GENAVC

Active local distribution network management for embedded generation

CONTRACT NUMBER: K/EL/00271/REP

URN NUMBER: 05/1588

The DTI drives our ambition of 'prosperity for all' by working to create the best environment for business success in the UK. We help people and companies become more productive by promoting enterprise, innovation and creativity.

We champion UK business at home and abroad. We invest heavily in world-class science and technology. We protect the rights of working people and consumers. And we stand up for fair and open markets in the UK, Europe and the world.

ACTIVE LOCAL DISTRIBUTION NETWORK MANAGEMENT FOR EMBEDDED GENERATION

CONTRACT NUMBER: K/EL/00271/REP
URN NUMBER: 05/1588

Contractor

Econnect Ltd

Prepared by

Dr Sara White

First published 2005

EXECUTIVE SUMMARY

Background

Traditionally, distribution networks have been operated as passive networks with uni-directional power flows. With the connection of increasing amounts of distributed generation, these networks are becoming active with power flowing in two directions, hence requiring more intelligent forms of management.

The report into issues for access to electricity networks published by the Ofgem/DTI Embedded Generation Working Group in January 2001 [1] called for new work in the area of active distribution network management. The report suggested an evolution from the present passive network control philosophy to fully active network control methods. In line with these recommendations Econnect is developing a new type of distribution network controller, called GenAVC™.

GenAVC™ is a controller for electricity distribution networks that aims to increase the amount of energy that can be exported onto the distribution networks by generating plants.

The UK is leading the world in electricity de-regulation and one aspect of this is the increasing demand for the connection of distributed generation. Active distribution network management is seen to be essential for networks to accommodate the levels of distributed generation that are predicted for 2010. The work being undertaken as part of this project is therefore at the forefront of international network management technology.

Purpose of GenAVC™

GenAVC™ is an innovative system which controls the control system of transformers at primary 33kV/11kV substations in distribution networks. Whilst trials have taken place at the 11kV level in the UK, the GenAVC™ system will operate at equivalent voltages elsewhere in the world. The purpose of the GenAVC™ system is to maintain the voltages of all the 11kV feeders connected to a primary 33kV/11kV substation within statutory limits. When a new generation plant is connected to the distribution network, voltages may be moved outside those limits. Installing the GenAVC™ system would enable the connection of such generation plants without the need for upgrade of the network which may otherwise be required to correct the voltage issues. GenAVC™ operates by making an estimation of the voltages on the network controlled by a primary substation transformer, using information about the state of the network collected from remote measurement units.

Objective of this project

- To design, build and install a GenAVC™ system at two trial sites in the UK
- To assess the performance of the GenAVC™ system on different network topologies and with different types of distributed generation (DG) plants

- To investigate the adaptation of GenAVC™'s control functionality to the network topology and the type of DG plant
- To integrate the GenAVC™ system with the operational requirements and communications facilities of two Distribution Network Operators (DNOs)

Work carried out

The project incorporated the following activities.

Selection of trial sites

Two sites were selected with the help of the DNOs, based on the criteria that DG plants were already connected to the network and that the connection points were sufficiently far from the primary substation. The first site is at Martham 33/11 kV primary substation, in the EDF Energy (EPN) network, located in South East England. Two existing generating plants, Bloodhill wind farm and Somerton wind turbine, are connected to Martham primary substation via two different 11kV feeders. The second site is at Morton Park 33/11 kV primary substation, in the United Utilities network located in North West England. This substation operates in parallel with another substation (Pirelli 33/11 kV). One existing generating plant, Great Orton wind farm, is connected to Morton Park primary substation via one 11kV feeder.

Hardware specification, design and selection

The hardware requirement for the GenAVC™ system was to monitor voltage and current magnitude and phase angle at local points (primary substation) and remote points (generation sites and other network nodes) in the network. Specification of hardware requirements included the number of measurements, the type of measurements (analogue/digital), the frequency of measurements and the calculation of associated parameters. The appropriate hardware was then selected from Qualitrol-Hathaway's (partner in this project) product range, and consisted of an IDM T3 data acquisition unit, an industrially hardened PC (local storage unit) and an Ethernet hub tray.

Software specification, design, coding and testing

The overall purpose of the GenAVC™ software is to estimate the value of the voltages at every node in the network connected to a primary 33kV/11kV substation, and to derive from this information a command to be sent to the control system of the transformer to which the GenAVC™ system is connected. The GenAVC™ software takes the measurement data obtained from data acquisition hardware units and processes them through a state estimation function in order to calculate the voltage at every node on the network. It then uses this calculated information to decide what command to send to the control system of the transformer. The GenAVC™ software was designed using industry standard methodologies for software development and followed established quality assurance procedures. The software can be uploaded to the GenAVC™ unit at each trial site using remote communications. The final version of the developed software was installed at both trial sites in early 2005.

Operation in 'open loop' mode

Following the building of the GenAVC™ system at Econnect offices, it was installed and commissioned at the two trial sites. Hardware units were installed both at the primary 33kV/11kV substations and at remote points on the network where the GenAVC™ system requires measurements. The GenAVC™ system was then left to run in 'open loop' mode, which means that the GenAVC™ system was estimating the voltages on the network but was not controlling the transformer at the primary substations. Monitoring information was collected during this 'open loop' period.

Installation of confirmatory measurement equipment

Independent confirmatory measurement equipment was installed at several points on the network at the two sites, and the independently measured voltage values were correlated with the GenAVC™ estimated voltage values. The results show very good correlation between the estimated voltages and the measured voltages.

Reporting of performance to DNO collaborators

For both trial sites, the performance during operation in 'open loop' mode was reported to the collaborating DNOs following a sufficient period of GenAVC™ operating in 'open loop' mode.

Results

Analysis of the GenAVC™ system performance indicated that the system was capable of enabling significant additional generation capacity to be connected to 11kV networks whilst maintaining voltages within statutory limits. The analysis of the performance of the GenAVC™ system during operation in 'open loop' mode at both sites demonstrated the following.

- The system passed the commissioning tests
- The software was stable
- The hardware performed appropriately
- The communications reliability was good. Further experience is required with GPRS communication technology
- The estimation functionality performed appropriately (state estimator converged)
- The state estimation results correlated very well with the confirmatory measurements

These results give Econnect confidence that GenAVC™ is able to estimate the voltage throughout the network to a quantifiable accuracy, showing that GenAVC™ can satisfactorily control the network to remain within desired operational limits. These results were such that Econnect Ltd was confident in the performance of the GenAVC™ system and was willing to recommend to both DNOs participating in the trial that the installed GenAVC™ systems should be switched to operation in 'close loop' mode. In 'close loop' operation, the GenAVC™ system would actively control the primary substation transformer(s) and therefore actively control the voltages in the DNO network.

Both DNOs agreed that the trials would progress to operation in 'close loop' mode. There is a requirement for minor work to be carried out before switching to operation in 'close loop' mode, which will take place after the end of this project. Work on this project will continue and it is expected that operation in 'close loop' mode will be achieved within a few weeks of the date of this report.

Conclusions

Operation of the GenAVC™ system at two trial sites was undertaken in 'open loop' mode throughout the first half of 2005. Initial problems with the estimation functionality (state estimation not converging) were resolved by correcting errors in the network information. Following these corrections, analysis of the GenAVC™ output information during operation in 'open loop' mode showed that estimation of voltage values was such that the voltages on the network would be maintained within statutory limits.

Correlation of the GenAVC™ estimated voltages and the voltages obtained from the confirmatory measurement equipment was carried out for both trial sites. Results for both trial sites show that the voltage values obtained from the confirmatory measurement equipment fall entirely within the upper and lower limits of GenAVC™ estimated voltage values for the vast majority of time samples.

During operation in 'open loop' mode, since the GenAVC™ system had not been connected to the transformer at the primary substation, it did not affect the operating voltages on the network. Voltage values on an existing network were not expected to go out of statutory limits. It was therefore necessary to reduce the limits that the GenAVC™ system uses as its statutory network limits in order to observe how GenAVC™ would control the network voltage if it was connected to the transformer at the substation. GenAVC™ output information confirms that, in 'close loop' operation, GenAVC™ would correctly maintain the voltages within these limits for both trial sites.

One issue to address regarding the GenAVC™ system performance is in relation to a minor failure observed during operations in 'open loop' mode. If input data is lost from a remote GenAVC™ measurement equipment, then currently the GenAVC™ system will continue to use the last measurement values it has received. The GenAVC™ system needs to be modified so that loss of information is detected and the GenAVC™ system suspends its control of the transformer until the information flow is restored.

Agreement was received from both DNOs to move from operation in 'open loop' mode to operation in 'close loop' mode provided that the following issues were resolved.

- Trial site at Martham
  - Modify the GenAVC™ system to suspend the GenAVC™ control of the transformer following a loss of communication with the wind farm at Bloodhill
  - Submit voltage profiles referenced to LV (in addition to the 11kV profiles already provided)

- Trial site at Morton Park
    - Modify the GenAVC™ system to suspend the GenAVC™ control of the transformer following a loss of communication with the wind farm at Great Orton
    - Resolve communications timing mismatch between the wind farm at Great Orton and the Morton Park primary substation

Recommendations

This project has clearly demonstrated the suitability of the GenAVC™ system for controlling voltages on an 11kV network. It is recommended that the technology employed here be developed for a full commercial product.

As a result of this work, several working prototype GenAVC™ systems have been designed, built and tested. Beyond the end of this project, the prototype equipment will remain on site at the two trial locations until such time as operation in 'close loop' mode has been achieved and a significant period of satisfactory operation in 'close loop' mode has taken place.

The next steps will be to

- Demonstrate the long-term operation of the GenAVC™ system
- Develop the functionality of the GenAVC™ system
- Adapt the GenAVC™ system to operate on alternative hardware platforms
- Investigate further communications technology to improve the reliability of communication with GenAVC™ remote data acquisition units and to enable remote access to confirmatory measurement equipment
- Undertake an approvals process as appropriate to the client base for the product

The concept of the GenAVC™ system has the potential to mitigate voltage rise issues and to enable an increased level of distributed generation to connect to the distribution network. This system will potentially enable distributed generation plants to connect to the 11kV level with connection costs lower than if the GenAVC™ was not installed, and to defer reinforcement costs for the DNO.

TABLE OF CONTENTS

1 INTRODUCTION

Background

Traditionally, distribution networks have been operated as passive networks with uni-directional power flows. With the connection of increasing amounts of distributed generation (DG), these networks are becoming active with power flowing in two directions, hence requiring more intelligent forms of management.

The report into issues for access to electricity networks published by the Ofgem/DTI Embedded Generation Working Group in January 2001 [1] called for new work in the area of active distribution network management. The report suggested an evolution from the present passive network control philosophy to fully active network control methods. In line with these recommendations Econnect is developing a new type of distribution network controller, called GenAVC™.

The UK is leading the world in electricity de-regulation and one aspect of this is the increasing demand for the connection of distributed generation. Active distribution network management is seen to be essential for networks to accommodate the levels of distributed generation that are predicted for 2010. The work being undertaken as part of this project is therefore at the forefront of international network management technology.

GenAVC™ is a new controller for electricity distribution networks that aims to increase the amount of energy that can be exported onto the distribution networks by generating plants. Econnect had previously conducted an eighteen-month feasibility study into GenAVC™, supported by a SMART award. The study concluded that it was technically feasible to implement a first generation GenAVC™ system, which would control the voltage of the part of an 11 kV network (or equivalent voltage level) that is supplied by a single primary substation.

Aims and objectives

The overall aim of the project was to demonstrate the ability of the first generation GenAVC™ system to control the voltage in a part of a distribution network with distributed generation plants already connected.

This was to be achieved by installing two GenAVC™ pilot systems, with the following key aims.

- To design, build and install a GenAVC™ system at two trial sites in the UK
- To assess the performance of the GenAVC™ system on different network topologies and with different types of distributed generation (DG) plant
- To investigate the adaptation of GenAVC™'s control functionality to the network topology and the type of DG
- To integrate the GenAVC™ system with the operational requirements and communications facilities of two Distribution Network Operators (DNOs)

Each installation consisted of a control unit installed at a 33/11 kV substation, which communicated with measurement equipment installed at other locations on the network supplied by that substation. These other locations were at the point of connection of any existing distributed generation plants and at points on the network where large voltage variations were expected.

The main objectives of the project were as follows.

- Complete a detailed design specification and costing for the installation of a pilot GenAVC™ system at each trial site
- Construct and test two GenAVC™ systems for installation at the trial sites and one GenAVC™ system for development at Econnect offices
- Install and commission two GenAVC™ systems at the trial sites. This would require contractual frameworks to be set up between the project collaborators, the DNOs and the distributed generation developers
- Complete monitoring of operations in 'open loop' mode and finalise the GenAVC™ system. During operation in 'open loop' mode each GenAVC™ system would calculate what command would be issued to the control equipment of the transformer at the primary substation, but the GenAVC™ system would not control that equipment. Following evaluation of this phase, any required modification to the GenAVC™ system would be carried out
- Agree with the participating DNOs to change the operation of the GenAVC™ systems from 'open loop' to 'close loop' mode and carry out that change in operating mode
- Monitor the operation in 'close loop' mode and prepare a final report on the performance of the GenAVC™ system

Benefits

The potential benefits of the GenAVC™ system have been identified as follows.

- Increased distributed generation capacity on existing distribution networks. GenAVC™ will greatly increase the capacity of distributed generation that can be connected to 11 kV networks. Studies undertaken prior to this project had indicated, for example, that at one trial site the GenAVC™ system would enable the level of distributed generation connection to that section of the network to be more than doubled. This represents a significant contribution towards meeting the 2010 UK government targets for renewable energy and combined heat and power (CHP) generation
- Increased number of small distributed generation projects connected to the distribution network. GenAVC™ will provide a cheaper connection than the traditional methods for overcoming voltage issues, such as installing cables and overhead lines with larger conductors. This will allow an increased number of small distributed generation projects to be connected, which would otherwise not be economically viable

Previous work
Econnect had been granted a DTI SMART award in February 2001 to conduct a feasibility and design study for the GenAVC™ system. This work identified the potential for two types of GenAVC™ systems.

Both types would include a real-time control program running on a hardware unit that would receive information from measurement equipment over communication links. The first type would control a single voltage control device at a 33/11 kV substation to which distributed generation was connected. The second type would dispatch distributed generators and would schedule controls for devices including substation voltage control devices, circuit breakers and reactive power compensators.

The study which resulted from the SMART award project concluded that it was technically feasible to implement a first generation device, based on the first type described above, which would control the voltage of the part of an 11 kV network that is supplied by a single primary substation. The study found that this product could move into the implementation stage of development immediately.

Project Collaborators
The collaborators on the project described in this report were Econnect Ltd, Qualitrol Hathaway, the University of Manchester, United Utilities and EDF Energy. Econnect Ltd was the project manager for the project and provided the background intellectual property and the majority of the software development. Qualitrol Hathaway provided the hardware equipment and some of the software development, and organised the communication systems at the two trial sites. The University of Manchester (formally UMIST) was subcontracted to carry out simulation work. United Utilities and EDF Energy both provided trial sites for the GenAVC™ prototype systems, information about their network, and installation and commissioning assistance and supervision. Eon UK (previously Powergen Renewables) and Cumbria Windfarms assisted in allowing their wind farm sites to host the remote GenAVC™ measuring equipment.

Acknowledgements
The project team is pleased to acknowledge the very valuable support that the United Utilities and EDF Energy teams have provided to this project. We would also like to acknowledge the support to this project of the owner of the existing generation plants, Eon UK and Cumbria Windfarms.

This project has been partly funded by the UK Department of Trade and Industry, and this support is also acknowledged.

Project overview
The project plan incorporated the following activities.

- Selection of trial sites
- Hardware specification, design and selection
- Hardware procurement, installation and commissioning

- Software specification, design, coding and testing
- Simulation of network performance with and without the GenAVC^{TM} system
- Procurement and installation of confirmatory measurement equipment
- Monitoring and analysis of operation in 'open loop' mode at the two trial sites
- Reporting of performance of operation in 'open loop' mode to collaborating DNOs
- Obtaining agreement from collaborating DNOs to change from operation in 'open loop' mode to operation in 'close loop' mode
- Monitoring and analysis of operation in 'close loop' mode at the two trial sites
- Final reporting on the project activities

<u>Selection of trial sites</u>

The two trial sites used in this project were selected with the help of the collaborating DNOs. The criteria applied for selection were that the chosen section of network would need to have DG plants already connected and that the connection points of these plants would need to be sufficiently far from the primary substation. The distance was important as voltage rise issues are much more likely to arise for DG plants connected to an 11kV feeder at a point far from the primary substation than for DG plants connected to a point close to the primary substation.

This was to ensure that the GenAVC^{TM} system would be operating under a scenario as close as possible to its final application environment. The existing 11kV networks selected already had DG plants connected, so no voltage issues were expected on these networks. This made the trial of the GenAVC^{TM} system safe. At the same time it was possible to simulate the final application environment where the GenAVC^{TM} would be installed, which would be a network where the connection of a new DG plant would cause the voltage levels to go outside statutory limits.

The first site selected is at Martham 33/11 kV primary substation, in the EDF Energy (EPN) network. It is located in the middle of Martham village, near Great Yarmouth in South East England. Martham primary substation operates as a standard 33/11kV substation with two 15MVA transformers, although two 7.5MVA transformers are connected in parallel on one side, with a single 15MVA transformer on the other side. In total, there are 5 outgoing 11kV circuits feeding a mixture of small villages and rural properties. There are two existing wind generation plants, each connected to a different circuits. One of these, Somerton, is a single 1.6MW wind turbine (which did not have remote measuring equipment installed at site as part of the GenAVC^{TM} trial). The second, Bloodhills, consists of ten wind turbines, each rated at 225kW (total 2.25MW), and hosts remote voltage, current and phase angle measuring GenAVC^{TM} equipment communicating with the GenAVC^{TM} equipment at the Martham Primary substation.

The second site selected is at Morton Park 33/11 kV primary substation, in the United Utilities network. It is located on the edge of the western suburbs of Carlisle in North West England. It contains two primary 11MVA transformers with six outgoing 11kV circuits. Two further 11kV feeders connect Morton Park primary substation to the nearby Pirelli Primary Substation, to provide security of supply to this single 7.5MVA transformer primary substation. Morton Park supplies a range of suburban and rural housing and also some industrial loads (e.g. a milk processing plant). Pirelli primary substation supplies a tyre factory. There is one existing wind generation plant connected to Morton Park primary substation. The wind farm at Great Orton consists of six wind turbines, each rated at 660kW (total 3.9MW), and hosts remote voltage, current and phase angle measuring GenAVC™ equipment communicating with the GenAVC™ equipment at the Morton Park substation.

2 GenAVC™ SYSTEM DESIGN

Overall system design

Active voltage control techniques can help DNOs to achieve the connection of the level of generation necessary to meet government targets for renewable energy without other types of costly network reinforcement, whilst maintaining compliance with the Electricity Safety, Quality and Continuity Regulations (ESQCR) [2]. A key element of any such technique is real time feedback from remote locations on the network, a task compounded in difficulty by the lack of existing monitoring equipment on distribution networks at the 11kV voltage level.

Econnect Ltd has developed an advanced automatic voltage control (AVC) solution, GenAVC™, which helps DNOs to control their networks by maintaining electricity supply standards and reducing the cost of required network reinforcements.

Figure 1 shows a typical application of this advanced AVC solution, with Remote Terminal Units (RTUs) measuring voltage values which are placed at a few key locations on the network. These RTUs also gather information on power flows at generation sites. The measurements from the RTUs are communicated to a control unit located at the primary substation.

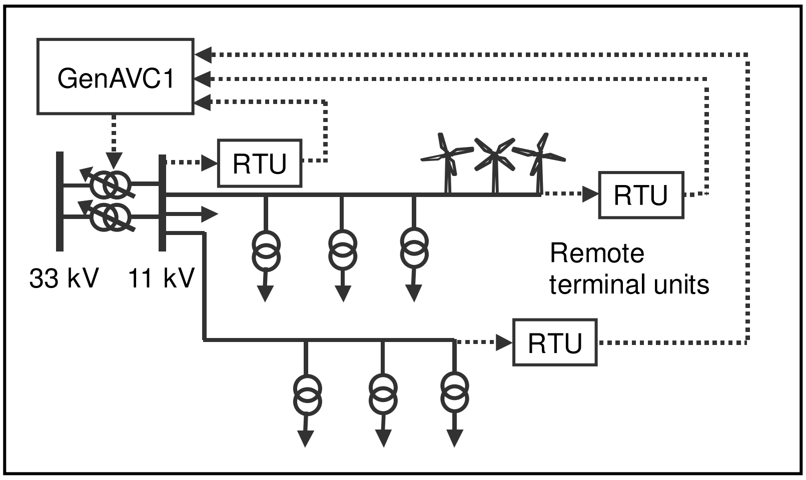

Figure 1 – Example of the GenAVC™ system on an 11kV network

This advanced AVC system combines these measurements with a model of the network to estimate the current state of the network, particularly the voltage profiles on each circuit connected to the primary substation. The estimated voltages are checked against acceptable voltage limits held within the model. Should an estimated voltage value approach these limits, a control signal is passed to the AVC relay of the transformer to adjust its voltage set point appropriately. The consequent tap change operation on the primary transformer results in all voltages remaining within acceptable limits. The state estimation of the network is constantly updated, which ensures all tap change operations are appropriate responses to the real time conditions of the network as a whole. Thus, a change in level of a wind farm's power output or of the local demand can be accommodated on the network without voltage levels exceeding statutory regulations.

The recent publication of the document 'ETR126' by the Energy Networks Association (ENA) [3], referring to voltage management for networks incorporating distributed generation, identifies the approach described above as a viable solution to allow a higher capacity of generating plants to connect to the distribution network than could otherwise be accommodated using conventional techniques.

The GenAVC™ system design comprises three key components.

- Hardware
- Communications
- Software

A simplified diagram of the hardware and software components of the GenAVC™ system is shown in Figure 2. This diagram shows an LSU (Local Storage Unit) taking measurements at a main substation and another LSU sending data from a remote site.

At a remote site there is one DAU (Data Acquisition Unit) collecting local data using a CSS (Continuous Slow Scan) function, which is connected to the LSU. The LSU software records this data and transmits it, using one of several types of communications media, to the LSU at the main substation.

At the main substation there is one DAU connected to the LSU. This LSU collects local and remote data and sends this data to the RSU and GenAVC™ software.

Local and remote data is utilised by the GenAVC™ software to estimate voltage profiles on each circuit connected to the primary substation. The estimated voltages are checked against acceptable voltage limits held within the model. Should an estimated voltage value approach these limits, a command output is sent by the GenAVC™ software to a programmable logic controller (PLC). The PLC is connected to the primary substation AVC relays, allowing the GenAVC™ system to control the target voltage of the transformer AVC.

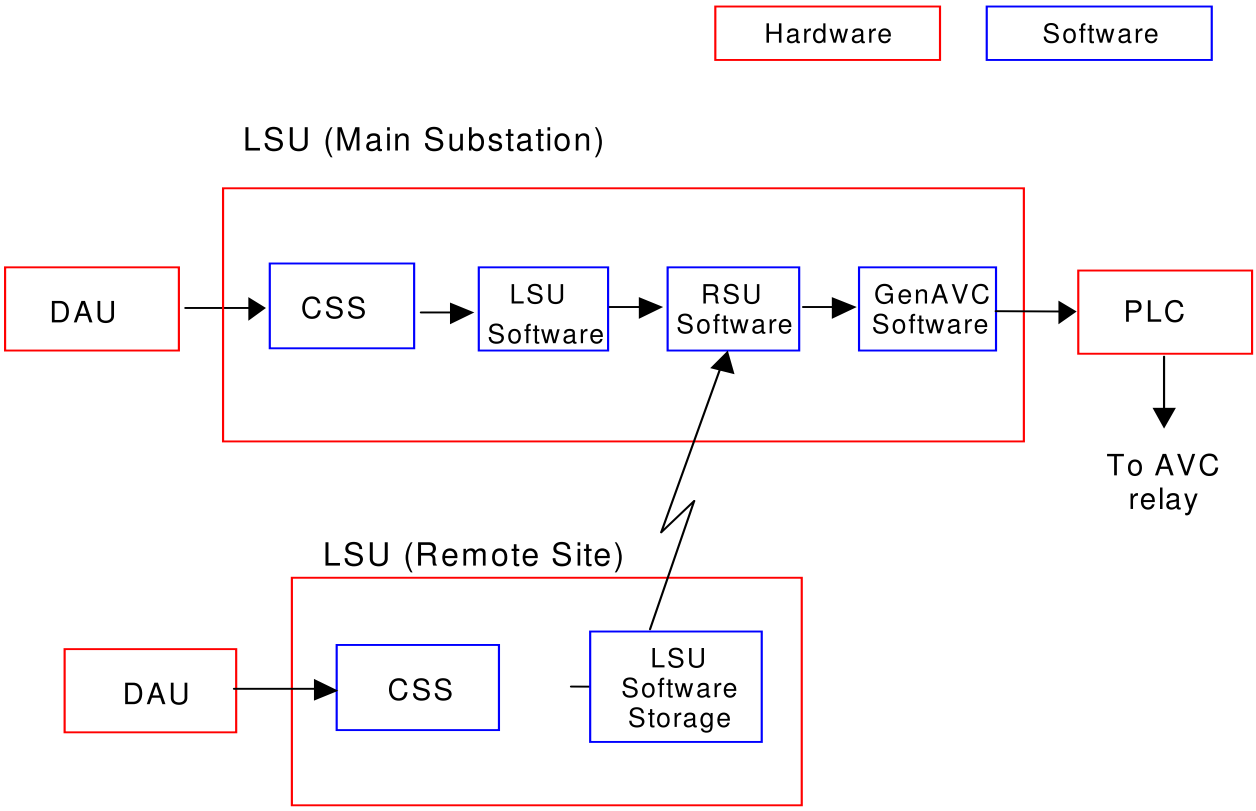

Figure 2 - Simplified diagram of the GenAVC™ system hardware and software components

<u>Hardware design</u>

The general requirement for the hardware design is to acquire a number of measurements from local and remote sites and calculate single-phase real and reactive power quantities. These calculations are logged, time stamped and made available to the GenAVC™ state estimation software.

The hardware must be immune from the effects of the type of severe electrical disturbances that can be experienced in a substation environment.

DAU

A Data Acquisition Unit (DAU) is a hardware device that allows the GenAVC™ system to collect electrical measurements from the network. There is one local DAU at the substation where the GenAVC™ system is installed, and several remote DAUs at other points on the network, where measurements are to be transmitted back to the LSU unit in the primary substation.

Each DAU can be connected to multiple voltage transducers (VTs) and current transducers (CTs). Measurements from these transducers are constantly logged, and are retrieved when requested by the RSU software, using a communication system.

The following measurements are logged.

- Line-to-line voltage: rms magnitude and phase angle
- Current: rms magnitude and phase angle

The voltage magnitude measurements are used directly by the GenAVC™ state estimation software, along with real and reactive power values, which are calculated by the software from the voltage and current magnitudes and phase angles.

LSU

The Local Storage Unit (LSU) is an industrial standard PC running the Linux operating system.

The LSU is the platform on which the GenAVC™ software is executed. It also provides storage for configuration files, log files and data from the DAUs. The LSU communicates with the following.

- The local DAU
- The programmable logic controller (PLC)
- The remote DAUs
- Remote PCs (used for monitoring and upload of software upgrades)

PLC

The programmable logic controller (PLC) consists of a set of software-controlled electronic relays, which are connected to the primary substation AVC relays, allowing the GenAVC™ system to control the target voltage of the transformer AVC.

The PLC also signals its relay status to the GenAVC™ software to confirm that the hardware has performed the requested actions.

The PLC has a failsafe mode, which, should it receive invalid or no regular signals from the GenAVC™ software, results in the PLC automatically disconnecting from the AVC relay of the transformer. The transformer AVC relay then reverts to the normal mode of operation which it would adopt when the GenAVC™ system is not connected. In the event of any failure in the GenAVC™ system, the PLC will place itself in this failsafe state within a short time of any failure.

Additional safety switch

In addition to the fail safe mode of the PLC described above, there is a switch between the PLC relays and the AVC relays which enables an engineer to disconnect and re-connect the GenAVC™ system from and to the transformer. Disconnection of the GenAVC™ system using the safety switch causes the transformer AVC relay to revert to its normal mode of operation which it would adopt when the GenAVC™ system is not connected. The safety switch can be operated as follows.

- Locally, by an engineer activating it manually on-site in the substation
- By an engineer or an automatic system activating it remotely via the substation SCADA (Supervisory Control and Data Acquisition) system

Communication design

This section describes the communication technologies that can be applied to the GenAVC™ system. The design of the communication system is site specific and depends on the distance between the different LSUs installed on the network.

Ethernet

Ethernet uses "Cat 5" cables containing copper wires to interconnect devices in a local area network. It is cheap, commonly available and allows high-speed data transfer.

The primary substation and the remote measurement locations are each provided with a local area network interconnecting all devices at their individual locations using a 10BaseT Ethernet hub.

Wireless Ethernet Bridge

A wireless Ethernet bridge uses radio communications to interconnect remote Ethernet devices. Sites up to 15km apart can be connected with externally mounted antennas.
This is a simple and inexpensive solution, but use of this technology is limited by terrain, as line of sight communication is required between the two ends of the link.

Pilot Wire Ethernet Bridge

A pilot wire Ethernet bridge employs a router to organise signals between remote devices interconnected by a pilot wire cable which is run between the sites.

This arrangement is commonly used where suitable twisted-pair pilot cables already exist between the sites.

GPRS Router

A GPRS router enables communication using the General Packet Radio Service (GPRS), which allows data transfer over mobile phone networks (Global System for Mobile Communications, GSM).

The equipment itself is relatively inexpensive. However, there are ongoing costs for transferring data over the GPRS network. There is a potential vulnerability to the non-guaranteed connection afforded by this type of communication link, especially if the local GSM network coverage incorporates low redundancy.

Communications design for the two trial sites

The two trial sites used for this project had different communications design and employed several of the communication technologies described above. The communications system used for the two trial sites is shown in Figures 3 and 4.

For the trial site on EDF Energy's network, a wireless LAN (local area network) is used between the LSU at Martham substation and the LSU at Bloodhill wind farm.

For the trial site on United Utilities' network, GPRS is used between the LSU at Morton Park substation and the LSU at Great Orton wind farm. In addition, a pilot wire Ethernet bridge is used between the Morton Park and Pirelli substations.

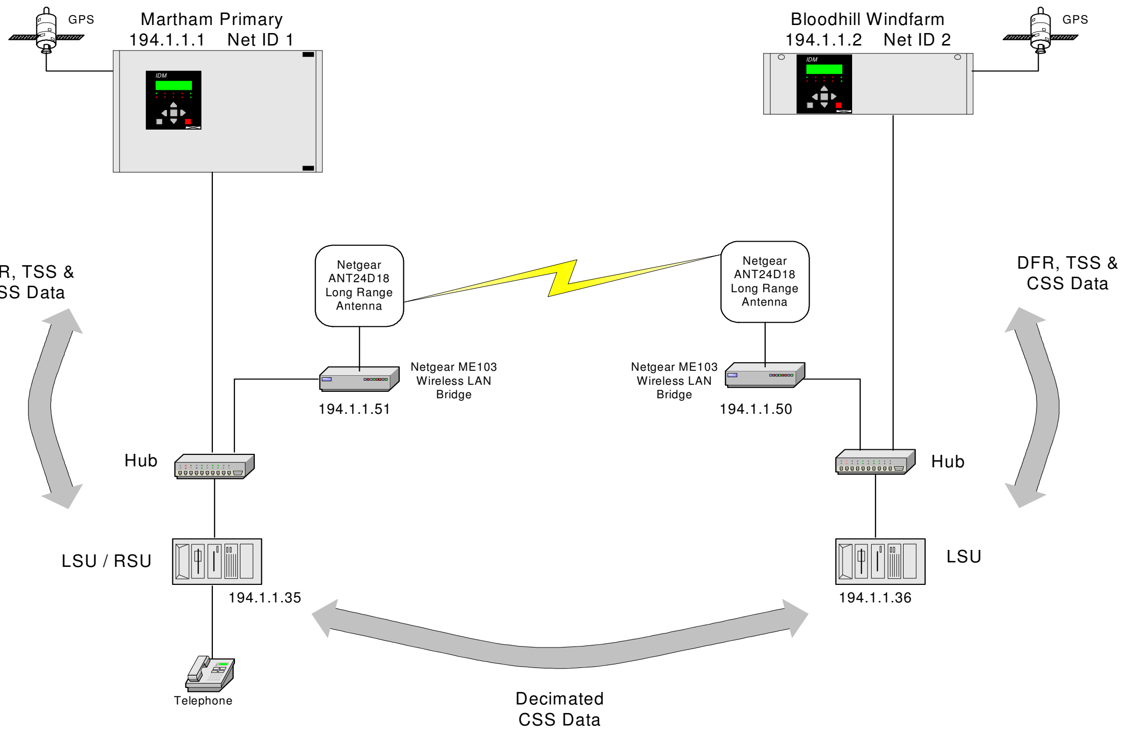

Figure 3 – Communications system for EDF Energy trial site at Martham

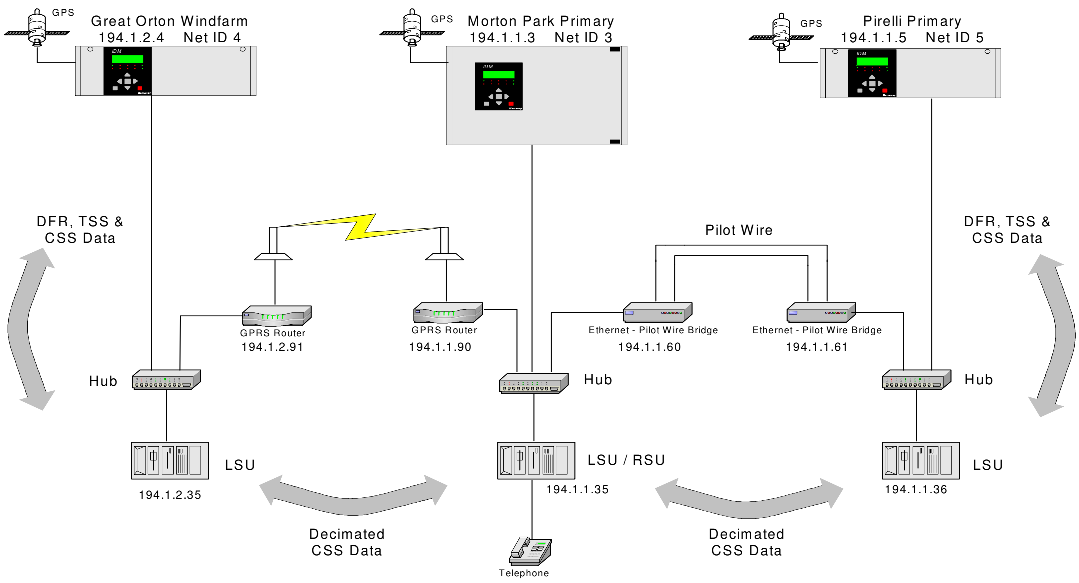

Figure 4 – Communications system for United Utilities trial site at Morton Park

Software design

The overall purpose of the GenAVC™ software is to estimate the value of the voltages at every node in the network connected to a primary 33kV/11kV substation, and to derive from this information a command to be sent to the control system of the transformer to which the GenAVC™ system is connected. The GenAVC™ software takes the measurement data obtained from the data acquisition hardware units (DAU) and processes them through a state estimation function in order to calculate the voltage at every node on the network. It then uses this calculated information to decide what command to send to the PLC, which forwards them to the AVC relay of the transformer.

A simplified block diagram of the GenAVC™ software is shown in Figure 5. The software consists of four main modules.

- Measurement Processing: this module uses static network information data from a file stored on the LSU unit, together with actual network measurements from the DAUs, to create a measurement vector for use by the state estimation
- State Estimation: this module calculates the state of every node on the network from the values of the measurement vector
- Automatic Voltage Reference Setting (AVRS) Control: this module compares the voltages from the state estimation module with network limits and decides whether a target adjustment is necessary
- Output and PLC Driver: If a target adjustment is required this module translates the required action into the correct form for the PLC to forward a

signal to the AVC relay of the transformer, which may result in a tap-change action on the transformer

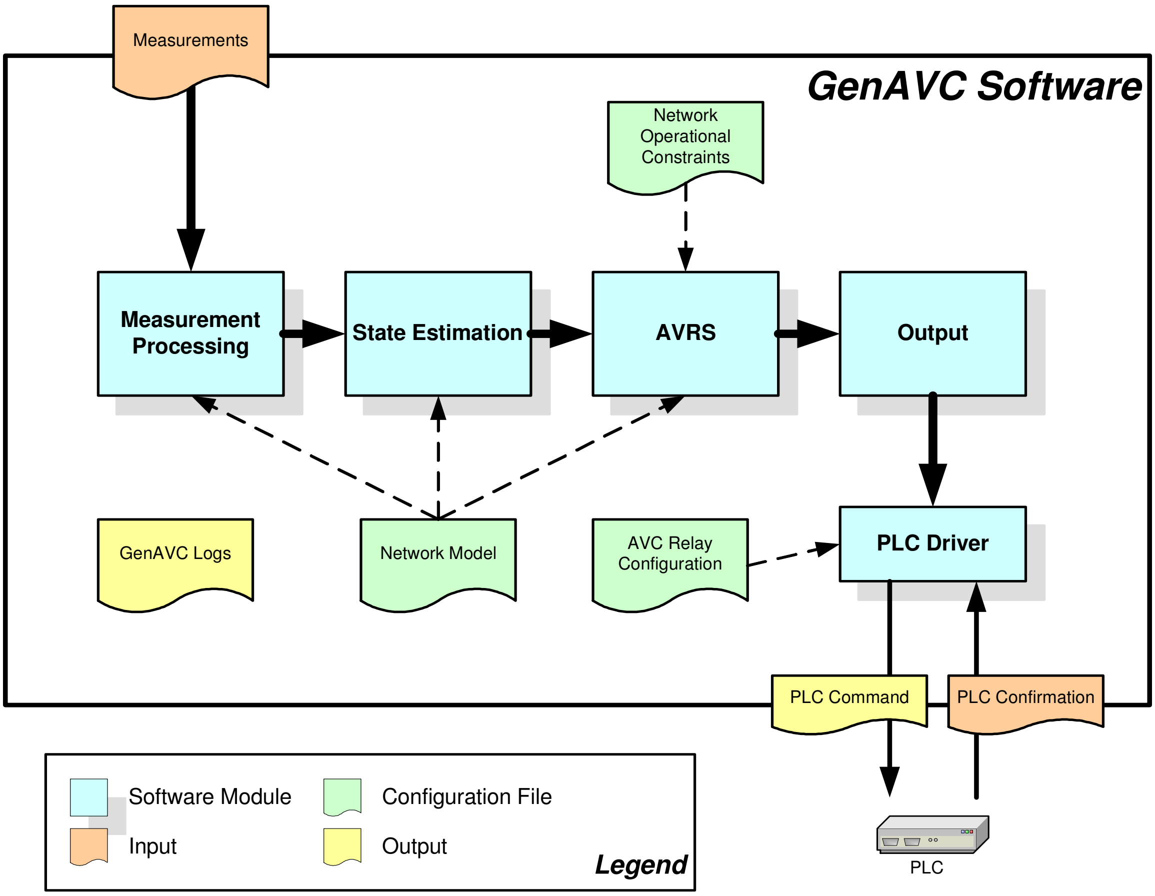

Figure 5 – Block diagram of GenAVC™ software

3 GenAVC™ HARDWARE TESTING AND INSTALLATION

Hardware at Martham trial site

Martham primary substation hardware

Martham primary is the primary substation whose AVC relays are controlled by the GenAVC™system. The following components are installed at the substation.

- Local DAU
- LSU running the GenAVC™ software, with a built in modem for dial-up connection
- PLC to control AVC target voltage selection relays
- Wireless Ethernet Bridge with antenna
- Ethernet Hub

Bloodhill wind farm hardware

Electrical measurements are also taken at Bloodhill wind farm where the following equipment is installed.

- Remote DAU
- LSU to collect and send data
- Wireless Ethernet Bridge with antenna
- Ethernet Hub

Figure 6 - GenAVC™ installation at Martham primary substation, adjacent to substation panels

Figure 7 - Remote measurement equipment at Bloodhill wind farm

Hardware at Morton Park trial site

Morton Park substation hardware

Morton Park is the primary substation whose AVC relays are controlled by the GenAVC™ system. The following components are installed at the substation.

- Local DAU
- LSU running the GenAVC™ software, with a built in modem for dial-up connection
- PLC to control AVC target voltage selection relays
- GPRS Router
- Ethernet – Pilot Wire Bridge
- Ethernet Hub

Pirelli substation hardware

Pirelli is the primary substation operating in parallel with the Morton Park substation. Its AVC relay follows those at Morton Park when their targets are adjusted by the GenAVC™ system. The following components are installed at the substation.

- Local DAU
- LSU to collect and send data
- Ethernet – Pilot Wire Bridge
- Ethernet Hub

Great Orton wind farm hardware

Electrical measurements are also taken at Great Orton wind farm where the following equipment is installed.

- Remote DAU
- LSU to collect and send data
- GPRS Router
- Ethernet Hub

Figure 8 - GenAVC™ installation at Morton Park, adjacent to two Automatic Voltage Control (AVC) relays

4 SOFTWARE DEVELOPMENT, TESTING AND INSTALLATION

Software development

The two parts to the software system are

- The Qualitrol Hathaway software modules: the LSU software, the RSU software and the CSS software
- The Econnect GenAVC™ software

The two parts were developed independently by Qualitrol Hathaway and Econnect. They were then successfully integrated to create the whole software system that underlies the GenAVC™ system.

Software testing

The GenAVC™ was designed using industry standard methodologies for software development and followed established quality assurance procedures. It consists of several modules which were built and tested independently.

A step by step integration of the modules was then carried out with integration tests carried out at each stage. The software created after each integration step was first tested on a development machine at Econnect using a test harness. It was then uploaded to a LSU GenAVC™ unit at the Morton Park substation to verify correct operation on-site.

The successful completion of the tests for the final integration step provided a fully tested version of the GenAVC™ software.

Software installation

Final software installation of the integrated and tested GenAVC™ software occurred in February 2005 for the Morton Park site (United Utilities) and in March 2005 for the Martham site (EDF Energy). Following the final software installation and software commissioning tests, the GenAVC™ system was left operating in 'open loop' mode. Operation in 'open loop' mode involved the installation and operation of all hardware and software for the GenAVC™ system, with the connection between the PLC and the AVC relay of the transformer disabled. Therefore all operational functions of the GenAVC™ software and hardware could be tested and monitored, without final control of the AVC relay.

GenAVC™ hardware and software commissioning tests

The purpose of these tests was to check that the GenAVC™ system operated correctly after being installed and operated in 'open loop' mode. The outline of the testing strategy adopted is shown in Figure 9.

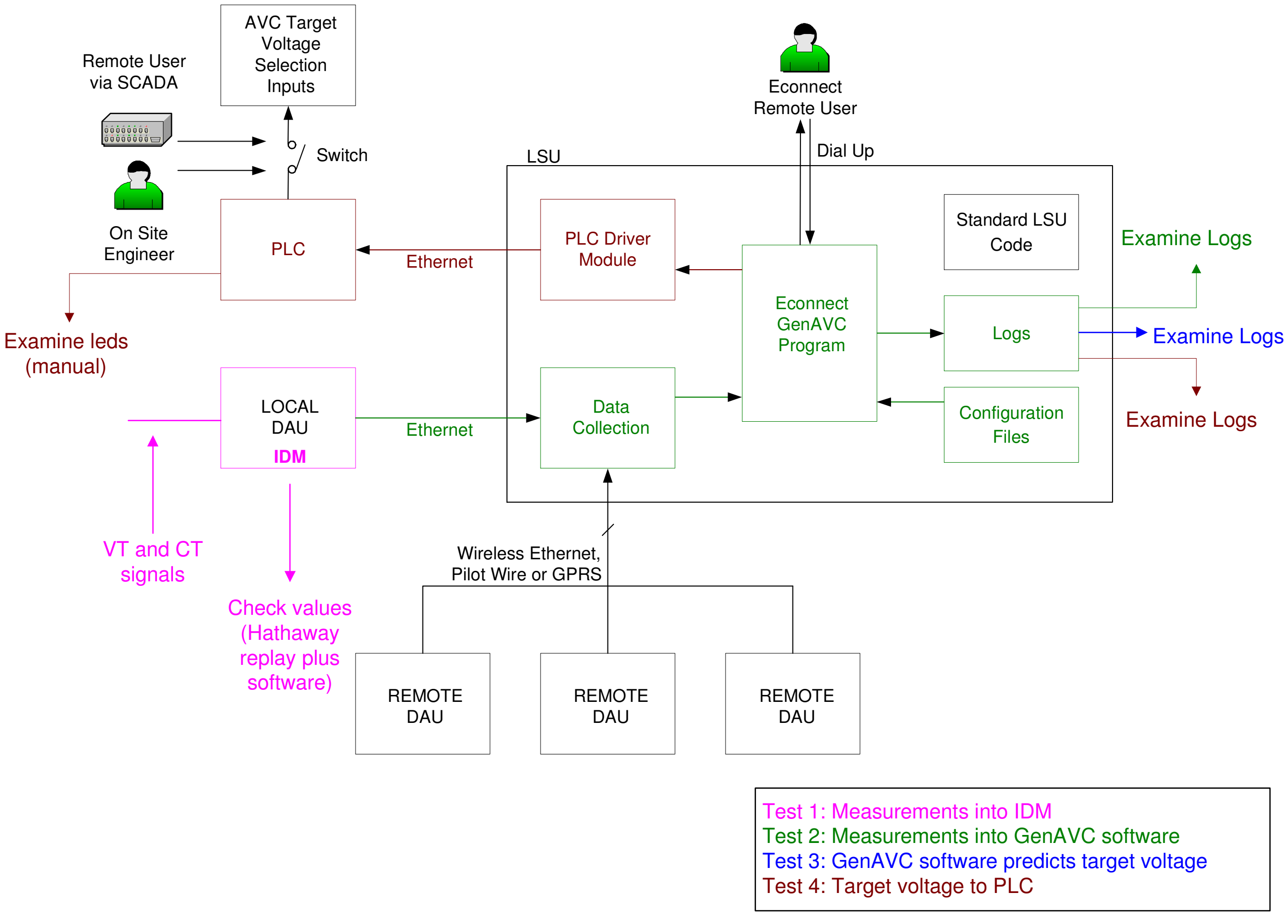

Figure 9 – Commissioning testing strategy

Four types of tests were carried out to check that the GenAVC™ system, including both hardware and software elements, was operating correctly. In addition, failure conditions were checked to ensure that where the GenAVC™ system fails, the AVC relay returns to normal operating mode without control from the GenAVC™ system.

The commissioning tests were completed for the Morton Park trial site on 18th March 2005 and on 4th May 2005 for the Martham trial site. All tests were passed successfully, apart from a minor failure observed during the failure condition tests. The GenAVC™ system recorded a loss of input when the DAU was powered down but the GenAVC™ system did not suspend its operation. A simple amendment to the software will be carried out to ensure that the GenAVC™ system suspends its operations some short time after a loss of data input. This amendment is part of the activities that will be completed prior to switching to operation in 'close loop' mode.

The process for installing and commissioning a future GenAVC™ system will follow the same steps as are detailed above. After all of the commissioning tests have been completed satisfactorily, the GenAVC™ system would be switch to operation in 'open loop' mode. When correct operation in 'open loop' mode is confirmed, the connection between the GenAVC system and the AVC relay of the transformer would be enabled, and the GenAVC™ system would enter full service and operate in 'close loop' mode.

5 CONFIRMATORY MEASUREMENTS

In order to verify the operation of the GenAVC^{TM} prototype systems installed at the two trial sites, the following methodology was used.

- Install measurement equipment at points in the network where the GenAVC^{TM} system is making predictions for voltage values
- Compare the predicted voltage values from the GenAVC^{TM} system against the actual voltage values measured for the same time period. Check the voltage values measured against the highest and lowest voltage values estimated by the GenAVC^{TM} system

Measurements have been made on the low voltage (LV) side of ground-mounted power transformers. LV load currents were also measured to enable the calculation of the 11kV voltage values from the LV voltage values, taking into account the load-dependant variable voltage drop across the transformer. This was necessary as the GenAVC^{TM} system predicts voltage values on the 11kV network, not the LV network. The requirement for measurements was for a time stamped record of the following quantities.

- One phase-to-earth voltage
- Corresponding line current and phase angle (or power factor)
- Alternatively, real and reactive power measurements

In selecting the locations of the confirmatory measurements, consideration was given to the ease of installation (ideally a ground-mounted transformer with accessible busbar) while meeting the requirements that the location should be towards the extremities of the network in order to give the most useful verification of the estimated voltage values.

On the EDF Energy network at Martham, these measurements have been taken at the following locations. Figure 10 shows the location of the confirmatory measurements on the Martham network.

- Acle feeder – St. Margaret's Way (Fleggburgh)
- Damgate (Martham Village) feeder – Fords Farm (Horsey)

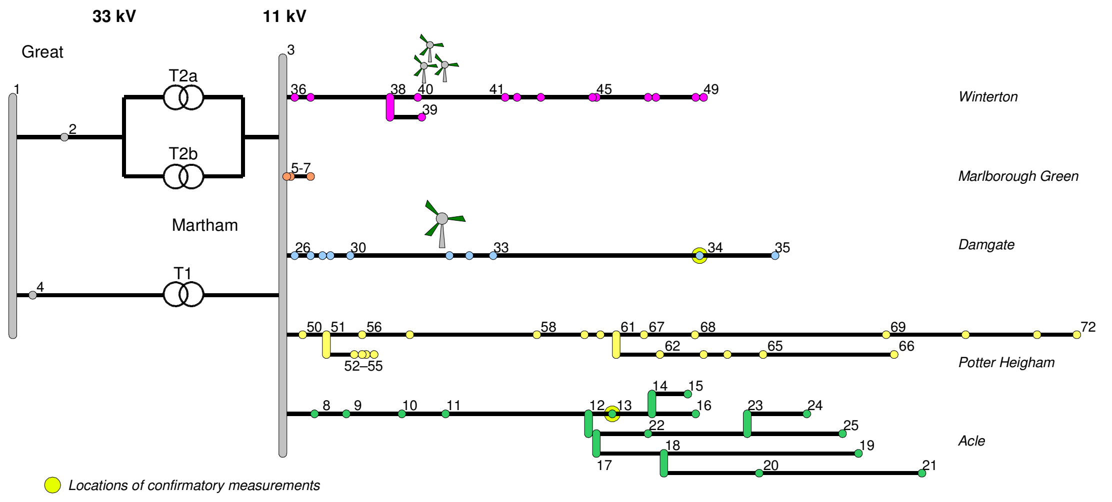

Figure 10 - Location of the confirmatory measurements on the Martham Network

On the United Utilities network at Morton Park, these measurements have been taken at the following locations. Figure 11 shows the location of the confirmatory measurements on the Morton Park network.

- Nestles Rural feeder – Durdar, Bridge End (Dalston), Nestles Rural and Nestles

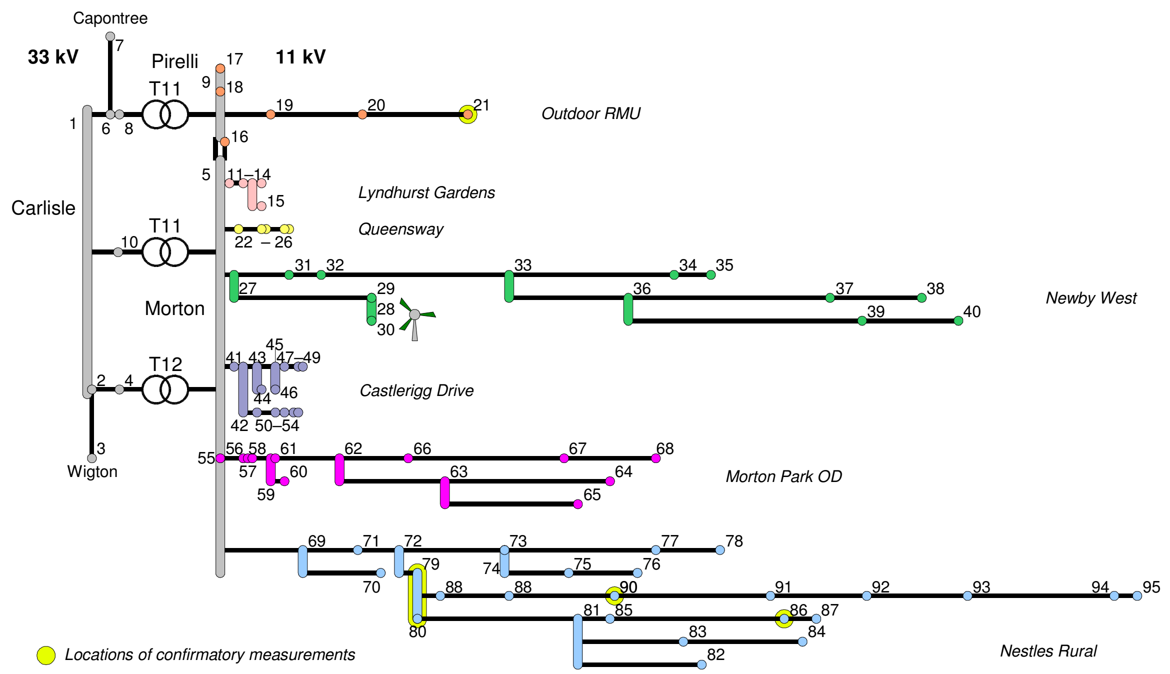

Figure 11 - Location of the confirmatory measurements on the Morton Park network

Results of comparison between confirmatory measurements and GenAVC™ predictions for Martham

Figure 12 shows the correlation between estimated voltage values and measured voltage values for one point on the network (node 13). The graph below shows good correlation between estimates and the measured voltages. The results were obtained and correlated over a 2-week period.

The confirmatory measurements consist of a range within which the actual voltage lies. This range falls entirely between the upper and lower limits of the GenAVC™ estimated voltage values for the vast majority of time samples at this node.

The VT neutral of a second confirmatory measurement location (node 34) was found to be suspect, so unfortunately not enough data was obtained to produce a correlation between the confirmatory measurement and the GenAVC™ estimation for that location.

The results for node 13, however, give Econnect confidence that the GenAVC™ system is able to estimate the voltage throughout the network to a quantifiable accuracy, enabling the GenAVC™ system to satisfactorily control the network to remain within required operational limits.

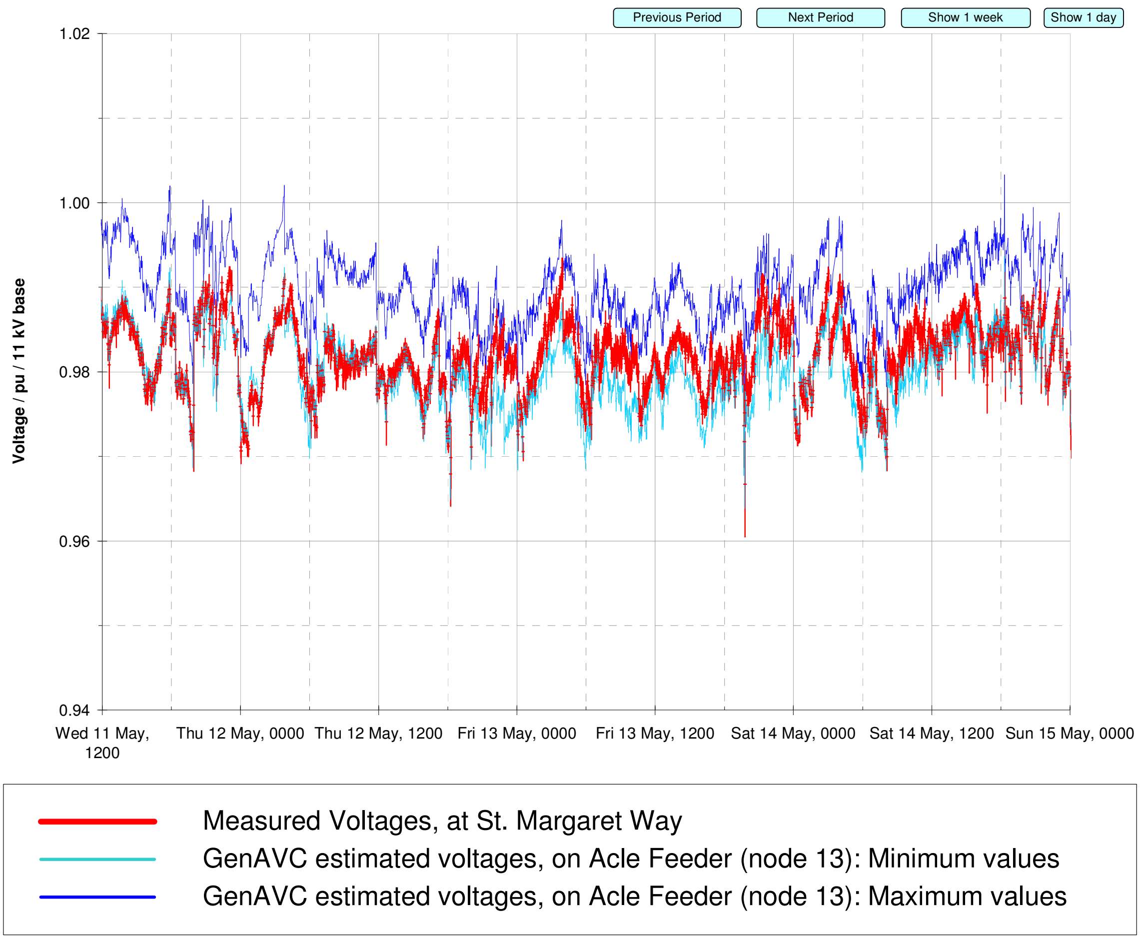

Figure 12 - Correlation between estimated and measured voltages at node 13 – Martham

Results of comparison between confirmatory measurements and GenAVC™ predictions for Morton Park

Figure 13 and 14 show the correlation between the GenAVC™ estimated voltage values and the measured voltage values for two points on the network (nodes 86 and 90). The graphs below show good correlation between estimates and the measured voltages. The results were obtained and correlated over a one month period.

The confirmatory measurements consist of a range within which the actual voltage lies. This range falls entirely between the upper and lower limits of GenAVC™ estimated voltage for the vast majority of time samples at both nodes. For a few time samples the measured voltage range extends outside of the estimation limits, which can be seen on the graphs as red lines extending beyond the limit of the blue lines. However, due to the measurement method used, the actual voltage may be within the estimated limits. Econnect consider the frequency, duration and depth of these excursions not to be significant so as to be detrimental to the operation of GenAVC™.

An accidental disconnection in the auxiliary power supply of a third set of confirmatory measurements (nodes 80 and 21, which are physically located next to each other at Nestle Rural) prevented the collection of sufficient confirmatory measurement values, so unfortunately not enough data was obtained to produce a correlation between the confirmatory measurement and the GenAVC™ estimation for that location.

The results for nodes 86 and 90, however, give Econnect confidence that GenAVC™ is able to estimate the voltage throughout the network to a quantifiable accuracy, enabling GenAVC™ to satisfactorily control the network to remain within required operational limits.

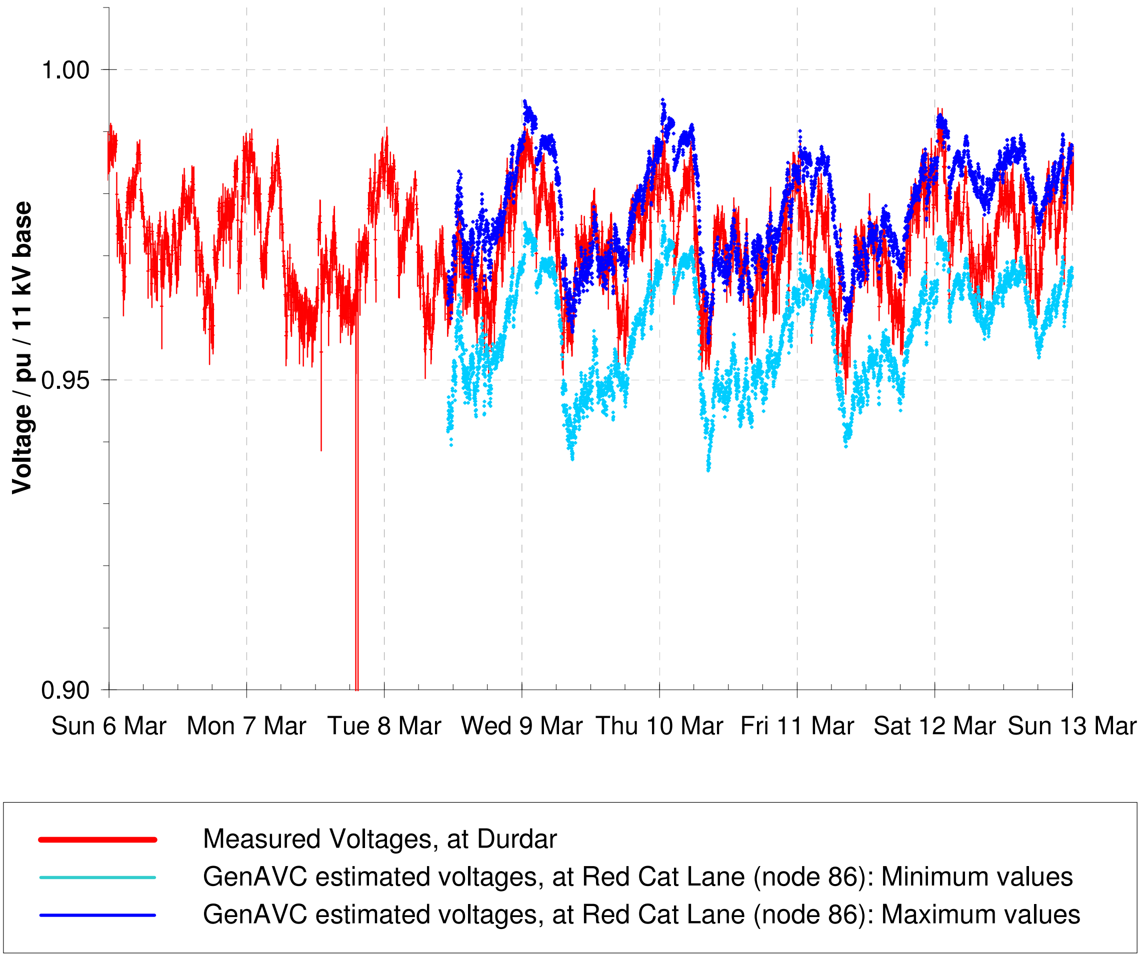

Figure 13 - Correlation between estimated and measured voltages at node 86 – Morton Park

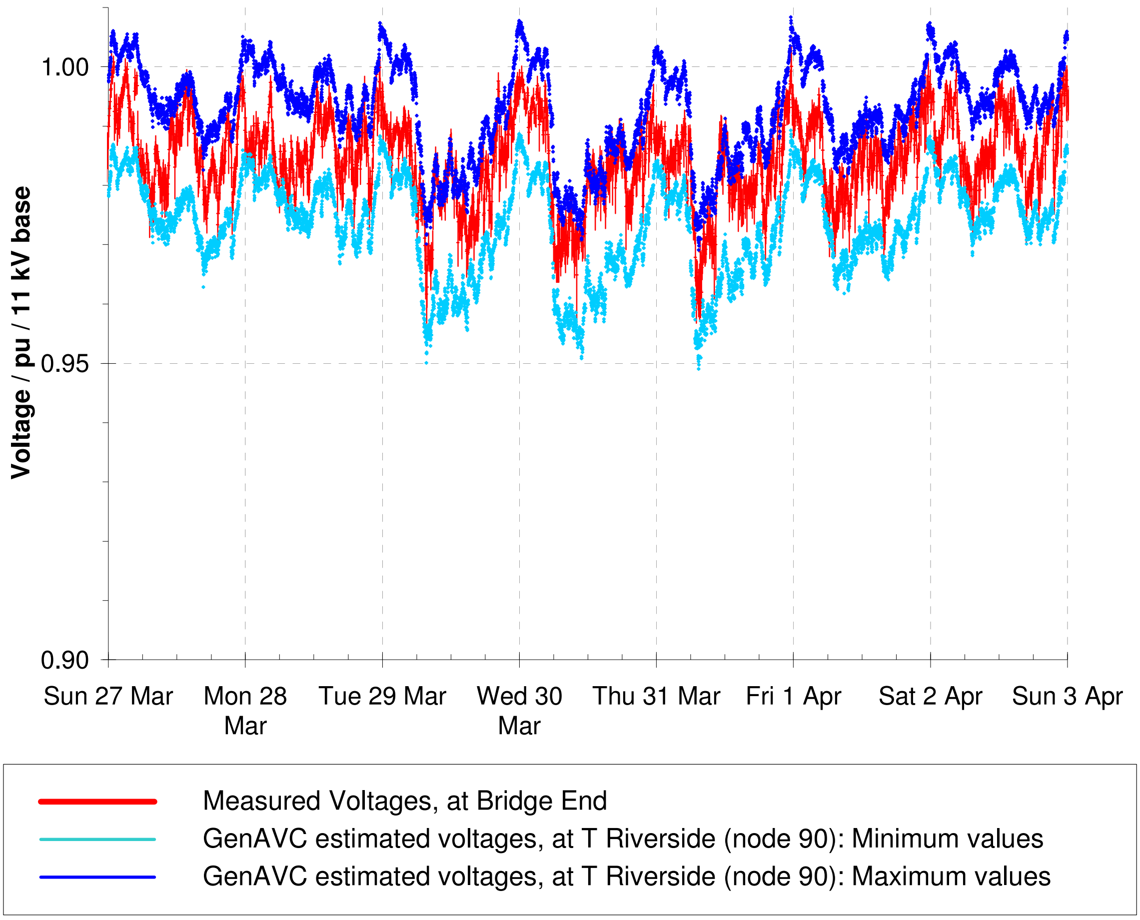

Figure 14 - Correlation between estimated and measured voltages at node 90 – Morton Park

6 CLOSING THE LOOP

Martham trial site performance

The GenAVC™ prototype system has been operating satisfactorily since the middle of March 2005 at the Martham trial site. The software is correctly processing the actual measurements and producing correct change requests to be forwarded to the AVC relays of the transformer.

The effect of the GenAVC™ system on network voltage levels is dependent on the parameters applied to both the GenAVC™ system and the AVC relays of the transformer. In the situation for which it has been designed, it is expected that in the absence of GenAVC™ system some of the voltage on the network may be out of desired or even statutory limits for some of the time.

Bearing in mind that the amount of generation currently connected does not require the GenAVC™ system to maintain the network voltages within limits, in order to simulate the effect of the GenAVC™ system as designed, it was proposed to reduce the control limits to values within which GenAVC™ will operate. In this way the GenAVC™ system would control the network voltage to a narrower band than would normally be expected.

During the period of operation in 'open loop' mode, the GenAVC™ lower and upper control limits were set at 0.95pu and 1.015pu respectively. The output log readings confirm that the GenAVC™ system has correctly maintained the voltage within these limits. For operation in 'close loop' mode of the GenAVC™ system it was proposed to set the GenAVC™ control limits to 0.95pu and 1.04pu.

Figure 15 shows an example of the results produced by the trial in 'open loop' mode. The trace clearly shows attempted actions to increase the AVC relay target voltage when it is estimated that a point in the network may be beneath the lower voltage limit. Conversely, when it is estimated that a point in the network may be above the upper voltage limit an attempt is made to decrease the AVC target voltage.

The following aspects of this graph should be noted.

- The maximum and minimum voltages include an uncertainty band to ensure that the voltages are kept within limits. Therefore, the actual minimum voltage may be above the minimum shown on the graph. Similarly the actual maximum voltage may be beneath the maximum shown on the graph
- Because GenAVC is operating in 'open loop' mode, the actions produced by GenAVC are logged but do not impact on the AVC relays. Therefore, output steps can be seen until the output reaches its limit
- Target 6 (on the right-hand scale) represents no adjustment to the AVC relay target voltage. Each integer above 6 represents a 1.5% increase in target voltage; each integer below 6 represents a 1.5% decrease in target voltage
- The algorithm controlling the target adjustment will prevent changes to the target that could cause the opposite limit to be exceeded. Because the target

voltage adjustment steps are 1.5%, if the upper limit is exceeded and the minimum voltage is within 1.5% of the lower limit, no action will occur. Conversely, if the lower limit is exceeded and the minimum voltage is within 1.5% of the upper limit, no action will occur

- Because the limits have been selected to work with existing running voltages, most adjustments are in the upward direction. In a normal running situation, with the limits correctly chosen, it would be expected that most adjustments to AVC relay target voltage would be in the downward direction. The graph demonstrates correct operation of the GenAVC with the limits so chosen

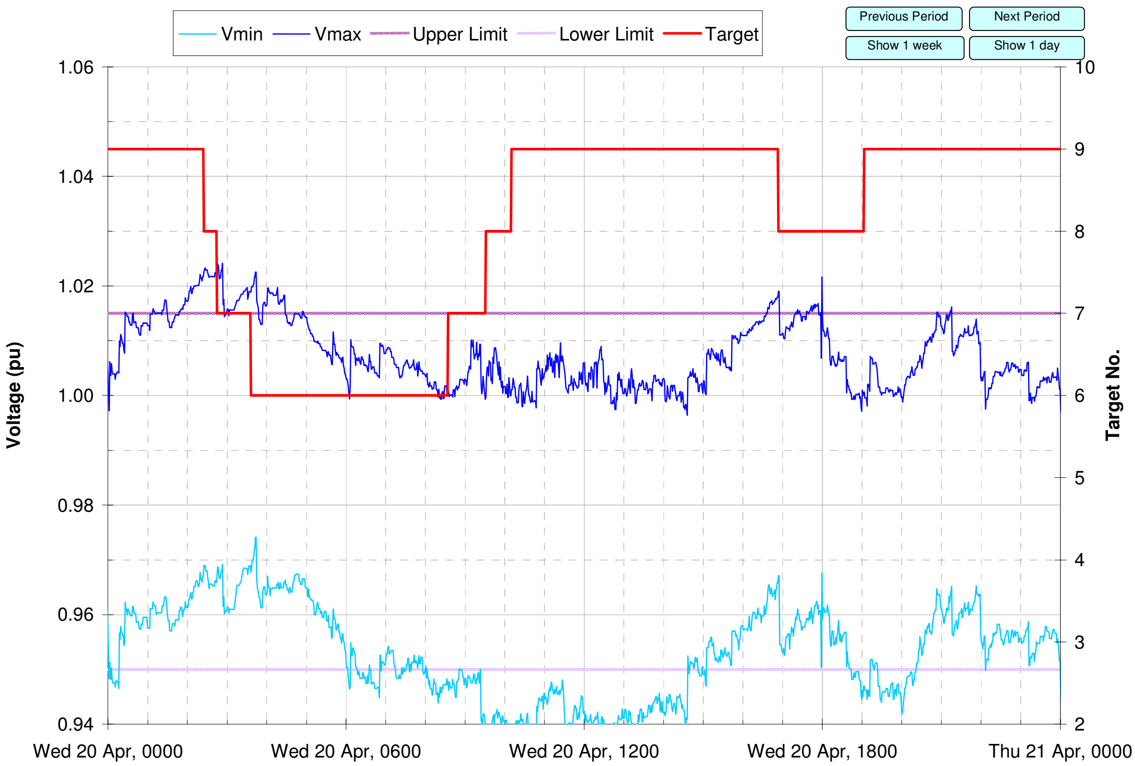

Figure 15 - Graph showing recorded actions of GenAVC™

The data collected during the commissioning and monitoring phases of the operation of the GenAVC™ system in 'open loop' mode has confirmed the following.

- The GenAVC™ system correctly predicts the voltages on the Martham network. This has been validated using confirmatory measurements
- The GenAVC™ system correctly processes the predicted voltage information with the actual measurements to produce a request for change to be forwarded to the AVC relays of the transformer. This has been validated during the commissioning tests and monitoring period
- It has been demonstrated that the GenAVC™ prototype system will keep the voltage on the Morton Park network within the required limits at all times

It was recommended to EDF Energy on 18th July 2005 that the trial should proceed to operation in 'close loop' mode. EDF Energy agreed that the GenAVC™ system could switch to 'close loop' operation contingent upon provision of further detailed information regarding the effect of the GenAVC™ system on the LV network, in addition to the effect of the GenAVC™ system on the 11kV network already demonstrated.

Therefore these activities will be carried out beyond the end of this research project.

Morton Park trial site performance

The GenAVC™ prototype system has been operating satisfactorily since the beginning of March 2005 at the Morton Park trial site. The software is correctly processing the actual measurements and producing correct change requests to be forwarded to the AVC relays of the transformer. The communications with one of the remote measurements in the GenAVC™ system has occasionally been troublesome, due to issues with provision of mobile network data services. Consideration is being given to changing the mobile network provider.

The effect of the GenAVC™ system on network voltage levels is dependent on the parameters applied to both the GenAVC™ system and the AVC relays of the transformer. In the situation for which it has been designed, it is expected that in the absence of the GenAVC™ system some of the voltages on the network may be out of desired or even statutory limits for some of the time.

Bearing in mind that the amount of generation currently connected does not require the GenAVC™ system to maintain the network voltages within limits, in order to simulate the effect of the GenAVC™ system as designed, it was proposed to reduce the control limits to values within which GenAVC™ will operate. In this way the GenAVC™ system would control the network voltage to a narrower band than would normally be expected.

During the period of operation in 'open loop' mode, the GenAVC™ lower and upper control limits were set at 0.93pu and 1.02pu respectively. The output log readings confirm that the GenAVC™ system has correctly maintained the voltage within these limits. For operation in 'close loop' of the GenAVC™ system it was proposed to set the GenAVC™ control limits to 0.95pu and 1.04pu.

The data collected during the commissioning and monitoring phases of the operation of the GenAVC™ system in 'open loop' mode has confirmed the following.

- The GenAVC™ system correctly predicts the voltages on the Morton Park network. This has been validated using confirmatory measurements
- The GenAVC™ system correctly processes the predicted voltage information with the actual measurements to produce a request for change to be forwarded to the AVC relays of the transformer. This has been validated during the commissioning tests and monitoring period
- It is confidently expected that the GenAVC™ prototype system will keep the voltage on the Morton Park network within the required limits at all times

It was recommended to United Utilities on 21st July 2005 that, following resolution of any remaining communications issues, and contingent upon provision of further detailed information regarding the correlation of confirmatory measurements and GenAVC™ voltage estimation, the trial should proceed to operation in 'close loop' mode. United Utilities agreed to this schedule of activities and therefore these activities will be carried out beyond the end of this research project.

DISCUSSION AND CONCLUSIONS

Very good progress has been made throughout this project in developing a prototype GenAVC™ system that operates according to requirements.

Hardware

The hardware specification, purchase and installation were completed in stages throughout the project. Hardware used for the GenAVC™ system has operated satisfactorily throughout the period of site trials.

Further GenAVC™ system development will consider the potential to utilise alternative hardware platforms for some or all of the system components. A change of hardware platform may entail updates to the existing GenAVC™ software.

The stand-alone hardware data loggers utilised for confirmatory measurements performed well. However, for future GenAVC™ systems it is advisable that data loggers have a remote communication function to enable data to be downloaded at regular intervals without the need to visit the site where they are installed, and to confirm that the data loggers are working correctly.

Communications

The communications specification, purchase and installation were completed in stages throughout the project. The two trial sites utilise different communications technology, and future GenAVC™ systems will require site-specific communications infrastructure.

Initial teething problems were experienced with the communication technologies at both sites, which have enabled us to develop our knowledge of these technologies. All problems were resolved, with the only remaining issue being related to the provision of mobile network data services. This will be addressed as part of the on-going work which will take place after the end of this project.

Software

The software specification, design, coding and testing were completed in stages throughout the project. The software was developed using industry standard methodologies for software development and followed established quality assurance procedures. The software has been organised in a series of modules which have been tested and integrated step by step. After each integration step, the resulting software was uploaded to the GenAVC™ unit at the Morton Park substation to verify correct operation on-site.

The final version of the GenAVC™ software was installed at the two trial sites in early 2005. The GenAVC™ software operated in a stable and reliable manner through to the end of the project in late July 2005.

Further GenAVC™ software development has been identified to extend the functionality currently provided. The following tasks will be carried out beyond the end of this project.

- To update the software following the trial results
- To adapt the software to suit alternative hardware platforms
- To develop a graphical user interface to enable the users to configure and monitor the GenAVC™ system
- To add the ability to import industry standard network data to enable dynamic updates to the network information held within the GenAVC™ system
- To add advanced reporting capabilities on the basis of detailed user requirements

Trial results

Operation of the GenAVC™ system at two trial sites was undertaken in 'open loop' mode throughout the first half of 2005. Initial problems with the state estimation not converging were found to be due to errors in the network information. Analysis of the GenAVC™ system output information during the commissioning tests and the monitoring phase showed that, once converging, the state estimation results for voltage estimates gave reasonable values which were within statutory limits.

Correlation of the voltages values estimated by the GenAVC™ system and the confirmatory measurement voltage values was completed for both trial sites. Results for both Morton Park and Martham trials show that the confirmatory measurement range falls entirely within the upper and lower limits of the GenAVC™ estimated voltage values for the vast majority of time samples at both sites.

During 'open loop' operation, since the GenAVC™ system has not affected the operating voltages on either network and network voltages are not expected to go out of regulatory limits, it has been necessary to reduce the GenAVC™ control limits to observe change operation requests to the AVC relays of the transformer in the GenAVC™ system. Values of 0.95pu and 1.015pu were used at Martham, and 0.93pu and 1.02pu for Morton Park. Output log readings confirm that, in 'close loop' operation, the GenAVC™ system would correctly maintain the voltage within these limits for both trial sites.

One issue to address regarding the GenAVC™ system performance is in relation to the minor failure observed during commissioning tests. If input data is lost from a GenAVC™ remote measurement equipment, then currently the GenAVC™ system continues to use the last measurement values it has received. The required response is for the GenAVC™ system to suspend its operations some short time after a loss of data input. Operation in 'close loop' mode was not achieved at either site during the lifetime of this project. However, agreement was reached that operation in 'close loop' would begin immediately following further simulation work on the Martham network to confirm the effect of the GenAVC™ operation on the low voltage network. Operation in 'close loop' mode at Morton Park was agreed subject to provision of further detailed information regarding the correlation of confirmatory measurements and GenAVC^{TM} voltage estimation and demonstration of reliable GPRS network operation.

<u>Recommendations and further work</u>

This project has clearly demonstrated the suitability of the GenAVC^{TM} system for controlling voltage on the 11kV network. It is recommended that the technology employed here be developed for full commercial product.

As a result of this work, a working prototype GenAVC^{TM} system has been designed, built and tested.

Beyond the end of this project, prototype equipment will remain on site at the two trial locations until operation in 'close loop' mode has been achieved (estimated by end of September 2005) and a significant period of satisfactory operation in 'close loop' mode has taken place.

The next steps will be to

- Demonstrate the long-term operation of the GenAVC^{TM} system
- Develop the functionality of the GenAVC^{TM} system
- Adapt the GenAVC^{TM} system to operate on alternative hardware platforms
- Investigate further communications technology to improve the reliability of communications with GenAVC^{TM} remote data acquisition units and to enable remote access to confirmatory measurement equipment
- Undertake an approvals process as appropriate to the client base for the product

The concept of the GenAVC^{TM} system has the potential to mitigate voltage rise issues and to enable an increased level of distributed generation to connect to the distribution network. This system will potentially enable distributed generation plants to connect to the 11kV (or equivalent) network voltage level with connection costs lower than if the GenAVC^{TM} was not installed, avoiding the expensive reinforcement costs for the network operator that would result from installing larger conductors, or even dedicated lines back towards the primary substation.

7 REFERENCES

[1] "Embedded Generation Working Group Report into Network Access Issues: Volume 1. Main Report and Appendices", Department of Trade and Industry, 2001.

[2] "Electricity Safety, Quality and Continuity Regulations (SI 2002/2665)", HMSO, 2002.

[3] "Guidelines for actively managing voltage levels associated with the connection of a single distributed generation plant", Engineering Technical Report 126, Energy Networks Association, 2004.

8 ACRONYMS

AVC	Automatic Voltage Control
AVRS	Automatic Voltage Reference Setting
CHP	Combined Heat and Power
CSS	Continuous Slow Scan
CT	Current Transformer
DAU	Data Acquisition Unit
DG	Distributed Generation
DNO	Distribution Network Operator
ENA	Energy Networks Association
ESQCR	Electricity Safety, Quality and Continuity Regulations 2002
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
LAN	Local Area Network
LSU	Local Storage Unit
NRC	Negative reactance compounding
OLTC	On-line tap changer
PLC	Programmable Logic Controller
rms	Root mean square
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
VT	Voltage Transformer