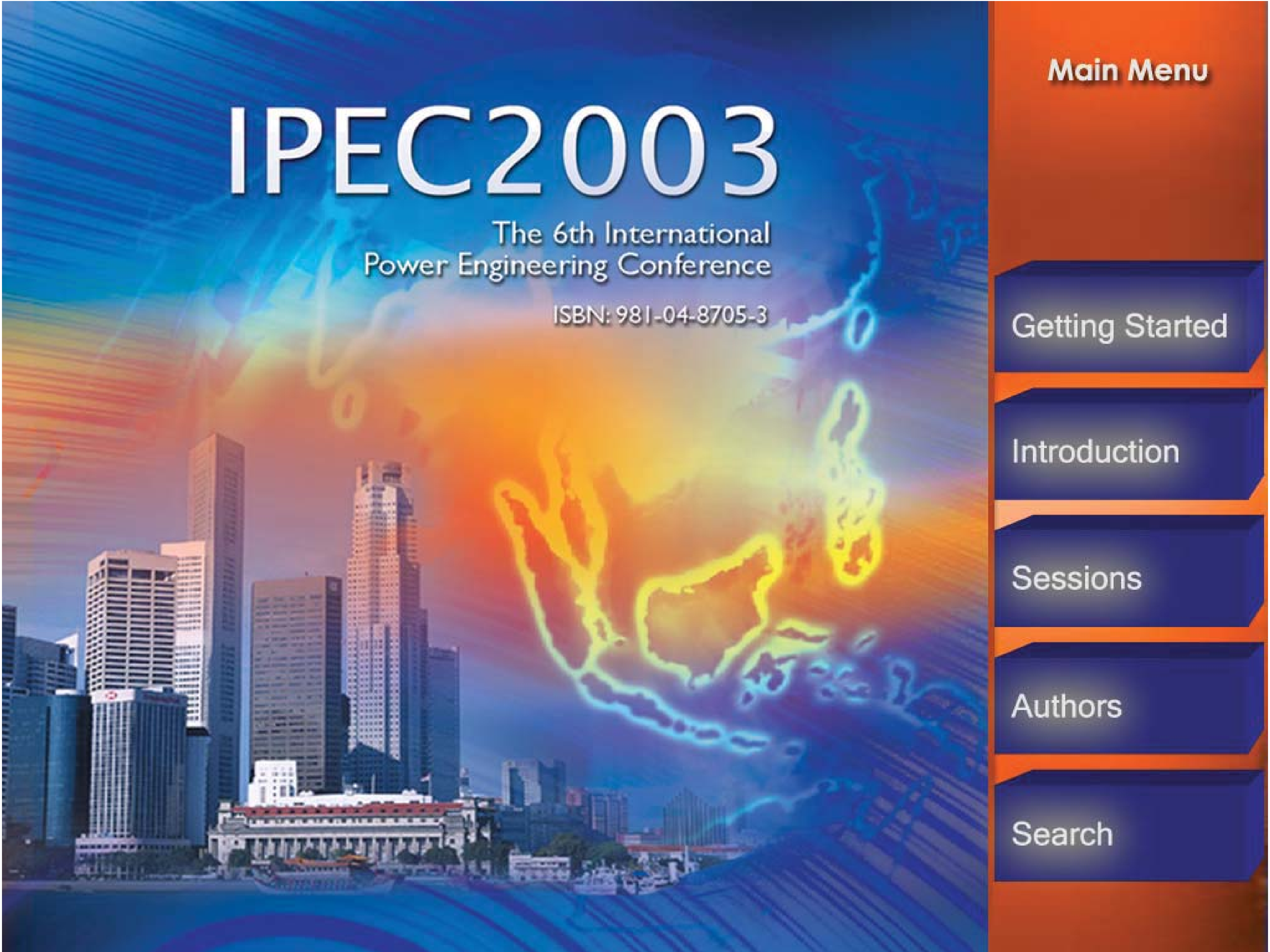
IPEC2003
The 6th International
Power Engineering Conference
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Message from Chairmen

On behalf of the Organizing Committee of the Sixth International Power Engineering Conference 2003 (IPEC2003), we take great pleasure and honor in welcoming all delegates to Singapore.

The main challenge facing today's power engineering professionals remains that of satisfying the ever-increasing demand for reliable and high quality electricity by the most economical means. The key to meeting this challenge is to use the appropriate technologies and to complement them with sound industrial and managerial skills. This is particularly true in the light of the globalization of the world economy, where the utility industry is no exception. In order to prosper in this increasingly competitive market, electrical supply networks must provide quality service at prices acceptable to customers.

At the same time, one can see the tremendous growth and advances made in information technology in recent years – these developments show that the technology lends itself surprisingly well in helping us meet the new challenges. The identified theme of IPEC2003, "Information Technology in Today's Electricity Market" is therefore very topical and timely.

IPEC, a biennial event since 1993, has always attracted in excess of 200 delegates on every occasion. IPEC2003 is particularly successful in that it has attracted 378 abstracts from 34 countries. After a rigorous review process, 187 full papers have been finally selected and included in the conference proceedings. The papers will be presented in 35 technical sessions over two-and-a-half days. In addition, a small exhibition of the latest products and services in power engineering has also been arranged in conjunction with the Conference.

For IPEC2003, we are extremely grateful to Professor Su Guaning, President, NTU, for taking time off from his busy schedule in officiating at the Conference Opening. We would also like to thank the IEE and IEEE for sponsoring our distinguished keynote speakers, Dr M. Kennedy and Dr M. Begovic respectively, to the Conference. Dr Kennedy and Dr Begovic will address delegates on how information technology can impact the operation, control and protection of electrical networks - topics which are truly befitting the Conference theme.

We would also like to express our appreciation to members of the International Advisory Committee who were instrumental in the conference organization. We thank all authors, session chairpersons and delegates for their support, and wish all of you a successful, stimulating and productive meeting and a pleasant stay in Singapore. To our supporters in the utility, equipment manufacturing and marketing industries, our sincere thanks for sponsoring some of the conference events, for placing the eye-catching advertisements in the souvenir magazine and for taking part in the exhibition displays.

Last but by no means the least, our sincere thanks to our fellow team members on the Organizing Committee and to those colleagues and friends who have been working behind-the-scenes. Without their unfailing cooperation and hard work, the event would simply not have been possible.

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Chair, Organizing Committee

SC Soh
Co-Chair, Organizing Committee

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IPEC 2003 Conference Schedule

Day	Time	Event/Location			
THURSDAY	08.00-08.45	Registration (Level 1, outside Pacific Ballroom 3)			
	09.00-10.00	Opening Ceremony Guest of Honour: **Professor Su Guaning** (Level 1, Pacific Ballroom 3) Keynote Address *Keynote Speaker 1: **Dr. Malcolm William Kennedy***			
	10.00-10.30	Tea Break (Level 1, Foyer)			
	10.30-11.15	*Keynote Speaker 2: **Dr. Miroslav M. Begovic***			
	11.15-12.30	**TA-1 (Ocean 2)** Power System Analysis and Stability Enhancement	**TA-2 (Ocean 3)** Distribution Protection	**TA-3 (Ocean 4)** Power Quality Improvement	**TA-4 (Ocean 5)** Neural Networks Applications
	12.30-14.00	Lunch (Level 3, Summer House)			
	14.00-15.30	**TP-1 (Ocean 2)** System Stability Enhancement	**TP-2 (Ocean 3)** Partial Discharge	**TP-3 (Ocean 4)** Harmonics	**TP-4 (Ocean 5)** Power Converters
	15.30-16.00	Tea Break (Level 2, Foyer)			
	16.00-17.30	**TP-5 (Ocean 2)** Transient Stability and Voltage Stability	**TP-6 (Ocean 3)** High Voltage Engineering	**TP-7 (Ocean 4)** Active Filters	**TP-8 (Ocean 5)** Power Electronics and Drives
	19.00-22.00	**Banquet** (Level 1, Pacific Ballroom 3)			
FRIDAY	09.00-10.30	**FA-1 (Ocean 2)** Distributed Generation and Energy Management	**FA-2 (Ocean 3)** Condition Monitoring	**FA-3 (Ocean 4)** Power Quality Analysis	**FA-4 (Ocean 5)** Power Electronic Drives and Applications
	10.30-11.00	Tea Break (Level 2, Foyer)			
	11.00-12.30	**FA-5 (Ocean 2)** New Energy Systems	**FA-6 (Ocean 3)** Advanced Signal Processing Applications	**FA-7 (Ocean 4)** Power System Economics	**FA-8 (Ocean 5)** Modeling of Power System Components
	12.30-14.00	Lunch (Level 3, Summer House)			
	14.00-15.30	**FP-1 (Ocean 2)** Operations and Control	**FP-2 (Ocean 3)** Modeling and New Algorithms	**FP-3 (Ocean 4)** Power Market Models	**FP-4 (Ocean 5)** Power System Analysis and Modeling
	15.30-16.00	Tea Break (Level 2, Foyer)			
	16.00-17.30	**FP-5 (Ocean 2)** New Applications to Transmission Systems	**FP-6 (Ocean 3)** AI and UP-Based Protection	**FP-7 (Ocean 4)** Network Management and De-regulation	**FP-8 (Ocean 5)** AI Applications
SATURDAY	09.00-10.30	**SA-1 (Ocean 2)** Distribution Automation	**SA-2 (Ocean 3)** High Voltage Analysis	**SA-3 (Ocean 4)** Power Market and De-regulation	**SA-4 (Ocean 5)** Power Electronics Applications
	10.30-11.00	Tea Break (Level 2, Foyer)			
	11.00-12.30	**SA-5 (Ocean 2)**	**SA-6 (Ocean 3)** System Reliability	**SA-7 (Ocean 4)** Generation Optimization in Power Market	**SA-8 (Ocean 5)** Motor Drive Systems
	12.30	Lunch (Level 3, Summer House)			
	13.15 or 14.00	Post Conference Tours (meet outside Pacific Ballroom 3, Level 1)			
		Tuas Power Ltd (Departure at 13.15)		Singapore City Tour (Departure at 14.00)	

Note: Ocean 2, Ocean 3, Ocean 4 & Ocean 5 are located at Level 2

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Power System Analysis and Stability Enhancement

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P KUMKRATUG, M H HAQUE, Nanyang Technological University, SINGAPORE

TA-1.2 Power System Stability Improvement Using Superconducting Magnetic Energy Storage Unit, P2251
A ABU-SIADA, W B LAWRANCE, W W L KEERTHIPALA, Curtin University of Technology, AUSTRALIA

TA-1.3 Small Signal and Transient Stability of Power Systems with FACTS devices: Modeling, Simulation and Analysis Using SIMULINK, P2003
U P MHASKAR, A M KULKARNI, Indian Institute of Technology Bombay, Powai, INDIA

TA-1.4 Development of SVC Fuzzy-Logic Adaptive Controller for Stability Enhancement of Power Systems, P2042
X YANG, *T S CHUNG, *D Z FANG, Tianjin University, CHINA, *The Hong Kong Polytechnic University, HONG KONG S.A.R.

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R BOEL, G JIROVEANU, University of Ghent, BELGIUM

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TA-2.4 Detection of Breaking Conductors on MV Overhead Lines, P2022
K J V RENSBURG, D BIRTWHISTLE, Queensland University of Technology, AUSTRALIA

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H H TUMBELAKA, C V NAYAR, K TAN, *L J BORLE, Curtin University of Technology, AUSTRALIA, *The University of Western Australia, AUSTRALIA

TA-3.2 Adaptive Unified Power Quality Conditioner for Improving Power Quality, P2248
L H TEY, P L SO, Y C CHU, Nanyang Technological University, SINGAPORE

TA-3.3 An Efficient Approach for Placement of Active Power Line Conditioners in a Power System for Mitigating Voltage Distortion, P1108
G CHANG, H L WANG, S Y CHU, National Chung Chang University, TAIWAN

TA-3.4 Analysis of Series Voltage Restorer-Load Dynamics, P1002
J LI, S S CHOI, D M VILATHGAMUWA, Nanyang Technological University, SINGAPORE

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Neural Network Applications

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M YEDROUDJ, F J CHAKIB, W L NG, Singapore Polytechnic, SINGAPORE

TP-1.6 **Application of Fuzzy Logic to Transient Stability Assessment, P2006**
C K BABULAL, P S KANNAN, Thiagarajar College of Engineering, INDIA

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A I MASWOOD, Nanyang Technological University, SINGAPORE

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A ABU-SIADA, W W L KEERTHIPALA, Curtin University of Technology, AUSTRALIA

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M AL-DABBAGH, R ABDUL JABBAR KHAN, RMIT University, AUSTRALIA

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FA-4.3 **Negative Output Super-Lift Luo-Converters, P2012**
F L LUO, Nanyang Technological University, SINGAPORE

FA-4.4 **Sizing of Switched Reluctance Machine for Starter/ Alternator of Hybrid Electric Vehicles, P2179**
J FAIZ, K MOAYED-ZADEH, University of Tehran, IRAN

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Session FA-5

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ACTIVE FILTERING APPLIED TO A LINE-COMMUTATED INVERTER FED PERMANENT MAGNET WIND GENERATOR

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Abstract

In this paper, the implementation of a shunt active power filter (APF) for compensating reactive and harmonic currents generated by a line-commutated inverter (LCI) in the permanent magnet synchronous generator (PMSG) wind energy conversion systems (WECS) is presented. The system consists of wind turbine and PMSG with a sensor-less MPPT and a LCI to deliver the power to the grid. The filter consists of a three-phase current-controlled voltage source inverter (CC-VSI) with a filter inductance at the ac output and a dc-bus capacitor. The CC-VSI is operated to directly control the ac grid current to be sinusoidal and in phase with the grid voltage. The switching is controlled using ramptime current control, which is based on the concept of zero average current error. The simulation results indicate that the filter is able to handle the reactive and harmonic currents, so that the grid currents are sinusoidal, in phase with the grid voltages and symmetrical. The filter also can operate accurately regarding the wind variation.

Keywords
Active Power Filter, Line-commutated inverter, WECS

1 INTRODUCTION

Permanent magnet synchronous generator (PMSG) wind energy conversion systems (WECS) generally operate in variable-speed variable-frequency mode. In order to achieve optimal power extraction from the wind, a maximum power point tracking (MPPT) controller is implemented. Then, the AC-DC-AC link is used to interconnect the WECS to the grid. Commonly, the link consists of an uncontrolled rectifier and a line-commutated inverter.

As wind speed is constantly varying, the PMSG produces variable-voltage and variable-frequency, which cannot be fed directly to the grid or loads. A three-phase diode rectifier is used to convert the output of the PMSG to dc current. The line-commutated inverter controls the power flow from the dc reactor to the grid according to the maximum power operating point.

The line-commutated inverter (LCI) is commonly used to transfer power from a dc reactor to the three-phase ac grid [1, 2] because of low cost, simplicity, reliability and availability at high power levels. However, it produces reactive and harmonic currents that could lead to problems for the power system operation. Instead of attempting to modify the LCI topology and control to mitigate the problems, a three-phase shunt Active Power Filter (APF) can be installed between the output inverter and the grid as a practical solution. The combination of a line-commutated SCR inverter with an APF has some benefits compared to other interface options [2].

2 WIND ENERGY CONVERSION SYSTEM (WECS)

The WECS considered in this work consists of a PMSG driven by a fixed pitch wind turbine, a three-phase diode rectifier and a LCI as AC-DC-AC link to the grid as shown in figure 1.

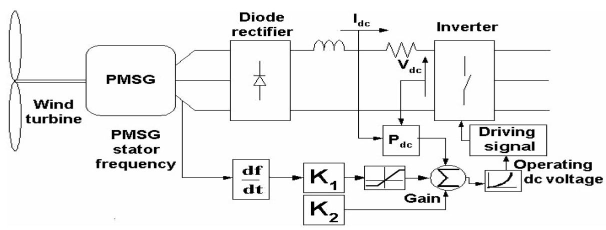

Figure 1 Sensor-less WECS system

A sensor-less control scheme [3] is a simple and robust MPPT system. The sensor-less control system consists of two signal-tracking loops, namely a ‘power mapping’ loop that is related to the output power from PMSG WECS, and a PMSG frequency derivative loop to give tuning to the first loop. At a given wind speed, the output power at the dc link is used to estimate the optimal dc operating voltage through the ‘power-to-voltage mapping’ curve. Using the results determined by both loops, the LCI sets its firing angle to generate dc bus/link voltage and to control the power flow to the grid according to maximum power operating point.

2.1 Wind Driven PMSG Characteristics

The loading characteristic of the PMSG WECS can be easily determined by connecting an adjustable load resistor to the output rectifier unit of the PMSG. Figure 2 shows the calculated corresponding output power of the PMSG (CRESTA-Curtin) for wind speeds ranging from 4 to 12m/sec [3], where the generator maximum power curves show the different operating dc voltages and currents over a range of wind speeds. In order to extract the peak power from the WTG at a given wind speed, the WECS has to match closely to the maximum power curve.

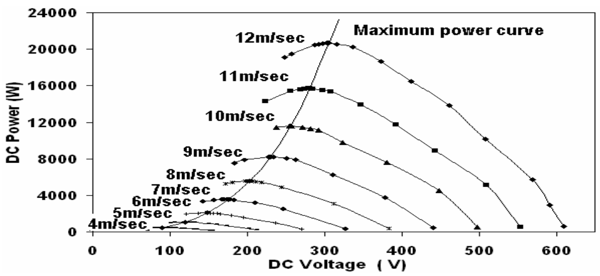

Figure 2 Predicted DC Power characteristics of the WECS

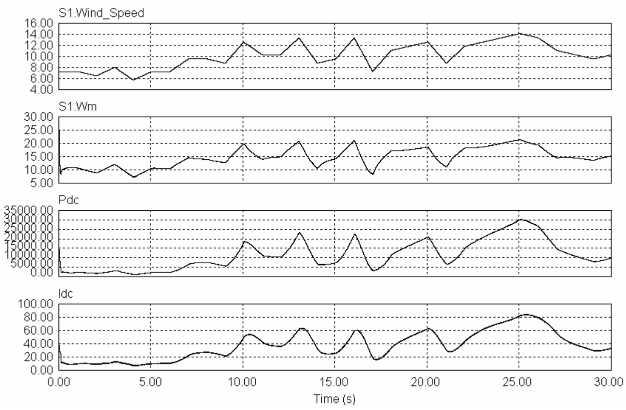

Figure 3 Dynamic conditions of the WECS

The dynamic condition of the WECS due to a random change of wind speed is shown in figure 3. The wind speed time characteristic is a first order reconstruction of continuous wind-speed that based on wind data recorded in ACRE's laboratory in Western Australia with a sampling rate of 1 sample/sec [3]. As the wind speed increases or decreases, the MPPT controller is able to track the maximum power point closely, although the inertia of the turbine-generator and the energy storage elements in the circuit reduce the response speed. From figure 3, the rotor speed, dc power and dc current at the dc reactor can follow closely the wind-speed curve. However, by using a LCI, not only active power but also reactive power and harmonics are delivered to the grid.

3 THE LINE-COMMUTATED SCR INVERTER (LCI)

The design and theoretical analysis of the LCI has been already well documented such as [4]. Basically, the 6-pulse line-commutated converter is a current source inverter (CSI) and consists of a three-phase thyristor or SCR bridge and an inductive filter at dc side. When the firing angle of the thyristor is between 90^o and 180^o, the bridge circuit operates in the inverter mode.

DC voltage and current of the LCI converter are given by:

$$V_d = \frac{3\sqrt{2}V_L}{2\pi N}[\cos\alpha + \cos(\alpha+\gamma)] \qquad (1)$$

$$I_d = \frac{\sqrt{2}V_L}{2N X_T}[\cos\alpha - \cos(\alpha+\gamma)] \qquad (2)$$

α = firing angle
γ = commutation angle
X_T = transformer leakage reactance

The LCI is inherently compatible with an ac system, and will naturally commutate with the line frequency. However, because of ac-side reactance effects on the commutation process, the LCI has to operate at firing angles less than 180^o to guarantee against commutation failure. This requirement on firing angle causes non-unity displacement power factor operation. A notching effect also appears on the ac line voltage during commutation. Another disadvantage is that the line current waveform will be a quasi-square wave with high harmonic content.

4 A THREE-PHASE SHUNT ACTIVE POWER FILTER (APF)

The three-phase shunt active power filter is a three-phase current controlled "voltage-source inverter" (CC-VSI) with a mid-point earthed, split capacitor in the dc bus and inductors in the ac output. It is essentially three independent single-phase inverters with a common dc bus.

Conventionally, a shunt APF is controlled in such a way as to inject harmonic and reactive compensation currents based on calculated reference currents. The injected currents are meant to "cancel" the harmonic and reactive currents drawn by the non-linear loads. However, the reference or desired current to be injected must be determined by extensive calculations with inherent delays, errors and slow transient response. In this scheme (see figure 8), the CC-VSI is operated to directly control the ac grid current rather than its own current. The grid current is sensed and directly controlled to follow symmetrical sinusoidal reference signals, which are in phase with the grid voltage [5, 6]. Hence, by putting the current sensors on the grid side, the grid current is forced to behave as a sinusoidal current source and the grid appears as a high-impedance circuit for harmonics. By forcing the grid current to be sinusoidal, the APF can automatically provide the harmonic, reactive, negative and zero sequence currents for the LCI, following the basic current summation rule:

$$i_{grid}\,(t) = i_{APF}\,(t) + i_{inverter\,(LCI)}\,(t) \qquad (3)$$

The sinusoidal grid current reference signal is given by:

$$i_{ref}\,(t) = k(t)\, v_{grid\text{-}1}(t) \qquad (4)$$

where $v_{grid\text{-}1}(t)$ is the waveform of the fundamental component of the grid voltage, and $k(t)$ is obtained from an outer control loop regulating the CC-VSI dc-bus voltage. This can be accomplished by a simple PI control loop. This is an effective way of determining the required magnitude of active current required, since any mismatch between the required load active current and that being forced by the CC-VSI would result in the necessary corrections to regulate the dc-bus voltage. In the VSI topology used in the APF, the dc-capacitor voltage must be greater than the peak of the ac grid voltage. Controllability is ensured by the proper relative sizing of the inverter filter inductance L_{inv} and the choice of the dc bus voltage so that the two output pwm states (per phase) will always result a corresponding opposite polarity current error signal slopes.

The performance and the effectiveness of the filter are enhanced by the use of the ramptime current control technique to control the CC-VSI [7]. The principle operation of ramptime current control is based on the concept of zero average current error (ZACE). In this application, the current error signal is the difference between the actual grid current and the desired/reference grid current waveform. The ramptime control produces switching instants, which result in the current error signal crossing zero at intervals of half the desired switching period. Hence the current error signal spends half the time on alternate sides of zero, resulting in an average value of zero, a close following of the reference signal, and a switching period (and hence switching frequency) very close to the desired value.

4.1 The Shunt Active Power Filter And The Line-Commutated Inverter

The shunt type APF acts to eliminate the reactive and harmonic currents produced by non-linear loads from the grid current by injecting compensating currents intended to result in sinusoidal grid current with unity power factor. This filter has been proven to be effective in compensating harmonic current sources [8]. In this case, the LCI is considered as a harmonic current sourcing load because the LCI is a current source inverter (CSI) and produces harmonic and reactive currents to the grid.

During commutation of the LCI, current spikes occur in the grid currents as seen in figure 5. This is because PCC-A and PCC-B are tied together producing a relatively large voltage across each phase line inductance, resulting in a relatively large *di/dt* in each of the two phase-currents, with each current moving away from the reference current. Consider the commutation process between SCR A and B as shown in figure 4. During that time, the voltage difference between line A and B at the PCC is zero ($v_{PCC\text{-}A} = v_{PCC\text{-}B}$). Since $v_b > v_a$, a commutating current (= i_B) builds up at the outflow of i_A so that,

$$i_A + i_B = I_d \qquad (5)$$

$$di_B/dt = -\,di_A/dt. \qquad (6)$$

Applying Kirchhoff's current law at PCC, and ignoring dI_d/dt as being negligible, then the rate of change of each current is given by

$$di_{ga}/dt = di_A/dt + di_{APFa}/dt \qquad (7)$$

$$di_{gb}/dt = di_B/dt + di_{APFb}/dt \qquad (8)$$

$$di_{gb}/dt + di_{ga}/dt = -\,(di_{APFb}/dt + di_{APFa}/dt) \qquad (9)$$

where i_A is $i_{inverter(LCI)}$ phase A and i_B is $i_{inverter(LCI)}$ phase B, and I_d is dc current.

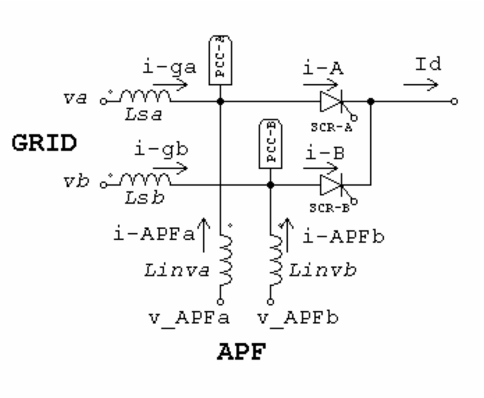

Figure 4 Circuit equivalent during commutation process

The effects of (9) can be seen in the figure 7. The APF is unable to eliminate the current spikes since it cannot decouple PCC-A from PCC-B. The APF attempts to compensate for the larger current error, and returns the current to the reference value within 200 µsec as seen in figure 7. The magnitude and duration of the current spikes is dependant on the size of *Linv*, the APF dc-bus voltage, and the speed of response of the APF. In this case the APF inductors are roughly half the size of the line inductance (transformer inductance), and the speed of response is less than half a switching period (< 25 µsec). Strict controllability is lost during the commutation since the current error signal moves away from zero regardless of switch position. However, as soon as the commutation has finished, controllability is returned, and the APF is able to force the grid current to return to the reference value.

To reduce the spikes, the CC-VSI can be constructed so that its minimum *di/dt* can exceed the maximum *di/dt* permitted by the LCI. This can be done by increasing the V_{dc} (the APF dc-bus voltage, which is across the two split capacitors) or decreasing the *Linv*. However, there is a compromise in the selection of *Linv* and V_{dc} because decreasing the *Linv* will increase the high switching frequency ripple in the ac grid currents. Also it will increase the *di/dt* of the switches during commutation process because the ac reactances seen by the LCI becomes smaller. Increasing V_{dc} will increase the stress of the switches.

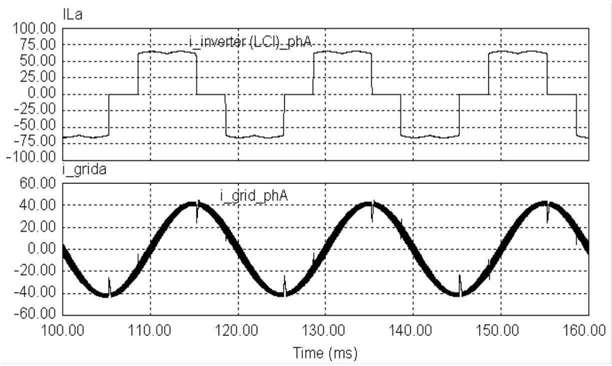

Figure 5 LCI current and grid current - phase A

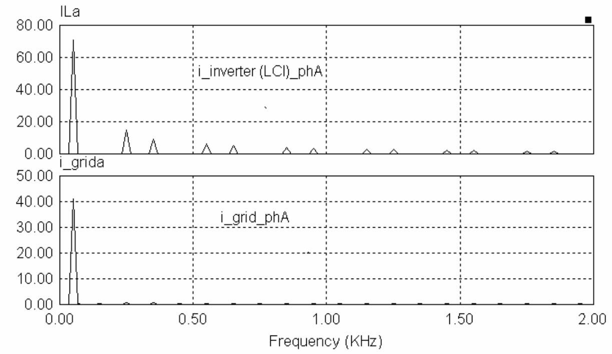

Figure 6 The spectrum of LCI current and grid current - phase A

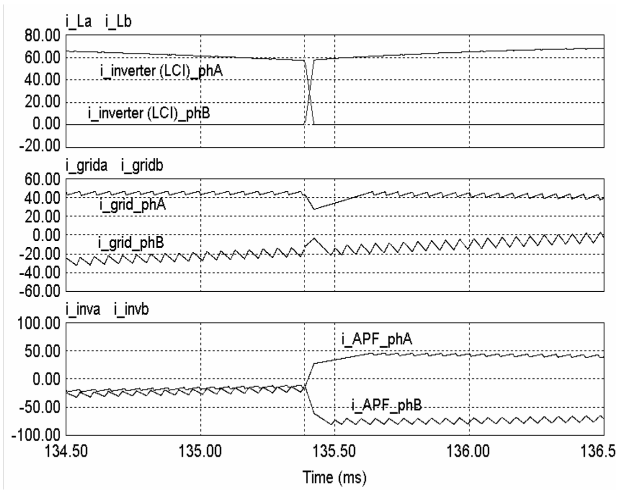

Figure 7 LCI, grid, and APF currents during commutation

5 THE WECS WITH THE SHUNT ACTIVE POWER FILTER

The APF for grid-current waveform control action is much faster than the dynamic behavior of the wind power extraction. The inertia of the turbine-generator also restricts the rotor speed from rapid fluctuation. Furthermore, the firing angle of the 6-pulses LCI can be updated 6 times in a cycle or every 3.33 msec (for 50 Hz), so that the LCI output can be controlled only at intervals of 3.33 msec. Therefore, the APF (in this case using 20kHz switching frequency) is suitable for WECS with a line-commutated SCR inverter and is able to be coordinated with the MPPT controller.

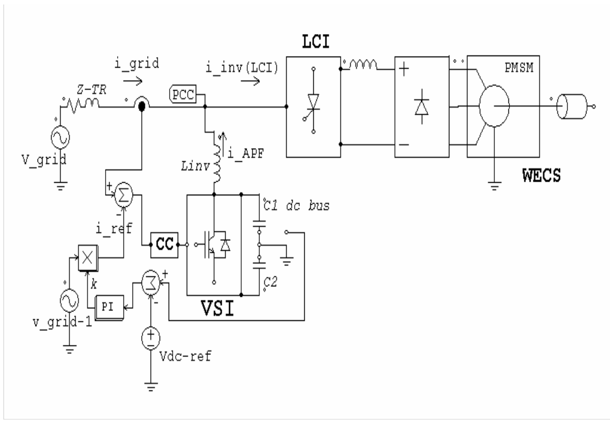

Figure 8 The APF – WECS system configuration

To show a compensation for a PMSG WECS with LCI, a computer simulation was conducted to test the system configuration shown in figure 8. It consists of a 20 kW PMSG WECS connected to the grid through a 40 kVA transformer with Z_{TR} = 5%. The three-phase shunt active power filter (APF) is connected between the transformer grid and the LCI. In this case, the capacitor voltage at the APF dc bus is 800 V and the filter inductance (*Linv*) = 2.3% on a kVA base of 40 kVA and a V base of 400 V_{rms}.

The simulation results of dynamic and steady state condition are presented in figure 9 to 12. Figure 9 shows that the three-phase shunt APF is able to eliminate the reactive and harmonic currents significantly. The grid current is sinusoidal with small commutation spikes and high switching frequency ripple (because the system is without a high switching frequency filter). However, from the current spectrum (up to 2 kHz) in figure 6, the spikes and the ripple do not contribute significantly to the low order harmonics. The grid currents are also symmetrical in magnitude and phase. From figure 10, it can be seen that the phase angle is 180^o of the grid voltage, so that the power flows to the grid.

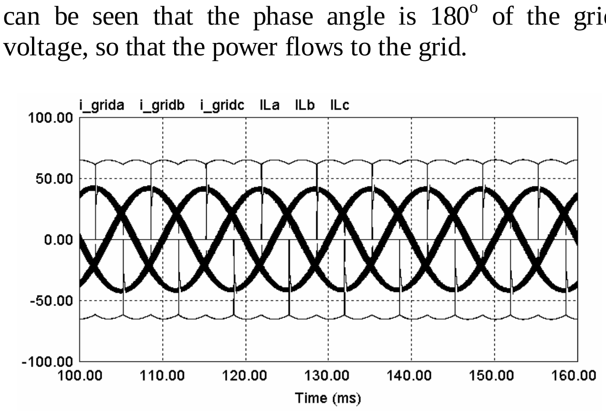

Figure 9 Filtering result under steady state, three-phase LCI and grid currents

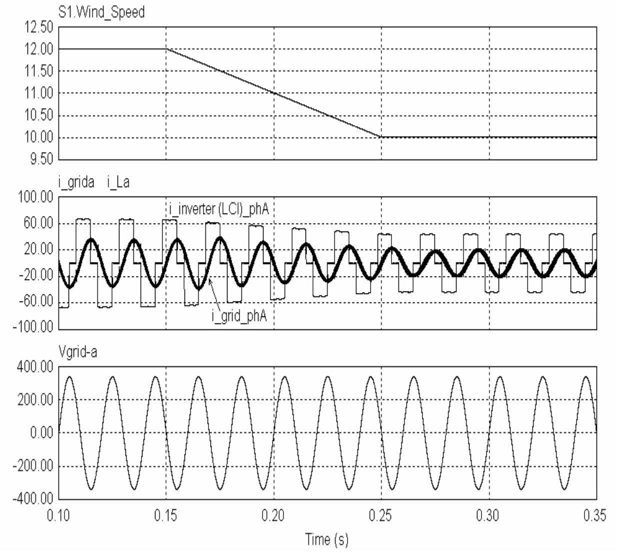

Figure 10 Filtering results under wind-speed changing

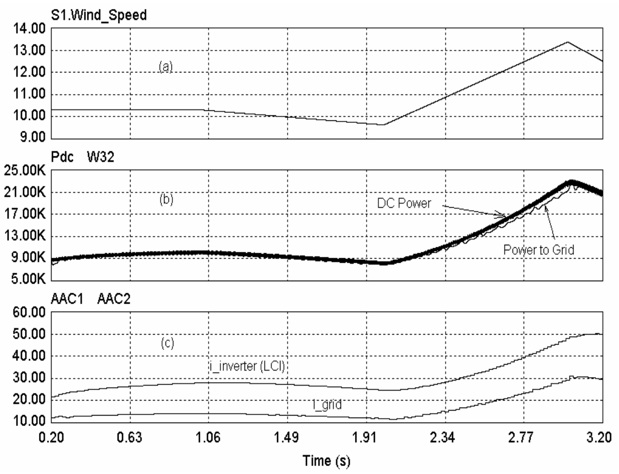

Figure 11 (a) Wind speed (b) Power flow (c) LCI and grid currents (rms value)

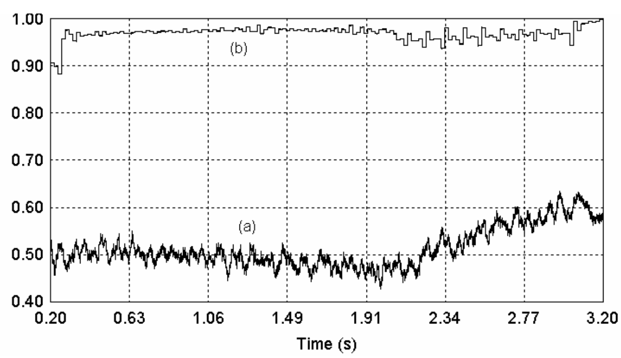

Figure 12 Total power factor (a) output LCI (b) at the grid

Furthermore, the APF has to be operated in dynamic condition because the wind speed is always changing randomly and the power flow as well, as shown before in figure 3. If the wind speed changes from 12 m/sec to 10 m/sec within 0.1 sec, the LCI current also changes in magnitude and phase. The APF is able to operate accurately so that the grid current is always sinusoidal and at 180^o phase to the grid voltage. Its magnitude corresponds to the active power delivered to the grid.

From figure 11, it is shown that the grid rms current after compensation is reduced significantly. The output rms current from the LCI is high because it contains reactive and harmonic components. Although the rms currents decrease, the active power filter does not affect the power flow. The active power delivered to the grid is similar to the dc power produced by PMSG through an uncontrolled rectifier. The small difference is related to the losses. The total power factor after compensation is nearly unity (figure 12-b). While the total power factor of the LCI output is very low, especially when the wind speed is low and the available power is low. The total power factor is calculated from:

$$PF = \frac{I_1}{I_{rms}} \cos \alpha \qquad (10)$$

where I_1 is the fundamental current.

6 CONCLUSION

This paper proposes the implementation of a three-phase active power filter to a line-commutated inverter fed PMSG WECS. The APF is operated to directly control the ac grid current to be sinusoidal and in phase with the grid voltage. From the simulation results, this system can compensate the reactive and harmonic currents generated by the LCI and provide nearly unity power factor operation, because there is still spikes and high switching frequency ripple. The APF can handle the dynamic condition due to wind speed variation and the LCI operation.

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