Low Cost Solutions for Balancing Three Phase Feeders to SWER Systems

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ABSTRACT

Single wire earth return systems, (SWER), are widely used in sparsely settled regions and are a very low cost distribution solution. As the SWER systems are connected as phase to phase loads, the three phase side of a SWER feeder transformer can see significant unbalance. Although effort is made to balance the loads, this can not be entirely achieved. Currently, tap changing voltage regulators are used in either an open or closed delta to provide magnitude compensation, however this still leaves the possibility of phase unbalance.

As one major feature of SWER is the low capital cost, it is necessary to explore the feasibility of any proposed solution to ensure that the cost is not prohibitive. A simple, low cost solution uses switched capacitor compensation and this approach is explored, using simulation, to determine the cost effectiveness and practicality. The simulation case study gives an indication of the rating of the capacitors required and the applicable control strategies. The results indicate a feasible, low cost solution applicable to SWER systems.

1. INTRODUCTION

Single wire earth return systems, (SWER), have been widely used for power distribution in regions where the population and load density is relatively low, [1-4]. In many areas of Australia including Central Queensland, many rural electrification systems had been established by State operated electricity boards during the sixties, seventies and eighties under community service initiatives. SWER systems would typically supply loads of 100kW to 200kW scattered over a line length that might exceed 300km. The distribution voltage is typically 12.7kV or 19.1kV, the phase to ground voltages for 22kV or 33kV three phase systems. Consumers were connected by a single phase transformer which produced two single phase outputs in a 240-0-240Vac centre tapped arrangement. In earlier Central Queensland systems a consumer transformer was typically 10kVA but this has now increased to 25kVA for a standard connection.

As the power industry has progressively privatized, the case for capital expenditures on these systems has progressively become more difficult to make. Improvements cannot be funded from the revenues that these systems can provide. As a consequence improvements to cater for load growth are difficult to justify. The existing SWER systems are progressively becoming more heavily loaded. The most visible consequence is an increasing frequency of voltage regulation related problems. In Queensland a SWER task force has been established to investigate the issues faced by these systems. This issue is significant internationally and a wide range of power electronic solutions has been proposed to improve the power quality of SWER customer supplies, [5-7].

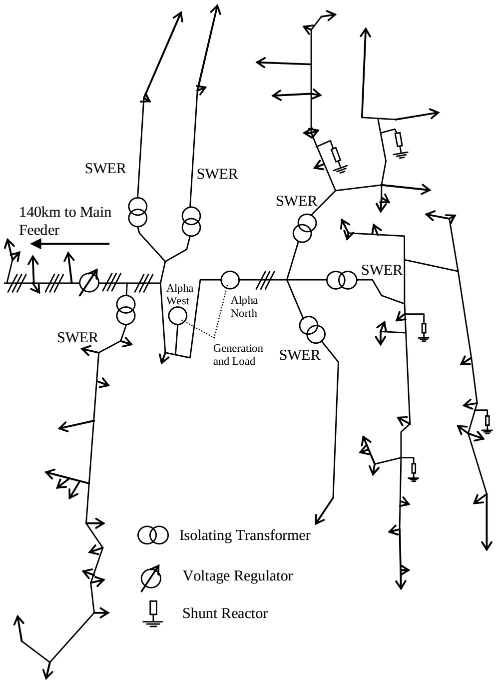


Figure 1. Typical connection of multiple SWER systems at the end of a long radial feeder line

The specific issue addressed by this paper is the voltage unbalance caused by SWER systems at the three-phase feeder. A typical feeder may service a number of SWER branches at the end of a radial distribution line as shown in Figure 1. Figure 1 represents an actual system at Alpha, Queensland where the feeder supplies approximately 2MVA of load which includes many SWER loads in the 100kVA to 200kVA range. The SWER systems are single phase systems and connected across two phases of the feeder system. It is possible to provide some balancing by connecting different SWER lines across different phases, however once the systems are established it is virtually impossible to redistribute the load to different phases as growth occurs. In addition to this, the geographical separation may result in different climatic conditions and hence different heating/cooling loads on different systems. The result is an increasing level of unbalance at the three-phase point of connection. Apart from the impact on three phase consumer power quality, the presence of voltage unbalance complicates the connection of local generation to support the three phase feeder. Distributed generation, [8-9], is an attractive option in these locations as transmission losses are becoming significant. It has been observed that diesel generation, with a conventional alternator interface, may face sufficiently unbalanced currents to cause negative sequence protection trips.

2. POSSIBLE SOLUTIONS

The problem of unbalanced voltage is not new in power systems and many solutions are currently used in the transmission area. The key contribution of this paper is to examine how compensation methods might translate, in an economically justifiable way, into the distribution area. A key issue for this application is cost. The developmental, capital and operating costs all must be controlled.

Thyristor Controlled Reactors (TCR's) are widely used internationally. While the majority of applications are related to voltage and reactive power control where TCRs are combined with capacitor banks to form static reactive power compensators, (SVCs) there are well established phase balancing applications especially in the railway power supply area. In these cases unbalanced loads can be converted to balanced unity power factor loads by the unbalanced connection of reactive elements across the supply phases.

Power electronic solutions including both fully active "complete" solutions and hybrid active/passive "tailored" solutions have been well presented in the literature. Power electronic solutions are elegant, but include a greater degree of technical risk and a higher degree of cost. Cost has been the major factor in the extremely limited uptake of power electronic solutions for power quality at the transmission power level.

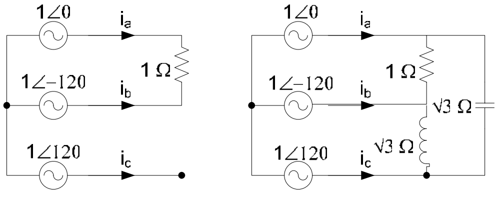
As one major feature of SWER is the low capital cost, it is necessary to explore the feasibility of any proposed solution from that perspective. Power electronic solutions will be difficult to justify on an economic basis in SWER applications. Solutions involving passive components would seem to be the most cost effective solution and these will be developed in this paper.

3. PASSIVE COMPENSATION OF UNBALANCED LOADS

Figure 2(a) shows a simple example of a single phase to line to line load, which would represent a worst case of unbalance with equal positive and negative sequence components. This is representative of a SWER load which is connected as a line to line load via an isolating transformer. Zero sequence currents are not present in the three wire backbone feeder. The values in Figure 2 are per unit to enable the solution to be generalised. In this specific application the degree of unbalance expected is of the same order as the loading on a single SWER line connection that is up to approximately 200kVA. The currents drawn in this load case are as shown in Table 1.

Table 1. Phase Currents and Sequence Components – Line to Line Case.

Phase	Sequence
$i_a = \sqrt{3}\angle -30$	$i_P = 1\angle 0$
$i_b = \sqrt{3}\angle 150$	$i_N = 1\angle -60$
$i_c = 0$	$i_0 = 0$



(a) (b)

Figure 2. (a) A standard "worst case" unbalanced load. (b) Passive balancing network for this case.

Figure 2(b) shows the balancing network which would be required to ensure the supply sees only unity power factor positive sequence currents. The currents drawn in this compensated case are shown in Table 2.

Table 2. Phase Currents and Sequence Components – Balanced Case.

Phase	Sequence
$i_a = 1\angle 0$	$i_P = 1\angle 0$
$i_a = 1\angle -120$	$i_N = 0$
$i_a = 1\angle 120$	$i_0 = 0$

It is possible to calculate a value of L and C for any unbalanced load which will provide this balancing compensation. This static case indicates that the compensating elements will have a rating of $1/\sqrt{3}$ times the load rating, or $1/\sqrt{3}$ times the negative sequence component of the load.

4. DETERMINATION OF PASSIVE COMPONENT VALUES FOR COMPENSATION

The passive compensating components may be placed at any of the three positions shown in Figure 3. Table 3 shows the positive and negative sequence current vectors produced by placement of passive components in these locations. The determination of values and location of components to compensate a given load requires three steps:

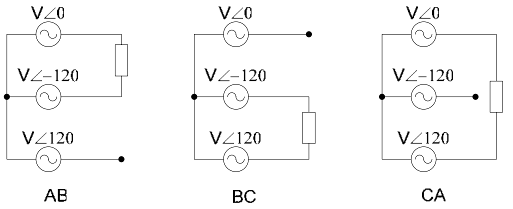


Figure 3. Possible locations of compensating elements.

Table 3. Sequence components for different passive component placements.

	Capacitor	Inductor
AB	$i_P = \frac{V}{X}\angle 90$ $i_N = \frac{V}{X}\angle 30$	$i_P = \frac{V}{X}\angle -90$ $i_N = \frac{V}{X}\angle -150$
BC	$i_P = \frac{V}{X}\angle 90$ $i_N = \frac{V}{X}\angle -90$	$i_P = \frac{V}{X}\angle -90$ $i_N = \frac{V}{X}\angle 90$
CA	$i_P = \frac{V}{X}\angle 90$ $i_N = \frac{V}{X}\angle 150$	$i_P = \frac{V}{X}\angle -90$ $i_N = \frac{V}{X}\angle -30$

1. Determine the negative sequence component to be compensated.
2. Invert this to determine the negative sequence component to be generated by the compensator.
3. Determine the appropriate combination of available vectors to generate the vector required in step 2.

The complete set of vectors is shown in Figure 4.

Considering the case presented in Section 3, the vectors are shown in Figure 5. Resolving the required vector into the two nearest available vectors as shown in Figure 5 yields the same solution presented in Section 3. The inductor and capacitor current magnitudes are 1/√3 times the required negative sequence current magnitude. The same solution may be achieved using only inductors as shown in Figure 6(a) or capacitors, as shown in Figure 6(b).

As would be expected, if purely capacitive or purely inductive compensation is used, then the individual elements must be larger to provide the same level of compensation. In Figure 5, the maximum individual element rating is 1/√3 times the negative sequence component and there are six separate compensating elements.

For the case illustrated in Figure 6, the maximum element rating is 2/√3 times the negative sequence component, however there are only 3 elements. Also, if only capacitors or inductors are used, the result is no longer unity power factor, but is either leading (capacitors) or lagging (inductors).

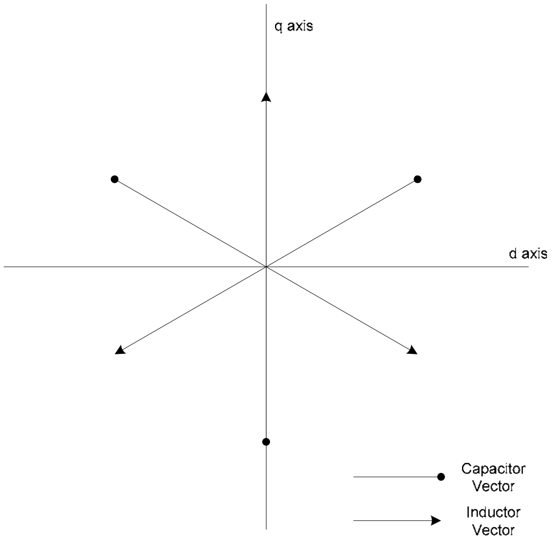


Figure 4. Complete negative sequence vector set available with capacitors and inductors.

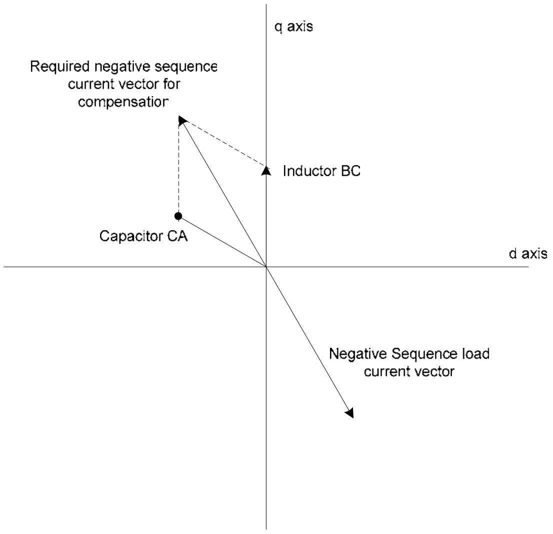


Figure 5. Generation of negative sequence vector by resolving to nearest two available vectors.

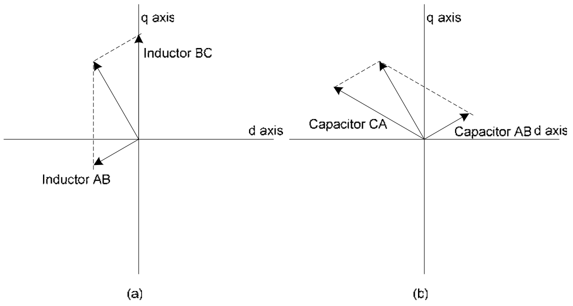


Figure 6. Vectors required for compensation of single phase load. (a) Inductor Vectors. (b) Capacitor vectors.

5. IMPLEMENTATIONS FOR SWER

One of the primary advantages of SWER is the low capital cost, compared to other distribution networks. It is necessary to optimise the implementation of the balancing network so that this cost advantage is not negated.

5.1. TRADITIONAL IMPLEMENTATIONS

Solutions to unbalance have been applied in transmission networks with fixed capacitor banks and TCR's to provide variable control. Typically this implementation would require the capacitors to be sized to meet the total leading reactive VArs required and then the inductor must be oversized to negate the capacitance when lagging VArs are required. The inductor is variable from zero (totally capacitive) to maximum (totally inductive) by thyristor control. This implementation will be taken as the benchmark, but would not be suitable for SWER applications due to the higher capital cost. This approach would require the following components and ratings as a multiple of the negative sequence component:

- 3x Inductors, Rating = 1.16 each
- 3x Capacitors, Rating = 0.577 each
- 3x Thyristors

In instances where power factor is less important than balancing, this may be achieved with a reduced subset of components. Alternative implementations for SWER will now be discussed.

5.2. ALTERNATE IMPLEMENTATIONS

In Section 4, it was illustrated that balancing compensation may be achieved with only capacitors or inductors. This approach suffers from the disadvantage that only balancing can be achieved, but not VAr control.

If only inductors are used, the currents are balanced, but lagging. Inductors are easily controlled in this application and have been reliably applied at transmission levels for this type of balancing. As inductors are typically a custom element and individually design for the application, there is typically a higher installed cost per VAr than capacitors, which may make them less attractive in this application. The element ratings for this case are:

- 3x inductors, Rating = 1.16 each
- 3x Thyristors

If only capacitors are used, the currents are balanced but leading. Capacitors have a disadvantage in that switching transients can be produced, [10]. These can be avoided if thyristors and point on wave controls are used to ensure switching at the correct time and voltage to avoid transients. Whilst there may be little cost differences between thyristors or mechanical contactors, thyristors are a loss element and this will impact on the operating cost. If the switching is to be infrequent, perhaps every few hours, mechanical switches can be used with or without auxiliary switches and networks to provide pre-charging. In spite of these limitations, capacitors can be inexpensive so the approaches for implementing a variable capacitor should be discussed.

5.2.1. VARIABLE CAPACITOR IMPLEMENTATION

Figure 7 illustrates two implementations of a variable capacitance. Figure 7(a) shows a binary weighted capacitor bank, which allows the capacitance to be varied in discrete steps. If more resolution is required, more branches may be added to give more discrete steps. This approach will induce transient switching currents any time the capacitance value is changed, requiring more complex switching circuitry to minimise the transient. An advantage of this approach is that the bank size can be easily increased by adding branches. The element ratings required in this case are:

- 3x Binary Distributed Capacitor banks, Rating = 1.16 each
- 3x Contactors/Thyristors per binary branch

Figure 7(b) shows a reactor controlled capacitor. This approach uses a fixed capacitance in parallel with a variable inductor. The inductor rating is equal to the capacitor rating, so that when the inductor is fully in the branch draws no current. This approach will only induce switching transients when the change in balancing conditions requires shifting of the capacitive element to a different pair of phases. The transient can be minimised with simple precharging networks to ensure the capacitor is always charged to the peak of the voltage and switching only at the peak. The element ratings for this case are:

- 3x Capacitors, Rating = 1.16 each
- 3x Inductors, Rating = 1.16 each
- 3x Thyristors

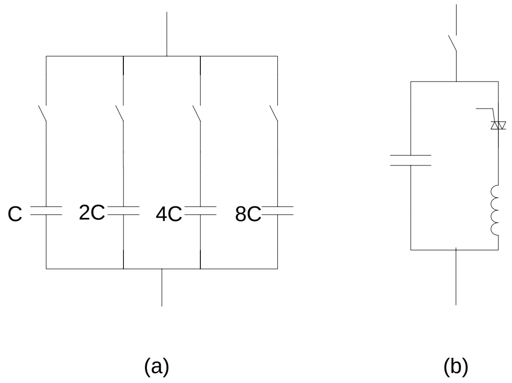


Figure 7. Variable thyristor implementations. (a) Binary switched capacitors. (b) Reactor controlled capacitor.

5.2.2. SUMMARY OF OPTIONS

Of the available options, the one which offers potential for lowest capital cost is the use of binary weighted capacitors. This offers the lowest total VAr rating of the passive components required and makes use of relatively inexpensive components. The use of this approach in a practical case study will be presented.

6. CASE STUDY

The case study presented considers the system shown in Figure 1.The main feeder is considered to be stiff and the impedances of the 140km feeder line are 119-j56. The end of the feeder branches into a number of SWER lines, as well as feeding a couple of large load centres, with some local generation. Figure 8 shows a simplified model which will be used to demonstrate this system.

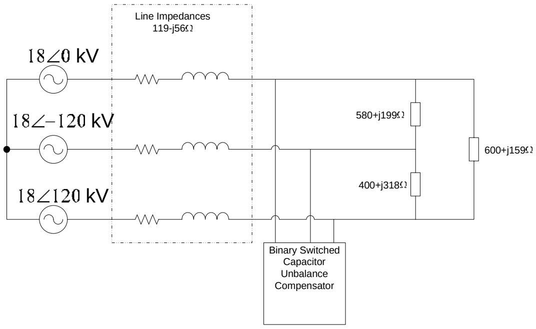


Figure 8. Simplified network for Case Study.

In this model, the load is modelled as a delta connected impedance. The values of the impedance used in the case study have been obtained by approximation of actual impedances for a static case from the real system. The binary switched capacitor network is sized such that a much larger amount of negative sequence current could be compensated. As a result, in the simulation results shown in Figures 9-13 the capacitors are fixed at less than half of the total capacitance (5.6μF per branch). The capacitors required in this case are:

- Phases AB - No Capacitance
- Phases BC - 2.25μF
- Phases CA - 2.63μF

Figure 9 and 10 show the line currents and voltages respectively for the case presented. The unbalance present in these waveforms is obvious and it is clear that the unbalanced currents have resulted in unbalanced voltages at the point of connection of the load.

Figure 11 and 12 show the load and supply currents respectively for the system with purely capacitive compensation. The capacitive compensator is able to reduce the negative sequence component of current to negligible levels. Although not obvious in Figure 12, some small negative sequence component is present. The binary weighted capacitors can only offer discrete steps, and if the capacitance required for full compensation falls between these steps, the nearest step must be chosen. Therefore, some small negative sequence component would be expected.

The phase voltage balance is also improved as the currents drawn now present the same magnitude of voltage drop in each phase.

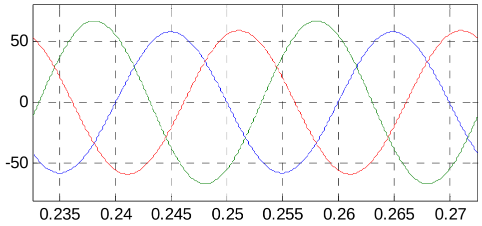


Figure 9. Line currents for uncompensated system.

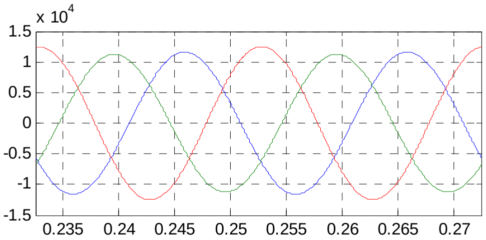


Figure 10. Line voltages for uncompensated system.

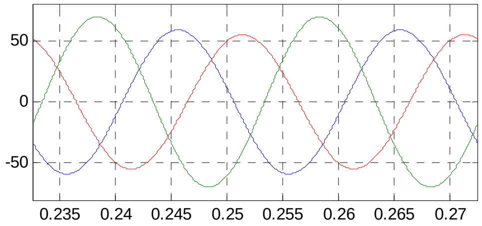


Figure 11. Load currents for compensated system.

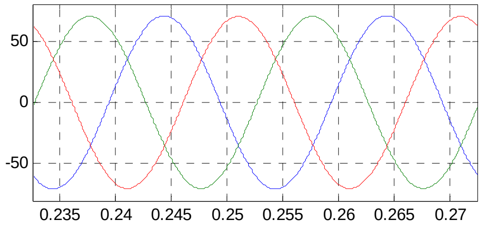


Figure 12. Supply currents for compensated system.

Figure 13 shows the supply voltages and currents for the compensated case. Section 4 indicated that the power factor of the current would be influenced if purely capacitive compensation was used. Figure 13 shows that the supply currents are balanced, but leading, due to the capacitive nature of the compensation.

As the amount of negative sequence in the load varies, and the compensating capacitance changes, the power factor seen by the supply will fluctuate. This is one potential drawback of using purely capacitive compensation in areas where leading power factor is not easily tolerated by the connected generation equipment.

7. FURTHER OPTIMISATION

At the distribution levels, the ratings of the compensating components are more manageable with simple switching elements. Figures 4, 5 and 6 all show that to achieve any balancing; only two elements are required, however they may be switched between a different pair of phases for different unbalanced cases.

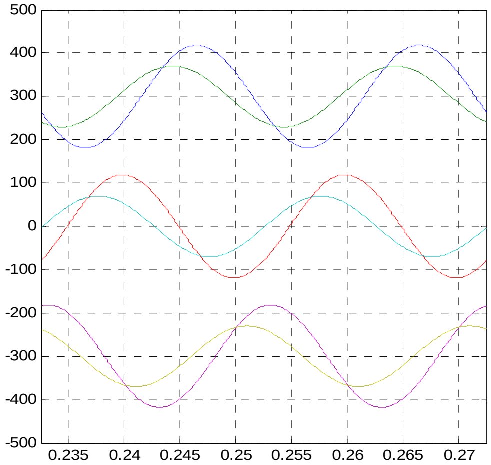


Figure 13. Supply voltage (scaled by 100x) and current in each phase.

The elements required for compensation of unbalance may be reduced to either of the following combinations with contactors or power electronic switches to shift the connection to a different pair of phases as required. This arrangement is shown in Figure 14. Clearly there is a need for interlocking of the switch elements to avoid a line to line short but this may be readily achieved.

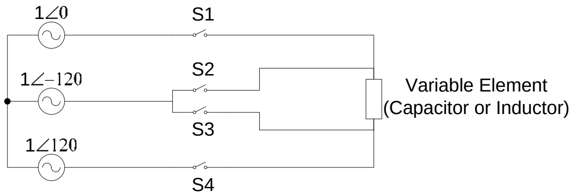


Figure 14. Connection to allow element to be connected between any two phases.

The compensation may then be achieved by any of the following combinations:

1. 2x Variable Capacitors (each rated at 1.16x Negative Sequence)
2. 2x Variable Inductors (each rated at 1.16x Negative Sequence)
3. 1x Variable Capacitor (rated at 0.577) and 1x Variable Inductor (rated at 0.577)

Of these options, number 3 gives the lowest total VAr rating required and allows unity power factor to be achieved. This option will be explored further in future papers.

8. CONCLUSIONS

This paper has explored the implementation of low cost solutions to the problem of balancing three phase feeders to SWER distribution schemes. The mechanism of passive balancing is developed and a process for determining the amount of compensation is presented. A simplified case study based on an actual SWER distribution feeder is used to demonstrate that such compensation is possible using purely capacitive elements. Purely inductive or mixed inductive and capacitive elements may also be used based on different cost/performance considerations. Finally, some options for further reducing the component count, and hence the overall cost of the compensation, at distribution levels is presented. Future work will investigate suitable control strategies for automation of the compensator and implementation of the reduced component count systems.

9. ACKNOWLEDGEMENTS

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