A SMART DISTRIBUTION TOOLBOX FOR DISTRIBUTION SYSTEM PLANNING

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ABSTRACT

The distribution system planner should be able to coordinate smart grid solutions in order to find cost effective expansions plans. These plans should be able to deal with new added system uncertainties from renewable production and consumers while guaranteeing power quality and availability of supply. This paper proposes a structure for distribution systems planning oriented to help the planner in deciding how to make use of smart solutions for achieving the described task. Here, the concept of a system planning toolbox is introduced and supported with a review of relevant works implementing smart solutions. These are colligated in a way that the system planner can foresee what to expect with their combined implementation. Future developments in this subject should attempt to theorize a practical algorithm in an optimization and decision making context.

INTRODUCTION

Before the emergence of smart grid solutions, the distribution system planning (DSP) pursued either the creation of an adapted network (greenfield planning) or the augmentation and adequation of the existing facilities meeting future load requirements. This was done by implementing a "predict and provide" approach that attempted to build a topological structure installing traditional network equipment and reinforcements.

A change in operation paradigm which has been taking place in recent years in many countries is that large fossil fuel plants are being substituted by numerous small renewable energy resources at distribution level. This penetration of renewable production and the incorporation of other system components like electric vehicles and dynamic line rating (DLR) added new uncertainties to the system behavior. These uncertainties are difficult to predict and are correlated through other stochastic elements as for instance weather conditions; forecasting errors are inevitable and could endanger the system operation. Even when some of these uncertainties could be considered within the grid design, the planner still struggles attempting to solve network issues using components like lines, cables and power transformers. Such equipment does not offer enough flexibility to cope with new added uncertainties, and either overinvestment or unacceptable levels of reliability or power quality could be a result of this.

There is a need of a planning structure that allows the system planner to firm up the system security, continuity of supply and voltage quality, by means of implementing new smart grids solutions. Some authors have brought these smart solutions into the DSP: In [1], the integration of smart grid solutions is discussed and a classical peak load approach is compared against a profile approach based on demand side. The work in [2] proposes a framework for the deployment of a smart grid infrastructure based on a smart grid maturity model evaluation. In [3], a technical-economical approach for the evaluation of active distribution network projects oriented to smart grid enabling technologies for voltage control is presented. In [4], a smart grid planning model integrating the LV network and demand side management for load peak shaving is implemented. In [5], the current practices in distribution planning and an overview of several emerging trends and challenges for smart planning are presented.

Many other works have considered smart grid elements within the grid expansion problem. However, to the best of our knowledge, a comprehensive structure to clarify the purpose behind implementing the different smart solutions and to encompass them in what the authors of this article call "the planner's toolbox", has not been developed yet. The aim of this article is to propose a planning structure through the categorization of smart grid solutions and its interactions. The purpose is to shed some light on how they could be embedded into the planning process and how the planner could foresee the benefits of implementing solutions in a certain fashion.

The paper is organized in the following manner: The levels of uncertainty and the classical DSP strategy will be discussed first. The new solutions will be presented within the planner's toolbox framework and next, such solutions will be discussed and linked through an interaction chart. The conclusions drawn from this study and the references will be presented at the end of this work.

LEVELS OF UNCERTAINTY

In power distribution planning, uncertainty stands for lack of truthfulness in depicting the behavior of stochastic processes like the power production from renewable resources (mainly photovoltaic and wind power), the power consumption from electric vehicles (EVs), electric heating and the rest of the traditional load. The combination of possible realizations for them could recreate an inconvenient operational scenario. Stochastic fluctuations can occur at different time scales impacting the system in different forms. Fluctuations at a time scale of seconds can occur because of shading clouds that change the irradiation in photovoltaic (PV) panels. Wind power production changes little in the order of seconds except for wind turbulences that can affect the production in the range of 10 seconds. These fluctuations can produce power quality variations and can contribute to abnormal power quality events. Fluctuations in the time scale from minutes to hours can impact system operation; in the range from hours to days and even weeks can impact operation planning and maintenance planning. Uncertainties could also come from: costumer involvement in demand management programs, dynamic line rating (which is weather dependent), and changes in regulatory frameworks (which can be considered a long term administrative uncertainty).

CLASSIC SYSTEM PLANNING STRATEGY

The classical DSP "fit and forget" approach consists in determining the appropriate network reinforcements necessary to meet future load conditions. The investment, maintenance and operation costs, power losses costs and charges for non-compliance of power quality (PQ) and quality of service (QoS) regulations are frequently objectives to be optimized. The DSP can be stated as a single stage or a multi-stage problem. The work in [6] offers a classification of multi-stage methodologies. The DSP is in nature a mixed integer nonlinear problem which has been popularly solved implementing heuristics algorithms. Genetic algorithms and clever adaptations to this specific problem are amongst the most popular formulations [7, 8]. Also ant colony system [9] and immune system [10] heuristics have been applied. The branch exchange algorithm for reconfiguration was early implemented into the DSP in [11]. The integral planning of the MV-LV networks has been addressed in a mixed integer linear model by [12].

Load Forecasting and Load Profiling

The distribution planner needs to anticipate load growth considering amount, location and timing. This information is provided by a spatial load forecasting. In [13], a simulation based forecasting addresses the reasons that are behind load growth: change in the number of consumers buying electric power and change in per capita consumption among consumers. In comparison with trending methods, it needs quite more data and handling but provides high spatial resolution and longer range of prediction. The information provided by customers plus the obtained data from the Advanced Metering Infrastructure (AMI) allow the classification of customers into clusters. These, can be linked to hourly load profiles and in this way the compound behavior of the load can be studied for system planning purposes [15]. However, regarding renewable production, the variability of these resources in the time scales from seconds to days makes it difficult to forecast. This can lead to prediction errors that must be handled by the load following reserves [14]. Further discussions regarding the production uncertainty issue will be presented in the forthcoming.

Reconfiguration and Reliability

Network feeder reconfiguration and switching allocation plays an important role in DSP and system reliability and it is possible to consider it during planning stages for automation of the grid. The operational behavior of the grid in quantifiable terms, i.e. performance indices, operational costs, penalizations, cost of losses, etc., is highly dependent on topology and reconfiguration ability. Some works address these topics [16]. Additionally, reliability can approximately be modeled and quantified for DSP [17]. Based on the type of regulation and the requirements set by the regulator, other network planning will result.

Under this perspective, there is only one way of making the system more capable of dealing with changing conditions: intensive investment on traditional equipment. The heuristic algorithms for network design draw (in an intelligent way) components from a range of network solutions to solve for the operational restrictions. *This could be thought as if network solutions were tools inside a toolbox that a handy man has for fixing stuff. What if we could improve that toolbox? What new tools should we add to it?*

THE PLANNER'S TOOLBOX

The distribution system planner makes use of a number of components to build a future distribution grid that fulfills the different requirements. Classically a limited number of tools were available: overhead lines, underground cables, transformers, circuit breakers, disconnectors and other switchgears.

The concept of smart-distribution grids has added a number of new tools completely under the control of the grid operator: dynamic line rating, power electronics in the distribution grid and storage in the distribution grid.

The first one introduces a new level of uncertainty as the transfer capacity will vary with (uncertain) weather conditions. It has also been shown that the potential of dynamic line rating is best achieved when it is combined with curtailment of production and/or consumption.

Next to these completely grid-based solutions, a number of new tools have come available that require the involvement of the network user: compulsory curtailment of production and/or consumption, compulsory requirements on reactive power in production and/or consumption, voluntary curtailment (where customers can subscribe and the curtailment is compulsory for subscribed customers only), curtailment fully based on market principles, storage on customer-side of the meter, and other ancillary services offered by the network user.

Customer side involvement will also introduce additional uncertainties at planning and/or at operational stage.

In Fig. 1, these new tools have been organized. The distributed generation (DG), the transportable storage and the demand side management (DSM) are the elements the planner can combine to define grid reinforcements and feeder reconfiguration capabilities. Instead of planning the grid for peak load scenario, combination of these elements can result in a more cost effective plan. The planner can implement renewable DG accompanied with static storage for avoiding production shedding, promoting load shaving and increasing hosting capacity (HC). The charging stations consumption will be affected by changes in real time pricing and hence they are able to participate in DSM programs. The different types of storage are entitled to participate as mitigation devices of power quality issues and they can be handled by the distribution system operator (DSO) as PQ suppliers. Real time pricing is provided by the market operator of the primary energy market through the AMI to the consumers. Since the Transmission system operator (TSO) and the DSO both possess production resources and storage abilities, this market operator could be necessary to coordinate them and to provide a spot price of electricity. In [18] a new distribution system structure links the HV network with the MV-LV networks for a coordinated operation of grid control and power production of plug-and-play DG and traditional bulk power plants. In this, the volatility in the T&D interface is reduced letting DERs meet fluctuating MV-LV energy needs. The management of energy can be undertaken at distribution level by implementing a direct control of distribution system components [19]. Both the TSO and DSO can exert manual and digital control on the distribution system, acting over buffering loads, DG, storage devices, and converters.

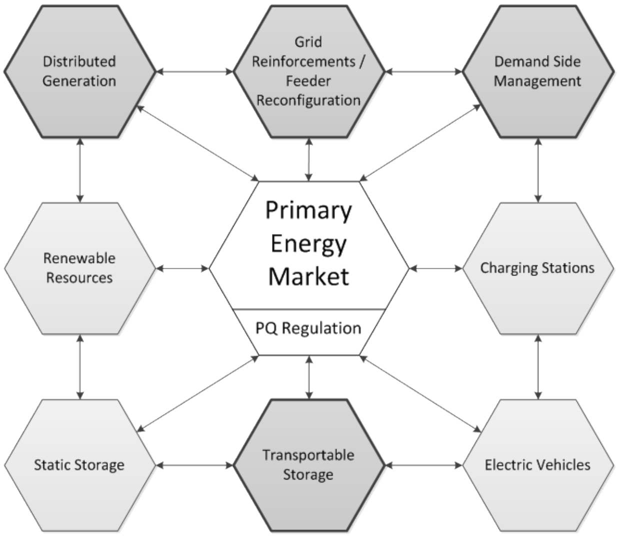

Fig. 1. The planner's Toolbox Structure.

Deeper understanding of smart solutions is required to provide the planner with the appropriate guidance in implementing them in a form that best suits the system needs. An overview of such solutions and a N2 chart for blending outcomes from different approaches will be presented next.

SMART PLANNING SOLUTIONS

Distributed Generation

The sitting and sizing of predefined DG options can be considered in the grid expansion problem as in [20], and also peak cutting oriented DG as in [21]. Dispatchable generation adds controllability to the distribution grid while increasing security. Non-dispatchable generation reduces flexibility; those distributed energy resources (DER) can provide reactive support. The impact of introducing new DER can be evaluated through the concept of HC introduced in [22].

Reactive power from DG

In [23] the power capability limits of different DG systems, such as synchronous generators, PV systems and wind generators, are defined. Other compensation systems must be included in the DSP. Most of the existing works on distribution system planning have considered DG as purely active resources. An important reason to take into account the reactive power capability of the distributed elements is that some power quality issues, like sags and swells, respond to a poor reactive power support and control.

Handling of uncertainties

Load and generation uncertainties can be considered in the form of weighted scenarios [10]. These scenarios can be filtered by implementing the controlled greedy encoding method as in [7] or through clustering of similar system states [23]. Another approach for dealing with the same problem is to design for an average scenario and then consider variations, which follow a probability density function as in [10]. In [23], probability density functions (PDFs) for representing the stochastic behavior of wind speed, solar radiation and load demand are presented. Those PDFs can be estimated via traditional methods like maximum likelihood estimation, least squares or Bayesian statistics, as a sum of weighted sub-PDFs. A single PDF for modeling uncertainties is commonly used. Time-series models like the wind power model presented in [24] are suitable for modeling accurately the stochastic behavior of DER in short time scales.

Storage

Energy storage can enhance the usability of the grid and provide reactive support. Hence it acts as a PQ supplier. In the case of distributed energy storage (DES) there are operational characteristics like charging restrictions, non-energy related cost and the purpose of its implementation (typically load leveling), which must be considered in the siting and sizing optimization problem [25]. The stationary storage helps in increasing hosting capacity. A method for quantifying grid limitations in terms of HC and dimensioning storage solutions is presented in [26]. Transportable storage characterized by a short useful life, can help to defer the grid investments and then be reutilized as stationary storage in buildings. The transportable storage in the hands of the DSO can be implemented for grid purposes only; it could become more efficient when aggregators or independent operators owning this type of storage use them for market oriented applications [27]. This can give a lot of flexibility to cope with uncertainties without the high investment and operational costs of storage becoming a barrier.

Electric Vehicles

Electrification of the transport sector can provide a platform where vehicles can remain connected to the grid and deliver energy stored in their batteries (Vehicle to Grid or V2G) [28]. Mobile storage from EV's could be managed through an aggregator as virtual power plants and participate in ancillary services market or trade energy in the day-ahead market. For this, deployment of smart grids technologies and more specifically intelligent metering and bidirectional communication are needed [29]. Charging Stations are going to affect LV and MV distribution networks meaning that their implementation should come along with grid reinforcements. If properly planned and managed, these can improve grid performance in terms of efficiency and PQ [30]. Also, charging stations can act as responsive demand by allowing EV's to absorb excessive renewable generation as an alternative to its curtailment [31]. This type of storage can also serve as power quality supplier.

Demand Response

Smart meters installed by the utility are used as interface between consumers and the real time pricing of the electricity, to enable their demand responsiveness [32]. Demand side management (DSM) could also be implemented as direct command over buffering loads (which is more beneficial), and this could be thought as a second resource for solving problematic foreseen scenarios. The demand control devices or DR controllers could interact through the AMI in an auction where they respond to a given energy price, obeying to cost functions that express the device's preferences and operations constraints. Also a double-sided auction where all devices, consuming and producing, send their aggregated cost functions to the central controller for deducting the clearing price based on the objective [33]. DR can provide ancillary services. In some cases it can respond faster than ramping thermal and hydro power plants [34].

Power Quality

The prediction of performance indices is the basis for including PQ in planning stages. In [35] an estimated reliability index (SAIFI) and a PQ index (dips/year) are optimized along traditional planning costs in a multi-objective approach, implementing a weighting method. In [36], the distribution network expansion in the presence of DG is achieved by considering voltage dips frequency and magnitude constraints. In [37] compensation solutions for mitigating voltage dips have been included .

Power Quality Assessment

The mixture of Gaussian distributions presented in [38], the critical distance approach developed in [39] and the probabilistic load flow approach [40], are examples on how the power quality performance in planning stages can be estimated. In [40], uncertainty in load and renewable production, the correlations between the different sources of uncertainty at time scales shorter than one minute and stochastic modeling are considered.

Power Quality Regulations

A minimum but acceptable power quality system level must be set; neither too high for avoiding overinvestments nor too low that would result in frequent disruptions of service. Service Level agreements as proposed by [41] could be used for this purpose. According to [42] penalties or incentives can be designed to control the harmonic current emissions. In the case of voltage disturbances like voltage dips, swells or interruptions, an economic signal could be set to encourage investments in power quality mitigation infrastructure. A power quality market structure could be implemented. In [43], taxes and tradable emission rights for limiting the amount of pollution regarding each type of PQ issue are proposed. In the PQ market, the planner could find solutions for some operational issues. Investment in traditional equipment or mitigation devices due to performance deterioration could be transferred to the interested stakeholders.

From the reviewed works, relevant benefits of integrating smart grid solutions into the DSP have been drawn. A chart depicting the relevant benefits of combining them is shown in Fig. 2. As complimentary reading, the work in [25] addresses different issues solved with this type of no-network solutions.

CONCLUSIONS

The sources of uncertainty have been identified and stochastic models for them have been found. Their correlations must be studied further. The errors in weather forecasting can be reduced but cannot be avoided; they lead to subsequent forecasting errors in renewable power production and perhaps in DLR. The lack of robustness in dealing with these uncertainties has led us to find a clear need for restructuring the planning activity. Rules for handling the penetration of electric vehicles are not very clearly stated yet and electrical heating is developing very fast; both are expected to interact with DR and ancillary services. These facts, amongst others, have made us think on an alternative in order to avoid leaving the whole problem in forecasting hands. The proposed toolbox combining not only traditional reinforcement solutions but smart grid solutions is totally conceivable. The concept of a planner's toolbox and its structure is a first step towards this purpose and should be expanded and further detailed in future works. An algorithmic structure should be developed and applied for finding real planning solutions.

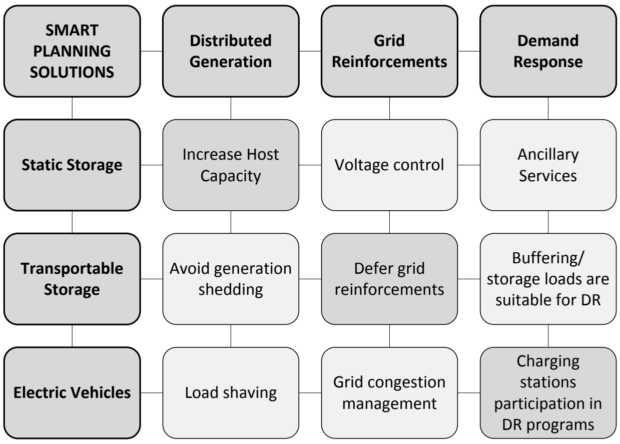

Fig. 2. Combination of smart grid solutions

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