Reactor Solutions for Voltage Control of SWER Systems

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ABSTRACT

Ergon Energy operates tens of thousands of kilometers of Single Wire Earth Return (SWER) distribution feeders in remote parts of Queensland to deliver electrical energy to small customer loads, scattered sparsely over vast areas. Ergon Energy has identified voltage regulation as one of the key issues being faced in this area, as loads continue to grow in rural distribution networks. These voltage regulation issues cause capacity limitations on the SWER feeders. Voltage drop during peak load periods is one issue, but high voltages during low load periods caused by the Ferranti effect is another key factor on long SWER feeders. Currently, Ergon uses fixed shunt reactors to control line overvoltages during low load periods, but these reactors add to the line load during peak load conditions.

At AUPEC 2005, Central Queensland University presented a thyristor controlled reactor option as a potential solution to this problem. This paper follows on from this and presents two lower technology solutions, namely switched reactors and saturable reactors. Both options aim to reduce the steady state voltage range between peak load and low load, thus freeing up additional capacity on the SWER feeder for growing load. This paper presents the development of both options and comments on the suitability of the options to perform to the required specifications. PSCAD/EMTDC is used to model the problem.

1. INTRODUCTION

A SWER feeder is a unique distribution line that consists of a single conductor energised at high voltage, typically 12.7 kV or 19.1 kV in Australia. It 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 various reliability advantages due to the small number of components. There is over 150,000 km of SWER feeders currently in use in Australia [1].

Due to recent strong electrical load growth in Queensland, rural distribution systems that were designed with a certain load limit, are now operating beyond their original specifications. In the past 30 years, the standard SWER connection transformer size has risen from 5 kVA or 10 kVA to 25 kVA [2] [3]. One of the big factors in Queensland's recent load growth has been the lowering cost of air conditioning. In the past few years, the market has been flooded with low cost air conditioning units, making household air conditioning common rather than a luxury. This is putting high demands on both rural and urban distribution systems.

One of the key issues pertaining to SWER feeders is that of voltage regulation. Capacity limitations are occurring due to voltage regulation issues. During very light load periods the SWER line capacitance creates voltage rise issues toward the end of the feeder due to the Ferranti effect. To combat this issue, fixed shunt reactors are used to control voltages. Unfortunately these reactors add to the load during peak load periods and excessive voltage drop limits the load capacity of the feeder.

One of the SWER feeders in the Ergon Energy network that is being used as a case study is the Jericho North feeder. This is a 19.1 kV SWER feeder near the township of Jericho in Central Queensland.

The Jericho North SWER feeder is very large with 415 km of total feeder length. There are 52 customer loads drawing a total peak load of 185 kVA at the nominal voltage. The base system model and its development in PSCAD/EMTDC (PSCAD) is described in [4].

The following graphs in Figure 1 and 2 show the voltages measured at various points in the network for various loading conditions.

SWERV100 is the voltage measuring node at the isolation transformer. SWERV128, SWERV146 and SWERV173 are voltage measuring nodes at three points near the extreme ends of the feeder.

After a PSCAD initialisation period of approximately 0.1 seconds (where the source voltage ramps up to its rated value), the load varies from 100% of the known peak load down to 30% of peak load between 0.5 and 1.5 seconds.

This simulates an approximately daily load curve, although the time period is greatly shortened for the purposes of this modelling.

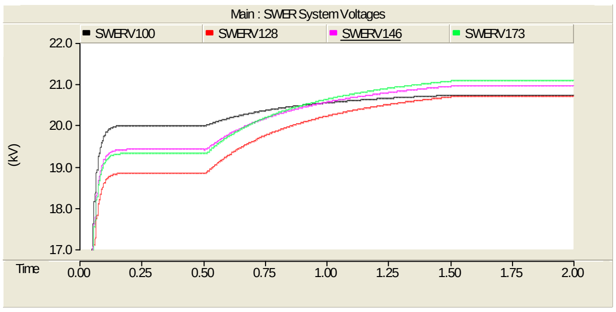

Figure 1 – Voltages without Shunt Reactors showing high voltages at low load

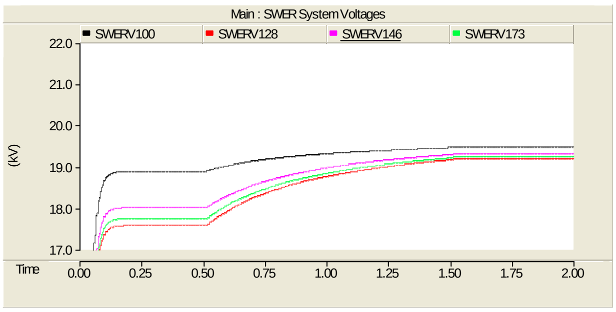

Figure 2 – Voltages with shunt reactors showing controlled voltages at low load but low voltages at peak load

The output graphs clearly demonstrate the voltage regulation issues being experienced. During periods of low load, significant generation of reactive power due to the Ferranti effect cause voltage rise at the ends of the feeder. Without shunt reactors the voltages are excessive (up to +10%). During peak load the voltage at the ends of the feeder are quite low. The shunt reactors clearly add to the load burden and worsen the voltage drop (down to – 9%). The target range for acceptable voltage is ±5% or approximately 18 kV to 20 kV for a 19.1 kV SWER feeder.

2. SWITCHED REACTOR VOLTAGE REGULATION

One obvious solution to the fixed shunt reactor problem where the reactors are needed at low load but need to be removed at peak load, is to switch the reactors, similar to the way that shunt capacitors are switched in and out of service when required.

One issue with switching a 25 kVA 19.1 kV reactor is that the switchgear required for such an operation costs more than the reactor itself. 33 kV switchgear would be required and the minimum circuit breaker rating available is no less than 630 A.

The proposed solution involves using a standard 25 kVA customer SWER transformer to step down the voltage to 250 V and use a low voltage reactor. This approach is described in [5] for another voltage regulator solution. Low voltage switchgear is commonly available and economic. Low voltage reactors are also simpler and less expensive.

The initial solution is a 25 kVA 250 V iron cored reactor connected to the secondary of a 25 kVA 19.1/0.25 kV single phase transformer.

The switched reactor model has been developed in PSCAD using a single phase reactor model. The transformer rating is set to 25 kVA and the leakage reactance is set to 1 pu. The secondary winding is short circuited. The copper losses are entered to give a resistance that sets the Q factor of the reactor to 50 at 50 Hz. The saturation element is enabled. According to [6], the inrush for an iron cored reactor is in the range of 3 to 5.5 pu. The inrush current dc offset of a real reactor is very slow to decay due to the relatively low losses of a reactor, however in this model the inrush current decays within approximately 6 cycles. This is not considered an inadequacy of the model because the simulation durations are shortened and simulation events are compressed; so this is very suitable. The air cored reactance element in the transformer model is adjusted to give the appropriate inrush current magnitude.

PSCAD control components are used to simulate the control scheme of the reactor switching. The voltage at each reactor location is measured (at low voltage). If the reactor circuit breaker is open and the voltage is above 262 V (20 kV primary or +5%), then the reactor switches in after a time delay. If the reactor circuit breaker is closed and the voltage is less than 231 V (17.65 kV primary of -7.5%) then the reactor switches out of service. The actual primary operating voltage of the latter switching operation is 18.15 kV (-5%) but allowance is made for the voltage drop in the reactor transformer when the reactor is in service.

Figure 3 shows the voltage measured in the SWER feeder system for a similar 100% to 30% of peak load ramp shown in previous voltage plots. Eight switched reactors are placed into service in place of the eight existing 25 kVA fixed reactors. A significant improvement in voltage range can be seen. This provides opportunity to increase the feeder load. Figure 4 shows the voltages for a 150% to 30% of peak load variation. Except for one point which is slightly outside the acceptable voltage range at 150% load, the system performs adequately with 50% more load.

It is evident however that there can be step changes in voltage that are up to 5% which would be noticeable by customers as voltage flicker even though it would be expected that these reactors would only be switched a few times per day. AS/NZS 61000.3.7 sets an absolute limit of 4% for switching frequencies up to once per hour. This issue is caused by a number of reactors switching simultaneously and/or by the size of the reactor.

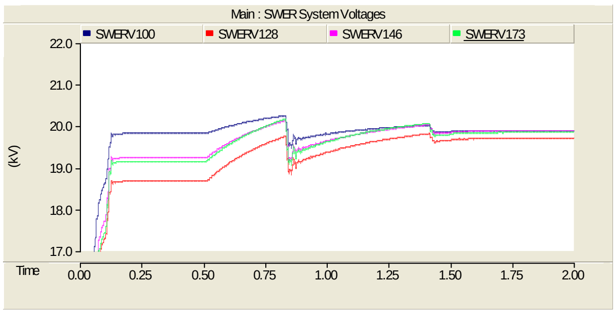

Figure 3 – Voltage with 25 kVA switched reactors with common time delay (100% maximum load case) (ignore initialisation <0.2 s)

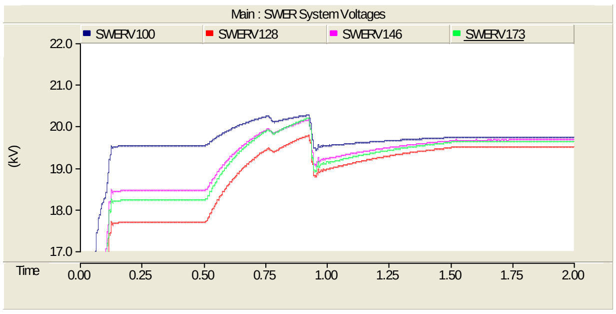

Figure 4 – Voltage with 25 kVA switched reactors with common time delay (150% maximum load case) (ignore initialisation <0.2 s)

There are two possible solutions for this problem. The first is to set the time delays of the reactors at different locations accordingly, ie setting the reactors closer to the ends of the SWER feeder with shorter time delays than reactors close to the isolation transformer. This is to prevent hunting of reactors as the system tries to reach equilibrium after a change in load conditions and prevents all the reactors switching simultaneously. The second solution is to split each reactor into two smaller reactors that are switched separately. This is an easy change to make at low voltage because the equipment is relatively inexpensive.

Figure 5 shows the voltage plots for the case with different time delays. The voltage step change can still be up to 3% which is most probably acceptable for the low numbers of switching operations likely per day, but further improvements are possible.

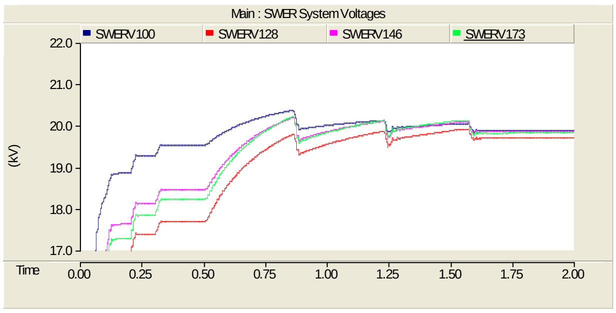

Figure 5 - Voltage with 25 kVA switched reactors with different time delays (150% maximum load case) (ignore initialisation <0.3 s)

Figure 6 shows the voltage plot for the 2 x 12.5 kVA reactor case. The voltage step is reduced to 2% and given the low switching frequency that would be envisaged, this is considered acceptable.

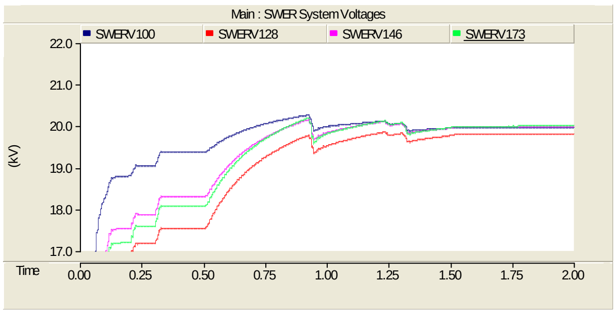

Figure 6 – Voltage with 25 kVA reactors replaced with 2 x 12.5 kVA reactors with different time delays (150% maximum load case) (ignore initialisation <0.3 s)

This analysis shows 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%.

3. SATURABLE REACTOR VOLTAGE REGULATION

The concept of using saturable reactors in place of the existing fixed shunt reactors is very similar to the switched reactor scenario. The system needs to add shunt reactance during low load periods and remove shunt reactance during peak load periods.

One elegant solution that has been used in transmission networks around the world, involves the use of fixed saturable reactors [7]. The main difference between these three phase applications and the proposed SWER application is the complexity of the reactor. In the three phase application a very complex core and winding structure is used to derive the required performance curve and control harmonics. This is not possible with a single phase reactor in the same manner.

The main advantage of this saturable reactor scheme over the previously described switched reactor scheme is that no additional switchgear or controller is required, beyond what is already in place with the existing fixed shunt reactors. The saturable reactors would simply replace the existing shunt reactors.

The saturable reactor model has been developed in PSCAD using the UMEC single phase transformer component. This component allows the manual entry of the saturation V-I curve which allows the user to control the voltage where saturation begins and the degree of saturation (or the slope of the V-I curve). The base rating of the reactor is arbitrarily chosen as 10 kVA and the intention is that under saturation conditions the reactor will draw additional reactive current to increase the "effective" rating of the reactor.

For this application the saturation curve in Figure 7 has been developed based on test data from an example transformer core [8]. The V-I curve has been lowered so the reactor starts to saturate just below 1 pu voltage.

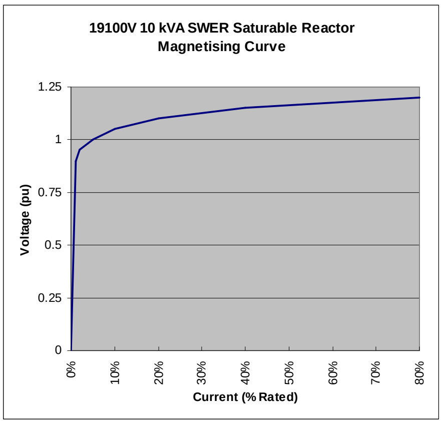

Figure 7 – Reactor saturation characteristic

The reactor was modelled in PSCAD and the supply voltage was varied to determine the reactor current. Figure 8 shows the reactor current at 1 pu voltage.

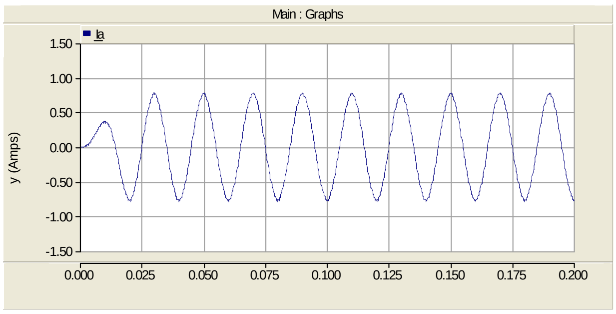

Figure 8 – Reactor current at nominal voltage of 19.1 kV

The RMS current at 1 pu voltage is 0.52 amps. Figure 9 shows the reactor magnetising current at 1 pu voltage and it can be seen that the reactor is beginning to saturate, although the saturation is not significant because the reactor is operating just on the knee point of the V-I characteristic.

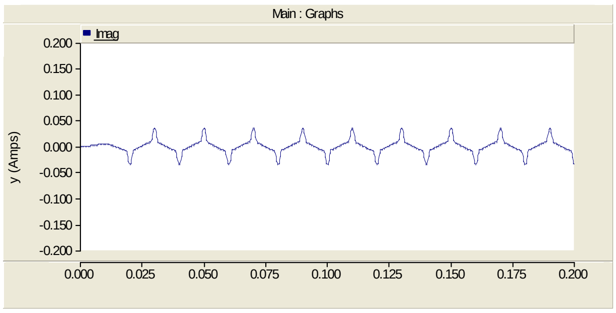

Figure 9 – Reactor magnetising current at nominal voltage of 19.1 kV showing the reactor is starting to saturate

Figure 10 shows the reactor current at 1.1 pu voltage and it can be seen that the reactor is in deep saturation. The RMS current has increased by over 30% to 0.7 amps.

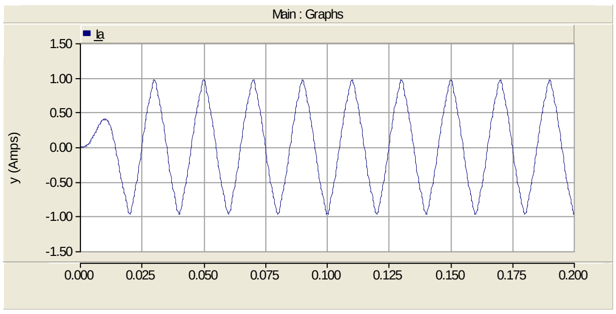

Figure 10 – Reactor current at +10% voltage (or 21 kV) showing saturation

Figure 11 shows the magnetising current of the reactor and significant saturation can be seen. This causes harmonic currents to be introduced to the supply and these are detailed in Table 1. The third harmonic is the predominant harmonic and this is expected.

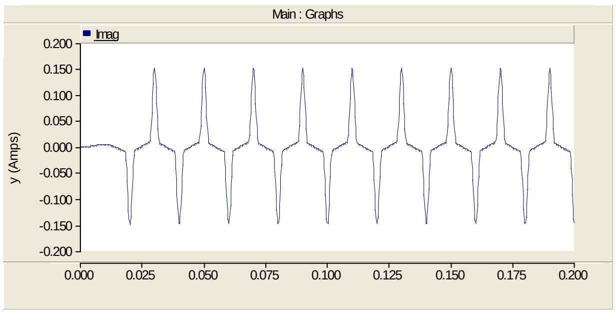

Figure 11 – Reactor magnetising current at +10% voltage (or 21 kV) showing significant saturation

Table 1 – Harmonic current distortion in the reactor current for various supply voltages (% of fundamental)

Voltage	2^{nd}	3^{rd}	5^{th}	7^{th}
1.0 pu	0.0%	1.0%	0.7%	0.5%
1.05 pu	0.01%	2.3%	1.6%	0.9%
1.1 pu	0.05%	5%	3%	1.5%

In the case study system model, eight saturable reactors are modelled in place of the eight existing fixed reactors. Once again the load is ramped from 150% to 30% of peak load between 0.5 and 1.5 seconds and Figure 12 shows the voltage profile. It can be seen that the voltage regulation is certainly improved from the existing case, however due to the 10 kVA base rating, there is still a reactive burden on the feeder at peak loads which is causing lowered voltages.

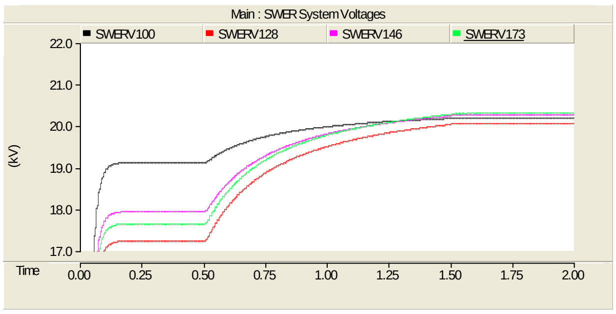

Figure 12 – SWER Voltages with saturable reactors

Table 2 shows the harmonic voltage distortion measured at various locations on the feeder. Table 3 shows the harmonic current distortion at the isolation transformer.

Table 2 – Harmonic voltage distortion at various points in the SWER feeder (% of fundamental)

Bus	2^{nd}	3^{rd}	5^{th}	7^{th}
Bus 128	0.01%	0.75%	0.16%	0.05%
Bus 146	0.01%	0.8%	0.16%	0.05%
Bus 173	0.01%	0.9%	0.17%	0.05%

Table 3 – Harmonic current distortion in the SWER isolation transformer (% of fundamental)

Bus	**2nd**	**3rd**	**5th**	**7th**
SWER ISO	0.1%	2.0%	0.18%	0.13%

These values are lower than the allowable harmonic voltages and currents in AS61000 [9], however harmonics need to be given special consideration in SWER systems due to electromagnetic induction into telecommunications circuits. The 7th harmonic is of most concern due to the psophometric weighting of this harmonic although third and fifth harmonic may still be the limiting factor due to their higher values [10]. This is not the subject of this paper which is concentrating on voltage regulation but needs to be considered further if the saturable reactor solution is to be progressed.

4. CONCLUSIONS

The paper has demonstrated that the use of switched reactors in lieu of fixed reactors will control voltages within an acceptable range and improve overall voltage regulation performance. The optimum solution is to provide multiple smaller reactors at each existing reactor substation to prevent voltage flicker from becoming an issue. The results presented show the potential to increase the SWER feeder load by 50% and still generally maintain acceptable voltage regulation.

However, the studies have shown that with the increased load, there maybe one or more locations where even with all reactors switched out of service, lower than acceptable voltages can occur. This is a factor of the existing SWER feeder design that may require investigation on an individual basis separate from a reactor voltage regulator scheme. In any case the voltages are dramatically improved from the existing situation.

The use of saturable reactors has been demonstrated and whilst they can effectively control high system voltages during low load periods, they still add to the load burden of the feeder during peak loads. Therefore the ability to increase the feeder capacity is somewhat limited with this solution. Harmonics may also be of concern.

5. ACKNOWLEDGEMENTS

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