The ITB Journal

Volume 5 | Issue 1 Article 15

2004

Novel Design of a Variable Speed Constant Frequency Wind Turbine Power Converter.

Aodhan MacAleer
Department of Electrical Engineering, Limerick Institute of Technology, Limerick, Ireland., Aodhan.MacAleer@lit.ie

Joe Dunk
Department of Electrical Engineering, Limerick Institute of Technology, Limerick, Ireland., Joe.Dunk@lit.ie

Recommended Citation

MacAleer, Aodhan and Dunk, Joe (2004) "Novel Design of a Variable Speed Constant Frequency Wind Turbine Power Converter.," *The ITB Journal*: Vol. 5: Iss. 1, Article 15.
doi:10.21427/D7T74K
Available at: https://arrow.tudublin.ie/itbj/vol5/iss1/15

Novel Design of a Variable Speed Constant Frequency Wind Turbine Power Converter

Aodhán MacAleer[1] & Joe Dunk[2]
[1] Department of Electrical Engineering, Limerick Institute of Technology, Limerick, Ireland.
[2] Department of Electrical Engineering, Limerick Institute of Technology, Limerick, Ireland
[1]Aodhan.MacAleer@lit.ie
[2]Joe.Dunk@lit.ie

Abstract

The operation and efficiency of wind turbines at present are hampered by the variable speed nature of wind, yet the constant speed requirements of electrical generators, hence wind turbines speeds are generally held down to a constant value regardless of wind conditions. This paper presents a novel design for a power converter that can produce a fixed output suitable for grid connection, while operating at variable speed governed by the available wind power. This novel design utilizes advances in high power, high frequency solid-state switches (IGBT's) based on an ADSP-21990 fixed-point mixed-signal digital signal processor (DSP). At present the system has been designed and simulated using Matlab and is currently in the build and test stage.

Keywords: Wind turbines, Variable Speed Constant Frequency, Power Converters, Pulse Width Modulation, DSP.

1. Introduction

Datta, Rajib and Ranganathan (2002) have stated that grid-integrated Wind Energy Conversion Systems (WECS) should generate at constant electrical voltage/frequency, determined by the grid. However, it is also advantages to vary the mechanical speed of the turbine/generator to maximise power capture with fluctuating wind velocities.

In the case of weak grid networks like Ireland's to successfully install wind turbines, a knowledge of the wind turbine impact on the grids is essential, this area is currently receiving intense focus in Ireland and European from wind turbine manufactures and grid controllers. The importance of this has currently led to a wind turbine moratorium [19] by the Electricity Supply Board (ESB) national grid preventing any addition wind turbines connecting to the grid until problem issues are solved.

2. Variable Speed Fundamentals

Albert Bertz (1947) proved that the amount of energy that can be successfully taken from the wind as the "power coefficient (C_p)", and calculated that the maximum physically value to be 59.3%, however in practise due to drag losses and losses in the mechanically components, power coefficients are often much less. The power coefficient is defined by Hau (2000) as the ratio of the extractable mechanical power to the power contained in the wind stream.

Another term principal in understanding wind turbine technology is the Tip-speed-ratio (TSR), which is defined as the ratio between the rectilinear speed of the blade tip and the wind speed. The advantages of variable speed WECS over fixed speed systems can be more easily understood from the C_p-TSR relationship (figure 1), which is indicative of all Horizontal Axis Wind Turbines (HAWT).

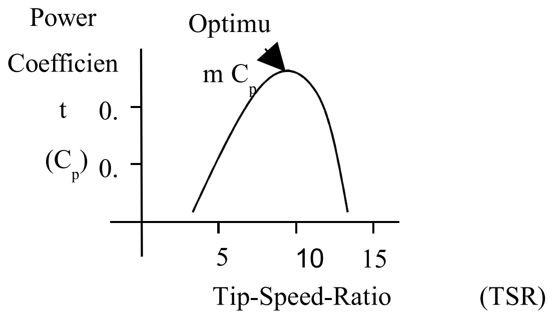

Figure 1 C_p-TSR relationship

Constants speed wind turbines are designed to operate near the optimum power coefficient at wind speeds that occur most often at the particular site. However from an understanding of the TSR (Ratio of the Tip Speed to Wind Speed), for a constant speed machine having a fixed speed rotor, a change in wind speed will cause a change in the tip-speed-ratio, hence fixed speed machines will often be operating at a non-optimal power coefficient, i.e. when the wind speed is above or below operating wind speeds for the specific wind turbine.

A variable speed system differs in that a changing wind speed will create a change in the rotor speed i.e a change in the rotor tip-speed, hence the TSR stays constant because both wind speed and tip speed change simultaneously. Hence a variable speed machine operates at near optimum power coefficient regardless of the varying wind velocity, excluding over speed operation where the rotor speed is restricted to prevent self-damage.

The added power capture from variable speed wind turbines, has been proved by Carlin (1995) to be on average up to 10% more annual energy. Additional advantages to variable speed operation include reduced loads on the drive train, and reduced turbine rotor fatigue loads, which reduce the overall turbine cost considerably.

In addition to improved energy capture possible with variable speed operation, ease of synchronisation to the grid is also an added benefit possible since the current can be controlled from zero to rated value via inverter control, unlike fixed speed operation where large inrush currents can pose problems for the grid.

3. Topical Issues

The Irish Electricity Supply Board National Grid (ESBNG) has called for a wind energy moratorium pending the resolution of the power systems reliability issues. This topic is especially specific to the Irish Network due to its largely isolated status, however this problem is currently being examined by other European network providers, due to the widespread increase in wind energy installation due partly to the Kyoto agreement fallout.

In a recent presentation [9] to the Joint Oireachtas Committee the Commission for Energy Regulation (CER) made the point that future & present wind turbines planned installations do not meet the requirements of the grid code, failing on several technical issues. The main provisions that wind farms struggle to comply with are “Fault Ride Through, Voltage and Frequency variations” among others.

Fault rise through refers to the reaction of power stations to faults on the transmission line, wind farms tend to trip of the system unlike conventional generator which continue generating regardless, this isolation from the grid could be significant when it can be argued the grid needs the extra generation the most, this is most prevalent to older manufactured wind turbines that are directly connected to the grid for speed stability etc.

This power converter designed is only peripheral connected to the grid, mainly for synchronisation to the grid, and does not require external signal to control generation, excitation or speeds, hence the serious technical issues presented by the ESB national grid will be solved in the most part.

4. Wind Turbine Configurations

Analysis and design of a power converter for wind turbine applications cannot be done without reference to the generator configuration used for power generation. Since in particular the rectifier and generator configuration are inextricably linked, hence in order to design or analyse the rectification process it is first necessary to consider the orientation and design of the power generator.

In wind turbine design the two main electrical machine synchronous or asynchronous can be utilised, synchronous machines are commonly encountered in the generating mode, and tend to be more in demand for large scale fuel burning power generation among other things due to their ability to generate reactive power and so improve the power factor of the installation. Although more expensive initially than an equivalent asynchronous generator slightly higher efficiency are possible, to offset the initial cost.

Synchronous machines are almost always brush-less, since the slip rings have been dispensed with in favour of static excitation hence brush-less systems, this development is mainly due to the progress and availability in power electronics components (diodes & thyristors for example) in recent years. Brush-less systems in the pass have been constructed using a stator with a distributed winding and a rotor with salient pole field windings. These are supplied through rotating diode rectifiers assembly, fed by a shaft-mounted exciter.

Asynchronous generators or induction generators (IG) as they are commonly known tend to be ether squirrel cage or wound rotor type, both referring to the physical properties of the rotor. IG may be designed to operate at more than one speed fixed speed by pole changing, where the stator winding can be switched between pre-determined number of poles, this is however not a widely used method. Slip rings IG or wound rotor (also termed doubly fed IG) involves removing the squirrel cage rotor and replacing it with a rotor with windings connected via slip rings to external elements (sometimes power converters). Principle disadvantages of wound rotor IG include higher initial cost compared to an equivalent squirrel cage IG, and maintenance due to the slip rings brushes.

However at present the most common electrical system utilised in commercial wind power plants is the induction generator (IG) directly connected to the grid. A major drawback is that the reactive power flow and thus the grid voltage level cannot be controlled. Another drawback associated with fixed speed systems is that the blade rotation causes voltage fluctuation of a frequency of 1 to 2 Hz on the grid. This fluctuation problem is not solved by using several turbines; on the contrary, Svensson (1996) states that if several identical wind turbines are installed in a wind park, the rotors can synchronize with each other and the power fluctuations are superimposed in phase.

The choice of synchronous versus asynchronous machine is dependant very much on the requirement of the wind turbine designer. In [8] Svensson states that the standard electrical system for fixed speed wind turbines tend to be squirrel cage asynchronous (induction) generator directly connected to the grid. This form of power generation is first-rate in reducing the reactive power demand and a capacitor bank is installed to compensate for the no-load current of the generator. In addition a thyristors equipped soft starter can be used to reduce the inrush currents present when the wind turbine is first connected to the grid.

For wide speed ranges i.e. variable speed operation, Larsson (1995) states that the synchronous generator with a rectifier and a thyristors inverter is the most common orientation. It should be noted that this combination is for wide speed ranges, it is possible to use induction motors with slip control to provide some limited variable speed operation, although for a smaller scope of wind speeds. The major advantages of synchronous generators compared with the induction generator is that it can be directly connected to the simple diode rectifier, however the synchronous generator is mechanically more complicated compared to the induction generator.

As previously stated synchronous generators have separate excitation and therefore do not require a power supply line like induction machines, however the output voltage of a SG is lower at lower speeds therefore the author presents a combination involving a boost converter between the rectifier and the DC link capacitors. The design makes use of a synchronous generator coupled to an uncontrolled diode rectifier, to reduce losses presented by more traditional use of induction generators with controlled rectifier bridges. At lower speed the boost chopper pumps the rectified generator voltage up to the DC link value necessary for the line side converter operation, therefore:

$$V_{DC} > V_{Line-Peak}$$

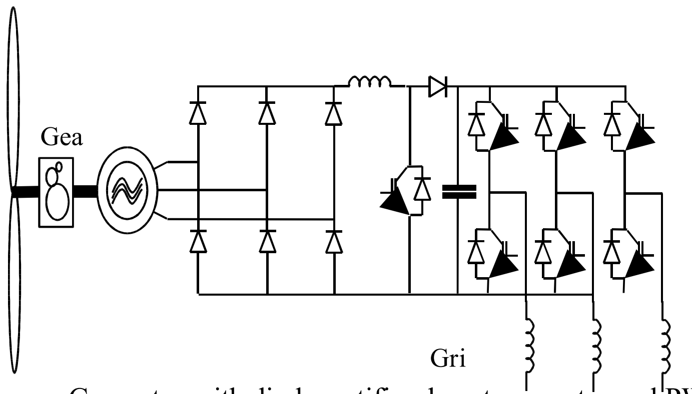

Figure 2 Synchronous Generator with diode rectifier, boost converter and PWM inverter

An additional advantage of using a synchronous generator based power converter is that it is also possible to use multipolar permanent magnet generators providing gearless operation hence increasing efficiency and reducing overall costs.

5. Basic Design Specification

The basis of this novel method of power conversion is constructed around a 16-bit Analog Devices ADSP-21990 fixed-point mixed-signal digital signal processor (DSP). The ADSP-21990 has a dedicated interface for Pulse Width Modulation (PWM) generation, and an on-

board 8-channel 12-bit analogue to digital converter (ADC), which can be controlled via software by the Analog Devices Visual DSP++ 3.0 development system.
The author achieves variable speed constant frequency power operation converter based on DSP control of fast switching IGBT's, it is also possible to measure the input and output and control a *buck*-boost converter using the same DSP board functionality.

With the aid of Matlab's powerful Simulink simulator, using a specialised power based add-on called SimPower it was possible to design the entire power converter with the aid of true-to-life waveforms for the main variables such as current and voltage.

The SimPower Model of the rectifier coupled to a programmable AC source can be seen from figure 3, although it is possible to represent the synchronous generator via SimPower, the final design will be tested via a computer controlled programmable AC source that can follow a practical real life speed pattern, hence the source used for simulation. In addition the voltage waveform generated by the diode rectifier input and output can be seen in figure 4, unfortunately DC outputs under variable AC rectifier inputs cannot possible be displayed in the limited scope of this paper.

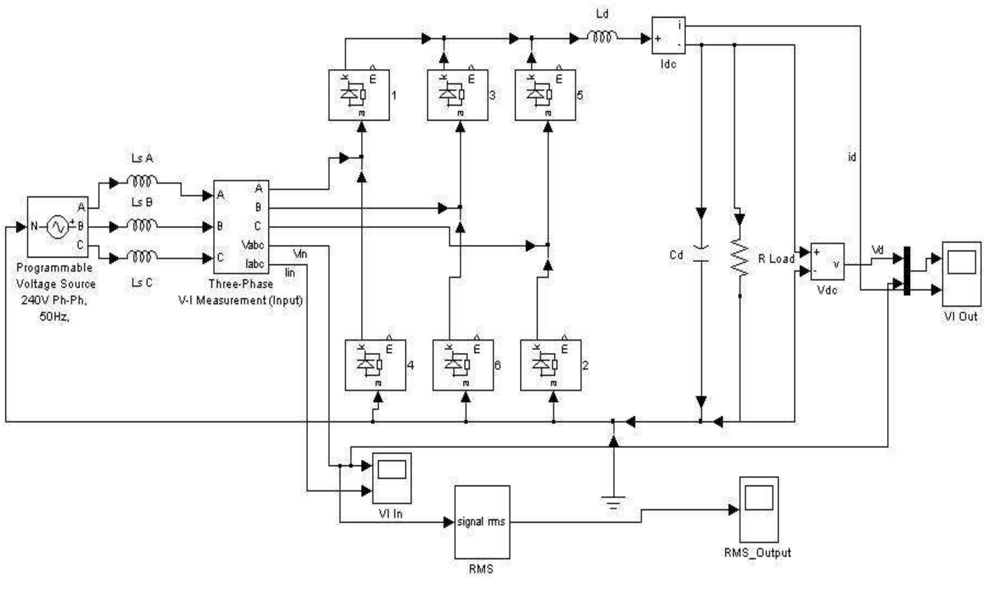

Figure 3 Diode Rectifier with Programmable Source

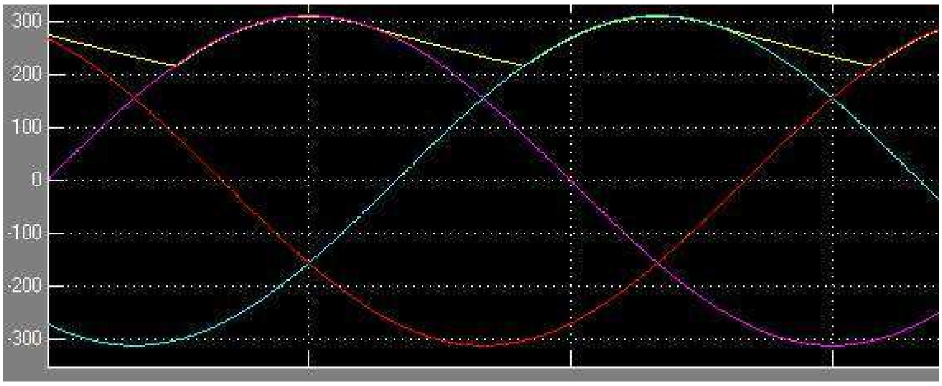

Figure 4 Input & Output Voltage Waveform

The SimPower model of the inverter as can be seen from figure 5 comprises of three separate two arm universal bridges each consisting of IGBT's semiconductors, an external PWM signal built up to provide the switching for the bridges, a fixed DC source has been used for an input for demonstration purposes instead of the DC link capacitor and boost converter, the output and input voltage waveforms of this system can be seen from figure 6. It is not expected that the final solution when built will operate identical to and produce the waveforms shown and in reality although the semiconductors are modelled with internal resistance and inductance etc. in practise substantial filtering will also be necessary.

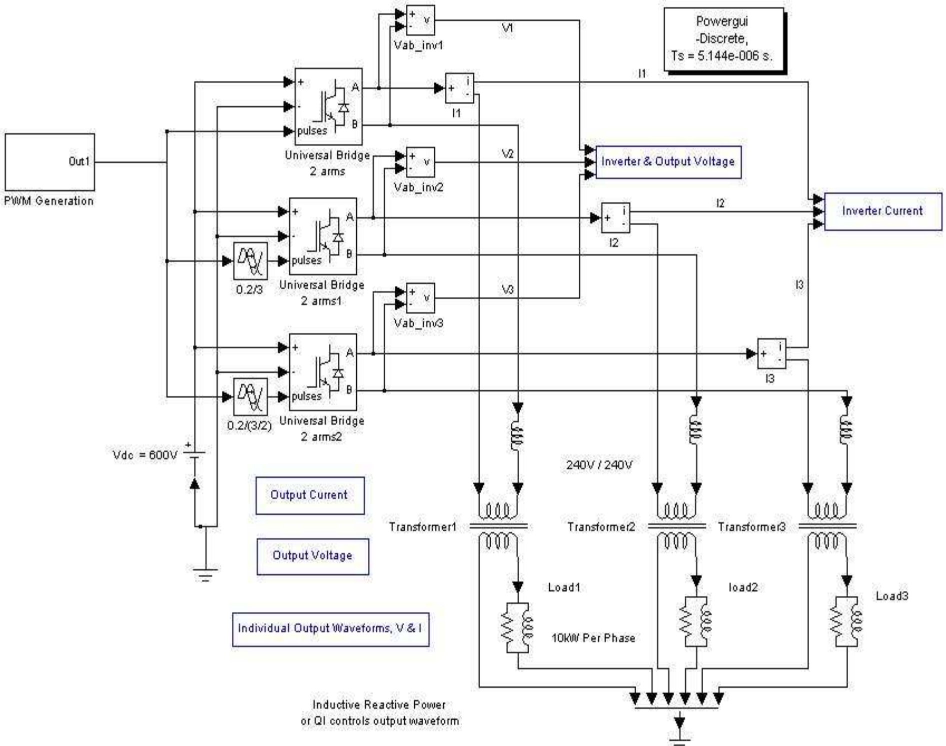

Figure 5 PWM IGBT Inverter Simulation

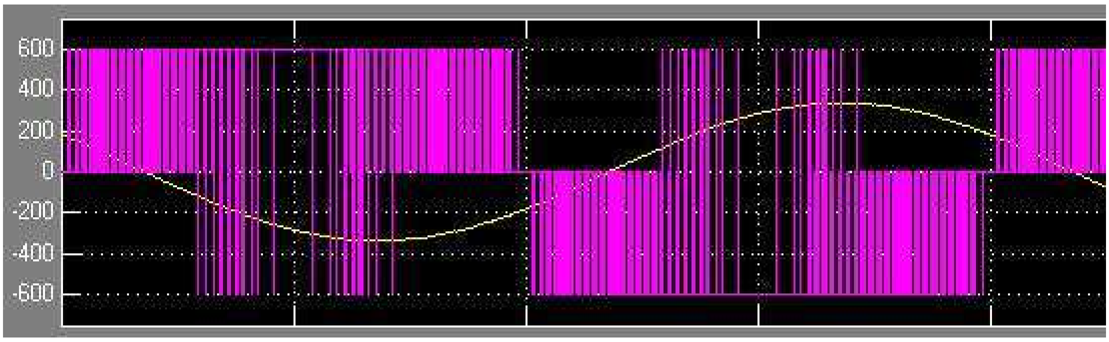

Figure 6 Inverter Input & Output Example Waveform

6. Distortion

Krien (1998) makes the point that distortion is an inevitable result of the non-linear switching behaviour of power electronics circuits, hence filtering of the output is necessary due to the switching requirement of the IGBT's inverter and boost converter.

Since power converters are based around the fundamental concept of a switching methodology, an infinite serious of fourier components called harmonics will always be present to some extent. Therefore the output of a conversion process will always contain unwanted component requiring filtering in an attempt to produce a near ideal source. Harmonics or harmonic distortion refers to this collection of unwanted components and the term ripple is often used for DC equivalent of this unwanted elements.

The term total harmonic distortion (THD) will be of most interest in evaluation the quality of the line value determined by the power, and is generally a standardised measurement of harmonics for AC applications. THD in this case is defined as the ratio of the RMS values of unwanted components in relation to the fundamental. In Europe the definition for THD is giving as:

$$\text{THD} = \sqrt{\frac{\sum_{n=2}^{\infty} c_n^{\,2}}{\sum_{n=1}^{\infty} c_n^{\,2}}} = \sqrt{\frac{f^2\text{rms} - f^2{}_1\text{rms}}{f^2\text{rms}}}\, f(t)$$

c_n = Fourier Coefficients

f = Signal $f(t)$

In order for the converter to be effective the THD absolute maximum governed by the European standard EN50160-2000 can be no more than 8%. This value is set has an absolute maximum by the European Standard, which the ESB National Grid works from, however the grid voltage level at the point on connection is also an independent factor for the desired maximum THD.

7. Conclusion & Further Work

This paper describes the advantages of variable speed wind power generation over the more traditional fixed speed, in that 10% increased energy capture and less fluctuation from the wind turbine passing on to the grid as with standard induction generator directly coupled to the grid.

The author has presented a configuration utilizing a synchronous generator coupled to an uncontrolled diode rectifier, a boost converter and a DSP controlled inverter. Matlab's Simulink SimPower add-on models of the design are presented with their associated waveform displaying input/output voltages for the basic diode rectifier and PWM controlled inverter.

Further research is necessary in the area of grid synchronisation using the DSP control, in addition further work is crucial in order to produce a fault ride through method based on the current power converter design.

References

[1] **Datta, Rajib and V.T. Ranganathan** (2002). "Variable-Speed Wind Power Generation Using a Double Fed Wound Rotor Induction Machine – A Comparison with Alternative Schemes", IEEE Transactions on Energy Conversion, Vol 17, No. 3.

[2] **Svensson**, J (1996). "Possibilities by Using a self-commutated voltage source inverter connected to a weak grid in wind parks," 1996 European Union Wind Energy Conference and Exhibition, Goteborg, Sweden, 20-24 May 1996, pp. 492-495.

[3] ***Eric Hau*** *(2000). Wind Turbines, Fundamentals, Technologies, Application, Economics,* Springer**.**

[4] ***P.W. Carlin, A.S. Laxson, E.B. Muljadi*** *(2001). "The history and state of the Art of Variable-Speed Wind Turbine Technology", National Renewable Energy Laboratory, NREL/TP-500-28607.*

[5] ***Schreiber, D.*** *"Applied Designs of Variable Speed Wind Turbines and New Approaches", Application Manager, Semikron International, Nuremberg, Germany.*

[6] **A. Larsson, O. Carlson, G. Siden (1995).** "Electrical Generating Systems in Wind Turbine Applications", Stockholm Power Tech, Stockholm, Sweden, June 18-22.

[7] **Philip T. Krien**, **(1998)** "Elements of Power Electronics", New York, Oxford University Press, 1998

[8] **Jan Svensson (1998**) "Grid Connected Voltage Source Converter – Control Principles and Wind Energy Application", Technical Report No. 331, Dept of Electric Power Engineering, Chalmers University of Technology, Sweden.

[9] **Commission of Energy Regulation (CER) (2004)**, Presentation to the Joint Oireachtas Committee on Agriculture and Food, 28th January 2004.

[10] **N. Mohan**, **T.M. Undeland, W.P. Robbins, (1995)** "Power electronics, converters, applications and design", J. Wiley and Sons.

[11] **E. Muljadi, K. Pierce, P. Migliore**, **(1998)** Control strategy for Variable-Speed, Stall-Regulated Wind Turbines, National Renewable Energy Laboratory, NREL/CP-500-24311.

[12] **McDade, J., Reddoch, T.W., and, Lawler, J.S (1985)** "Experimental Investigation of a Variable-Speed, Constant-Frequency Electric Generating System from a Utility Perspective." DOE/NASA/4105-1, NASA CR-174950.

[13] **NASA, (1982)** "MOD-5B Wind Turbine System Concept and Preliminary Design Report." NASA CR-168047.

[14] **R. Pena, J.C. Clare, G.M. Asher, (1996)** "A double fed induction generator using a back-to-back PWM converters supplying an isolated load from a variable speed wind turbine", IEEE Proceedings – Electr, Power Applications., Vol. 143, No. 5.
[15] **Carlson O., Hylander J., (1981)** "Some methods to connect a Wind power Induction Generator to eh utility Network," International colloquium on wind energy, Brighton, UK.
[16] **Dubois, Maxime R., (2000)** "Review Of Electromechanical Conversion in Wind Turbines", Report EPP00.R03.
[17] **Pierik J.T.G., Veltman A.T., de Haan S.W.H., Smith G.A., Infield D.G., Simmons A.D., (1994)** "A new class of converters for variable speed wind turbines", EWEC 1994
[18] **Reeves, E.A**., **(1990)** Handbook Of Electrical Installation Practise, Second Edition, Blackwell Scientific Publication.
[19] **Commission for Energy Regulation (CER),** The Moratorium on Issuing Connection Offers, December 2003