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Rural Single Wire Earth Return distribution networks – Associated problems and cost-effective solutions

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ABSTRACT

Single Wire Earth Return (SWER) systems are used for supplying electricity at low cost, where electricity supply is required for small populations of people dispersed across wide geographical areas. It is principally used for rural electrification, but is also used for other isolated loads and light rail.

The existing SWER distribution systems have been stretched with the sharp growth of their loads because of customers' change of lifestyle, which has introduced additional load of air conditioning equipment, motors driven by variable-speed drives and inverters. This paper proposes cost-effective solutions to address the problem of voltage regulation and compensation of the unbalancing effect of SWER lines on the three-phase feeder of these lines, which have been exacerbated by this load growth.

To improve the voltage regulation problem, a LV switchable reactor has been designed, a prototype made and tested in the field. Also, an unbalance compensator has been designed to reduce the unbalancing effect of SWER lines. Two case networks have been used to perform simulation studies on the effectiveness of both proposed solutions. At first, a case study is used to demonstrate the impact of a switchable reactor on improving voltage regulation. Then, another case study shows that installation of a switchable reactor and an unbalance compensator simultaneously on a SWER distribution system effectively improves voltage regulation and reduces unbalancing effects.

1. Introduction

Rural electrification has been a long struggle around the globe. Many obstacles had to be overcome before widespread use of rural electric power became practical [1]. There are still many people in the world who are deprived of many advantages of electric energy; about 1.45 billion people (22% of the world population) were deprived access to electricity in 2008 (about 85% of those people lived in rural areas) [2]. Electrification rates remain extremely low in many developing countries, as low as 10% in some African countries, for example, as illustrated in Fig. 1 [2]. Rural electrification is an area in which social justice and equity dictate that there is a need, but political and economic realities are such that the need is often subordinated [3]. The World Bank has been encouraging the expansion of simple systems for rural electrification to reduce the cost of the grid extension [4].

In 1920, Lloyd Mandeno introduced Single Wire Earth Return (SWER) distribution systems in New Zealand. Later in 1947, he published a paper proposing SWER as economic alternative to the standard three-phase distribution systems for rural areas [5]. A brief explanation of SWER systems is provided in [6]. Nowadays SWER distribution systems are used in Australia, New Zealand, South Africa, Canada (Saskatchewan), Brazil, Laos, USA (Alaska) and Iceland. Other countries, for example, Angola, Burkina Faso, Botswana, Namibia, and Mozambique are considering SWER as a means of extending their rural electrification [7]. SWER distribution lines are used extensively in remote parts of these countries as an economic means to deliver electrical energy to small customer loads, scattered sparsely over vast areas. These SWER systems are normally supplied from very long three-phase distribution feeders. In many areas of Australia, rural electrification systems were established by the State Electricity Boards during the 60s, 70s and 80s under community service initiatives.

A SWER line is a unique distribution line that consists of a single conductor, energized at a relatively high voltage, which uses the earth as a return path for load currents, rather than a dedicated neutral or earth conductor. This makes it incredibly simple and economic to construct and it has many advantages due to its small number of components. There are over 150,000 km of SWER lines currently in use in Australia. Individual loads are typically less than 100 kW. Distances between customers can range from less than 1 km up to 25 km.

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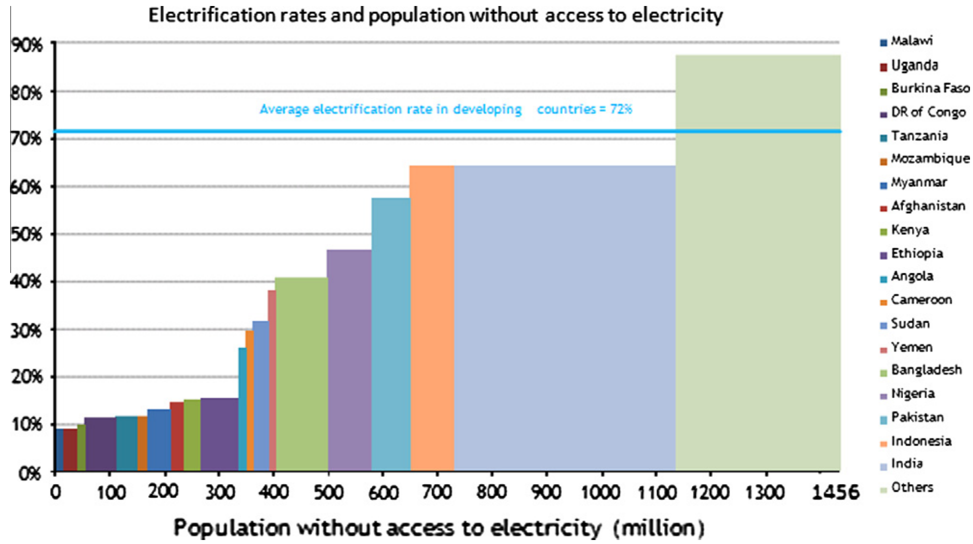

Fig. 1. People without access to electricity worldwide in 2008, source: World Energy Outlook (WEO), 2009 [2].

The SWER lines are normally supplied from long radial three-phase distribution feeders, typically at 11 kV or 22 kV, via isolation transformers which produce SWER line voltages of 12.7 kV or 19.1 kV, respectively. These three-phase feeders also supply other more concentrated loads such as small towns, industrial facilities, large farms and mine sites. As an example, a rural SWER system may supply 200 kVA to less than twenty consumers spread over 200 km. Although the system is very cost-effective, but it has the following disadvantages [8]:

- Usage of single-phase overhead lines with high-resistance values; the lines are typically three-strand galvanized steel. This feature results in high energy losses as high as 20% of the transformer capacity;
- The system capacity is limited by voltage drops and high voltage regulation;
- Line voltage rise due to the capacitive ground current on lightly loaded lines; shunt reactors are often applied to solve this problem, but they contribute to voltage drops at peak load times;
- Each SWER line is connected to only two phases of a three-phase feeder via an isolating transformer. This has an unbalancing effect on the three-phase feeder;
- Touch and step potentials exist when line current passes through to the earth.

Therefore, low-cost solutions should be devised to tackle some of the above problems.

The characteristics of the earth grounding is explained in [9]. The effect of ground properties on the performance of SWER systems in terms of harmonic generation and its effect on protection of such systems are covered by [10] and [11]. A power flow algorithm for SWER systems considering the explicit representation of the ground effects is discussed in [12]. A simple schematic of a SWER system is shown in Fig. 2. This is a 19.1 kV SWER line, which is connected to two lines of a 22 kV three-phase feeder via a 22/19.1 kV isolating transformer. This transformer provides a local earth return point for currents flowing in the SWER feeder.

Due to recent strong electrical load growth, rural distribution systems that were designed with specific load limits now operate beyond their original specifications. Therefore, it is required to upgrade the SWER systems to improve the reliability and quality of power supply to the rural customers. There are, basically, two options in improving the efficiency of electrical energy transfer in these feeders. One option is restructuring or augmenting the SWER lines. Another option is using new technologies to improve the efficiency with the existing lines. However, an important consideration in deciding on any option of upgrading these networks is the revenue earned from SWER systems. Low customer density results in low revenues. This makes justification of expensive upgrades difficult on an economic basis.

Several issues are associated with SWER systems that need to be addressed. One of the key issues pertaining to SWER feeders is that of voltage regulation. During very light-load periods the SWER line capacitance creates voltage rise toward the end of the feeder. To combat this issue, fixed shunt reactors are used to control voltages. Unfortunately, these reactors add to the load during peak load periods. As a result, excessive voltage drop limits the load capacity of the feeder.

A second challenging issue related to the SWER distribution systems is their drawing of unbalanced currents from a three-phase feeder. It is possible to manually balance the three-phase feeder by judicious allocation of SWER loads across all three phases; however, unbalanced loading can still occur due to variable loads on the SWER feeders. This can cause customer voltage quality problems. Unbalanced loading results in uneven voltage drops in the phases. This problem is more profound on long untransposed feeders. It is difficult to maintain proportional load uniformity between SWER systems due to dissimilarities in customer usage patterns. This problem is exacerbated by the geographic locations of the loads, which make the load patterns change in different ways compared to each other and also change patterns with the change in meteorological conditions. The current practice for balancing is to apply voltage regulators that attempt to control the magnitude balance of the voltages. This approach cannot omit phase angle unbalances.

A third issue with regard to SWER systems is their limited capacity of power flow. Normally, high-resistance conductors have been used for SWER lines to reduce the cost. This has made the SWER distribution systems exhibit relatively high energy losses. A challenging problem is how to increase the capacity of these systems with low-cost technologies, but maintain voltage regulation within an acceptable margin. Capacity limitations are mostly due to the voltage regulation constraints, so by addressing the voltage regulation problem, this issue will be partially solved.

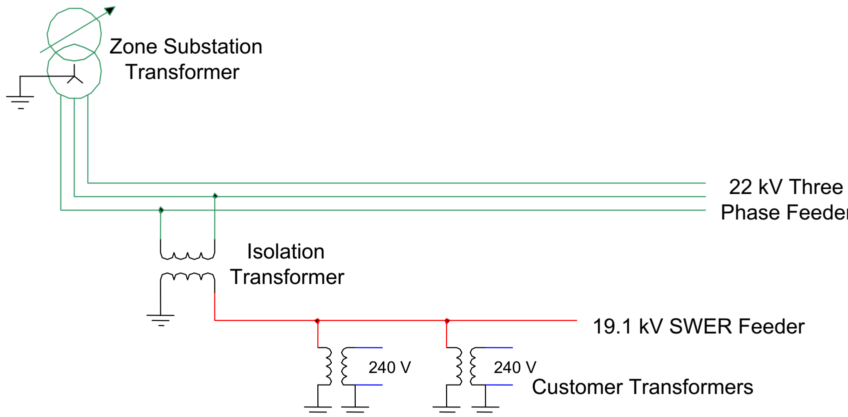

Fig. 2. Schematic diagram of a SWER distribution system.

The various means by which SWER distribution systems may be upgraded are discussed in [13], where a financial comparison of various options has also been provided. The following options have been analysed: (1) Traditional improvements include upgrading of isolating transformer, upgrading of distribution transformers, additional HV voltage regulators, change of conductors for the SWER lines, converting single lines to duplex SWER lines, and (2) using new technologies to improve SWER distribution systems, which include LV voltage regulators, switchable shunt reactors, distributed generation support, one-spot (point) generation support, energy storage systems and network demand management.

From various options for improving SWER distribution systems, several solutions were proposed in [14]. Fig. 3 shows the schematic of a few methods that can be used to improve the performance of the system. These include a series HV voltage regulator, a HV shunt reactor and a three-phase diesel generator, which are currently used separately or in a combination. Other solutions range from HV three-phase FACTS, HV single-phase FACTS, real power injection (renewable energy generators), and phase balancing.

After comparing various solutions in terms of their effectiveness in improving voltage regulation and voltage quality with particular consideration of their costs, it was concluded that two specific solutions are feasible and cost-effective. The first solution is a LV switchable shunt reactor (connected to the low voltage side of a SWER distribution transformer) to improve voltage regulation and the second solution is a balancing compensator.

Proposed solutions are explained in the following sections. Section 2 explains a switchable reactor scheme, suitable for installation at the low voltage side of a SWER distribution transformer, to improve voltage regulation. Section 3 describes a balancing scheme to reduce the unbalancing effect of a SWER line on a three-phase distribution feeder. Two case studies have been simulated to study these two schemes and their interactions [15]. Section 4 covers the case studies.

2. Voltage regulation

Due to very long line lengths and sparse distribution of customer transformers and loads, line charging currents on SWER lines can be significant. Due to this, during periods of light loading, significant voltage rise can occur towards the end of the feeder creating quality of supply issues for customers. To combat this problem it has been usual to install several fixed shunt reactors along each SWER line to reduce the capacitive loading and control voltages at light loads. However, these reactors increase the load of the system at peak load time. Distributed generation along SWER lines has been proposed to improve voltage regulation and reduce feeder losses [16]. This strategy is effective at controlling voltages and reducing feeder losses; however, the solutions considered in this paper have to be low-cost, simple and not maintenance intensive.

A solution to the problem, where the reactors are needed at low load but should be removed at peak load, is to switch the reactors. Each reactor can be switched via a contactor or a circuit breaker. Due to the high feeder voltage of 19.1 kV, this is unlikely to be economical unless a step-down transformer is installed and the reactor and switchgear is implemented at low voltage. Normally, the distribution utility responsible for SWER systems has a stock of standard step-down transformers, which reduces the cost. An additional enhancement to this system would be to split the reactor into two or more smaller reactors to provide finer control. Fig. 4 shows a typical scheme [17]. The proposed solution involves using a standard 25 kVA customer SWER transformer to step down the voltage to 500 V and using a low voltage reactor.

3. Balancing scheme

It is very common to have several SWER lines connected to a three-phase feeder. Uneven SWER feeder loading can significantly contribute to the unbalance of three-phase voltages and their angles. Although in three-phase transmission systems the unbalance problem is dealt with using static var compensators (SVC's), this

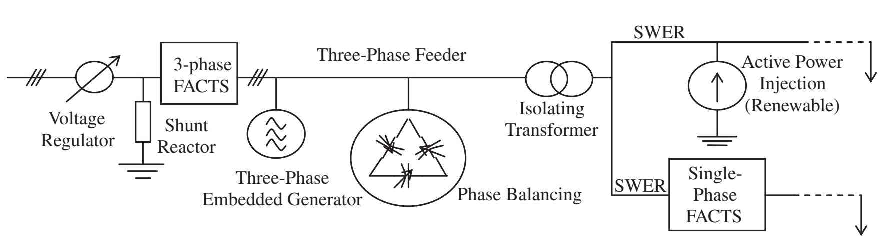

Fig. 3. Various schemes to enhance the performance of a three-phase distribution feeder and SWER lines.

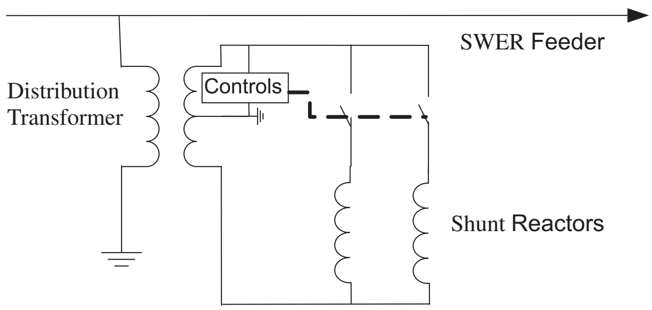

Fig. 4. Switched reactor scheme.

solution may not be applicable for SWER systems. A SVC is a variable reactive power device that can be inductive or capacitive depending on the system requirements. They generally consist of a fixed capacitor bank with a thyristor controlled reactor. In Australia, SVC's are traditionally used for both voltage control in long transmission systems and unbalance control where large single-phase traction loads exist. As a major feature of SWER systems is their low capital cost, a SVC on the three-phase line feeding SWER networks may not be feasible for a SWER distribution system. It is necessary to explore the feasibility of any proposed solution to ensure that the cost is not prohibitive.

In order to design a low-cost scheme for reducing the unbalancing effect of SWER networks, we start from the principles. It has been proved in the literature that any unbalanced load can be balanced by using only inductors or capacitors. The reactive power control textbook by Miller [18] summarises the key concepts from Gyugyi et al.'s paper [19]. The procedure is as follows:

It is assumed that the load admittances are of the following form and are complex and unbalanced:

$$Y_{AB} = G_{AB} + jB_{AB}$$
$$Y_{BC} = G_{BC} + jB_{BC}$$
$$Y_{CA} = G_{CA} + jB_{CA}$$

where G is the equivalent shunt conductance and B is the equivalent shunt susceptance of a load.

Compensating branch admittances represented by $B\gamma$ are connected across the phases to correct the power factor to unity and balance the phases. These admittances are given by [18]

$$B\gamma_{AB} = -jB_{AB} + (G_{CA} - G_{BC})/\sqrt{3}$$
$$B\gamma_{BC} = -jB_{BC} + (G_{AB} - G_{CA})/\sqrt{3}$$
$$B\gamma_{CA} = -jB_{CA} + (G_{BC} - G_{AB})/\sqrt{3}$$

A positive or negative answer designates whether the compensation for each phase is capacitive or inductive. Therefore, by only using capacitive or inductive elements in parallel with the load, balancing can be achieved. The capacitor or inductor will cause a negative sequence current to flow in the three-phase supply to compensate for the negative sequence current created by the unbalanced load. This will dramatically improve voltage unbalance.

In practice, a simple control strategy is to measure the negative sequence load current and determine the required capacitance or inductance to create an equal and opposite negative sequence current to cancel it. It can be shown that a capacitor connected across phases A–B creates a negative sequence current of:

$$I_2 = \frac{\sqrt{3}Vab}{Xab} \angle 150 \text{ Å}$$

Similarly, an inductor connected across phases A–B creates a negative sequence current of:

$$I_2 = \frac{\sqrt{3}Vab}{Xab} \angle -30 \text{ Å}$$

If this calculation is conducted for each capacitor and inductor combination, the following chart in Fig. 5 of negative sequence vectors is produced. The negative sequence vector angle is set by the component type (capacitor or inductor) and the phase connection. The negative sequence vector magnitude is set by the component value.

Knowing these relationships is very useful in cancelling negative sequence load currents.

The procedure is very simple:

- Measure the load currents downstream of the point of connection of the compensator;
- Calculate the negative sequence current using symmetrical components;
- Determine the compensating vector with the closest opposite (180° out of phase) angle to the negative sequence load vector angle; and
- Set the magnitude of the compensating negative sequence current equal to (or as close as possible to) the magnitude of the negative sequence load current.

This procedure only requires a single capacitor or single inductor to be switched across two phases. Whilst there will be occasions where the negative sequence current vector will not be exactly opposite to the negative sequence load current, provided it is close, a significant reduction in negative sequence load current will be seen by the source (upstream of the compensator).

To achieve a reasonable level of control, the capacitor and inductor should be divided into a small number of stages. The total capacity of compensation required is dependent on the source impedance at the compensation point and the maximum expected load unbalance. The higher the fault levels in a system, the less impact the unbalanced load would have to create unbalance voltages and the smaller would be the size of the compensator.

For weak systems, such as those under investigation in this paper, the procedure is suggested as follows:

- Determine the worst unbalance current for which the compensator should be able to rebalance;
- Determine the negative sequence current for that load;
- Convert this current to kVA using the phase to phase voltage;
- Size the compensating capacitance and inductance for this kVA; and
- Arbitrarily determine a reasonable number of stages to give relatively smooth range of current magnitudes and also give consideration to the maximum size of each capacitor or inductor in relation to switching transients.

This solution to the problem of phase unbalance can be easily implemented on the feeders supplying the SWER networks. This paper has applied this scheme to a typical SWER case study (next section). The simulation case study gives an indication of the rating of the capacitors required and the applicable control strategies to determine the capacitor switching for a given unbalance condition. The simulation study also investigates voltage regulation under this compensation strategy and interaction between the capacitor switching and the tap changing action of the regulators. The results indicate a feasible low-cost solution applicable to SWER systems.

4. Case studies and field tests

4.1. Case network

Ergon Energy Corporation – a distribution utility in Queensland, Australia – operates one of the lowest customer density networks in the western world using SWER lines. This network poses unique

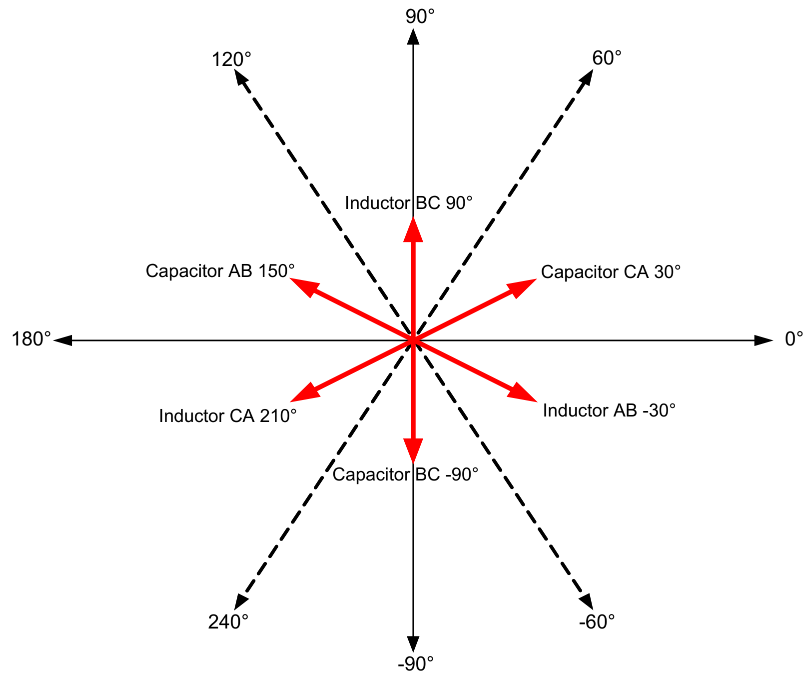

Fig. 5. Negative sequence compensating vectors.

challenges in providing low-cost and reliable electricity supply. The map shown in Fig. 6 shows the extent of the SWER networks in the area supplied by Ergon Energy [20]. The lines displayed on the map indicate the SWER systems, which extend from coastal regions to remote inland rural areas.

In order to illustrate the huge size of this system in terms of distances covered by the network, an area of the map (shown with an oval ⬭) is zoomed in and is shown in Fig. 7. This is the power distribution system in the central west area of Queensland, between the towns of Barcaldine and Alpha. The figure shows a 22 kV feeder that supplies power from Barcaldine to some small towns, farms, mines and residential customers. This backbone feeder is about 140 km long and has many branches. Among these branches are several SWER lines. A part of this network will be used for case studies, as follows in sub-sections B and C.

4.2. Voltage regulation case study

A part of the network in Fig. 7 (i.e. the Jericho North feeder) was used as a voltage regulation case study. The simplified schematic of this system is shown in Fig. 8. The SWER line voltage is 19.05 kV and this system supplies 43 consumer load points. Two load points are 25 kVA and the others 10 kVA giving a total consumer transformer connection of 460 kVA (summation of individual peak loads). The system isolation supply transformer is rated at 150 kVA. Nine 25 kVAr shunt reactors are distributed across the system. The SWER system has a backbone conductor with lighter spur conductors. The back bone is 141 km of 3/4/2.5ACSR/GZ. The spurs total 223 km of 3/2.75SC/GZ. Over the 364 km of the SWER network it has a total capacitive loading of 270 kVAr.

The SWER feeder voltages were obtained (using PSCAD modelling) at various points in the feeder network. As shown in Fig. 8, V100 is the voltage measuring node at the isolating transformer. V102, V113, V125, V139, V146, V153, V164, V169, V174 and V180 are voltage measuring nodes at various points on the SWER line. Acceptable voltages would fall between ±5% of nominal voltage (approximately, between 18 kV and 20 kV).

A base system model has been developed using a PSCAD software package. The loads have been modelled as constant impedance loads. That is, the load (i.e. the power consumed) varies with voltage. This is indicative of heating, cooking and lighting loads common of domestic consumers, but does not model the constant power loads such as induction motors with a good accuracy. However, the constant impedance load assumption is considered satisfactory for the purpose of this model which is to investigate potential new voltage regulator applications. Fig. 9 shows the standard load model that has been created in PSCAD.

Several PSCAD control components have been used to enable the load to be set at any preset value between 30% and 200% of the existing peak feeder load. In addition to this, an option allowing the load to automatically ramp between any two load values over a set time period has been created using the PSCAD control components. This will simulate the daily load curve.

For all cases, the 22 kV source was fixed so that all voltage regulation was confined to the SWER system itself. The load was initially 70% of the existing peak load (as provided by Ergon Energy) and was automatically ramped from 70% up to 100% and back down to 70% of peak load to simulate a daily load curve. The simulation was run over only 12 s in PSCAD environment due to the long processing time, but the graphs could easily be visualized to show, say, a 12 h period of a normal daily load variation. Note that the initial values of these voltages at $t = 0$ and a short period after that are due to simulation and should be ignored.

Fig. 10 shows the voltage profile at various measuring points if shunt reactors were not installed on SWER lines. As shown in the figure, whilst the load is light at the beginning of the period, the system voltages are elevated. As the load increases over time, the inductive part of the load cancels the capacitive charging current of the feeder and the resistive part of the load causes voltage drop over the feeder. The end result is a lowering of voltage. As the load decreases after the peak, the voltages once again rise. Therefore, without shunt reactors, the voltages at peak load would be acceptable, but the voltages at light loads at all points would be too high.

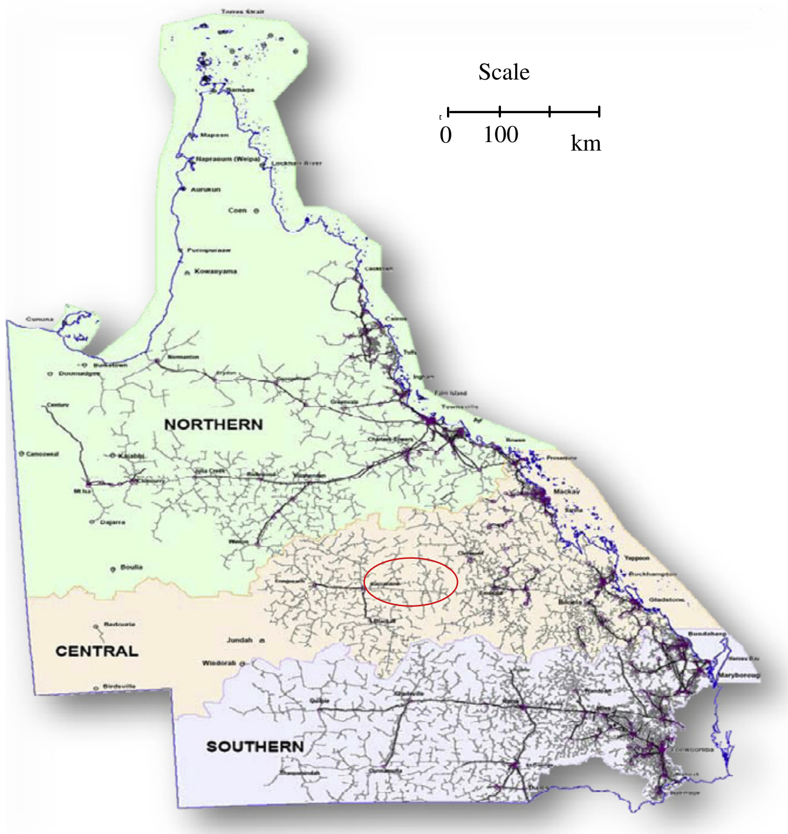

Fig. 6. The SWER network in rural areas of Queensland, Australia.

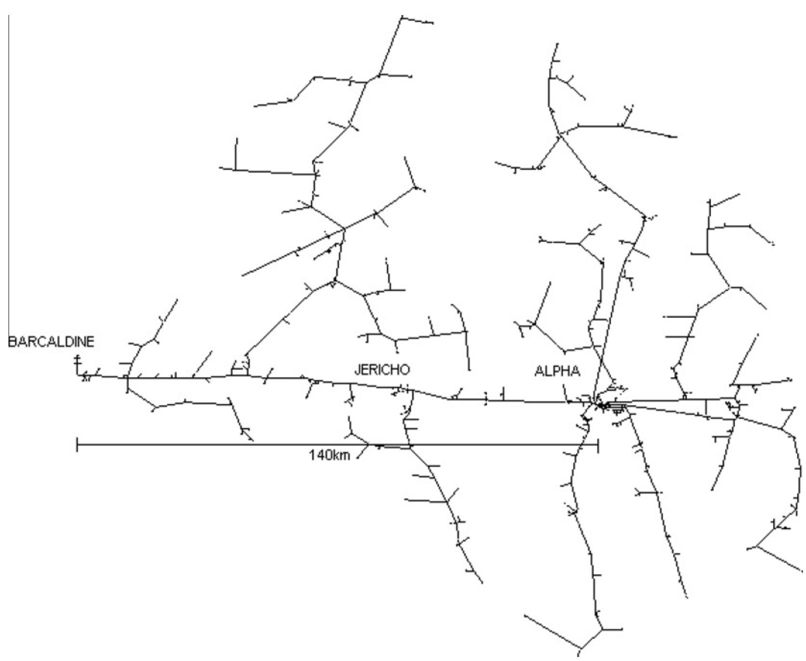

Fig. 7. The network shown by the highlighted oval (◯) in Fig. 6.

Fig. 11 shows the voltages at the same locations, but with fixed shunt reactors installed on the SWER line (this is the current practice used by Ergon Energy). The figure shows the reactors cancel most of the capacitive line charging currents so the voltages are controlled during light-load periods, but as the load increases the voltage decreases and in some locations is below the acceptable limit. This leaves no scope for increasing the SWER line loads in the future.

Fig. 12 shows the effect of the proposed switchable reactors with the original daily load curve. This graph shows that the

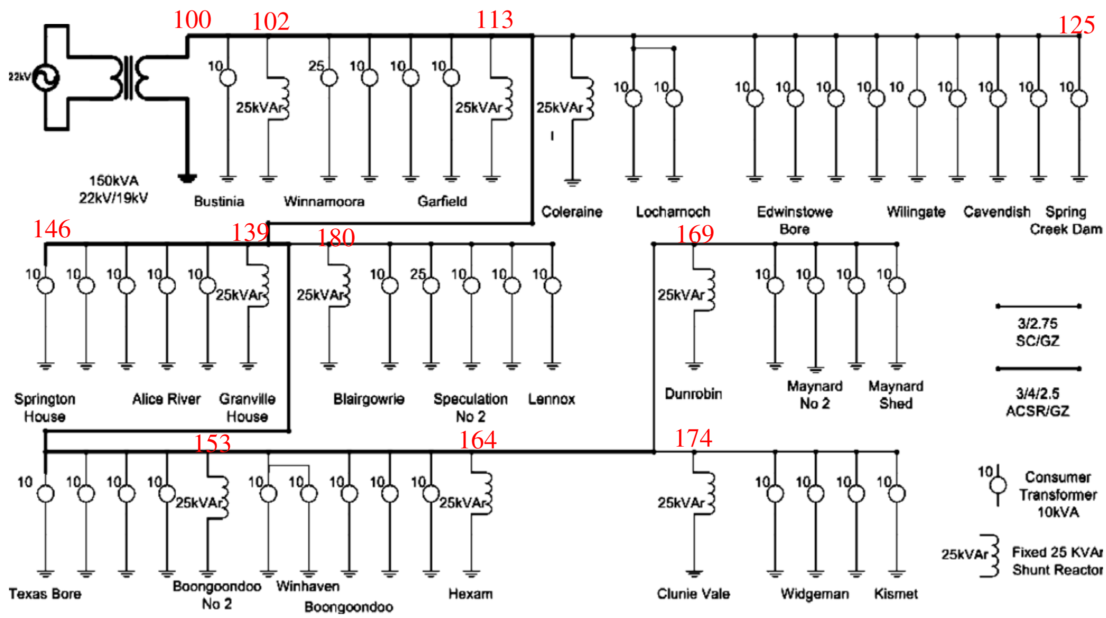

Fig. 8. Simplified schematic of Jericho North SWER system.

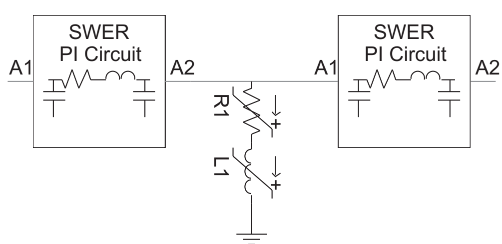

Fig. 9. Variable load model.

voltage at all points of the feeder are controlled well within the acceptable ±5% range. The switchable reactors are initialized in the open position and the immediate correction of high voltages can be seen in the initial part of the simulation as several reactors switch into service. The switching of reactors (in and out) can be seen as step changes in voltage. The voltage step is about 2% and given the low switching frequency that would be envisaged, this is considered acceptable. There is one location where the voltage regulation is still unacceptable, however this is a single spur with large customer load at the end. This particular spur could be corrected by other means (reconductoring, for example).

The improvement in voltages provides the opportunity to assess the performance of the compensated line with additional load. The system studies have shown that it is possible to dramatically improve the voltage regulation of the existing system by using switched reactors and even increase the load capacity of the SWER feeder by 50%.

A prototype of the proposed switchable reactor was designed and implemented [21]. The prototype used two 460 Vrms, 54 mH, 12.5 kVA controlled reactors. These were manufactured by Power Safe Magnetics for $2195 (Australian) each. The reactors were bench tested for temperature rise and quality factor. They were installed and tested in the field on one of Queensland SWER networks (in Stanage Bay). The hysteresis control was used with the following set points:

- Connection of the first inductor occurs when the secondary voltage rises 0.5% above nominal voltage, the second inductor stage is connected if the voltage exceeds nominal voltage by 1%;

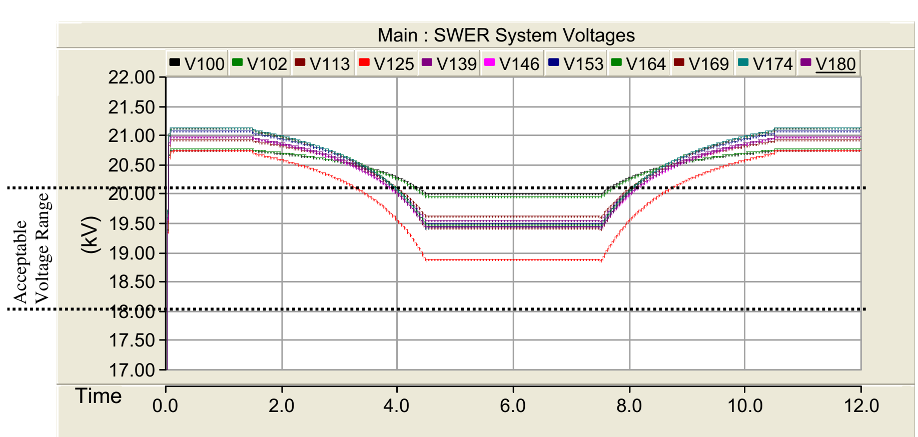

Fig. 10. Voltages without shunt reactors at various points of the SWER line.

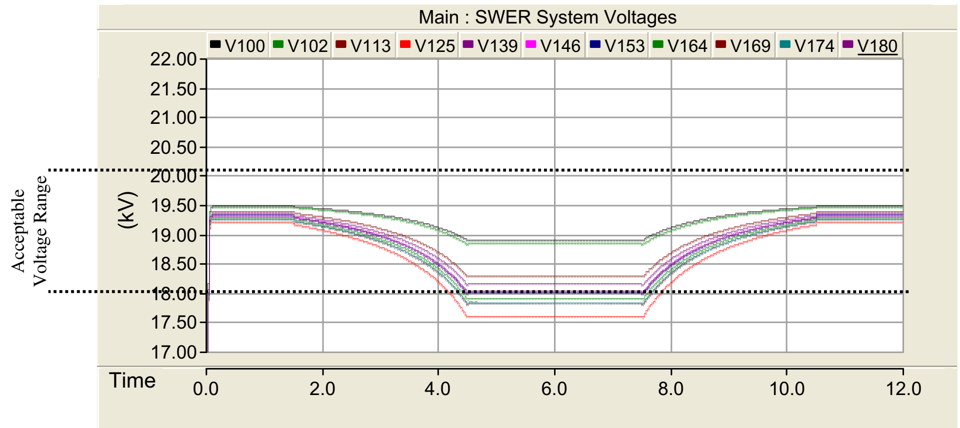

Fig. 11. Voltages with fixed 25 kVA shunt reactors.

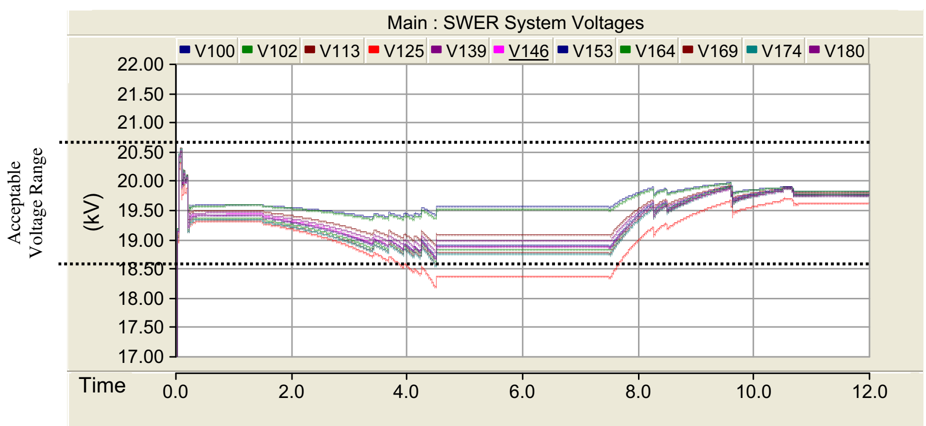

Fig. 12. Voltages with 2 × 12.5 kVA switchable reactors replaced in place of fixed 25 kVA shunt reactors.

- Disconnection of the second inductor stage occurs when the secondary voltage falls 3% below nominal voltage, the first stage disconnects when the voltage falls 3.5% below nominal voltage.

Field tests were performed after installation of switchable reactors. For illustration, the voltage profile for two typical days and the switching behaviour of the reactor are shown in Figs. 13 and 14 (the voltage is measured at the installation point of the switched reactor).

Fig. 13 shows a normal day and Fig. 14 shows a day when a heavier than normal load is applied to the system between 2 pm and 11 pm. These figures show that both reactors are on when the voltage is more than 18.4 kV, one is on when the voltage is approximately between 18.0 kV and 18.4 kV, and both reactors switch off when the voltage is below a threshold, e.g. 18.0 kV (the level of switching voltages depend on the nominal voltages set by the taps of transformers and can be also adjusted from the control panel). It should be noted that the nominal voltage at the Stanage bay SWER system was set at 18.5 kV (it was a tap 6 territory during the field tests) rather than a more usual 19.1 kV. Also, the purpose of the field tests were mainly performance testing of the switchable reactors themselves rather than voltage regulation, which was considered a secondary aim. In other words, the sizes of the switchable reactors were not optimised for voltage regulation. In the figures, a particular attention should be given to the periods of time when both reactors are switched off (during low voltage times); if fixed reactors (unswitchable) were used instead, we would expect even lower voltages at those times.

Particularly, notice that in Fig. 14 both reactors are switched off between 2 pm and 11 pm (and here is where the currently used fixed reactors would further push the voltage lower).

4.3. Case study for a combination of unbalance compensator and voltage regulator

In order to conclude this paper, in this section we demonstrate that both proposed solutions (switchable reactor voltage regulator and unbalance compensator) will effectively work together in a combined three-phase feeder and SWER network. An example rural network consisting of a very long 22 kV three-phase feeder and a series of SWER line connections has been modelled using PSCAD. The network is a part of the SWER distribution system shown in Fig. 7, but is simplified to improve simulation time. The network model contains the following components:

- 80 km three-phase 22 kV feeder;
- One set of delta connected step voltage regulators toward the end of the feeder;
- 1.5 MVA of balanced three-phase and SWER load distributed along the feeder with the majority toward the end of the feeder representing multiple SWER connections;

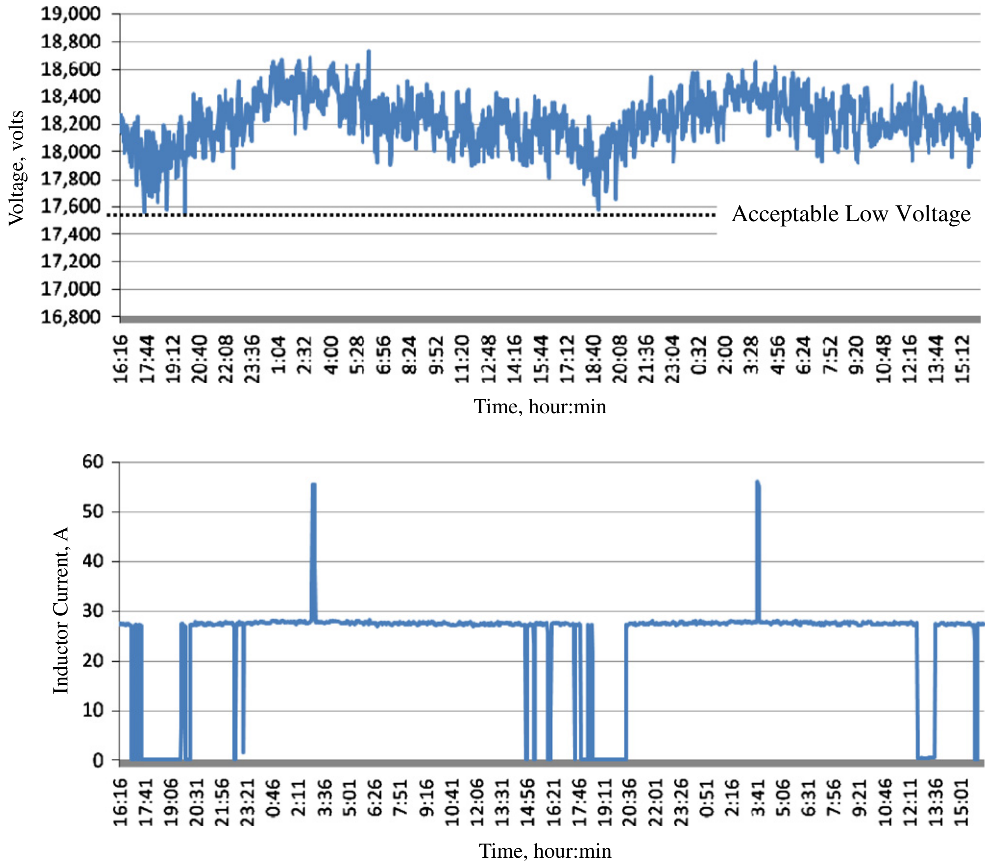

Fig. 13. Voltage profile and switching behaviour of the switched reactor on a normal day.

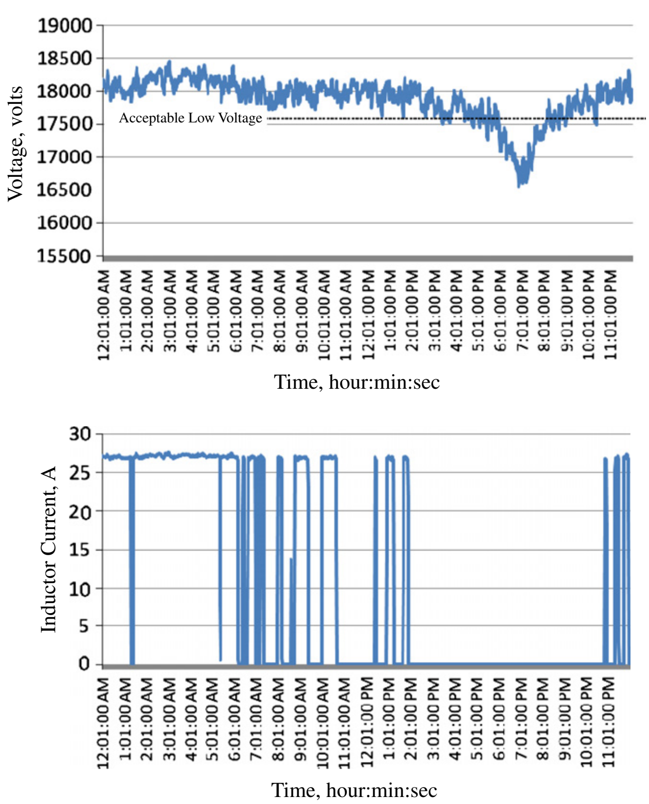

Fig. 14. Voltage profile and switching behaviour of the switched reactor on a day when a load more than usual is exerted on the system between 2 pm and 11 pm.

- One 19.1 kV SWER feeder at the end of the three-phase feeder, with variable load, and 8 switched reactor devices, in lieu of fixed shunt reactors; and
- One 180 kVA, three step 22 kV unbalance compensator toward the end of the three-phase feeder, but upstream of the SWER connections (this is sized to the maximum expected unbalance).

All but one SWER feeder are simplified and lumped at the three-phase feeder to reduce processing time. The PSCAD simulation takes hours to run if all SWER lines are modelled in detail. Only the SWER line of interest, i.e. the one which is equipped with the switchable reactor, is modelled in complete detail.

The three-phase load is fixed rather than representing a daily load curve, to simplify the output graphs for the reader. If both the three-phase and SWER load were variable, essential features in the output graphs, demonstrating the effectiveness of the compensating devices would be more difficult to interpret.

Fig. 15 shows a simplified single line diagram of the modelled system.

Fig. 16 shows the load current waveform toward the end of the 22 kV feeder where the SWER connections are made. The SWER line load has been allocated at 150% of the original data provided by Ergon Energy to account for the desired future load growth. The unbalance can be seen (unequal magnitudes of load currents in the three phases).

Fig. 17 shows selected voltages (at various points of the feeder) from the fully modelled SWER line with its fixed shunt reactors attempting to control voltages during light-load periods. It can be seen that the voltages during the peak load period are unacceptable when fixed shunt reactors are used, which is the current practice for the SWER networks in Australia. The unbalance

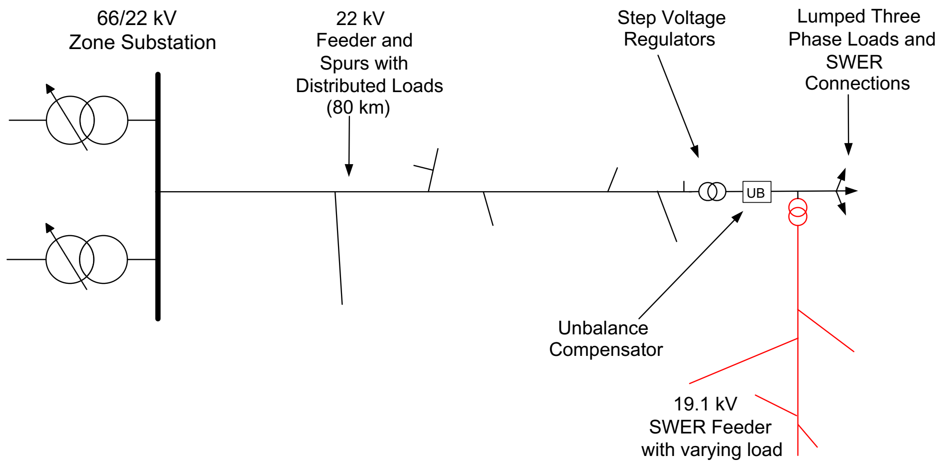

Fig. 15. System model to study the impact of both an unbalanced compensator and switchable reactors.

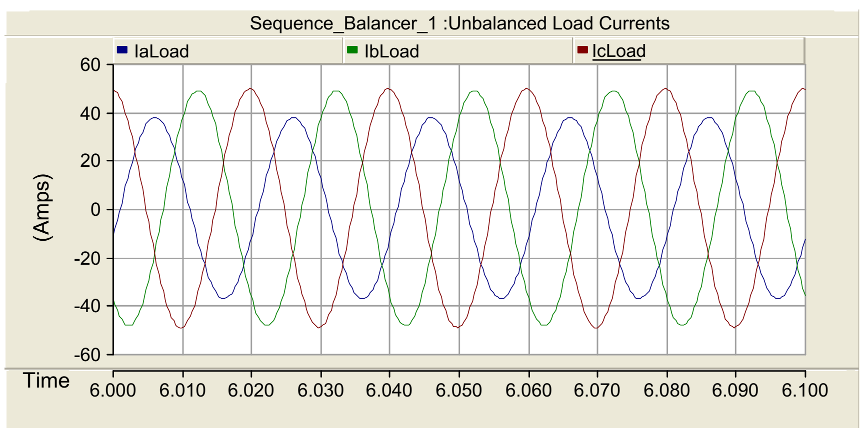

Fig. 16. The three-phase feeder load currents downstream of the unbalance compensator.

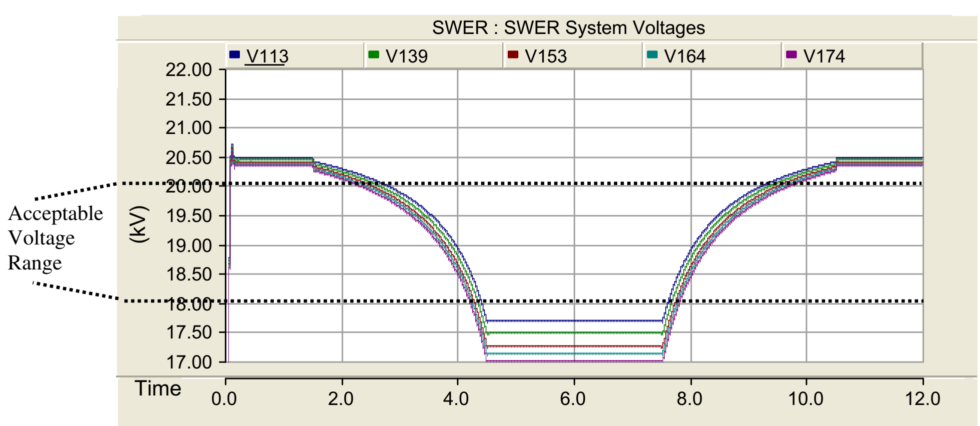

Fig. 17. Selected SWER feeder voltages when only fixed shunt reactors are used (current practice).

compensator was added to the model and the fixed shunt reactors in the SWER line were replaced with the switchable reactor devices.

Fig. 18 shows how the unbalance compensator reduces the level of the load current unbalance. The line current unbalance is reduced to approximately 5% from 15% in Fig. 16. In doing so the voltage unbalance is decreased to less than 0.5% from 3% compared to the system without compensation.

Fig. 19 shows that the switchable reactor on the SWER line effectively controls the voltages at various points on the SWER feeder to the nominal values ±5% (even with a 50% increased load). This should be compared to Fig. 17, where fixed shunt reactors were used and the load was at the nominal 100%.

No adverse interactions between the unbalance compensator and the switched reactors are observed. Both devices work effectively. The reactors are switched on at light load and are switched

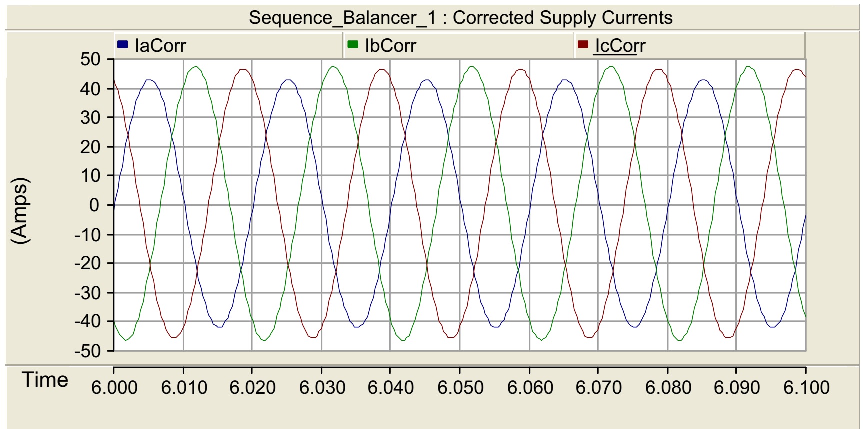

Fig. 18. The three-phase feeder compensated supply currents upstream of the unbalance compensator.

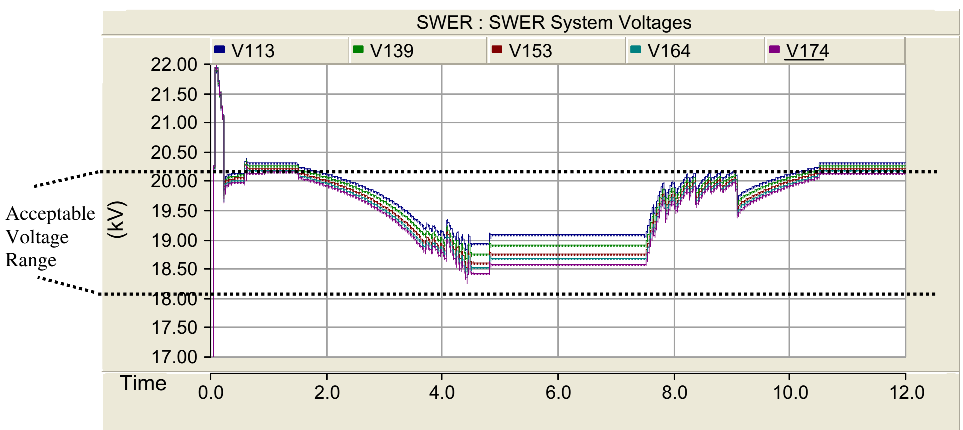

Fig. 19. Selected SWER feeder voltages (proposed combination of switchable reactors and unbalanced compensator).

off at heavy load; on the other hand, the balancing compensators are on during the peak load and are off during light loads. Combined together, the voltages are regulated and the unbalanced effects are reduced to acceptable values (Figs. 19 and 18 compared with Figs. 17 and 16, respectively).

5. Conclusions

In this paper, two cost-effective solutions have been proposed to solve the voltage regulation problem and the unbalancing effect problem of Single Wire Earth Return (SWER) distribution networks, which are used for the electricity supply of rural areas in Australia, New Zealand, South Africa, Brazil, Laos, Canada (Saskatchewan), USA (Alaska), Iceland and some other countries. A low voltage (LV) switchable shunt reactor is proposed in lieu of the high voltage (HV) fixed shunt reactor, currently used to prevent excessive voltage rise at the time where the load is low on a SWER line. It is shown that by switching off the reactors at peak load times, the voltage regulation of the system improves. This will help the network accommodate the recent load growth on the system. Also, a simple economic balancing scheme is proposed to improve the voltage unbalance of three-phase feeders which supply SWER lines.

Two case networks have been modelled using PSCAD by introducing several user-defined components. The proposed switchable reactor and balancing compensator has been added to the case networks. The study demonstrates the effectiveness of both proposed solutions. Ergon Energy Corporation in Australia has installed a switchable reactor, designed and made by the authors, on one of their rural distribution SWER networks, i.e. Stanage Bay SWER in Queensland

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