Thyristor Controlled Reactor Methods to Increase the Capacity of Single Wire Earth Return Systems

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Abstract

Single wire earth return systems are a widely applied low cost power distribution method used in many rural areas. In Central Queensland a single SWER system supplying approximately 100kW may extend more than 300km. These systems often use shunt reactors to compensate the effects of line to ground capacitance. Recent patterns of load growth are forcing the upgrading of these systems. As voltage regulation is the determining factor, the replacement of fixed shunt reactors with controllable reactors provides an opportunity to significantly increase the system capacity. A study of the North Jericho SWER system shows a capacity increase of approximately 85% can be achieved.

1. Introduction

Single wire earth return systems, (SWER), have been widely used for power distribution in regions where the population and load density is relatively low, [1-3]. In many areas of Australia including Central Queensland, many rural electrification systems had been established by State operated electricity boards during the sixties, seventies and eighties under community service initiatives. SWER systems would typically supply loads of 100kW to 200kW scattered over a line length that might exceed 300km. The distribution voltage is typically 12.7kV or 19.1kV, the phase to ground voltages for 22kV or 33kV three phase systems. Consumers where connected by a single phase transformer which produced two single phase outputs in a 240-0-240Vac split winding arrangement. In earlier Central Queensland systems a consumer transformer was typically 10kVA but this has now increased to 25kVA for a standard connection. Figure 1 shows a typical single phase customer transformer,.

As the power industry seeks to limit increases in energy charges the case for capital expenditures on these systems has progressively become more difficult to make. Improvements cannot be funded from the revenues that these systems can provide. As a consequence improvements to cater for load growth are difficult to justify. The existing SWER systems are progressively becoming more heavily loaded. The most visible consequence is an increasing frequency of voltage regulation related problems. In Queensland a SWER task force has been established to investigate the issues faced by these systems. An important option identified by the taskforce is to apply new technologies into aging SWER systems to release capacity for load growth. Universities were seen by the taskforce as solution facilitators for ideas put forward by power industry specialists.

Power electronic solutions to SWER problem have been proposed, [4]. It is possible to rectify and re-invert at a consumer connection point to alleviate even extreme voltage regulation issues. These solutions are more technically complex but are certainly achievable. This paper will examine an intermediate approach to improving the capacity of SWER systems at a lower capital cost.

Figure 1: A SWER Customer Transformer

2. Controllable Shunt Reactors

Many SWER systems include shunt reactors to control the effects of the line charging capacitance. One effect, the Ferranti effect, causes the line voltage to rise with distance. In most distribution systems this effect is not particularly visible but 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 of the line capacitance 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. In addition to the problems caused by isolation transformer and earth design overloads the load unbalance imposed on the three-phase supply network often leads to unacceptable system voltage unbalance. Shunt reactors may be needed to allow a moderately sized transformer to excite the line.

In a SWER system that is suffering from under voltage at heavier loads, an obvious solution is to add some element of control to the shunt reactors. The industry has always recognized the immediate advantages in removing the reactors at higher loads. There have been considerable costs attached to this. While the reactors are small, typically 25kVAr or approximately 1.3Arms at 19kV, 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 kV can readily be replaced by inductors rated at 480V connected across the secondary of a 25kVA 19kV to 240V-0-240V transformer. This then allows the switching to be performed at low voltages. If switching at 480V is readily performed by conventional contactors or thyristors. A thyristor switch will introduce approximately 100W in conduction loss due to its forward drop but mechanical contacts, and corresponding wear will be avoided. A further advantage of a thyristor element is the capacity for phase control. A relatively simple microprocessor or even an analogue controller will give a capacity to continuously vary the inductor element. It now becomes possible to convert the inductor to a controllable voltage regulation device.

The paper will show that this approach can be readily applied to a SWER system and will yield a significant increase in system capacity by effectively removing the shunt reactors as the system voltage falls under load. The Jericho North system will be presented as a case study that highlights the scale and complexity of a SWER system. This case study will also critically examine two important side effects of this solution, namely the impact on the supply transformer loading and the potential for harmonic generation.

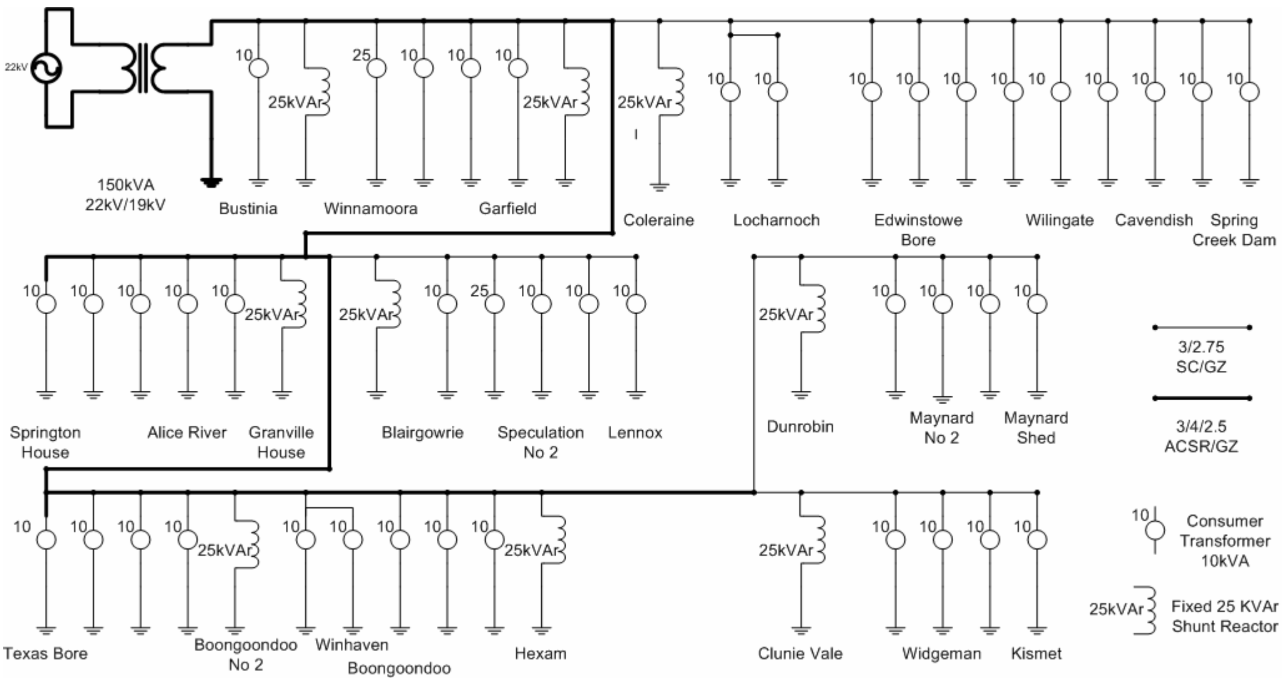

Figure 2: Jericho North SWER System – Simplified Schematic

3. THE JERICHO NORTH SWER SYSTEM

The Jericho North SWER system is between Barcaldine and Alpha in Central Queensland. A simplified schematic is shown in Figure 2. This is a rural area focussed on the production of beef. The transmission voltage is 19kV and system supplies 43 consumer load points, many of which are bores or pumps. Two of the load points are 25kVA transformers and the others are 10kVA giving a total consumer transformer connection of 460kVA. The system isolation supply transformer is rated at 150kVA. A total of nine shunt reactors are distributed across the system each with a 25kVAr rating. The SWER system is arranged as a backbone conductor with lighter spur conductors. The back bone is 141km of 3/4/2.5ACSR/GZ, a conductor with three aluminium and four steel conductors. The spurs total 223km of 3/2.75SC/GZ, an all steel conductor. Table one contains the conductor parameters.

The line capacitance generates a capacitive charging requirement of 753VAr/km for the 3/4/2.5ACSR/GZ backbone conductor and 732VAr/km for the 3/2.75SC/GZ conductor. Over the 364km of the SWER system this becomes a total capacitive loading of 270kVAr. The need for 225kVAr of shunt reactors is now apparent, the line current is 180% of the supply transformer rating. The existing transformer is incapable of energising the line without the reactors present. The earthing system current at this point now exceeds its safe design limit and cannot be allowed to operate. After the addition of the reactors the transformer loading at no consumer load is expected to be approximately 45kVAr leading with a resistive component to cover the no load loss. Customer load addition will improve the peak SWER system load power factor which will be close to unity power factor operation.

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. Thyristor Controlled Reactor System

This paper proposes the substitution of each fixed shunt reactor by a thyristor controlled reactors coupled via a standard 25kVA 19kV to 240-0-240V transformer as shown in Figure 3. It will be later shown that it is preferable from a harmonic current viewpoint to split the 25kVAr inductor into two halves that are sequentially controlled. The TCR is to be controlled to regulate the voltage at the local point of connection. Above the regulation set point voltage, in this case 19kV, the thyristor firing angle is progressively adjusted to increase the inductor current.

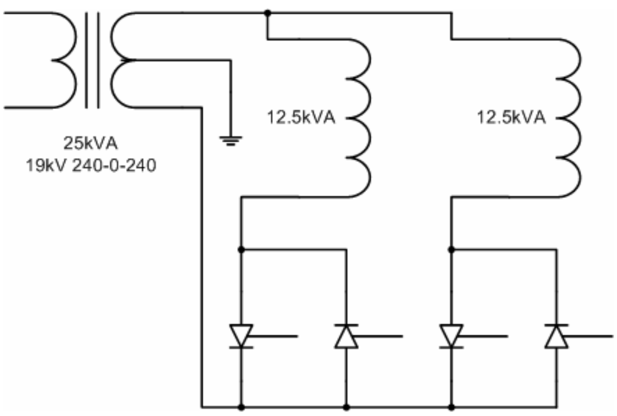

Figure 3: Thyristor Controlled Reactor

The voltage at the point of connection can be detected with an independent voltage transformer. An alternative is to determine the connection point voltage from the transformer secondary. Some error will be introduced by the transformer impedance but this is known and in principle a feed forward correction can be made as a function of the inductor current. During the simulation study, true RMS voltage at the 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. A proportional integral control action is used with the following gain settings:

- Proportional Gain: A voltage error of 500Vrms yields rated inductor current;
- Integral Gain: A voltage error integral of 500Vrms seconds yields rated inductor current.

5. Simulation Studies

The use of conventional power system analysis software is not possible for full simulation of reactor switching and control effects. 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 thyristor 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. If simulations are run over some seconds of operation, that is a few hundred cycles, any interaction of TCRs can also be observed. This modeling approach provides a great deal of insight but is rather time consuming with simulations taking several hours to complete. The model features are:

- The topological layout follows the construction drawings, a total of 76 physical transmission line sections are identified and implemented;
- π section models are used and physical sections over 10km in length is broken into equal length multiple π sections of a maximum 10km in length;
- The reactors have a Q factor of 50;
- The isolation transformer turns ratio is 22kV:19kV; 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 turns ratio is 19kV to 240-0-240;
- Consumer loads are modeled as 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	19.27	19.00	18.76	18.58
Garfield	19.35	18.84	18.40	18.03
Coleraine	19.34	18.78	18.28	17.87
Granville House	19.36	18.81	18.33	17.93
Blairgowrie	19.35	18.74	18.19	17.73
Boongoondoo No 2	19.38	18.75	18.19	17.72
Hexam	19.37	18.71	18.14	17.65
ClunieVale	19.37	18.69	18.10	17.59
Dunrobin	19.37	18.68	18.09	17.57
Maynard Shed	19.38	18.65	18.02	17.47
Kismet	19.38	18.67	18.04	17.50
Spring Creek Dam	19.35	18.65	18.02	17.49
Lenox	19.34	18.73	18.17	17.69
Springton House	19.37	18.78	18.25	17.82

Table 2: System Voltages (kV) with Fixed Reactors

Table 2 reports the system voltage at the location of each reactor. 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 19.38 kV. For comparative purposes a low voltage limit of -6% below nominal system voltage, or 17.86 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 17.47 kV or 8.05% 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 114kVA and this is the estimated load capacity of the existing SWER system.

Controlled reactors are now introduced and the system loading was progressively increased. To reduce run times in the voltage regulation studies each 25 kVAr controlled reactor is modeled by a single controlled inductor. Figure 4 shows the cycle by cycle dynamic voltage response at Dunrobin for a 50kVA load case for the first 5 seconds after the system is energised. The system voltage is initially 20.5kV but is tightly controlled to 19kV within a few seconds. There is some indication that the TCRs do interact during the initial stabilization period suggesting that the controller gains should not be further increased.

Table 3 reveals the voltage regulation performance over a range of loading conditions. Very significant gains in capacity have been made, 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 between the 200kVA and 250kVA load case suggest the -6% limit is reached at 212kVA of loading. This is an increase of 85%. Similar results were achieved during conventional power system modeling at Ergon Energy.

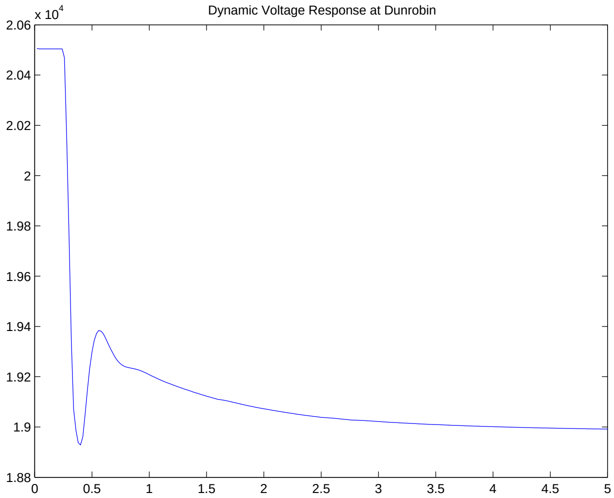

Figure 4: Dynamic Voltage Response at Dunrobin.

6. SENDING END TRANSFORMER CAPACITY

The use of TCRs improves voltage regulation across the system and would allow a significant load increase. Practically this can only be realised if the sending end isolation transformer capacity is increased. The currents would be well within the capacities of the conductors used but earthing design would also need to be upgraded. Table 4 shows the transformer loading for the existing situation. The reactors and transformers contribute 4.6kW and 4.7kW of the no load loss respectively. Table 5 shows the same results for the TCR equipped system. It should be noted that the real power in the loads will vary with the system voltage regulation. These tables should not be used to compare the system losses. The real powers developed by the loads are higher in the TCR controlled system as the consumer voltages are higher.

To maintain voltage regulation at higher loads, the TCRs reduce their inductive current demand exposing the transformer to higher levels of capacitive current. At loadings of 50kVA and 100kVA, Table 3 shows a rise in the voltage at Bustina. This is due to the action of the reactors at the remote ends of the line resulting in an increase in capacitive current at the sending end.

Location	0 kVA	50 kVA	100 kVA	150 kVA	200 kVA	250 kVA
Bustinia	19.27 (full)	19.17 (full)	19.26 (full)	19.34 (full)	19.14 (full)	19.03 (out)
Garfield	19.35 (full)	19.08 (full)	19.07 (full)	19.06 (regulating)	18.70 (out)	18.4 (out)
Coleraine	19.34 (full)	19.02 (regulating)	18.97 (out)	18.90 (out)	18.49 (out)	18.15 (out)
Granville House	19.36 (full)	19.06 (full)	19.05 (full)	19.03 (regulating)	18.63 (out)	18.29 (out)
Blairgowrie	19.35 (full)	19.01 (regulating)	18.98 (regulating)	18.91 (out)	18.44 (out)	18.04 (out)
Boongoondoo No 2	19.38 (full)	19.03 (full)	19.02 (regulating)	18.98 (out)	18.50 (out)	18.10 (out)
Hexam	19.37 (full)	19.01 (regulating)	19.01 (regulating)	18.97 (out)	18.46 (out)	18.04 (out)
Clunie Vale	19.37 (full)	19.00 (regulating)	18.99 (regulating)	18.94 (out)	18.42 (out)	17.98 (out)
Dunrobin	19.37 (full)	18.99 (regulating)	18.98 (regulating)	18.92 (out)	18.40 (out)	17.96 (out)
Maynard Shed	19.38	18.96	18.91	18.81	18.25	17.78
Kismet	19.38	18.98	18.93	18.85	18.30	17.84
Spring Creek Dam	19.35	18.88	18.69	18.50	17.97	17.51
Lenox	19.34	19.00	18.95	18.87	18.38	17.97
Springton House	19.37	19.02	18.97	18.91	18.47	18.10

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

Load	Current	kVA rating	Power kW
No Load	3.23	62	15
50 kVA	3.04	58	51
100 kVA	4.52	85	85
150 kVA	6.46	120	117

Table 4: Transformer Rating – Existing SWER System

The higher system capacity can only be accessed if the transformer rating increases. The existing system contains 364 km of conductor probably representing a sunk cost exceeding $3 million. A transformer upgrade is certainly a viable option and likely to be much cheaper than reconstruction.

7. HARMONICS

Thyristor controlled reactors do generate harmonic currents that are a considerable fraction of the fundamental current, [5]. The third harmonic peaks at 38% of the reactor rated fundamental current at a delay angle, $\alpha = 141^{o}$. An important feature of the TCR device is that the harmonic phase angles are fixed and only sinusoidal odd harmonics are present. The line capacitance plays a major role in absorbing the higher frequency harmonic current and currents above the third harmonic have a negligible impact. The worst supply voltage distortions occur when a significant number of reactors are in the regulating range. The 100kVA load case has the highest harmonic impacts of the cases studied.

The voltage regulation study used TCRs with a single 25kVA inductor and it was found that distortions as high as 5.1% occurred at the extreme end of the system for example at the Dunrobin site. As this exceed the 4% limitation imposed by AS 2279 for a single odd harmonic, the studies were re-run with each 25 kVAr TCR implemented using a pair of 12.5kVA inductors that are sequentially operated. Sequential operation ensures that only one inductor is proportionally controlled at a time with the second inductor operated fully on or fully off. This halves the distortion current. With this TCR arrangement the worst voltage distortions reduced to 2.2% at the Dunrobin site for the 100kVA load case.

Load	Current	kVA rating	Power kW
No Load	3.23	62	15
50 kVA	4.47	86	53
100 kVA	7.48	144	95
150 kVA	6.46	200	139
200 kVA	10.8	207	169
250 kVA	11.8	225	195

Table 5: Transformer Rating – TCR SWER System

Figure 5 shows the nine TCR currents for the 100kVA loading case. A range of operating states can be seen. The TCRs at Bustinia and Garfield are operating at full capacity while Coleraine is fully removed. Blairgowrie, Clunievale and Dunrobin are operating below 12.5kVAr on a single inductor. Hexam appears to be operating close to 12.5kVA on a single inductor. The TCRs at Boongoondoo No.2 and Granville House operate between 12.5kVAr and 25kVAr with a one controlled inductor and the remaining inductor section in full conduction.

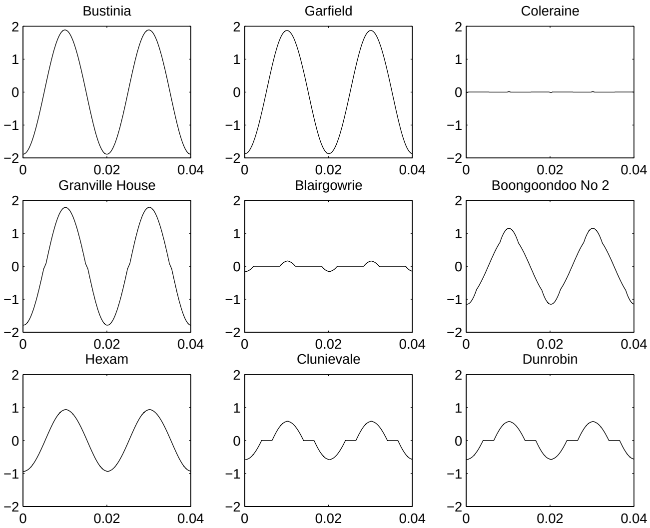

Figure 5: TCR Currents 100kVA Loading Case

Figure 6 shows the sending end isolating transformer voltage and current. The voltage waveform contains 1.1% of third harmonic. For the current a Fourier analysis shows the fundamental and third harmonic currents to be 7.35Arms and 0.74Arms respectively. The third harmonic currents represent 10% of the fundamental. These enter the 22kV system but will be significantly cancelled if similar TCR controlled SWER systems are connected across the other phases. The lack of phase diversity for the TCR devices will ensure that the third harmonic currents will act as zero sequence components. Normal star-delta connections will largely prevent the third harmonics from leaving the 22kV feeder if the connected SWER systems are reasonably balanced and produce comparable levels of third harmonic current.

8. 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. A TCR can be broken up into a number of inductors that can be sequentially controlled to limit the harmonic impacts to acceptable levels. This paper has demonstrated the capacity of this approach to provide a realistic solution for enhancing existing systems.

9. ACKNOWLEDGEMENTS

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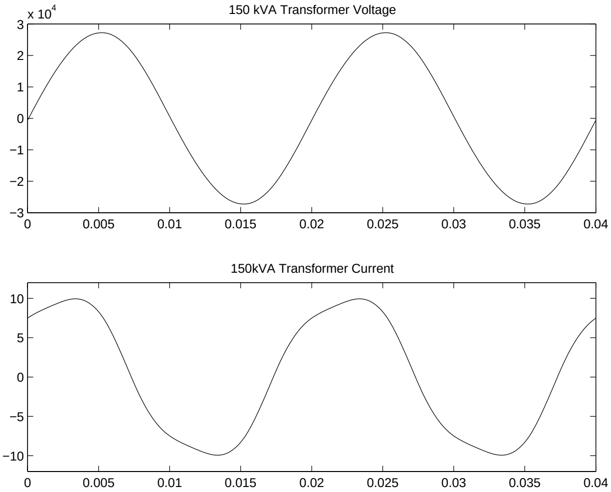

Figure 6: Sending End Voltage and Current – 100kVA.

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