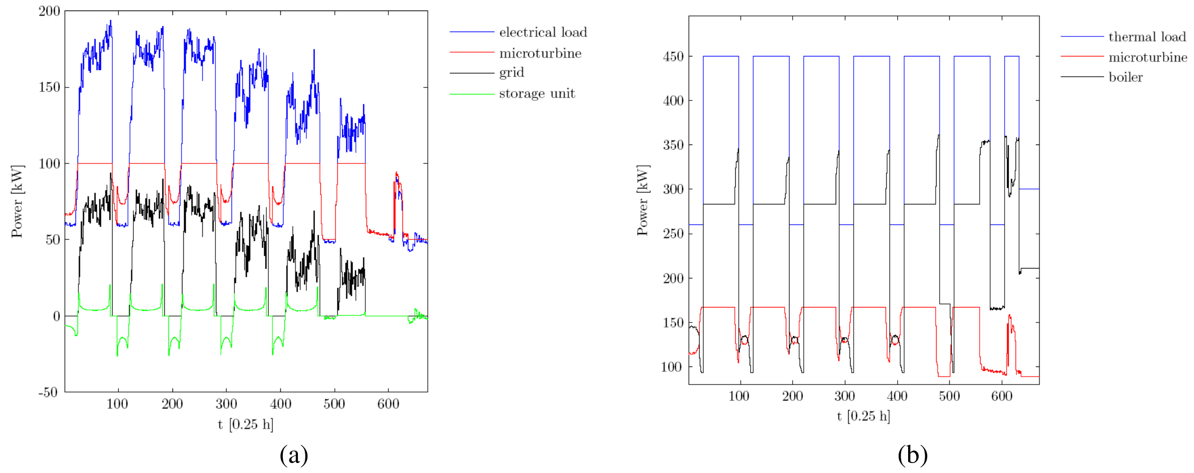

Figure 5 - Proposed solution without the possibilities of power export: (a) for electrical power set-points and (b) for thermal production

4.2 Intra-day scheduler

The developed intra-day scheduler acts at 15-minutes time intervals. It collects the system state information and the short term forecasts on the mean production available from renewable resources and load requests. Then it calculates the three-phase power flows and, if some technical constraints is violated or the voltages values are too far form the rated value, it starts a linear optimisation procedure that minimises the root mean square value of the voltage deviations, taking also into account the results of the day-ahead economic scheduler.

The structure of the scheduler is illustrated in *Figure 6*. The model of the distribution system is implemented in the EMTP-RV software package, which incorporates a three-phase load-flow module [5,6]. The other functions of the scheduler have been implemented in Matlab which is able to exchange data with the EMTP-RV model and to start the load flow calculations.

The objective of the linear programming problem is:

$$\min_{\Delta P_1 \ldots \Delta P_n, \Delta Q_1 \ldots \Delta Q_n} \left\| \begin{bmatrix} K^P_{1,1} & \ldots & K^P_{1,n} & K^Q_{1,1} & \ldots & K^Q_{1,n} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ K^P_{i,1} & \ldots & K^P_{i,n} & K^Q_{i,1} & \ldots & K^Q_{i,n} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ K^P_{m,1} & \ldots & K^P_{m,n} & K^Q_{m,1} & \ldots & K^Q_{m,n} \end{bmatrix} \begin{bmatrix} \Delta P_1 \\ \ldots \\ \Delta P_n \\ \Delta Q_1 \\ \ldots \\ \Delta Q_n \end{bmatrix} + \begin{bmatrix} \Delta \overline{V}_1 \\ \ldots \\ \Delta \overline{V}_i \\ \ldots \\ \Delta \overline{V}_m \end{bmatrix} \right\| \qquad (6)$$

where ΔV_i are the voltage deviations at m selected buses (at the previous iteration), $\Delta P_1 \ldots \Delta P_n$ and $\Delta P_1 \ldots \Delta P_n$ are the optimal variations of active and reactive power operating levels and $K_{i,j}^P$ ($K_{i,j}^P$) are the sensitivity coefficients, previously inferred by a series of load flow calculations, each corresponding to a single small variation of a distributed resource output.

Objective function (6) is completed with a “penalty term” that penalizes the set-points variations from the values calculated by the day-ahead economic scheduler. The linear programming problem takes into account all the technical constraints, including generators capabilities, security reserves and the limit on the power transfer with the feeding MV network, which is considered as the slack bus for the load-flow calculation. The scheduler includes also a function that finds the most convenient value of the power import form the MV network and handles the islanding condition.

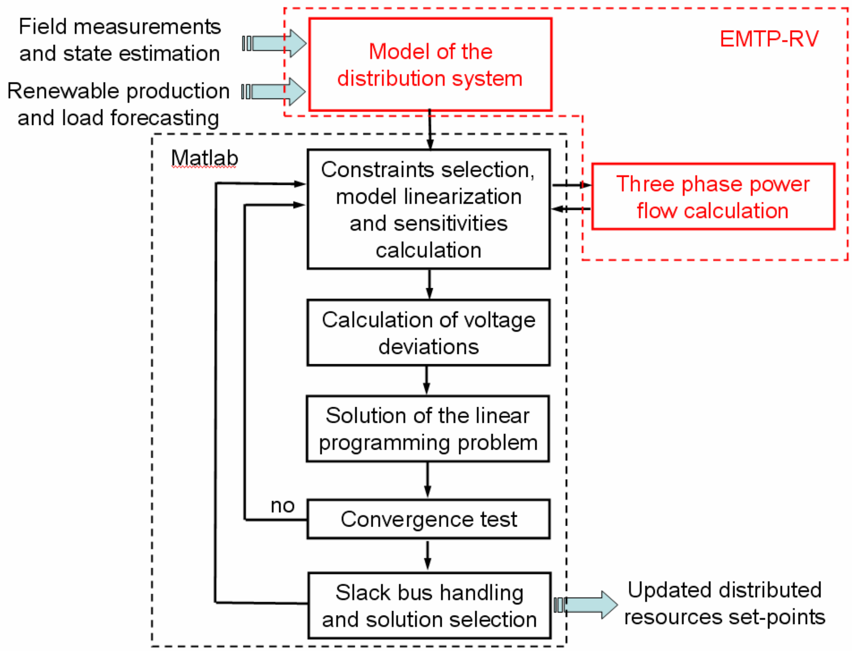

Figure 6 - Structure of the short-term intra-day scheduler.

In *Figure 7*, an example of the improved load profile achieved by means of the proposed optimisation procedure is illustrated for a 15-bus LV distribution system, equipped with a 100 kW microturbine and three batteries (a 45 kW REDOX, a 64kW ZEBRA and 100kW lead-acid batteries). The figure shows the voltage profile in the 9 selected buses before and after the optimisation procedure, for the case of 6 kW and 3 kVAR forecasted load variation. Such a system is a possible configuration of the DG test facility settled in Cesi (see Section 6). *Table III* reports the active and reactive power operating points of the distributed resources before and after the optimisation procedure.

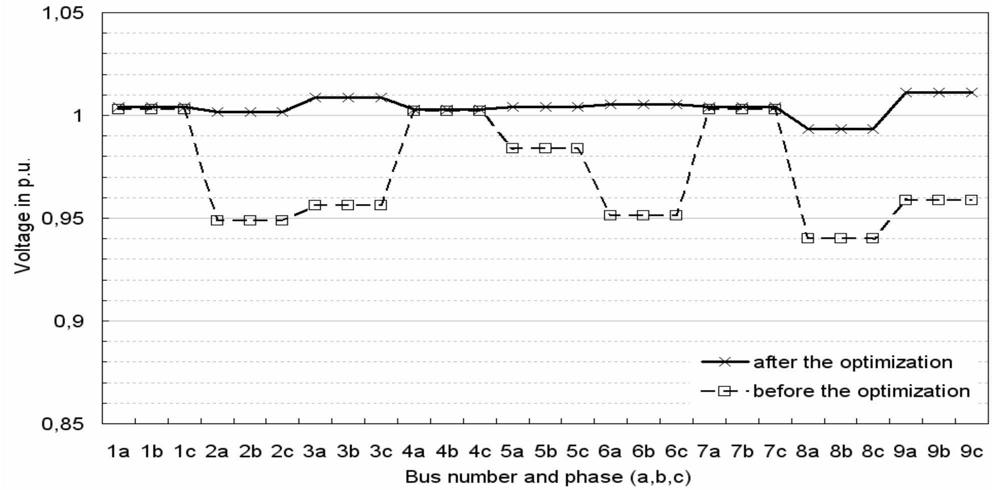

Figure 7 - Voltage profiles before and after the application of the optimisation procedure.

Table III - Active and reactive power outputs of the distributed resources before and after the optimisation procedure for the case of Figure 7.

	Initial outputs	**Final outputs**
P_{Pb}	9.3 kW	26.6 kW
P_{RDX}	13.7 kW	7.1 kW
P_{Zbr}	0 kW	0 kW
$P_{\mu T}$	50 kW	50 kW
Q_{Pb}	47.5 kVAR	50 kVAR
Q_{RDX}	8.5 kVAR	4.4 kVAR
Q_{Zbr}	-1.2 kVAR	8.2 kVAR
$Q_{\mu T}$	-14.3 kVAR	-15.2 kVAR

P_{Pb} , Q_{Pb} lead acid battery outputs,
P_{RDX} and Q_{RDX} Redox battery outputs,
P_{Zbr} and Q_{Zbr} Zebra battery outputs,
$P_{\mu T}$ and $Q_{\mu T}$ microturbine outputs)

5 DER CONTROL SYSTEMS: DROOP CONTROL

When several distributed energy resources (DER) are placed in the same distribution sub-grid, they must be able to work in parallel with the grid as well as with other devices of the same type. If the aim is also to allow the sub-grid to survive to partial or total black-out of the system, islanding and augmenting the supply continuity, the DER control systems must even be able to automatically manage the transition between grid-connected and voltage islanding.

Usually the control schemes of generators used for grid-connected operation are very different from those of generators used in islanding or stand-alone applications. In islanded networks the control system has to fix the set points of voltage and frequency, while in grid-connected operations the control system has to respect the defined set-points of active and reactive power.

To develop a system able to manage the transition from one situation to the other, two different techniques can be hypothesised. The first technique consists in equipping the system with two control algorithms, that face the two different operating conditions, and in developing a method to switch from one to the other when necessary. The second method consists in merging the two controls algorithms in a unique one in order to go through the two different operating conditions considering that one is a disturbed expression of the other. The drawbacks of the first hypothesis are (a) the need of fast, and consequently expensive, communication systems between DER and the centralised controller, in order to quickly identify the islanding conditions and timely switch to the right control algorithm; (b) the necessity, once switched, to rapidly initialise the new control algorithm in order to reduce transient disturbances.

It appeared easier and more convenient to investigate the second hypothesis rather than resolving these difficulties. For this purpose, it was then necessary to choose if integrating the control functions of voltage and frequency in a power regulator or inserting the power control in a voltage and frequency regulator.
It has been chosen to insert the voltage and frequency regulation into a power control scheme, since it easily allows several machines to run in parallel. Moreover this control technique has already proven its validity since it is very similar to the control algorithm adopted for the synchronous machines placed on the transmission network, and known as *droop curves control* [7].

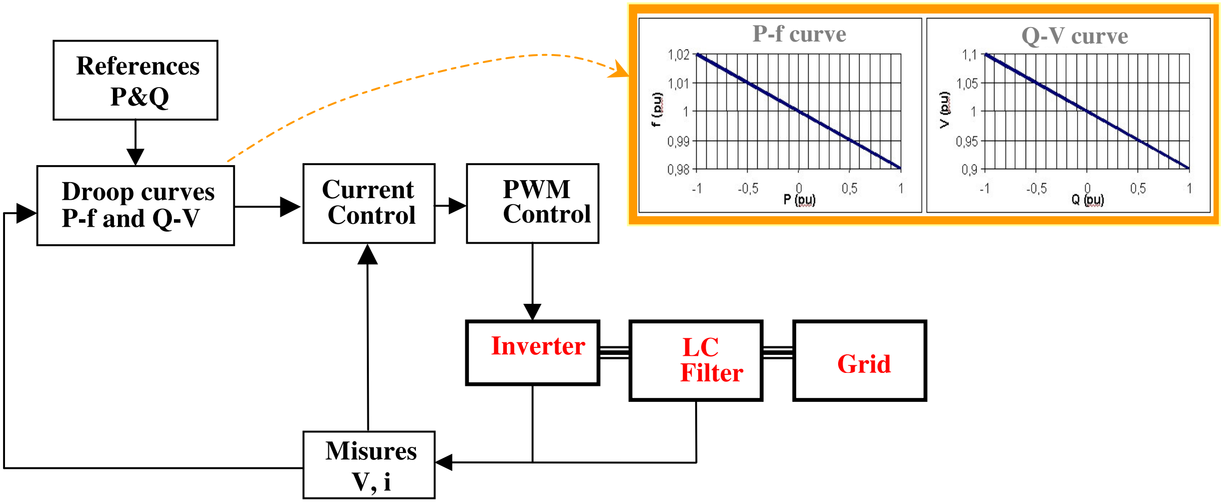

Figure 8 - Designed control systems for DG with inverter interfaces.

Starting from available control systems, modifications have been done in order to realise the control system shown in the above figure. The traditional droop curves of synchronous generators, which define relationships between the active and reactive power produced by the generators and the measured voltage and frequency, have been adapted to the characteristics of low voltage networks. These new curves have been successively inserted in the control scheme in order to modify the active and reactive power set-points with regards to voltage and frequency variations. The machines have been put in operation in the test facility for distributed generation set up during the research project (see section 6).

6 USE OF A TEST FACILITY FOR DISTRIBUTED GENERATION

The architecture of the dispatcher and control system for distribution networks with high penetration of distributed generation has been implemented and experimented in a test facility for DG settled in Cesi. The test facility consists of renewable generators, co-generation plants, energy storage systems and controllable loads that can be connected in different points of an automated low voltage grid working in radial, ring and meshed configurations.
It is composed of a 10 kW hybrid photo-voltaic (PV) system - several PV modules, a battery storage, a diesel engine and a simulated wind generator -, five PV fields for a total nominal power of 14 kW, a 10 kW solar thermal dish Stirling (named Eurodish), a 10 kW bio-mass CHP plant, a 105 kW micro-turbine CHP plant, a 3 kW PEM fuel cell, a 42 kW / 2 hours Vanadium Redox Battery, a 100 kW / 30 seconds flywheel for Power Quality, a 100 kW / 1 hour Pb battery, a 64 kW / 30 minutes high temperature Zebra battery, a remotely controllable resistive-inductive three-phase load of 100 kW plus 70 kVAR, a 150 kVAR capacitive load and several R/L loads with local control.
A supervision and data acquisition system (DAS) has been set up in order to record and analyze the experimental data derived from the field tests, to monitor power quality and electrical transients and to communicate the on-line information to the dispatcher and control system.

The DAS user interface is constituted by a normal personal computer with a standard browser. All the distributed energy resources and measurement units can be easily accessed through the "http protocol" and the acquired data are stored in a database.
The centralised controlling and dispatching functions are implemented on an industrial computer settled in the MV/LV electrical substation. The systems inside the network use communication technologies such as powerline (PLT frequency band 1-30 MHz) and wireless (Wi-Fi protocol IEEE 802.11b/g) for the information exchanges.

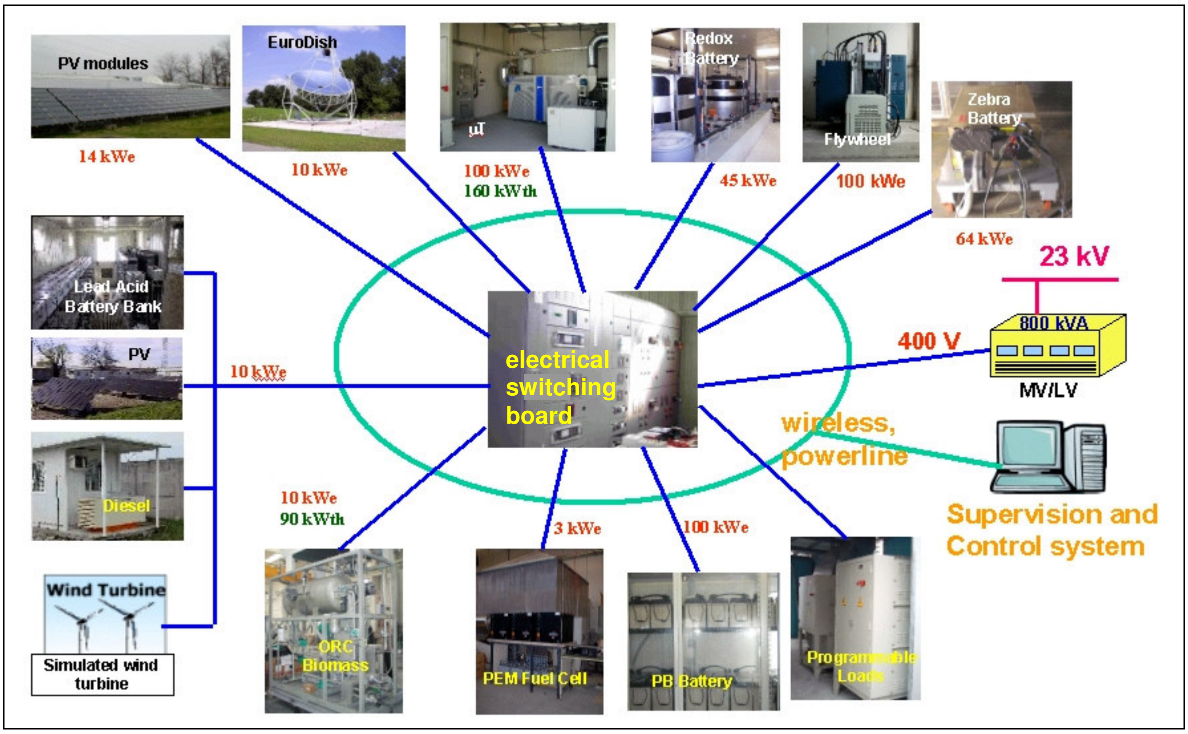

Figure 9 - Overview of the test facility for DG.

The test facility is used:

- to assess and evaluate new DG technologies in terms of performances, power quality and safety
- [8];
- to optimize the performances and management of new DG technologies;
- to test the dynamic response of DG systems to sudden load changes, voltage dips and conditions of phase unbalance or loss of phase;
- to test DG for improving the power quality;
- to test autonomous micro-grid operation, including islanding and reconnection to the main grid;
- to develop and to test supervision, central and local controllers functions finalized to optimize the micro-grid operation in islanding and grid connected conditions;
- to support utilities and the final users in the development of pilot sites realization and improvement.

7 CONCLUSION AND FUTURE ENHANCEMENT

With the introduction of DG, electrical distribution networks are expected to lose their passive character, an issue that poses new problems and opportunities for the operation of these systems. For the above reasons, DG has been a paramount subject in power systems' research in recent years.
The main aim of the research activity carried out has been to apply and validate the results of studies and analyses on DG by means of the technologies available in an existing test facility for DG, where generators and storage units have been experimented together with communication, supervision and control systems.

New effort is needed to fix some concepts and to complete the development of systems that are presently at a prototypal stage. Moreover, a better integration is necessary between the technical constraints due to the respect of the power quality in the distribution grid and the economic optimisation in the use of the distributed resources.

ACKNOWLEDGEMENTS

The authors warmly thank L. Bisone, C.A. Bettoni, M. Bosetti, F. Napolitano and M. Di Silvestro for their help in the implementation of the software and in performing the computations.

BIBLIOGRAPHY

[1] A. Aussem, F. Murtagh, “Combining neural network forecasts on wavelet transformed time series” (Connection science – special issue on Combining neural nets, Vol. 9, No. 9, pp. 113-121, 1997).

[2] A.B. Geva, Scale Net-Multiscale neural-network architecture for time series prediction (IEEE Trans. on Neural Networks, Vol. 9, No. 5, pp. 1471–1482, 1998).

[3] B.L. Zhang, Z.Y. Dong “An adaptive neural-wavelet model for short term load forecasting” (Electric Power Systems Research, Vol. 59, 121–129, 2001).

[4] A. Capasso, W. Grattieri, R. Lamedica, A. Prudenzi, “A bottom-up approach to residential load modeling” (IEEE Trans. on Power Systems, Vol. 9, No. 2, pp. 957-964, 1994).

[5] J. Mahseredjian, S. Lefebvre and X.-D. Do, “A new method for time-domain modelling of nonlinear circuits in large linear networks” (11th Power Systems Computation Conference – PSCC -, Proceedings Vol. 2, pp. 915-922, August 1993).

[6] J. Mahseredjian, L. Dubé, L. Gérin-Lajoie, “New Advances in the Simulation of Transients with EMTP: Computation and Visualization Techniques” (Proceedings of 7th International Conference on Modeling and Simulation of Electric Machines, Converters and Systems, Montreal, August 2002)

[7] S.Papathanassiou, D.Georgakis, N.Hatziagyriou, A.Engler, C.Hardt: “Operation of a prototype Micro-grid system based on micro-sources equipped with fast-acting power electronic interfaces (PESC - 31st Power Electronics Specialist Conference , Aachen, June 2004).

[8] A.Bertani, C.Bossi, F.Fornari, S.Massucco, A.Morini, F.Silvestro: “Combined Use of Simulation and Test Site Electrical Networks for Assessing and Evaluating Distributed Generation Possibilities and Performances” (CIRED – 18th International Conference and Exhibition on Electricity Distribution, Turin, June 2005).