A GENERIC MODEL OF A VIRTUAL POWER STATION CONSISTING OF SMALL SCALE ENERGY ZONES

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ABSTRACT

The main aim of the research carried out at Durham University is to increase the value of Small Scale Embedded Generators (SSEG) by aggregating and controlling their outputs and grouping them in zones, where controllable load and energy storage devices could be also present. The value is determined by measuring their ability to interact with the electricity market effectively, displace fossil fuel plant, reduce network losses and contribute to power system operational tasks. This paper presents a PSCAD/EMTDC model of a Virtual Power Station (VPS) consisting of Small Scale Energy Zones (SSEZs) connected to the Low Voltage (LV) distribution network. A SSEZ is defined as a controllable section of LV network containing a mixture of SSEGs, distributed storage and load [1].

INTRODUCTION

The UK government's policy relating to renewable energy and Combined Heat and Power (CHP) is expected to lead to a continuous increase in Distributed Generation (DG). In order to meet the government's target for 2010, approximately 10 GW of additional DG will have to be connected to distribution networks. As a consequence there is considerable industry interest nationally and internationally regarding the particular issue of how to integrate large numbers of SSEGs into public LV networks. There is consensus that distribution networks must be transformed from passive entities to active systems being monitored and managed to facilitate the proliferation of DG.

However, this growth will only be achieved if there are sufficient market incentives. The UK electricity market does allow for late forecasting of generation output (one hour in advance) but it is expensive to collate this information from many SSEGs, on an ongoing basis. This research suggests that if SSEGs are aggregated and their outputs combined within an SSEZ they will be able to trade larger amounts of electricity as a group of generators. This should result in SSEGs being able to command a higher price in the electricity market thus increasing their value and stimulating their growth.

The key question this research seeks to answer is, to what degree can SSEGs, load and energy storage be manipulated and controlled, while maintaining power quality and security of supply to electricity customers, and to what degree does this level of control have the ability to increase the value of SSEGs ? The first step in attempting to answer this question is the development of a model for a Virtual Power Station (VPS), which is considered as the highest level of aggregation. This VPS consist of a considerable number of SSEZs each with different mixes of generation, load and storage [2]. The second step is the analysis of the challenges faced when trying to integrate SSEZs in the LV distribution network with different levels of renewable energy penetration.

MODELLING METHODOLOGY

A Virtual Power Station is defined by considering three levels of aggregation:

- The first, and lowest, level includes aggregation and control of a number SSEGs, load and energy storage devices connected to a section of LV distribution network. This is called a Small Scale Energy Zone.
- The second level includes aggregation and control of a number of the SSEZs and this is called a MV/LV substation.
- The third, and highest, level includes aggregation and control of a number of MV/LV substations and this is called a Virtual Power Station.

As the level of aggregation increases, the level of detail in the model decreases:

- *First Level*, each SSEZ comprises of four LV network segments and three of them are represented as lumped load (24 customers) and lumped generation while one of them is represented in detail (Figure 3).
- *Second Level*, the detailed MV/LV substation comprises of four Small Scale Energy Zones and three of them are represented as lumped load (96 customers) and lumped generation while one of them is represented in detail (Figure 2).
- *Third Level*, the VPS comprises of a section of LV network with a radial layout, with eight MV/LV substations (11.5/0.433kV). Seven of the substations are represented as simple lumped generators and lumped load while the last one is represented in detail. In total there are 384 domestic single-phase house loads on each substation (Figure 1).

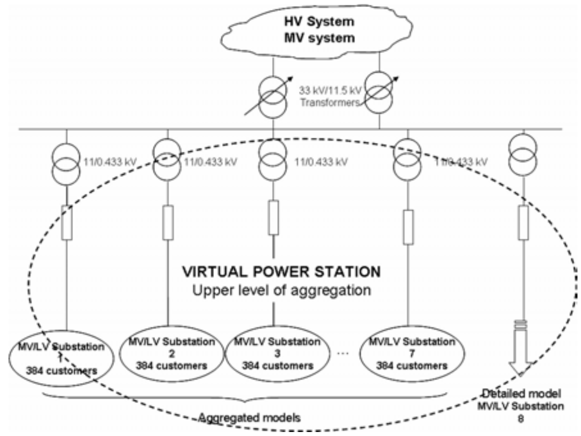


Figure 1 Virtual Power Station model

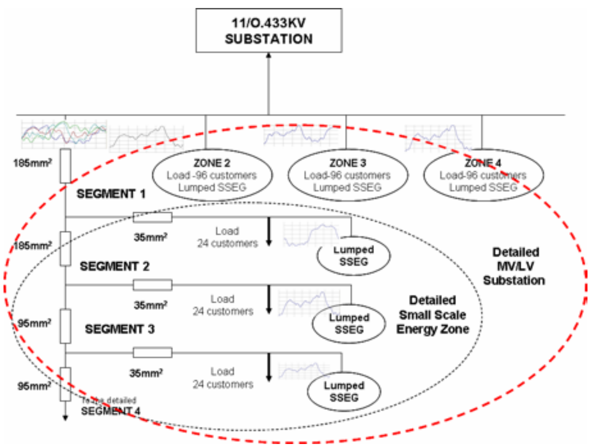


Figure 2 MV/LV substation model

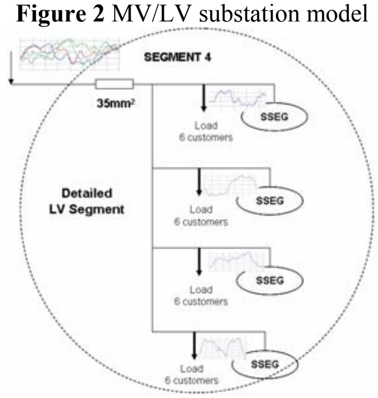


Figure 3 Detailed LV Segment model

NETWORK MODEL CHARACTERISTICS

A three-wire representation of the MV/LV network [2] has been developed using PSCAD/EMTDC. The system comprises of 192 SSEZs distributed along the LV network with a total of 18,432 customers supplied. Each SSEZ supplies 96 customers. Domestic load figures produced by the Electricity Association have been used, which show that for each domestic single-phase house, taking diversity into account, the minimum demand is 0.16kW. The loads do not represent any particular type of housing stock and they are taken from average demand. The system is based on the low voltage reference impedance quoted in IEC Technical Report 60725, which covers between 90% and 98% of connected customer impedances in the UK, as well as on data approved by work stream 3 of the DTI / Ofgem Technical Steering Group.

The HV/MV substation feeding the MV network comprises of two transformers in parallel with a nominal 7.5/15MVA Cyclic Emergency Rating (CER) equipped with on-load tap changers. Each of the eight MV/LV substations feeding the LV network comprises a single transformer 11/0.433kV ground-mounted transformer of vector group Dy11, with a rating of 0.5MVA [3]. All 11kV and 0.400kV cables have been represented in PSCAD/EMTDC using the R, L equivalents of three sizes of cable: 185mm^2, 95mm^2 and 35mm^2. Three phase feeder cables have been represented by three such components with no mutual coupling. Domestic loads have been represented as purely resistive components.

LIBRARY OF SMALL SCALE EMBEDDED GENERATORS

A number of detailed and aggregated models of SSEGs were developed by the authors as presented in Figure 4.

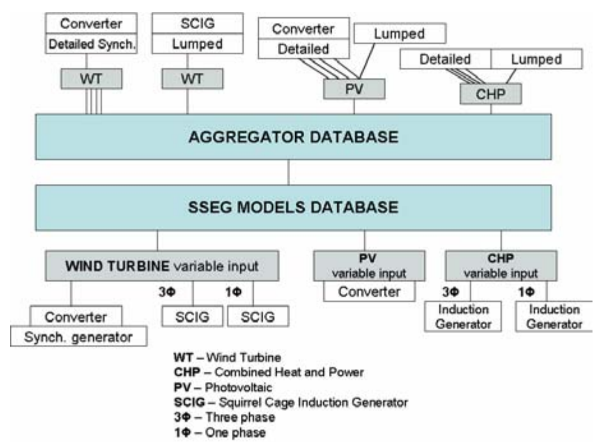
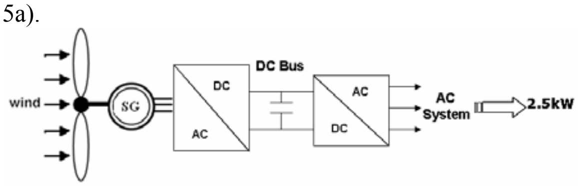


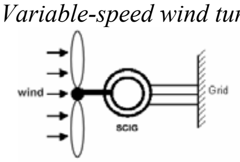
Figure 4 PSCAD models database

Wind turbine models

For the variable wind speed turbine model a 2.5 kW, 3 bladed, wind turbine is connected to a permanent magnet synchronous generator with 8 pole pairs. The nominal power is reached at a wind speed of 10m/s specific to the urban environment. The variable wind speed with an average of 10.743m/s input was applied using an X-Y transfer function block as an interface with an external file containing the turbulent wind speed data generated using the method outlined in the [4]. In order to connect the output of the synchronous generator to the grid a full AC/DC/AC converter is implemented. The converter is composed of a diode rectifier, a DC bus with a storage capacitance and a 6-pulse bridge thyristor inverter (Figure 5a).



a) Variable-speed wind turbine



b) Constant wind speed turbine model

Figure 5 Wind turbine models

For the constant wind speed turbine model, direct grid connected, a 2.5kW, 3 bladed horizontal axis wind turbine is connected to a Squirrel Cage Induction Generator (Figure 5b).

PV model

A DC controllable voltage source was used in order to model a photovoltaic generator. The voltage is controlled through an X-Y transfer function block as an interface with an external file containing a specific input data for the photovoltaic systems. In order to connect to the grid a DC/AC converter is implemented which is composed of a DC bus with a storage capacitance and a 6-pulse bridge thyristor inverter.

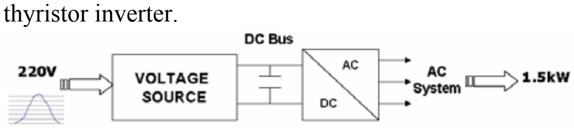


Figure 6 Photovoltaic system model

MicroCHP model

For modelling a microCHP a simplified model with the induction machine is used. The power output is compared with a reference and the error is passed through a PI controller and the output of the PI controller adjusts the mechanical torque.

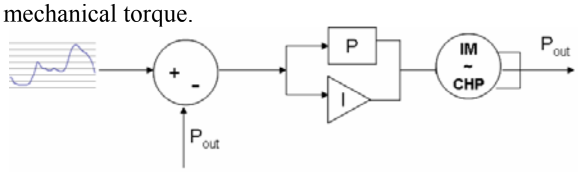


Figure 7 Simplified CHP model

The MV/LV network model is very flexible and along with the SSEGs library, allows the construction of a number of generation scenarios. For example a mixture of wind and photovoltaic generation (wind dominant or PV dominant), a mixture of CHP and wind (wind or CHP dominant) or a mixture of wind, PV and CHP generation.

SIMULATION RESULTS

Using the model developed for the VPS a set of parameters was investigated for different penetration scenarios:

- Voltage profile inside a SSEZ.
- Cable thermal analysis.
- Reverse power flow through the 11.5/0.433kV distribution transformer.
- Reverse power flow through the 33/11.5kV primary transformer with the maximum number (192) of SSEZs connected to the LV network.

The levels of penetration were considered for the minimum load condition from 0% as a base for comparison through 100% penetration (all customers have a 1.1kW SSEG installed) up to 190% penetration (all customers have a SSEG of approximately 2.2kW installed). Table 1 presents the VPS maximum capacity for different penetration scenarios.

Table 1 SSEZs maximum capacity for different penetration scenarios

No of SSEZs	VPS Maximum Capacity				
	Penetration Scenarios				
	38%	76%	114%	152%	190%
192	7.68 MW	15.36 MW	23.04 MW	30.72 MW	38.4 MW

It was found that the aggregation of a number of wind turbines smoothes the net power output compared to the power output from an individual turbine. Figure 8 shows the variation in power output, as a percentage of the average output, for a single wind turbine and for the aggregated outputs of 2, 3 and 4 turbines (see Segment 4 in Figure 3). It can be seen that the variations decrease, from approximately 7% to 2%, as the number of turbines being aggregated increases.

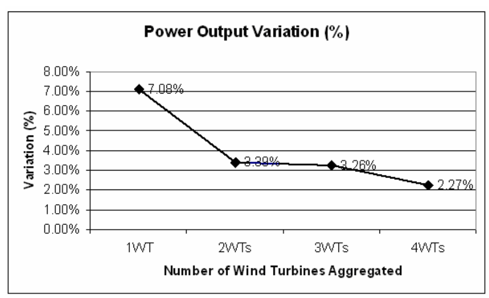


Figure 8 Power output variations for different numbers of WTs aggregated

The network constraints at different levels of aggregation and for different penetration scenarios, as presented in Table 1, were identified through simulation. For a uniform distribution of SSEGs inside of a SSEZ, defined as the first level of aggregation (Figure 2), the primary constraint is voltage rise and this occurs for 114% penetration (Figure 9).

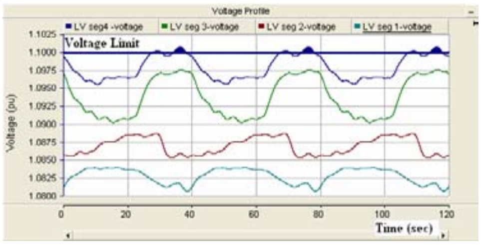


Figure 9 Voltage profile on each segment for 114% penetration, variable wind speed

Other limitations are on the 11/0.433kV substation, defined as the second level of aggregation. The first constraint at this level is due to the thermal cable constraints and occurs on the 185mm^2 feeder cables required to connect a cluster of SSEZs. The threshold is initially reached at a penetration of 76% (Figure 10).

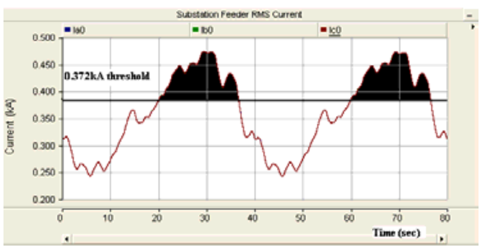


Figure 10 Measured current of 185mm^2 cable of substation feeder for 76% penetration

At the same level of aggregation the second constraint is due to the reverse power flow through the distribution 11/0.433kV transformer and begins to occur at 114% penetration (Figure 11).

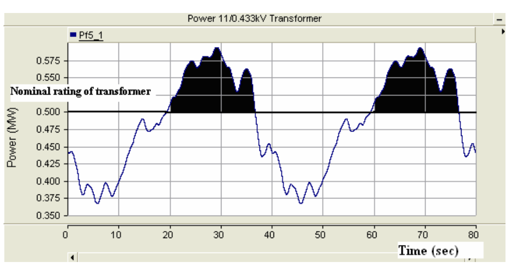


Figure 11 Power flow through 11/0.433 kV distribution transformer for 114% penetration

At the VPS level, defined as the upper level of aggregation, for 192 SSEZs connected, the reverse power flow through primary 33/11.5kV transformers is the limiting factor and occurs at different penetration levels between 38% and 85% (see Table 1) depending on transformer rating quoted and the reverse power flow capability of the tap changer mechanism.

In summary, the 33/11.5kV primary transformer is the limiting factor for the connection of the VPS to the distribution network; the thermal constraint of the feeder cable from the distribution substation and the reverse power flow through distribution transformers are the limiting factors for the MV/LV substation connection within a VPS and finally voltage rise inside a SSEZ is the limiting factor for the connection of individual SSEGs.

CONCLUSIONS

In conclusion, this generic model allows the degree to which aggregation and control can be performed to be assessed. The model allows this analysis to be carried out at three levels of aggregation and detail. The second stage of this research is to investigate whether this aggregation and control has the ability to improve the value of SSEGs and therefore stimulate their growth. The aggregation and control should result in a more predictable, reliable and significant source of real and reactive power i.e. a Virtual Power Station. The VPS's capacity and controllability is a key determinant of the value that would be assigned to it by a network operator or by a supply company. This generic model has facilitated the identification of the network constraints associated with high penetrations of SSEGs and therefore has highlighted key areas on which new control techniques must focus. It has also helped identify opportunities relating to improved interactions with future energy and ancillary services markets. This model will be used further to develop and evaluate control techniques to overcome the network constraints and to increase the commercial and environmental value of SSEGs.

Acknowledgments

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