Distributed Energy Resources Management with Cyber-Physical SCADA in the Context of Future Smart Grids

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Abstract — In the energy management of a small power system, the scheduling of the generation units is a crucial problem for which adequate methodologies can maximize the performance of the energy supply. This paper proposes an innovative methodology for distributed energy resources management. The optimal operation of distributed generation, demand response and storage resources is formulated as a mixed-integer linear programming model (MILP) and solved by a deterministic optimization technique CPLEX-based implemented in General Algebraic Modeling Systems (GAMS).

The paper deals with a vision for the grids of the future, focusing on conceptual and operational aspects of electrical grids characterized by an intensive penetration of DG, in the scope of competitive environments and using artificial intelligence methodologies to attain the envisaged goals. These concepts are implemented in a computational framework which includes both grid and market simulation.

I. INTRODUCTION

Concerns related with sustainable development and energy availability put the energetic issues in the foreground of political and social issues, requiring a new vision for future power systems, characterized by intensive use of distributed generation (DG) and a need to efficiently integrate DG in competitive electricity markets.

From the technical point of view, there are problems that must be overcome to take advantage of the envisaged intensive use of DG. The problem is even more complex as the energy sector in general and the power sector in particular is in a process of deregulation and market liberalization [1]. The last decade has seen important steps forward in the development of the smart grid and microgrid concepts, as fundamental basis for intensively using renewables in an intelligent way. Implementation of these concepts has just begun but the already obtained results show that success is reachable [2].

This paper deals with a vision for the grids of the future, focusing on conceptual and operational aspects of electrical grids characterized by an intensive penetration of DG, in the scope of competitive environments and using artificial intelligence methodologies to attain the envisaged goals[2]. These concepts are implemented in a computational framework which includes both grid and market simulation. This approach envisages to optimally managing the energy resources considering the goals and the behavior of the involved players [3]. On one hand, the considered energy resources include generation resources, storage and also the opportunities provided by demand response. On the other hand, an intelligent and flexible SCADA, using cyber-physical paradigm, allows that existing resources are used by agents other than their owners, according to a priori established contracts. This means for instance that other players' owned DG should be considered in optimization studies but the use of these DG resources has to respect contractual relationships among the involved players.

The paper includes a case study based on real data which results make clear the advantages of the proposed approach.

II. VISION FOR THE FUTURE GRIDS

Daily use of automation features has proved its advantages and transmission and distribution (T&D) automation have been evolving over time. Currently, T&D systems are remarkably reliable in most developed countries. However, this does not mean that there is no need for change as several new factors have appeared requiring significant changes in power network operation.

Power system structure has changed from the paradigm of a vertically integrated utility to a new paradigm that involves deregulation, companies focused on one function (generation, transmission or distribution) and the emergence of a complex

new set of players in a market environment [1,2]. These players include generation companies, transmission companies, distribution companies, and other very relevant players (system operators, market operators, brokers, marketers). This new paradigm gives place to a competitive environment where the players need to have adequate strategic behavior in order to accomplish their goals.

Another significant change is the increase of distributed generation resources [3-9]. These have a significant contribution of renewable sources contributing to accomplish energy policy goals related with environment (helping to contain greenhouse effect gas emissions increase). On the other hand, power generation with a more local vision can help increasing the whole power system efficiency (reducing losses in transmission and distribution and using more adequate primary sources for each energy requirement).

These changes result in a completely new paradigm for energy systems, requiring power systems to adopt new planning and operation methodologies. As the adoption of new methodologies has, in many cases, to be supported by equipment changes the overall costs can be very huge. At the present state, significant changes have already occurred in power systems, with most developed countries adopting competitive electricity market paradigms and accommodating a significant amount of distributed generation.

In the future, power systems will have to deal with a much larger-scale integration of DG and other distributed energy resources (DER), such as storage resources, and provide to market agents the means to ensure a flexible and secure operation. In fact, the new paradigm allows a much richer interaction involving a much higher number and diversity of players. As these are acting in a competitive environment and each of them envisages maximizing its profits, the new methodologies for network planning and operation must take this into account.

This cannot be done with the traditional power system operation. Power system operation in a centralized way, easier to design and conform to the power industry practice leads to a lack of flexibility (e.g. inflexible predetermined automation schemes and limited robustness to failures), limiting DG increase (some DG connections are refused due to technical constrains) and players actuation.

Power systems have been evolving in the last decades, adopting new methods and techniques but the overall philosophy of power system operation remains the same, with punctual changes. In order to evolve to future power system, able to address the new challenges in a flexible and secure way, the technological and methodological changes must be addressed in global terms. Distribution networks require new protection, control and operation philosophy to cope with these challenges. DG, namely renewable-based producers, with diverse dimension, must have the means to play in the competitive environment.

Another important aspect is that in the traditional paradigm of power system operation the strategic decisions were taken by a small number of large size actors and were mainly based on supply and network resources. Recent changes have proven that the demand side can have a relevant influence on the whole process [2, 10, 11]. In this new paradigm consumers and electricity buyers can play a much more active role and a lot of strategic decisions are to be taken by the demand side.

Electricity buyers can present diverse sizes, from small domestic consumers to large industrial plants. These can aggregate themselves, using adequate strategic decision-support in order to accomplish their goals. As a result, the most probable scenarios for the future energy systems will include a diversity of aggregators. A part of these will be mainly concerned with the development/aggregation of distributed energy resources with consumer/buyers needs in mind.

The demand side can take advantage of these aggregation philosophy in terms of the access to the aggregated resources (namely generation resources) but also benefit from an increase in scale resulting from the aggregation (gaining access to a set of decision-support and operational means that are inaccessible to small size individual players). Access to these means can allow to address topics such as energy efficiency, demand response, and distributed generation, and storage planning and use in a much more intelligent (and profitable) way.

The problem is that the present paradigm of electrical networks is not able to cope with this new philosophy. Apart from technical limitations directly derived from the network equipment (e.g. protection devices not prepared for two-way flows in distribution networks) that must be changed where required the main problem deals with the current centralized decision and control philosophy. This is the fertile land where smart grids are expected to evolver over the coming years.

III. OPTIMAL MANAGEMENT OF ENERGY RESOURCES

Keeping the balance between load and generation is the basic rule of all power systems. In order to assure this balance, the daily load curve can be well forecasted and the available elements must be optimally managed.

Characteristics of the system elements:

- Load – The power system includes controlled and uncontrolled loads. Load diagrams are forecasted.
- Generator – The generators have many technical constraints, namely minimum/maximum capacity and speedup ratio.
- Storage – In the present state of the art it is not economically feasible to store large amounts of electricity. For storage purposes, small systems use super condensers and batteries, larger systems use pumped water storage, pressurized air, hydrogen generation, etc. The storage units have double characteristics: they can act as loads with limited capabilities, and later they may turn into generators. Due to the losses of transformation the storage presents efficiency performance well behind 100%.

In the last years all over the world in general and in Europe in particular, the power sector has been undergoing considerable changes. There are established common rules for

the internal electricity market and, nowadays, all customers can freely choose their own electricity supplier.

Symmetric markets allow electricity buyers to act as important players in a competitive environment. For this purpose, load aggregators must ensure a good knowledge concerning consumption patterns and demand side management opportunities. Demand elasticity can be the key to take advantage of opportunistic strategies, both in the market environment and in the scope of the aggregator.

However, strategic behavior based on demand elasticity must be based on consolidated knowledge concerning electricity consumer's behavior. The knowledge about consumption patterns is very important for load aggregators and electricity suppliers, as it provides the basis for the accomplishment of agreements concerning electricity prices, and for the definition of marketing policies and innovative contracts and services.

The characterization of electricity consumers' behavior relies on past consumption data, but also on consumption trends and strategies. Historic data can be used to extract knowledge concerning consumption behavior using adequate data mining techniques. Consumption classes can be extracted from the knowledge of the real costumer's electrical behavior and also from additional external features information, such as activity type code, hired power value, consumed energy, etc [12].

An integrated management of distributed energy resources (DER) can be materialized trough the implementation of the Virtual Power Producer concept [13]. The aggregation of loads in the scope of Virtual Power Producers gives place to a more complex and richer new agent type, which can be called a Virtual Power Player (VPP). VPPs provide the means to optimize the aggregated DER and to improve the Demand Side Management (DSM) of their aggregated loads [14].

IV. FLEXIBLE SCADA

SCADA systems have been used for years in power utilities with great success. They have evolved trough times according to technological evolution and to some utility needs. It seems that SCADA systems, as we know them, may rapidly become a thing of the past. However, this is itself an old idea, born in the nineties, when terms such as open and flexible promised a complete revolution in this area. Although heavy efforts have been made and are going on [15], this evolution seems to be some steps behind what would be feasible in the present context. A significant part of the ongoing research is concerned with cyber security issues, which became even more sensitive after 11th September 2001.

Some characteristics of SCADA systems presently commercialized can be pointed out [15]:

- Today's SCADA systems are able to take advantage of the evolution from mainframe based to client/server architectures. These systems use common communications protocols like Ethernet and TCP/IP to transmit data from the field to the central master control unit;
- SCADA protocols have evolved from closed proprietary systems to an open system, allowing designers to choose equipment that can help them monitor their system using equipment from a variety of vendors;
- SCADA systems are widely used to monitor and control critical infrastructure utilities;
- While SCADA protocols are more open today, there is not yet a clear consensus of which protocol is the best.

Presently utilities still purchase SCADA systems and are mostly dependent from SCADA vendors to customize them, at the moment of purchase and later. Even if this is the reality, the present state of the art would allow a different concept of SCADA to be already in daily use. As the required technology exists and diverse factors are urging SCADA systems to a radical change, one can guess that significant changes are about to appear.

SCADA systems have been used in transmission networks for several decades. They provide control center operators with real-time data concerning the network state and allow remote manual, automatic or semi-automatic procedures.

For distribution networks, automation is a relatively new reality, which has mainly been implemented during the 1980s and 1990s. For distribution networks maneuvers (e.g. switching, capacitor and transformer tap control) assume an important role, giving place to Distribution automation (DA). Using remote communications a larger or smaller number of these maneuvers can be remotely done. In certain cases, the maneuvers are not only remote but also automatic, allowing easing the operation of the large number of distribution network components that require to be controlled.

DA meant a significant advance for distribution network operation allowing handling in a much easier and quicker way network switching and outage situations. Although the initial emphasis has been on the use in transmission, SCADA system rapidly appeared as a good solution also for distribution network. SCADA allows remote maneuvers and also provides network operators with a picture of the network state.

Making the new paradigm possible requires decision decentralization and the adequate means to implement it. This is certainly not the case of current SCADA systems. These are intended for the monitoring and supervision of equipments owned (or at least operated) by a very limited number of entities (one in most case). It is assumed that there is a fixed entity to operate each piece of equipment (there is of course flexibility to operate at different levels, such as locally or remotely, but in the scope of the same entity such as a distribution or transmission company).

In the future, DER owned by a large set of diverse entities will represent a significant part of the overall resources. It is not possible to adequately plan and operate the system if DER are not considered as taking part in the solution of power system problems. For this, it is required to have decentralized intelligence and decision ability. It is equally important to

have SCADA based on a power system model which is based on the new paradigm.

This imposes to consider both the physical part of each power system component and its cyber dimension, which requires a SCADA based on a cyber-physical model of the power system. Power system components are important because of:

a) *the relevance of their physical existence and operation features (P);*
b) *the availability of relevant information we may have about them in decision centers (I);*
c) *the permission to operate them (O).*

The relevance of one specific component for the solution of a particular problem must be evaluated considering simultaneously a), b) and c). In fact, it is not at all relevant to have a component with the adequate characteristics to solve a problem if one does not have access to the required information about it in due time to take a decision. None of these is of any value if one does not have the permission to operate this component.

In the current state of arte, SCADA systems consider these three conditions in a very limited way, using the logic of serving a single entity that uses each SCADA. In the future, SCADA will have to consider the same three conditions in the scope of competitive environments where each entity SCADA has direct access to its own components. When negotiated, each SCADA can also have access to information and operation of other players owned components. Moreover, in many cases, once these permissions, and the conditions under which they should become active, are defined, the permission should be automatic and transparent to the users. Like this, real-time operation is guaranteed and market and ownership issues are respected.

V. CASE STUDY

In order to optimally manage of all the available resources and loads in order to achieve the established goals, the operator needs relevant information to define the amount of energy generated by wind energy, photovoltaic energy, fuel cell, mini-hydro, Combined Heat and Power (CHP), and the storage battery charging and discharging. The main goal of operators is minimize the operation cost.

Decision making requires taking into account the following considerations:

- The wind power generation strongly depends on the weather. To have enough precision, the generation capability only can be estimated for a period of 24 hours in advance;
- The photovoltaic generation can be forecasted in a precise way;
- For fuel cells and CHP the total generated energy is determined by the amount of the fuel;
- Mini-hydroelectric plants have a limited quantity of stored water and low generator capacity;
- Storage battery discharging is limited by a maximal discharging capacity and existing storage energy;

- The loads are forecasted considering several aspects, however most of the loads can be controlled under certain limits (using DSM - Demand Side Management);
- To ensure system balance, the VPP can settle terms of Reserve

The main objective is to carry out an optimal dispatch taking into account all the available energy resources, the forecasted load, load profiles, and the referred considerations.

The surplus energy is used for charging the storage battery. The different generation units costs are considered. The optimal schedule of the demand and generation can be made for the envisaged time horizon (e.g. 5 minutes, 1 hours, 1 day, 1 week).

For solving this continuous constrained problem we have implemented it in Cplex using GAMS platform [16].

The constraints of the problem have been explicited taking into consideration four different operation modes:

1. There is a surplus energy that can be stored;
2. The generation is not enough to assure the supply of the total load, therefore the battery is discharged;
3. In case of lack of generation based on renewable sources (wind, water and/or sun shine) the battery, CHP and Fuel Cell come into operation;
4. In insufficient energy generation case the load must be shed.

The objective function of the mixed-integer linear model is the total cost for a given period (T) and must be minimized. Fig. 1 represents the functional diagram of implemented algorithm.
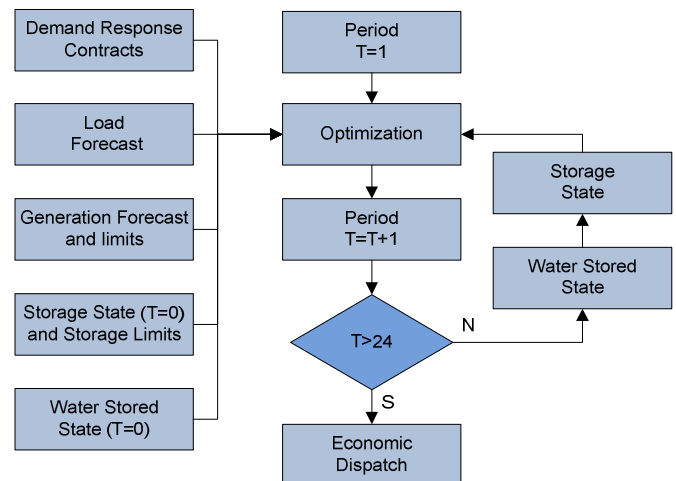

Fig. 1. Algorithm Function Diagram

To illustrate the generality and the effectiveness of the proposed methodology the present case study considers real data. The used data have been prepared starting from a real data base that was released by the Portuguese distribution company. This database includes data of 229 medium voltage customers, which has been collected during a 3 months period in summer and during a 3 months period in winter. Using this dada, the typical daily load curve of each customer has been determined [17]. Through data preprocessing step, 21 customers were discarded from the initial data, remaining 208

consumers to be analyzed. With all data completed, a representative load curve has been obtained by averaging the daily load diagrams of each customer [17].

The VPP has detailed information not only about the consumption of all customers but also about the characteristics of their loads and of industry electrical needs. It is very important to have and understand the real electricity needs of all consumers. This knowledge is crucial for an adequate management of all the available resources, including the use of demand response.

Solving the optimization problem has allowed to obtain the optimal renewable energy generation dispatch, taking into account the cost of each generation technology. Several simulations have been done in order to understand the importance of the consideration of different load profiles.

In this simulation we have considered the following generation prices: Wind, photovoltaic and hydro 4 c€/kWh; cogeneration 7 c€/kWh; fuel cell 9 c€/kWh.

Fig. 2 presents the obtained results for the load supply in a situation when all the consumers do not admit load shedding, independently of the time of the day. Analyzing Fig 2 it is possible to see that there is an amount of undelivered energy in time slices 10 to 18.
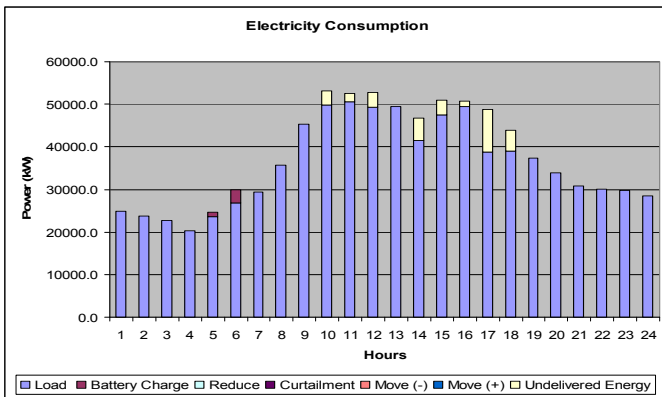

Fig. 2. Energy consumption without load management

Fig 3. shows the optimal generation scheduling for the same situation.
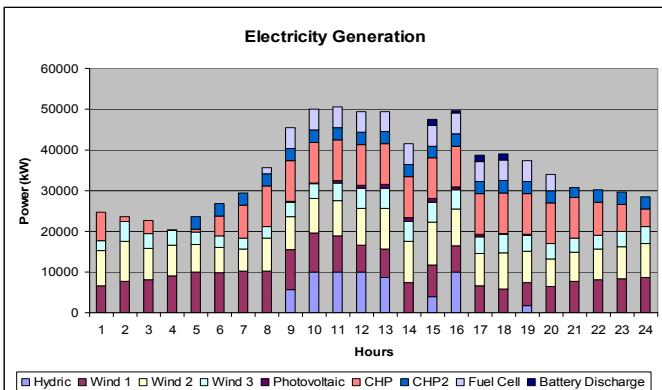

Fig 3. Optimal generation scheduling without load management

Considering contracts with all profiles types, the VPP can manage the generation and consumption to reduce the undelivered energy to the important loads. For the same demand, we will consider a set of contracts that allow using demand side flexibility. In this work we considered the following consumption profile clusters:

Profile 1 – The electrical consumer that will not admit at all to be without electricity, independently of the time of the day; Such as computers systems, vital tasks to the industry process;

Profile 2 – The consumer that allows being without electrical service supply at any time of the day; Such as decorative lightning, luminous fountain;

Profile 3 – The consumer that allows some reduction in the electrical service and not the entire electrical supply. It will be need to know exactly the electrical energy amount that the consumer allows to curtailment, as well as the time of the day and eventually the loads that will be curtailed; Such as Illumination, Air condition and other heating systems (reduction in 1 or 2 degrees), compressed air (reduction about 0,5-1 bar in air pressure), escalators speed;

Profile 4 – The typical electrical consumer that allows dislocate some electrical energy consumption for the hours that the electricity price is cheaper. Such as some tasks that can be done at any hour of the day (washing machine, Ice-field).

Fig. 4 shows the results for electricity consumption in this situation. It can be seen that the VPP has been able to manage the resources so that there is not any undelivered energy for priority loads. Demand side flexibility is used by moving a part of the load for off-peak periods, reducing, and curtailing a part of the loads. The battery is charged in two periods.
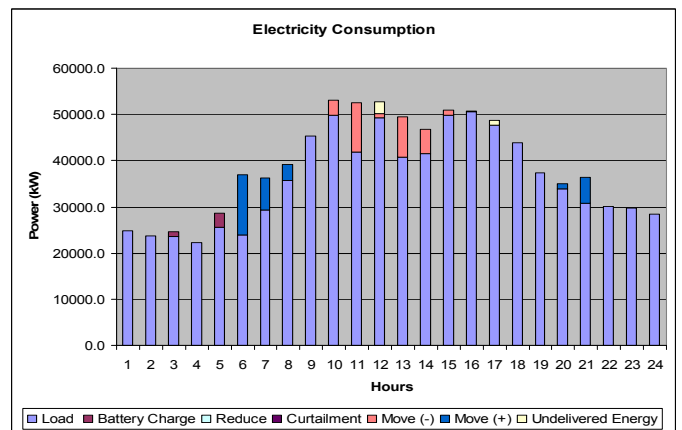

Fig. 4. Energy consumption with load management

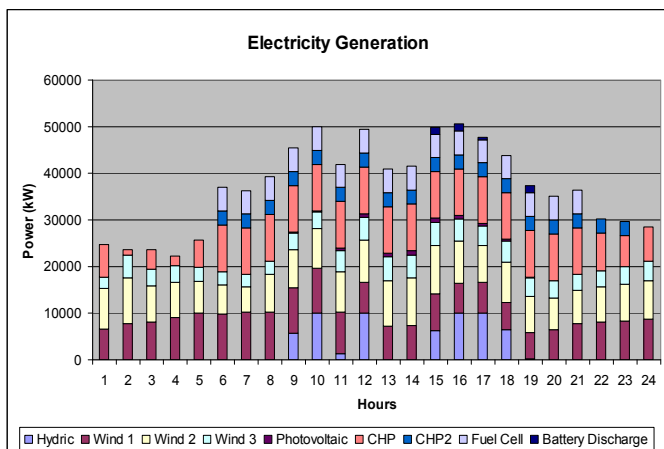Fig. 5 shows the optimal generation scheduling for this situation.

Fig. 5. Generation with load management

In this simulation the consumers profile with more impact on the results are the consumers that allow moving some electrical energy consumption for the off-peak hours. The other consumers are important to balance the time slices with a small difference between generation and consumption.

VI. CONCLUSION

This paper deals with a vision for the grids of the future, focusing on conceptual and operational aspects of electrical grids characterized by an intensive penetration of DG, in the scope of competitive environments.

This approach envisages to optimally managing the energy resources considering the goals and the behavior of the involved players. On one hand, the considered energy resources include generation resources, storage and also the opportunities provided by demand response. On the other hand, an intelligent and flexible SCADA, using cyber-physical paradigm, allows that existing resources are used by agents other than their owners, according to a priori established contracts.

The paper presents the results of the application of the proposed methodology to a real consumers set. The dispatch has been formulated as a mixed integer linear programming problem and programmed and solved in GAMS platform using CPLEX.

The main goal of the case study presented in this paper is to minimize the total operation cost which includes generation costs, storage charging and discharging costs, and demand side flexibility use costs, subjected to all the operational technical constraints. The VPP must assure a permanent balance between generation and consumption undertaking the required load curtailment, when this is necessary, in an optimized way.

The obtained results demonstrate that the proposed methodology is effective and robust. It is also efficient as it requires low execution time. The proposed method helps to minimize the operation costs taking into account all the available energy resources and the demand side flexibility.

In the future work we will include the wind and sun forecast errors.

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