Voltage Regulation at Sites With Distributed Generation

Nick Hiscock, Terence G. Hazel, *Senior Member, IEEE*, and Jonathan Hiscock

***Abstract*—In some large industrial sites, generator groups are operated through interconnectors. At such sites, the management of the power flows across the network can be problematic, specifically in situations where the availability of local generation cannot always meet the diverse load demand in that area. This problem will be illustrated by a case study. Under these conditions, the use of an interactive power system state estimation model is critical for managing the supply of real and reactive power to the distributed loads across the network. One aspect of this control implies that voltage levels at key nodes across the network must be adjusted to influence the contribution of reactive power from the generation under varying load conditions. Embedding such a function in a power management system will be discussed. This paper describes how a power system state estimator is used to apply adaptive settings to network voltage control systems that can also operate in "stand-alone" mode to provide a robust level of voltage stability. Other issues concerning the use of distributed generation are discussed with respect to voltage levels and state estimation.**

***Index Terms*—Automatic voltage control (AVC), automatic voltage regulator (AVR), distributed generation, interconnected power system, power factor, power management system (PMS), power transformer.**

I. Introduction

WHERE AN industrial site generates electrical energy for its own use and is operated in an island mode or loosely tied to the main grid system, the management of energy demand can be problematic. As with all networks the energy generated must be equal to the load demand at all times. An imbalance in the generator/load relationship will cause voltages to become abnormal and/or the power system frequency to change.

The control of voltage levels across a network is carried out predominantly by motorized tap-changing transformers equipped with automatic voltage control relays [1]. At a site where a transformer supplies a load, the normal requirement is to maintain the voltage at a preset level in accordance with the local statutory or operating standards. Where transformers form part of a transmission system, tap-changing transformers used to control the voltage levels may additionally be utilized to force reactive energy to flow between nodes such that the generation capability is optimized.

In large power systems, the effect of a short term excess or lack of generation does not greatly affect the performance of the network. However, when the network is relatively small, such as an industrial installation, an imbalance in generation can quickly lead to an uncontrolled situation. Methods have been developed that, when used in conjunction with a power management system (PMS), can provide robust control of voltage levels at network nodes in stand-alone mode or operate using enhanced set-point values as directed by the PMS.

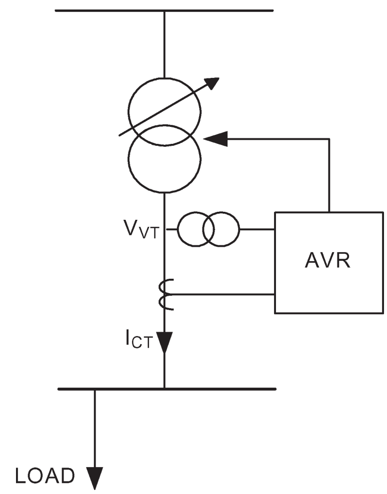

Fig. 1. Basic voltage control.

II. Voltage Control

The simplest form of voltage control can be utilized where a single transformer supplies a load as shown in Fig. 1.

The automatic voltage regulator (AVR) measures the voltage and the current ($V_{\rm VT}$ and $I_{\rm CT}$) at the load side of the transformer. The measured voltage is compared with the reference voltage setting of the AVR ($V_{\rm ref}$). If the difference exceeds the tolerance setting of the AVR, a tap change is initiated to adjust the transformer voltage to a satisfactory level. To avoid a tap change for short-term voltage fluctuations, it is normal practice for a time delay to take place prior to initiation of the control. This is shown in Fig. 2, where the measured voltage ($V_{\rm VT}$) increases until it is outside the dead-band, at which point the AVR initiates a "tap down" command after a time delay and the measured voltage returns to normal. This form of control may additionally include a load-related voltage boost using $I_{\rm CT}$ as a measurement to compensate for load-related voltage drops.

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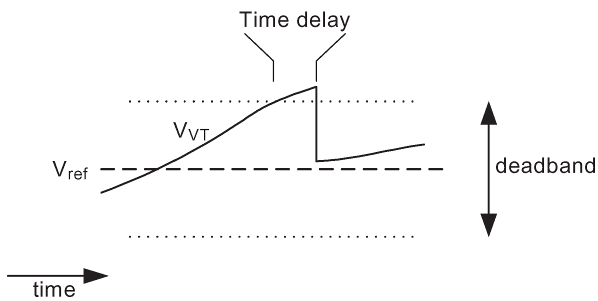

Fig. 2. AVR target voltage and deadband.

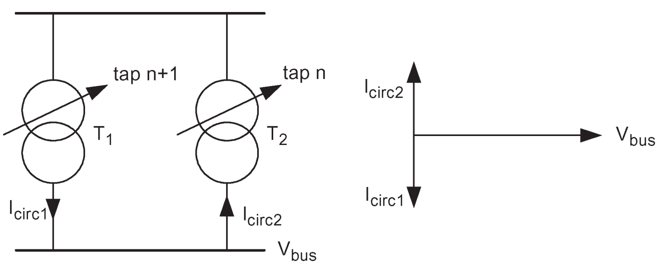

Fig. 3. Circulating current between two paralleled transformers.

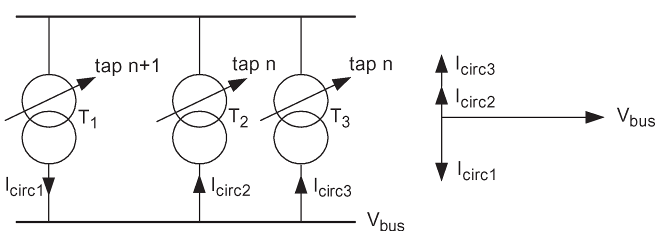

Fig. 4. Circulating current between three paralleled transformers.

It is common practice to parallel transformers to give a higher security of supply [2]. If the open circuit terminal voltages of the paralleled transformers are not identical, a circulating current will flow between them. This current will be highly reactive since the transformers are highly inductive. Fig. 3 shows two paralleled identical transformers, T_1 and T_2, on different tap positions and corresponding vector diagrams. For clarity, load current is ignored. T_1, being on a higher tap position, will attempt to produce a higher output voltage than T_2 and therefore exports circulating current into T_2. The bus-bar voltage, V_{bus}, will be the average output voltage of the transformers.

Fig. 4 shows three parallel identical transformers, with T_1 on a higher tap position than T_2 and T_3. The corresponding vector diagram shows that T_2 and T_3 share the imported circulating current.

If paralleled transformers operate using AVRs for the control of voltage level, a method to maintain the tap position to the point where a circulating current is minimized must be included in the design of the control system. If allowed to operate independently using only voltage control, the tap changers will drift apart and, while the voltage will be the average of their terminal voltages, 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 their efficiency [3]. In a worst case scenario, this may lead to one or both transformers tripping on high winding temperature.

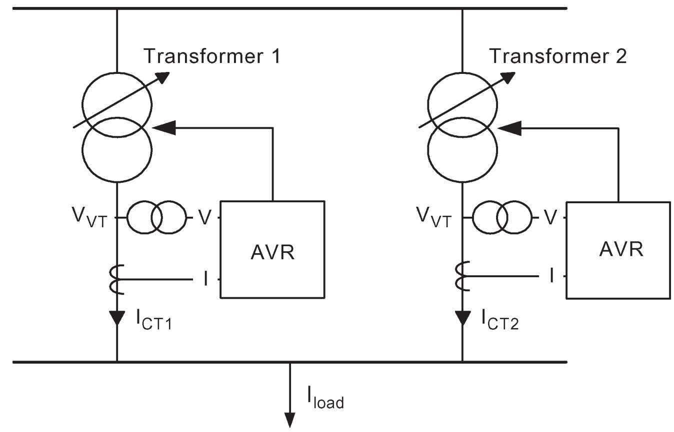

Fig. 5. Two paralleled transformers.

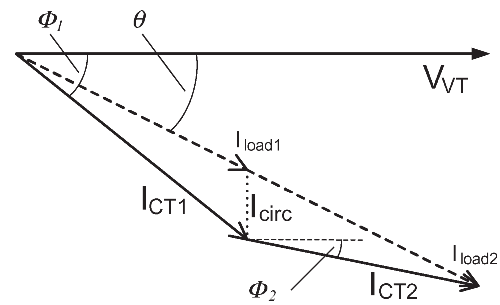

Fig. 6. Vector diagram for calculation of circulating current.

A master/follower method of control can be used to maintain parallel transformers on the same tap positions. This method is predominantly used in older schemes and has some disadvantages.

1) Parallel transformers must be identical.
2) Parallel transformers must be fed from the same primary source.

Two modern methods for voltage control of paralleled transformers that do not have the disadvantages associated with master/follower are discussed.

A. Circulating Current Control

This method requires that the loads of each transformer operating in parallel are summed and provided to each AVR for comparison with the individual transformer load. Fig. 5 shows a site with two paralleled transformers feeding a load. Transformer T_1 is on a higher tap position than T_2. Each transformer has a connected AVR that measures the transformer voltage and current. Fig. 6 shows the corresponding vector diagram.

By reference to Fig. 6, the circulating current flowing through each transformer I_{circ} is calculated as follows:

$$I_{\mathrm{circ}} = I_{\mathrm{CT1}}[\sin\phi_1 - \cos\phi_1 \tan\theta] \quad (1)$$

$$I_{\mathrm{circ}} = I_{\mathrm{CT2}}[\cos\phi_2 \tan\theta - \sin\phi_2] \quad (2)$$

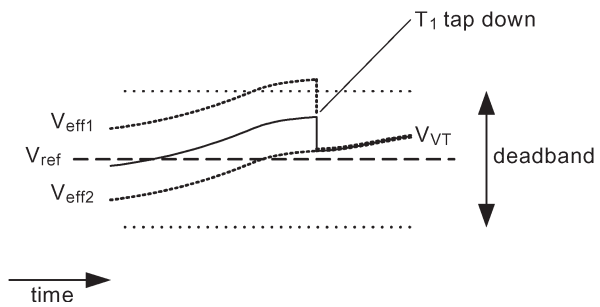

Fig. 7. Voltage profile for an increasing system voltage.

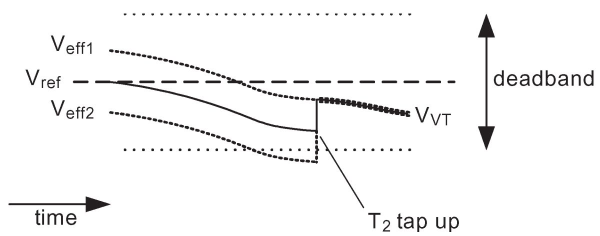

Fig. 8. Voltage profile for a decreasing system voltage.

where

$I_{\rm load}\lfloor\!\underline{\ \theta}$ summed transformer load;
$I_{\rm CT1}\lfloor\!\underline{\ \phi_1}$ measured current on T_1;
$I_{\rm CT2}\lfloor\!\underline{\ \phi_2}$ measured current on T_2.

The derived value for $I_{\rm circ}$ is used to bias the voltage level measurement of each AVR to produce an "effective voltage." The effective voltage $(V_{\rm eff})$ is used by the AVR for control and calculated as follows:

$$V_{\rm eff} = V_{\rm VT} + kI_{\rm circ} \quad (3)$$

where

$V_{\rm VT}$ voltage transformer (VT) voltage measurement;
k constant;
$I_{\rm circ}$ calculated circulating current.

As can be seen from (3), positive circulating current (an export), as seen by T_1 in Fig. 5, increases the effective voltage, whereas negative circulating current (an import), as seen by T_2 in Fig. 5, decreases the effective voltage.

The effect of the bias can be seen in Fig. 7, which shows that T_1 and T_2 arrive at the same tap position when T_1 taps down from position $\rm n+1$ to n as a result of its effective voltage, $V_{\rm eff1}$, exiting the dead-band, and the circulating current is minimized.

The same result is achieved for a decreasing system voltage profile when T_2 taps up from position n to $n+1$, as shown in Fig. 8.

Circulating current control can operate accurately at any load power factor. It has a major operational disadvantage, however, where networks are interconnected and transformers and/or generators operate in parallel across that network. In this situation, the transformer groups can tap apart and result in large reactive currents flowing between them.

B. Reactive Current Control

This method has a major advantage over circulating current control, particularly in that it allows transformers to be operated

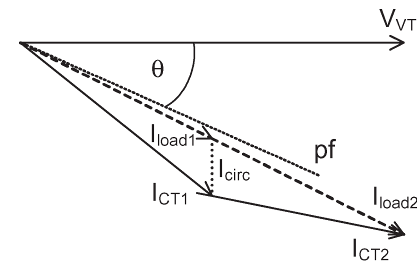

Fig. 9. Vector diagram for reactive current control.

in parallel across a network without large reactive currents flowing in-between. In this method the summed load current is assumed to operate at a power factor, $\rm pf_{sys}$, as shown in Fig. 9 and, unlike the circulating current method, the value of summed transformer currents is not required. The circulating current, $I_{\rm circ}$, can be calculated using (1) and (2), where $\cos\theta$ is the assumed power factor $\rm pf_{sys}$. The voltage measurement used by the AVR is calculated as in (3).

Although the actual power factor at a particular time may not be the specified power factor $\rm pf_{sys}$, the deviation will not be large under normal load conditions. Voltage control will therefore be well within the acceptable tolerance. If the deviation is large, the effect will be an error due to load current being considered as circulating current by the scheme [4]. This error can be used to advantage where generation operates in parallel with tap-changing transformers, as will be described later.

In circumstances where the load power factor may vary substantially, the reactive current bias can be reduced to offset the measurement error. In this case the transformers will still operate to the optimum tap positions, but will also allow a through flow of reactive current at the expense of a small voltage error. An example of how this is achieved is presented in Appendix A.

III. Generator Control

The design of a generator determines the limits of real and reactive power that can be supplied to a network. The real power that a generator supplies is determined by the input of fuel to the driving mechanism. The reactive power, being the other component required by the network, is derived from the level of excitation applied to the generator.

The excitation also determines the generator terminal voltage. There are several methods by which a generator may be controlled when operating in a network where power is supplied from more than one point. Of these methods, two are most commonly used for industrial sites.

A. Power Factor Control

This form of control is commonly applied at industrial sites where a generator is operating in parallel with a transformer. The transformer effectively controls the voltage. By having the generator in power factor control, there is no possible control conflict between the generator AVR and the transformer AVR. The disadvantage of this form of control is that under low

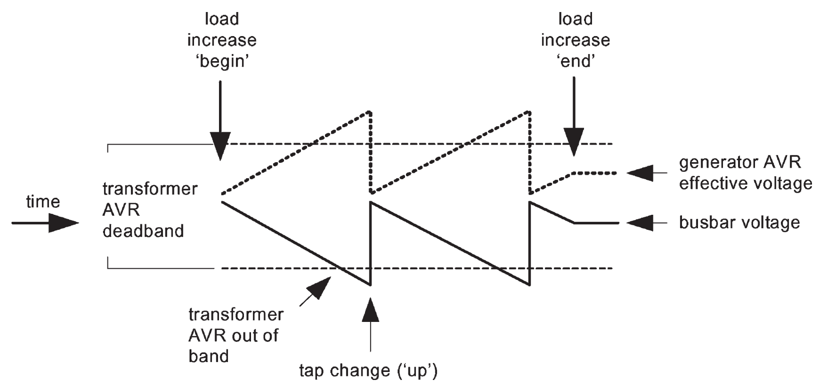

Fig. 10. Generator and transformer AVR responses to an increase in load demand.

voltage (LV) conditions where additional reactive power is required, the spare reactive capacity of the generator is not available for use. It can only be made available by decreasing the power factor set point, but this infers coordinated regulation with other voltage control systems.

B. Voltage Control

This form of control is also used at industrial sites where generators are operated in parallel with transformers and there is a requirement to provide a proportional reactive load support under varying circumstances.

A generator can precisely control the voltage of the bus-bar to which it is connected provided that it is the only generator on the bus-bar. The bus-bar may also be supported, for security of supply, by remote generation via a constant ratio transformer, with the transformer impedance acting to attenuate the effect of the operating levels of remote loads and generation. If the support network is relatively weak, the generator will easily control the bus-bar voltage.

If however, the transformer and support network is strong, the generator will not be able to easily control the bus-bar voltage. In this case, the generator excitation must operate in voltage droop mode such that a decrease in the bus-bar voltage will result in an increase in the production of reactive power by the generator, and vice-versa. This is the same concept as frequency droop used for the regulation of active power. A typical value for this voltage droop is 5.5%, i.e., a 100% change in reactive power corresponds to a 5.5% change in the generator bus voltage.

As the demand for reactive power changes, the voltage measurement on both the generator and transformer voltage regulators are biased to enable the required droop. The generator control is continuously adjusted, whereas the transformer AVR operates only after the effective voltage (the voltage measurement plus the bias) is first, outside the "normal" deadband and second, after a time delay. Fig. 10 demonstrates the interaction of the control systems and the effective bus-bar voltage, where load demand increases and then stabilizes at the new level. During the change, the generator AVR continuously adjusts the excitation to produce more reactive power.

The transformer AVR, however, only responds with step changes, the "effective voltage" determining the point at which each AVR measures the voltage as "out of band." During this process, the bus-bar voltage will be as shown in Fig. 10, with the actual value mainly dependent on the impedances of the generator and transformer. Fig. 10 shows the generator and transformer effective voltage to be slightly different at the completion of the adjustment, this being the closest tap position obtainable by the transformer.

As the generator control has a very small voltage hysteresis and the transformer tap changer operates to give a step change in voltage, the bus-bar voltage will rarely be identical to the AVR set-points. However, the difference will be practically small and is therefore acceptable.

When more than one generator operates on a common bus, each will contribute reactive power to maintain the voltage. The disadvantage of this method is that the voltage will vary slightly as a function of the load. As the load increases (assuming a fairly constant power factor), the voltage will slightly decrease. It is common to have some type of secondary generator regulation such as load-sharing modules, to adjust the voltage set points of all generators to maintain the voltage within an acceptable range.

IV. Distributed Generation

Where generation is distributed around a network, the voltage levels at the various nodal points will determine the magnitude and direction of the reactive power flowing in each part of the network. In situations where transformers form part of the network, the combination of voltage control and the bulk impedance presented by the transformers at the point of common coupling will restrict the ability of the generation to supply the reactive load demand. This situation is particularly applicable to large industrial installations.

The management of voltage levels in a network is executed to achieve two objectives:

1) regulation of the voltage level at the point of use;
2) adjustment of voltage levels at key nodal points to enable the transport of reactive power between interconnected generation and load centers.

When voltage control is used to encourage the flow of reactive power across a network, there is a limitation with the conventional design of an AVR that uses reactive current control for paralleled transformers (note, however, that this form of control is the only system that will operate safely with remotely paralleled transformers).

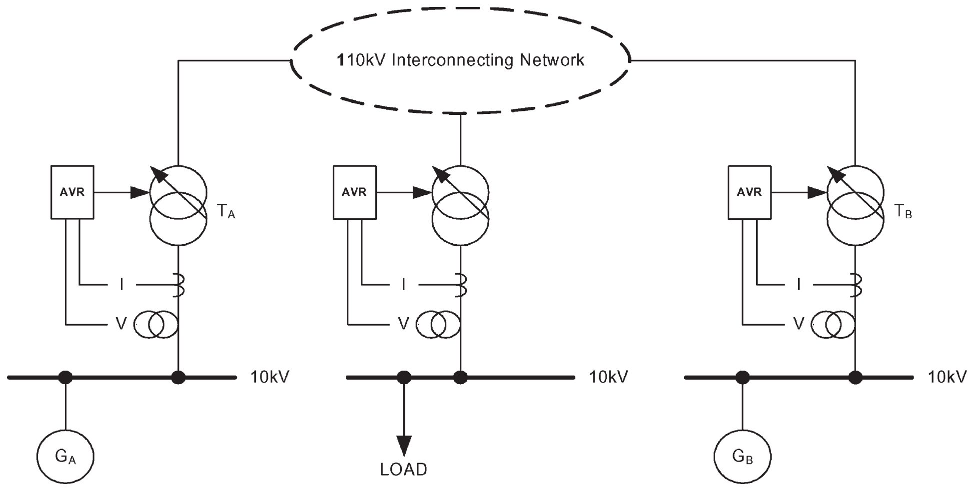

Fig. 11. Interconnected power system.

As described previously, a change in the power factor of the transformer load is calculated as a circulating current and the AVR measurement circuit is biased to prevent the flow. This effect can be diminished by a reduction of the circulating current bias setting to a level that is sufficient to maintain paralleled transformers at the correct tap positions, while at the same time allowing reactive current to flow across the network.

There are limitations to a generator output, both for real and reactive current. In any event, the vector sum of these currents cannot exceed the generator maximum rating. If the generator is operated to maintain the system voltage, its ability to do this is limited by the generator maximum rating and the local reactive power demand.

An example of an interconnected network is shown in Fig. 11, where generators $G_{\rm A}$ and $G_{\rm B}$ supply load to a bus-bar. The generating points are interconnected by step-up transformers to a 110 kV network. The load is supplied through a step-down transformer with conventional voltage control.

If the maximum reactive output of a generator is reached, reactive current must be imported from a remote generator. In this example, generator $G_{\rm A}$ is producing the maximum reactive current while the other unit $(G_{\rm B})$ has spare capacity. Assume here that the generators are operating to control the reactive power output and maintain the bus-bar voltage at a constant level. If the reactive power demand of the load increases, $G_{\rm B}$ will be required to supply it, otherwise the voltage level at $G_{\rm A}$ and the load bus-bar will become low.

This objective can be achieved by subtle adjustment of the primary/secondary ratios of transformers $T_{\rm A}$ and $T_{\rm B}$. Referring again to Fig. 11, assume that the network is shown at balance with $G_{\rm A}$ generating its output limit of reactive current. Assuming that the demand for reactive current at the load center increases, the voltage at $G_{\rm A}$ will drop so that the generator rating is not exceeded. In an extreme case, this situation can lead to a higher local demand coincident with a further fall in voltage, ultimately leading to a complete failure of $G_{\rm A}$.

If $G_{\rm B}$ has spare capacity, reactive current can be supplied by adjustment of the tap position of $T_{\rm B}$. Through an increase in the ratio of transformer $T_{\rm B}$ (decrease in tap position), the voltage output to the higher voltage network is increased and leads to an increase in the flow of reactive current to the load; the voltage at the load is also maintained at the correct level by virtue of the local AVR. This method of control is an enhancement to the use of reactive current control by generator field control. It can be utilized to overcome the additional limitations of the network impedances that may force a generator to operate at the limit of its rating in terms of current, voltage, and temperature.

A. Selection of Controlled Voltage

The ability of a voltage control mechanism to change voltage is dependent on the relative impedance of the primary and/or secondary networks.

If a generator is set to control the voltage on a bus-bar that is also connected to a tap-changing transformer set for control of the voltage to that bus-bar, any adjustment to the transformer AVR set point will change the flow of reactive current to or from the higher voltage network.

Under some operational circumstances, e.g., loss of $G_{\rm B}$ in Fig. 11, a lack of generation at remote points on the network may result in unsatisfactory voltage across the higher voltage system. Under this condition, one solution is to allow generator $G_{\rm A}$ to control the voltage of the lower voltage bus-bar and the transformer voltage control system to control the higher voltage system. This facilitates a robust and safe control method whereby the voltage levels at all points are measured and controlled. If, however, generator $G_{\rm A}$ is out of service and voltage control of the lower voltage bus-bar is lost, then the transformer voltage control must be switched to control the lower voltage bus-bar.

In practice, control of the high voltage (HV) side terminal voltage is difficult. Reference to Fig. 11 shows the normal location of the VT and current transformer (CT) on the LV side, this also being the normal control point. Measurement of current and voltage on the HV side is therefore practically impossible for conventional equipment.

B. Virtual VT

A practical and well-designed solution is provided by the development of a "virtual VT" algorithm. This algorithm uses

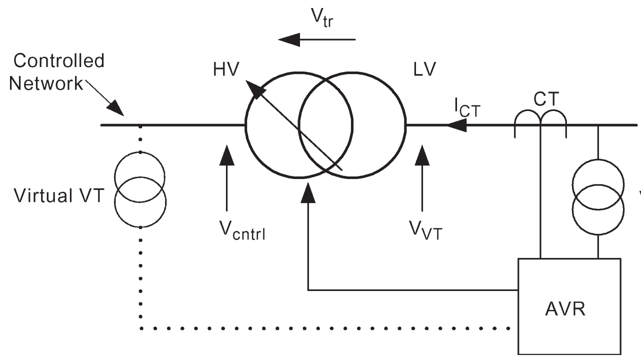

Fig. 12. Control of HV side of transformer.

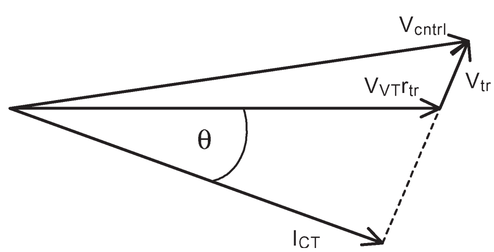

Fig. 13. Vector diagram for control of HV side of transformer.

the fixed voltage and current measurement reference points of the transformer to calculate the voltage on whichever side is to be controlled.

Where the measurement and control points are the same, the algorithm is simple and the control voltage is basically the measured voltage from the VT. When the reference and control points are on different sides of the transformer, the algorithm is more complex. To calculate the control voltage, several factors are taken into account:

1) transformer primary/secondary ratio;
2) transformer winding impedance;
3) transformer load current;
4) transformer load power factor.

It is commonly the case that a power transformer has the highest primary/secondary ratio on the lowest tap position. In this case the actual ratio, r_{tr}, is calculated as follows:

$$r_{\mathrm{tr}} = \frac{\mathrm{HV_{nom}}}{\mathrm{LV_{nom}}} \times \left(1 - \frac{(p_{\mathrm{act}} - p_{\mathrm{nom}}) \times V_{\mathrm{step}}}{100}\right) \tag{4}$$

where

$\mathrm{HV_{nom}}$ nominal HV voltage (in kilovolts);
$\mathrm{LV_{nom}}$ nominal LV voltage (in kilovolts);
p_{nom} nominal tap position;
p_{act} actual tap position;
V_{step} voltage tap spacing (in percent).

A practical estimate of the actual transformer impedance Z_{act} taking into account the current tap position is made. This assumes that the impedance changes linearly through the transformer

$$Z_{\mathrm{act}} = Z_{\mathrm{tr}} \times \left(1 - \frac{(p_{\mathrm{act}} - p_{\mathrm{nom}}) \times Z_{\mathrm{step}}}{100}\right) \tag{5}$$

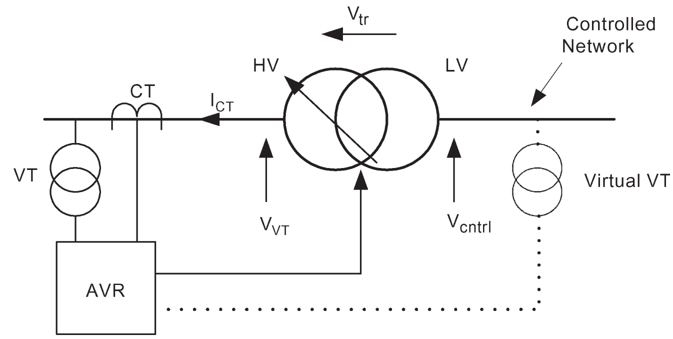

Fig. 14. Control of LV side of transformer.

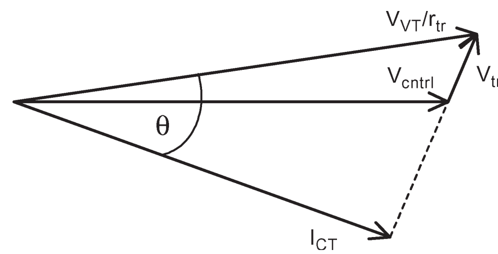

Fig. 15. Vector diagram for control of LV side of transformer.

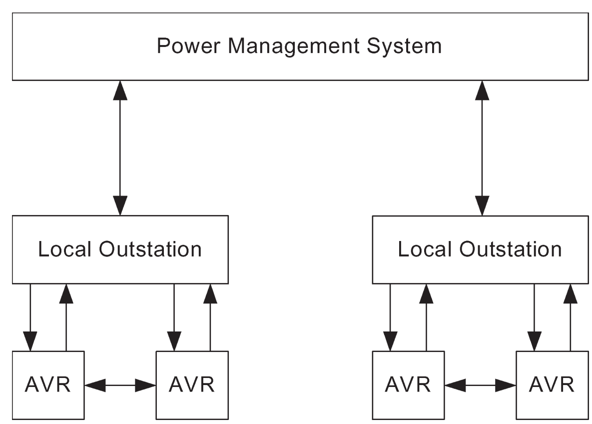

Fig. 16. PMS data flows.

where

Z_{tr} transformer nameplate impedance (in percent);
p_{nom} nominal tap position;
p_{act} actual tap position;
Z_{step} impedance tap spacing (in percent).

As the dominant component of the winding impedance is reactive, the effect of winding resistance can be largely ignored, although for better accuracy a factored value can be included in the calculation.

The voltage dropped through the transformer V_{tr} can be calculated on the LV or HV side of the transformer as follows:

$$V_{\mathrm{tr}} = \sqrt{3}\left(\frac{\mathrm{LV_{nom}^2}}{S \times 100}\right) \times Z_{\mathrm{act}} I_{\mathrm{LV}} \angle(90 - \theta) \tag{6}$$

$$V_{\mathrm{tr}} = \sqrt{3}\left(\frac{\mathrm{HV_{nom}^2}}{S \times 100}\right) \times Z_{\mathrm{act}} I_{\mathrm{HV}} \angle(90 - \theta) \tag{7}$$

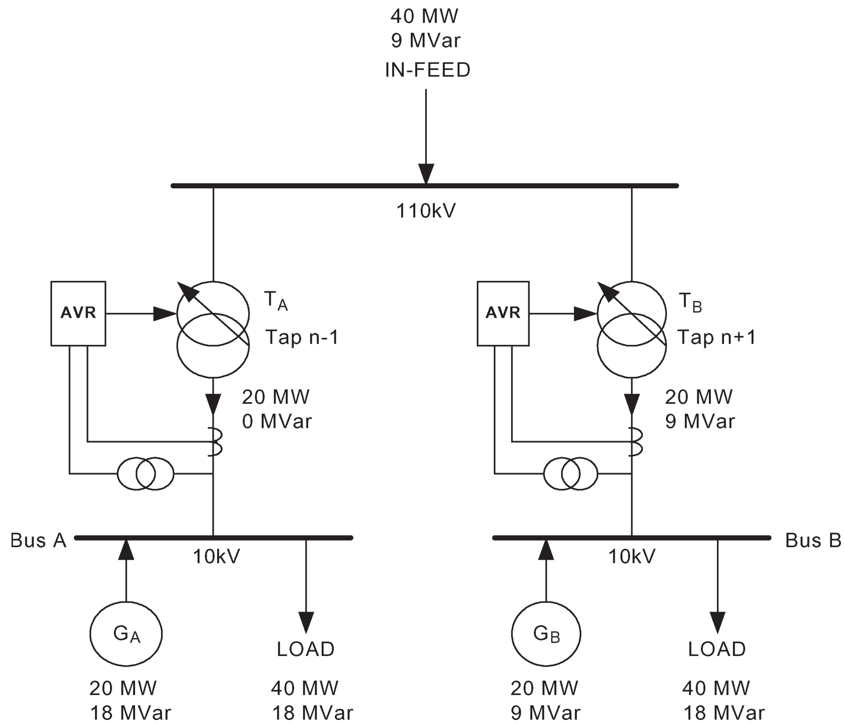

Fig. 17. Unequal share of generator reactive power output.

where

$\mathrm{LV}_{\mathrm{nom}}$	nominal LV voltage (in kilovolts);
$\mathrm{HV}_{\mathrm{nom}}$	nominal HV voltage (in kilovolts);
S	transformer rating (in megavoltampere);
Z_{act}	actual transformer impedance (in percent);
I_{LV}	measured transformer LV load current;
I_{HV}	measured transformer HV load current;
$\cos\theta$	load power factor (θ in degrees).

1) Measurement LV—Control HV: This scenario is shown in Fig. 12, where the CT and VT are on the LV side and the control point is on the HV side of the transformer.

The relationship between the control voltage (V_{cntrl}) and the measured voltage (V_{VT}) is shown in vector form in Fig. 13 and mathematical form in

$$V_{\mathrm{cntrl}} = V_{\mathrm{VT}} r_{\mathrm{tr}} + V_{\mathrm{tr}} \tag{8}$$

where

r_{tr}	actual ratio of the transformer, calculated using (4);
V_{tr}	voltage drop through the transformer windings, calculated using (6).

2) Reference HV—Control LV: This scenario is shown in Fig. 14, where the CT and VT are on the HV side and the control point is on the LV side of the transformer.

The relationship between the control voltage (V_{cntrl}) and the measured voltage (V_{VT}) are shown in vector form in Fig. 15 and mathematical form in

$$V_{\mathrm{cntrl}} = \frac{V_{\mathrm{VT}}}{r_{\mathrm{tr}}} - V_{\mathrm{tr}} \tag{9}$$

where

r_{tr}	actual ratio of the transformer, calculated using (4);
V_{tr}	voltage drop through the transformer windings, calculated using (7).

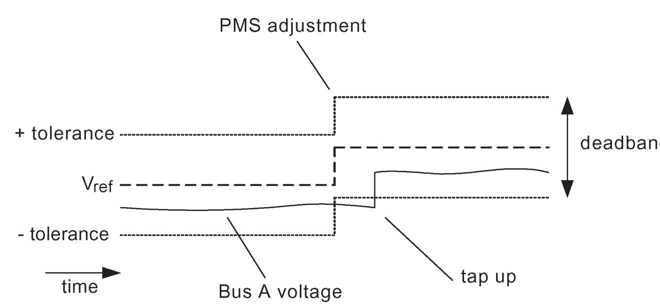

Fig. 18. Increase in AVR set point by PMS.

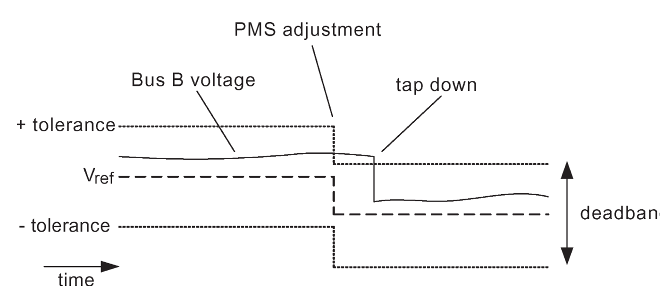

Fig. 19. Decrease in AVR set point by PMS.

V. State Estimation

The development of an AVR incorporating the virtual VT has been completed and evaluated to act under the direction of a PMS that incorporates a network state estimation algorithm. It is the PMS that commands the transformer AVR to regulate either the HV or LV side of the transformer depending on the overall configuration of the power system.

Following a state estimation cycle, the voltage levels at various points on a network may be required to change. This action may be carried out by direct control of the various

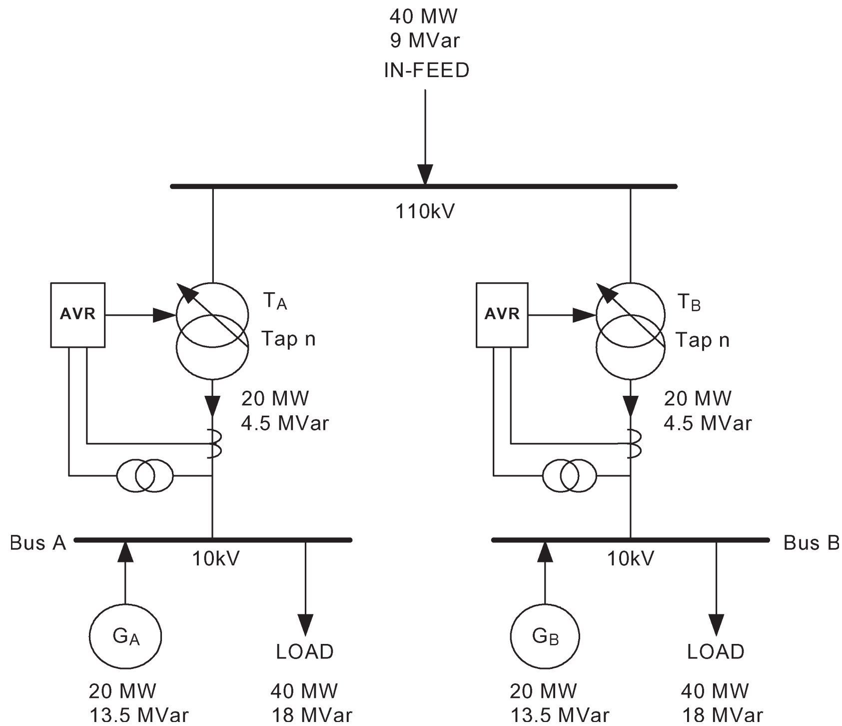

Fig. 20. Equal share of generator reactive power output.

tap-changing transformers that form part of the network. In reality this control would be enabled through a communications system and require interface devices to control the tap change mechanisms. A failure of the communications would render all control inoperative and lead to a possible unstable condition.

A robust approach is to maintain discrete voltage control at each bus-bar, where tap-changing transformers are installed using AVRs that are able to accept remote set-point adjustments from the PMS and operate using a "virtual VT" measurement algorithm to allow the selection of measurement and control points. Under this operating regime, a failure in communications will leave the AVR equipment in operation and maintain voltage levels in a safe manner.

Two methods for the remote adjustment of voltage set-points can be implemented; hard-wired inputs or transmission of data set-point values using an industry standard protocol. Fig. 16 demonstrates the organization of data flows associated with the remote AVR equipment and the PMS, and indicates a "hard-wired" configuration between the local outstation and each AVR at a site.

A further advantage in the design of the AVR is the inclusion of a peer-to-peer communication medium that will facilitate the transfer of load data between the units operating in parallel. Using summed load information, each AVR can optimize its operating point based on the total connected load to the common bus-bar. If a unit is to be switched in or out of service, each AVR can operate to minimize and load related voltage drops.

As an example, the PMS could instruct an AVR to adjust its operating set-point to facilitate an imminent switch-out. This process can be carried out by the AVRs such that all reactive current is transferred from the unit to be switched out onto the units that will remain in service. Following the switch-out, the AVRs will revert to normal operation and the bus-bar voltage will remain unchanged. This avoids step jumps in the voltage that could be detrimental to correct operation of the process equipment.

VI. Case Study

The manipulation of reactive power flows around a network by set-point adjustments from the PMS to transformer AVRs has been discussed. This simple case study shows how a change to an AVR reference voltage can result in a change in reactive power flows.

Fig. 17 shows a simple power network in which two generators are interconnected through an HV network via tap-changing transformers T_A and T_B. Generator G_A supplies more reactive power than G_B.

The PMS increases the reference voltage setting of the AVR (and shifts the dead-band accordingly) on T_A, which then taps up to tap position n and consequently increases its reactive power contribution to bus A. This is shown in Fig. 18.

The PMS decreases the reference voltage setting of the AVR on T_B, which then taps down to tap position n and consequently decreases its reactive power contribution to bus B. This is shown in Fig. 19.

The resulting power flows are shown in Fig. 20. The generators now share the reactive power supply equally and the bus-bar voltages are maintained at the correct level.

VII. Conclusion

Generators and tap-changing transformers can be used to control the level of voltage throughout a network. The transformers in the network also influence the direction and magnitude of the reactive component of power that flows to the loads.

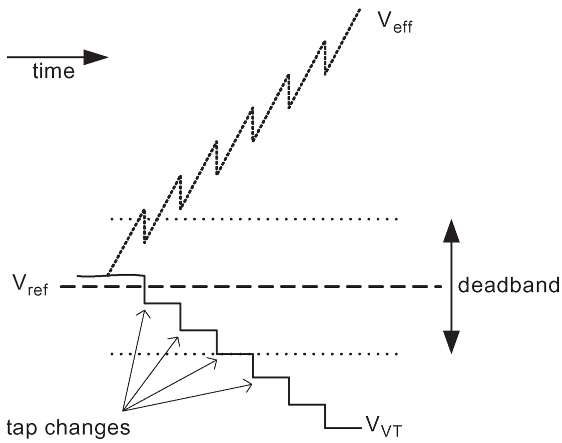

Fig. 21. Effective voltage change at full bias.

Management of the distribution of reactive power from generators to loads can be achieved through the use of a PMS and state estimation algorithm acting to influence voltage levels at key points across the network. In the event of a failure or loss of communication between the PMS and the voltage control equipment, the local voltage control systems will maintain the voltage conditions at an acceptable level.

To achieve the required level of control for the transformers, two key requirements have been identified:

1) a reactive control principle with reduced sensitivity;
2) a measurement technique that includes an algorithm for the control of voltage from either side of the transformer.

A case study has demonstrated that the use of a PMS in conjunction with suitable voltage control equipment provides an efficient and robust method for the control of voltage levels and management of reactive power flows.

Appendix
Reduced AVR Bias

The reactive current control method is used to minimize circulating current flowing between paralleled transformers. The calculation of circulating current is based on the deviation of the transformer load current power factor from an assumed value, pf_{sys} (see Section II-B). It may be required that an increase in reactive power is supplied by the transformer. If this happens, a deviation in load power factor will be observed and interpreted as circulating current. If the deviation in power factor is large, the AVRs will produce a bias that may lead to the transformers tapping to the end of the tapping range. This is shown in Fig. 21, which shows the voltage profile for the paralleled transformers shown in Fig. 5 (for T_A and T_B on tap position n) as the reactive power steadily increases. The bias, as calculated using (3), causes the effective voltage on both AVRs to increase, resulting in both transformers tapping to the lowest tap position.

If a reduced bias setting is applied to the AVR, the increase in reactive power flow can be accommodated, as shown in Fig. 22.

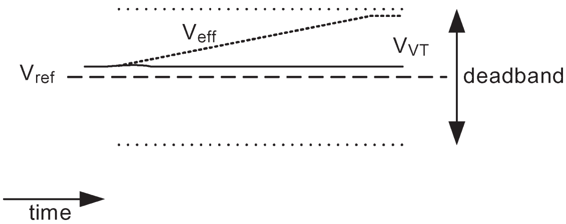

Fig. 22. Effective voltage change at reduced bias.

The amount by which the bias is reduced to produce the required reactive power flow is calculated by considering the droop characteristic of the generator AVR. The transformer AVR must match the generator AVR drooping characteristic so that they may share their reactive power contributions equally.

The reduced bias setting will still maintain paralleled transformers on optimum tap positions using reactive current control for the minimization of circulating current.

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