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fenix

'… a step towards the future of electricity networks'

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Characterisation of Virtual Power Plants

- **Table of Contents**
- **Executive Summary**

Table of Contents

EXCUTIVE SUMMARY

Context

Current power system analysis tools, Energy and Distribution Management Systems and energy market interfaces can handle relatively large systems representing hundreds of participants. However, extending the capabilities of these tools to incorporate millions of distribution network feeders and millions of DER and end users would pose serious challenges to system operation. As an alternative, the FENIX project proposes the concept of the Virtual Power Plant (VPP), composed of a large number of distributed generators and responsive loads, that can be readily used in existing market and system management infrastructures enabling DER to participate in energy markets and offer system management services.

By utilising the concept of the VPP a number of subsystems containing clusters of DER and loads can be aggregated and controlled by appropriate decentralized energy management systems (DEMS). With this in place, the central transmission system controller does not require direct control of individual DER. Furthermore, this approach can also be used to optimise the position of VPP portfolios in the commercial energy markets, to make contracts for sale of power and system ancillary services.

To explore the feasibility of using the VPP to integrate DER, this report develops techniques for the quantification of the steady state and dynamic characteristics of VPPs. Definition of these quantitative characterisations will then enable VPPs to plug into existing EMS functions, and participate in system management activities as well as market based transactions, highlighting at the same time the requirements for decentralised energy management tools to aggregate and control the DER portfolios.

Report overview

The report is framed by a description of the basic VPP concept and the two types of VPP identified in the FENIX project; the Commercial and Technical VPP (Chapter 2). Following this, the FENIX value chain is developed (Chapter 3). The value chain illustrates the links between actors in the FENIX architecture that contribute to the VPP and highlights the potential for evolution and maturation of the FENIX VPP. Detailed characterisation of the VPP is undertaken in the technical chapters. These provide a comprehensive set of algorithms illustrating how a portfolio of DER can be characterised as a single VPP (Chapter 4 & 5) and explore VPP control options with a distributed pricing methodology (Chapter 6).

The report also includes a review of the state-of-the-art and gap analysis of the existing EMS tools and decentralised energy management systems (Chapter 7). This explores the market interfaces that connect commercial generators to the energy markets and their applicability to the VPP and details options for VPP control strategies to aggregate, optimise and dispatch the VPP portfolio of DER.

Chapter summaries

Chapter 2: The VPP concept and definitions

This chapter details the VPP concept, the different types of Commercial and Technical VPP, and their interactions and use by energy system actors. The VPP can be used by actors in the system to facilitate access for the DER units in the portfolio to a wide range of markets. VPP can be used to facilitate generator trading in the wholesale energy markets (e.g. forward markets and the Power Exchange), as well as to provide services to support transmission system management (for example, various types of reserve, frequency and voltage regulation). In the development of the VPP concept, these activities of market participation and system management and support give rise to two different types of VPP these are described as the Commercial VPP (CVPP) and Technical VPP (TVPP).

The CVPP is a representation of a portfolio of distributed energy resources that can be used to participate in energy markets in the same manner as transmission connected generating plant. Being part of a CVPP allows DG and demand to access the benefits of aggregation with other units, but the portfolio characterisation does not include the impact of network conditions. The TVPP portfolio characterisation includes the influence of the network. The TVPP provides visibility of energy resources connected to the distribution network to the TSO, allowing DG and demand to contribute to transmission system management activities. Aspects of the TVPP can also facilitate use of generation and flexible demand capacity in the distribution networks should active network management be desirable.

The functionality and utilisation of the CVPP and TVPP is dependent on the evolution of the power system under scrutiny. In systems with a moderate level of DER but passively managed distribution networks, the role of the TVPP can be minimal. The functionality of the TVPP becomes more relevant in systems with very high penetration of DER and the requirement for active network management at distribution level.

Chapter 3: FENIX Value Chain
The FENIX value chain is the complete hardware and software chain which allows DERs to act (via the CVPP and TVPP) in an aggregated manner on the energy market within network specific constraints, to deliver services to meet the operational requirements of a new decentralised energy system. The FENIX value chain develops the idea of system evolution highlighted in the previous chapter, which recognises that FENIX functionality will mature and evolve as the power system develops and as ICT solutions are adopted.

The FENIX approach needs a chain concept which brings value to both small DERs as well as for the VPP operators, and network operators which support DER integration. The FENIX chain comprises of the following levels: DER level, concentrator level, and VPP (CVPP and TVPP) level. Each level is described in terms of its basic concept and then developed to illustrate the basic and advanced functionality expected as the system evolves and technology matures.

Chapter 4: Steady state characterisation of VPP
Steady-state characterisation of the VPP demonstrates how a DER portfolio can be used to create commercial contracts in the competitive energy market environment (CVPP characterisation) and to offer technical system management services (TVPP characterisation).

The aim of aggregating a portfolio of DER into a CVPP is to enable its market participation in a manner similar to a conventional power plant. The method of aggregation should be chosen in a way that reduces imbalance risk compared with individual DER operation in the market, and maximises commercial opportunities for the portfolio as a whole, while at the same time takes into account the uncertainties related to the output of individual DERs. The technique of stochastic optimisation was chosen to solve this problem.

The methodology of DER aggregation within a CVPP is focused on optimising the performance of DER portfolio in the day-ahead market, given the inherent uncertainty associated with DER production and corresponding imbalance risk exposure and cost associated with diversions from the contractual position. The model however assumes that portfolio cost parameters and statistical properties regarding the future energy output are known. The objective is to maximise the portfolio's expected profit in the forward market and various short term power exchanges.

Several types of portfolio structures were analysed, some of which incorporated wind (as a typical representative of intermittent technology), and some with conventional generation. For all situations, stochastic optimisation was used to construct the portfolio supply curve, indicating the optimal contracting level for a given day-ahead price under output uncertainty. While analysis relates primarily to the wholesale market performance, it can be extended to cover the portfolio balancing activities or providing scheduled ancillary services.

Since CVPPs will partly consist of DER with highly variable output, the stochastic characteristics of these fluctuations are of great importance when characterising the DER portfolio. As a part of this report, the stochastic properties of wind farms (as an example of fluctuating DER) are examined in greater detail. The principles of this analysis can be rather easily translated to other DER technologies demonstrating high output variability (e.g. PV cells, heat-led CHP etc.).

The CVPP allows DER to be used to offer various commercial services, however it does not include the impact of the network on the portfolio characterisation. For real time network management and an understanding of the actual capabilities of a portfolio of DER resources the network influence can be considered in the characterisation. This is the characterisation of a TVPP. To develop these aggregated characteristics of a complete system, which includes network constraints and losses along with generation and demand characteristics the Optimal Power Flow (OPF) algorithm is used. This calculates the steady state of a TVPP portfolio within its network location, respecting at the same time all relevant constraints (power balance, voltage, network flow etc.)[1]. The key outputs are the output profile and marginal cost of a group of DER connected to a particular network area.

Different objective functions can be formulated for the problem, such as maximising export or import capability, minimising the fuel cost or minimising the VPP re-dispatching cost. In the approach developed, a number of OPF calculations are required to obtain the TVPP parameters so the objective function is modified accordingly. First, the TVPP scheduled output is calculated by aggregating the scheduled output from all DER and load in the system taking into account network losses. The second stage is to calculate the maximum MW export and import of the TVPP. In the next stage the PQ curve is derived along with the cost of re-dispatching the TVPP from the scheduled output.

Using this approach, it is envisaged that when there is a change in DER operating conditions, the OPF algorithm will be updated close to real time via high-speed communication system. The study presented provides an illustrative example using a generic UK Distribution Network model to demonstrate the concept of TVPP.

Chapter 5: Dynamic Characterisation of VPP Using Network Aggregation Methods
Dynamic characterisation explores methods for the real time characterisation of the changing capabilities of a DER portfolio bound by a specific location. This approach will highlight the possibilities for providing visibility of the capabilities of a portfolio of DER for real-time network operation. The TVPP portfolio is composed of multiple DER of various technologies with various operating patterns. As such, the characteristics of the TVPP may vary significantly in time. Furthermore, as DERs that belong to a TVPP will be connected to various points in the distribution network, the network characteristics (network topology, impedances, losses and constraints) which also vary in time, will also impact the overall characterisation of the VPP.

A dynamic aggregation is carried out to inform the characterisation of the TVPP and highlight the changing characterisation of an aggregated DER portfolio in the network context. The study observes different types of DERs based on synchronous and asynchronous technologies (fixed and variable speed wind generator) including doubly fed induction generators (DFIG), and machines with power electronic interfaces, in particular in terms of their dynamic parameters (R_{eq}, X_{eq}, X'_{eq}, X''_{eq}, T'_{deq}, T''_{deq}, H_{eq} etc.), regulation system (Droop etc.) and reserves (active and reactive output limits etc.). It then presents and compares static aggregation methods for electrical power networks, based on Ward, REI and EIT methods.

An example for an aggregation network incorporating synchronous machines is presented to illustrate the aggregation methods. The procedure to form a TVPP by using the methods presented preserves the initial static behaviour (losses and voltage profile), as well as the dynamic behaviour when facing a disturbance (e.g. short-circuit). It shows that the presented methods for aggregated network and dynamic aggregated generators in order to form a TVPP are adequate and can be applied for steady-

[1] It is however important to note that although the real time exercise of control functions of CVPPs will be instructed by the DSO through TVPP functions, submission of technical and cost characteristics of DER to real time markets will use the intelligence behind the functions of TVPP. In other words TVPP functionality will be of interest not only to system operators (monopoly function) but also to competitive segments of the market (suppliers, generators, aggregators), to allow them to take advantage of changes in network availability.

state and dynamic analyses. The results demonstrate that dynamic TVPP characterisation capable of plugging into existing EMS tools is possible.

Chapter 6: Distributed control of VPP

In principle, there are two approaches to implementation of active distribution networks and distributed control: one that is based on a hierarchical control architecture using DEMS philosophy (that will be demonstrated in FENIX Northern and Southern scenarios), and the other that exploits an intelligent agents-based distributed control, that is intended to be demonstrated in a laboratory environment. This chapter explores the potential for pricing based control of portfolios of DER in a single network area using a Multi–agent system (MAS) approach. Multi-agent systems are a key-technology for realizing distributed control and coordination in electrical power systems dominated by distributed energy resources. The current state-of-the-art in the computer science field provides a strong underpinning for application of the technique in CVPPs, where the underlying flow network is not being considered. However, the current multi-agent systems theory does not provide clues for TVPP operation, where the state of the flow network is in the heart of the control objective. Operating a TVPP in the distribution part of the future smart grid will utilise mechanisms currently being used or introduced in electricity transmission. The mechanisms of active management developed for the transmission system need to be translated first into computer science theory, or more specific multi-agent systems theory, before they are suitable for the active distribution grid of tomorrow. We performed such a translation for congestion management using locational pricing.

Current Computer Science methods for market-based allocation of flow resources ignore transport network characteristics and constraints. This limits their applicability in larger-scale industrial applications, which often are distributed over a large regional area and use congested transport networks. In this chapter we have presented a theoretical framework and an algorithmic method for finding transport network feasible solutions in market-based flow resource allocation. The framework describes a pricing scheme that enforces the electronic equilibrium market to find solutions that are feasible for the underlying transport network, i.e. obeying network constraints and accounting non-constraining network characteristics such as network losses and network-inherent storage. This pricing scheme is generally applicable to all types of flow resources. The constrained optimization problem that follows from the theoretical framework is solved by the distributed algorithm described in the second part of the chapter. We have shown that, under conditions of demand and supply elasticity, this algorithm converges to a unique solution. Further, we demonstrated the algorithm for a medium-sized network.

Chapter 7: Review and Analysis of VPP Management System Configurations

This chapter reviews the state-of-the-art in decentralised energy management systems which provide the aggregation, optimisation and control functionality for the DER portfolio. It also reviews the present state-of-the-art for central market systems (as a part of EMS) that provide the interface between market participants and the wholesale energy markets and balancing mechanisms. The reviews of DEMS and EMS market interfaces also provide the basis for a gap analysis of these tools to identify the additional functionality required to accommodate the C/TVPP.

Decentralised Energy Management Systems

The purpose of the DEMS system is to operate Decentralized Energy Supply Systems (DESS) in an "optimized" way. "Optimized" does in this context mean that the operation shall be carried out on optimized operation cost/profit and shall consider all inflicted technical, contractual and environmental constraints. A DESS may consist of a certain number of generation units, storages, flexible and inflexible demands as well as energy exchange contracts and primary energy sources connected via an energy flow topology.

The fields of application of the DEMS are decentralized energy supply systems of electrical utilities, industries or IPPs and for facility management companies. The DEMS system is not meant to be a substitute for all possible automation equipment necessary for operating the components of a DESS; there must be at least that much local automation equipment available to allow the basic operation of DESS components ensuring component and personal safety in the absence of the DEMS system.

DEMS provides the aggregation, control and optimization functionality necessary to operate a CVPP portfolio. The current state-of-the art already allows this functionality in optimizing a DER portfolio for participation in the wholesale energy markets. However, further developments in the DEMS tool are required to include the provision of ancillary services in this optimization. Although the DEMS tool is already well adapted for presenting DER as a CVPP, further developments are also needed in the communications links between the CVPP/DEMS and other new actors in the power system that emerge from the FENIX vision. Development is required on the interaction between the CVPP and FENIX box to ensure all potential for DER interaction and control is captured. Further innovation is also needed to facilitate interaction between the CVPP and TVPP (the DEMS and the DMS system) to allow DER visibility for the DSO and to allow DER data to be aggregated with real time network information.

EMS and Trading Tools
Central Market Systems are increasingly integrated into Energy Management systems for Transmission or Distribution System Operators. Current products deployed in deregulated markets worldwide available in this area can be characterised as:

- System Operator Scheduling tools, to address the management of energy schedules.
- Market balancing tools, to balance generation and load in real-time, and to manage congestion that may occur in the power system.
- Settlement tools, to run an efficient settlement service consisting of the settlement and billing calculation process, publishing of statements to participants, maintenance of the settlement configuration, and a full auditability.
- Market participant trading tools, typically designed to cover discrete business processes and flexibly interface with third-party systems using standard communication protocols. These will consist of several components to provide functionality in the Planning, Operation and Settlement Phases:
    - Planning phase: Power Scheduler (PS), Forecast Manager (FM), Trade Manager (TM), Risk Manager (RM), Contracted Volume Notification Engine (CVN)
    - Operational phase: Intraday Plant Optimisation (IPO), Energy Bidder Module (EB), Power Scheduler (PS), Electronic Despatch and Logging (EDL), Control, Asset Monitor (AM)
    - Settlement phase: BM reporting agent (BMRA), Automated Meter Reading (AMR), Meter Data Manager (MDM), Shadow settlement (SS), Intra Balancing Circle Settlement (ICS)

The gap analysis of the existing EMS market interface tools identified the requirement for additional functionality that would allow intraday optimisation. Particularly relevant for a CVPP portfolio that has the capabilities to adjust the output of individual DER to balance aggregated VPP output close to real time to prevent imbalance. In addition, the settlement process requires further development for applicability to the VPP and its DER constituent parts. At present settlement will stop at the level of the aggregated VPP portfolio. Additional work is required to develop a settlement process to allocate profits and penalties to individuals in the VPP portfolio.

Chapter 8: Conclusions
The main challenge facing power systems with increasing levels of distributed generation and active and responsive loads is how to integrate these resources into system management and network and market operation. However, this challenge is confounded by the scale of the challenge to integrate potentially millions of participants into energy management systems and market interfaces designed for a fraction of these interactions.

The FENIX project developed the concept of the VPP to overcome these practical challenges. In this deliverable we explored the concept of the VPP and developed the new concepts of the technical and commercial VPP as practical derivations of the VPP concept to aid interaction of DER in the commercial energy markets as well as in the technical operation of the power system.

The technical chapters of the report then demonstrate the possibilities for characterisation of the VPP portfolio, and use of these resources under various control approaches. Key technical achievements in this report have been:

- Development of a stochastic optimisation technique for characterisation of CVPP portfolio;
- Development of algorithms for steady state characterisation of TVPP;
- Comparison of methods for dynamic network characterisation which includes identification of TVPP characteristics, and
- Development of algorithm for distributed control of TVPP portfolio and network congestion management using a locational pricing technique.

Building on these contributions, a review and gap analysis of existing DER aggregation, optimisation and control tools and of existing market interfaces highlighted areas where additional functionality is required to integrate VPPs into the existing system.

This work is a key contribution to the Northern and Southern Scenario demonstrations as it scopes the developments necessary in the DEMS aggregation and control tools, and in the energy market interfaces, to allow the VPP concept to be demonstrated according to the developed use-cases. It also makes a major contribution towards the development of commercially viable tools for large scale integration of DER into the electricity markets as well as the management and daily operation of power system.