Proceedings of the Second IASTED Africa Conference
Power and Energy Systems (AfricaPES 2008)
September 8-10, 2008 Gaborone, Botswana

TOWARDS A PRACTICAL PARTIAL CORE TRANSFORMER - COMPENSATION OF REACTIVE POWER REQUIREMENTS WITH A VSC

Vijay Bendre, Prof. Pat Bodger, Dr. Alan Wood
Department of Electrical and Computer Engineering
University of Canterbury (UofC)
Private Bag 4800, Christchurch 8140
New Zealand
Vbe18@student.canterbury.ac.nz, bodger@elec.canterbury.ac.nz, alan.wood@canterbury.ac.nz

ABSTRACT
Partial core inductors and transformers for high voltage testing of generator insulation have been designed, developed and built by the University of Canterbury since 2002. A partial core transformer is a compromise between a traditional full core and coreless transformer. It consists of a laminated ferromagnetic central core around which the primary and the secondary windings are wound. The outer limbs and the yokes are not present. This makes a partial core transformer superior to its full core counterpart as far as cost, weight and ease of transportation are concerned, while maintaining its functionality.

The lack of a closed core reduces the magnetising reactance (X_m) and increases the reactive power requirement of the partial core transformer. This paper deals with the application of a single phase voltage source converter (VSC) based STATCOM to a low voltage partial core transformer, to compensate the inherent higher lagging VArs of the partial core transformer. Hence the transformer, with an added compensator, can be used like a normal full core transformer.

The single phase partial core transformer with a STATCOM is modelled using PSCAD/EMTDC software. A simple, yet robust control system is designed. Simulation results reveal the performance of the STATCOM and partial core transformer with inductive, capacitive and resistive loads.

KEY WORDS
Partial core transformer, STATCOM, modelling and VAr compensation

1. Introduction

A transformer is a stationary apparatus which transforms electric power in one circuit into electric power of the same frequency in another circuit with differential voltages [1]. A conventional single phase power transformer has two inductive windings separated electrically but linked magnetically by a path of low reluctance i.e. through a closed or full core of the ferromagnetic material as shown in figure 1(a). Generation of a high core flux density using a relatively low magnetising current is possible because of the high permeability of the ferromagnetic core. Transformer designs with high voltages per turn for the windings are possible due to the ferromagnetic core, which minimises the lengths of the winding material used and hence lowers the copper losses [2]. These features cannot be accomplished in a cost effective, light weight coreless transformer. The percentage magnetising current in a coreless transformer is a much higher percentage (>95 %) of its total current rating, which is the major hurdle.

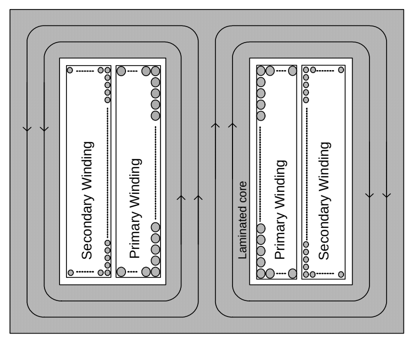

Figure 1(a). A Full Core Transformer

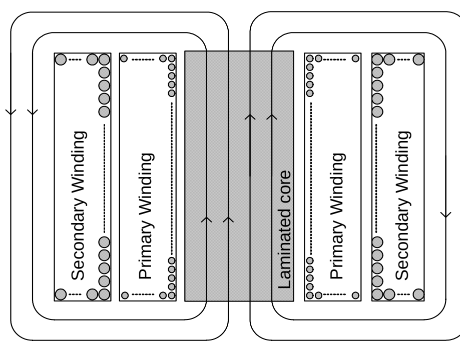

Figure 1(b). A Partial Core Transformer

A compromise between a full core and coreless transformer is a partial core transformer. It consists of a laminated ferromagnetic central core around which the primary and the secondary windings are wound. The outer limbs and the yokes are absent as shown in figure 1(b). The combination gives a better magnetisation than a coreless transformer and maintains the leakage flux at an acceptable level. This also means that the overall weight and volume of the partial core units can be significantly reduced. They are also easy to manufacture [2].

Since 2002, the University of Canterbury has designed, built and developed high voltage resonating partial core inductors and transformers for high voltage testing of generator insulation [3][4][5]. Many of the hydro-generators in New Zealand were successfully tested with this compact HV resonant testing kit which weighs approximately 300 kg. This has replaced a full core HV resonant testing kit weighing around 6 tonnes.

2. Concept of STATCOM Controlled Partial Core Transformer

In the case of a partial core transformer, the lack of closed core reduces the magnetising reactance (X_m) significantly and increases the reactive power requirement. Thus it draws a higher magnitude of lagging current from the supply as compared to its full core counterpart. If this demand is supplied by a compensator which can make the mains supply redundant as far as the reactive component is concerned, the partial core transformer can be used like a full core transformer. Its applications can be found where weight, size and ease of transportation are the major priorities e.g. relocatable compensating systems [6].

In recent years there has been significant progress in the development of voltage source converter (VSC) based reactive power controllers. The ability to generate reactive power without the presence of large reactive energy storage elements makes them very useful in power applications. In a three phase system, this is accomplished by making the currents circulate through the phases of the a.c. system with the aid of power switching devices [7].

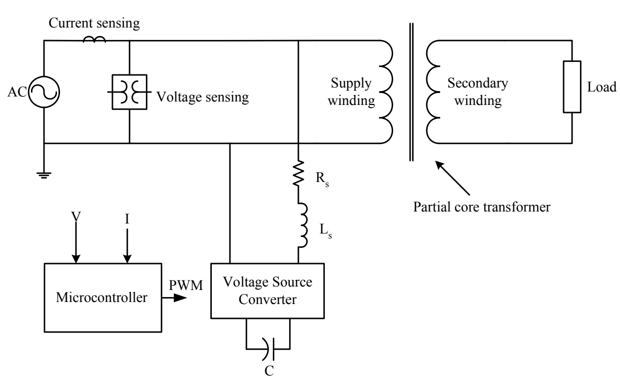

Figure 2. Proposed STATCOM Controlled Scheme for a Partial Core Transformer

As shown in Fig. 2, a single phase VSC-based STATCOM is connected to the supply side (or the low voltage side) of the partial core transformer. In order to minimise the total harmonic distortion in the supply current, the a.c. terminals of the converter are connected to the a.c. mains supply through a first order low pass filter [8].

L_s is the series inductance, R_s represents the active losses of the converter and C is the capacitor on the DC side. Proper sizing of the DC capacitor is essential for satisfactory transient performance, controlling ripple on the DC side and lowering the system cost [8].

2.1 Controlling the Reactive Power by a STATCOM

As shown in equation 1, the magnitude and nature (inductive or capacitive) of reactive power (Q) exchange between the STATCOM and the system can be adjusted by controlling the voltage drop across the equivalent series impedance (X) between the a.c. side of the STATCOM and the system voltage.

$$Q = \frac{V_{STATCOM} - V_s}{X} V_s \qquad (1)$$

where $V_{STATCOM}$ and V_s are the magnitudes of STATCOM output voltage and system voltage respectively. If Q is positive, the STATCOM delivers reactive power to the system. Otherwise STATCOM absorbs reactive power from the system [9]. The $V_{STATCOM}$ can be controlled either by adjusting the modulation index of the PWM waveform or by changing the phase angle α between the $V_{STATCOM}$ and V_s. In this paper later scheme is employed.

3. Parameters of a Single Phase Partial Core Transformer

A 2.52 kVA, 90/345/90 V, 50 Hz low voltage partial core three winding transformer with rectangular windings is chosen to perform experiments on and is modelled using PSCAD/EMTDC software. In order to determine its parameters, short circuit and open circuit tests were performed on all the three windings.

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 the primary side)	Z_{ps} = 0.296 + 0.308 j	Ω
	Z_{st} = 0.31 + 0.271 j	Ω
	Z_{pt} = 0.50 + 0.024 j	Ω
No load losses	0.04	p.u.
Copper losses	0.1	p.u.
X_m	5.1	Ω

These parameters are presented in Table 1, where, p, s and t denote the primary (supply), secondary (high voltage), and tertiary (unused) 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 and 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 [10].

4. Design of the STATCOM

The STATCOM design is considered not only for compensating the reactive power required by the lower X_m of the partial core transformer, but also for generating/absorbing additional VArs if required by the load to reduce the burden on the mains. The value of X_m of the partial core transformer is calculated as 5.1 Ω, which requires 1586 VArs to be supplied by the STATCOM. The rating of the STATCOM is considered as ±2 kVAr.

4.1 Current Rating of the STATCOM

The current rating of the STATCOM is related to the total reactive power delivered to the load and partial core transformer for compensating X_m.

$$Q_{total} = V_s \times I_s \tag{2}$$

where V_s is the a.c. mains voltage (i.e. 90 V r.m.s.) and I_s the STATCOM line current. After substituting the values of V_s and Q_{total} (i.e. 2 kVAr) the current rating of the STATCOM is 22.22 A. [11].

4.2 Determination of Series Inductance (L_s)

The equation for determining the series inductance for a single phase STATCOM is derived from [12].

$$L_s = \frac{V_d \times m_a}{4 \times f_s \times I_{ripple(p-p)}} \tag{3}$$

where, L_s is the series inductance, V_d is the DC voltage across the electrolytic capacitor, m_a is the modulation index (= 1), V_s is the supply voltage (i.e. 90 V). The switching frequency, f_s of the PWM synthesised is chosen as 1350 Hz. $I_{ripple(p-p)}$ is the peak-peak ripple current which is allowed to be 6% of the total current. Thus the peak-peak ripple current is given by

$$I_{ripple(peak-peak)} = 2\sqrt{2} \times 0.06 \times 22.22 = 3.77 \text{ A.} \tag{4}$$

For calculating L_s, the maximum magnitude of V_d ($\approx \sqrt{2}V_{STATCOM}^{max}$) is taken into account. From equation 1, it can be seen that the magnitude of STATCOM output voltage controls the reactive power exchange between the STATCOM and the system assuming that the system voltage and the series impedance are kept constant. Re-writing the equation 1, for the maximum rated reactive power (= 2000 VAr) that the STATCOM can deliver.

$$2000 = \left(\frac{\frac{V_d}{\sqrt{2}} - 90}{\omega L_s} \right) \times 90 \tag{5}$$

Substituting the value of $I_{ripple(peak-peak)}$ in eq. 3 and simultaneously solving the equations 3 and 5, magnitudes of V_d = 244.3 V and L_s = 12 mH are obtained. Approx. voltage drop across the pair of power switches is assumed to be 6 V and added to V_d and hence V_d becomes 250.3 V. Series resistance, R_s representing the active losses assumed to be 0.3 Ω.

4.3 Choosing the Value of DC Capacitor (C)

Selection of the DC capacitor is a compromise between the transient performance of the system and the voltage ripple on the DC side. The equations for proper sizing of the DC capacitor for one inverter system are detailed in [10]. The DC capacitor peak to peak voltage ripple is given by $\Delta V_c = \frac{m_a I}{2\omega C}$ from which the value of C can be derived,

$$C = \frac{m_a I}{2\omega \Delta V_c} \tag{6}$$

The selected value of DC voltage ripple is 15 V, which is 6% of the selected V_d (= 250 V). After substituting the required values in equation 6, the magnitude of the DC capacitor is found to be 2357 μF. The nearest commercially available value is 2350 μF.

4.4 Control System Design

The control system derived is simple with an indirect approach of a dc capacitor voltage control as shown in Fig (3). This can be implemented on a compatible micro-controller or DSP chip. The voltage V_s and the current, I_s, are measured from the supply side. I_s is measured by sensing the voltage drop across R_{sense}, (0.01 Ω) the current sensing resistor. In order to obtain reactive component of the supply current, phase angle is between I_s and V_s is measured by zero crossing detection. False or multiple zero-crossing detections are avoided by filtering the current and voltage signals.

The supply current is then decomposed into real and reactive components. The reactive component of the supply current is then compared with the reference (Ref I_q). The error signal thus obtained is processed by a PI

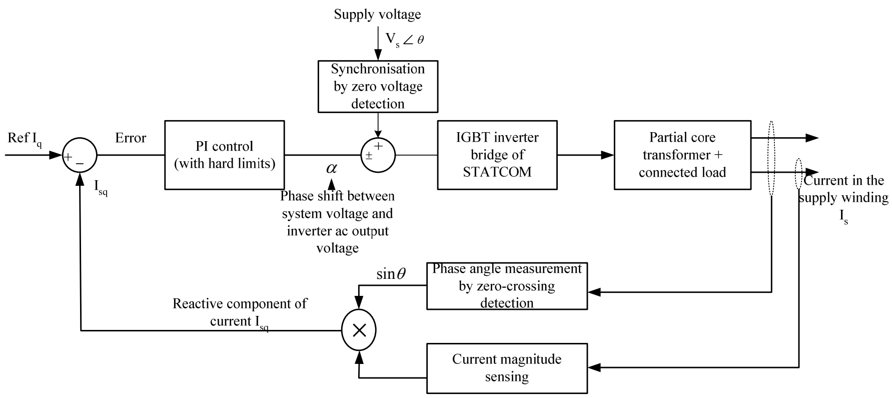

Figure 3. Automatic Control System Implemented for the STATCOM Controlled Partial Core Transformer.

controller that generates the appropriate angle, α , which determines a phase shift between the output of the converter and the mains voltage. Depending on whether the load seen by the STATCOM is an inductive or capacitive, the angle α is added or subtracted from the synchronised supply voltage angle, θ respectively. This controls the real power exchange between the STATCOM and the system, and thus the DC capacitor voltage is regulated [10] [13]. The scheme also should work for 3-phase transformer.

The values of proportional (k_p) and integral constants (k_i) of the PI controller can be derived from Bode plot or root locus analysis [14]. In this application, reliability, robustness, simplicity and cost effectiveness are more important than the transient response of the system. The selected values for k_p and k_i are 0.241 and 2.41 respectively.

5. Simulation Results

Performance of a 2.52 kVA, 90/345/90, 50 Hz partial core single phase three winding transformer (of which one of the winding is kept open) connected to the ± 2 kVAr single phase STATCOM is simulated on a digital computer by using PSCAD/EMTDC software.

Table 2
Parameters of the Single Phase STATCOM to be Connected to the Partial Core Transformer

Parameter	Value	Unit
V_s	90	V
Q	± 2000	VAr
L_s	12	mH
R_s	0.3	Ω
V_d (max)	250.3	V
ΔV_c	15 (6% of 250)	V
C	2350	µF
f_s	1350	Hz

Table 2 summarises the main parameters of the system.

5.1 Operation of the Partial Core Transformer on No Load

Under no load, without any compensation the partial core transformer draws current of magnitude 17.6 A. Application of the STATCOM reduces this burden on the supply and only the real component of current i.e. 2.8 A is drawn from the supply side. Power factor at the supply side is improved from 0.08 (lagging) to 0.99 (leading). The supply current waveform is, injected with the ripple. The waveforms of the supply voltage, supply current, current flowing through the DC capacitor and DC side voltage are shown in Fig. 4.

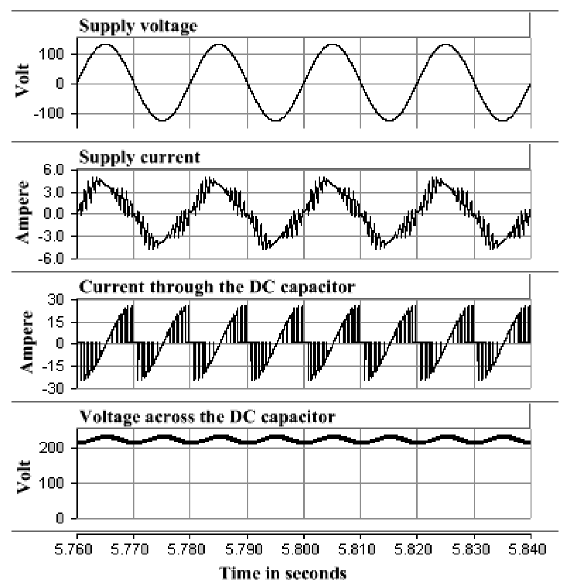

Figure 4. Behaviour of the Supply Voltage, V_s, Supply Current, I_s, Current on DC Side and Voltage across the DC Capacitor when the STATCOM Controlled Partial Core Transformer is Excited on No-Load.

5.2 Operation of the Partial Core Transformer under an Inductive Load Situation

An inductive load of 473 VAr is connected to the high voltage winding of the partial core transformer. Before connecting the STATCOM to the supply side, total current drawn from the supply was 22.5 A. This current is reduced to its real component i.e. 3.7 A after the STATCOM connection. Power factor at the supply side is improved from 0.08 (lagging) to 0.99 (leading). Thus this portable transformer kit can be well used for inductive loads. The waveforms of the supply voltage, supply current, current flowing through the DC capacitor and DC side voltage for the inductive load are shown in Fig. 5.

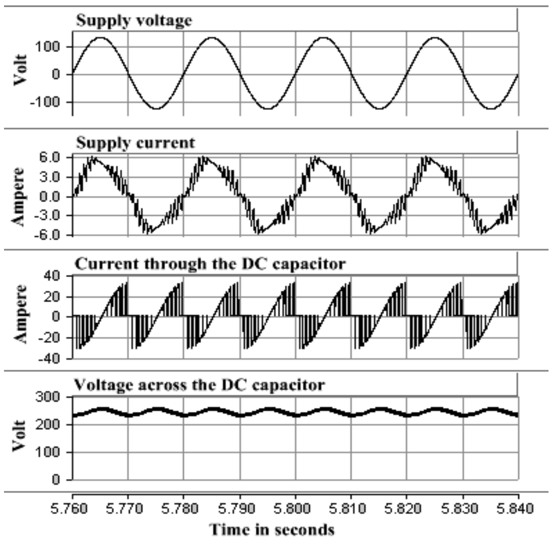

Figure 5. Behaviour of the Supply Voltage, V_s, Supply Current, I_s, Current on DC Side and Voltage across the DC Capacitor when the STATCOM Controlled Partial Core Transformer is Excited with an Inductive Load Connected to its HV Winding.

5.3 Operation of the Partial Core Transformer with a Capacitive Load

Though most of the loads connected to the distribution system are inductive in nature, some loads which are encountered while testing generators, transformers, cables etc are capacitive in nature. The low magnetising reactance of the partial core transformer itself compensates much of the capacitive reactance; hence higher capacitive loads up to 3000VAr can be well handled by the proposed system. When the STATCOM absorbs reactive power, DC capacitor voltage reduces and hence percentage ripple content in the DC voltage increases.

Capacitive load of 3000 VArs is connected to the high voltage winding of the partial core transformer and it draws 17.6 A from the supply. After application of the STATCOM, the current drops down to 4.8 A. Power factor on the supply side has improved from 0.19 (leading) to 0.97 (lagging). Harmonic distortion and ripple content in the supply current are much lesser as compared to the loads are inductive in nature. Fig. 6 shows the waveforms of the supply voltage, supply current, current flowing through the DC capacitor and DC side voltage for the capacitive load.

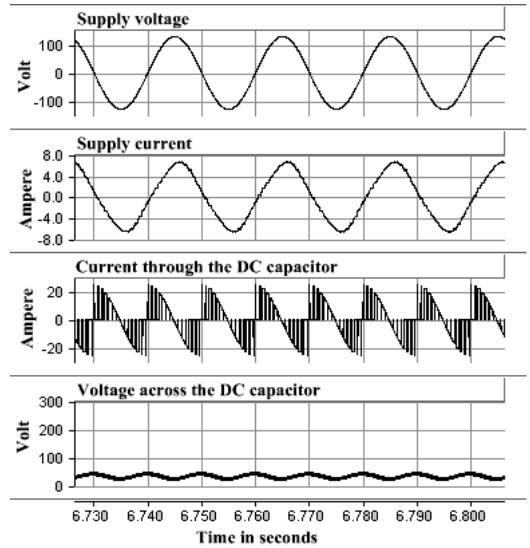

Figure 6. Behaviour of the Supply Voltage, V_s, Supply Current, I_s, Current on DC Side and Voltage across the DC Capacitor when the STATCOM Controlled Partial Core Transformer is Excited with a Capacitive Load Connected to its HV Winding.

5.4 Transient Response of the System

Fig. 7 shows the transient performance of the STATCOM connected partial core transformer. Initially, a capacitive load of 1536 VArs (as seen from the STATCOM) is connected to the HV winding of the transformer.

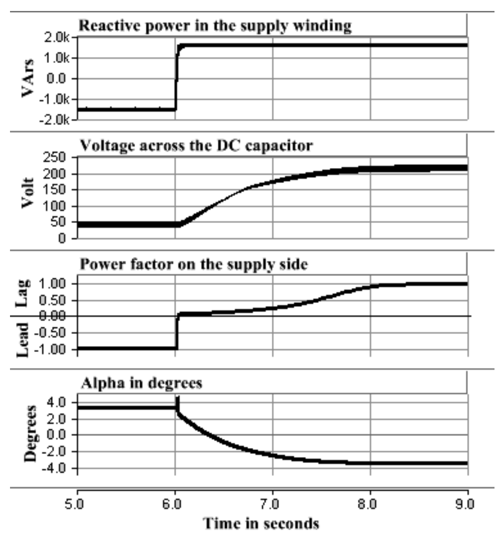

Figure 7. Transient Response of the STATCOM

Suddenly, at 6^{th} second the load is removed, and the load seen from the STATCOM becomes inductive having magnitude of 1564 VArs. Simulations show that STATCOM can handle this sudden change of 1536 VArs (leading) to 1564 VArs (lagging) without loss of stability. Voltage on the DC side increases approximately from 41 V to 213 V. Angle corresponding to the phase shift, α, changes from $+3.30^o$ to -3.67^o. Power factor changes from 0.99 leading to 0.97 lagging.

6. Implementation of the Proposed Scheme using a PIC18F4680 Microcontroller

Work is in progress to develop a prototype of the proposed system. Implementing the full control system digitally reduces the complications, the need for passive components and the cost of manufacture, yet allows greater flexibility.

All required peripherals like A/D converters with 10 bit resolution, enhanced PWM module with auto shutdown and restart capability, comparators, etc. are incorporated in one chip with 10 different oscillator modes. The simulated control system in PSCAD/EMTDC can be implemented in the microcontroller.

7. Conclusion

The partial core transformer is a compromise between a conventional full core transformer and a coreless transformer. It is superior to its full core counterpart as far as cost, weight and ease of transportation are concerned, while maintaining its functionality.

In case of a partial core transformer, the lack of closed core reduces the magnetising reactance (X_m) and increases the reactive power requirement and hence may not be useful as a power transformer. For overcoming the above problem, the concept of a single phase VSC based STATCOM controlled partial core transformer is detailed in this paper. Simulations in PSCAD/EMTDC software reveal the performance of the proposed scheme. The single phase VSC based STATCOM supplies the required reactive power for compensating the magnetising inductance and hence only the real component of the current is drawn from the supply side. The performance of the proposed scheme is tested for lagging as well as leading loads. Though the STATCOM makes the supply redundant as far as reactive power is concerned, it also injects ripple into the supply current.

The transient response reveals that the system is stable with no oscillations. The size of the DC capacitor is a trade off between the transient response and ripple content. With the application of a STATCOM, a partial core transformer can be used like a conventional full core transformer with added compensation.

References

[1] B. L. Theraja, A. K. Theraja, *A textbook of electrical technology* (New Delhi: S. Chand and Compnay Ltd. Vol. 2, 1998)

[2] Bodger, P. S., David Harper, Matthew Gazzard, Matthew O'Neil, Enright W. G., Towards a usable mains frequency partial core transformer, *AUPEC* 2002, Melbourne, Australia, 29 Sept-2 Oct. 2002.

[3] M. C. Liew and P. S. Bodger, Applying a reverse design modeling technique to partial core transformers, *Journal of Electrical and Electronics Engineering, 22*(1), 2002, 85-92.

[4] Bodger P. S., Enright W. G., A resonant transformer for high voltage testing of generator stators, *Australasian Universities Power Engineering Conference,* 2003 and *Australian Journal of Electrical and Electronics Engineering, 1*(3), 2004, 179-185.

[5] 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.

[6] Hanson, D. J., Horwill, C., Gemmell, B. D., Monkhouse, D. R., A STATCOM-based relocatable SVC project in the UK for National Grid, *IEEE/PES Asia pacific T&D Conference and Exhibition,* 6-10 Oct 2002, 1202-1207.

[7] J. Doval, C. M. Penalver, A. Lago, A. A. Nogueiras, J. Marcos, Considerations of DSP controlled VSC based STATCOM, *IEEE International Symposium on Industrial Electronics,* 9-11 June 2003, 397-400.

[8] Muhammad H. Rashid, *Power electronics handbook* (San Diego, California: Academic Press, 2001).

[9] Yiqiao Liang, C. O. Nwankpa, A new type of STATCOM based on cascading voltage source inverters with phase-shifted unipolar SPWM, *IEEE Trans. Industry Applications, 35*(5), Sept. 1999, 1118-1123.

[10] Stevenson William D., *Elements of power system analysis* (USA: McGraw Hill Electrical and Electronic Engineering series, 4th edition, 1982).

[11] Bhim Singh, S. S. Murthy, Sushma Gupta, Analysis and design of STATCOM based voltage regulator of self excited induction generators, *IEEE Trans. Energy Conversion, 19*(4), December 2004, 783-790.

[12] Mohan, Undeland, Robbins, *Power electronics converters, applications and design* (NJ: John Wiley and Sons, Inc. 3rd edition, 2003).

[13] Hingorani N. G., Gyugyi, *Understanding FACTS concepts and technology for flexible AC transmission systems* (NJ: IEEE Press, 2000).

[14] John O' Reilly, Alan R. Wood, Chris Osauskas, Frequency domain based control design for an HVdc converter connected to a weak AC network, *IEEE Trans. Power Delivery, 18*(3), July 2003, 1028-1033.