Load Modelling for Medium Voltage SWER Distribution Networks

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Abstract—The supply of electricity to customers dispersed across wide geographical areas using the Single Wire Earth Return (SWER) distribution system has been adopted in many rural areas in Australia. This network system is the most economically practical method of supplying continuous power to scattered rural customers. With the increased demand for high power devices such as air conditioners and periodic events such as pumping, as well as the use of long and high impedance feeders, it becomes difficult to maintain good voltage regulation on these networks. Modelling of electrical networks is an important aspect of network analysis. However, current models for SWER networks do not reflect the conditions and voltage drops expected on the actual networks. The use of customer energy data and load diversity rules, in load allocation procedure, provides an opportunity to develop significantly more accurate models. The case studies of the Mistake Creek North and Stanage Bay SWER networks in Central Queensland show a significant improvement in the accuracy of the developed models reflecting the actual network performance.

Indexing Terms: SWER; Single Wire Earth Return; Power Distribution Systems; Load Modelling; Rural Electrification

I. INTRODUCTION

There are still many people in the world who are deprived of many advantages of electric energy. The World Bank has encouraged the expansion of simple systems for rural electrification to reduce the cost of the grid extension [1]. 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 an economic alternative to the standard three-phase distribution systems for rural areas [2]. In many areas of Australia, rural electrification systems were established by the State Electricity Boards during the sixties, seventies and eighties under community service initiatives. SWER distribution lines are used extensively in remote parts of Queensland and other states of Australia, 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. The cost benefits of SWER systems have also been utilised by other nations; for example, New Zealand, South Africa and Brazil have applied this technology to extend rural electricity supply [3]. The SWER lines are normally supplied from long radial three-phase distribution feeders typically at 11 kV or 12 kV, which produce SWER line voltages of 12.7kV or 19.1kV, respectively. As an example, a rural SWER system may supply 200kVA to less than twenty consumers spread over 200km. Although the system is very cost effective, but it has a few disadvantages including high losses and poor voltage regulation [4].

SWER networks typically had small-size loads; therefore, Distribution Utilities used conductors with small cross sectional areas. However, as the loads on these networks have increased, the problem of increased losses and voltage drop at high loads is now a common problem. On the other hand, at the off-peak times increased level of voltage due to line charging is observed. So, it is difficult to maintain good voltage regulation without utilising methods to minimise the effects of both phenomena [5].

Modelling of electrical networks is an important aspect of network analysis. Network models provide a representation of how the network will behave under certain conditions or loads. By using proper models, the effects of faults, voltage drop, load growth, contingency conditions, maintenance schedules and future customer connections can be analysed. Load modelling is a very important part of power system modelling. The current load models used by utility companies for SWER networks do not reflect the conditions and voltage drops expected on the actual networks. This paper uses customer energy data and load diversity rules in the load allocation procedure, which provides an opportunity to develop significantly more accurate models. The case studies of the Mistake Creek North and Stanage Bay SWER networks in Central Queensland, Australia, show a significant improvement in the accuracy of the developed models reflecting the actual network performance.

II. MODELLING CONSIDERATIONS FOR SWER NETWORKS

SWER spurs can be either isolated or un-isolated from the feeders which are used to energise them. Isolated SWER lines are more common. An isolating transformer is used to isolate SWER lines from their feeders. This ensures the feeders energising the SWER do not carry zero sequence currents, so that earth leakage protection may still be used on the feeders. Figure 1 shows a typical SWER network configuration [6].

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The system must be able to handle the peak power consumption that may occur. When there is more than one customer on a single supply, it is unlikely that the peak demands of each customer will occur at exactly the same time. The observed peak load is, therefore, smaller than the combined peaks of each of the customers. This coincidence is measured by a coincidence factor. Diversity is another measure to represent the same phenomena and is defined by the inverse of the coincidence factor. The diversity factor is the measure of how much higher the customer’s individual peak is compared to its contribution to the group peak [7].

For SWER systems the location of the load along the line has a significant effect on the characteristics of the system. The voltage regulation will be significantly different when putting the majority of the load at the start or end of the SWER spur. This, combined with the limited number of customers and long feeders, can mean that single customer temporary peak load may have to be considered when computing the capability requirement of the SWER system.

### III. LOAD ALLOCATION METHODS CURRENTLY USED

Ergon Energy uses a software package titled Distribution Network Information System (DINIS). This is the standard tool used by Ergon Energy to model and analyse their distribution and subtransmission systems. The load profiles for each of the distribution feeders or SWER isolation transformers are generally known. However, each of the customers’ load profiles on the network is unknown. Load allocation allows the assigning of loads to each of these customer transformers from the total load recorded. The peak load on the feeder or isolation transformer is used for load allocation. This allows capturing the network in maximum demand condition so as to determine if the quality of power supplied is suitable. This will result in a linear model with respect to the change in load.

Load allocation performed in DINIS assigns loads evenly at every point on the network based on the distribution transformer ratings. This way of allocating loads is a suitable approximation for the short urban networks where diversity is high. However, for SWER networks, with a small customer base and the network conditions described previously, this form of assignment may result in large inaccuracies. The primary source of the inaccuracy is that the distribution of loads on a SWER network has a low diversity factor. Using the usual method of load allocation for high-diversity networks may result in the model not reflecting the actual SWER network, as shown in Figure 2.

![Figure 2. Metered data and original model voltage drops versus total load on the isolating transformer](image)

As shown in this figure, the results predicted by the current DINIS model using this allocation scheme are significantly lower than the actual metered data.

### IV. ESTIMATING AVERAGE LOAD OF DISTRIBUTION TRANSFORMER USING CUSTOMER ENERGY DATA

After Diversity Maximum Demand (ADMD) is the maximum demand per customer after diversity is considered. As the number of customers is increased, the ADMD is reduced. ADMD may be obtained using Equation (1).

\[
ADMD = \frac{MD}{N \times DF}
\]

where, MD is the maximum (total) demand, N is number of customers and DF is the diversity factor.

Figure 3 shows that the higher the diversity, the smaller the contribution of the individual customer peak demands to the group peak demand (smaller ADMD) [8].

The ADMD figures for built-up areas are available or are easily obtainable, due to the simplicity of their calculation. However, due to the unavailability of a methodology and guidelines for deriving load diversity for SWER networks, no written recommendation or methodology for calculation of ADMD figures exists which is specifically aimed at SWER distribution systems. Furthermore, if standard ADMD figures are used, each customer is treated equally. However, customers located towards the end of the network have more significant effects on the power quality observed on the SWER systems. This means that the standard ADMD figures do not represent an accurate measure for the SWER system as a whole. Therefore, in this paper energy data has been used to get a more accurate distribution of loads on the network.
Usually, each customer uses a different amount of energy in kilowatt hours. This energy use will give an indication of which customers exert more load on the system. Without knowing the customer load profile, it is not possible to determine if this energy usage was from a number of short peaks or from continuous use. It is known, however, that higher energy uses translate to higher average loads.

The ‘Connect’ database, a part of Feeder STAT software used by Ergon Energy, offers an interface which allows for accessing data of the customers who are connected on the network. The customer details and energy consumption data are recorded in this Connect database. For use in modelling, the energy data for each customer was converted to an average kilowatt figure. This was accomplished by dividing the total kilowatt hour consumption of the customer by the total days in the metering period. Energy data for each customer was split into tariffs where applicable. Some tariffs are only on for specified times during the day and this had to be considered when finding the hourly average. Instead of taking the average over 24 hours, for some tariffs the average was taken only over the time that the tariff is usually on. The different tariff results were then added to form the final figure.

V. LOAD FACTOR DIVERSITY CORRECTION

Models represent a single state of the network; and the most important state is the time of heavy load. Increasing the load of customers towards the end of the network (by scaling the average loads obtained in the previous section) is an effective way of accomplishing this. This will, in effect, reduce the diversity at the end of the network or in other words increase the coincidence that the end customers will have peak loads at similar times, thus capturing the network in a more demanding condition.

Equation (2) is used to determine the diversity factor for a number of customers connected to a distribution transformer (in a normal three phase distribution system). Application of this to SWER networks will not be accurate due to the large distances between the customer connections. However, it will provide an estimation of the diversity factor. The selected region of customer loads towards the end of the network can then be scaled by the diversity factor to increase their loads.

\[
DF = 1 + \frac{2}{\sqrt{N}}
\]  

(2)

The resultant data is then entered into DINIS for each of the distribution transformers. Although this will also result in a linear model with respect to the load, the model will represent a better average condition of the actual network.

VI. VERIFICATION OF THE MODEL ACCURACY

A. Metered Data Acquisition and Analysis

To have a reference for the developed network models, the existing performance of the network needs to be investigated. This requires the collection of power quality data at various points in the networks. Furthermore, this data will be used to verify the accuracy of the developed models against the recorded network performance.

Power Quality (PQ) meters are installed on most major urban and rural feeders and Zone Substations on Ergon Energy’s distribution network. However, comprehensive metering is not available on most SWER networks, which are the focus of this paper.

Two SWER networks have been selected for modelling in this paper. The networks are the Mistake Creek North SWER and the Stanage Bay SWER, both in Central Queensland, Australia. Raw data from PQ meters for selected networks was acquired from the SWER improvement group at Ergon Energy. This data was taken from previous studies, projects or investigations into customer complaints.

The analysis of metered data has shown that the correlation factors between the recorded voltages and the total load on the network (at the isolating transformer node) are higher compared to the correlation factors for the recorded voltages and loads on the distribution transformer. Figure 4 shows the scatter plots for the Stanage Bay SWER network voltages versus loads at the distribution transformer and Figure 5 shows the scatter plots for the same network voltages versus loads at the isolating transformer. These figures demonstrate that the voltage levels can be different at any point of the network at any given load condition. This is due to the changes on other parts of the network. The figures also suggest that the load profiles for an individual distribution transformer will be different from the load profile of the SWER distribution network as a whole (at the corresponding isolating transformer).

Similar scatter plots for the Mistake Creek North SWER illustrate the same conclusion. These figures are not shown here for the sake of brevity.
The PQ data readings have been recorded on the low voltage side of the distribution transformers and as such the transformer losses and tap settings need to be considered. Mistake Creek North SWER distribution transformers are all set on nominal tap. For Stanage Bay SWER distribution transformers towards the end of the network a boost of 2.5% setting is used. Since only MV distribution voltages are modelled in DINIS, modelled voltage levels recorded and compared to the metered and original model values.

It would be ideal to run load flows on the models using the conditions for all of the recorded data. However, due to the practical time restrictions of manually performing all the load flows, only specific times are chosen, i.e. 8am, 7pm and 7:30pm times are used to simulate the network during both morning and afternoon peak demand times. The 3am and 2pm times are used for day and night light loads. Another time of interest is after 9pm when the pumping loads are usually connected. For this the 9:30 pm time has been used.

The following are the steps taken to set the modelled values:
1. Allocate load for the original and new model. Load for the original model is allocated using the method currently used as explained in section III. For the model proposed by this paper, energy data figures have been used as explained in section IV.
2. For the proposed model, determine the diversity factor for the chosen region of distribution transformers at the end of the network and increase their loads by this diversity factor.
3. Set the generator voltage on the model to the recorded isolating transformer voltage (in per unit).
4. The total load on the SWER network is to be scaled to the metered load on the isolating transformer.
5. Run load flow and record the voltage drop percentage at the metered distribution transformer.
6. Repeat the process from 3 to 5 for all data points.

C. Results

Modelling was conducted to investigate the effect of using the proposed method against the original model. The energy data was prepared as mentioned in section IV and the process was followed as described in section B for both the original and the energy data model. The modelling was done for the following time periods and the results are plotted on scatter plots comparing the 2 models and metered values.

Mistake Creek North SWER:
  - Mistake Creek North Isolator
  - B.S.C Camp 338612 (20 kVA Customer Transformer close to Mistake Creek North Regulator)
- 20/02/2007 12:00 – 26/02/2007 12:00
  - Mistake Creek North Isolator
  - Bulliwallah No.1 338544 (20 kVA Customer Transformer near end of feeder)
  - Cudgee Park No.3 338558 (10kVA Customer Transformer near start of feeder)
Stanage Bay SWER:
- 21/12/2006 12:05 – 01/02/2007 13:30
  - Stanage Bay Isolator
  - Stanage Bay No.1 100180 (50 kVA Distribution Transformer at near end of feeder)

An example of the plotted results is shown in Figure 6. From observation, for Bulliwallah No.1 distribution transformer on the Mistake Creek North SWER, the new model results are significantly closer than the original model to the actual metered values.

VII. ANALYSIS OF RESULTS

The method established in section VI(B) should improve the accuracy of the models to resemble the actual state of the network. To verify this, it is important to compute how the new model resembles the metering data more accurately. Using metering data as the point of reference will allow for direct comparison of the two models. Voltage error values are computed by taking the modelled results from the metered data. Negative values signify the models showing higher results compared to the metered values, while positive values show lower results.

Histograms are constructed by using the two model voltage errors relative to the metered values on the x-axis and the number of times this occurred on the y-axis, as shown in Figure 7. Since metered values are the point of reference, the closer the modelled distributions will be to zero % voltage error, the more accurate is the model. This also allows computing descriptive statistics on the data to get the mean and the standard deviation. These values will be used to analyse how close the models are to the actual metered values.

In each case, the mean of percent voltage error predicted by the proposed model is considerably smaller than the original model as shown in Table I. Particularly, for Bulliwallah No. 1 distribution transformer, which is located at the end of a long SWER line (Mistake Creek North), the mean voltage error is only 0.1% (with a negative sign indicating that the voltage drop predicted by the model is slightly more than the actual metered values). This is to be compared with the mean voltage error of 1.55% predicted by the current model used by Ergon Energy (with a positive sign indicating that the current model underestimates voltage drops).

Table II shows that for the range of two standard deviations, the encompassed voltage errors are skewed towards predicting lower voltage drops (underestimating) for the original model compared to the proposed model, which resembles more towards normal distribution around the actual metered values.

![Figure 6 Voltage drop at Bulliwallah No1 distribution transformer scatter plot against the total load on the isolating transformer](image)

![Figure 7 Bulliwallah No. 1, Mistake Creek North SWER, % voltage drop error distribution between models and metered data.](image)

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SUMMARY OF MEAN VOLTAGE ERROR AND STANDARD DEVIATION FOR THE PROPOSED AND ORIGINAL MODELS</th>
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</thead>
<tbody>
<tr>
<td>Distribution transformer</td>
<td>Mean Voltage Error</td>
</tr>
<tr>
<td>Bulliwallah No1</td>
<td>-0.01</td>
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<tr>
<td>Cudgee Park No3</td>
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<td>B.S.C Camp</td>
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<tr>
<td>Stanage Bay No1</td>
<td>-0.6668</td>
</tr>
<tr>
<td>Original Model</td>
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<tr>
<td>Bulliwallah No1</td>
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<tr>
<td>Cudgee Park No3</td>
<td>1.2671</td>
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<tr>
<td>B.S.C Camp</td>
<td>0.6946</td>
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<tr>
<td>Stanage Bay No1</td>
<td>1.8173</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>RANGE OF TWO STANDARD DEVIATIONS (95.45% OF DATA) FOR THE MODELS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution transformer</td>
<td>New Model</td>
</tr>
<tr>
<td>Upper %</td>
<td>Lower %</td>
</tr>
<tr>
<td>Bulliwallah No1</td>
<td>-1.6858</td>
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<td>Cudgee Park No3</td>
<td>-1.1645</td>
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<tr>
<td>B.S.C Camp</td>
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<tr>
<td>Stanage Bay No1</td>
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<tr>
<td>Original Model</td>
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</tr>
<tr>
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<tr>
<td>B.S.C Camp</td>
<td>-0.9590</td>
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<tr>
<td>Stanage Bay No1</td>
<td>-0.5377</td>
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</table>
VIII. CONCLUSIONS

This paper has proposed a technique for modelling SWER network loads, which utilises readily available customer energy data and diversity factor approximation to develop more accurate SWER network models compared to the existing models used by utility companies in Australia. The current load models used by utility companies for SWER networks do not reflect the conditions and voltage drops expected on the actual networks. This paper uses customer energy data and load diversity rules in the load allocation procedure, which provides an opportunity to develop significantly more accurate models.

Several case studies have been modelled. In each case, the mean voltage error predicted by the proposed model is considerably smaller than the original models currently used by the utility companies. Also, the error distributions are a lot closer to the actual metered values when one or two standard deviation ranges are considered. The proposed methodology has shown great promise in producing more accurate models. It has shown that the accuracy of models can be significantly improved, and is a stepping stone for further investigation and development in this area.

REFERENCES


Nasser Hosseinzadeh (IEEE-M’86) is currently with Swinburne University of Technology, Melbourne, Australia. Earlier, he had worked as a senior lecturer at Central Queensland University in Australia, as a lecturer at Monash University Malaysia and as an assistant professor at Shiraz University. His special fields of interest include power system analysis and planning, power system stability, application of intelligent systems in engineering, power distribution networks and engineering education. Dr. Hosseinzadeh is a registered member of Engineers Australia, a member of IEEE and also is on the Australian Panel APC1 System Development and Economics of CIGRE.

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