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Virtual Power Plants: an Answer to Increasing Distributed Generation

K. El Bakari, *Member, IEEE*, and W. L. Kling, *Member, IEEE*

***Abstract*-- In the future an adaptive power system is required to integrate the emerging distributed generation (DG) and renewable energy sources (RES). Since most present power systems are based on active controlled transmission network and passive distribution network, the development of smart grids in the distribution network will facilitate and enhance the growth of DG&RES. To develop smart grids, active control of both distribution network and DG&RES is needed. This research employs the virtual power plant (VPP) concept to develop active control of the present and emerging DG&RES.**

This paper discusses the impact of DG&RES and highlights the advantages of the VPP concept taking major technical, economical and regulatory aspects in consideration.

***Index Terms*-- Distributed Generation, Power system operation and control, Virtual Power Plant.**

I. INTRODUCTION

The development and increase of DG&RES in the past few decades have introduced new operational challenges to the network operators but it has also opened an opportunity for re-engineering the electrical power system drastically.

Nowadays DG technologies (including RES) have undergone enhancements such as:

- Improvement of the efficiency of solar cells from few percentages up to 20-24%;
- Increase of capacity of wind generators from few kW up to several MW;
- Development of micro-, bio- and multi-fuel-CHPs to replace conventional CHPs;
- Development of fuel cell technologies;
- Increase of efficiency and capacity of storage devices;
- Introduction of new renewable energy resources as tidal generators, small hydro generators, etc.

The ongoing development of DG and power related technologies will lead to competitive power generation and which will partially replace centralized power supply. For example the EU countries aim to reach up to 20% of their energy supply from renewable energy resources by 2020 [1]. So, the expected increase of competitiveness of distributed generation in the future will give consumers the opportunity to purchase more DG units and participate in future electricity markets. On the other hand the intermittent energy contribution from these prosumers will evolve to decrease control possibilities on balance and stability of the power supply system. For this reason an adaptive power system is required to integrate the emerging amount of DG in the nearby future.

The next chapter discusses the impact of DG on present power system while employing traditional control strategies. This is followed by an introduction of the concept of Virtual Power Plant (VPP) as an alternative control strategy to the increased number of DG units in future power systems. Then the major implications of the integration and operation of VPPs in the power system are highlighted to finally discuss the development of smart grids at distribution level by employing the VPP concept.

II. IMPACT OF DG ON POWER SYSTEM

The expected increase of DG in the future will change the power system operation drastically at all voltage levels of nowadays top-down structure. Network operators must consider the intermittent output of DG during design and operation of new networks as will as during fitting DG units in existing grids [2]. Since most present power systems imply an active controlled transmission network and passive distribution network, it is necessary to develop active control strategies for the distribution network in order to facilitate the increase of DG. Otherwise continuing the integration of DG in the distribution network according to traditional control strategy will lead to different operational problems. In the following paragraphs challenges regarding grid capacity, voltage control and short-circuit fault protection are briefly discussed.

A. Load and congestion management

Traditionally the grid capacity (C_{grid}) is dimensioned according to the expected maximum load flow demand (L_{max}) so that:

$$L_{\max} \le C_{grid} \qquad (1)$$

With the introduction of DG devices the DG generation (G_{DG}) is represented in (1) as:

$$L - G_{DG} \le C_{grid} \qquad (2)$$

In fact (2) is only valid for network design when considered at different load and DG supply scenarios. For this reason the minimum grid capacity is defined by two worst

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case scenarios:

1. High demand and low DG supply, which can occur at rush hours of windless (windmills), cloudy (solar cells) and warm (CHP) working day.
    a. Demand = maximum load
    b. DG supply = minimum generation capacity
2. Low demand and high DG supply, which can occur at midday of windy (windmills), sunny (solar cells) of moderate cold (CHP) holiday or weekend day.
    a. Demand = minimum load
    b. DG supply = maximum generation capacity

According to these two worst case scenarios (2) can be transformed into:

$$\begin{aligned} &Scenario\,1: \left|L_{\max} - G_{DG,\min}\right| \le C_{grid} \\ &Scenario\,2: \left|L_{\min} - G_{DG,\max}\right| \le C_{grid} \end{aligned} \qquad (3)$$

Due to these conditions more load is tolerated in proportion to increase DG supply but also DG supply must not exceed the limits defined by scenario 2. The DG supply is calculated as shown below:

$$G_{DER} = \sum\nolimits_{n=1}^{x} \left(G_{\mathrm{DER(n)}} \times g_{(n)}\right) \times g_{(x)} \qquad (4)$$

- x = number of DG categories
- g(n) = simultaneous factor for DG category n, i.e. CHPs, windmills, PV systems, etc.
- g(x) = simultaneous factor between DG categories, g(x)=1 in case of one category.
- In general g=1 if all DG units are simultaneously delivering their maximum capacity.

In both scenarios exceeding the grid capacity will trip the protection devices leading to total blackout of energy supply through concerned distribution substation. But the network operator may have developed tools to manage congestion during the worst case scenarios. In this case congestion management will reduce the number of disconnected costumers.

B. Voltage control

If no measures are taken when high penetration level of DG occurs, the intermittent energy output of these devices can cause fluctuation in the power supply from other plants depending on different conditions/situations like radiation intensity for solar cells, wind velocity for windmills, availability of (bio) fuels for CHPs, etc. In a passively controlled distribution network increase of DG supply will also increase the voltage which cause insulation damage to equipment and unsafe situations for the end users.

In order to control the required voltage level of the end users it is necessary to calculate the voltage drop at each point in the network. If the imaginary part of the voltage deviation is neglected then the magnitude of voltage deviation can be based on the real part which can be calculated as:

$$\left|\Delta V\right| \approx \left|I \times R \times \cos\varphi + I \times X \times \sin\varphi\right| \qquad (5)$$

In general terms, the voltage deviation is limited according to international standards like IEC 50160 in Europe and the American ANSI C84.1. If the deviation limits are represented in (Vmax) and (Vmin) for the illustrated network in Fig. 1, the range of voltage variations in this network can be explained through three different demand and supply scenarios.

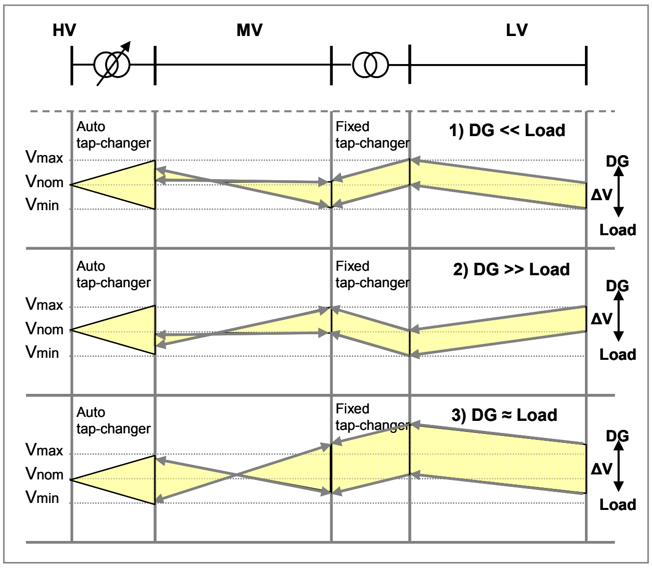

Fig. 1 Voltage variations due to demand and supply

Because in the distribution network the tap-changer of most MV/LV transformers has a fixed set-point, the behavior of load and DG at LV level will determine the voltage variation at both LV and MV level. The automatic tap-changer of the HV/MV transformer will attempt to keep the MV level within the tolerated limits, as shown through the arrows in Fig. 1. Therefore, in such a distribution network the regulator of the HV/MV transformer is also assigned to compensate load and supply changes at LV level. Since this compensation is limited by the rang of regulation of the regulator, large differences from the designed load and supply ratio may move the MV and LV levels beyond the tolerated limits (Vmax) and (Vmin).

When the load demand is much larger than DG supply, first scenario, the maximum load caused by the LV end users will decrease the voltage level at the primary side of MV/LV transformer. The automatic tap changer of HV/MV transformer will move to a higher set-point in order to compensate. Further increase of the LV load will lead to under voltages at the end of MV and LV feeders since the regulator of the HV/MV transformer will stay within the range of regulation. In minimum load situation, the voltage level at the secondary side of the MV/LV transformer is driven to a maximum because of the fixed set-point. The automatic tap changer of HV/MV transformer will move to the minimum set-point in order to compensate. Therefore, further decrease of the load, caused by increase of DG supply, will lead to exceeding the tolerated limit (Vmax). In this case LV end users nearby the MV/LV transformer may suffer insulation damages to equipment and unsafe situations.

In order to maintain the required voltage level the network operator may choose to fix the set-point of MV/LV transformer at lower level for situations where DG supply is much higher than load demand, the second scenario. In this case a shortage of DG supply will decrease the voltage level at the secondary side of MV/LV transformer to reach the minimum level (V_{min}). This level is exceeded by further decrease of DG supply or an increase of load demand.

For the situations in which the network operator is able to plan an adequate balance between DG supply and load, the intermittent characteristics of both demand and supply will nevertheless result in a range of voltage variations as illustrated in the third scenario. Large unbalances between demand and supply at LV level will lead to exceeding the tolerated limits.

The above scenarios explain that passive control of distribution network with DG will lead to insufficient voltage control as both load demand and DG supply possess intermittent characteristics. Changing the design and operation of this network, for example from radial to meshed, may reduce the risks of exceeding the regulated voltage limits.

C. *Short-circuit protection*

While the traditional power system can be seen as top-down supply system, nowadays DG will lead to bi-directional power supply. In case of top-down power supply short-circuit currents in the distribution network will be driven from one source, centralized generation at HV levels, while in bi-directional system DG will provide multiple source contribution to the fault current as shown in Fig. 2. In some cases the bottom-up contribution of DG (I_C) reduces the top-down current (I_B) below the tripping level of the protection.

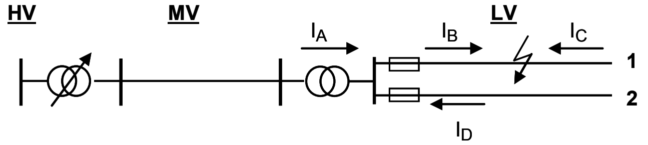

Fig. 2 Contribution to short circuit current

With smaller impedances and large DG capacity, the fault current contribution (I_D) may also trigger the protection of feeder 2 in Fig. 2 resulting in an interruption of the power supply to costumers connected to feeder 2. The DG units will then switch off when the voltage level jumps outside the tolerated minimum limit.

Voltage dips caused by short-circuit faults elsewhere in the distribution network may trip the protection of the DG units if the tolerated voltage limits of these units are conservatively set. On the other hand, a single-phase fault to a MV feeder which is indirectly earthed may not be seen by the protection of DG in the LV network. If the protection switched off the MV feeder and the DG supply at LV level is large enough at that moment, then the LV network will operate as a stand-alone island leading to uncontrolled situations.

III. DEVELOPMENT OF VPP TO MANAGE DG

In the previous paragraph the impact of DG implementation in the distribution network was demonstrated through discussing different operational problems which may occur if no measures are taken. Because of those operational risks it seems that the development of DG creates more disadvantages than benefits. In fact the benefits of DG penetration weigh much higher than the integration challenges we must overcome. In general terms, the benefits of DG can be found in their contribution to the diversification, efficiency and sustainability of the power supply as they reduce or replace the use of conventional energy resources. To facilitate this development, the present power system must adapt to the growth of DG. Therefore, active control of DG should be introduced in the distribution network as passive controlled networks seemed to be insufficient to integrate high amounts of DG.

In the following the concept of Virtual Power Plant (VPP) is employed to facilitate more active control of DG in the distribution network.

A. *VPP concept*

The VPP can be defined as “an information and communication system with centralized control over an aggregation of distributed generation, controllable loads and storage devices”. Its main function is to control the supply and manage the electrical energy flow not only within the cluster, but also in exchange with the main grid. It represents a single entity to the system operator and electricity markets and enables visibility and control over a cluster of distributed generation. A VPP at a high-development stage can also offer ancillary system and power quality (PQ) services. The VPP is thus a controlled operation of aggregated DG units as illustrated in Fig. 3. In such a VPP active control is obtained through an ICT infrastructure which consists of intelligent devices and smart meters, wireless and cable connections, central control computer (CCC) and software applications.

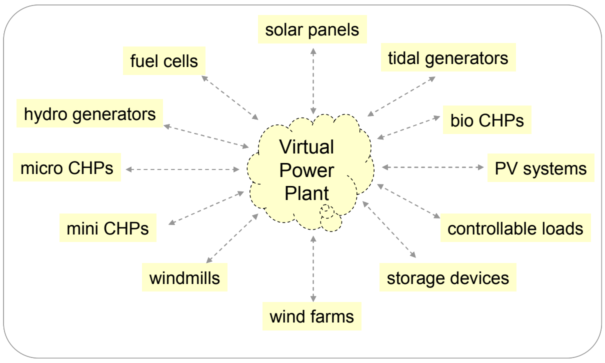

Fig. 3 Aggregation of DG, controllable loads and storage devices in VPP

As in present situation most DG, controllable loads and storage devices are invisible to network and system operators, their aggregation into a VPP will enable their visibility to the VPP operator (VPPO) in first place and finally to the network and system operator. At distribution level, the VPPO can be an independent system operator (ISO) or the distribution system operator (DSO). When more VPPs are developed in a service area of the transmission system operator (TSO), once again they can be aggregated by this TSO into a large scale virtual power plant (LSVPP) as shown in Fig. 4.

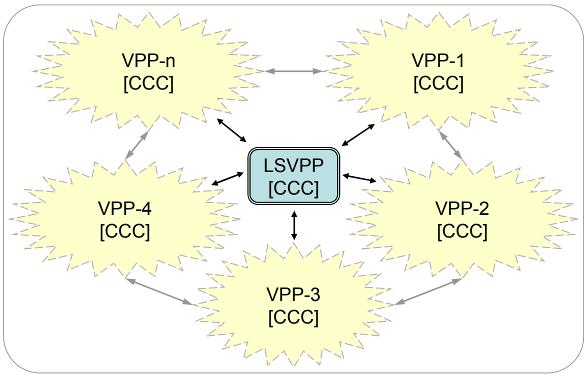

Fig. 4 Aggregation of VPPs into LSVPP

B. VPP design

The major aspects that determine the design of a VPP are the technological possibilities, commercial and economical opportunities and regulatory constraints. The available ICT technologies will facilitate the required communications, control and management system to achieve the commercial and economical targets of the VPPO and DG owners within the regulatory constraints of the hosting country. In addition, the control strategy of the distribution network as well as the properties of the available DG units, storage devices and controllable loads may produce technical conditions which the VPP has to meet.

In the following the major technical, commercial and regulatory aspects concerning the VPP design are discussed.

Technical aspects of VPP

The initial focus of VPPO during the design and development is to control and operate the available DG units, storage devices and controllable loads. For this purpose the required ICT infrastructure as well as forecasting, monitoring and control applications should be developed. The VPPO may chose to make use of available ICT and software facilities if these meet the requirements.

In order to monitor and control DG supply smart metering and control devices have to be installed at the costumers sites. These metering and control devices communicate through intermediate devices (agents) with the CCC. Due to the size of the VPP, geographical distribution of DG units and available DG categories a VPPO can chose for centralized or decentralized operation. Obviously larger VPPs require decentralized operation which is achieved through adding decision making functionalities to the intermediate agents according to predefined algorithms. In this case a multi-agent system is established within the ICT infrastructure of the VPP [**3**], as shown in Fig. 5.

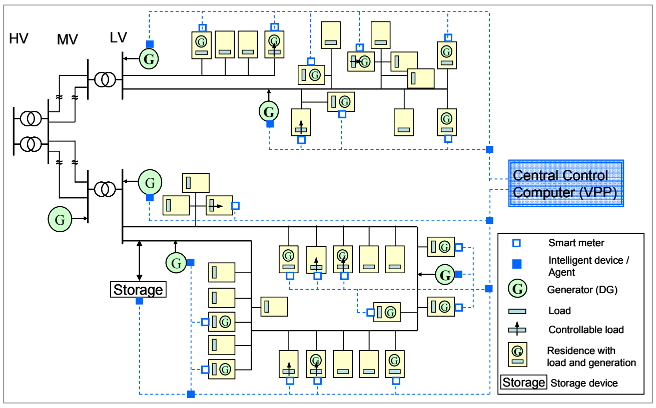

Fig. 5 VPP with decentralized control through agents

As the properties of the VPP system are also based on the required services by the VPPO, DSO and contracted DG owners, this control system involves huge data transfers between smart meters, agents and CCC in order to manage the available DG and deliver the contracted energy and services. Recent developments like the broadband cable (glass fibre) or wireless (WMAX) communications can provide connections with enough speed and capacity to transfer the required data. With such an ICT system the VPP can be presented to the system operator as a single technical entity which is able to offer ancillary system services.

Commercial and economical aspects of VPP

The VPP represents all contracted DG units in the wholesale electricity markets as a single commercial entity. In order to participate in these markets, the VPPO needs to develop or make use of software applications that are able to forecast the power generation of the VPP. The required information for the forecasts can be retrieved from contract information with DG owners in combination with weather forecasts, historical and actual production data. In this case each contract includes information about the maximum capacity and commitment of the contracted DG unit. Based on those information the VPPO is able to predict the power generation of the VPP and to develop production schemes which make it possible to participate in the wholesale electricity market.

When the production scheme is achieved the VPP power delivery and participation can be distinguished and divided into two main parts, the base and variable schemes, as shown in Fig. 6.

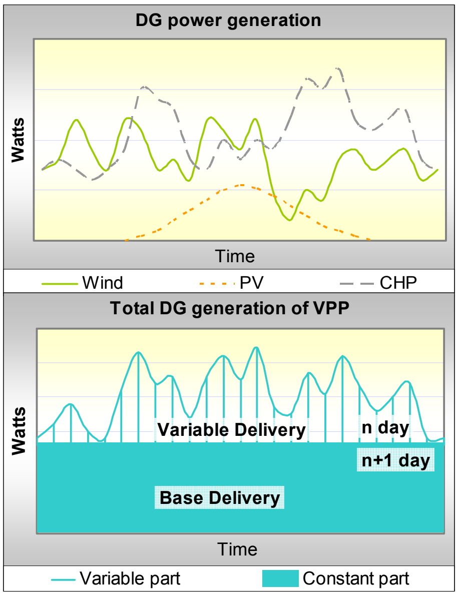

Fig. 6 DG generation related to VPP delivery to grid

If the profiles in upper part of Fig. 6 are the predicted power generation of the joined prosumers and other energy producers with PV panels, windmills and CHPs, the sum of these will form the total generation of the VPP as shown in the lower part of that figure. As the delivery scheme is based on the total generation profile of the VPP, the constant part 'Base Delivery' can be traded in the day-ahead or long term market while the variable part will be traded on shorter periods.

Regulatory aspects of VPP

The separation between generation and transmission in unbundled electricity markets will result in a situation where the VPPO is situated next to the network operator. Therefore, depending on regulatory constraints of the hosting country, the VPP operation could be separated from or merged with the network operation. Nevertheless, the VPPO will introduce the VPP to the electricity market and position it in future electricity markets as shown in Fig. 7.

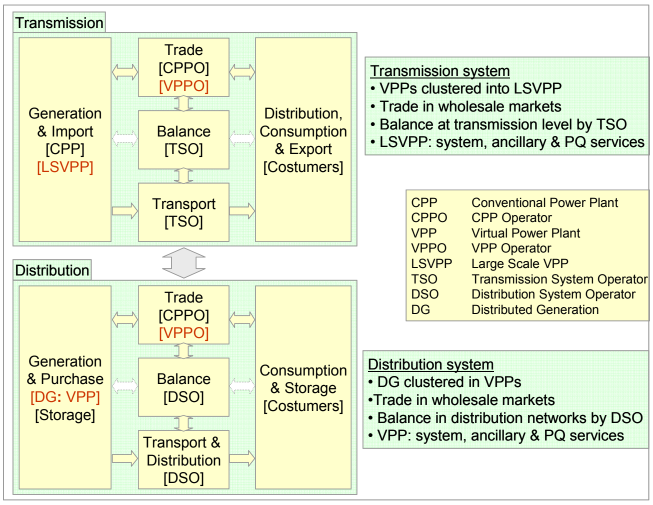

Fig. 7 Position of VPP in future electricity markets

At transmission level the individual VPPs which form a collective LSVPP can be handled by the TSO in with the same sense as the conventional power plant (CPP), while the power generation at distribution level of each VPP can be separately traded in the wholesale electricity market by the VPPO.

C. *VPP operation*

Based on the design aspects mentioned in the previous subchapter, the VPP can be operated according to the algorithm shown in Fig. 8.

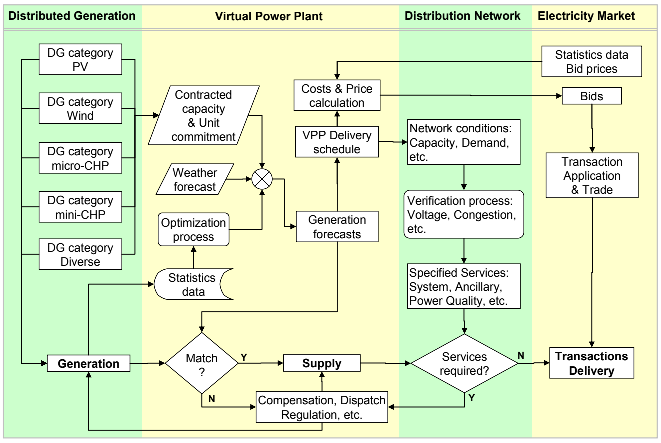

Fig. 8 Operation algorithm of VPP

While the statistics and historical data form the basis for the optimization process, the generation forecasts are based on weather forecasts and the retrieved information about the contracted capacity and commitment of the DG units. The VPP is then able to make the delivery schedule and calculate the costs en price per kWh. Supported by statistics and historical data of bid prices the VPPO will bring out bids in the wholesale electricity market. In the meanwhile, the VPP delivery schedule is verified by the DSO and compared with the network conditions in order to specify whether specific services by the VPP are required. In case the DSO requests certain ancillary or PQ services to maintain the required voltage level or prevent congestion, the VPPO will take necessary measures by compensating, adjusting, dispatching or regulating the VPP supply. The same measures will be taken when the actual generation of the DG units differs from the forecasts.

IV. INTEGRATION OF VPP IN THE POWER SYSTEM

As the VPP controls the DG actively, it should be able to prevent or reduce the operational problems related to the integration of DG, as discussed in chapter 2. This assessment is briefly described for both distribution and transmission networks in the following.

A. *Integration of VPP in distribution network*

In general, the VPP facilitates the visibility of the aggregated DG units and their impact on the distribution network to the VPPO as well as the DSO. In addition, the ICT infrastructure of VPP, which provides active control, can be employed to introduce active control to the passive distribution network as illustrated in Fig. 9.

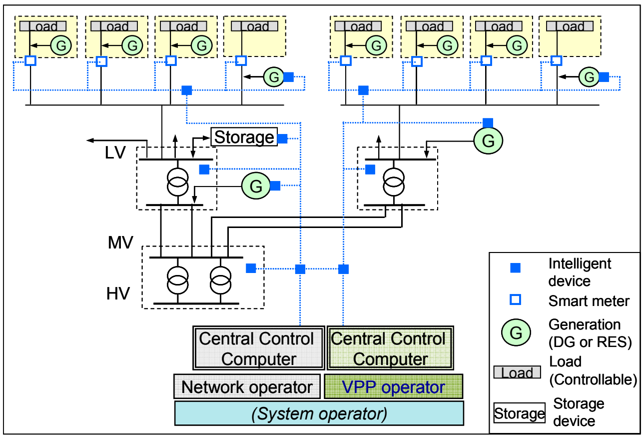

Fig. 9 ICT infrastructure of VPP and distribution network

Other advantages of the VPP system can be found in managing the operational problems concerning load and congestion management, voltage control and short-circuit protection.

Load and congestion management

When a VPP is established the VPPO is able to cooperate with the DSO in order to prevent congestion and maintain system stability due to the VPP operation algorithm, shown in Fig. 8. Blackouts of power supply during the worst case scenarios, as described in subchapter 2.1, can be prevented as well as limiting the number of disconnected costumers during congestion management.

Voltage control

With active control over the DG units in the distribution network, the VPPO can offer services to the DSO concerning the voltage control. To prevent high voltage at the secondary side of the MV/LV transformer, according to the first scenario in Fig. 1, the VPPO can increase the supply of available DG and storage units or decrease the demand through the available controllable loads. The VPP control service can also be offered to prevent exceeding the tolerated voltage limits in the other scenarios by adjusting the amount of supply and demand of the VPP due to the operation algorithm stated in Fig. 8.

Short-circuit protection

If no measures are taken, the contribution of DG to a short-circuit current may introduce negative effects to the operation of the network protection, as discussed in subchapter 2.3. In order to reduce or eliminate these effects a tight coordination between DSO and VPPO is required.

To prevent a bottom-up DG contribution in case of short-circuit fault, which may dazzle the protection of a faulty feeder, the monitoring and control devices of the VPP can be employed to act as differential protection of the feeder. When the direction and magnitude of the currents at both sides differs a decentralized command will be given to the DG protection to switch off. The connection speed and (re)action time of the intelligent devices will determine whether such options will be effective. Such automated and decentralized solutions to protection issues will be easier to develop and coordinate making use of ICT infrastructure of VPP.

B. *Integration of LSVPP in transmission system*

When the LSVPP, aggregated VPPs, covers a significant percentage of load demand in a region or country, their contribution may offer options to compensate unforeseen loss of conventional power plants. In this case the TSO may consider the available power by LSVPP as a reserve capacity with which voltage and frequency control is achieved during disturbances.

Adequate forecasts of LSVPP power production delivered by the VPPOs make it possible to the TSO to take in time measures in order to reduce the intermittent effect of DG and secure the power supply. In addition, the ability of VPPs to reduce operational problems at distribution level create opportunities to use analogous methods at transmission level in order to manage the load flow and congestion, voltage level and frequency in a properly protected transmission network.

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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 the network operator Liander part 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 integrating distributed generation and renewable energy sources in the electricity infrastructure.

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 is 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 Power 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.