A Thyristor Controlled Three Winding Transformer as a Static Var Compensator

Vijay Bendre, Prof. Pat Bodger, Dr. Alan Wood.

Department of Electrical and Computer Engineering, The University of Canterbury, Christchurch, New Zealand.

Abstract:

This paper details the design of a thyristor controlled three winding partial core resonant transformer specially designed for testing generator insulation. The tertiary winding of this transformer is closed through a Thyristor Controlled Reactor (TCR). Firing angle control of an anti- parallel connected pair of thyristors provides continuous variation of reactive power. Modelling of the three winding transformer in PSCAD/EMTDC reveals the design criteria and performance of the proposed scheme. Automatic control of thyristor valves will be achieved by sensing the reactive power in the primary winding, i.e. low voltage winding. The exact magnitude of the firing angle for the thyristors at which the primary winding supplies only real power for overcoming losses and attains almost unity power factor, will be determined by a PI controller. Thus, only the real component of current is required from the supply. Nearly all the reactive power of the iron core and TCR counterbalances the leading VArs produced by the generator insulation. Fine tuning of thyristor firing angles avoids any over or under compensation of the system. Consideration is also given to keeping total harmonic distortion (THD) and overall power quality on the high voltage side within standard limits.

1. INTRODUCTION

In the past few years the University of Canterbury has successfully designed, developed and built partial core inductors and transformers for testing stator insulation of large hydro generators in New Zealand [1][2][3]. The U of C high potential testing kit has proved its superiority over conventional full core high voltage transformer testing kits as far as cost, weight and ease of transportation, etc. are concerned. In order to limit the supply current to its real component only, the generator insulation capacitance (X_c) is resonated with the magnetizing reactance (X_m) of the partial core transformer by manually adjusting the transformer's central core. This is difficult due to the magnetic forces involved and the necessary proximity of the operator to the high voltage. In order to overcome this problem, there is a need for continuous control of reactive power.

A third winding around the already existing two windings, along the direction of main field flux is proposed. Due to magnetic coupling, an e.m.f. will be generated in the third winding. A controller can be put on the third winding which is responsible for modifying the var absorption characteristics of that winding for compensating the capacitive vars required by HV winding. This will limit the supply current.

A small prototype of the three winding partial core transformer has been built in the laboratory. Short circuit and open circuit tests were performed for revealing its electrical parameters. Unlike a practical HV testing transformer, where the turns ratio is much higher and even a small magnitude of capacitance requires a large current from the supply, in the prototype model the turns ratio and hence the supply current are small. In order to demonstrate the effectiveness of TCR control, a high capacitance load (5 μF) is connected on the high voltage side of the prototype transformer.

2. CONCEPT OF THYRISTOR CONTROLLED THREE WINDING TRANSFORMER

As shown in Fig. 1, the tertiary winding of the three winding transformer is closed through an anti-parallel connected pair of thyristor valves. If the leakage reactance of this transformer is not high enough, an additional current limiting reactor in the tertiary winding is essential. As the magnetically coupled tertiary winding is connected to thyristor valves, their switching may inject transients and harmonics into the other windings. Harmonics are detrimental to the test object and transformer themselves but also an a.c. high potential test with polluted supply may not be accepted as per standards. Firing angle control of these thyristor valves provides a continuous variation of reactive power.

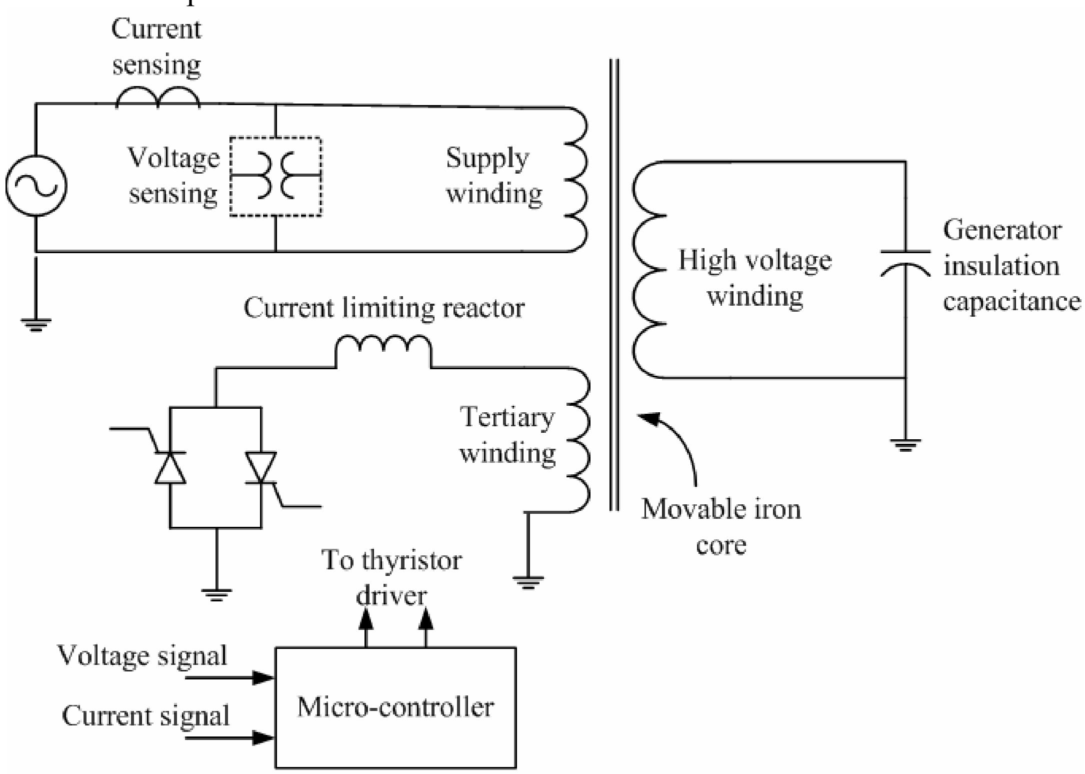

Fig. 1 Proposed thyristor controlled scheme for partial core three winding resonant transformer.

3. PARAMETERS OF SINGLE PHASE THREE WINDING TRANSFORMER

An available partial core three winding transformer was chosen on which to perform experiments and simulations using the PSCAD/EMTDC software package. The transformer is a 2.52 kVA, 90/345/90 V, 50 Hz partial core three winding transformer with rectangular windings. In order to determine its parameters, short circuit and open circuit tests were performed on all three windings. These parameters are presented in Table 1.

Table 1: Electrical characteristics of the chosen partial core three winding transformer

Parameter	Value	Unit
Rated apparent power	2.52	kVA
Rated winding voltages	90/345/90	V
Rated winding currents	28/7.30/28	A
Short circuit impedances (All referred to primary side)	Zps = 0.296 + 0.308 j	Ω
	Zst = 0.317 + 0.271 j	Ω
	Zpt = 0.508 + 0.024 j	Ω
No load losses	0.04	p.u.
Copper losses	0.1	p.u.

where, p, s and t denote primary (supply), secondary (high voltage), and tertiary (control) windings respectively. Z_{ps} is the leakage impedance measured in the primary winding when the secondary winding is short circuited and the tertiary winding is kept open. Z_{st} is the leakage impedance measured in the secondary winding when the tertiary winding is short circuited and the primary winding is kept open. Z_{pt} is the leakage impedance measured in the tertiary winding when the primary winding is short circuited and the secondary winding is kept open.

4. MODELLING IN PSCAD/EMTDC

Fig. 2 shows how a basic model of thyristor controlled three winding transformer as a SVC is implemented in PSCAD/EMTDC software. In order to identify its main characteristics, at first the model is analysed in open loop. Secondly, automatic control is implemented to show the effectiveness of the TCR at providing accurate var compensation. This will limit the supply current only to its real component.

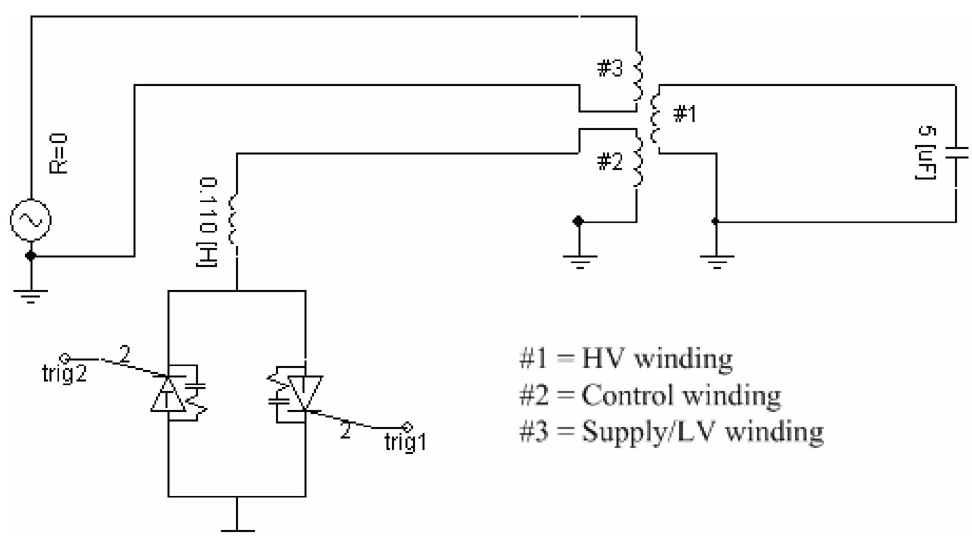

Fig. 2 A model of the thyristor controlled three winding transformer in PSCAD/EMTDC.

The controllable range of the TCR firing angle, α, extends from 90° to 180°. A firing angle of 90° results in full thyristor conduction with a continuous sinusoidal current flowing through the

TCR. As firing angle is varied towards 180°, the current flows in the form of discontinuous pulses of symmetrically located in the positive and negative half cycles [4]. Firing signals for thyristor valves are derived from the voltage controlled oscillator (VCO). It generates a repeating, 0 to 360 degree ramp function waveform corresponding to 50 Hz. This waveform is used as a reference in the above control circuit [4].

Thus at $\alpha = 180^o$, the tertiary winding behaves like a open circuit. Under this situation, most of the reactive power required by the high voltage winding is supplied by the supply winding unless the position of the core is adjusted for delivering the same. In this case the core is supplying 22 VArs (lagging).

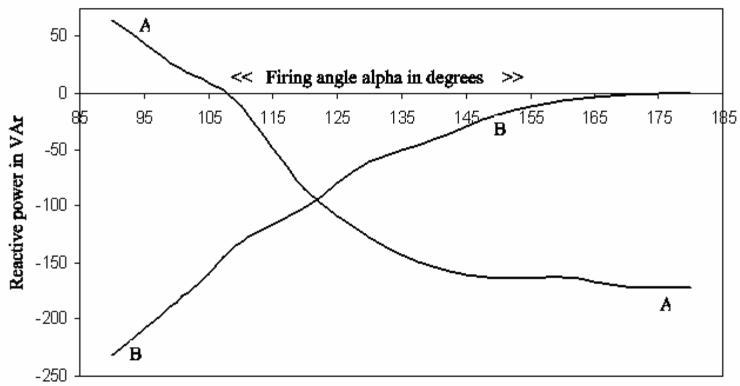

Fig. 3 Variation of the reactive power in the supply winding (AA) and the control winding (BB) with respect to firing angle alpha.

In Fig. 3, as α is reduced gradually, more and more inductive reactive power is absorbed by the tertiary winding. This reduces the burden of reactive power from the supply side. For a typical value of α, leading vars required by the capacitive load on the HV side are almost exactly compensated by the total lagging vars supplied by tertiary winding and the core. Under this situation power factor at the supply side is almost unity and current drawn from the supply side is limited to its real component only.

In practice, the magnitude of the required reactive current may exceed 300 A. The chosen model of the three winding partial core transformer for demonstration purpose is very small, and has a LV to HV turns ratio only of 3.83. Thus current and var requirements referred to LV winding are lower.

5. AUTOMATIC CONTROL

The actual application requires the TCR to be controlled in a closed loop fashion. As shown in Fig. 4, the reactive power is measured in the LV winding and is compared with the reference. The error signal is then processed by a PI controller that generates the appropriate firing angle levels. Before firing signals are sent to the interpolated signal generators, the output of the PI controller is converted to angle units and properly conditioned to keep the angle within the limits, i.e. $90^o \leq \alpha \leq 180^o$. These angle units are then compared against the saw tooth waveforms generated by the VCO and firing signals to be fed to the thyristor valves are generated.

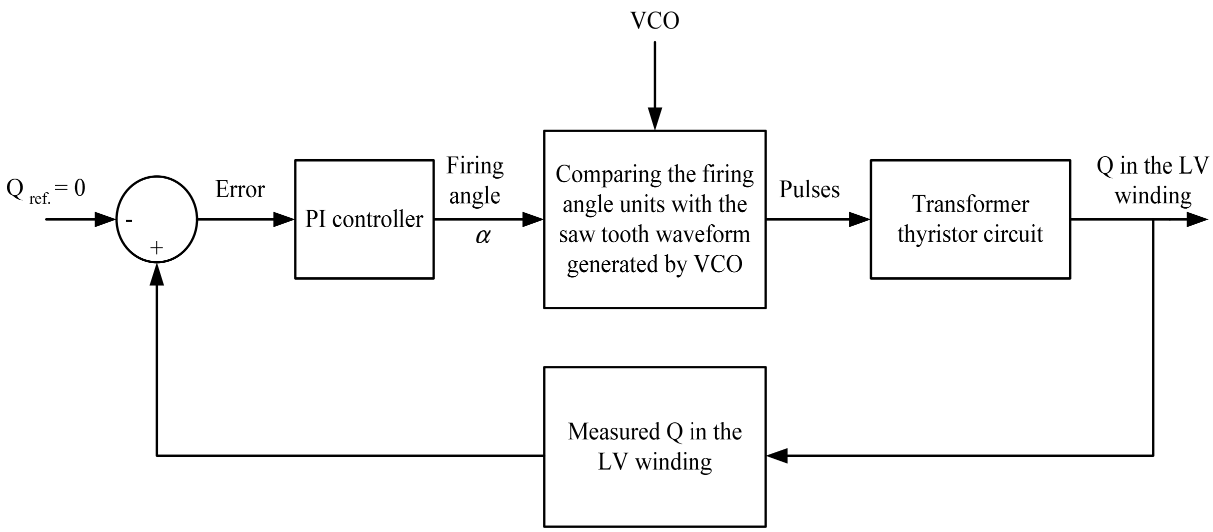

Fig. 4 Automatic control strategy implemented in PSCAD/EMTDC

6. BEHAVIOUR OF REACTIVE POWER IN ALL THREE WINDINGS

In order to demonstrate the effectiveness and accuracy offered by the proposed system, initially, the circuit breaker in the tertiary winding is open and the total reactive power required by a capacitive load on the high voltage side is supplied by the core and the supply. At 0.2 sec, the circuit breaker is closed and the TCR starts operating. The initial value of the firing angle is 180^o.

The TCR firing angle starts reducing and increasing its conductivity. As more and more reactive power is absorbed by the tertiary winding, the requirement of reactive power from the supply drops. At a steady state condition it supplies negligible reactive power. Fig. 5 demonstrates the behaviour of reactive power in the three windings.

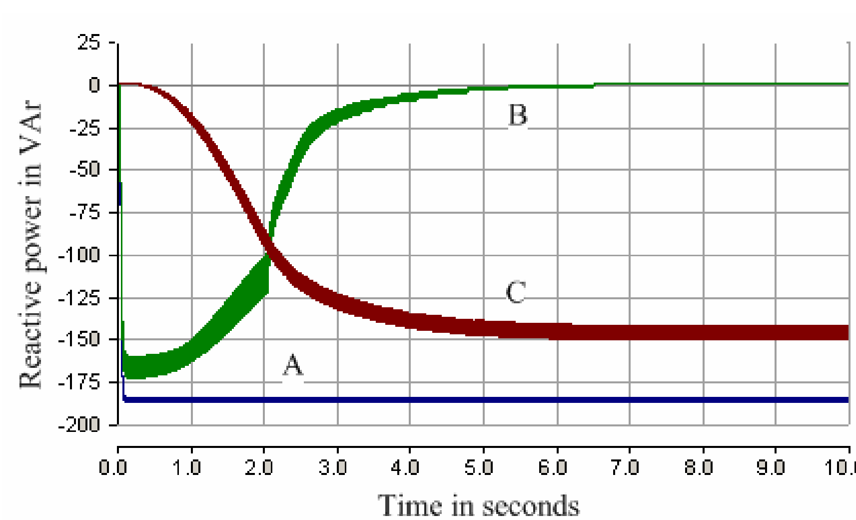

Fig. 5 Reactive power - (A) in the HV winding, (B) in the LV winding, (C) in the control winding

The point at which the delivered reactive power from the LV and control windings are equal, i.e. $Q_{lv} = Q_{cv}$, an abrupt change in the behaviour of reactive power on LV side is observed. Under this condition the magnitude of the 3rd order harmonic currents in the LV and the control winding are observed to reach their peak as shown in Fig. 6.

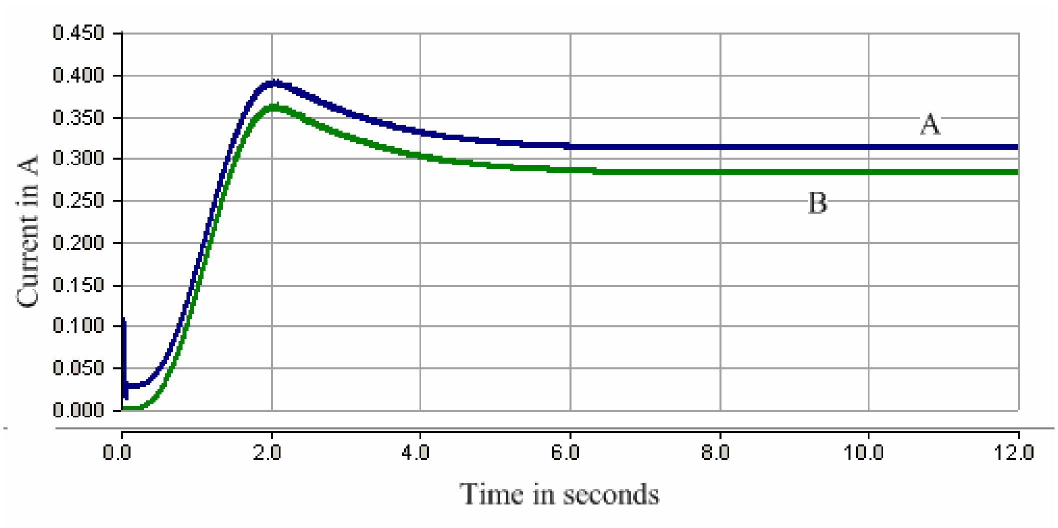

Fig. 6 Third harmonic component of the currents flowing though the supply (A) and the control (B) windings

7. REDUCTION OF CURRENT FROM THE SUPPLY SIDE

As total var requirements are fulfilled by the tertiary winding, the reactive component of current from the supply side diminishes and the total value of current is reduced from 2.2 A to 1.16 A i.e. a 47 % drop. On the other hand, the current in the control winding increases to 1.65 A.

The current waveforms on the LV and the control winding no longer remain sinusoidal but are now injected with harmonics. The current total harmonic distortion (I_{THD}) observed in the supply side winding is 29.7 % and that in control winding is 19.34 %. The current on the high voltage winding is sinusoidal with much less harmonic distortion (I_{THD} << 0.3%) which is acceptable by standards. As high potential tests are required to be performed only for one minute, harmonic distortion may not be a big issue on the LV side. However if the client needs to maintain good power quality on supply side, then increasing the value of the current limiting reactor on the tertiary side is a better option. Magnetising current and flux linkage in the core remain constant as before. Fig. 7 shows the currents in the three windings along with the magnetising current and the flux linkage.

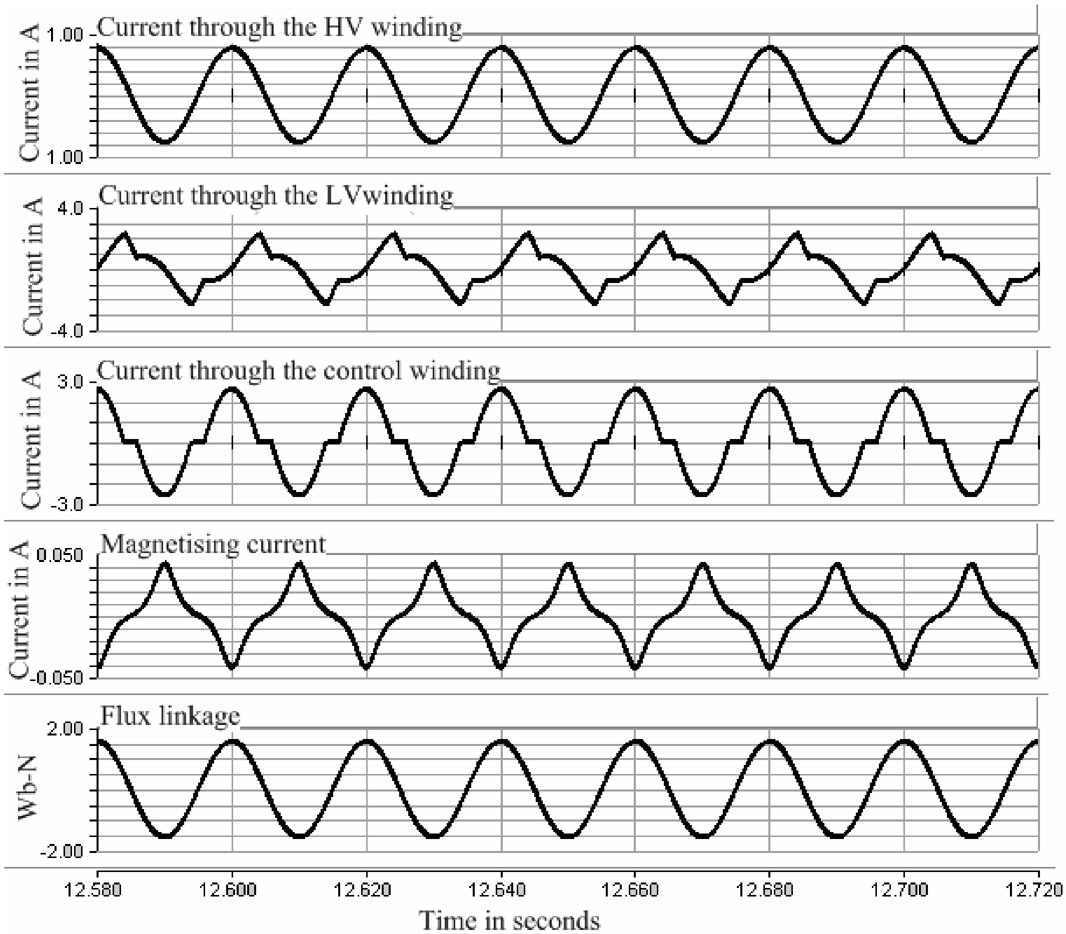

Fig. 7 Waveforms showing the nature of the currents flowing through the windings.

8. POWER FACTOR AND HARMONICS

When the three winding transformer was evaluated with the TCR, injection of dominant 3rd and 5th order harmonics in the LV winding worsened its overall performance. When harmonics are present, the traditional power factor definition (PF_D) must be modified so that all frequencies present are included, not just the fundamental frequency [5]. As noted previously, when the TCR was applied to three winding transformer, the I_{THD} increased from 1.22% to 29.7%. This effectively lowered the true power factor to 0.97. The increased harmonics reduce the effectiveness of the fine-tuning power factor capabilities of the TCR branch because it can compensate only for PF_D [5]. Fig. 8 shows the fundamental and harmonic components of the currents in the three winding transformer with TCR application.

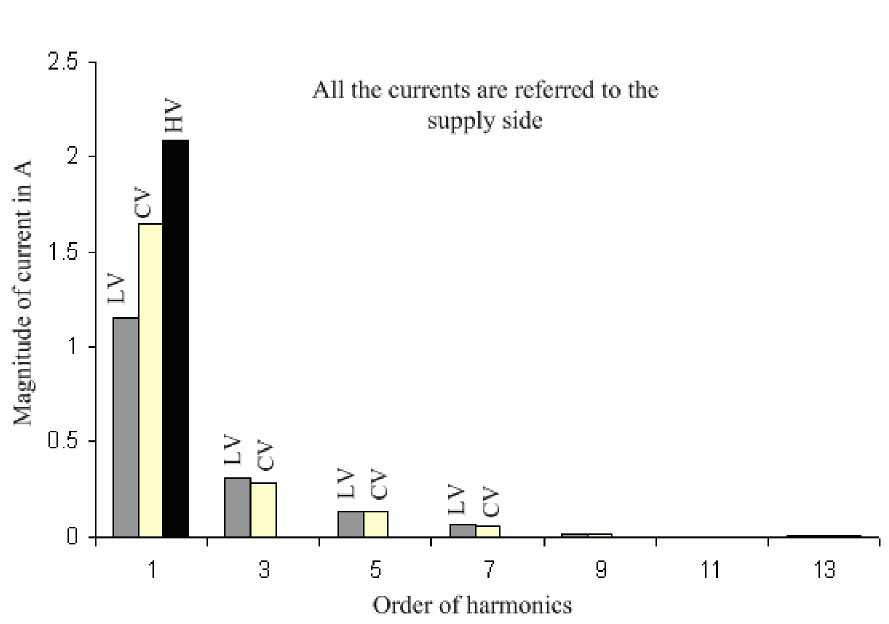

Fig. 8. Fundamental and harmonic components of the currents in the three winding transformer, with TCR application

9. OVERALL EVALUATION OF THE PROPOSED SCHEME

The overall evaluation of the proposed scheme is demonstrated in Table 2. Currently experiments are continuing on the prototype, however a three winding partial core high voltage testing transformer will be designed which will employ a TCR for controlling and minimising the supply current. Considering the cost and rating of the devices, a better option may be to supply 80% of vars required by adjusting the position of the core and of 20% by employing a TCR in the tertiary winding for automatic and fine var control.

Table 2 Effectiveness of TCR controlled three winding transformer.

Parameters in LV winding	Without TCR in tertiary winding	With TCR in tertiary winding	% Change
R.M.S. Current.	2.2 A	1.16 A	47.4
Reactive power supplied.	165 VAr	0 VAr	100
Displacement power factor.	0.52 (leading)	0.97 (leading)	-86.5
Real power	118 W (max)	110.5 W (max)	6.33

10. CONCLUSIONS

The U of C high voltage partial core resonant transformers have been successfully used to perform a.c. high potential tests on the stator insulation of various hydro-generators in New Zealand. Manually adjusting the the transformer's central core is difficult due to the magnetic forces involved and the necessary proximity of the operator to the high voltage.

For overcoming the above problem, the concept of the thyristor controlled partial core three winding transformer is detailed in this paper. The implementation of the proposed scheme in PSCAD/EMTDC reveals its performance. Simulations show that the TCR in the control winding is capable of absorbing the leading vars produced by capacitive load on the HV side without any overcompensation. Under this situation, the supply winding attained a higher power factor with 47.7 % drop in the supply current. The real power consumption is also dropped.

Although the application of TCR in the control winding has not significantly affected the power quality on the HV side, other windings show remarkable growth in the I_{THD} in them worsening the overall performance and lowering the value of power factor to less than unity

Designing a three winding transformer and current limiting reactor in such a way that firing angle values close to 90^o absorbs all vars without overcompensation is one of the best solutions for overcoming poor power quality problem, but this reduces the control range of the TCR.

Considering the cost and rating of the devices, a better option may be to supply 80% of vars required by adjusting the position of the core and of 20% by employing a TCR in the tertiary winding for automatic and fine var control.

11. REFERENCES

[1] M. C. Liew and P. S. Bodger, "Applying a reverse design modeling technique to partial core transformers," Journal of Electrical and Electronics Engineering, 2002, Vol. 22, No.1, pp. 85-92.

[2] Pat Bodger, Wade Enright, "A resonant transformer for high voltage testing of generator stators," Australasian Universities Power Engineering Conference, 2003 and Australian Journal of Electrical and Electronics Engineering, Vol. 1, No. 3, 2004, pp. 179-185.

[3] Enright, W. G. and Bodger, P. S., "Short time rated and protected high voltage a.c. testing of generator stators using parallel resonant circuits", Best paper : non-member, EEA, Christchurch, New Zealand, 18-19 June, 2004.

[4] R. Mohan Mathur, Rajiv K. Varma, "Thyristor based FACTS controllers for electrical transmission systems," IEEE Press, A John Wiley & Sons publication, 2002, pp. 62-64

[5] Scott Zemerick, Powsiri Klinkhachorn and Ali Feliachi, "Design of a microprocessor-controlled personal static var compensator (PSVC)," Power Engineering Society Summer meeting, 2002, IEEE, Vol. 3, pp. 1468-1473.