Power System Adequacy and Cost/Worth Assessment Incorporating Virtual Power Plants

ABSTRACT

A variety of factors such as the emergence of novel business models in deregulated power markets, adoption of smart grid technologies, economic recession as well as climate change has led to a proliferation of distributed energy resources (DER) in low and medium voltage power networks over the last decade. The DER portfolio can consist of any given combination of renewable and/or conventional source based distributed generators (DG), energy storage devices (ESD) as well as controllable loads. Today's distribution networks are therefore gradually getting transformed from their traditional 'passive' roles to an 'active' system featuring advanced coordination and control of its constituent DER components and protection equipment. Indiscriminate addition of DERs on the demand side, however, poses a number of visibility and security related challenges for the system operators, primarily owing to the modest capacities most DERs possess (a few kW to a few MW) coupled with the inherent intermittencies associated with renewable resources. The concept of aggregating several active distribution network components like DERs and loads in the form of a virtual power plant (VPP) has therefore often been proposed for tackling the above mentioned challenges.

The incorporation of VPPs into conventional power systems, however, introduces several additional problems in the execution of traditional adequacy assessment procedures. Since the VPP is to be represented as a single entity with respect to the transmission grid, the proposed methodology must take into consideration the combined effects of the VPP's constituent DERs and local loads along with relevant information about its internal distribution network parameters like topology and constraints. In the current literatures pertaining to the reliability evaluation of power systems incorporating VPPs, the system studies are all carried out at the distribution network level, meaning that they fail to quantify the average energy that the VPP can export to the transmission grid after meeting local distribution network demands and constraints. Additionally, the evaluation of system reliability at the distribution level does not adequately portray the possible improvements which can be brought about in the overall system reliability due to the

injection of excess energy into the external grid by the VPP. This thesis addresses these limitations by proposing generic methodologies for performing generation and bulk power system adequacy assessments and cost/worth analysis incorporating VPPs.

A Monte Carlo simulation based generation adequacy assessment methodology incorporating VPPs is presented first. The disparate operating characteristics as well as capacities of individual DGs and local loads along with information about distribution network features like topology and constraints are combined together to form an equivalent model of a VPP using a linearized network flow based optimization formulation. The VPP is mathematically represented as a single entity with respect to the transmission grid, and it's 'prosumer' (producer/consumer) characteristics are portrayed using a probability density function. The equivalent VPP model is used in conjunction with several new indices introduced for quantifying different aspects of the VPP's performance. Key reliability indices are presented for quantifying the VPP's contributions in improving overall system reliability. Impacts of changes in the total installed VPP generation capacity as well as the load forecast uncertainty on the VPP performance indices and the system reliability indices are also analyzed.

A general methodology for investigating the impacts of incorporating ESDs into a VPP model and subsequently using it for performing generation adequacy studies is proposed next. A linear programming based multi-stage optimization formulation is presented for combining the stochastic hourly-output based models of several DGs, ESDs and loads along with distribution network features like topology and constraints into an aggregated probabilistic representation of the VPP. Several modes pertaining to the charging/discharging of the distributed ESDs are integrated with the formulation using a fair energy allocation based operating strategy. The VPP performance indices are suitably modified for quantifying the impacts of the ESDs' incorporation into the VPP profile. Sensitivity studies are carried out for analyzing the effects of variations in the ESD rated capacities and charging/discharging periods on the VPP performance and system adequacy indices.

A systematic procedure for assessing bulk power system adequacy incorporating the equivalent VPP model developed before is introduced next. A linearized DC load flow based multi-objective optimal power flow (OPF) formulation is proposed for performing transmission network contingency analysis. The OPF problem minimizes the total load curtailment and generation costs for the system, while also enabling priority dispatch of the VPP output (if available) into the external grid. The VPP performance indices are suitably modified for highlighting the impacts of transmission network constraints and contingencies on the VPP profile. Key reliability indices computed at the system as well as at individual transmission bus levels are presented, and the impacts of changes in factors such as the VPP's point of connection to the transmission grid and the failure rates of transmission lines on the VPP's performance metrics as well as on the bus and system adequacy indices are also studied.

The DC load flow based OPF formulation described before is then combined with composite system cost/worth analysis techniques for determining an optimal DER portfolio for the VPP so as to minimize the total perceived costs pertaining to the VPP's participation in day-ahead electricity markets. The costs associated with the VPP are sub-divided into five categories – import, customer interruption, operation, investment and revenues – and different DER configurations are examined to determine the optimal portfolio which offers the highest cost savings for the VPP aggregator. Impacts of changes in the VPP's point of connection to the transmission grid on the configuration of the optimal DER portfolio determined are also investigated.

The overall methodology proposed in this paper is tested using the Roy Billinton Test System (RBTS) as well as the IEEE Reliability Test System (RTS). Two distribution network test beds are separately used for modeling the VPP: the RBTS Bus 4 distribution network and the (larger) IEEE 69-bus distribution network. Sequential Monte Carlo techniques are employed for performing the simulations as part of this thesis. Several extensions to the studies performed in this thesis are listed as potential areas of future research work. The results presented in this thesis can not only provide valuable information to the VPP aggregator and the system operator regarding important facets of the VPP's performance, but also offer them critical insights pertaining to the economic benefits which can be obtained from incorporating VPPs into existing power networks.