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A DYNAMIC VIRTUAL POWER STATION MODEL COMPRISING SMALL SCALE ENERGY ZONES

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ABSTRACT

Concerns over global warming and high oil prices are expected to lead to a continuous increase in electricity generated by distributed renewable energy sources and Small Scale Embedded Generators, SSEGs. This increase in SSEG will pose numerous technical challenges for Distribution Network Operators. The Small Scale Energy Zone concept seeks to overcome these challenges using appropriate coordinated control. An SSEZ is defined as a section of Low Voltage network with a high penetration of SSEGs, controllable loads and energy storage units. This paper puts forward the concept of the Virtual Power Station, consisting of a number of aggregated SSEZs , which has the potential to offer significant improvements in the commercial value and environmental impact of the installed SSEGs by enabling provision of ancillary services. In order to evaluate the effectiveness of this concept, a dynamic power system model of a VPS has been developed.

1 INTRODUCTION

The UK government's policy on 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 20% renewable target for

2020, significant amounts of DG will have to be connected to distribution networks (Department of Trade and Industry, 2007). SSEG (Small Scale Embedded Generation) is seen as an important part of the additional DG that is required to meet these targets. As a consequence there is considerable industrial interest, both nationally and internationally, regarding the integration of large numbers of SSEGs into public Low Voltage (LV) networks. SSEGs are defined in Engineering Recommendation G83/1 (The Distribution Code Review Panel of Great Britain, 2003) as any source of electrical energy rated up to, and including, 16 Ampere per phase, single or poly-phase, 230/400V ac.

However, the forecast for high concentrations of SSEG could pose considerable problems for Distribution Networks Operators (DNOs). Technical obstacles to the large scale deployment of SSEGs include: (i) steady-state voltage rise limits (Cipcigan et al., 2007, Lyons et al., 2006, Trichakis et al., 2006), (ii) voltage unbalance limits (Jenkins et al., 2000), (iii) operating distribution network circuits above their thermal limits (Hadjsaid et al., 1999) and (iv) reverse power flow through distribution transformers exceeding their thermal limits (Cipcigan and Taylor, 2007). Aggregation of a large number of generators, however has the potential to offer significant improvements in the commercial value and environmental impact of the installed SSEGs by providing ancillary services such as local voltage control and spinning reserve to DNOs.

The main aim of the research therefore, is to increase the value of SSEGs by aggregating and controlling their outputs and grouping them into zones, where controllable loads and energy storage devices could also be present. This paper presents a dynamic PSCAD™/EMTDC™ model of a generic UK distribution network consisting of SSEZs connected to the LV distribution network. The network topology and data was approved by a number of UK DNOs and was deemed to be representative of typical UK distribution networks (Ingram et al., 2003). The model enables SSEG impact studies, identification of critical nodes and development and evaluation of control techniques.

The paper is structured in the following manner. Future distribution networks and concepts which have been developed to overcome network constraints and maximise the economic benefit of SSEG are discussed in Section 2. Section 3 describes the PSCAD™/EMTDC™ VPS (Virtual Power Station) model. The critical nodes and the MV and LV network impact studies that were performed to identify them are described in Section 4. Finally, in Section 5, conclusions are drawn on the validity of the model and the importance of the critical nodes to the development of active network management algorithms.

2 BACKGROUND

Recent years have seen a steadily growing interest in the exploitation of renewable energy sources and this has resulted in increasing numbers of SSEGs connecting to distribution networks. A review of the literature indicated that the majority of the research in this area focussed on facilitating connection of DG to High Voltage (HV) or Medium Voltage (MV) networks and by comparison the study carried out on the effects of large penetration of SSEGs on LV networks has been limited.

The possible impacts of SSEG on the operating parameters of distribution networks, the size and extent of any technical factors which could limit the wider take up of SSEGs in the UK was analysed in (Ingram et al., 2003). It was found that with the use of a 0% tap position on the tap-changer of 11/0.433kV transformers, the voltage at the remote end, under minimum and maximum loading conditions, would be within voltage limits for the zero generation case. The operation of SSEG however, results in an increase in LV system voltage. This is due to generator power cancelling out some or the entire domestic load and also due to excess generator real power flowing back through a mainly resistive network to the distribution transformer. The results show that a voltage rise limit violation occurs when more than 50% of the customers have 1.1kW SSEG units installed under minimum load conditions.

Microgrids have been proposed to solve the technical issues associated with large concentrations of SSEG (Microgrids, 2003 - 2005, More Microgrids, 2006 - 2009, Lasseter et al., 2004). These networks feature active network control systems that ensure operational and infrastructural limits are observed. Moreover, these systems are likely to add functionality to the distribution network by adding islanding ability to sections of network and possibly facilitate the delivery of ancillary services to DNOs.

The Virtual Power Plant (VPP) concept was conceptualised in (Pudjianto et al., 2007, Caldon et al., 2004, Schulz et al., 2005, Bignucolo et al., 2006, Dielmann and VanDerVelden, 2003) to allow a more effective integration of Distributed Energy Resources (DER) into the existing power systems. The VPP was used to aggregate a number of small generators, close to the load, to supply both thermal and electrical power and to provide an interface between the system components in order to enhance their visibility and control (Caldon et al., 2004). An optimisation algorithm is proposed to integrate many DGs into a VPP which will be able to sell both thermal and electrical power (Caldon et al., 2004, Schulz et al., 2005).

3 VIRTUAL POWER STATION MODEL CONTAINING SSEZS

PSCAD™/EMTDC™ is a three-phase power system representation software package and is capable of detailed modelling of power systems containing up to several hundred buses or nodes. EMTDC™ simulates power system scenarios in continuous time by solving a series of differential equations in a time-stepped manner. It features detailed, time domain electrical models of power system components making it well-suited to dynamic analysis.

In order to allow a flexible analysis of different generation mixtures and penetration level scenarios a generic UK distribution network model was developed. A three-wire representation of the MV/LV network was modelled dynamically in PSCAD™/EMTDC™. The system comprises of 192 SSEZs with wind generation distributed uniformly within the LV network. Each SSEZ contains 96 customers therefore 18,432 customers are supplied in total. The summation of each of these SSEZs is referred to as a Virtual Power Station (VPS) which acts as an interface with the 33kV network, DNO and TSO (Transmission System Operator). Load demand figures produced by the *Electricity Association* show that the minimum and maximum demand figures are 0.16kW and 1.3kW respectively after diversity has been taken into account (Ingram et al., 2003). Different levels of detail and different levels of aggregation were defined in order to allow a flexible analysis. As the level of aggregation increases, the level of detail in the model decreases as illustrated in Figure 3.1.

(i) VPS Level

The VPS comprises of a section of LV network with a radial layout, with eight MV/LV substations (11.5/0.433kV) feeding a total of 32 SSEZs. Seven of the substations are represented as simple lumped generators and lumped loads while the last one is represented in detail. In total there are 384 domestic single-phase house loads on each substation (Figure 3.1(a)).

(ii) Substation Level

The detailed MV/LV substation comprises of four SSEZs and three of them are represented as lumped loads (96 customers) and lumped generation while one of them is represented in detail (Figure 3.1(b)).

(iii) SSEZ Level

Each SSEZ comprises of four LV network segments and three of them are represented as lumped loads (24 customers) and lumped generation while one of them is represented in detail (Figure 3.1(b)).

(iv) Detailed Segment Level

This consists of 4 branches each containing 6 load customers and a 2.5kW 3-phase SSWT (Figure 3.1(c)).

Figure 3.1: *Hierarchical structure of the VPS model*

To enable development of the VPS model a customised PSCAD™/EMTDC™ library of models was developed for different generation types, domestic load and energy storage. The salient characteristics of the VPS model are presented in the following subsections.

3.1 Primary Transformers

The HV/MV primary substation feeding the MV network comprises of two transformers in parallel with a nominal rating of 7.5MVA and a CER (Cyclic Emergency Rating) of 15MVA. A primary substation with two transformers has a firm or secure capacity of 15MVA in the winter, which is reduced to only 7.5MVA in the summer (Forbes et al., 2003). Each transformer has a per unit impedance of 18%, an X/R ratio of 15 and is equipped with an OLTC on the HV winding. Its connection group is Yy0, which corresponds to an in phase wye-connected primary and a wye-connected secondary winding (Ingram et al., 2003).

The conventional three single-phase transformer model is used in PSCAD™/EMTDC™ and the positive sequence leakage and copper losses were calculated using the transformer X/R ratio. This model was chosen as balanced transformer loading conditions were maintained throughout the simulations. The primary-substation 33/11.5kV transformers are modelled with OLTCs with a 1.67% tap step which is used to ensure that the MV voltage is maintained between 11.0kV and 11.1kV (Cipcigan et al., 2007, 2002). The upper bound of 1.1p.u. and lower bound of 0.94p.u. are the UK low voltage statutory limits of the 0.433kV network (2002).

3.2 Distribution Transformers

Each of the eight MV/LV distribution substations feeding the LV network comprise of a single ground-mounted transformer 11/0.433kV of vector group Dy11 (a delta-connected primary and a wye-connected secondary winding) with a rating of 0.5MVA. The transformer has an impedance of 5% and an X/R ratio of 15 (Ingram et al., 2003). As the 11/0.433kV transformers are not equipped with an OLTC therefore the LV voltage cannot be changed without a corresponding change in the MV voltage.

3.3 Underground cables

The 400V distribution cables are constructed with aluminium conductors. All 400V cables have been represented in the PSCAD™/EMTDC™ model as resistance and reactance equivalents of three cable sizes (185 mm^2, 95mm^2 and 35mm^2) with no mutual coupling. The equivalent cable parameters used in the models are presented in Appendix A and it is clear that the cable resistance is significantly greater than the cable reactance (Ingram et al., 2003).

3.4 Domestic load model

Domestic loads have been represented as purely resistive components. Load demand figures produced by the Electricity Association show that the minimum and maximum demand figures are 0.16kVA and 1.3kVA respectively after diversity has been taken into account (Ingram et al., 2003).

3.5 Wind turbine model

A wind turbine model was developed in PSCAD™/EMTDC™ and the parameters used for simulations are based on a commercially available Small Scale Wind Turbine (SSWT) designed for an urban environment (Dutton et al., 2005). The 2.5kW nominal power is reached at a wind speed of 10.7ms^{-1}. This mean wind speed was chosen to represent a day with a significant amount of available wind power and it can be seen that most urban wind turbines operate at rated power output at 10.7 ms^{-1} .

In the model developed in PSCAD™/EMTDC™ a 2.5kW, 3 bladed horizontal axis wind turbine is connected to a squirrel cage induction generator as shown in Figure 3.2.

Figure 3.2: *Small Scale Wind Turbine Model*

For variable wind speed conditions, a time series of turbulent wind speed data is used as the input to the model using an X-Y transfer function block as an interface with an external file containing an accurate model of the wind that includes turbulence effects. The wind model used spectral density functions derived from real wind data to generate typical winds profiles around a mean wind speed. Most importantly the model must account for the turbulence effects that exist in real winds and this is described in more detail in (Stannard et al., 2007). The model permits diversity to be modelled under variable wind conditions and a sample of the simulation results for the aggregated power output of up to four SSWTs connected on an LV segment, are presented in Figure 3.3.

Figure 3.3: *Wind speed data and power output on each wind turbine (Segment 4)*

The simulation results demonstrate that aggregation of a number of wind turbines rapidly smoothes the net power output compared to the power output from an individual turbine (Stannard et al., 2007). Figure 3.4 shows that even with only four turbines aggregated the variability of the power output reduces noticeably. This aggregation effect is central to the VPS concept.

Figure 3.4: *Percentage variance of SSWT power output as aggregation is increased*

3.6 Battery storage model

In order to investigate active voltage control of an SSEZ, an energy storage system has been modelled in PSCAD™/EMTDC™. The real power flow export and import from this system is used to control the system voltage at these nodes on the network. The energy storage system is illustrated diagrammatically in Figure 3.5.

Figure 3.5: *Block diagram of the energy storage system model*

The system consists of four primary model elements: power controller; inverter system; battery and the connection to LV network. The power controller represents the centralised or distributed controller that is implemented in the system. A distributed voltage controller is implemented in this particularly study.

3.6.1 Battery Model

The lead-acid battery is the most widely available electrical energy storage available to domestic users. The specific energy and specific power levels of lead acid batteries are quite low; however their low cost is seen as a major advantage and are therefore seen as the most likely form of small scale energy storage in the short term. The model is developed as a combination of the improved battery model proposed in (Ter-Gazarian, 1994, Benini et al., 2000, Hageman, 1993) and the work in (Bumby et al., 1985) to estimate the SOC which is itself a non-linear function of the open circuit voltage. Self discharge is neglected as are the effects of aging at present. The PSCAD™ battery model is shown in Figure 3.6.

Figure 3.6: *PSCAD™ model of the lead acid battery*

The voltage equations for this battery model are defined (1, 2). The equation used depends on whether the battery is charging or discharging.

$$V_{'term} = V_{0\% SOC} + V_{SOC} + I_{batt} R_{ic} \quad (1)$$

$$V_{'term} = V_{0\% SOC} + V_{SOC} + I_{batt} R_{id} \quad (2)$$

The system consists of two voltage sources $V_{0\% SOC}$ and V_{SOC}, two variable resistances R_{ic} and R_{id} and the input to the system is the variable current source. The value of the variable current source is calculated from the modelled battery terminal voltage and the power of the inverter model on the battery side.

The variable resistances are dependent on the State of Charge (SOC) of the battery and the charge/discharge current. This is not a linear relationship. A relationship between these resistances and the SOC is established for charging and discharging and functions are used to approximate this relationship. These characteristics of the battery are established by battery testing and analysis and from manufacturer data.

$V_{0\% SOC}$ is used to model the open circuit voltage of the battery bank at 0% SOC. This is taken from manufacturer data. V_{SOC} accounts for the effect of battery SOC on open circuit voltage. The relationship between open circuit voltage and SOC is modelled using manufacturer data and a LUT (Look-Up Table). The SOC itself is a function of the current entering or leaving the battery.

The discharge current has a non-linear effect on the SOC. The most commonly used equation to derive the capacity of a battery at a specific current is the Peukert equation (Bumby et al., 1985).

$$I_i^n \tau_{ci} = const \quad (3)$$

where: -

I_i discharge current

τ_{ci} is the time to discharge the battery completely (hours)

n constant derived from manufacturer data

The A-h (Ampere Hour) rating C_i is defined as: -

$$C_i = I_i \tau_{ci} \quad (4)$$

The A-h rating of batteries is almost always given at the 20 hour rate. This implies that the battery A-h rating stated is only valid if discharged at a rate that results in the battery reaching a fully discharged state from a fully charged one in 20 hours.

Manipulation of (3) and using the manufacturers A-h rating C_{20} and (4) gives: -

$$C_i = C_{20}\left(\frac{I_{20}}{I_i}\right)^{n-1} \tag{5}$$

Assuming a constant discharge current the state of charge maybe expressed as: -

$$SOC = 1 - \frac{C_{Di}}{C_i} \tag{6}$$

where: -

$$C_{Di} = I_i \tau_{Di} \tag{7}$$

and τ_{Di} is the discharge time.

(4), (5), (6) and (7) are manipulated and assuming a constant charge current I_i gives: -

$$SOC = \frac{\left(1 - \left(I_i \tau_{Di}\right)\right)}{C_{20}\left({}^{I_{20}}\!/\!{}_{I_i}\right)^{n-1}} \tag{8}$$

Consider a small change in SOC, ΔSOC in a short time period Δt in seconds, where I_i is constant: -

$$\Delta SOC = \frac{-I_i \Delta t}{(3600)(C_{20})\left({}^{I_{20}}\!/\!{}_{I_i}\right)^{n-1}} \tag{9}$$

$$\frac{\Delta SOC}{\Delta t} = \frac{-I_i}{(3600)(C_{20})\left({}^{I_{20}}\!/\!{}_{I_i}\right)^{n-1}} \tag{10}$$

$$\Rightarrow \frac{d(SOC)}{dt} = \frac{-i(t)}{(3600)(C_{20})\left({}^{I_{20}}\!/\!{}_{I_i}\right)^{n-1}} \tag{11}$$

This expression can be evaluated in PSCAD™/EMTDC™ using some basic logarithmic manipulation. The output of this expression is then integrated using the integrator function of the CSMF (Control System Modelling Functions) library in PSCAD™/ EMTDC™.

During charging, a constant charge efficiency can be assumed (Bumby et al., 1985). Similarly an expression for the rate of change of SOC is formed on this assumption: -

$$\frac{d(SOC)}{dt} = \frac{I_i \eta_c}{(3600)(C_{20})} \tag{12}$$

Where η_c is the efficiency of the charge process. This efficiency is calculated from an analysis of experimental data.

The PSCAD™/EMTDC™ battery model selects the rate of change of SOC expression depending on whether the battery is charging or discharging. The battery model is validated using actual data from testing on the energy storage system in the Experimental SSEZ.

3.6.2 Bi-directional Inverter System Model

A three-phase synchronous machine model is used to model a three-phase VSI (Voltage Source Inverter) system (Osika et al., 2005) as the high frequency effects of these converters are ignored in this instance.

A PI controller in the inverter power control block sends a torque command to the inverter system. This system consists of the synchronous machine with its field winding controlled by a PI controller. This is used to control the current flowing through the field winding so that the desired reactive power is produced. In this case the desired reactive power is zero to ensure unity power factor operation. Controllers within the machine model, control the phase current so that the desired torque and thus the desired power is exported or imported by the system. The power used by this machine is then used to compute the power required from the battery system using experimental data characterising the efficiency of a Sunny Island 4500™ (2003).

4 APPLICATION OF VPS MODEL TO IDENTIFY CRITICAL NODES

The VPS model was used to simulate a number of SSEG penetration scenarios. This allowed the maximum SSEG penetration levels to be determined and also the critical nodes in the network, where constraints were first reached. These critical nodes can then be used as the basis for control system design to alleviate the constraints and reach increased penetration levels without degrading security and quality of supply.

4.1 Impact studies

This generic model has facilitated the identification of the penetration levels at which network constraints will be met by evaluating the impact of increasing penetrations of SSEG. The penetration levels were increase from 0% penetration (no customer SSEG installations) through 100% penetration (all customers have a 1.1kW of SSEG installed) up to 200% penetration (all customers have 2.2kW of SSEG installed). If the VPS described previously is used as a model, 2.2kW of SSEG per customer would result in a VPS with approximately 40MW of installed capacity. The simulation conditions were designed to exhibit a worst case scenario in terms of the impact of SSEG within the LV network. Therefore each load customer was assigned the Electricity Association's minimum demand figure of 0.16kVA (Ingram et al., 2003), a mean wind speed of 10.7 ms-1 was used and the SSEGs were distributed uniformly across the section of network considered.

Based on the dynamic VPS model comprising SSEZs the following network limitations were identified:

(i) The RPF through the 33/11.5kV primary transformer is the limiting factor for the VPS connection to the primary substation. It was found that the reverse power flow capability of the primary transformers could be exceeded at a penetration level of approximately 80% contingent on the rating of the transformers and the reverse power flow capability of the tap changer mechanisms (Cipcigan and Taylor, 2007, Levi et al., 2005) see Figure 4.1.

Figure 4.1 Reverse power flow through the primary transformer

(ii) RPF through the distribution transformers is the limiting factor for the connection of distribution substation to the VPS. The constant wind speed study indicates that the 500kVA rating of the 11/0.433kV distribution transformer would be exceeded at 107% generation penetration (Cipcigan and Taylor, 2007) see Figure 4.2.

Figure 4.2 Power flow through 500kVA distribution transformer, 114% penetration

(iii) The thermal rating for each feeder cable emanating from the substation is the limiting factor for the SSEZ's connection to the distribution substation and occurs if each customer has installed an SSEG with a rating of approximately 2kW (190% penetration) (Bungay and McAllister, 1997) see Figure 4.3.

Figure 4. 3 Current flowing in 185 mm^2 LV cables, penetration 190%

(iv) The voltage rise within an SSEZ is the limiting factor for SSEG connection. This research indicates that voltage control is the primary issue of concern when large amounts of SSEG are connected to the LV network and the threshold occurs when all customers are supplying 0.44kW generation at a minimum load of 0.16kW [3-5], see Figure 4.4.

Figure 4.4 Voltage profile on each LV segment

4.2 Critical nodes of the VPS

The simulation results indicate that only a limited number of controllers need to be deployed at each level of aggregation. The critical nodes as were identified in the UK generic distribution network are defined as follows and are illustrated in Figure 4.5.

(i) On Segment 4 an *SSEG critical node* for controlling the voltage rise inside of an SSEZ is defined. This particular LV segment is located at the remote end of the distribution network.
(ii) On each SSEZ cable emanating from the distribution substation an *SSEZ critical node* is defined and active control measures are required in order to overcome the thermal ‘pinch points’.
(iii) On each 11/0.433kV distribution substation an *SSEZ cluster critical node* is defined and centralised control is required for limiting the RPF through the distribution transformers.
(iv) On 33/11.5kV primary substation a *VPS critical node* is defined.

Defining *critical nodes* in the system enables prioritisation of the active network controllers that need to be implemented. In addition, this prioritised strategy of controller deployment can reduce the number of active network controllers installed while ensuring that technical requirements are met with and operational goals are achieved.

Figure 4.5: *Critical nodes in the system based on constraints identified in the modelling study*

5 CONCLUSIONS

The anticipated growth in SSEG is likely to introduce a number of challenges for the operation of distribution networks. SSEGs operating individually have limited value from an economic and environmental point of view but the value attributed to each individual SSEG can be greatly augmented by aggregating large numbers of SSEGs. The VPS concept, introduced in this work, consisting of multiple SSEZs increases the value of each SSEG by enabling interaction with the market in terms of dispatchable power and ancillary services. To enable the evaluation and development of this concept a dynamic model of a benchmark VPS is developed based on a generic UK network. This model has been applied to evaluate the effects of aggregation and to identify critical nodes within the distribution network and also to assess SSEG penetration levels. It will be applied in future work to develop distributed and centralised active distribution network control algorithms. The VPS concept can then be assessed in terms of its ability to ensure satisfactory network operation and meet operational goals.

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7 REFERENCES

The Electricity Safety, Quality and Continuity Regulations. (2002),

NTUA (2003 - 2005) *MicroGrids* [Online]. Available at: http://www.microgrids.eu/index.php?page=index (Accessed: November 2008).

NTUA (2006 - 2009) *More MicroGrids* [Online]. Available at: http://www.microgrids.eu/index.php?page=index (Accessed: November 2008).

Department of Trade and Industry, (2007) *Meeting the Energy Challenge, A White Paper on Energy.* (CM7124).

European Commission under the Intelligent Energy – Europe Programme (2008) *Catalogue of European Urban Wind Turbine Manufacturers*

[Online]. Available at: http://www.urban-wind.org/ (Accessed: November 2008).

Engineering Recommendation G83/1, Recommendations for the connection of small-scale embedded generators (up to 16 A per phase) in parallel with public low-voltage distribution networks. (2003), pp.60.

Benini, G., Castelli, A., Macu, E., Poncino, M. and Scarsi, R. (2000) "A discrete-time battery model for high-level power estimation", *Proceedings of Automation and Test in Europe Conference and Exhibition.* 27-30 March: pp. 35 - 39.

Bignucolo, F., Caldon, R., Prandoni, V., Spelta, S. and Vezzola, M. (2006) "The Voltage Control on MV Distribution Networks with Aggregated DG Units (VPP)", *Universities Power Engineering Conference, 2006. UPEC '06. Proceedings of the 41st International.* Newcastle upon Tyne, UK, 6-8 Sept.: pp. 187-192.

Bumby, J. R., Clarke, P. H. and Foster, I. (1985) "Computer modelling of the automotive energy requirements for internal combustion engine and battery electric-powered vehicles", *IEE Proceedings - Generation Transmission and Distribution,* 132 Pt. A, (5), pp. 265-279.

Bungay, E. W. G. and McAllister, D. (1997) *Electric Cables Handbook.* Blackwell Science Inc.

Caldon, R., Patria, A. R. and Turri, R. (2004) "Optimisation algorithm for a virtual power plant operation", *Universities Power Engineering Conference, 2004. UPEC 2004. 39th International.* 6-8 Sept.: pp. 1058 - 1062.

Cipcigan, L. M. and Taylor, P. C. (2007) "Investigation of the reverse power flow requirements of high penetrations of small-scale embedded generation", *IET Renewable Power Generation,* 1, (3), pp. 160 - 166.

Cipcigan, L. M., Taylor, P. C. and Trichakis, P. (2007) "The Impact of Small Scale Wind Generators on LV Distribution System Voltage", *International Conference on Clean Electrical Power, 2007. ICCEP '07.* Capri, Italy, 21-23 May: pp. 9 - 13.

Dielmann, K. and VanDerVelden, A. (2003) "Virtual power plants (VPP) - a new perspective for energy generation?" *Modern Techniques and Technologies, 2003. MTT 2003. Proceedings of the 9th International*

Scientific and Practical Conference of Students, Post-graduates and Young Scientists. Fachhochschule Aachen, Juelich, Germany, 7-11 April: pp. 18 - 20.

The Carbon Trust, Dutton, A. G., Halliday, J. A. and Blanch, M. J. (2005) *The feasibility of building mounted integrated wind turbines (BUWTs): Achieving their potential for carbon emissions reduction.* (2002-07-028-1-6).

The Carbon Trust & Department of Trade and Industry, Forbes, I., Luby, S. and Harrison, S. (2003) *Renewable Network Impact Study Annex 3: Distribution Network Topography Analysis.* (CT-2004-03).

Hadjsaid, N., Canard, J. F. and Dumas, F. (1999) "Dispersed generation impact on distribution networks", *Computer Applications in Power, IEEE,* 12, (2), pp. 22 - 28.

Hageman, S. C. (1993) "Simple PSpice Models Let You Simulate Common Battery Types", *EDN*, pp. 117 - 132.

Department of Trade and Industry, Ingram, S., Probert, S. and Jackson, K. (2003) *The impact of small scale embedded generation on the operating parameters of distribution networks.* London, UK: (K/EL/00303/04/01).

Jenkins, N., Allan, R., Crosley, P., Kirchen, D. and Strabac, G. (2000) *Embedded Generation.* London, UK.

Lasseter, R., Akhil, A., Marnay, C., Stephens, J., Dagle, J., Guttromson, R., Meliopoulous, A. S., Yinger, R. and Eto, J. (2004) *Integration of Distributed Energy Resources: The CERTS MicroGrid Concept.* (LBNL-50829).

Levi, V., Kay, M. and Povey, I. (2005) "Reverse power flow capability of tap-changers"*, 18th International Conference and Exhibition on Electricity Distribution, CIRED 2005.* Turin, Italy, 6 - 9 June: IEE, pp. 4-43.

Lyons, P. F., Taylor, P. C., Cipcigan, L. M., Trichakis, P. and Wilson, A. (2006) "Small scale energy zones and the impacts of high concentrations of small scale embedded generators"*, International Universities Power Engineering Conference; UPEC 2006.* Newcastle upon Tyne, 6 - 8 Sept.: pp. 128-132.

Osika, O., Degner, T., Hardt, C., Lange, H., Vandenbergh, M., Dimeas, A., Georgakis, D., Kamarinopoulos, A., Papathanassiou, S., Goodwin, A. J., Elmasides, K., Iliadis, G., Barnes, M., Fitzer, C. and Kariniotakis, G. (2005) *Description of the laboratory micro-grids.* (DH1).

Pudjianto, D., Ramsay, C. and Strbac, G. (2007) "Virtual power plant and system integration of distributed energy resources", *Proceedings of the IET - Generation, Transmission and Distribution,* 1, (1), pp. 10 - 16.

Schulz, C., Roder, G. and Kurrat, M. (2005) "Virtual power plants with combined heat and power micro-units", *Future Power Systems, 2005 International Conference on.* 16 -18 Nov.: pp. 5.

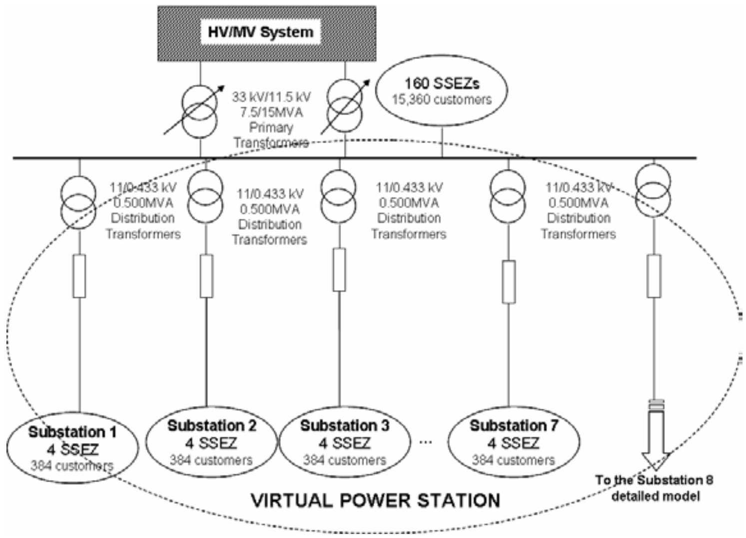
SMA. (2003) *Sunny Island - Installation and Operating Instructions. Bidirectional Battery Inverter SI4500 for stand-alone applications, V.3.1.* SMA Regelsysteme GmbH.

Stannard, N., Bumby, J. R., Taylor, P. and Cipcigan, L. M. (2007) "AC and DC aggregation effects of small-scale wind generators", *Renewable Power Generation, IET,* 1, (2), pp. 123.

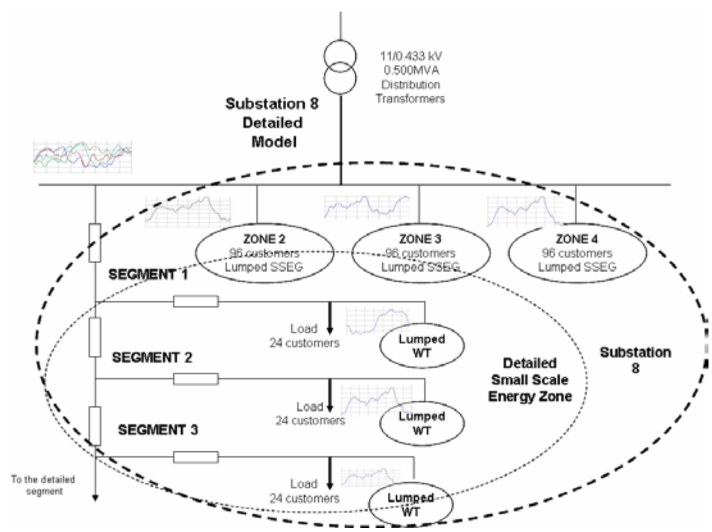
Ter-Gazarian, A. (1994) *Energy Storage for Power Systems.* IEE: London.

Trichakis, P., Taylor, P. C., Cipcigan, L. M., Lyons, P. F., Hair, R. and Ma, T. (2006) "An investigation of voltage unbalance in low voltage distribution networks with high levels of SSEG", *International Universities Power Engineering Conference; UPEC 2006.* Newcastle upon Tyne, 6 -8 Sept.: pp. 182-186.

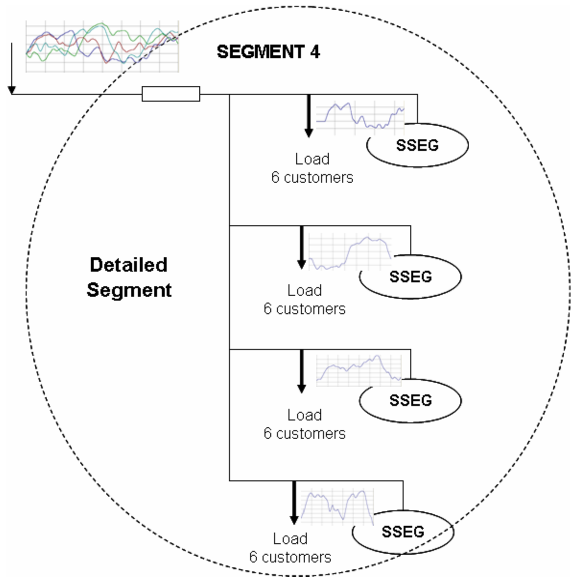
Figures



(a) VPS level



(b) Distribution substation and SSEZ levels



(c) Detailed LV segment level

Figure 3.1: *Hierarchical structure of the VPS model*

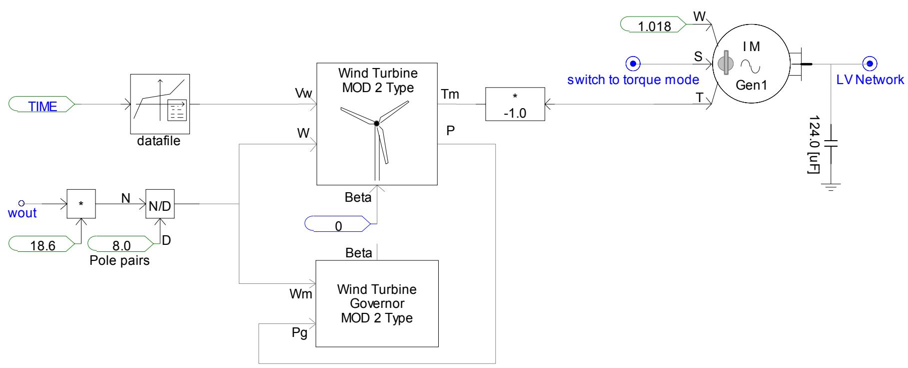


Figure 3.2: *Small Scale Wind Turbine Model*

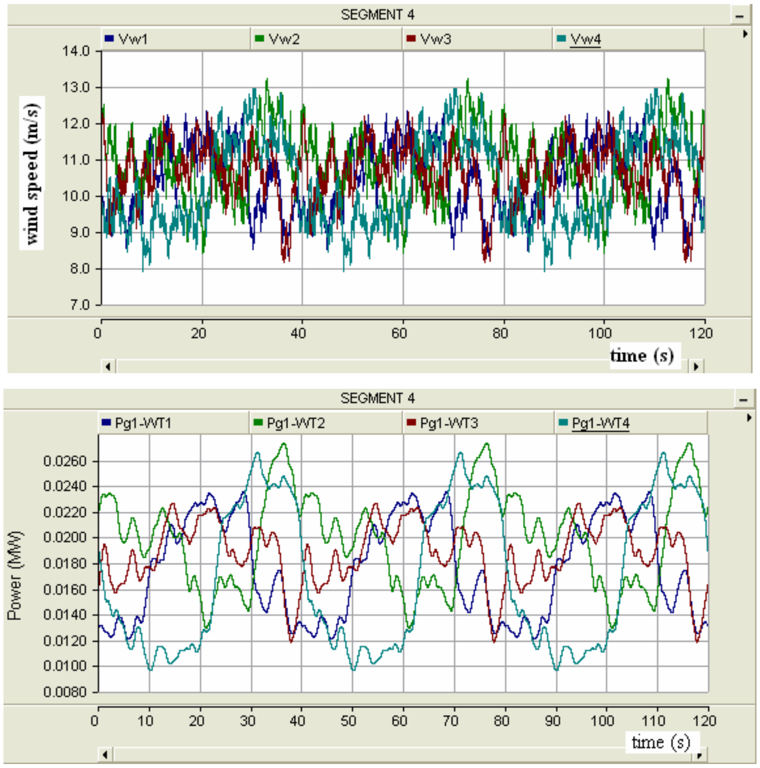


Figure 3.3: *Wind speed data and power output on each wind turbine (Segment 4)*

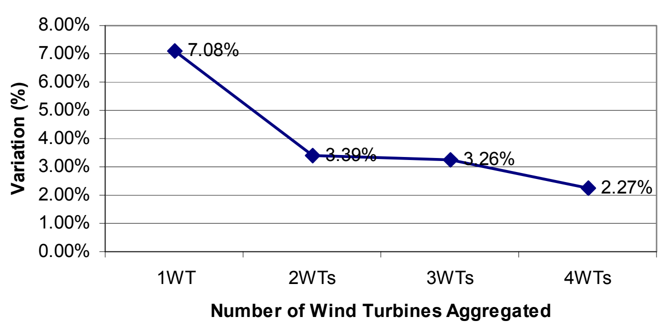


Figure 3.4: *Percentage variance of SSWT power output as aggregation is increased*

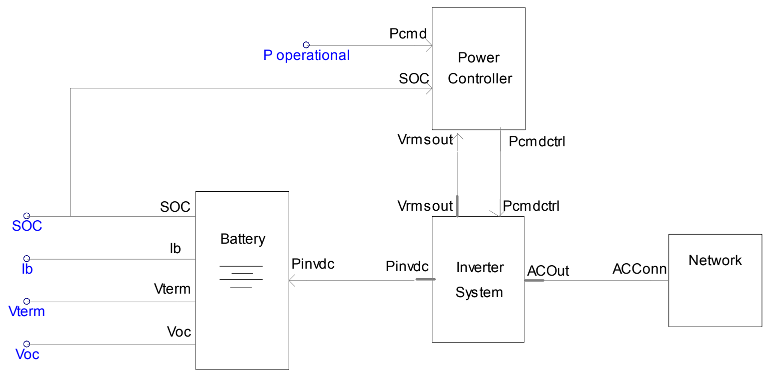


Figure 3.5: *Block diagram of the energy storage system model*

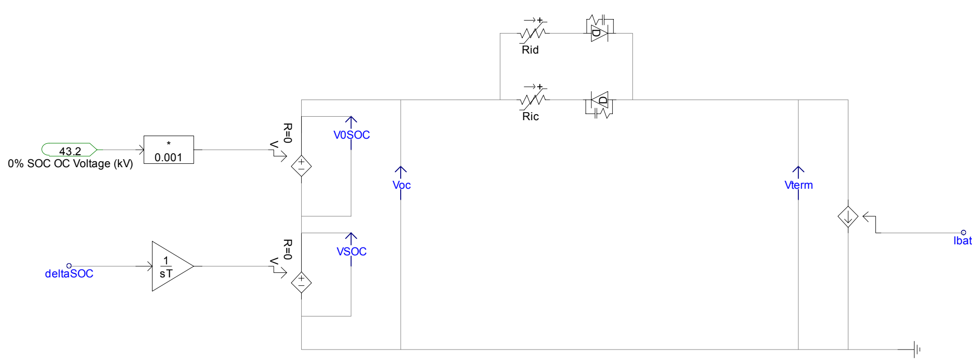


Figure 3.6: *PSCAD™ model of the lead acid battery*

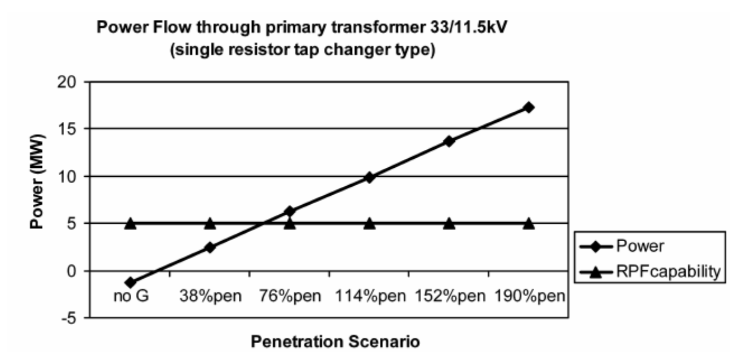


Figure 4.1 Reverse power flow through the primary transformer

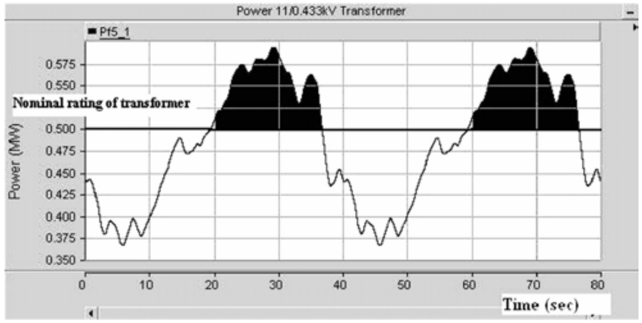


Figure 4.2 Power flow through 500kVA distribution transformer, 114% penetration

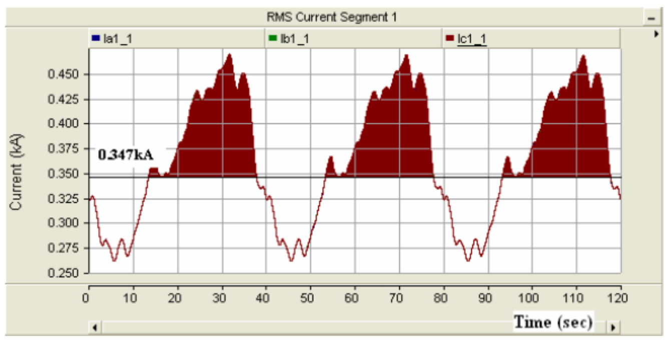


Figure 4. 3 Current flowing in 185 mm^2 LV cables, penetration 190%

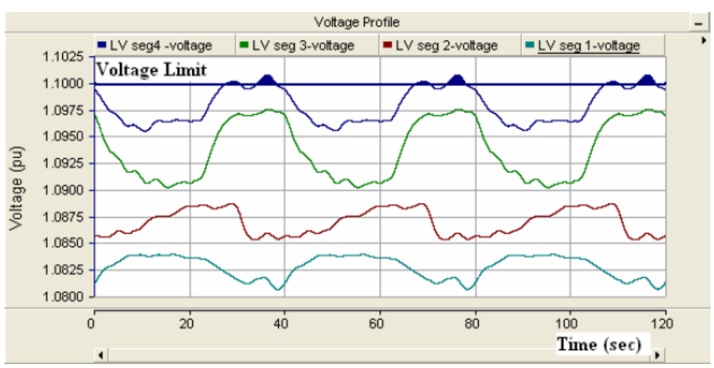


Figure 4.4 Voltage profile on each LV segment

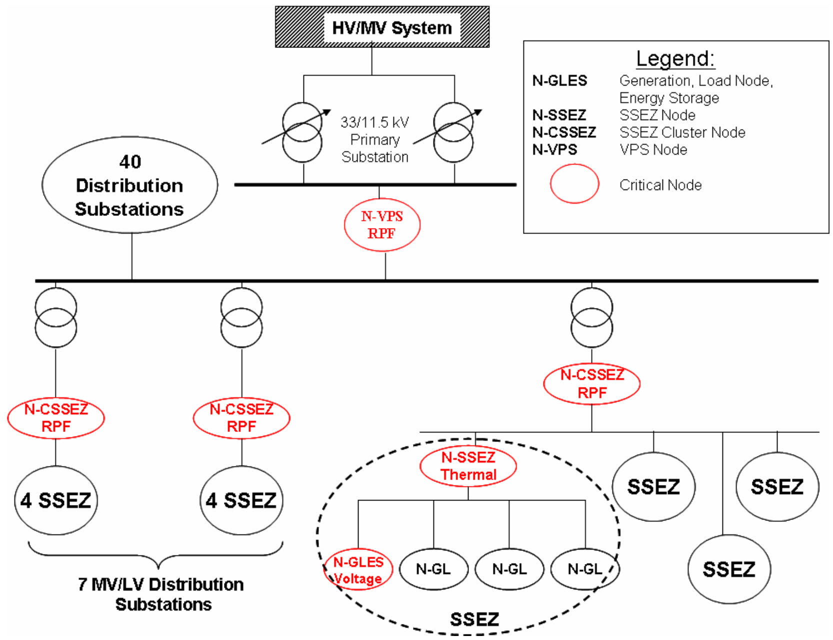


Figure 4.5: *Critical nodes in the system based on constraints identified in the modelling study*

APPENDIX A

Low Voltage distribution cable parameters used in PSCAD™/EMTDC™ model are presented in the following tables.

Table A.1: Cable parameters for185mm^2 Aluminium conductors

3-phase, CNE cable, 185mm^2 Aluminium conductors	
Resistance	0.164 Ω/km (ph) 0.164 Ω/km (N)
Reactance	0.074 Ω/km (ph) 0.014 Ω/km (N)
Cable length	2 LV segments each of 75m long

Table A.2: Cable parameters for 95mm^2 Aluminium conductors

3-phase, CNE cable, 95mm^2 Aluminium conductors	
Resistance	0.32 Ω/km (ph) 0.32 Ω/km (N)
Reactance	0.075 Ω/km (ph) 0.016 Ω/km (N)
Cable length	2 LV segments each of 75m long

Table A.3: Cable parameters for 35mm^2 Aluminium conductors

3-phase, CNE cable, 35mm^2 Aluminium conductor	
Resistance	0.851 Ω/km (ph) 0.9 Ω/km (N)
Reactance	0.041 Ω/km (ph) 0.041 Ω/km (N)
Total length	4 LV segments each of 30m long