ADVANCED VOLTAGE CONTROL FOR NETWORKS WITH DISTRIBUTED GENERATION

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ABSTRACT

With increasing levels of distributed generation, the control of voltage levels across distribution networks requires a system that can function under dynamic operating conditions. Problematic effects of distributed generation and the associated changes in power flow are inaccurate Load Drop Compensation, voltage rises at the points of generator connection and impaired voltage control for paralleled transformers.

This paper describes a voltage control methodology that has been developed to solve these problems for use in voltage control relays that control On Load Tap Changing power transformers.

INTRODUCTION

A key aspect of electricity supply quality in a power system is the optimum application of voltage levels to all transmission and distribution networks. With significant penetration of distributed generation, the distribution network has become an active system with power flows and voltages determined by the generation as well as the loads [1]. Growing customer expectation and use of sophisticated electrical equipment puts an added responsibility upon the network operator to ensure that the delivered level and quality of supply is maintained within the parameters set down by the regulatory bodies, while at the same time permitting the maximum amount of distributed generation to be installed and operated.

Automatic voltage control of the electrical network is implemented by use of voltage control relays (VCR's) which control motorised On Load Tap Changing (OLTC) power transformers. The regulating point is usually some distance from the load centre of the network, which means that the load may not be delivered at the desired voltage level due to the resistive and reactive voltage drops on the line between the load and the source. Furthermore, the largest voltage drops occur under the heaviest loading conditions, i.e. at peak times.

Load Drop Compensation (LDC) is a technique used to offset these voltage drops across a network caused by load current, where the target voltage of the regulator can be adjusted such that the load is delivered at the optimum voltage level. The LDC is applied in proportion to the ratio of the actual load to the full load, and is expressed as a percentage boost at full load. For example, a setting of 5% will raise the regulator target voltage by 5% at full load, and by 2.5% at half load. Application of LDC therefore relies on correct measurement of the load.

Distributed generation units, particularly wind turbines, are often connected into a distribution network at locations remote from where the level of voltage is controlled. The output from these generators is variable and determined largely by the unpredictable nature of the power source such as wind, wave, sunlight etc. This implies that the load contribution of the transformers will also be unpredictable. The effect of LDC under these conditions may result in a change to the optimised voltage level across the network.

Where a generator is at a remote point on a feeder, the voltage conditions at the point of connection will vary depending on the power output from the generator and the power factor. When the generator is operating, the voltage at the connection point can rise, possibly to an unacceptable level. In this case it may be necessary to attenuate the voltage level in order to achieve an acceptable overall voltage range for the total connected network.

To provide security of supply transformers are operated in parallel. When paralleled transformers are on different tap positions (and therefore have different ratios) reactive circulating currents will flow between them, incurring losses. Several control methods exist that minimise circulating current between paralleled transformers such as Master-Follower, Circulating Current and Negative Reactance.

The Transformer Automatic Paralleling Package (TAPP) is a modified negative reactance method widely used in the UK and abroad [2]. It has many advantages over other methods and is accurate at normal system power factors. However, the method suffers from errors incurred by load power factor deviations. Distributed generators can cause appreciable changes in load power factor and therefore may impair the voltage control system.

CONVENTIONAL VOLTAGE CONTROL

An example of conventional voltage control for OLTC power transformers without distributed generation is shown in figure 1. The VCR controls the tap changer and takes readings of the transformer load current (I_{TL}) and voltage. The total load is supplied by the transformer ($I_{TL} = I_1 + I_2$).

LDC is applied in proportion to the measured transformer current to give maximum boost at full load. This is implemented in the VCR with the application of a voltage bias to the relay basic target voltage.

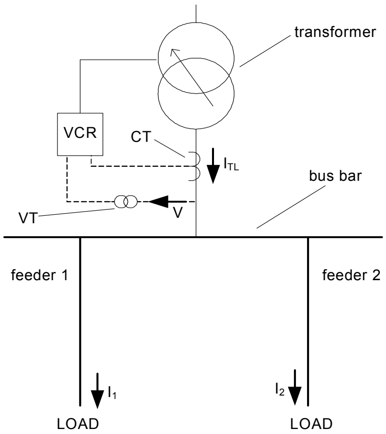

Figure 1 *Site without distributed generation*

Figure 2 shows the voltage profiles along each feeder with and without application of LDC. As can be seen, without LDC load I_2 is delivered outside of voltage limits as a result of voltage drops (both loads are considered here to be at the end of the feeders). However, both loads may be delivered within limits by application of LDC.

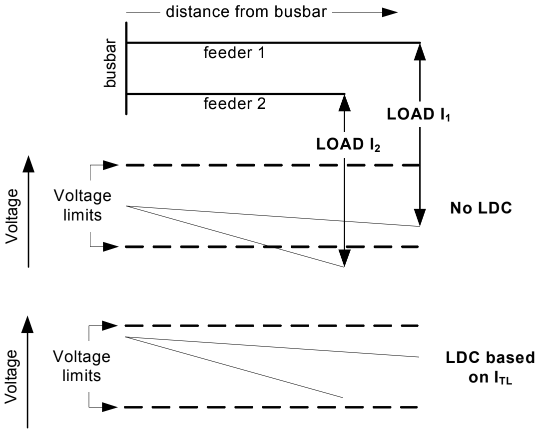

Figure 2 *Voltage profiles for feeders*

Control of paralleled transformers using TAPP is based on the comparison of measured transformer power factor with a 'target' power factor (normal load power factor) to calculate circulating current. The circulating current is then used to apply a proportionate voltage bias to the relay such that appropriate tap changes are initiated and the circulating current minimised. The TAPP method is shown in figure 3.

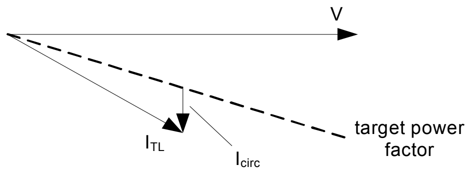

Figure 3 *TAPP method*

EFFECT OF DISTRIBUTED GENERATION

Figure 4 shows the example site with a generator connected at the load end of feeder 1. When the generator is running the measured transformer current, I_{TL}, no longer represents the load connected to the busbar. An increasing generator output results in a decreasing load contribution from the transformer, and since LDC is applied in proportion with measured transformer current, decreasing LDC.

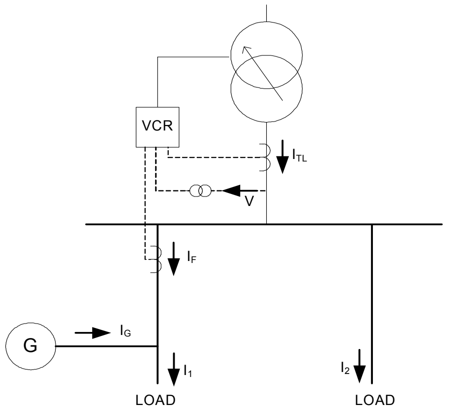

Figure 4 *Site with distributed generation*

The generator also affects the voltage profile along the feeder to which it is connected. As the generator output increases, the voltage drop between the busbar and the point of connection decreases. Where the generator supplies the entire load on feeder 1 there is no voltage drop in this section of feeder. As the generator output increases further such that it supplies some of the load on feeder 2 as well, there is a voltage rise from the busbar to the point of connection. The resulting voltage profiles for this scenario are shown in figure 5. It can be seen that load I_2 is delivered at an unacceptable voltage level due to the reduction in LDC.

Distributed generators can have a profound effect on the measured power factor at the transformer. Where a generator output is at a power factor that is different to the target (0.96 lagging is normal for most networks), the deviation will be interpreted as circulating current and the appropriate voltage bias applied to the relay target. This can cause incorrect voltage levels on the system.

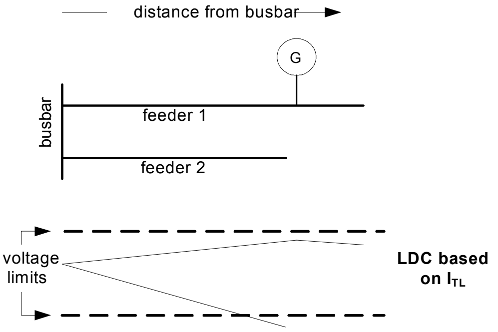

Figure 5 *Voltage Profiles for Feeders with Distributed Generation*

GENERATOR ESTIMATION

A solution to the problems associated with distributed generation utilises an extra current measurement that can be used to estimate the generator output (I_G) and the true load connected to the busbar ($I_1 + I_2$) [3]. The extra current measurement must be made on the feeder that has connected generation, as shown by I_F in figure 4.

From the two current measurements (I_{TL} and I_F) it is possible to calculate the load on feeder 2 as follows:

$$I_2 = I_{TL} - I_F \qquad \ldots(1)$$

With knowledge of the normal load share between the two feeders (from historical data or spot measurements when the generators are not running), it is possible to infer the load on feeder 1 as follows:

$$I_1 = (I_{TL} - I_F)R_{load} \qquad \ldots(2)$$

where $R_{load} = I_1 / I_2$

The true load, I_{load}, can then be calculated and used to apply sufficiently accurate LDC at all times:

$$I_{load} = I_1 + I_2 \Rightarrow I_{load} = (I_{TL} - I_F)(1 + R_{load}) \qquad \ldots(3)$$

The application of LDC based on the true load results in high voltage conditions on feeder 1 due to the voltage rise at the connection point, as shown in figure 6a. One way of achieving satisfactory voltage conditions is to constrain the generator. Indeed, a current approach to accommodating distributed generation is to limit the generator rating based on the maximum allowable voltage rise at minimum feeder load [4]. However, this is not ideal since the aim should be to generate as much 'green' energy as possible. Another way is to use the estimation technique to calculate the generator output and use it to modify the target voltage level of the VCR.

The generator output, I_G, can be calculated and used to apply a voltage attenuation to counter the voltage rise:

$$I_G = I_1 - I_F \Rightarrow I_G = [(I_{TL} - I_F)R_{load}] - I_F \qquad \ldots(4)$$

The voltage attenuation is applied in proportion to the estimated generator output and is referred to as Generator Compensation (GC). The application of GC results in acceptable voltage conditions as shown in figure 6b.

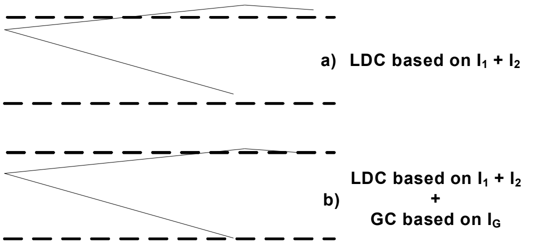

Figure 6 *Voltage Profiles with Load and Generator Estimation*

ENHANCED TAPP

Voltage errors incurred in TAPP mode of control as a result of distributed generation may be reduced to an insignificant level if the true load is used in calculations. Enhanced TAPP calculates two types of circulating current; that between transformers paralleled at a site (site circ) and that between transformers paralleled across a network (network circ) [5]. The method is shown in figure 7, where I_{group} represents the sum of the paralleled transformer loads (requires inter-VCR communications) and I_{load} represents the true busbar load as described in the previous section.

Site circulating current is calculated by comparing the measured transformer current, I_{TL}, with the sum of measured transformer currents, I_{group}. This calculation is not affected by distributed generation since associated power factor deviations will be identical for I_{TL} and I_{group}. Site circulating current is minimised by application to the VCR of corresponding voltage bias.

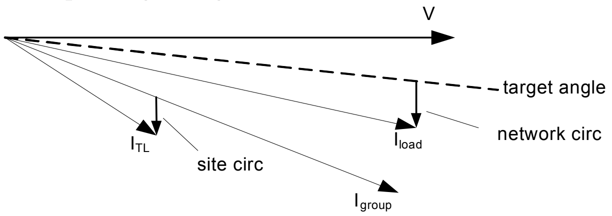

Figure 7 *Enhanced TAPP method*

Network circulating current is calculated by comparing the estimated true load current, I_{load}, with the target power factor. A deviation in power factor will be interpreted as circulating current with remote transformers, but may be a genuine change in load power factor, in which case a voltage error results. In order to minimise network circulating current but also reduce this error, a ‘damped’ bias is applied enabling transformers to be operated in parallel across a network.

APPLICATION

Power flow studies for part of a distribution network with high levels of distributed generation have shown that the generator estimation technique can be used to provide optimisation of voltage levels and minimisation of losses. Part of the network study is shown in figure 8.

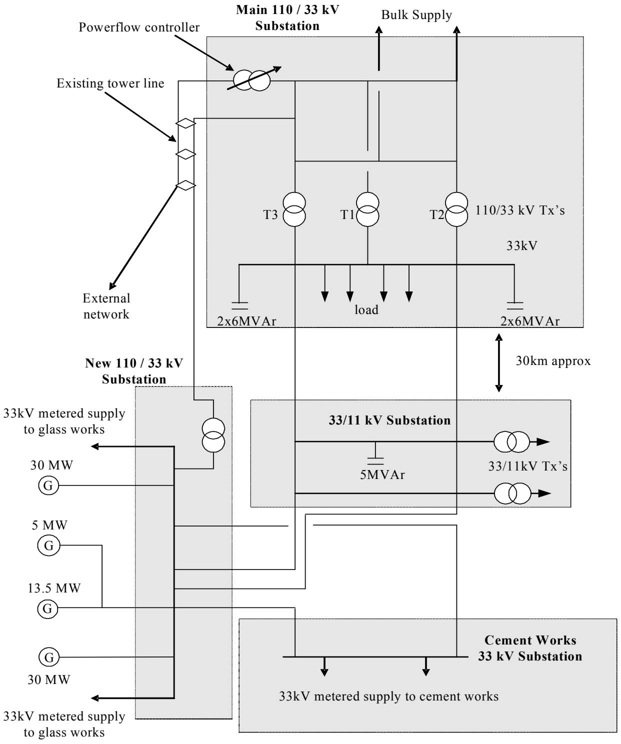

Figure 8 *Distribution Network in Northern Ireland with 78.5 MW wind generation*

The study showed that for high levels of generator export the 33 kV bus voltage at the cement works substation rises to the upper end of the range. Clearly this is typical behaviour for distribution networks with high levels of distributed generation. This voltage rise is limited by tapping of the 110/33 kV transformer at the new substation, but must be accompanied by a reduction of the 33 kV bus voltage at the main 110/33 kV substation in order to maintain the reactive power flows across the network and minimise losses.

This may be achieved by application of the generator estimation technique where voltage attenuation is applied in proportion to the calculated generator output. Paralleled transformers at the main substation and across the network may be controlled using Enhanced TAPP to minimise any circulating current and further reduce losses in the system.

DISCUSSION

Distributed generation has implications for the control of voltage levels across the network. Methodology has been developed to solve issues such as inaccurate LDC, voltage rises at points of connection and impaired control of paralleled transformers.

The methodology has been described using an example of a simple network with a single distributed generator. It may be applied to more complex networks where there are several generators on separate feeders. It is based on an estimation of generator output(s) and relies on knowledge of the network loads.

In most distribution networks where load profiles closely follow each other this knowledge is readily obtainable by simple measurement or reference to historical data. In more complicated networks, such as the network shown in figure 8, it may be required to analyse load information more carefully to be able to apply the most appropriate ‘load share ratio’ (R_{load} in equation 2). More accurate calculation of generator output(s) and application of appropriate voltage levels at regulation points in complex networks could require state estimation techniques that provide robust estimation of the network state [6].

The implementation of the described methodology in a VCR facilitates advanced voltage control of distribution networks and a potential increase in generation levels without the need for reinforcement.

Acknowledgments

The authors would like to thank NIE and Quinn Group for access to network data.

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