This article discusses the application of transformer Automatic Voltage Control (AVC) to networks in which generation is embedded, with reference to the application of MicroTAPP voltage control to these systems.

The issues addressed are the particular problems that can occur if the application of voltage control does not take into account the presence of generation. It addresses any requirements on a local (ie distributed) level. An overall network solution may make use of a network automation system to set up the Voltage Control Relay (VCR) for the system conditions. This, however, is a network management issue and is not relevant to the voltage control application.

Voltage control basics

The simplest form of AVC can be used where a single transformer supplies a single load (see Figure 1). If the load is some distance from the transformer, there may be a voltage drop in the line. The AVC relay measures the voltage and the current ($V_{VT}$ and $I_{CT}$) and makes an estimate of the voltage at the load ($V_{eff}$) using a model of the line ($R_{line} + jX_{line}$). This represents the ideal situation: in reality, there are usually a number of loads on a transformer distributed at different distances (electrically) from the transformer, so the model of the line will always be a compromise. The model is normally set up to establish a constant voltage point at the mid-point of the network, thus achieving a minimum overall variation between no-load and full-load conditions.

It is common practice to parallel transformers in order to give a higher security of supply (see Figure 2). For a site with two transformers in parallel, the load on each transformer is half of the total load. In order to obtain the correct voltage boost it is necessary to summate the loads of all paralleled transformers ($I_{load} = I_{CT,1} + I_{CT,2}$). If the open circuit terminal voltages of the paralleled transformers are not identical, a circulating current will flow around them. This will be reactive since the transformers are highly inductive. If two paralleled transformers operate the simple AVC scheme described above, eventually one transformer will be on the highest tap and the other on the lowest tap. The busbar voltage will be an average of their terminal voltages and a high amount of circulating current will flow between them. This will cause an unnecessary power loss within the transformers and the network, reducing their useful capacity and efficiency. Therefore, the main aims of any voltage control scheme must be to:
- Maintain the correct voltage at the customer, taking into account line voltage drops
- Minimise reactive circulating current around paralleled transformers, and across networks

Application of MicroTAPP

The MicroTAPP scheme, based on the negative-reactance AVC scheme, resolves the measured current of each transformer into load and circulating elements. Figure 3 shows the current seen by an AVC relay ($I_{circ}$) with respect to its phase voltage ($V_{VT}$). The circulating current ($I_{circ}$) is resolved from $I_{CT,1}$, being the deviation from a set-point of system power factor ($pf_{sys}$). This element of current is then used to bias the voltage control in order to minimise the circulating current.

Line Drop Compensation (LDC) corrects for system voltage drops...
so that customers receive as close to ideal voltage as is possible. The total load on the busbar is calculated by summatting transformer currents $I_{CT,1}$ and $I_{CT,2}$ (see Figure 3) and this is used to calculate a bias to apply to the voltage control. These two simple elements together achieve the main aims of voltage control. Other benefits of this system are that:

- The system is extremely simple
- Transformers and tap-changers on a site do not have to be identical
- Incoming voltages can be different
- Transformers can be paralleled across networks.

Although the actual power factor at a particular time may not be the specified power factor $\text{pf}_{\text{sys}}$, as long as the deviation is not large the voltage control will be satisfactory. If the actual power factor varies greatly from the set-point, the effect will be an error in the controlled voltage, as the load current will be considered as circulating current by the TAPP scheme.

**Varying power factors**

In circumstances where the load power factor can vary substantially, the TAPP scheme with its power factor set-point may not be a viable option. An alternative scheme, known as the true circulating current scheme, is described below and can be used in these circumstances. *Figure 4* shows the current seen by two AVC relays $I_{CT,1}$ and $I_{CT,2}$ with respect to their phase voltages $V_{VT}$ (when the transformer LV circuit breakers are closed the measured voltages will be identical). The load currents, $I_{\text{load},1}$ and $I_{\text{load},2}$, have the same power factor. Transformer 1 is on a higher tap position than Transformer 2, hence a circulating current, represented by $I_{\text{circ}}$ in the diagram, will flow. If the measured currents, $I_{CT,1}$ and $I_{CT,2}$, are summated, the network power factor can be found. The true load on each transformer and its contribution to circulating current can be established. Therefore LDC error is eliminated.

**Embedded generation**

For this discussion, an example network is used and is shown in *Figure 5*. For the purpose of explanation a single transformer is shown supplying load to a nominal 33 kV busbar and the load is assumed to be unity power factor. Three circuits are supplied from the busbar. Load C is interconnected to a remote substation, and, for operational flexibility, the voltage control to the transformer tap changer is configured for reactive control (TAPP). If Load C is not interconnected to another site, true circulating current control can be implemented.

The basic voltage level is set to 33 kV and, at the transformer load shown (400 L), the load drop compensation (LDC) applied at 4% increases the busbar voltage to about 34.3 kV. These figures are used for the purpose of explanation only. A number of scenarios involving generation embedded in this network are discussed.
Small asynchronous generator

Small generators can be embedded remote from the busbar and supply part of or the entire feeder load. It is unlikely that a generator in this location would be capable of supplying the total substation load. Figure 6 shows a generator connected to supply the feeder load. The generator reactive load is supplied from the source through the transformer (50R), with the result that the transformer contributes a smaller load to the busbar, at a lower power factor owing to the increase in reactive current.

As the real load is reduced, the LDC effect is reduced causing the LDC boost voltage effect to be reduced to 3%. Since voltage control is in TAPP mode, the decrease in power factor causes an error in the VCR target voltage that results in a further 1% reduction in voltage. When the generator is running, the busbar voltage is reduced to 33.7 kV from the desired 34.3 kV.

Solution

If the generator contributes an insignificant load relative to the transformer, the effect on the VCR will be insignificant. If the generator causes a significant change to both the transformer load and power factor, steps can be taken to exclude feeder load A from the transformer current applied to the VCR CT input. The transformer load will ignore the effect of all generation connected along feeder A. This can be achieved by use of a ‘Load Exclusion Module’ (LEM) applied at Point A. The module subtracts Load A from the current measured by the VCR CT. The current seen by the VCR will now be of the correct power factor and the LDC effect will be slightly reduced to 34 kV (since it does not include Load A). This can be corrected by a small increase to the LDC setting.

Large asynchronous generator

Large generating capacity would most likely be connected at the busbar and be able to supply a high proportion of the site load. Figure 7 shows a generator connected at the busbar. The generator reactive load will be supplied from the transformer, the result being that the transformer contributes only reactive current to the busbar. In this case, the power factor of the transformer load will swing towards 0° lagging and, depending on the magnitude of the reactive current, have a significant effect on the VCR target voltage. The real load is reduced further, the LDC effect being 1% instead of 4%.

The large reduction in the apparent power factor also results in a target voltage error, say a further 2%. The sum of these effects is that, when the generator is running, the busbar voltage is reduced to 32.7 kV from the desired 34.3 kV. The generator will cause a significant change to the transformer load and the power factor. If the generator current is excluded from the VCR CT input, the transformer VCR will ignore the effect of the generation and assume the load is connected only to the outgoing feeders. The VCR will, therefore, remain accurate at all times (34.3 kV). Again, this can be achieved by use of the load exclusion module, applied at Point B.

Synchronous generator

Figure 8 shows a generator connected to the busbar. The generator is set to produce power at the system power factor and the transformer VCR will control the busbar voltage level. The generator in this case is supplying virtually the complete busbar load, leaving the transformer at no-load. As the transformer is at no-load, the LDC effect is zero and the voltage reduces to the basic set-point level of 33 kV.

Solution

The generator will cause a significant change to the transformer load. If the generator current is excluded from the VCR CT input, the transformer VCR will ignore the effect of the generation and assume the load is connected only to the outgoing feeders. The VCR will, therefore,
remain accurate at all times (34.3 kV). If the overall supply source is strong (high fault level) in relation to the local busbar, the solution will allow energy to be supplied into the higher voltage network. This can be achieved by use of the load exclusion module, applied at Point B.

**Large synchronous generator**  
Figure 9 shows a generator connected at the busbar and power being exported into the higher voltage network. If the generator is set to produce power at the system power factor and the transformer VCR set to control the busbar voltage level, the system voltage may be in serious error. The sense of LDC will be in reverse and a corrective action by the VCR will increase the primary/secondary winding ratio, thus making the secondary voltage reduce to a point where the voltage is below the basic voltage level by an amount equivalent to the LDC setting value, in this case to 32.3 kV. In this situation, LDC cannot be used, which is operationally restrictive. If the primary system has a relatively low fault level the transformer voltage control may have to be disabled completely.

**Solution**  
The generator will cause a significant change to the transformer load. If the generator current is excluded from the VCR CT input, the transformer VCR will ignore the effect of the generator and assume the load to be connected only to the outgoing feeders. If the overall supply source is weak (low fault level) in relation to the local busbar it may be required to transfer voltage control to the higher voltage network when the generator is running and allow the voltage of the local busbar to be controlled by the generator. The MicroTAPP voltage control system can be configured in this situation to operate in pseudo VT mode. Under this operating condition, the existing LV, VT and CT are used, and the voltage at the transformer HV terminals is calculated. The MicroTAPP then operates the tap changer to maintain the incoming voltage at the correct level.

**Conclusion — see table below**

<table>
<thead>
<tr>
<th>Generation type</th>
<th>Asynchronous generation</th>
<th>Synchronous generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (relative to network strength)</td>
<td>Small</td>
<td>Large</td>
</tr>
<tr>
<td>Expected location</td>
<td>Embedded remote from busbar</td>
<td>Busbar</td>
</tr>
<tr>
<td>Voltage control</td>
<td>At point of generation</td>
<td>Transformer AVC</td>
</tr>
<tr>
<td>Of HV network</td>
<td>by System</td>
<td>by System</td>
</tr>
<tr>
<td>Special requirements</td>
<td>None</td>
<td>Use LEM</td>
</tr>
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