Development and Operation of Virtual Power Plant System

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***Abstract*—Nowadays a virtual power plant (VPP) represents an aggregation of distributed energy resources (DER) and may include controllable loads as well as storage devices [1]. This concept is considered as a promising technology to allocate energy and redirect power flow in the distribution network. In addition, its ICT infrastructure can be deployed to the transition of passive distribution network towards active network [2]. On the other hand it is possible to make use of the available ICT infrastructure which belongs to established smart grid functions to create VPPs. Furthermore, as shown in previous work [3], the VPP system can cope with operational problems caused by high penetration level of DER in the distribution network.**

However, while the virtual power plant concept is considered as a promising technology to manage large numbers of DER, the establishment of such a system might liberate several challenges to its developer. This work focuses on providing options for the development and operation of the VPP system considering major technical, regulatory and socio-economical challenges. These options are mainly based on studies and experiences which are obtained during the development of a VPP pilot by a distribution network operator in the Netherlands. The main objectives of this pilot are to develop and test the balancing and network services as well as energy trade provided by the VPP system. Based on the methodology and techniques of Systems Engineering a scalable, traceable and modular VPP system is achieved. This methodology is also found effective during the definition of needed 'VPP pilot'-tests which are related to the requirements of the VPP stakeholders..

***Index Terms*—Distributed power generation, Power system control, Systems Engineering, Virtual power plant.**

I. INTRODUCTION

Due to the sustainable development and the increase of energy demand, which is leading to higher prices and concerns about availability in the future, distributed energy resources (DER) and other newcomers are encouraged by most countries.

In the future large numbers of DER must fit in the power system while the rules and demands on the security, reliability and quality of power supply are becoming increasingly strict. This implicates that the intermittent contribution of DER as well as the energy flow in the power system should be actively controlled. Mostly this is a fact in high voltage grids, the majority of distribution networks are passively controlled and most DER units are not even visible to the distribution network operator (DNO). In this work the concept of the virtual power plant (VPP) is selected in order to control the contribution of DER by the VPP operator while the DNO will accomplish active control on the distribution network.

As explained in previous work [1-3] the VPP system is able to provide the following opportunities:

- Energy trade: participation in wholesale market representing the contracted DER owners.
- Network services: support of load and congestion management and improving the power quality.
- Balancing: limited control of supply and demand at local and regional level as well as performing peak shaving.

The purpose of a VPP pilot is in first place to test these functions in different local networks and then aggregate those local VPPs (LVPP) into a regional VPP (RVPP) which will be tested for several VPP functions. Fig. 1 illustrates such a pilot with four test districts for the LVPPs which contain different types of DER, controllable loads and storage devices. In addition few charging points of electrical vehicles are included in the tests.

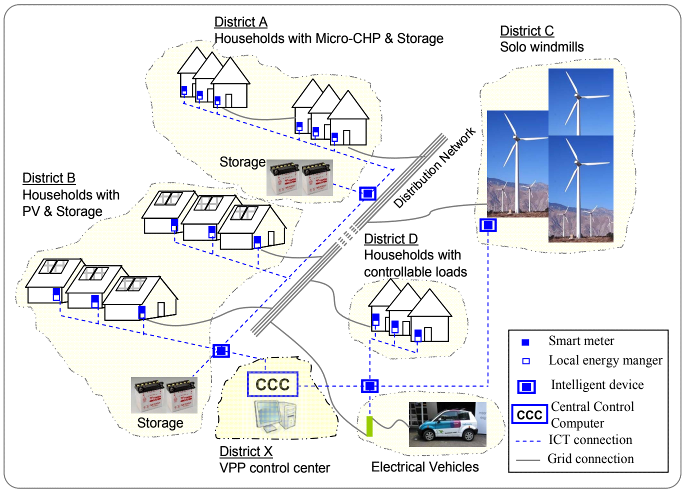

Fig. 1 Components and clusters of VPP pilot

In order to perform the tests a model of LVPP is developed that fits in any small community and which is scalable to a RVPP. Thus, each district in Fig. 1 represents a LVPP while

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the combination of these districts form a RVPP.

DNOs as well as commercial parties will be able to develop LVPPs for small neighbourhoods or districts and if convenient aggregate them into a modular RVPP system. In addition, a group of RVPP systems can be aggregated into a so-called large scale virtual power plant (LSVPP) which serves the transmission system operator (TSO) to maintain system stability and increase the reliability of power supply [3]. In this way a power system is created in which huge numbers of DER are controlled and managed by commercial parties, DNOs and TSOs.

In fact there is a large variety of possibilities to create a pioneering VPP system that satisfies technical, regulatory and economical requirements of the energy market. The first challenge which we were confronted with during the development of such a VPP system is that the variety of possibilities demands for a structured way of design which can be found in the methodology of Systems Engineering. The International Council on Systems Engineering (INCOSE) [4] have defined Systems Engineering as “An interdisciplinary approach and means to enable the realization of successful systems. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.”

According to INCOSE and literature on Systems Engineering [4-7] a VPP should be considered as a System-of-Systems (SoS) which consists of interacting system elements and other systems.

The focus of the next chapter is on the development of a scalable LVPP module which can be added to a RVPP. For this purpose the techniques of Systems Engineering are exploited while focussing on the Context-based Systems Engineering [6]. In chapter 3 the operation of both LVPP and RVPP systems is discussed while considering the needed tests based on the requirements of the VPP stakeholders. This paper will end up in chapter 4 with conclusions and recommendations for future work.

II. VPP SYSTEM ENGINEERING

As stated in the previous chapter the objectives of the LVPP cell in a district or small community are in general focussing on:

- Facilitating energy trade to optimize the benefits for participants (= owners of DER & VPP);
- Providing network services to network operator to alleviate network congestion and prevent excessive expenditures;
- Participating in energy balancing to increase system stability and reliability.

According to Context-based Systems Engineering a LVPP is defined as a System-of-Systems (SoS) while each of trade, network services and balancing can be described as System-of-Interest (SoI), see Fig. 2.

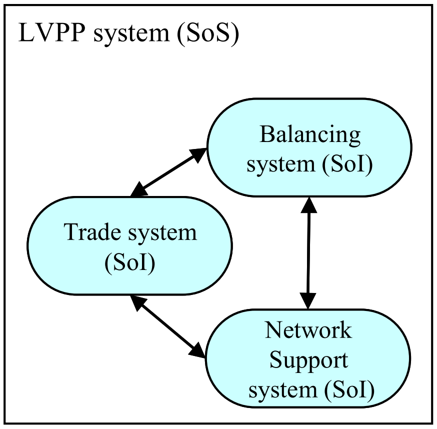

Fig. 2 Context-based LVPP system

As several LVPP systems can be aggregated into the modular system of RVPP, the technical requirements of the RVPP are added to those of other stakeholders. Table 1 contains a list of possible stakeholders of the LVPP system and a simplified description of their main interests or requirements.

TABLE I
LVPP STAKEHOLDERS AND THEIR REQUIREMENTS

Local Virtual Power Plant (LVPP)	
Stakeholders	**Interests / requirements**
RVPP	1 Data collection from LVPPs 2 execute central commands
DER owners	3 facilitate power generation by DER 4 return on investment
VPP operator	5 provision of value adding and ‘smart’ services 6 increase of benefits for stakeholders 7 return on investment
Network operator	8 reliable power supply to customers 9 prevention of excessive expenditures to expand grid capacity
Regulator	10 compliance with codes 11 compliance with privacy rules 12 compliance with standards 13 kWh prices and margins
Energy Supplier (Contractor)	14 delivery of contracted energy 15 reliability of contracts 16 charges of delivered energy
Balance responsible party	17 accurate forecasts of supply and demand 18 specification of reserve resources 19 participants in primary and secondary control
Suppliers of products	20 provision of smart hardware and software products to operators 21 provision of smart services to operator 22 increase of the volume of sales
Service providers (Communication)	23 provision of communication services 24 increase of the volume of sales
Service provider (Metering)	25 provision of metering services 26 increase of the volume of sales

Based on the interests and requirements in table 1 on one hand and technological possibilities on the other the architecture baseline and design of a LVPP system is developed, see Fig. 3.

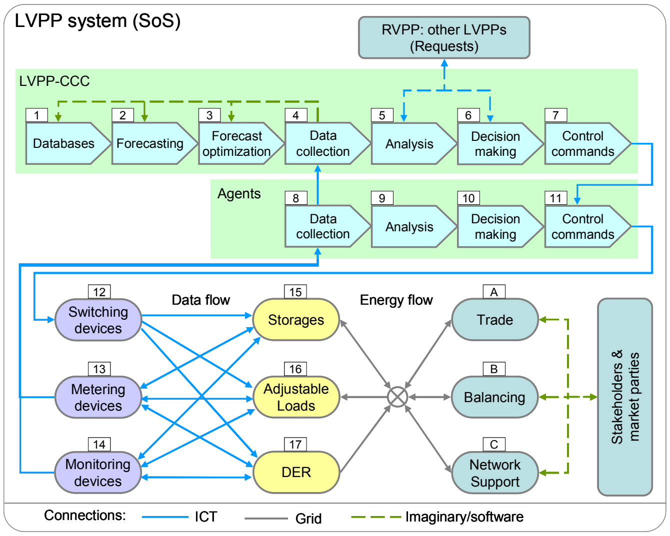

Fig. 3 LVPP system

The LVPP software algorithms in the central control computer (CCC) make use of agents to collect selected data and pass on central commands. Besides, these agents make decisions for the underlying network based on predefined algorithms and collected information. Therefore, the LVPP system contains centralized as well as decentralized actions which are invoked due to requirements initiated by either System-of-Interests A, B or C. With these possibilities the VPP operator is able to translate the requirements of other stakeholders into actions of the VPP. While the software algorithms in the CCC calculate and make decisions for the LVPP, the interactions with other LVPPs take place through the CCC as shown in Fig. 4.

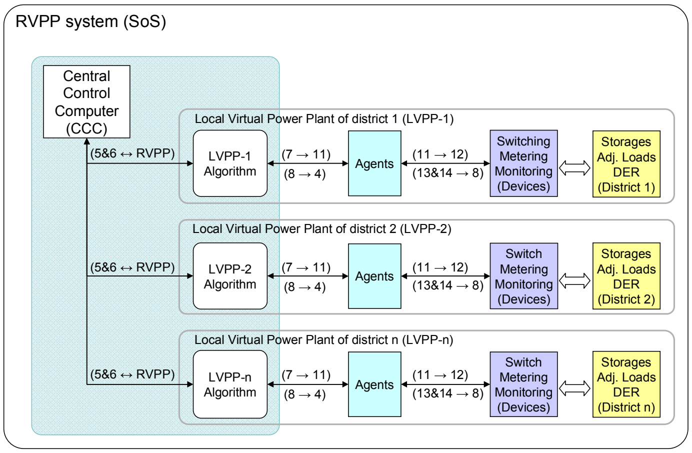

Fig. 4 RVPP system

After the development of a LVPP that meets the requirements of the stakeholders, it is considered by the RVPP as a subsystem that interacts with other similar subsystems through the CCC. In this case the RVPP can be defined according to Systems Engineering as ‘System-of-Systems’ while the ‘Systems-of-Interest’ of RVPP are similar to those belonging to LVPP, namely: the trade, balancing and network support systems. Thus, dependent on the level of consideration each of the LVPP, RVPP or LSVPP is regarded as a SoS, see Fig. 5.

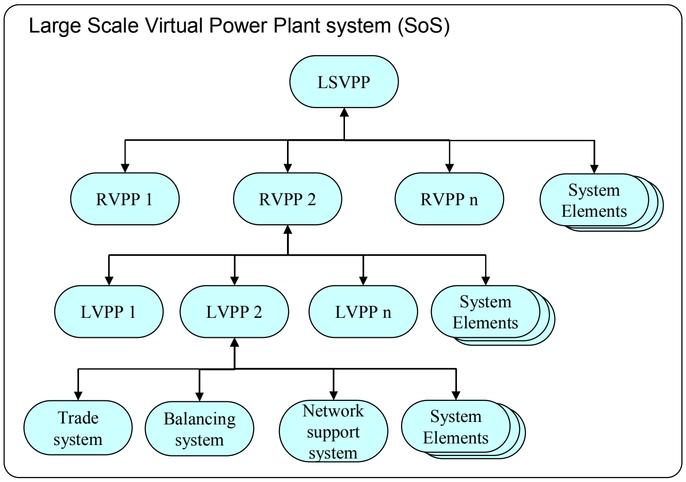

Fig. 5 Hierarchal position of VPPs within the LSVPP system

III. Operation of VPP system

The operation of the VPP system serves the trade, balancing and network support systems which are according to Systems Engineering described as ‘Systems-of-Interests’ (SoI). In the following paragraphs each SoI is separately discussed while evaluating which functions of these systems should be tested during the VPP pilot.

A. *Trade (SoI)*

The described LVPP system in previous chapter can contain wind turbines, PV systems, micro-CHPs and other DER as well as controllable loads and storage devices. As stated in table 1 the main requirements of the owners of these newcomers can be summarized as:

- Facilitate the intermittent power generation: as DER owners appreciate the comfort of passive participation, an in-house energy management system might compensate and facilitate this behaviour.
- Achieve high positive rate of return-on-investment (ROI): investments should be compensated as soon as possible. This one of other interests can be accomplished through participating in demand side response by placing available adjustable loads and storage devices at the disposal of the LVPP.

Due to these requirements the LVPP should add value by increasing the revenues of the intermittent power generation in first place and secondly by integrating demand side management in order to profit from network and ancillary services.

As discussed in previous work [1-3], participation of DER owners in the wholesale energy market collectively will provide more benefits than separately. Moreover the volume-threshold for power producers may prevent small DER owners to trade their energy individually. In VPP operation the generation profiles are combined during the forecasting process in order to provide the power generation schemes to the wholesale market. Deviations from those forecasts are compensated by the available storages and controllable loads.

During the VPP pilot, see Fig. 1, participation in the intraday and day-ahead markets is simulated and tested in order to evaluate the accuracy of predictions and forecast algorithms for both LVPP and RVPP. Then the commitment of prosumers and other energy users is compared with their actual contribution or demand response in order to determine the range of regulation for the VPP output. It should be noted that in practice both DER owners and participants in demand side response are represented by the RVPP operator as a single entity in the wholesale market.

B. Balancing (SoI)

The VPP is able to participate in the energy balancing market by employing the available DER units, storage devices and controllable loads. The Balance Responsible Party (BRP) is in particular interested in this VPP operation and might make use of this opportunity under certain requirements.

In order to contribute to the primary control the fast power response is obtained from rotating (synchronous) generators, super capacitors and fast batteries. The duration of the primary control is presented in seconds in Fig. 6, while the secondary control is covered by increasing the generation of reserve DER units, such as (micro-)CHPs, for a period in minutes followed up decreasing the demand through employment of controllable loads during few hours until the top-down power supply is recovered. Therefore, the employment of all available newcomers are included in the VPP operation as well as the operations of virtual synchronous generator and demand side management.

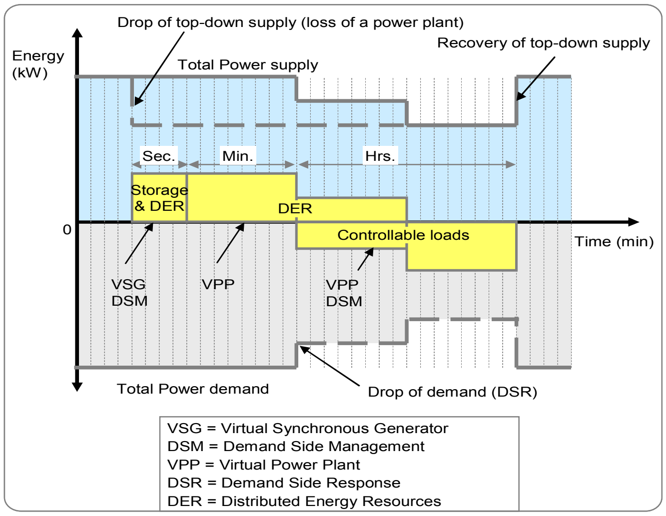

Fig. 6 Balancing with VPP system

In the pilot the short, medium and long term balancing of the energy flow are tested while monitoring the time needed for the initiation and employment of storage devices, controllable loads and DER units. The short and medium term balancing will be held in local distribution networks within the LVPPs in the predefined districts A, B and D, shown in Fig. 1, while the long term balancing will be held for the RVPP operation. In addition, the RVPP will perform ‘peak shaving’ operation mode as a service to offer Balance Responsible Parties while VPP operator is acting as a Balance Supporting Party.

C. Network Services (SoI)

As the increase of load or generation might urge the network operator to expand the capacity of the network, it is also possible to prevent overload or congestion through reducing load or generation. Within the VPP operation its operator can offer network services to the distribution network operator if required. Therefore, the relief of congestion and load management with the help of LVPP are tested according to predefined limitations in the local networks within districts A and D. Peak shaving and redirecting the energy flow in local grids are also the focus of these tests.

IV. CONCLUSIONS AND FUTURE WORK

Based on the methodology of Systems Engineering a modular and scalable VPP system is developed in which a large scale VPP system is build up from similar regional VPP systems. In their turn each regional VPP system consists of similar local VPP systems which are comparable with the building stones. Moreover, the same services with regard to trade, balancing and network support can be provided at all levels of the modular VPP system. Only the scale of these services varies due to the hierarchal position of the VPP. These services are considered as opportunities for the stakeholders of the VPP system as they include:

- Facilitating DER owners to trade their energy production as well as exploiting storages and controllable loads;
- Providing the VPP stakeholders the opportunity to benefit from participating in the primary, secondary and tertiary control.
- Supporting network operators in load and congestion management as well as peak shaving to increase the reliability and security of power supply.

The tests in the field of energy trade, balancing and network services are related to the requirements of the VPP stakeholders. Further tests will need to be executed and evaluated in order to weigh up the added value of the developed VPP system.

V. REFERENCES

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VI. BIOGRAPHIES

Khalil El Bakari received the ing. degree in electrical engineering from the HTS Amsterdam in 1993. Since then he is working in the electricity Transmission & Distribution and recently for Liander, the network operator of Alliander. From 2005 to 2007 he finished the ‘Master of Business in Energy Systems’ at the Delft University of Technology. Since 2008 he part-time joined the Eindhoven University of Technology to conduct a PhD research project on grid integration of distributed generation and renewable energy sources.

Wil L. Kling received the M.Sc. degree in electrical engineering from the Eindhoven University of Technology, the Netherlands, in 1978. From 1978 to 1983 he worked with Kema, from 1983 to 1998 with Sep and since then up till the end of 2008 he was with TenneT, the Dutch Transmission System Operator, as senior engineer for network planning and network strategy. Since 1993 he has been a part-time Professor at the Delft University of Technology and since 2000 also at the Eindhoven University of Technology, the Netherlands. From December 2008 he is appointed as a full professor and chair of Electrical Energy Systems group at the Eindhoven University of Technology. He is leading research programs on distributed generation, integration of wind power, network concepts and reliability issues.