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ON THE INTEREST OF THE VIRTUAL POWER PLANT CONCEPT IN THE DISTRIBUTION NETWORKS

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SUMMARY

The multiplicity of distributed energy resources within the distribution networks may represent a major problem for the system. Considering their small size and their potential great number, these sources are not always visible and dispatchable. These two functions are nevertheless essential for the system safety as soon as these sources are no more marginal. In addition, a part of this production may be mostly of "intermittent / renewable" type (wind, photovoltaic panels). The output power for this type of production cannot be completely guaranteed in spite of the recent progress in predictions methods. To solve this problem, one of the advanced concepts consists of an aggregation of these small resources (combined if necessary with certain loads) in a virtual production unit, which we call "Virtual Power Plant". On this basis, we can plan to solve the problems of intermittency. The challenge is then to develop a strategy for optimal operation of the virtual power plant, based on the use of the modern transmission techniques and information technology.
Seen from the grid, the development of DER raises also new problems. But considering the proximity between these DERs and the load, they can also offer new services to the grid. Thus, a win-win approach can be defined. In this perspective, the VPP concept appears to be an interesting solution to aggregate services and guarantee them.
The paper presents three aspect of the development of VPP concept:

- The problem of optimal control of the DER including intermittent sources.
- The risk management techniques which could be used for the VPP management.
- The problem of voltage regulation in a distribution network, using a coordinated control of DER.

The concept of VPP appears them to be feasible, as most of the technologies to be used to implement it are existing. This concept will be more specifically studied within the European project FENIX (Flexible Electricity Networks to Integrate the eXpected "energy evolution") [10] that aims to characterise the interest of aggregation for electricity markets and grids. It projects to develop a distributed system control architecture completed by Information and Communication architecture and proposals for a supporting market and commercial structure. Several field tests are planned to validate practically some of the concepts studied.

KEYWORDS

Virtual Power Plant – Distributed Energy Resources – Renewable – Optimisation – Trading – Energy Market – Network Service – Risk Assessment

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1) The need of a win-win approach in distribution networks

For more than a century, electricity grids have evolved delivering energy to our societies with an increasing level of security and quality. They have been developed in a centralized manner with a tendency to increase the size or production units to improve the efficiency. But since the end of the last century, the development of local sources of energy has been greatly encouraged, mainly for environmental reasons. As Distributed Energy Resources (DER) are in most of the cases prototype technical solutions to the growing environmental regulatory requirements, latest technologies are economically not viable in comparison with conventional generation benchmarks requiring policy makers to incentive the most promising technologies. Some of these technologies such as Wind generation have reached sufficient technical maturity to offer new technical services to network operators opening new revenue opportunities and so improving their overall financial return. In Europe, significant amounts of DER of various technologies are now operating in response to the climate change and the necessity to enhance fuel diversity.

At distribution level, Power systems have been traditionally designed to operate with unidirectional power flow, from the source (transmission system) to the loads. In some European country, the level of development of DER is now so high that it is beginning to cause operational problems: those equipments have been connected to the grid without taking care of the system environment and the grid itself. Unlike centralized generation, those DER are generally not yet dispatched and their production is mainly related either to environmental conditions for wind or solar generators or to the need for heat for CHP generators. The price at which the energy is bought is generally high enough to encourage the DER owners to maximize their production without any consideration for the needs and the situation of the electrical system they are delivering their energy into. Adding DER to a distribution system imposes new operating conditions on the network, such as reverse power flow, voltage rise, increased fault levels, reduced power losses, harmonic distortion and stability problems. This has often led system operators, electric utilities, governments or regulatory boards to define technical specifications for the grid connection and the operation of DER units.

This situation is acceptable as long as the DER share in the production mix stays marginal. But as soon as it is no longer the case, there is a need for a new organization that can simultaneously enlarge the mix of production to these new comers for environmental reasons without endangering the security, the quality of supply, and the economy of the system as a whole. The question raised is then how to find a win-win approach between the system which is used to deal with big manageable production plan and a lot of small producers that are scattered, uncontrolled, intermittent and sometimes hardly predictable. The object of this paper is to show that aggregation of these DER's is probably one of the ways to be explored in order to reach this win-win approach. This is the reason why the European Commission is supporting on this subject a mid to long-term R&D project called FENIX lead by Iberdrola but in which most authors of this paper are involved.

2) The concept of virtual power plant.

2.1) A new actor in the market …

The deregulation process implemented through the various European Countries has developed new market-based mechanisms where conventional generation is contracted through various market instruments.

As DER have historically been considered in scenarios of reduced penetration under subsidized regimes, the energy they produced was originally exchanged under mandatory market regimes where Distribution System Operators must buy all the energy produced under preferential tariffs, the associated costs being uplifted to wholesale market participants through general network access tariffs. The same DERs have however reached sufficient penetration in some European countries to potentially create significant market distortions. Moreover their growing generation technical

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capability potentially allows them to qualify for participation into energy short-term and reserve markets [1].
Both financial investors and regulators have therefore recently shown interest into the integration of these Resources into wholesale markets, under the obvious condition that these resources have to be aggregated as a Virtual Power Plant level to act as a Balancing Responsible Party (as per the ETSO role model definition) of a significant size (typically more than 10MW).

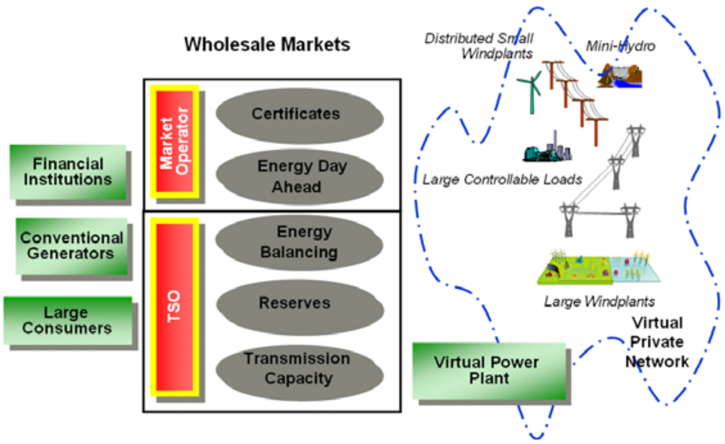

Fig.1. New market structure.

The decision to move from a tariff based to a market based mechanism requires by experience a long maturity cycle (5 to 10 years referring to continental Europe) where regulators have a key role to align on one hand DER subsidies with market based revenue stream and raise on the other hand sufficient awareness and confidence to DER Owners and Operators to convince them to conduct the necessary adaptations of their Energy Dispatch Process and learn how to best arbitrate between market instruments as well as manage the associated underlying risk.

2.2)….Who could also play a role for the network…

The decentralized production is likely to take an increasing part in the distribution networks. Although it poses some problems of connection and management, it may also offer advantages to the distribution network. To make this different potential features becoming a reality, the DER's have to be properly managed, and for that purpose, the principle of aggregation may be useful.
Potential DER benefits include:

- Deferral of high cost distribution system upgrade.Increasing energy demand years after years yields a need for investments in the distribution network. For instance, the capacity of transit of electrical components such as underground cables must be increased. With DER, there is an alternative to these investments by producing electricity downstream from the overloaded component in a controllable and reliable manner.
- Reliability. In case of blackout, including local failures, it might be possible to feed locally critical loads through part of the public network with DER.
- Reduction of lines losses. Due to the proximity with consumers, DER needs less energy to be transported and hence contribute in reducing line losses.
- Voltage control. The connection of a DER unit changes the voltage profile on the grid due to the change in both the active and reactive power flows in the network impedances. Generally, the voltage increases at the connection point and along the feeder. The control of the voltage or the reactive power is therefore an important issue for the Distribution Network Operator (DNO),
- Reduction of centralized generation reserve requirements. With the contribution of the DER, the reserves of production envisaged by the ancillary services, at the centralized level, can be reduced. Indeed, DER brings flexibility to the system and involves a reduction of the demand.
- Contribution to Ancillary services . These services are required to ensure that the System Operator meets its responsibilities in relation to the safe, secure and reliable operation of the interconnected power system. Opportunities will also emerge for DER to provide ancillary services.

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2.3) …But needs further developments before being largely used.

The potential benefit of DER for networks is now well identified. However, one of the most challenging issues regarding DER concerns their safe and economic integration into the grid. Indeed, small size but large scale, intermittency, cost per kW and ability to provide network services are some of the critical aspects that characterize DER integration. In addition, for large-scale penetration of DER, their management becomes of prime importance with regards to global security and cost. An emerging solution regarding DER management is the possibility to aggregate DER as a single virtual unit able to optimise and schedule DER while communicating with DSO (Distribution System Operator). It is a Virtual Power Plant (VPP) concept for DER and distribution grid. It has the advantage to reduce complexity by reducing the order of the system from network perspective and to optimize the portfolio from DER perspective. In addition, it is a promising tool for coping with intermittency and forecasting errors in particular when dealing with renewable sources.
The FENIX R&D project launched in October 2005 was initiated by Iberdrola and EDF and built with many others partners[1] to study further this concept of VPP in relation with network operation. But, prior to this date, the authors of this paper developed aspects of this concept, which will be presented in next chapters.

- IDEA worked on the optimal management of some DER and the chapter 3.1 presents some results in simple study case.
- AREVA developed tools for traders and shows in chapter 3.2 how useful they can be to manage DER and to share the risks between producers.
- EDF and IDEA tested a principle of coordinated voltage control adapted to distribution networks, which is presented in chapter 3.3.

3) Some aspects of the virtual power plant are available now.

3.1) Multi-sources production Optimization

The Virtual Power Plant (VPP) concept for DER allows optimising the portfolio from DER perspective. In addition, it is a promising tool for coping with intermittency and forecasting errors in particular when dealing with renewable sources.
In order to achieve some fundamental functions of VPP an optimisation algorithm is needed. Such an algorithm allows the aggregation for DER as well as for dispatchable loads to be obtained for an economic optimum with regards to DER operations and sizing while interacting with the grid and the market. The original approach of the optimisation process consists of finding and optimal solution for DER economic integration and contractual commitments by associating energy forecast from renewable with traditional DER based on micro CHP's and thermal storage.
Developing such optimisation algorithm requires appropriate DER models including storage and thermal processes. In the proposed work, models regarding electrical and thermal generation, Wind Farms, CHP plants, thermal storages, and the energy exchange with the Grid are developed. These models are integrated into the VPP concept (aggregation and optimisation). As a result, the VPP is able to behave as a single classical generating unit from the grid perspective while producing and selling both thermal and electrical energies.
In order to set up this "virtual" generation system, Distributed Unit Commitments (DUC) and optimal scheduling algorithms are developed. For a given unit commitment plan, economic dispatch determines the optimal loading of each unit. Derived from the well-known Unit Commitment problem, for the large-scale power generation, [2], [3], [4], [5], the DUC-VPP function determines the optimal scheduling of DER to meet expected system demand (or contractual agreements) and operating reserve requirements. This optimisation function considers different parameters as generator start-up and shutdown costs and time constants, technical limits, and availability of intermittent resources such

[1]Others Fenix consortium members : AREVA T&D Automation, ECN, ECRO SRL, EDF Energy, ILEX, IDEA, Imperial College, KORONA, LABEIN, NATIONAL GRID, REE, SIEMENS PSE, ZIV, SCALAGENT, ISET, The University of Manchester, VUA, W2M.

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as wind and sun. We consider that any variations of production compared to the contractual values are often heavily penalized. So their treatment becomes a critical aspect, [6].

In this context, the optimisation problem is initially formulated as a mixed integer, nonlinear minimisation algorithm with constraints (MINLP), where the objective function is the variable cost associated with the supply of thermal and electric energy to the consumers and to the network. If we take into account the uncertainties in wind and load forecasts, we obtain a stochastic multi-criteria programming problem.

In this section, three study cases are presented (see Tab.1). The purpose of this mixed generation is to optimally produce as much energy as possible from the renewable sources while guaranteeing contracted power in the day-ahead energy market [7]. The decision maker not only wants to maximise the expected profits, but also to minimise de risks (difference between guaranteed and real produced power).

The first study case relates to three independent wind farms (WF) dispersed in a distribution network. The installed power for each wind farm is: 5x330[kW], 3x600[kW] and 4x850[kW] respectively. Each wind farm makes an offer on the day-ahead energy market based on the wind forecast.

The second one aggregates these intermittent sources. Thus, through this aggregation combined with an adapted risk assessment tool, the VPP can offer 47.61 [MWh/day] in the day-ahead energy market. For this particular case, the penalised non-produced power decrease of 23% relatively to the first study case.

The last one relates to the introduction, in addition to existing intermittent sources, of the 5 CHP's (100[kW] nominal power) with thermal storage systems (Tab.1). If the wind power is higher than forecasted, it is possible to reduce the electrical output of the CHP and even to use electrical wind energy to produce the thermal energy needed by the "thermal demand". We evaluate the use of these CHP's systems through thermal energy demand and through their availability to improve the economic performance of the three wind farms. With these continuous sources utilisation, the VPP decision maker can improve his mixed energy offer. Thus, the penalised non-produced power decreases with aproximatively 55% relatively to the second study case.

Table 1. Main results for these three study cases (all energy values are in [MWh/day]).

		Study case 1 *Individual WF operations*	Study case 2 *Aggregated WF operation*	Study case 3 *Mixed generation*
Green production rate		100 [%]	100 [%]	95,7 [%]
Day-Ahead Anticipated Energy Production	WF 1	15.7	**47.6**	**56.2**
	WF 2	12.8		
	WF 3	21.1		
	Total	**49.5**		
Real Wind Energy Production	WF 1	9.9	38.4	38.4
	WF 2	10.1		
	WF 3	18.4		
	Total	38.4		
Real CHP Energy Production		-	-	**13. 6**
Penalised Non-Produced Energy		**11.1**	**9.2**	**4.2**
Selling energy to the grid		38.4	38.4	52.0

The results suggest that wind-farm owners can increase their incomes by participating in VPP provided that a good risk management strategy is used. Improved forecasting models can increase the benefits associated with day-ahead scheduling; the average revenue per kWh of wind production increases as the aggregation size of many wind farms.

3.2) Risk management

Once the market reaches the required maturity to attract the participation of DER (this major step is for instance about to be reached in Spain this year), it naturally drives the owners of DER to align their

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Energy Transaction process with the traditional asset-backed trading process raising their appetite for portfolio scheduling as well as risk management tools, fig.2.
These steps completely change the way the DER transact, developing new functional needs, [1]:

Trading and Risk

- Splitting of their generation physical capability into the best scenario of transactions offered in a given country (Certificates, Day Ahead Energy, Balancing Energy, Reserve Energy, Technical Constraints, ...);
- Assessment of several types of risk, such as the risks associated with the market price volatility or the risks related to their own DER forecast accuracy. This should provide plant owners to measure their likelihood of deviating against the optimum forecasted revenue;
- Accurate forecasting, scheduling and re-forecasting for each DER through the key short-term market steps (day ahead, intraday down to 5 minutes in some markets).

Dispatch Strategy

- Bidding and notification of short-term re-forecast through real-time electronic market process (xml based messaging);

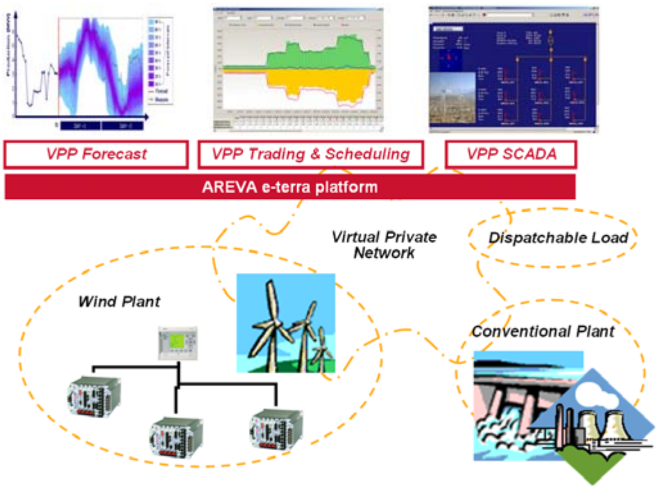

Fig.2. VPP-DEMS Structure.

- Coordinated resource control for the most Economical Dispatch of the resources taking into account the latest short-term schedules and reserve commitments, while acting on ramping capability of some resources of the portfolio (when available) or on the curtailment of other (wind turbines or controllable loads);
- Close monitoring of the deviations and associated imbalance penalties accounting for the final contractual commitments as well as the energy dispatched with the possibility to financially allocate these penalties to the DER of the portfolio having generated them.

In the most matured countries of Europe such as the United Kingdom or Holland, some large asset based companies aggregate their DER into their large asset portfolio and mitigate their unpredictability with alternate conventional resources such as gas turbines.
These companies have invested into the latest generation of optimisation and visualization techniques to support their transaction decisions through the constraints of real-time data management over large portfolio of generation and demand points.
Risk management and dispatch strategy becomes classical methods for asset companies and for DER, managed as VPP. These techniques will be used to improve the benefits of the owners. This will be used in relation with the energy markets as presented in this chapter, but also for local ancillary service markets. If DER's provide reactive power (VAR) to the network operator, we can imagine that a market and associated penalties could be set up to facilitate the exchanges between VAR provider and VAR user as network operator.

3.3) Using the aggregated power plant for Volt-VAR control

At the distribution level, connected DER do not yet really participate to automatic voltage regulation, which is performed with other means, like tap-changers, or capacitor banks. The aim of these last devices is to maintain MV voltage within standard limits. Large-scale integration of distributed generation in distribution networks may cause voltage management problems, but also may be able to provide means to solve theses problems if correctly controlled. Moreover, mutualisation and coordination of DER is a possible way to take advantage of a high DER penetration rate to manage voltage and make them able to provide ancillary services such as participation to voltage control [8].

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Optimised voltage control formulation

This part puts forward a possible way of voltage control with a transposition of Coordinated Voltage Control (CVC, [9]) principle used on transmission networks to the distribution system to perform an efficient way of managing reactive power. Applying CVC to a distribution grid involves the presence of several DER units downstream from a single substation.

CVC systems adjust the voltage of several pilot buses located in the controlled area. To do so, it computes a set of generator set point values every 10 seconds by minimizing a constrained multi-objective function. This function takes the voltage at pilot bus and generation buses, and the reactive power produced by each generator into account. The behaviour of the network is model linearly through sensitivity matrices. The three objectives are: minimization of voltage deviation at pilot buses, Minimization of reactive power production ratio deviation, and minimization of generators voltage deviation.

Studied network

The distribution grid studied is a real French MV network, with five outgoing feeders.

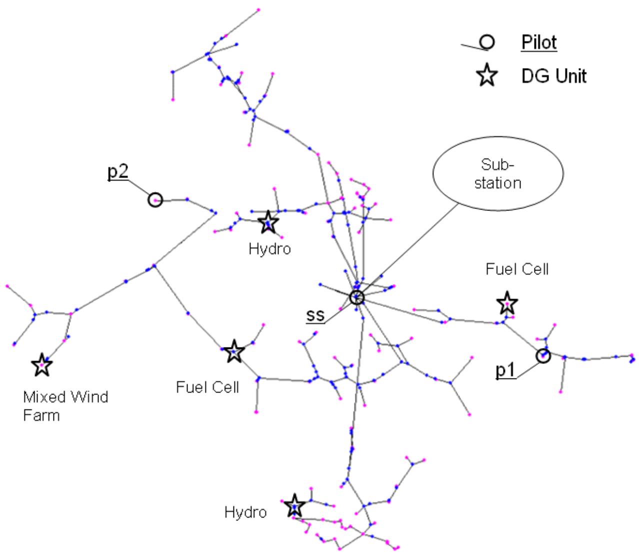

Fig.3. Study case distribution network.

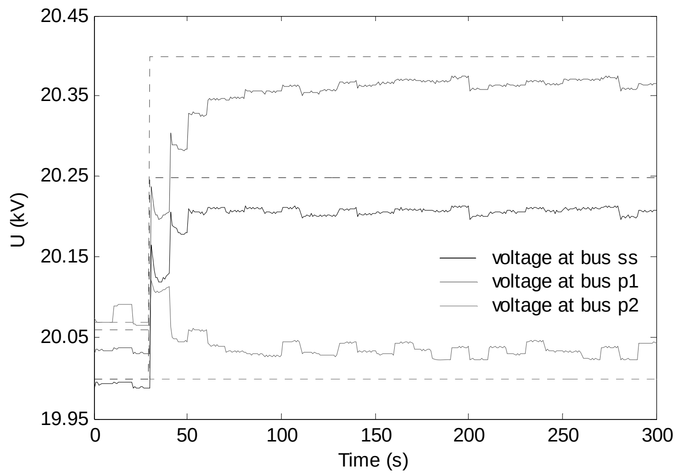

Fig.4. Multi-objective CVC response to multiple set-point step.

Five DER units rated from 0.9 to 3.75 MW have been added in the distribution system for the needs of this study, located as shown in Fig.3. Fig.3 also displays the location of the three pilot buses used in the CVC application (ss, p1, p2).

The total load in the distribution grid is about 21.2 MW and 10.2 MVAR. The DER units provide a total amount of 11.6 MW, and consume 1.35 MVAR (due to the asynchronous generators of the wind farm). Using several pilot buses in the same distribution grid allows obtaining a more homogeneous voltage plan and it also ensures a more precise voltage control at some sensitive connection nodes.

Fig.4 displays CVC response to pilot bus set-points step with the complete multi-objective function. The response time of CVC is less than 30 s, as can be seen on Fig.4. Considering a high enough DER penetration rate (and with a sufficient number of units), CVC systems might be an interesting way to reduce, defer and even eliminate future investments such as network reinforcement.

Wide area voltage control systems initially designed for transmission networks have been successfully transposed to a distribution network. But the main interest of CVC used in distribution level is that it enables aggregated DER to support secondary voltage control similar to the one dealing with classical generation units connected to HV grid. In addition, several DER units aggregated in a single virtual power plant may efficiently, with a sufficient penetration rate, deal with voltage regulation in distribution grid while coordinated with conventional MV voltage regulation devices.

The management of reactive power flows is presently studied as alternative strategies to heavier distribution network reinforcement. Several pilot projects have been launched in various parts of the

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world. These first projects demonstrate the interest of using Virtual Power Plant concepts also to respond to Distribution Grid technical constraints.

4) Conclusions

Utilities are now facing simultaneously several difficult challenges: how to integrate economically the increasing decentralized resources that are promoted for environmental reasons without endangering the actual level of security and quality while taking advantages of the business opportunity offered by the market?

Clearly the size and the number of the decentralised energy resources that should be coordinated to keep the system working properly might be a hurdle for their development. But simultaneously, these means of production are presenting an advantage on big power plants: they are situated near the consumption. One way to go through the difficulties for small DER's to be visible and more or less dispatchable as big units is probably to aggregate them which leads to the concept of virtual power plant.

But the aggregation of production assets allows first of all reduction of the risks, to guarantee the production and to increase the benefit of the producers in selling the energy on the market places. The tools for the traders, which are developed now, include production management features, which are very similar to those of virtual power plants. This shows clearly that a virtual power plant is able to increase the profitability of decentralised production.

As shown in the example of voltage regulation, the VPP can also be a useful concept to provide services to the distribution and transmission network. This aspect will be more specifically studied within the European project FENIX [10] that aims to characterise the interest of aggregation for electricity markets within two European scenarios. It projects to develop a distributed system control architecture completed by Information and Communication architecture and proposals for a supporting market and commercial structure. Several field tests are planned to validate practically some of the concepts studied.

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