Reactor based Voltage Regulators for Single Wire Earth Return Systems

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ABSTRACT

Single wire earth return systems, (SWER), are the lowest cost technology for rural power distribution and have global application. Voltage regulation is the determining factor for system capacity for long SWER systems. In long systems, directly connected shunt reactors are often used to compensate the effects of line to ground capacitance. The replacement of fixed shunt reactors with controllable reactors provides an opportunity to significantly increase the system capacity. Three methods of reactor control are studied. Thyristor controlled reactors or mechanically switched reactors can be connected via transformers. Alternatively, switched reactors can be connected to consumer transformers. A case study based on the North Jericho system shows the approaches capable of effecting capacity increases ranging from 82% to 100%.

1. INTRODUCTION

Single wire earth return systems, (SWER), are used for power distribution in regions where the population and load density is low, [1-3]. The technology is promoted by the World Bank as a lowest cost technology and will find growing applications in bringing supply to the estimated 2 billion persons globally without power, [2]. SWER systems typically supply loads of 100kW to 200kW scattered over a line length that might exceed 300km. The distribution voltage studied in this paper is 19.05kV, the phase to ground voltages for a 33kV three phase systems. Consumers where connected by a single phase transformer which produced two single phase outputs in a 240-0-240Vac split winding arrangement. In Central Queensland consumer transformers are typically 10kVA to 50kVA for a standard connection. Figure 1 shows a typical single phase customer transformer, [4].

The existing SWER systems are progressively becoming more heavily loaded and 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. An important option identified by the taskforce is to apply new technologies into aging SWER systems to release capacity for load growth.

Power electronic solutions to SWER problem have been proposed, [5]. These solutions are more technically complex but are certainly achievable. This paper will examine three methods of applying controlled reactors as an intermediate approach to improving SWER systems at a lower capital cost.

Figure 1: A SWER Customer Transformer, [4].

2. CONTROLLABLE SHUNT REACTORS

Many long SWER systems include shunt reactors to control the effects of the line charging capacitance. The Ferranti effect causes the line voltage to rise with distance. In SWER systems this effect is so pronounced as to make it difficult to maintain the consumers supply within the acceptable regulation range. A second effect is to increase the loading of the SWER system supply (isolation) transformer. The line charging current may be as high as twice the transformer rating. Earth designs and unbalance imposed on the three-phase supply network are additional factors.

The industry has always recognized the immediate advantages in removing the reactors at higher loads but there are considerable costs attached to this. While the reactors are small, typically 25kVAr or approximately 1.3Arms at 19.05kV, a switchable reactor will require a motorized high voltage switch, a voltage transformer and a suitable control element. The switch and the voltage transformers will have minimum costs that are much more influenced by the voltage rating than the reactor current. The resulting minimum costs are relatively high.

An alternative to switching on the high voltage side is to switch at lower voltages on a transformer secondary. Consumer transformers of 25kVA rating are produced in large quantities and are consequently moderately priced. Shunt reactors rated at 19.05 kV can readily be replaced by inductors rated at 480V connected across the secondary of a 25kVA 19kV to 240V-0-240V transformer. Three approaches are possible:

- Thyristor controlled reactors connected via dedicated transformers;

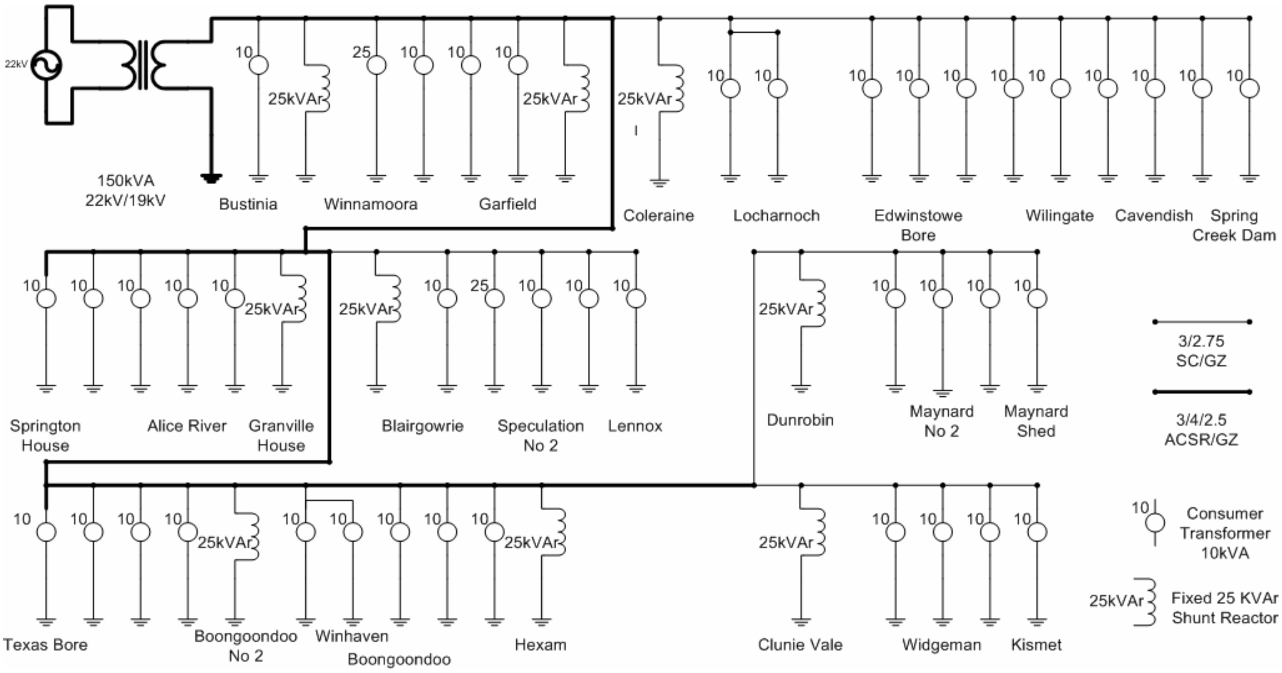

Figure 2: Jericho North SWER System – Simplified Schematic, [4].

- Contactor switched reactors connected via dedicated transformers;
- Contactor controlled reactors at the consumer transformer secondaries.

The over-voltage problem occurs at light load when many consumer transformers are lightly loaded. An opportunity exists to use the spare transformer capacity to connect reactors. Apart from avoiding additional transformer costs, additional core losses are avoided. The paper will show that all approaches can be readily applied to a SWER system and will yield a significant increase in system capacity. The Jericho North system will be presented as a case study that highlights the scale and complexity of a SWER system, [4].

3. THE JERICHO NORTH SWER SYSTEM

The Jericho North SWER system is between Barcaldine and Alpha in Central Queensland and simplified schematic is shown in Figure 2, [4]. The transmission voltage is 19.05kV and system supplies 43 consumer load points. Two load points are 25kVA and the others 10kVA giving a total consumer transformer connection of 460kVA. The system isolation supply transformer is rated at 150kVA. Nine 25kVAr shunt reactors are distributed across the system. The SWER system has a backbone conductor with lighter spur conductors. The back bone is 141km of 3/4/2.5ACSR/GZ. The spurs total 223km of 3/2.75SC/GZ. Table one contains the conductor parameters, [4]. Over the 364km of the SWER system has a total capacitive loading of 270kVAr.

4. CONTROLLED REACTOR SYSTEMS

This paper proposes the substitution of fixed high voltage shunt reactors by controlled reactors coupled via a standard 25kVA 19.05kV to 240-0-240V transformers. Three options are considered including thyristor controlled reactors as shown as shown in Figure 3, contactor controlled reactors as shown in Figure 4 and consumer transformer connected controlled reactors as shown in Figure 5.

Conductor	Parameters
3/4/2.5 ACSR/GZ	R0: 2.02 Ω/km; X0: 0.802 Ω/km B1: 2.086 μmho/km
3/2.75 SC/GZ	R0: 12.55 Ω/km; X0: 0.819 Ω/km B1: 2.029 μmho/km

Table 1: SWER Conductors, [4].

It has been shown previously by the authors that splitting the reactor into two sequentially controlled units is preferable from a harmonic voltage viewpoint for TCR applications, [4]. To allow a comparison of results, the contactor controlled reactors are similarly split to allow finer voltage control. In the case of the Figure 5, it is necessary to monitor the consumer load current and only apply the reactor load when the transformer capacity is adequate to supply both.

In every case the reactors are controlled to regulate the transformer secondary voltage at the local point of connection. This is an important constraint that avoids the need to provide a measurement transformer to monitor the high voltage system. The set points and control methods must be adjusted to compensate for the effects of the transformer reactance and voltage drop under the loads imposed by the reactors. During these studies, the true RMS voltage at the transformer secondary connection point was determined by squaring the voltage and detecting the mean with a second order low pass filter with poles at 10r/s. This delay was important in terms of system stability.

For the thyristor controlled reactor a proportional integral control action is used with the following gain settings:

- Proportional Gain: A voltage error of 500Vrms referred to the 19.05 kV system, yields rated inductor current;
- Integral Gain: A voltage error integral of 500Vrms seconds, referred to the 19.05kV system, yields rated inductor current.

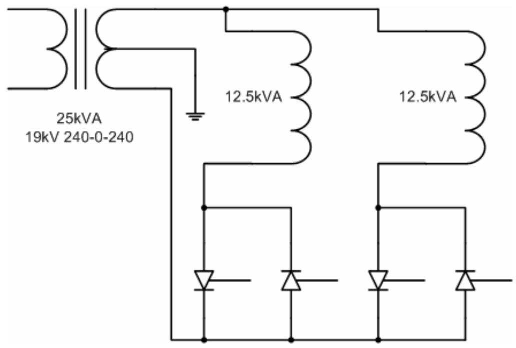

Figure 3: Thyristor Controlled Reactor.

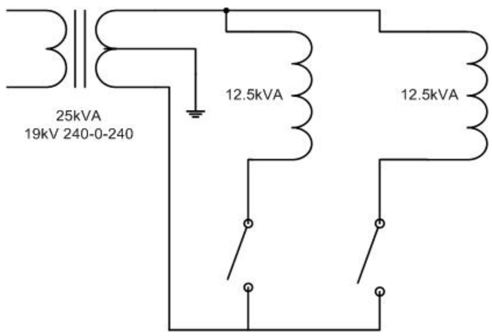

Figure 4: Contactor Controlled Reactor.

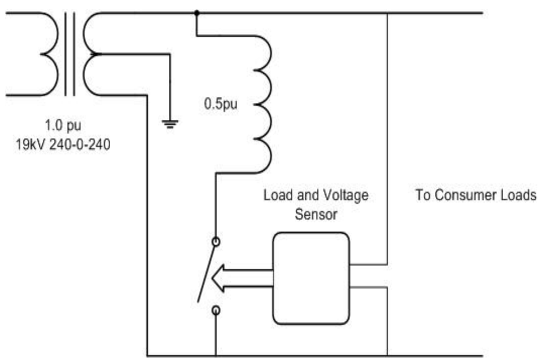

Figure 5: Consumer Transformer Connected Controlled Reactor.

For the contactor switched reactors 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%;
- Disconnection of the second inductor stage occurs when the secondary voltage falls 3.0% below nominal voltage, the first stage disconnects when the voltage falls 3.5% below nominal voltage.

Each inductor controller has a hysteresis width of 4% and this is selected to ensure that a switching limit cycle does not occur when an inductor is applied. The coupling transformer impedance is 3.6%. The switching of an inductor with a per-unit rating of 0.5 on the transformer base parameters causes a voltage drop of 1.8%. As this is much less than the hysteresis bandwidth the resulting voltage drop will not then cause the inductor to disconnect. The centre of hysteresis characteristic of the controller needs to be offset to allow for the coupling transformer voltage drop under load. Care needs to be exercised in evaluating the transformer turns ratio as normally the specified terminal voltages are loaded voltages and their ration differs from the turns ratio by the voltage regulation amount.

For the consumer connected controlled reactors the following apply:

- The reactor is rated at 50% of the consumer’s transformer rating and is only applied if the consumer load is less than 50% of the transformer rating;
- The inductor is applied when the secondary voltage exceeds nominal voltage by 0.5%;
- The inductor is removed if the secondary voltage falls 3.5% below nominal voltage.

In this case a total of 230kVA of reactor load was available distributed across 43 transformers. This represents a switched reactor system that is highly distributed and finely graduated.

5. SIMULATION STUDIES

The Jericho North System is studied using time domain simulations with the Matlab Simulink Power Systems Block Set. This is a time domain simulator with both control systems and power electronics modeling capacity. As the controlled reactors can be modeled on a cycle by cycle basis the harmonic performance of the system is observable as is the full range of control behaviors. The simulations are run over five seconds or 250 cycles allowing any adverse control interactions to be observed. The model features are:

- The topological layout follows the construction drawings, a total of 76 physical transmission line sections are identified and implemented;
- π sections are used with a maximum 10km length;
- The reactors have a Q factor of 55;
- The isolation transformer full load voltage ratio is 22kV:19.05kV; It has series impedances of 0.016 per unit resistance and 0.038 per unit reactance; The magnetizing branch resistance and reactance are 100 per unit and 200 per unit respectively;
- The 22kV system is modeled as a infinite bus;
- Each consumer transformer has per unit resistance and reactance of 0.026 and 0.025 per unit; the magnetising branch resistance and reactance are 100 and 200 per unit respectively; The full load voltage ratio is 19.05kV to 240-0-240;
- Consumer loads are linear constant impedance loads at 0.8 power factor calculated at 240V.

Base line studies of the existing system are first conducted with the fixed shunt reactors in place. Four loading conditions are studied, these are:

- No connected consumer load;
- Three consumer load cases of 50kVA, 100kVA and 150kVA.

The loading cases are uniformly distributed over each transformer of the system. The 150kVA load case, for example, corresponds to 32.6% loading at each consumer transformer.

Location	No Load	50 kVA	100 kVA	150 kVA
Bustinia	19.33	19.07	18.83	18.59
Garfield	19.41	18.92	18.48	18.03
Coleraine	19.40	18.85	18.37	17.87
Granville House	19.42	18.89	18.42	17.93
Blairgowrie	19.43	18.82	18.30	17.72
Boongoondoo No 2	19.45	18.83	18.28	17.71
Hexam	19.44	18.88	18.23	17.64
ClunieVale	19.44	18.78	18.19	17.58
Dunrobin	19.44	18.77	18.18	17.57
Maynard Shed	19.45	18.74	18.11	17.46
Kismet	19.45	18.75	18.13	17.50
Spring Creek Dam	19.41	18.73	18.11	17.49
Lenox	19.44	18.82	18.28	17.68
Springton House	19.43	18.85	18.34	17.81

Table 2: System Voltages (kV) with Fixed Reactors – Nominal Voltage 19.05kV

Table 2 reports the system voltages under load. The first nine sites listed are reactor locations ordered according to distance from the point of supply. Maynard Shed and Kismet are equally the most distant load points in the SWER system. Spring Creek Dam, Lenox and Springton House are at the ends of the major spur lines. The last five sites will be the points most likely to determine the system capacity due to voltage drop.

At no load the residual effects of the line capacitance elevate the voltages by as much as 2% above nominal, with points such as Kismet reaching 19.45 kV. For comparative purposes a low voltage limit of -6% below nominal system voltage, or 17.91 kV, is selected for the HV system. For a system load of 150kVA many sites fall below this limit and this is indicated by yellow shading of the affected cells in Table 2. Maynard Shed records 17.46 kV or 8.4% below nominal voltage. An estimate of system capacity can be made by interpolating between the results for 100kVA and 150kVA loading to estimate the load resulting in a 6% drop at this location. The result is 115kVA and this is the estimated load capacity of the existing SWER system.

Controlled reactors are now introduced and load cases run in 50kVA increments from no load to a 250kVA loading. Table 3 reveals the voltage regulation performance over a range of loading conditions for a TCR based approach. Table 4 reports the results under the same loading conditions for a switched reactor approach. Finally the results achieved for reactors located at the consumer transformer secondaries are shown in Table 5.

Very significant gains in capacity have been made in every case, much less of the system is below the -6% limit at 250kVA of load than was seen for the original system at 150kVA loading. Spring Creek dam is now the controlling point in terms of voltage regulation. Interpolation for loadings where voltage falls to the -6% limit for each case yields:

- TCR case – 208kVA (81% increase);
- Contactor Switched – 212kVA (84% increase);
- Consumer connected reactors – 230kVA (100% increase).

The increase for this TCR system, which includes the effects of controlling the TCR from the transformer secondary, is slightly lower than previously reported for a TCR solution that senses the HV system voltage, [4]. The TCR at Bustina is subject to a relatively small voltage range, 19.34kV to 19.00kV or less than 2% swing, and because of the transformer impedance, 3.6%, this is insufficient to force the TCR reactive power to vary across its entire range. The TCR remains partially in conduction even at 250kVA loadings. The solution is to relocate this TCR to region of the system with a wider voltage fluctuation to consumer load changes.

An interesting feature of the consumer reactor connected solution is a slight over voltage, 19.51kV or 1.023pu at Bustina for the 150kVA load case. This is easily dealt with by consumer transformer tapping as the voltage variation at Bustina is small. The consumer connected reactor system fares better at the higher loads as the reactor coupling transformers, and their magnetizing currents, are avoided.

6. SYSTEM EFFICIENCY AND NO-LOAD LOSS

At light load the losses in the reactors and controllers will contribute to the system loss. Systems that require a dedicated transformers incur additional losses with 1% or rating being lost as core loss and 2.6% of rating being lost as copper loss. In a TCR system the thyristor conduction losses are higher than the conduction losses in contactors. The estimated loss break up in a TCR based system with nine 25 kVA reactors is:

- Inductor loss, Q=55, 4.1kW;
- Coupling transformer loss, 8.1kW;
- Thyristor loss, (Estimated on V_t=1.2V and R_t=10mΩ), 0.7kW.

A TCR system would be expected to have no-load losses that are 8.8kW higher than the direct connection of HV reactors. The contactor controlled alternative is 8.1kW higher than the current solution. For the connection of inductors on the consumer secondaries the losses are:

- Inductor loss, Q=55, 4.2kW (for 230kVA of reactors);

Location	0 kVA	50 kVA	100 kVA	150 kVA	200 kVA	250 kVA
Bustinia	19.34	19.25	19.27	19.28	19.21	19.00
Garfield	19.39	19.15	19.05	18.84	18.74	18.33
Coleraine	19.38	19.09	18.93	18.78	18.52	18.07
Granville House	19.40	19.14	19.02	18.89	18.66	18.22
Blairgowrie	19.40	19.09	18.93	18.76	18.46	17.96
Boongoondoo No 2	19.41	19.11	18.96	18.81	18.52	18.01
Hexam	19.40	19.10	18.94	18.80	18.48	17.95
Clunie Vale	19.40	19.08	18.92	18.76	18.43	17.88
Dunrobin	19.40	19.08	18.91	18.75	18.41	17.86
Maynard Shed	19.40	19.04	18.83	18.63	18.26	17.68
Kismet	19.40	19.05	18.86	18.67	18.321	17.74
Spring Creek Dam	19.39	18.96	18.67	18.38	18.00	17.44
Lenox	19.41	19.08	18.90	18.72	18.40	17.89
Springton House	19.41	19.10	18.94	18.77	18.50	18.03

Table 3: System Voltages (kV) with Thyristor Controlled Reactors

Location	0 kVA	50 kVA	100 kVA	150 kVA	200 kVA	250 kVA
Bustinia	19.33	19.36	19.34	19.39	19.25	19.07
Garfield	19.37	19.29	19.14	19.09	18.78	18.40
Coleraine	19.36	19.23	19.03	18.93	18.56	18.13
Granville House	19.38	19.30	19.13	19.06	18.70	18.28
Blairgowrie	19.37	19.27	19.06	18.93	18.50	18.02
Boongoondoo No 2	19.39	19.32	19.11	19.00	18.56	18.07
Hexam	19.38	19.32	19.11	18.98	18.53	18.02
Clunie Vale	19.38	19.31	19.09	18.95	18.47	17.95
Dunrobin	19.38	19.31	19.08	18.94	18.54	17.92
Maynard Shed	19.38	19.27	19.01	18.82	18.30	17.74
Kismet	19.39	19.28	19.04	18.86	18.35	17.80
Spring Creek Dam	19.37	19.09	18.76	18.53	18.04	17.50
Lenox	19.37	19.26	19.04	18.89	18.44	17.95
Springton House	19.39	19.26	19.05	18.93	18.54	18.09

Table 4: System Voltages (kV) with Contactor Controlled Reactors

Location	0 kVA	50 kVA	100 kVA	150 kVA	200 kVA	250 kVA
Bustinia	19.29	19.17	19.36	19.51	19.33	19.24
Garfield	19.32	19.04	19.16	19.23	18.86	18.67
Coleraine	19.30	18.97	19.05	19.07	18.64	18.41
Granville House	19.34	19.02	19.13	19.20	18.78	18.59
Blairgowrie	19.35	18.96	19.04	19.07	18.59	18.42
Boongoondoo No 2	19.38	18.99	19.10	19.14	18.65	18.42
Hexam	19.40	18.98	19.10	19.13	18.61	18.37
Clunie Vale	19.41	18.96	19.08	19.10	18.56	18.29
Dunrobin	19.41	18.96	19.07	19.09	18.54	18.27
Maynard Shed	19.39	18.90	19.00	18.97	18.39	18.08
Kismet	19.40	18.92	19.02	19.01	18.44	18.14
Spring Creek Dam	19.23	18.82	18.78	18.67	18.12	17.77
Lenox	19.34	18.95	19.00	19.03	18.53	18.35
Springton House	19.32	18.96	19.02	19.07	18.62	18.38

Table 5: System Voltages (kV) with Consumer Transformer Connected Controlled Reactors

- Coupling transformer copper loss, at 50% loading, 0.65% of rating, 3.0 kW.

In this case the additional loss relative to high voltage reactors is only an additional 3.0kW. Table 6 shows the total losses recorded during simulation and these strongly support the loss estimates. There are slight differences in the no load voltage profiles for each case and this accounts for the variations. While consumer connected reactors are the most attractive from capital and no load loss standpoints, reactor switching will generate a larger voltage disturbance at the consumer connection point. If switchings are limited to a few each day this should not be a concern.

System	No Load Loss	Incremental Loss
HV Fixed Reactors	12.0kW	0kW
Thyristor Reactor Control	20.6kW	8.6kW
Contactor Controlled Reactors	20.2kW	8.2kW
Consumer Transformer Secondary Connected Reactors	14.7kW	2.7kW

Table 6: System No Load Losses

7. THE DYNAMIC PERFORMANCE OF CONTROLLED REACTOR SOLUTIONS

The dynamic performances of each reactor control method for a 100kVA load case is shown in Figure 6 to Figure 8. In each case reactor current is evaluated in an RMS sense each cycle and this is multiplied by the nominal reactor RMS voltage to give reactive power. This approach does capture some switching transient current and may overstate reactive power for the first few cycles after switching occurs. As the plot durations are 250 cycles this is a tolerable imperfection.

For the TCR system response shown in Figure 6 the proportional aspect of the control responds quickly to reduce the initial over voltage when the system is energised. Fine adjustment by the integral controller action then takes several seconds to occur.

Figure 7 shows the responses for switched contactors. Initially the system voltage overshoots causing many reactors to connect, especially at the far end of the line. Some then disconnect a few hundred milliseconds later. No further switching actions follow.

Figure 8 shows the response with inductors distributed to each consumer load point. In this case the total of all reactor powers is presented. The results are similar with many inductors first connecting in response to the system excitation and over voltage. Reactors towards the far end of the system then disconnect over a few hundred milliseconds.

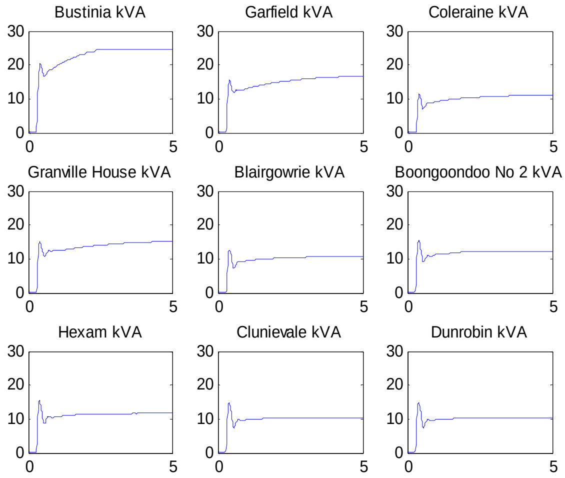

Figure 6. Start Up Reactive Power Responses of TCRs – 100kVA Load

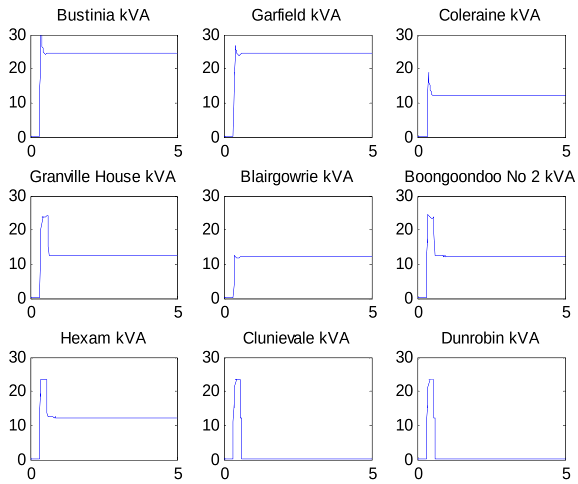

Figure 7. Start Up Reactive Power Responses of Contactor Switched Reactors – 100 kVA Load.

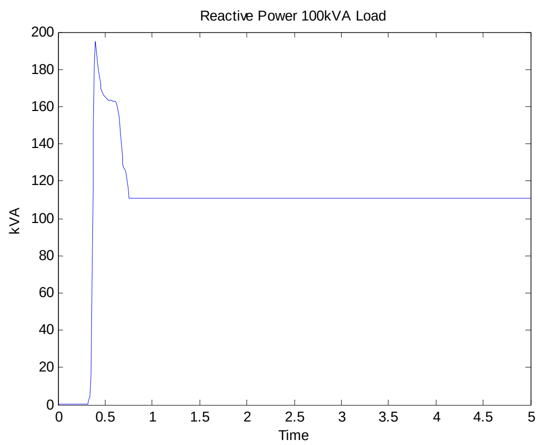

Figure 8. Start Up Reactive Power Responses of Consumer Transformer Switched Reactors – 100 kVA Load.

8. EXPERIMENTAL PROGRESS

A field demonstration of a 25kVA controlled reactor is currently progressing and should occur during 2006. Figure 9 shows one of two air cooled 12.5kVA reactors fabricated for these trials. The inductor was connected in a parallel resonant circuit arrangement for loss, temperature rise and core B-H curve measurements. A measured quality factor of 55 was achieved which is close to the practical limit for standard 50Hz designs with silicon steel cores and copper windings. No appreciable saturation occurs below voltages of 530Vrms and the core has at least a 10% margin of tolerance for system over voltages.

Loss minimization results in an inductor surface temperature rise of 30C and a hot spot over ambient temperature rise of approximately 50C. The hot spot rise was measured by a thermocouple placed between the windings and core. The life expectation of the class H insulation system is beyond 30 years and is appropriate for this application.

Figure 9: Voltage Control Reactor –12.5 kVA, 480Vrms.

Figure 10 shows a voltage control unit which combines with two commercial thyristor phase control units, (one only shown), to form the complete TCR management package. The two reactors and their control systems cost approximately $6,000AUD and represent a very economic solution when compared to the installed cost of the SWER system.

9. CONCLUSIONS

The replacement of fixed shunt reactors with controlled reactors can provide a low cost method of considerably increasing the capacity of SWER systems. Placement of the reactor on the low voltage side of a conventional transformer allows thyristor control to be achieved cheaply with thyristors or contactors. Either dedicated coupling transformers or consumer transformers can be used to connect voltage control reactors. This paper has demonstrated the capacity of this approach to provide a realistic solution for enhancing existing systems.

Figure 10: Voltage Control System and Commercial 480Vac, 40ArmsThyristor Phase Controller.

10. ACKNOWLEDGEMENTS

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