Load Transfers Between Feeders on a 3-Phase 3-Wire Distribution System Utilising Single-Phase Open-Delta Connected Regulators

Pannam R.A.[1], Nesdale K. M.[2] and Foster J.D .[3]

[1]South East Queensland Electricity Corporation Limited, P.O. Box 1461 Brisbane, Qld 4001 Australia
[2]Cooper Power Systems Pty Ltd, 6/175 Briens Rd, Northmead, NSW 2152 Australia
[3]Cooper Power Systems, P.O. Box 100, Franksville, WI 53126 USA

Abstract

The practice of using two single-phase regulators connected in an open-delta configuration for regulating voltage levels on three-phase distribution systems is quite popular amongst many utilities. Whilst the practice is economical and is an effective method of maintaining statutory voltage at the extremities of long feeders, consideration must be given to operating practices, particularly when transferring loads between feeders. This paper presents information which can be used to improve operating practices and reduce the possibility of customers being exposed to below statutory voltage during feeder switching operations.

1.0 Introduction

The South East Queensland Electricity Corporation Limited (*Trading name SEQEB*) is an electricity distribution corporation that purchases electricity in bulk from the Queensland transmission grid and distributes to over 900,000 customers in south east Queensland. SEQEB operates a transmission/sub-transmission system of 132 kV, 110 kV and 33 kV. SEQEB's distribution system is a 3-phase 3-wire 11 kV system with delta-star 11/ .415 kV distribution transformers.

SEQEB's area of distribution covers some 24,000 sq km that includes large areas of urban development: Brisbane City, the Gold Coast to the south of Brisbane, and the Sunshine Coast to the north. It also covers large rural areas in the coastal hinterlands, and to the west of Brisbane. It is in these rural areas that quite long 11 kV feeders exist, and it is necessary to use regulator stations along the feeders to achieve acceptable voltage at the extremities. The 11 kV feeders are generally run in radial configurations with open tie points between feeders available for load transfers during emergencies or maintenance.

2.0 Open Delta Connected Regulator Stations

SEQEB utilises two single-phase regulators connected in an open-delta (sometimes called "V") configuration on 11 kV feeders.

A voltage regulator is a tap-changing autotransformer with the ability to continuously monitor its output voltage and automatically adjust itself by changing taps until the desired voltage is obtained.

Dist2000 Conference
Sydney, Australia
November 4-7, 1997

Single-phase units (such as Cooper Power Systems VR-32 Voltage Regulators) typically offer +/- 10 % regulation via 32 taps (5/8 % per tap). This gives 10 % regulation per phase when used in an open-delta configuration and 15 % regulation per phase when used in a closed-delta configuration [1]. The microprocessor controls used in modern regulators offer a wide range of functions including full digital remote control, profile recording and bi-directional power flow capabilities.

A number of papers concerning the use of single phase voltage regulators on three-phase systems have been published [2],[3],[4]. They have focused primarily on the effects of regulators on fault current levels, and thus system overcurrent protection. In contrast, this paper examines operational issues associated with transferring load between feeders that have regulators, and the impact that it may have on earth fault protection.

Figure 1 illustrates how two single phase regulators are connected in open delta configuration.

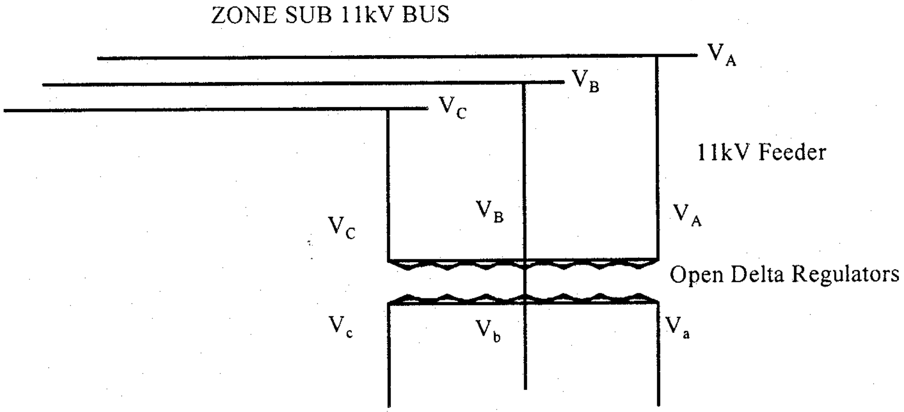

Figure 1 - Open Delta Configuration Connection Details

Figure 2 is a phasor diagram that illustrates how the open-delta connection achieves a boost in all three 11 kV line-to-line voltages.

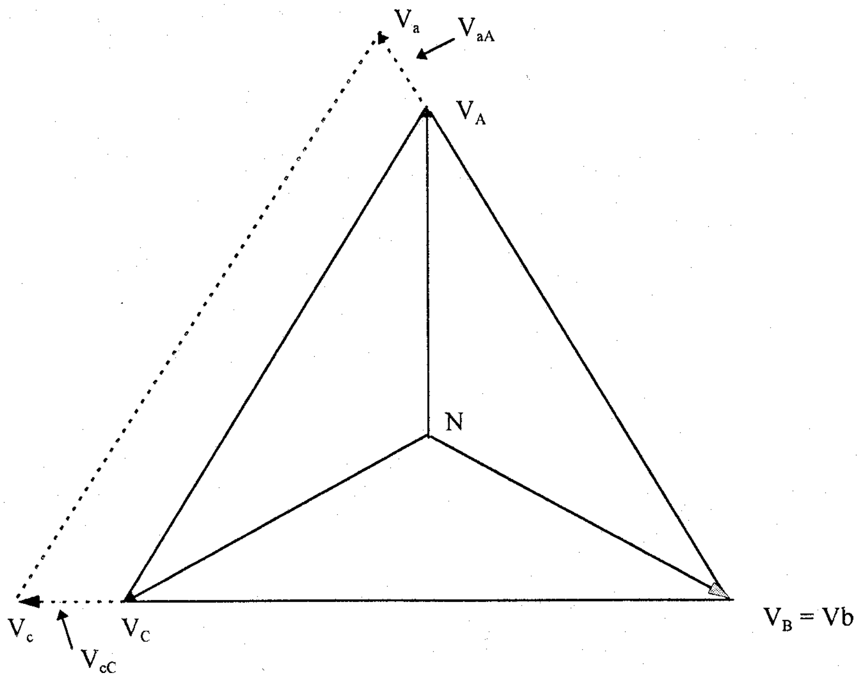

Figure 2 - Open Delta Regulator Phasor Diagram

With reference to figures 1 and 2: The regulator connected between$V_A$and$V_B$gives a boost in the line voltage represented by V_{aA} . Similarly the unit connected between V_B and V_C boosts the line voltage by V_{cC}. This effectively gives three balanced line-to-line voltages on the secondary of the regulator station being: V_{bc} , V_{ab}, andV_{ca}. (Note $V_B$andV_b are at the same point in figure 2).

3.0 Practical Operating Considerations

Typically 11 kV 3-wire 3-phase distribution feeders are supplied from the 11 kV bus of zone substations that have transformers of either 33/11 kV, 132/11 kV or 110/11 kV. In the case of 33/11 kV the transformers are delta-stars with the 11 kV star point being earthed, in many cases, through a neutral earthing resistor (NER) or neutral earthing reactor (NEX). In the case of 132/11 or 110/ 11 kV the transformers are star-delta connected with the 11 kV delta winding being earthed via an earthing transformer. No other earth points exist on the 11 kV system, because plant such as 11 kV capacitors do not have star points earthed. Figure 3 is a schematic diagram of a typical 33/11 kV system.

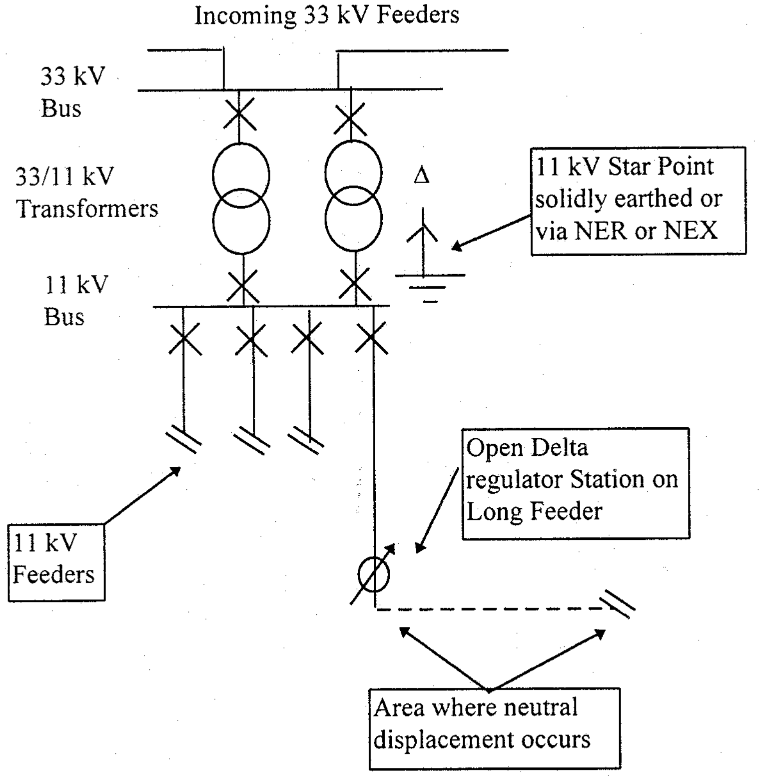

Figure 3
Typical 33/11 Zone Substation and Distribution System

When open-delta regulators are used they do produce some neutral displacement of the 11 kV system beyond the regulator station, this area is highlighted in figure 3. Figure 4 demonstrates by the use of phasors how the neutral displacement occurs. It illustrates the phase-to-neutral voltages on both the primary and secondary sides of the regulator and the associated neutral points (primary side neutral is N, secondary side neutral is n).

The neutral displacement, however, does not under normal circumstances cause a problem because all loads are connected phase to phase (ie delta-star 11 kV/415V transformers), and as previously mentioned no earth connections exist apart from the zone substation neutral. No physical connections to 'n' (see figure 4) exist, it is simply the theoretical neutral associated with the regulators output phase voltages.

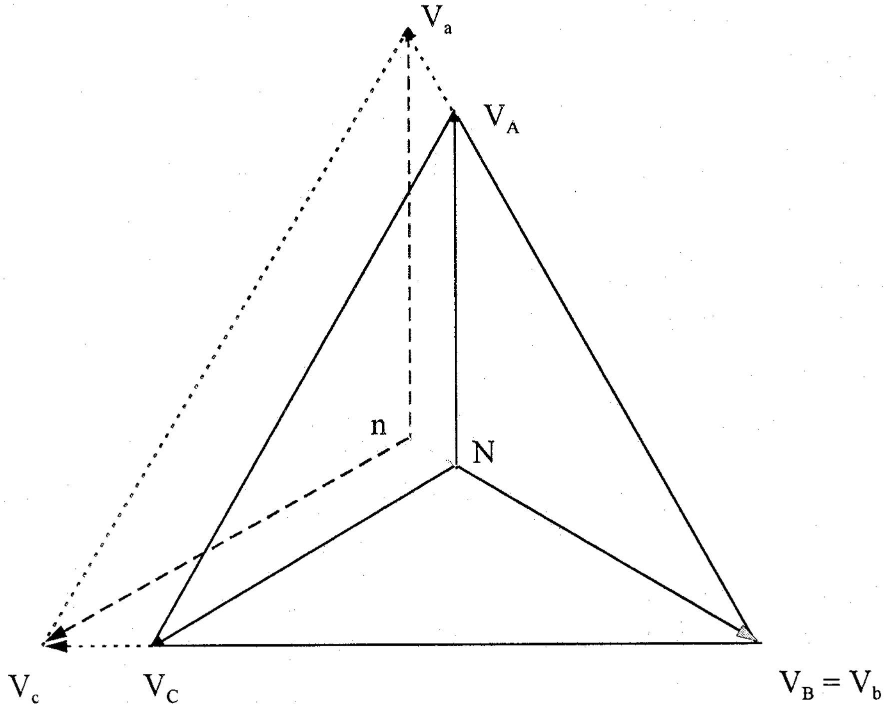

Figure 4
Phasor Diagram Showing Neutral Displacement

However, during paralleling of feeders to transfer load, the difference in neutral displacement between a feeder that has a regulator and one that does not may cause unbalanced currents to flow that are high enough to trip earth fault (E/F) protection. Earth fault protection at zone substations provided by an IDMT relay typically has a setting of 40 amps unbalance current. In the case of pole-mounted reclosers the E/F setting used by SEQEB is typically 20 amps.

Even if both feeders being paralleled have regulator stations, depending on the way in which the open delta is connected or even the tap settings, the regulators may still cause the feeder earth fault protection to trip.

To overcome this problem when paralleling feeders SEQEB has traditionally had a policy of placing all regulators on neutral tap (ie 1:1 tap ratio) during paralleling operations. Whilst this did solve the problem (as there is no neutral displacement when the regulator station is not boosting) it was causing many customers to be exposed to below statutory voltages during the switching operations.

The main aim of the study presented in this paper was to devise some simple rules to be used by system control staff when producing switching sheets for feeders that have open-delta regulators. The rules developed should be applicable to any feeder with any number of regulator stations and allow for the transferring of load between feeders without having to place all regulators on neutral tap or having black changeovers.

4.0 Investigation of Problem

The first stage of analysis is to consider the situation of paralleling a feeder that has a regulator station with one that does not [5]. Figure 5 illustrates the model that is used.

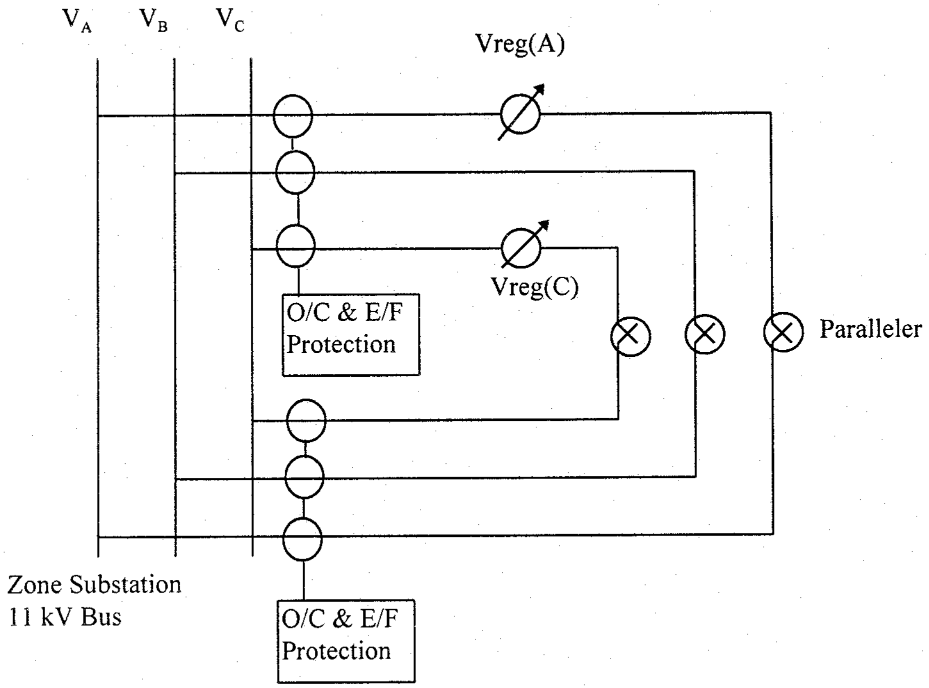

Figure 5
Model of 11 kV Feeder With Regulator Station

It should be noted in figure 5 that the regulators are shown as voltage sources in 'A' and 'C' phases, but the regulators are actually connected 'A' to 'B' and 'C' to 'B' phases. This is explained with reference to figure 2.

In figure 2 it can be seen that the single phase line-to-line regulators can actually be represented by adding to 'A' phase a voltage source of magnitude V_{aA} and to 'C' phase one of magnitude V_{cC}.

Furthermore, when analysing the circuit in figure 5 in terms of unbalance currents, with the paralleler closed, it is possible to ignore the substation 11 kV bus voltage and simply calculate the unbalanced currents in the closed loop caused by the regulator driving voltages Vreg(A) and Vreg(C).

In must be pointed out that the majority of the analysis that follows assumes:

- All regulators are boosting not bucking volts.
- Both regulators in the open-delta connection are on the same taps. (In practice each may be one or two taps different without causing an excessive problem).

The currents flowing in the three-phase loop when the paralleler is closed can be determined by considering the matrices:

$$[V] = [Z] \cdot [I] \qquad \text{(eqn 1)}$$

where

[V] = loop driving voltages in A, B, and C phases of the loop
[Z] = phase matrix representing the loop impedance
[I] = phase currents I_A, I_B, I_C

In the appendix to this paper a general solution for equation I is derived, and gives the resultant residual current ($I_A+I_B+I_C$):

$$I_{residual}\,(amps) = \frac{(\text{tap number}) \times 0.00625 \times 11000 \times \sqrt{3}}{Z_0\,(ohms)} \qquad \text{(eqn 2)}$$

Equation 2 can also be applied to the situation where there are regulator stations on both feeders, so long as the regulators are connected to identical phases. In this case instead of using the tap number in the equation, the difference in taps between the regulator on one feeder compared to the other is used. This has come to be known as "net tap difference." Furthermore, if all regulator stations are connected with the same phasing arrangements then the equation can also be applied to the situation where feeder X has one regulator and feeder 'Y' has two regulators. This is done by simply adding together the taps for the two regulators on feeder Y and comparing them to the tap position of the regulator on feeder X.

4.1 Simplification of Equation

A further simplification of equation 2 was made to make it easier to apply considering the type of information that is usually available when preparing switching sheets. For SEQEB's standard 11 kV line constructions it was found that the zero sequence impedance was between about 1.35 to 1.85 ohms per km, depending on ground resistivity, conductor type, construction type and conductor height. It was thought best to assume a fairly conservative value so 1.4 ohms/km was chosen which results in the equation simplifying to:

$$I_{residual}\,(amps) = \frac{(\text{net taps}) \times 85}{\text{feeder loop length }(km)} \qquad \text{(eqn 3)}$$

When this equation is used it is quite easy to determine the allowable taps that regulators may be on during paralleling operations without tripping earth fault protection, so long as the feeder lengths are known (or can be reasonably estimated).

4.2 Field Tests

Staff from SEQEB's South Coast Region conducted some field measurements of residual feeder currents when paralleling feeders that had open delta connected regulators [6]. The area where the tests were done was

Tamborine Mountain which is a rainforest area in the Gold Coast Hinterland. It is an area supplied by several 11 kV feeders all of which are quite long and have one or more regulators.

One of the feeders used for the tests had two regulator stations, and the other three. The tests consisted of measuring the unbalance currents in the 11 kV system for various numbers of net tap differences between the feeder. The results of the test, and a comparison with equation 3 is given in table 1. The feeder loop involved when the feeders were paralleled was 47 km in length, and the feeders were both supplied from Cades County Zone Substation.

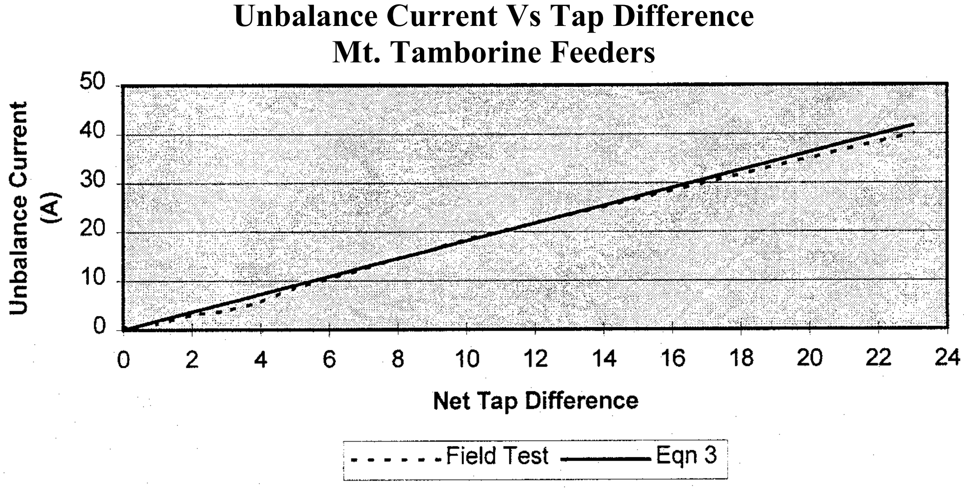

Figure 6
Field Test Results

Figure 6 indicates that a good correlation exists between equation 3 and the field test results.

4.3 Laboratory Tests

Equation 3 was also validated by Cooper Power Systems in their laboratories in the USA. The validation was done using a transient network analyser (TNA) on a model system configured to have parameters very similar to the Tamborine Mountain situation.

The analyser is a real-time analogue device consisting of actual resistance/reactance line models, physical transformer models and so on. Operating at approximately 20 V rms, the analyser accurately simulates real life system performance. Faults can be applied, switching operations can be performed, and the system response can be captured in real time.

The system modelled had two feeders each 25 km long (giving a loop length of 50 km) with regulator stations half way along each feeder. A comparison between the results obtained from the TNA and theoretical results using equation 3 is illustrated in figure 7.

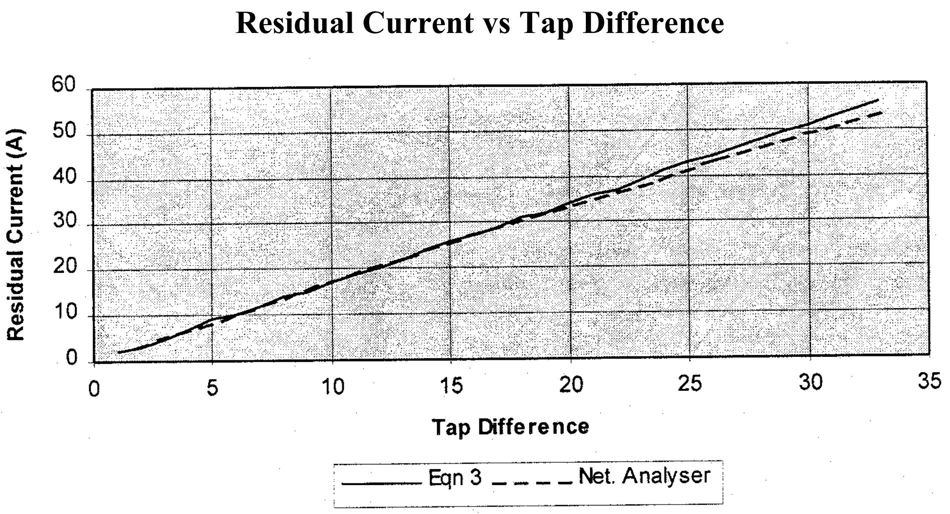

Figure 7
Laboratory Test Results

As in the case of the field test results, the laboratory tests also gave a good correlation with equation 3 as is indicated by figure 7.

4.4 Exceptions to the Rule

Data presented thus far was accepted and used within SEQEB to develop a simple standard operating procedure for switching of feeders with open-delta regulators. However, one or two situations have arisen where it has proven impracticable or incorrect to apply equation 3.

4.4.1 Feeders Supplied From Different Zone Substations

In this situation it is still acceptable to use equation 3. However, if one or both of the substations have a neutral earthing reactor (NEX) or resistor (NER) then equation 3 will give a conservative answer, ie using eqn 3 will calculate an unbalance current higher than what will occur in practice. The reason for this is that the NERs or NEXs form part of the zero sequence impedance (Z_0 in eqn 2) when the feeder paralleler between the substations is closed,

In this situation a more accurate calculation can be done using equation 2 and considering Z_0 to be equal to the feeder zero sequence plus three times the impedance of the NER or NEX at each of the substations. However, in the case of very long feeders the substation grounding impedances (used by SEQEB) tend to become insignificant relative to the zero sequence impedance of the feeders. Hence, equation 3 gives an answer fairly close to using equation 2 and considering the substation NER/NEXs.

4.4.2 Feeders in Close Proximity to Each Other

SEQEB does not normally run two 11 kV feeders along the same poles. However, occasionally future 33 kV circuits are used at 11 kV and are on the same poles as another 11 kV feeder. If the two circuits run on the same poles for any significant distance (say more than a kilometre or two) then the mutual impedance between the feeders significantly changes the effective zero sequence impedance. Hence, the assumption made regarding typical zero sequence impedance, used to go from equation 2 to equation 3, is not valid. Therefore application of equation 3 to the situation may result in one of the feeders tripping on earth fault during paralleling.

4.4.3 Too Many Regulator Stations on One Feeder

Usually the paralleling points for feeders that have regulator stations are quite some distance from the zone substation (whether both feeders are supplied from one zone substation or they come from different zone substations). Hence, usually both feeders are of similar length and each has a similar number of regulator stations.

However, in one situation in the SEQEB network it was found that a long 11 kV feeder with 3 regulator stations had to regularly be paralleled with a much shorter feeder from a different zone substation that only had one regulator [7]. Application of equation 3 in this situation and trying to balance the regulator taps between the feeders just did not prove practical. For example, if all the regulator stations are connected on the same phases, and all three regulators on the long feeder were on tap 10, then the short feeder needs thirty boost taps on its regulator to have no unbalance current flow. Even allowing a reasonable unbalance current, low enough to not trip earth fault protection, would require at least 23 taps (on the regulator) on the short feeder.

A possible solution to this problem is to rotate the phases of the three regulator stations on the long feeder, ie connect the first station V_b to V_a, V_b to V_c the second V_a to V_c, V_a to V_b, and the third V_c to V_b, V_c to V_a. Hence, if all three regulators can be brought to the same tap when transferring load then no neutral shift will result (because each regulator station displaces the neutral similar amounts, but each at 120° to the others). This then is the same as the case of paralleling a feeder with no regulators with one that has one regulator station (as discussed in section 4.0).

5.0 Conclusions

This paper has presented a method whereby the unbalance currents that may flow in feeders with open-delta connected regulators may be calculated fairly simply with a minimum of network data. The validity of the equation developed was verified by both field and laboratory measurements. The information presented can be used to tailor better operating practices for the transfer of loads in rural distribution systems.

6.0 References

[1] Cooper Power Systems (1993) How Step-Voltage Regulators Operate. Milwaukee, WI: Cooper Power Systems.

[2] Foster JD, Down D. (1993) The Effects of Line Regulators on Overcurrent Protection of 3-Wire Medium Voltage Distribution Systems (SE9302). Milwaukee, WI: Cooper Power Systems.

[3] Foster JD, Down D. (1995) The Effects of Line Regulators on Overcurrent Protection of 3-Wire Medium Voltage Distribution Systems: Part 11. Milwaukee, WI: Cooper Power Systems.

[4] Day TR, Down D. (1995) The Effects of Open-delta Line Regulation on Sensitive Earth Fault Protection of 3-Wire Medium Voltage Distribution Systems. Milwaukee, WI: Cooper Power Systems.

[5] Pannam RA, (1995) Report, An Investigation of Residual Currents That Occur When Paralleling 11 kV Feeders Containing Single Phase Regulators. SEQEB Network Investigations Dept, Brisbane, Australia.

[6] Wells L, (1993 & 1994) Reports: Paralleling 11 kV Single Phase Regulators. Brisbane Australia, SEQEB South Coast Regional Engineering.

[7] Curley J, (1997) Report: Continuity of Supply to the Bay Islands. Brisbane Australia, Network Investigations Dept South East Queensland Electricity Corporation.

APPENDIX

Analysing Unbalance Currents (ref figure 4) When Paralleler is Closed

$$[V] = [Z] . [I] \qquad \text{eqn (A1)}$$

Where: [V] = Loop driving voltages
[Z] = Impedance matrix (of the closed loop)
[I] = Circulating current

For'A'phase: V = $70n \angle 30°$
For'B'phase: V = 0
For'C'phase: V = $70n \angle 90°$

where: n = tap number
70 =volts per tap
30° & 90° angles are explained by reference to figure 2.

From this information a solution is obtained by the following steps:

- Impedance matrix is represented by the terms Z_S for the three diagonal terms and Z_M for all of the off diagonal mutual terms.
- Matrices are then multiplied out to get three simultaneous equations, and the equations added together, because the required residual current is the sum of 1_A, 1_B, 1_C.

$$I_A + I_B + I_C = \frac{70n\angle 30° + 70n\angle 90°}{Z_S + 2Z_M} \qquad \text{eqn (A2)}$$

- Next using standard equations for the conversion of sequence components to phase impedance components results in the equation:

$$I_{residual} = \frac{70n\angle 30° + 70n\angle 90°}{Z_0} \qquad \text{eqn (A3)}$$

- By trigonometry the numerator can be simplified to give:

$$I_{residual} = \frac{(\text{tap number}) \times 0.00625 \times 11000 \times \sqrt{3}}{Z_0} \qquad \text{eqn (A4)}$$

- Note: Assuming that load currents are balanced they do not have any impact on these calculations because the load currents of I_A, I_B, I_C equal zero when added together.

This is equation 2 in the main body of the report.