INTRODUCTION

In Europe generators are increasingly being connected to distribution networks, due to ambitious national targets for renewable energy and combined heat and power generation, set by governments in response to the 1997 Kyoto Protocol on climate change. Three factors that frequently limit the capacity of such a distributed generation project are fault level, thermal limits and voltage limits. Three methods that can be used to overcome the limitations on generator capacity due to voltage limits are [1]:

- Decrease automatic voltage control (AVC) relay target voltage
- Increase generator reactive power import
- Decrease generator active power export

An AVC relay controls one or more tap-changing transformers at a substation to maintain the lower voltage within a dead band that is centred on a target voltage. This paper describes a voltage controller that controls the AVC relay target voltage and discusses some of the practical considerations required to implement it at 33 / 11 kV primary substations in the UK.

VOLTAGE CONTROLLER DESCRIPTION

Figure 1 is a functional diagram of the voltage controller. There are two blocks: state estimation and control. The measurements, estimates and AVC relay target voltage, shown with black arrows, are real-time signals. The other inputs, shown with white arrows, are off-line data.

The state estimation block calculates the expected value and standard deviation of the voltage magnitude at each node on the network under control. To do this it uses voltage and power measurements, historical load data and network data such as topology and conductor impedances. It uses a weighted least squares algorithm, solved using the Newton Raphson method [2], which also calculates the state variable standard deviations [3].

The node voltage magnitude estimates are passed to the control block, which checks that each estimate is within its ‘control range’. The control range for each node is defined as the range of acceptable values for its voltage magnitude estimate. If an estimate falls outside its control range, the control block alters the AVC relay target voltage to initiate a tap change operation, so ensuring that all customer voltages remain within statutory limits.

Real-time measurements are taken both at the primary substation and at remote sites on the network, such as generator points of connection or nodes where large voltage variations are expected. As an AVC relay typically operates after a delay of between thirty seconds and two minutes, the remote measurements are communicated to the controller every few seconds. In order to minimise the data traffic, remote measurements are communicated only if they change by a significant amount. A ‘heartbeat’ data packet is sent every minute to check that the communications channel is working. Low power radio or public data network are considered suitable communications technologies.

CONTROL OF AUTOMATIC VOLTAGE CONTROL RELAY

Modern AVC relays have an external input to set the target voltage [4]. The controller initiates a tap operation by altering the target voltage input so that the difference between the voltage measured by the AVC relay and the target voltage is more than half the dead band. This results in the AVC relay initiating a tap-change operation and is similar to the control method presented in [5].

The voltage controller can control an AVC relay that is performing line drop compensation or negative reactance compounding, provided it has the impedance value and the current and voltage measurements used by the AVC relay. The voltage controller uses these to ensure that when it alters the AVC relay target voltage input to initiate a tap operation, the difference between the target voltage and the voltage measured by the AVC relay is larger than half the dead band.

If the voltage controller loses communications or fails, the AVC relay reverts to autonomous operation. This is achieved using a hardware refresh of the AVC relay target voltage input, which returns the target voltage to a set value in the absence of an input from the controller.

As the voltage controller allows the capacity of distributed generators to be increased, in the event of voltage controller failure, it is possible for a generator to cause an over voltage. Installing an over-voltage relay at each generator point of connection can prevent this.
NETWORK MODEL

Figure 2 shows an eleven-node model of an 11 kV network constructed using real data. A single 33 / 11 kV 1 MVA tap-changing transformer is located between nodes 1 and 2. The tap step is 1.43% and the AVC relay dead band is 2.5%. The transformer supplies four rural feeders and a hydro generator is connected at node 7. Power and voltage measurements are located at nodes 2 and 7 and a voltage measurement at node 6. Loads are connected to all the 11 kV nodes.

CONTROL RANGE

Figure 3 shows the control range for node 9 of the network shown in Figure 2.

STATE ESTIMATE ACCURACY

Method

The state estimation algorithm was run on the network model shown in Figure 2, using winter maximum load data.

The input measurements were modelled as independent Normal random variables with the following per unit standard deviations.

- Voltage measurements: $\sigma_v = 0.000833$
- Power measurements: $\sigma_p = 0.005$
- Load pseudo measurements: $\sigma_l = 0.333$

$\sigma_v$ was determined by equating six standard deviations to the accuracy of 0.5% for Class 0.5 voltage transformers. This was then multiplied by 0.1% as the accuracy of a typical modern voltage transducer.

$\sigma_p$ was determined as the product of the accuracies of a Class 0.5 current transformer and a Class 0.5 voltage transformer, summed across three phases and multiplied by a transducer accuracy of 0.5%.

Each of the unmeasured loads was modelled as a measurement, known as a ‘pseudo measurement’, with the winter maximum load value as the expected value and three standard deviations equated to this value. This implies a 99.73% level of confidence that the actual load is within +/-100% of the expected value. Pseudo measurements are calculated using load models and so their accuracy depends upon the accuracy of the load model. The above value for $\sigma_l$ was chosen to represent the output of an inaccurate load model, such as one based on distribution transformer rating.

Results

The state estimation algorithm models the node voltage magnitude estimates as Normal and calculates an expected value and standard deviation for each node. Figure 4 shows the voltage corresponding to three standard deviations for each estimate.
Discussion

The estimate at node 9 has the largest standard deviation, because it is furthest from a real-time measurement and has a relatively large load.

As real-time measurements are much more accurate than pseudo measurements, addition of real-time measurements improves the state estimate accuracy. This can be seen in the low estimate standard deviations at nodes 2, 4, 5 and 6. However, as real-time measurements are expensive, it is desirable to use the minimum number necessary to provide an acceptable control range.

The values in Figure 4 correspond to three standard deviations, which implies a 99.73% level of confidence that the actual node voltage magnitude is within plus or minus the value shown in Figure 4 from the expected value. If the required level of confidence is decreased, the values in Figure 4 are decreased and so the control range can be widened.

Figures 3 and 4 show that acceptable state estimate accuracy can be obtained with inaccurate pseudo measurements. However, the state estimation algorithm models the measurements as independent Normal random variables. This is likely to be reasonable for the errors in real-time measurements, but is likely to be inaccurate for load pseudo measurements [6]. It is possible that correlation between pseudo measurements could have a significant affect on the state estimate accuracy and so the control range width.

MONITORED VOLTAGE

Three phase voltages at the point of connection of a distributed generator were monitored at ten-minute intervals for a year.

Figure 5 shows the voltage frequency distribution for one phase, which is closely approximated by a Normal distribution. These results support the Normal model for the voltage magnitude estimates used by the state estimation algorithm.

The mean difference between two of the monitored phase voltages magnitudes was 0.25%, with a standard deviation of 0.25%. This confirmed the stated aim of the distribution network operator to maintain phase imbalance less than 1%.

As all three phase voltages need to be maintained within statutory limits, voltage imbalance needs to be taken into consideration when setting the control range. This is not shown in Figure 3, which assumes that it is already accounted for in the 1.012 and 0.94 operating limits.

CONTROL ALGORITHM SIMULATION

Method

To assess the performance of the control algorithm, the voltage on the network shown in Figure 2 was simulated at half hour intervals for a year.

The network loads were simulated using a year’s half hour metered primary substation and generator active power data and customer annual maximum demand data. The sum of the primary substation and generator active powers for each half hour were allocated to the load nodes in proportion to the node maximum demand, neglecting network losses. A fixed load power factor of 0.98 was assumed [7].

A scaling factor was applied to the generator active power data, so that generators of different capacities could be simulated. The generator was operated at unity power factor.

For each half hour of the year, the state estimation algorithm was used to run a deterministic load flow to calculate the primary substation active and reactive power flow and the node voltage magnitudes, given the simulated loads and generator power injection.

Two types of control for the primary substation tap-changer were simulated.
• An AVC relay that maintains the node 2 voltage in the range 0.987 pu to 1.012 pu.
• A voltage controller that alters the AVC relay target voltage to maintain all the node voltages within the range of 0.94 pu to 1.012 pu.

Results

Table 1 shows the maximum generator capacity that could be connected using the two types of control and the corresponding annual energy export.

<table>
<thead>
<tr>
<th>TABLE 1 – Control Algorithm Simulation Results</th>
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<tbody>
<tr>
<td>Generator Capacity (kW)</td>
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<td>Control Type</td>
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<tr>
<td>Generator Energy Export (x10^6 kWh)</td>
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Discussion

Table 1 shows that the voltage controller allowed the generator capacity and energy export to be more than doubled. This result should be taken as indicative, as there are a number of limitations in the simulation. The most significant limitation is that the simulation uses half-hour power data and therefore does not account for shorter duration voltage variations. Such voltage variations can be significant, particularly when the network voltage is high due to a high generator power output. To obtain an accurate comparison between the two control methods, data monitored at an interval of around ten seconds would be required.

FUTURE WORK

It is planned to install two controllers at two 33 / 11 kV primary substations in 2003. Initially the controllers will operate in a monitoring mode and if the results of these trials are satisfactory they will then be used to control the AVC relays.

To prepare for these trials, it is planned to simulate the networks supplied by the two primary substations. The simulation described above will form the basis for these simulations, with the following additions:

• More detailed network models of around 50 nodes
• Power and voltage data monitored at sub-minute intervals
• Inclusion of the state estimation algorithm and load model
• More than one primary substation transformer supplied from more than one 33 kV source
• A more detailed AVC relay model including line drop compensation and negative reactance compounding
• Generators constraining power based on a voltage measurement at the point of connection

CONCLUSION

A voltage controller for 11 kV primary substations for use with distributed generation has been described. The controller’s main features are a statistical state estimation algorithm and a control algorithm that work together to maintain the voltage at all the network nodes within statutory limits.

The way in which the voltage controller controls the AVC relay has been described. It has been shown that the voltage controller must maintain each node voltage magnitude estimate within a control range and factors that affect the control range have been described. These include the state estimate accuracy, which was calculated for each node of an example network model.

The voltage at a generator point of connection was monitored for a year and the results show that the voltage magnitude estimate model used by the voltage controller is reasonable.

The operation of the control algorithm was compared with that of an AVC relay in a simulation using the example network model. The control algorithm enabled the distributed generator capacity and energy export to be more than doubled.

REFERENCES