Panel Session: Energy Issues under Deregulated Electricity Energy Markets

(**Loi Lei Lai and Tom Hammons**)

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Topic: Critical Infrastructure of the Power System

INTRODUCTION

Until two decades or so, electricity was generally provided by vertically integrated utilities with a single utility providing electricity generation, transmission and distribution. Introduction of competition in electricity markets promoted interconnectivity of transmission systems across utilities, and "wheeling," which occurs when one utility provides transmission services across its lines for another utility. The benefit of increased transmission interconnectivity is that when one or two-generation facilities or transmission connections fail, other connections provide back up through alternative sources of generation and transmission capacity. Such breakdowns do occur on a regular basis, and usually are barely noticeable by consumers. Interconnections of generation and transmission systems across utilities mean that more back-up capacity is available for the local utility when it experiences an individual breakdown. The drawback to interconnectivity, however, is that when failures are more widespread, larger system failures are able to migrate across the entire region rather than be confined to the local utility.

It is believed that deregulation of electricity and lack of investment in the transmission network, particularly in transmission interconnections, are the main causes of major blackouts. While greater investment in the existing energy system could prevent blackouts, a better solution to the problems would be to introduce a cleaner, more efficient and more decentralized energy systems. Switching to energy efficient and renewable energy technologies, and the development of distributed generation systems could increase the reliability of the electrical delivery systems, making it less vulnerable to blackouts.

Power blackouts cause widespread havoc as well as losses to business. This highlights the dependency on electricity, as well as the general lack of strategic business contingency plans to deal with blackouts. Losses experienced as a result of a power failure include the loss of critical data, loss of productivity, lower efficiencies, damage to a company’s reputation, as well as inability to deliver products and services.

Information and communication technology will provide the tools to monitor, measure, and assess grid performance in real time, route power flows, reduce loads, and take measures needed to maintain grid stability. Including secure networks of sensors, communication links, information processors and dynamic algorithms would make the grids largely self-healing. Developments that are under way include semiconductors capable of handling high power flows; improved solid-state ac switches, controllers, inverters, and converters. Superconductivity cables

[#] Document prepared and edited by T J Hammons and better sensor and communication networks to detect and control disturbances on the grid are also being developed. Modern information and communication technologies could help power utilities to achieve highly secure energy systems.

Current research and development budgets for transmission and distribution (T&D) are relatively small and under pressure as a result of industry deregulation. As a consequence, it remains unclear how soon the information and communication technology developments supported under the Flexible AC Transmission System (FACTS) and other programs will become affordable to T&D operators and widely deployed.

Internal combustion engines, micro-turbines, fuel cells, and photoelectric arrays are in development and are becoming more cost competitive with technologies for centralized power plants. Locating distributed generation close to the load can mitigate or avoid grid congestion, reduce T&D line losses, and produce heat that may be recoverable for cogeneration. Distributed generation and distributed storage can be combined with onsite power conditioning to deliver good power quality and reliability for digital loads. Greater concern about energy and infrastructure security increases the value of distributed generation as a source of emergency or standby power.

In this new world of open competition, prices will be unbundled with lot of variability in the pricing options available to customers. These developments have created a requirement for substantial additional resources in the area of new product development, pricing and competitive intelligence. Many utilities must balance the need to exist in a competitive environment with the remaining obligation to serve some customers. They are exposed to greater price risks as long-term contracts that guarantee price and quantity are replaced by shorter-term transactions, including a thriving spot market in some fuels. Consumers, who are accustomed to stable electricity rates, now see prices that vary with supply and demand conditions. Due to the open competition, many utilities have recognized the need to develop substantially stronger marketing and risk management skills so as to effectively compete with the new power marketers and brokers in the marketplace.

Risk management is important in an open competitive environment because most firms which compete in an open competitive environment have shareholders and they would like to be sure that the earnings from their company is steady and reliable. Companies who do not manage the risks they face and consequently do not have a reliable earnings outlook may be viewed less favorably in the capital markets. Equally important is the fact that many firms entering the open market competitively are trading and selling electricity in new and different ways from anything they have previously experienced. With new operating methods and environments, it is important to know what new risks these firms now face, and how to deal with those risks.

Pricing models allow power providers to decide when to enter into mid term, long term or spot pricing deals. Without a model, these suppliers may become passive price takers and may be unable to compete with sophisticated trading/dealing market makers. Modeling of consumer behavior helps the generators and marketers of electricity to more accurately forecast demand in the various market segments and thus manage the risks of over/under production and buying/selling into unfavorable market conditions.

This Panel Session deals with the current state and problems in the deregulated power markets. The popular use of distributed generation has increased the importance of the protection and various techniques will be studied. Due to the increased use of digital devices that are very sensitivity to power quality issue, the application of wavelet for power quality analysis for practical data will be reported. Also case study on harmonics generation from railway operation will be demonstrated. In order to promote further the use of renewables, it is essential to keep the way of electricity generation cost down but power quality up. Some practical and novel methods will be discussed. No doubt, it is essential to know the equilibrium market point in order to maximize profit and minimize cost. A number of ways will be looked at and benefit in the use of intelligent technique will be demonstrated with a real power market. Risk management is one of the top issues in the energy sector Insurance issue in energy risk that will be looked at.

The Panelists and Titles of their Presentations are:

1. Norman Tse, City University of Hong Kong, Hong Kong. Practical Application of Wavelet to Power Quality Analysis (paper 06GM0790)
2. Davor Vujatovic, Engineering Manager, EDF Energy, UK and Qingping Zhang, City University, London, UK. Harmonics Generated from Railway Operation (paper 06GM0852)
3. Yuping Lu, Xin Yi and Xia Lin, Southeast University, China; and Ji'an Wu, Guodian Nanjing Automation Co. Ltd., Nanjing, China. An Intelligent Islanding Technique Considering Load Balance for Distribution Systems with DGs (paper 06GM0323)
4. Tze F. Chan, Hong Kong Polytechnic University, Hung Hom, Hong Kong and Loi Lei Lai, City University, UK. Three-Phase Induction Generator Operating on a Single-Phase System (paper 06GM0847)
5. Harald Braun, Xchnaging, London, UK. Insurance Issues for Energy Risk (paper 06GM0285)
6. Kit Po Wong and C Y Chung, Hong Kong Polytechnic University, Hong Kong. Evolutionary Computation Techniques for Power Market Equilibrium Determination (paper 06GM0804)
7. S N Singh, Indian Institute of Technology, Kanpur, India and I Erlich, University of Duisburg, Essen, Germany. Wind Power Trading Options in Competitive Electricity Market (paper 06GM0343)
8. Kwang Y Lee, Pennsylvania State University, USA. The Effect of DG using Fuel Cell under Deregulated Electricity Energy Markets (06GM1321)
9. Invited Discussers

Each Panelist will speak for approximately 20 minutes. Each presentation will be discussed immediately following the respective presentation. There will be a further opportunity for discussion of the presentations following the final presentation.

The Panel Session is organized by Tom Hammons (Chair of International Practices for Energy Development and Power Generation, University of Glasgow, UK) and Loi Lei Lai (Head, Energy Systems Group, City University, London, UK).

Loi Lei Lai and Tom Hammons will moderate the Panel Session.

PANEL SESSION PAPERS

1. Practical Application of Wavelet to Power Quality Analysis

Norman C. F. Tse, *CEng, MIEE, MHKIE,* City University of Hong Kong

Abstract--This paper presents a computational algorithm for identifying power frequency variations, sub-harmonics, integer harmonics and inter-harmonics, by using wavelet-based transform. The continuous wavelet transform (CWT) using the complex morlet wavelet is adopted to detect the harmonic frequencies presented in a power signal. The frequency detection algorithm is developed from the wavelet ridges and scalogram. A necessary condition is established to discriminate adjacent frequencies. The instantaneous frequency identification approach is applied for the determination of frequencies components presented in a power signal. An algorithm based on the Discrete Stationary Wavelet Transform (SWT) is developed to determine the amplitudes of the harmonic frequencies presented in the power signal from the coefficients computed by the CWT.

Index Terms—Amplitude estimation, complex morlet wavelet (CMW), continuous wavelet transform (CWT), discrete stationary wavelet transform (DSWT), instantaneous frequency estimation, industrial power, symlet wavelet, system harmonics, scalogram, wavelet ridges.

I. INTRODUCTION

Power quality has become a major concern for utility, facility and consulting engineers in recent years. International as well as local standards have been put in place to address the power quality issues [1].

To the facility managers and end users, frequent complaints by tenants/customers on occasional power failures of computer and communication equipment, and the energy inefficiency of the LV electrical distribution system are on the management's agenda. Harmonic voltage and current produced by nonlinear loads would cause extra copper loss in the distribution network, which on one hand will increase the energy cost and on the other hand would increase the electricity tariff charge. The benefits of using power electronic devices in the LV distribution system in buildings, such as switch mode power supplies, variable speed drive units, etc. to save energy are sometimes offset by the increased energy loss in the distribution cables by current harmonics and the cost of remedial measures required. Voltage harmonics caused by harmonic voltage drops in the distribution cables are affecting the normal operation of voltage sensitive equipment as well.

In order to improve electric power quality and energy efficiency, the sources and causes of such disturbance must be known on demand sides before appropriate corrective or mitigating actions can be taken [2] ,[3]. In the past harmonic distortion is predominantly due to integer harmonics. Nowadays the levels of sub-harmonics and inter-harmonics are rising significantly which make the harmonics problem even worse.

Since harmonics are steady state phenomenon, corrective measures available are basically by filtering and/or isolation. Yet, before deciding what corrective measures are to be adopted, the nature of the harmonics problems needs to be identified. A traditional approach is to use Fast Fourier Transform (FFT) to analyse harmonics contents contained in the power signal. The FFT has many attractive features. That theory of FFT has been fully developed and well known; scientists and engineers are familiar with the computation procedures and find it convenient to use as many standard computation tools are readily available. It is however easily forgotten that Fourier Transform is basically a steady state analysis approach. Transient signal variations are regarded by FFT as a global phenomenon. One example is that FFT transforms an electrical impulse into frequencies ranging from zero to infinity in the frequency spectrum.

As power quality issues such as sub-harmonics, integer harmonics, inter-harmonics, transients, voltage sag and swell, waveform distortion, power frequency variations, etc. are commonly experienced by electricity users, this paper attempts to develop an algorithm based on wavelet transform to identify power frequency variations, sub-harmonics, integer harmonics and inter-harmonics.

II. WAVELET TRANSFORM AND ANALYSING WAVELET

Wavelet Transform (WT) has been drawing many attentions from scientists and engineers over the years due to its ability to extract signal time and frequency information simultaneously. WT can be continuous or discrete. Continuous Wavelet Transform (CWT) is adopted for harmonic analysis because of its ability to preserve phase information [4], [5].

The wavelet transform of a continuous signal, f(t), is defined as [6]

$$Wf(u,s)=\langle f,\psi_{u,s}\rangle=\int_{-\infty}^{+\infty} f(t)\frac{1}{\sqrt{s}}\Psi^{*}\left(\frac{t-u}{s}\right)dt, \qquad (1)$$

where $\psi^*(t)$ is the complex conjugate of the wavelet function $\psi(t)$;
s is the dilation parameter of the wavelet; and
u is the location parameter of the wavelet.

The wavelet function must satisfy certain mathematical criteria [6]. These are

- a wavelet function must have finite energy; and
- a wavelet function must have a zero mean, i.e., has no zero frequency component.

The simplified Complex Morlet Wavelet (CMW) [7], [8] is adopted in the algorithm for harmonic analysis, which is defined as

$$\Psi(t)=\frac{1}{\sqrt{\pi f_b}}e^{\frac{-t^2}{f_b}}e^{j2\pi f_c t}, \qquad (2)$$

where f_b is the bandwidth parameter and;
f_c is the centre frequency of the wavelet.

The CMW is essentially a modulated Gaussian function. It is particularly useful for harmonic analysis due to its smoothness and harmonic-like waveform. Furthermore CMW is an analytic wavelet therefore is able to separate amplitude and phase information.

Strictly speaking, the mean of the simplified CMW in (2) is not equal to zero as shown in (3) below.

$$\int_{-\infty}^{+\infty}\Psi(t)dt=\frac{1}{\sqrt{\pi f_b}}\int_{-\infty}^{+\infty}e^{j2\pi f_c t}e^{\frac{-t^2}{f_b}}dt=e^{\frac{-f_b}{4}(2\pi f_c)^2} \qquad (3)$$

However the mean of the CMW can be made arbitrarily small by picking the f_b and f_c parameters large enough [8]. For example, the mean of the CMW in (3) with f_b=2 and f_c=1 is 2.6753×10^{-9} which is practically equal to zero. The frequency support of the CMW in (2) is not a compact support but the entire frequency axis.

The time support of the CMW in (2) is from -8 to 8 [9]. The value of f_b should not be larger than 9, otherwise the CMW cannot decline fast enough to zero within the time support.

III. HARMONICS FREQUENCY DETECTION ALGORITHM

Given a signal f(t) represented as

$$f(t) = a(t)\cos\phi(t). \tag{4}$$

The wavelet function in (2) can be represented as [10]

$$\Psi(t) = g(t)e^{j\eta t}. \tag{5}$$

The dilated and translated wavelet families [10] are represented as

$$\Psi_{u,s}(t) = \frac{1}{\sqrt{s}}\Psi\left(\frac{t-u}{s}\right) = e^{-j\xi u} g_{s,u,\xi}(t), \tag{6}$$

where $g_{s,u,\xi}(t) = \sqrt{s}\, g\left(\frac{t-u}{s}\right)e^{j\xi t}$; and $\xi = \frac{\eta}{s}$.

The wavelet transform of the signal function f(t) in (4) is given as [10]

$$Wf(u,s) = \frac{\sqrt{s}}{2} a(u) e^{j\phi(u)} \left(\hat{g}(s[\xi - \phi'(u)]) + \varepsilon(u,\xi)\right). \tag{7}$$

where $\hat{g}(\omega)$ represents the Fourier Transform of the function g(t).

The corrective term $\varepsilon(u,\xi)$ in (7) is negligible if $a(t)$ and $\phi'(t)$ in (4) have small variations over the support of $\psi_{u,s}$ in (6) and if $\phi'(u) \geq \frac{\Delta\omega}{s}$ [10]. If a power signal contains only a single frequency waveform, the corrective term can be neglected safely. However for a power signal containing harmonic frequencies from low frequency to high frequency, the corrective term will contribute to the wavelet coefficients, making the frequency detection not as straightforward.

The instantaneous frequency is measured from wavelet ridges defined over the wavelet transform. The normalised scalogram defined by [10], [11]

$$\frac{\xi}{\eta} P_W f(u,\xi) = \frac{|Wf(u,s)|^2}{s} \tag{8}$$

is calculated with

$$\frac{\xi}{\eta} P_W f(u,\xi) = \frac{1}{4} a^2(u) \left|\hat{g}\left(\eta\left[1 - \frac{\phi'(u)}{\xi}\right]\right) + \varepsilon(u,\xi)\right|^2. \tag{9}$$

Since $|\hat{g}(\omega)|$ in (9) is maximum at $\omega = 0$, if one neglect $\varepsilon(u,\xi)$, (9) shows that the scalogram is maximum at

$$\frac{\eta}{s(u)} = \xi(u) = \phi'(u)\,. \qquad (10)$$

The corresponding points $(u, \xi(u))$ calculated by (10) are called wavelet ridges [12]. The analytic amplitude is given by

$$a(u) = \frac{2\sqrt{\frac{\xi}{\eta} P_W f(u,\xi)}}{|\hat{g}(0)|} = \frac{2\sqrt{\frac{|Wf(u,s)|^2}{s}}}{1} = \frac{2|Wf(u,s)|}{\sqrt{s}}\,. \qquad (11)$$

IV. DISCRIMINATION OF ADJACENT FREQUENCIES

The Fourier Transform of a dilated CMW in (6) is represented as [10]

$$\Psi(sf) = \sqrt{s} e^{-\pi^2 f_b (sf - f_c)^2}\,. \qquad (12)$$

The function $\Psi(sf)$ can be regarded as a bandpass filter centered at the frequency f_c. The CWT of a signal is the convolution of the signal with a group of bandpass filters which are produced by the dilation of the CMW.

Suppose that (12) is represented as

$$\Psi(sf) = x, \qquad (13)$$

where x represents an arbitrary magnitude to be defined later.

Combining (12) and (13) gives

$$f = \frac{f_c}{s} \pm \frac{1}{s\pi\sqrt{f_b}} \sqrt{\left| ln\left(\frac{x}{\sqrt{s}}\right) \right|}\,, \qquad (14)$$

where $\frac{f_c}{s}$ is the centre frequency of the dilated bandpass filter; and the bandwith is $\frac{2}{s\pi\sqrt{f_b}} \sqrt{\left| ln\left(\frac{x}{\sqrt{s}}\right) \right|}$.

Figure 1 below shows the plot of the frequency support of two dilated CMW at scales s_1 and s_2 respectively.

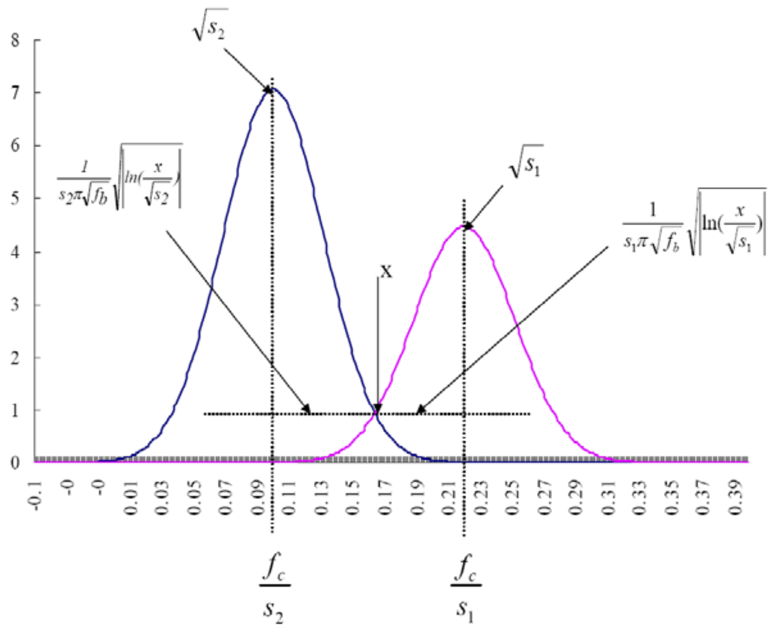

Fig. 1. Frequency plot of (14) for two CMWs at scales s_1 and s_2 respectively

If the two CMWs are used to detect two adjacent harmonic frequencies in a signal, with their frequencies represented as [9]

$$f_1 = \frac{f_s f_c}{S_1} \ \& \ f_2 = \frac{f_s f_c}{S_2}, \tag{15}$$

where f_s represents the sampling frequency, then

$$\frac{f_c}{S_2} - \frac{f_c}{S_1} \geq \frac{1}{S_2 \pi \sqrt{f_b}} \left(\sqrt{\left| ln(\frac{x}{\sqrt{S_1}}) \right|} + \frac{1}{S_1 \pi} \sqrt{\left| ln(\frac{x}{\sqrt{S_2}}) \right|} \right). \tag{16}$$

Assume that $s_2 > s_1$, (16) is simplified to

$$f_c \sqrt{f_b} \geq \frac{1}{\pi} \sqrt{\left| ln(\frac{x}{S_2}) \right|} x \frac{f_2 + f_1}{f_2 - f_1}. \tag{17}$$

For $s_2 \leq 300$ and $x \leq 0.01$, (17) becomes

$$\frac{1}{\pi} \sqrt{\left| ln(\frac{x}{S_2}) \right|} \leq 0.87. \tag{18}$$

Substituting (18) into (16) gives

$$f_c \sqrt{f_b} \geq 0.87 x \frac{f_2 + f_1}{f_2 - f_1}. \tag{19}$$

It is estimated that the magnitude of x should not be larger than 0.01. Equation (19) is used to determine the values of f_b and f_c in (2) for the continuous wavelet transform with complex morlet wavelet which is a necessary condition to discriminate adjacent harmonic frequencies in the power signal.

V. HARMONICS AMPLITUDE DETECTION ALGORITYM

Theoretically, once the harmonic frequencies presented in the power signal are identified by the algorithms developed in Section III and IV, the corresponding harmonics amplitudes would be determined readily by (11).

The values of $2\sqrt{\frac{|Wf(u,s)|^2}{s}}$ in (11) are produced in the process of generating the scalogram.

Due to the imperfection of the filters produced by the dilated CMWs and aliasing, the amplitudes detected are corrupted by noise. Simulation results show that the amplitudes for harmonics frequencies ranging from 50Hz to 1000 Hz have errors of the order of ±5%. Fig. 2 below shows a plot of the absolute coefficients generated by CWT for the harmonic frequency at 991.5Hz.

In Fig. 2, the vertical axis represents the magnitude of the absolute coefficients and the horizontal axis represents the data points. The small fluctuations as shown in the absolute coefficients plot are due to filter imperfection and aliasing.

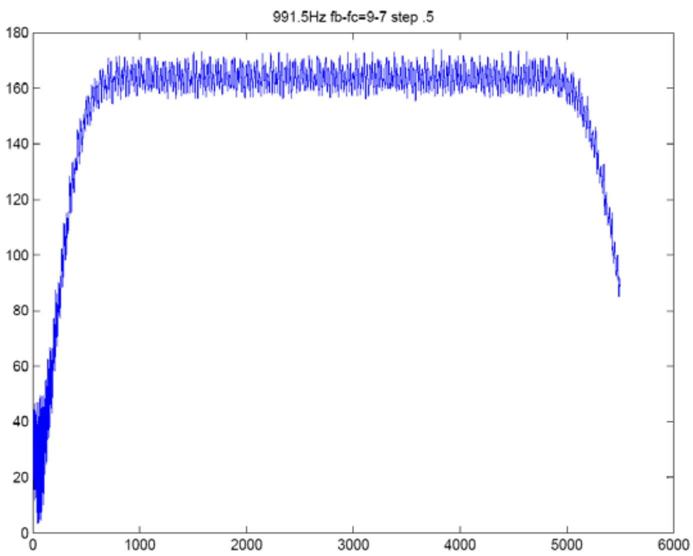

Fig.2. Absolute coefficients plot generated by CWT (using Complex Morlet Wavelet, f_b=9, f_c=7) for harmonic frequency at 991.5 Hz

Discrete Stationary Wavelet Transform (DSWT) [13] is adopted to remove the fluctuations appeared as noise superimposed on the absolute coefficients plot in Fig. 2.

The Symlet2 developed by Daubechies is used for the DSWT of the absolute coefficients. It is found that a decomposition level of 5 is sufficient for harmonic frequencies up to 1000Hz.

Fig. 3 shows the DSWT output of the absolute coefficients shown in Fig. 2 which clearly shows that the superimposing fluctuations are removed resulting in an accurate detection of the harmonics amplitudes.

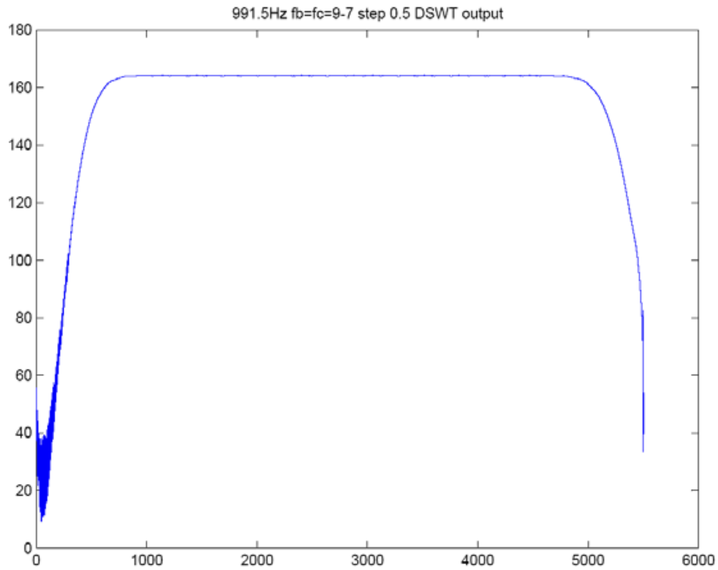

Fig.3. Coefficients generated by discrete stationary wavelet transform (using Symlet2 wavelet, level 5 decomposition) from the absolute coefficients generated by CWT (using Complex Morlet Wavelet, f_b=9, f_c=7) for harmonic frequency at 991.5 Hz

VI. SIMULATION SETTINGS

A simulated signal is used to test the validity and accuracy of the harmonics detection algorithm. The simulated signal contains a combination of the harmonic frequencies as shown in Table I.

TABLE I: HARMONIC FREQUENCIES CONTAINED IN THE SIMULATED SIGNAL

Harmonic Frequency (Hz)	Amplitude	Phase Angle (Degree)
50.1	311	0
102	280	5
149.5	248.8	7
249	217.7	10
371	186.6	15
412	155.5	20
550	155.5	25
620	124.4	-30
770	93.3	42
891	62.2	-61
991.5	31.1	82

The simulated signal is sampled at 20kHz. Since the highest harmonic frequency in the simulated signal is 991.5Hz, the number of data per cycle for 991.5Hz is approximately 20.

This is the minimum data size required for accurate amplitude representation. A higher sampling frequency would give a better representation of the harmonics amplitudes, but more data points are produced subsequently resulting in slow computation. For faster CWT computation, the simulated signal will be down-sampled for the detection of lower harmonic frequencies. The down-sampling settings are as shown in Table II. In any case a minimum of 20 data per cycle is maintained. The data size for CWT computation is set at 5000.

TABLE II: SAMPLIING FREQUENCIES AND SAMPLE DATA SIZE FOR HARMONIC FREQUENCIES OF THE SIMULATED SIGNAL

Frequency (Hz)	Sampling Frequency (Hz)	Data Size
50.1	1000	5000
102	2500	5000
149.5	5000	5000
249	5000	5000
371	10000	5000
412	10000	5000
550	16000	5000
620	16000	5000
770	20000	5000
891	20000	5000
991.5	20000	5000

The necessary condition discussed in Section IV for discrimination of adjacent frequencies requires that the complex morlet wavelet should be set at $f_b = 6$ and $f_c = 7$.

VII. SIMULATION RESULTS

The simulation results for harmonics frequency detection is shown in Table III. It can be seen that the frequency detection by the proposed algorithm is very promising, especially at high harmonic frequencies. While at low harmonic frequency detection, the scalogram plot is corrupted by high frequency components which exhibited as noise. It is proved that the necessary condition established in Section IV is successful in distinguishing adjacent frequencies.

TABLE III: HARMONIC FREQUENCIES DETECTION RESULTS

Harmonic Frequency (Hz)	Detected Frequency (Hz)	% Error
50.1	50.14	0.08%
102	102.04	0.04%
149.5	149.51	0.01%
249	249.10	0.04%
371	370.96	0.01%
412	412.00	0%
550	549.83	0.03%
620	620.16	0.03%
770	770.07	0.01%
891	891.15	0.02%
991.5	991.50	0%

The accuracy in the detection of harmonics amplitudes depends on the accuracy in harmonics frequencies detection. As seen from the results shown in Table IV, the harmonics amplitude detection results are very satisfactory. Except for 50.1 Hz, the amplitude detection errors for all the other harmonic frequencies are smaller than 0.5%.

TABLE IV: HARMONIC FREQUENCIES AMPLITUDE DETECTION RESULTS

Harmonic Frequency (Hz)	Harmonics Amplitude	Detected Amplitude	% Error
50.1	311	309.07	0.62%
102	280	279.17	0.29%
149.5	248.8	248.57	0.09%
249	217.7	216.72	0.45%
371	186.6	186.32	0.15%
412	155.5	155.35	0.10%
550	155.5	155.47	0.02%
620	124.4	124.32	0.06%
770	93.3	93.17	0.14%
891	62.2	62.21	0.02%
991.5	31.1	31.23	0.42%

The larger amplitude detection errors are found to be happened at 50.1 Hz and 249 Hz respectively. Table V shows a comparison of errors in harmonic frequencies detection and the corresponding amplitudes detection. It is observed that the frequency detection errors for these two frequencies are also comparatively higher. Therefore it is concluded that the accuracy in amplitude detection is affected by the accuracy in frequency detection.

TABLE V: COMPARASION OF DETECTION ERRORS IN HARMONIC FREQUENCIES AND HARMONIC AMPLITUDES

Harmonic Frequency (Hz)	% Harmonic Frequencies Detection Error	% Amplitudes Detection Error
50.1	0.08%	0.62%
102	0.04%	0.29%
149.5	0.01%	0.09%
249	0.04%	0.45%
371	0.01%	0.15%
412	0%	0.10%
550	0.03%	0.02%
620	0.03%	0.06%
770	0.01%	0.14%
891	0.02%	0.02%
991.5	0%	0.42%

Further refinements on both frequency and amplitude detection would be achieved by a careful choice of f_b and f_c of the complex morlet wavelet.

VIII. CONCLUSION

The harmonic frequency detection algorithm and the amplitude detection algorithm developed are able to identify the frequency contents of a power signal to a very high accuracy. The simulation results showed that for harmonics frequency detection, the errors are not bigger than 0.08%. For amplitude detection, the errors are not bigger than 0.62%. The proposed algorithm has successfully implemented the ridges and scalogram to extract frequency information from the power signal. The necessary condition established is able to distinguish adjacent frequencies successfully. The discrete stationary wavelet transform with Symlet2 wavelet is proved to be very useful in estimating the amplitudes of the detected harmonic frequencies.

It is observed that the accuracy in estimating the harmonic frequencies amplitudes relies on the accuracy in harmonic frequencies estimation. Further works to refine the algorithm in frequency information extraction would be needed.

IX. REFERENCES

[1] *IEEE recommended practice for monitoring electric power quality*, IEEE Standards Board, June 1995.

[2] L L Lai, W L Chan, C T Tse and A T P So, Real-time frequency and harmonic evaluation using artificial neural networks, *IEEE Transactions on Power Delivery*, Vol. 14, No. 1, January 1999, pp. 52-59.

[3] W L Chan, A T P So and L L Lai, Harmonics load signature recognition by wavelets transforms, *Proceedings of the International Conference on Electric Utility Deregulation, Restructuring and Power Technologies DRPT2000*, IEEE Catalog Number 00EX382, April 2000, pp. 666-671.

[4] Paul S Addison, *The Illustrated Wavelet Transform Handbook*, Institute of Physics Publishing Ltd., Bristol and Philadelphia, 2002.

[5] V. L. Pham and K. P. Wong, Wavelet-transform-based algorithm for harmonic analysis of power system waveforms, *IEE Proc. – Gener. Transm. Distrib.*, Vol. 146, No. 3, May 1999.

[6] Gilbert Strang and Truong Nguyen, *Wavelets and Filter Banks*, Wellesley-Cambridge Press, Wellesley, MA, January, 1996.

[7] Shyh-Jier Huang, Cheng-Tao Hsieh and Ching-Lien Huang, Application of morlet wavelets to supervise power system disturbances, *IEEE Trans. On Power Delivery*, Vol. 14, No. 1, Jan., 1999.

[8] Teolis, A., *Computational signal processing with wavelets*, Birkhauser, 1998.

[9] Misiti, M., Misiti, Y., Oppenheim, G., : '*Wavelet Toolbox for use with Matlab*,' (The Mathworks Inc., March 1996), pp. 6-43.

[10] Stephane Mallet, *A Wavelet Tour of Signal Processing*, Academic Press, 1998.

[11] Rene A. Carmona, Wen L. Hwang and Bruno Torresani, Multiridge detection and time-frequency reconstruction, *IEEE Trans. on signal processing*, Vol. 47, No. 2, Feb., 1999.

[12] Rene A. Carmona, Wen L. Hwang and Bruno Torresani, Characterization of signals by the ridges of their wavelet transforms, *IEEE Trans. on signal processing*, Vol. 45, No. 10 Oct., 1997.

[13] Anestis Antoniadis and Georges Oppenheim (Editors), *Wavelets and Statistics – Lecture Notes in Statistics*, Springer-Velag New York, Inc., 1995.

X. BIOGRAPHY

Norman, C. F. Tse was born in Hong Kong SAR, China on February 7, 1961. He graduated from the Hong Kong Polytechnic University (then Hong Kong Polytechnic) in 1985 holding an Associateship in Electrical Engineering. He obtained MSc degree from the University of Warwick in 1994. He is a Chartered Engineer, a Corporate member of the IEE and the Hong Kong Institution of Engineers. He is now working with the City University of Hong Kong as a Senior Lecturer majoring in building LV electrical power distribution systems. His research interest is in power quality measurement, web-based power quality monitoring, and harmonics mitigation for low voltage electrical power distribution system in buildings.

2. Harmonics Generated from Railway Operation

Davor Vujatovic, *Member, IEEE*, and Qingping Zhang

Abstract**—** This paper reports harmonics generated while typical high-speed railways are under operation. The solution in reducing harmonics by the use of installation of power electronic compensators, especially static VAR compensator (SVC), in the railway system during the procedure of railway infrastructure upgrading may not be a very easy solution. Discussions will be given and better method and approach will be proposed. In order to find effective solutions to balance the main drawback of SVC compensators, such as the harmonic currents injected into the railway catenary due to their highly non-linear characteristics. Analysis of a large volume of data, which had been collected in a practical high-speed railway project has been carried out to study the harmonics content. Negative consequences of SVC to the both railway and grid system could be minimized by the discussed approach.

Index Terms**—**Harmonics, railway system, reactive power

I. INTRODUCTION

NOWADAYS, many critical infrastructures, including those industries, institutions, and distribution networks and systems that provide a continual flow of the goods and services essential to a country's defenses and economic security and to the health, welfare, and safety of its citizens. These infrastructures are experiencing an important evolution, increasing their performances by the introduction of a series of new technologies. As a result, the interdependence between different kinds of infrastructures is increased and in many cases their vulnerability may also be increased.

Rail transportation can be an example of such evolution. Rail transportation is considered to be a critical infrastructure in many countries, since that much of their economy relies on it to supply the necessary components for its production. Railway infrastructure will certainly have to be upgraded to support the corresponding traffic increase. This upgrading may be realized by the introduction of new technologies on the existing infrastructure, avoiding therefore the construction of new infrastructure. In particular power electronics compensators are proposed as an interesting alternative to the construction of new lines and substations.

As we know, the electric power supplies all over the world are becoming under the pollution with harmonic currents caused by modern electronic equipment, such as many kinds of electronics compensators. These harmonics can cause interference with communication systems, generate extra losses in the wiring and transformers or even overload electrical systems. This problem is especially emerging in the networks of railways. Representing a non-linear load, trains generate harmonic currents, which therefore lead to a high level of reactive power. The national grids are in face of more charges on the bills for electricity due to this pollution.In the UK, the railway system plays a very important role. In some railway systems, to provide the required power to the trains,

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there are three 400kV connections to the National Grid Company (NGC), one of them is a dual connection [1,2]. Due to the nature of the traction load, i.e. single phase load with high content of harmonic currents, NGC have placed strict restrictions on the quality of supply at the intersections. In addition, there are restrictions on the voltage profile along the catenary system. Due to these requirements, the need for load balancing and voltage regulating equipment are essential.

II. STATIC VAR COMPENSATOR

In most of the industrial applications, thyristor-based and shunt connected systems have been proposed for railway VAR compensation. These devices are known as that of SVCs. They are composed of a capacitor, which is the VAR generator, and a Thyristor Controlled Reactor (TCR), which behaves as a variable VAR absorbing load (depending on the firing angle of the thyristor valve). The branch current is controlled by phase angle controller by firing pulse to the thyristors, which is the voltage across the reactor is the full system voltage at 90° firing angle and zero at 180°. The current through the reactor is the integral of the voltage, as thus it is fully controllable with the thyristor valve between the natural value given by the reactor impedance and zero. Thus, the SVC can inject or absorb a variable amount of reactive power to the railway network, adapting the compensation to the load conditions at each instant

In the SVC case, the amount of harmonics injected into the line depends on the firing angle. The harmonics flowing on the railway system can provoke some problems not only on the railway system but also in other systems related to it, for example, the electrical public utility.

Harmonic filter performance studies have to in addition to include transformer and grid impedances, since these make significant difference in the model. Unfortunately, when using SVCs as filter banks, SVCs themselves generate significant levels of harmonic currents which additionally burden the filters and increase harmonic voltages on the network.

In order to account for contribution from utility network background distortion to harmonic filter ratings, the utility grid background harmonic voltage has to be obtained from the grid. These harmonic voltage sources are considered as ideal voltage source, feeding the harmonic filter banks through the grid transformer.

For calculation of harmonic distortion it is essential to know the impedance characteristics of the system. For a power system, which can have a number of different configurations, it is impossible to specify the impedance as a complex number for each harmonic frequency. Such impedance would be valid only for one specific configuration during one specific load condition. Therefore, standard practice is to specify the impedance as area in the R/X – plane. This area, which covers every system configuration and load condition circumscribed by its perimeter, is often given as a circle.

As a practical Example, two SVCs are connected to the trackside 25kV busbar, one to the catenary and the other to the feeder. The SVCs are rated 3.5MVAr inductive to 41.5MVAr capacitive at 27kV. The SVCs consists of three filter banks and one TCR. The filter banks are tuned to the 3rd, 5th and 7th harmonic sized 26.5MVAr, 7.5MVAr, and 7.5MVAr respectively, i.e., 41.5MVAr in total. The TCR is rated 45MVAr giving 3.5MVAr on the inductive side. By the aid of phase angle control of the TCRs, a continuous variable output ranging from 3.5MVAr inductive to 41.5MVAr capacitive is obtained.

III. DATA ANALYSIS

Measurements on performance were carried out on a typical railway operation. Fig. 1 shows the variation of traction transformer catenary current that lasted for about 22 minutes and 30 seconds.

Fig. 1. Waveform for transformer catenary current

By using FFT and digital signal processing techniques, harmonics are determined and the second to fifth harmonics are included in Figures 2 to 5 respectively below:

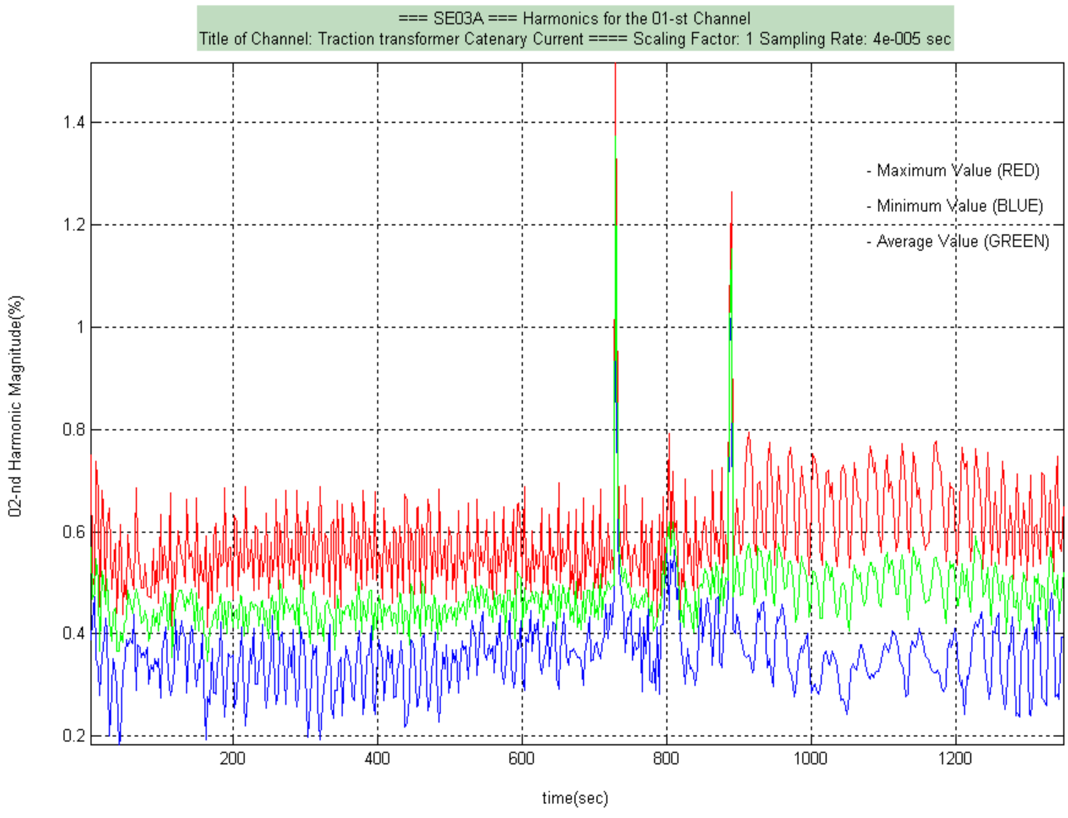

Fig. 2. Second harmonic

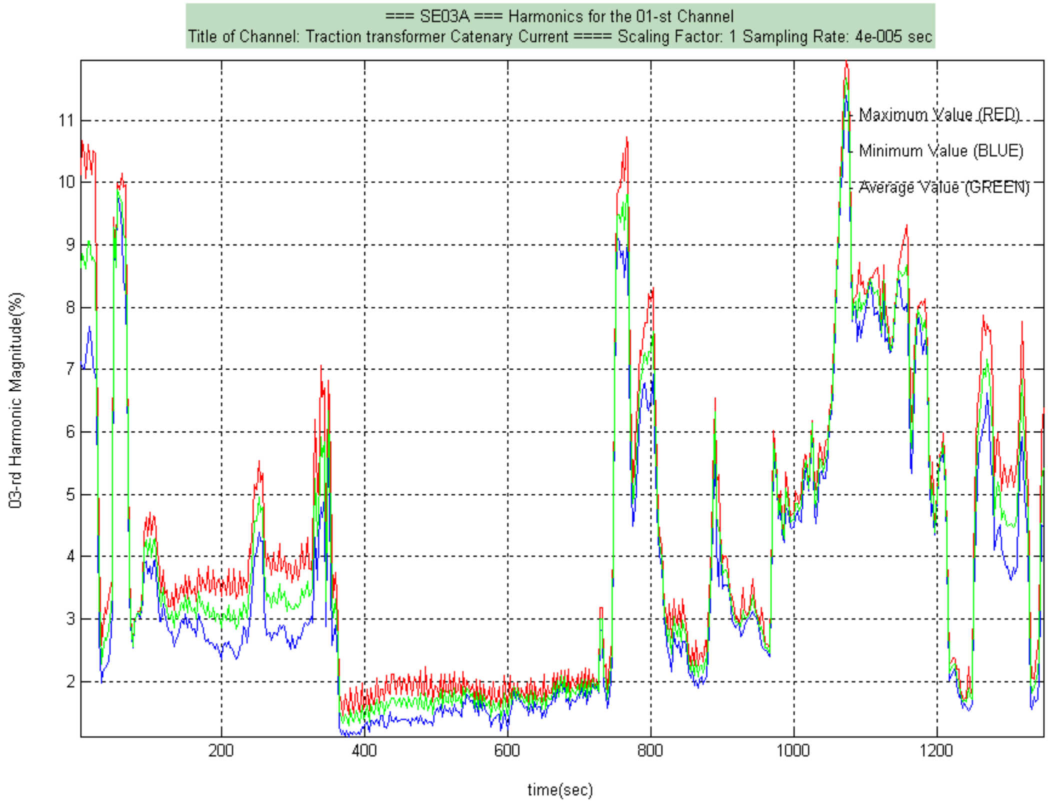

Fig. 3. Third harmonic

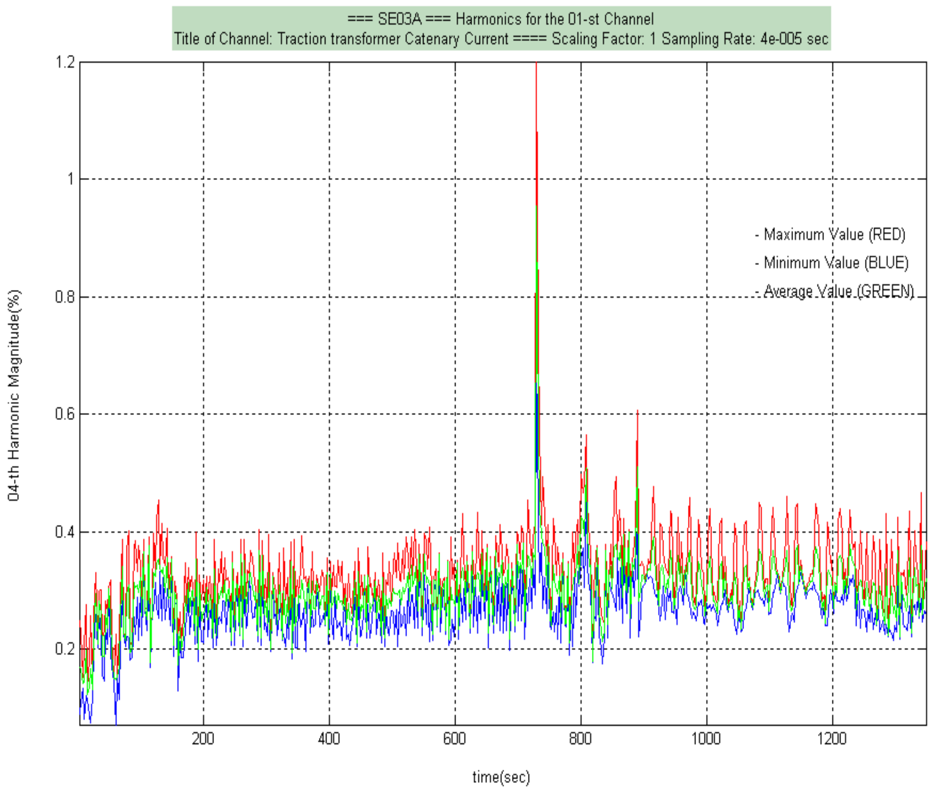

Fig. 4. Fourth harmonic

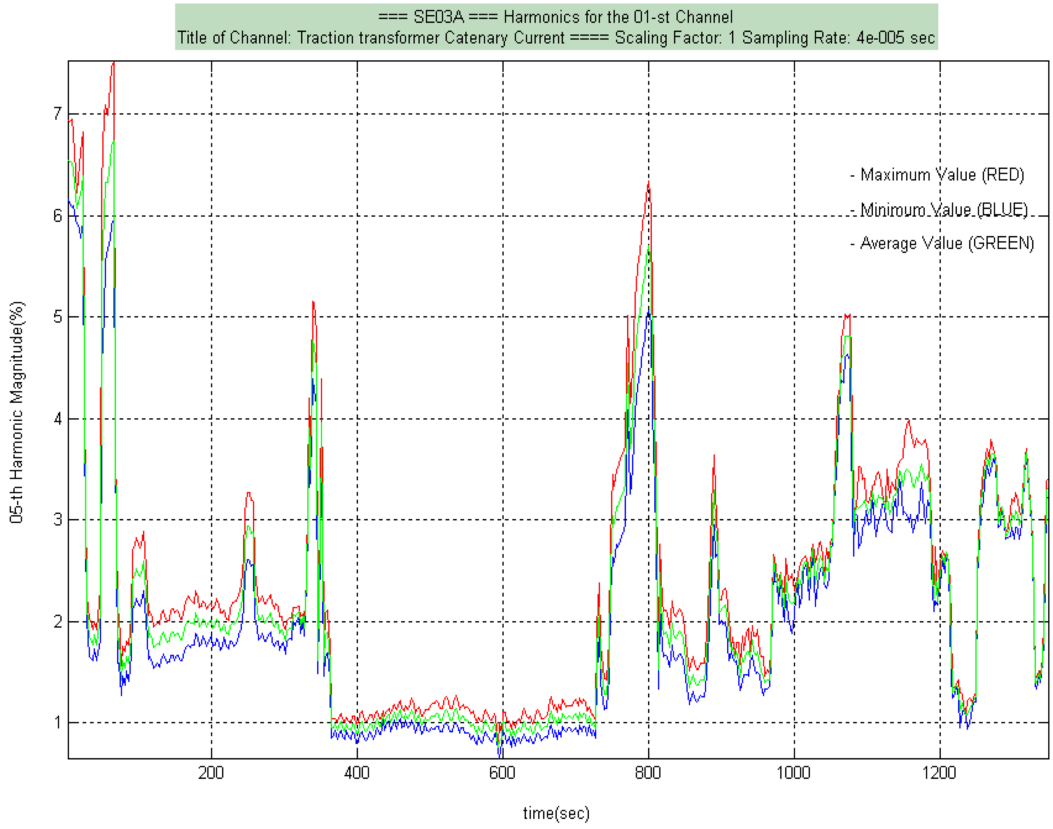

Fig. 5. Fifth harmonic

IV. CONCLUSION

This paper has presented the level of harmonics that can be produced from a railway system and under the deregulated energy industry, it is essential to understand ways to limit this problem and if harmonics are generated, it is required to know who needs to pay for it.

V. REFERENCES

[1] L L Lai and Q P Zhang, Signal analysis of data collected for railway performance evaluation – theory, program development and verification, report to EDF (Electricite de France) Energy, March 2004.

[2] L L Lai, Q P Zhang and C S Lai, Harmonics Analysis for Channel Tunnel Rail Link operation, report to EDF Energy, June 2004.

VI. BIOGRAPHIES

Davor Vujatovic obtained his B.Sc. in Electrical Engineering from Zagreb University, Croatia. Presently, he is Engineering Manager of the EDF Energy (Private Networks). He was Secretary of the DRPT 2000 International Conference on Electric Utility Deregulation and Reconstructing and Power Technologies that was co-sponsored by both the IEEE and IEE. He is a Member of the IEEE, IEE and CIGRE. His research interest is in studying impact of railway operation on power quality.

Qingping Zhang gained his BSc and MSc both in Computer Science from Nankai University, Tianjin and Fudan University, Shanghai, China respectively. Presently, he is working towards his PhD degree at City University London. His research interest is in computational intelligence application, in particular, the intelligent agent.

3. An Intelligent Islanding Technique Considering Load Balance for Distribution System with DGs

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Abstract-- The island is an important operation mode of distribution system with distributed generators. The principles of islanding are presented. Based on the simplified model of distribution system, a new concept of cell is defined and an islanding mathematic model as well as a heuristic islanding algorithm through combining cells is proposed. The algorithm can well satisfy the constraint conditions while the process of islanding, and achieve a feasible islanding scheme in a short time. Thus, the operation mode of distribution system can change swiftly under fault states. The load grade attribute is utilized to enhance islanding algorithm selective to load. Thus, the method ensures not only priority services for important loads, but also be compatible with the under-frequency load shedding.

Index Terms-- Distributed generation, island, distribution networks, operation mode.

I. INTRODUCTION

Under the deregulation of power utility, more and more distribution generations (DGs) are connected into the power distribution system and run in the network. This brings a great change to the network configuration and its operation mode, as a result, this leads to a big challenge for the traditional protection and control system [1]. At present, Standards for interconnecting DG with electric power systems [2, 3] mostly are based on the principle that the DG shouldn't bring influence upon the normal operation performance for the utility protection and control system. For example, it's demanded that the DG shouldn't actively participate in the voltage regulation. And for another instance, in case of a fault in the distribution system, it's demanded that the DG be quitted from the system to insure the right operations of the protection devices. In this way, in one hand, it guarantees the security of the system, on the other hand, it also brings damage to the normal operation of the DG. DG sacrifices the interest of the power supplier since it brings negative affection to the development of the distribution generation technology. Facing this challenge, it is demanded to study the new protection and control system for the distribution system, farthest explore the benefits of distributed generation system, at the same time avoiding its negative influences upon the security of the power system but guarantee its more efficient and reliable operation.

The island is a feasible operation mode of the distribution system after interconnecting with DGs, which refers to the independent power supply from the DGs to a part of distribution system. A new idea is: when the occurrence of the fault in the distribution system, with the guarantee of the security of the power system, it is recommended to keep the normal operation of the DG as much as possible, and transfer the distribution system to some island self-balance operation system, in this way, it not only reduces the affected area to improve the reliability of the power supply but brings benefit to the DG running company and the customers.

This paper brings about a new heuristic islanding strategy based on the wide-area measure and control system. According to the fault location and aided by the pre-fault real time sampling, it is studied that when the occurrence of a fault to the distribution system, how to achieve a feasible islanding scheme in a short time and insure the minimum power lost of the system.

II. THE ISLAND PARTITION PRINCIPLES

It should be considered the next two aspects of the principles:

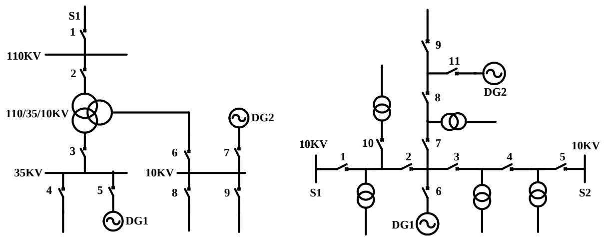
Firstly, it should consider the balance between the capacity of the load and generation, which not only make full use of the DG generation, but avoid overload it. So, the first island partition principle: under the precondition of the sum load is not more than the sum generation capacity, it is demanded that the island bear the load as more as possible.

Secondly, given the consideration that the various power users have their own demand for priority services, it is insured that with the island scheme the more important customers have the more priority power supple. The island partition principle 2: it is insured the island includes much more priority level load.

III. MATH DESCRIPTION OF THE DISTRIBUTION SYSTEM WITH DGS

A. The Simplified Model For Distribution System

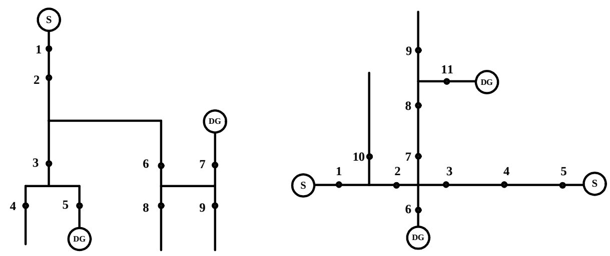
There are various grades voltage systems into which the DGs are incorporated. With the network differently connected, the DGs are also of the corresponding various incorporated ways: they are divided into the through substation busbar connected-into (fig1(a))and the through feeder one (fig1(b)).



(a) DG connect-into through busbar **(b) DG connect-into through feeder**

Fig. 1. Structure of distribution system and connection mode of DGs

It is through a math description for the simplified model of the distribution system based on the map theory, that the circuit breaker in the substation or set on the transmission with the measure and control function is considered as the node, the item between the adjacent nodes such as transmission, transformer or busbar is considered the edge. Fig 2 shows the simplified model of a distribution system.



(a) DG connect-into through busbar (b) DG connect-into through feeder

Fig. 2. Simplified model of distribution systems with DGs

It is shown from the fig 2 that there is a similar way to describe the different way of DGs into-connection for the different voltage levels.

B. The Load Cell and Source Cell

At present, it is impossible to install the measure and control device for every path line for the time being, so as not to get the affirm load value of each line. However, it can compute the load summation for some certain area, shown in fig2(b): through the flow value of nodes 1,2, and 10 it can get the above 3 node interconnected area load summation. It is introduced the concept of load cell, that is the minimum connected area built with the nearest adjacent nodes and it's between edge. If a twig path leading from a certain node, shown the ones from nodes 9, 10 shown in fig 2(b), they will construct the load cell with its own connected node respectively.

The source cell is constructed similar to the load cell. It is formed by the source, the source connected-into node and its inter-connection built area and used to symbol the power flow injection into the power system from the source.

The source cell and load cell have two common attributes: power attribute and node attribute. The power attribute of the source cell is marked with P_{Si}, which is a positive number, indicating the power out-flow from source cell S_i; and the power attribute of the load cell is P_{Li}, which is a negative number, indicating the power out-flow from load cell L_i. The node attribute of the source cell and the load cell are signified with the T_{Si} and T_{Li} respectively, which are they each cell boundary node-included aggregation.

In addition, the load cell owns the load grade attribute R_{Li}: the important load grade attribute is 1, the normal load grade is 2, and the lesser grade is 3.

Fig 3 is the cells partition formed from the fig 2(b), the distribution network. The area included in the circle denotes the cell, the power attribute marked with the negative or positive number in the circle, the node attribute marked with the nodes at the circle. The figure in the bracket is the serial number of the cell.

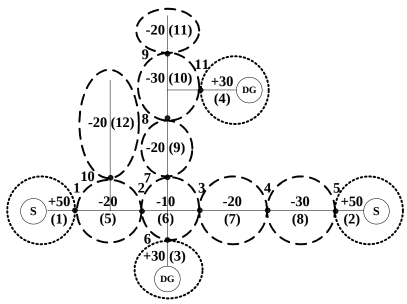


Fig. 3. Load cells and source cells

IV. THE CHART FLOW FOR DISTRIBUTION SYSTEM TRANSITION TO THE ISLAND

i) When the distribution system running normally, it is divided into several source cells and load cells according to its node position and adjacent relationship. Number the cells, and then form the cell adjacent table reflecting the cell-between adjacent relationship. After determination of node attribute for each cell, it can calculate the power attribute from the real-time sample of the nodes. For the utility source, in the island operation mode, it should be considered its maximum power output, of which it offers power to the most great amount load, thus its power attribute is set to be the rated value.

ii) When a fault happens, it is definite that the single fault is in a certain cell and the multi-fault in several cells. Relay protection will open the corresponding circuit breakers at the border nodes of these cells.

iii) Remove the fault located cell from the cell adjacent table, based on the pre-fault power attribute value to execute the island partition algorithm in forming the final island scheme.

iv) After that it transfers the power network to the island operation mode.

V. THE ARITHMETIC MODEL OF ISLAND PARTITION FOR THE POST-FAULT DISTRIBUTION SYSTEM

The final island scheme is regarded as the set formed by some source cells and load cells. So the island partition goal is described as: to combine more than one set by the healthy cells from the post-fault distribution system, and make the weighted summation of the load cells in the set the max. The weighted value reflects the importance level for the load.

(1) Goal function:

$$\max \sum_{i=1}^{n} \sum_{L_j \in H_i} \left| \lambda_{Lj} P_{Lj} \right| \quad (1)$$

n denotes the amount of sets, H_i is the (i)th set in sequence, L_j symbols the load cell in the set H_i, P_{Lj} symbols the power attribute of L_j. λ_{Lj} is the power lost affection ratio corresponding to the load grade attribute R_{Lj} for L_j, which can be determined according to the real situation, in this paper the grade load 1,2,3 relevant λ are 100,10,1 respectively. The more is the divided gap between different λ, the more can embody the importance of the high-grade load in the goal function, which provides priority for its inclusion into the island scheme.

(2) Constraint conditions

The power constraint in the set

$$\sum_{S_j \in H_i} P_{Sj} + \sum_{L_k \in H_i} P_{Lk} \geq 0 \quad i = 1, 2 \ldots n \quad (2)$$

The connection constraint of cells in the set

$$\forall S_j \in H_i, \quad \exists L_k \in H_i \text{ make } X_{Sj-Lk} = 1 \quad (3)$$

i = 1 , 2 … n

($X_{Sj-Lk} = 1$ means the cells S_j and L_k are adjacent,

$X_{Sj-Lk} = 0$ means the cells S_j 、 L_k are not adjacent)

$$\forall L_j \in H_i, \quad \exists L_k \text{ or } S_t \in H_i \text{ make } X_{Lj-Lk} \text{ or } X_{Lj-St} = 1 \quad i = 1, 2 \ldots n \quad (4)$$

(3) The sets not intersection constraint

$$\forall i, j \quad 1 \leq i, j \leq n \quad i \neq j, \quad H_i \cap H_j = \phi \quad (5)$$

VI. THE ISLAND PARTITION ALGORITHM

The island partition algorithm is a combination optimum issue; this paper brings about heuristic island partition algorithm, of which the island partition procedure insure the above constraint conditions be satisfied and get the feasible island partition scheme.

The concrete algorithm is described as follow:

(1) Without the consideration of the third grade load, it just in terms of the source cell and the first, the second grade load cells that to be involved in forming the preliminary island scheme.

1) For every source cell, it executes the cell expanding operation. The concrete method is: for every source cell S_i to search its adjacent 1 and 2 grade load cells in the cell adjacent table, and to inspect them in the order of grade from high to low, as long as find a certain adjacent load cell L_j satisfy the inequality $P_{Si} + P_{Lj} \geq 0$, it will be melted into S_i to form the new source cell S_i. So the new cell S_i includes the pre-melted 2 areas, S_i and L_j, with the power attribute turned into $P_{Si} + P_{Lj}$ and the node attribute into $T_{Si} \bigcup T_{Lj} - T_{Si} \bigcap T_{Lj}$. To modify the cell adjacent table according to the transition from pre-melting situation to the post-melting one: the pre-melting S_i, L_j adjacent cells (not include S_i and L_j themselves) become the adjacent cells to the new source cell S_i and the melted cell L_j is removed from the cell adjacent table. If the expanded source cell S_i is happened to be adjacent to another source cell S_k, the above two are merged together to form the new source cell S_i with its power attribute transited to $P_{Si} + P_{Sk}$ as well the node attribute to $T_{Si} \bigcup T_{Sk} - T_{Si} \bigcap T_{Sk}$, then followed the sequent modification to the cell adjacent table.

2) To perform the step 1) until its power attribute value is smaller than its all adjacent load cells owned load values.

1) At the cell adjacent table after step 2), in the order of the load grade from high to low to study the all 1, 2 grade load cell, when find a certain load cell L_m is directly adjacent to at least 2 source cells S_p 、 S_q, and $P_{Lm} + P_{Sp} + P_{Sq} + \ldots \geq 0$, then melt them in a new source cell S_p with its power attribute turned to $P_{Lm} + P_{Sp} + P_{Sq} + \ldots$, and its node attribute to $T_{Lm} \bigcup T_{Sp} \bigcup T_{Sq} \bigcup \ldots - T_{Lm} \bigcap T_{Sp} - T_{Lm} \bigcap T_{Sq} - \ldots$, renew the cell adjacent table consequently.

2) Keep on executing step 3) till it can't execute melting finally.

5) To check the new formed source cell if satisfy the cell expanding executive conditions after its step 3) and 4): under the satisfied source cells situation, algorithm will return back to step 1) to go on its procedure, and the unsatisfied one to get into the second stage.

(2) Consider the 3rd grade load cell, if the preliminary island scheme has the extra power supply for the 3rd grade load cell, and then add it to the island scheme:

Inspect all 3rd grade load cells in the cell adjacent table after execution of the 1st stage. If one certain 3rd grade load cell L_i has an adjacent source cell S_j satisfying the inequality $P_{Sj} + P_{Li} \geq 0$, then L_i is melted into S_j to form the new source cell S_j, and modifying power and node attribute and cell adjacent table.

After the above algorithm execution, the final source cells build the fault-after island scheme and the border nodes of the source cells are the final ones need to be opened.

Island partition algorithm adopts the selective melting operation to different grade load cells, and the melting sequence guarantees the priority power supply for important load. The procedure gives first consideration to the 1st and 2nd grade load cells farthest, in the end adds the 3rd ones the scheme. As a result, the algorithm do not guarantee the reliability service of the 3rd grade load, meanwhile, the involvement or not of the 3rd grade load cells will not bring influence to the performance of the island scheme in the whole. Also, as the under-frequency load shedding objects belong to the 3rd loads, this shedding operation will not be in conflicts with the island partition algorithm.

VII. EXAMPLE

Fig 4 is a typical distribution system with the DGs incorporated through busbar in the substation. The utility source ones (S1、S2) are the two lines from 220kv substations, and the distributed source ones（DG1、DG2、DG3、DG4） are connected to 10kV、35kV、10kV voltage level busbars respectively, with the pre-fault source cell power attribute marked by the value on the source. The 3 kinds of arrowhead are used to mark the different grade load: the wide one is the important load, the thin one is normal load and the dashed one is the lesser load, with the number on the arrowhead to mark the value of the load.

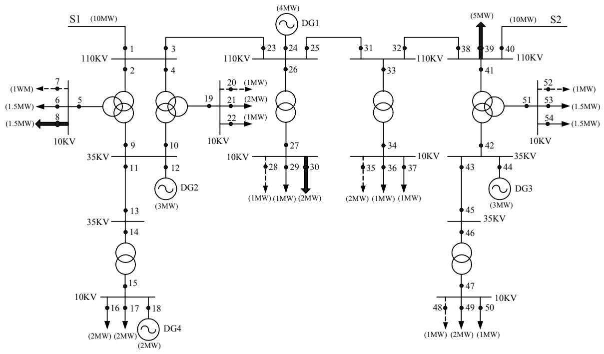


Fig. 4. A typical distribution system with DGs connected to bus bars

It is assumed that a fault occurred on the busbar connected nodes 1, 2, 3 and 4, and with the island partition algorithm it is the island scheme shown in fig 5.

The healthy area is divided into 3 islands, whose border nodes are : 1; 2, 4, 7, 17, 19; 3, 35, 48, and 52. These nodes are demanded to open when performing the island partition scheme.

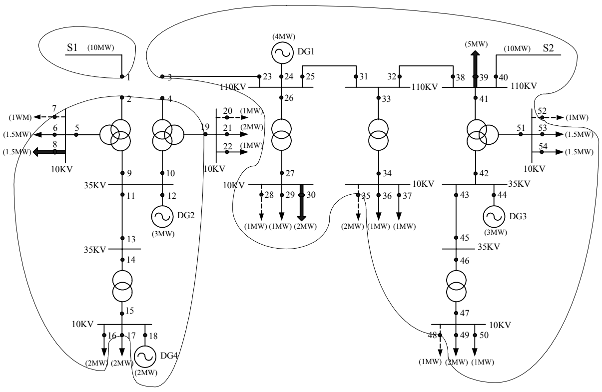


Fig. 5. After-fault islanding scheme of a distribution system with DGs connected to bus bars

Fig 6 gives us a typical distribution system with the DGs connected through the feeders. The utility sources (S1、S2、S3) are 3 busbars of 10kv, the number in the bracket is the power supply of each load cell, and the shadow frames mean the priority ones, the dashed lines mean the lesser loads.

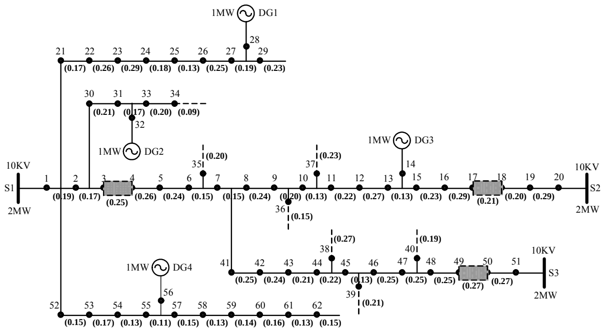


Fig. 6. A typical distribution system with DGs connected to feeders

It is assumed that a fault occurred on the feeder between node 1 and 2, and with the island partition algorithm it is the island scheme shown in fig 7.

The healthy area is divided into 5 islands, whose border nodes are : 1; 2, 4, 34; 7, 36, 37, 38, 39, 40; 24; 52, and 60. These nodes are demanded to open when performing the island partition scheme.

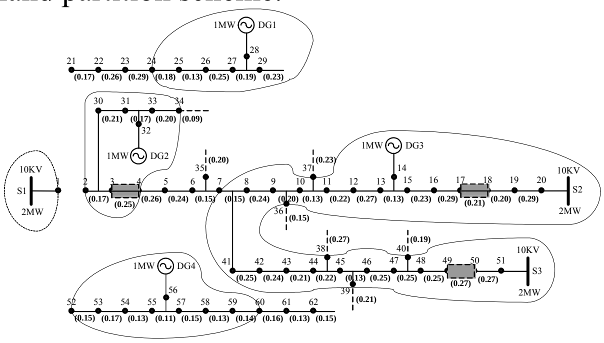


Fig. 7. After-fault islanding scheme of a distribution system with DGs connected to feeders

VI. CONCLUSIONS

Island is an important operation mode in the distribution system with DGs, which still supply a part of load from DGs with the occurrence of the fault, improving the power supply reliability of the distribution system.

This paper studied the method and procedure of the auto-transferring to the island operation mode. The island partition principle gives a comprehensive consideration to the specialties of the island running and the supply reliability demanded by the power system. The heuristic algorithm for the island partition well followed the island partition principle, and with its high speed it guarantied the faulted distribution system be fast transferred to the island operation mode, so it is feasible.

VII. REFERENCES

[1] Loi Lei Lai (Editor), Power System Restructuring and Deregulation: Trading, Performance and Information Technology, John Wiley & Sons, UK, Sept 2001.

[2] IEEE Std. 1547-2003, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems.

[3] UK Electricity Association 1991, Engineering recommendation G.59/1: Recommendations for the Connection of Embedded Generating Plant to the Regional Electricity Companies.

[4] Liu Jian, Cheng Hongli, Bi Pengxiang, A simplified model for distribution system[J], Proceedings of CSEE, 2001, 21(12): 77-82.

[5] J.Jyrinsalo, E.Lakervi, Planning the Islanding Scheme of A Regional Power Producer, Electricity Distribution, 1993.CIRED., 12th International Conference on 17-21 May 1993 Page(s):4.21/1-4.21/5 vol.4.

[6] K.Rajamani, U.K.Hambarde, Islanding and Load Shedding Schemes for Captive Power Plants, Power Delivery, IEEE Transactions on Volume 14, Issue 3, July 1999 Page(s): 805-809.

[7] B.A.Archer, J.B.Davies, System Islanding Considerations for Improving Power System Restoration at Manitoba Hydro, Electrical and Computer Engineering, 2002, IEEE CCECE 2002.Canadian Conference on Volume 1, 12-15 May 2002 Page(s): 60-65 vol.1.

[8] X.Ding, A.A.Girgis, Optimal Load Shedding Strategy in Power Systems with Distributed Generation, 2001 IEEE Power Engineering Society Winter Meeting, Feb, 2001, Page(s): 783-793 Vol.2.

[9] Mozina C.J, Interconnection Protection of Dispersed Generators in the new Millennium, Texas A&M University Conference for Protective relay Engineers, College Station, Texas, April 11-13 2000.
[10] R.C.Dugan, T.E.McDermott, Operating conflicts for Distributed Generation on Distribution Systems. Rural Electric Power Conference, Arkamsas, April, 2001.
[11] A.Girgis, S.Brahma, Effect of distributed generation on protective device coordination in distribution system, 2001 Large Engineering Systems Conference on Power Engineering, Nova Scotia, Canada, July, 2001.

VIII. BIOGRAPHIES

Yuping Lu was born in Danyang, China, in Oct, 1962. He was received the Ph.D. degree in electrical engineering from the City University, UK in 2003. He is working as a professor in Southeast University of china. His research interests are power system protection, especially digital relaying of generator-transformer unit, and protection and control technique in distribution system with DGs.

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Ji'an Wu was born in Suzhou, China, on Dec 14, 1960. He graduated from Southeast University in July 1982 and April 1989, and received B.E. and M.E respectively. Now he is working as chief engineer in Guodian Nanjing Automation CO.LTD. His interesting area is Power System Protection

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4. Three-phase Induction Generator Operating on a Single-phase Power System

T. F. Chan, *Member, IEEE*, and L. L. Lai, *Senior Member, IEEE*

Abstract— The general principle of phase balancing for a three-phase induction generator (IG) operating on a single-phase power system is investigated and a practical phase-balancing scheme is proposed. A phasor diagram approach enables the conditions of perfect phase balance to be deduced. The feasibility of the phase-balancing schemes is verified by laboratory experiments on a small induction machine.

***Index Terms*—**Induction generator, single-phase operation, phase-balancing.

I. INTRODUCTION

CONSERVATION of energy resources, environmental protection and sustainable development are the three major challenges that the world [1]. One important issue is to satisfy the energy needs of people without causing rapid depletion of the natural energy resources and degradation of the environment. In additional to environmental benefits, it can also help mitigate market power by enhancing competition on the power network. A general consensus among countries of the world is that greater emphasis should be placed on the use of renewable energy resources for electric power generation. Many developing countries, e.g. China, Nepal, Mexico, and others, have abundant renewable energy resources, but these resources are invariably located in remote regions, thereby creating a number of obstacles for their deployment. The problem can readily be solved if the region is already served by a three-phase grid. Local power systems that employ three-phase generators may be developed. The generators could be conventional wound-field synchronous generators, but over the past few decades increasing use is made of squirrel-cage type induction generators (IGs), particularly in wind energy systems and micro-hydro power systems. In the latter case, the grid provides frequency and voltage regulation, as well as the reactive power required by the IG. Due to the distributed nature of the energy resources, these power systems are usually small-scale in terms of rating. They may not be as efficient as central bulk power systems, but this disadvantage is offset by the reduction or even elimination of the transmission losses over long distances. The global trend of privatization and deregulation is a further impetus to the development of small scale distributed generation systems [2-3].

Even in developed countries, energy conservation and environmental protection can be achieved by extensive renewable energy programs and more widespread use of waste heat utilization and cogeneration [4]. For such applications, the low cost and flexibility of using induction generators result in their increasing popularity.

In remote regions of some developing countries, rural electrification is often based on single-phase generation and transmission/distribution systems [5]. This approach has the advantage that, for a given amount of capital investment, a wider area can be provided with electricity. There is thus a great need for the development of single-phase IGs. Although single-phase induction motors may be adapted for generator operation, it is often more economical, for ratings above 3 kW, to use standard three-phase induction machines [6]. With a suitable phase-balancing scheme, the three-phase IG can operate satisfactorily on a single-phase grid. A practical phase-balancing scheme invariably employs passive circuit elements, such as capacitance, inductance, or resistance.

The principle and operation of grid-connected three-phase IGs are well understood and are discussed in detail in many textbooks [7]. Performance analysis is based on the induction motor equivalent circuit, negative values of slip being used since the rotor

The general principle of phase balancing for a three-phase IG operating on a single-phase power system is investigated and a practical phase-balancing scheme is proposed. A phasor diagram approach enables the conditions of perfect phase balance to be deduced. The feasibility of the phase-balancing schemes is verified by laboratory experiments on a small induction machine.

II. PHASE-BALANCING USING PASSIVE CIRCUIT ELEMENTS

Plain single-phase operation of a three-phase machine is an extreme case of unbalanced operation. This stems from the fact that the line current flowing into the 'free' terminal of the stator winding is forced to be zero. To reduce the phase imbalance, an effective remedy is to inject a line current artificially into the 'free' terminal by using phase converters that comprise passive circuit elements. Fig. 1 illustrates the principle of phase balancing for an induction machine operating on a single-phase power system [5]. The rotor is assumed to be rotating in such a direction that it traverses the stator winding in the sequence A-B-C. For generator operation, the rotor speed must be slightly higher than the positive-sequence rotating field. Although special reference is made to a delta-connected machine in the following discussion, the principle is also applicable to a star-connected machine. A-phase of the IG is connected to the single-phase power system of voltage V, while the phase converters Y_1 and Y_2 are respectively connected across C-phase and B-phase. The current I_{L2} that results from the currents I_1 and I_2 through the phase converters constitutes the line current into the 'free' terminal of the generator. Apparently the phase balance is improved and indeed, by appropriate choice of the values of Y_1 and Y_2, perfect phase balance may be achieved.

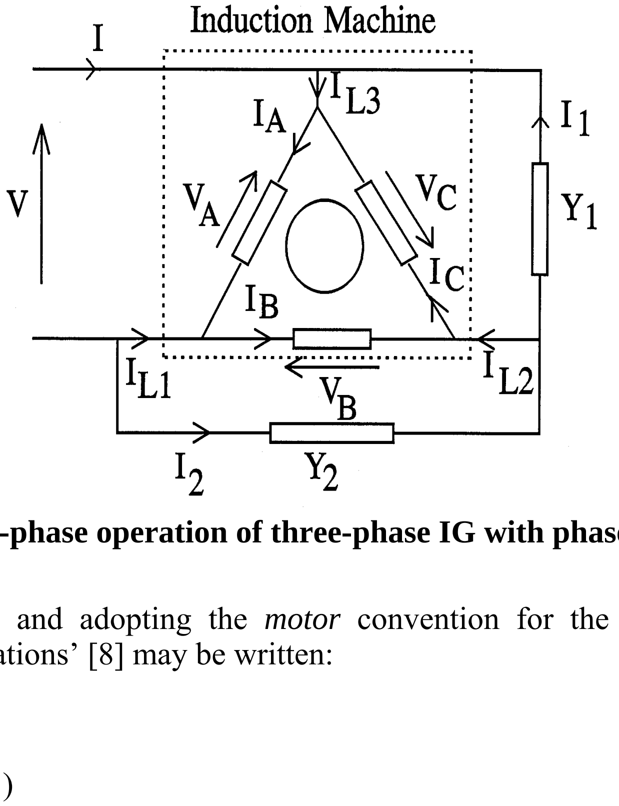

Fig. 1 Single-phase operation of three-phase IG with phase converters

Referring to Fig. 1 and adopting the *motor* convention for the induction machine, the following 'inspection equations' [8] may be written:

$$V = V_A \qquad (1)$$

$$V_A + V_B + V_C = 0 \qquad (2)$$

$$I_1 = V_C Y_1 \quad (3)$$

$$I_2 = V_B Y_2 \quad (4)$$

$$I_1 = I_B - I_C + I_2 \quad (5)$$

In association with the symmetrical component, the positive-sequence voltage V_p and negative-sequence voltage V_n can be determined as follows:

$$V_p = \sqrt{3}V \cdot \frac{Y_n + \frac{e^{-j\pi/6}}{\sqrt{3}} Y_1 + \frac{e^{j\pi/6}}{\sqrt{3}} Y_2}{Y_1 + Y_2 + Y_p + Y_n} \quad (6)$$

$$V_n = \sqrt{3}V \cdot \frac{Y_p + \frac{e^{j\pi/6}}{\sqrt{3}} Y_1 + \frac{e^{-j\pi/6}}{\sqrt{3}} Y_2}{Y_1 + Y_2 + Y_p + Y_n} \quad (7)$$

where Y_p and Y_n are, respectively, the positive-sequence and negative-sequence admittances of the IG.

For perfect phase balance, the negative-sequence voltage component V_n given by (7) should be equal to zero, hence

$$Y_p + \frac{e^{j\pi/6}}{\sqrt{3}} Y_1 + \frac{e^{-j\pi/6}}{\sqrt{3}} Y_2 = 0 . \quad (8)$$

By selecting values of Y_1 and Y_2 that satisfies (8), balanced operation of the IG may be achieved.

Based on the theory outlined before, a practical phase-balancing scheme for a three-phase IG operating on a single-phase power system has been developed and investigated. Fig. 2 shows the detail of the circuit connection.

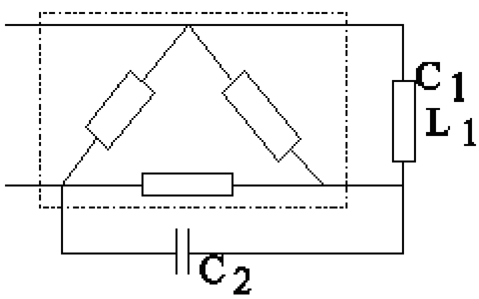

Fig. 2 Phase-balancing scheme for three-phase IG: $C_1(L_1)$-C_2 scheme

The $C_1(L_1)$-C_2 scheme shown in Fig. 2 employs only energy storage elements. For IG applications, the phase converter resistances can take the form of storage heating elements, auxiliary loads, or battery chargers. From the IG system's point of view, the power dissipated in these loads may be regarded as useful output as far as efficiency evaluation is concerned.

Using (8), it is possible to determine the values of the phase converters that result in perfect phase balance. As an illustration, consider the $C_1(L_1)$-C_2 scheme shown in Fig. 2. Assuming that Y_1 and Y_2 to be pure *capacitances* (i.e. $Y_1 = 0 + jB_1$; $Y_2 = 0 + jB_2$), (8) may be written as:

$$Y_p e^{-j\phi_p} + \frac{1}{\sqrt{3}} B_1 e^{j2\pi/3} + \frac{1}{\sqrt{3}} B_2 e^{j\pi/3} = 0 \tag{9}$$

where Y_p is the positive-sequence admittance of the generator and ϕ_p is the positive-sequence impedance angle.

Equating real and imaginary parts respectively to zero in (9), the values of the phase converter susceptances B_1 and B_2 are given by:

$$B_1 = \sqrt{3} G_p + B_p = 2Y_p \sin(2\pi/3 - \phi_p) \tag{10}$$

$$B_2 = -\sqrt{3} G_p + B_p = 2Y_p \sin(\phi_p - \pi/3) . \tag{11}$$

When $\phi_p = 2\pi/3$ rad, $B_1 = 0$ and $B_2 = \sqrt{3}Y_p$.

III. PERFORMANCE ANALYSIS

To check the feasibility of the above phase-balancing schemes, experiments were performed on a 2.2-kW, 220-V, 50-Hz, 4-pole, delta-connected induction machine IG whose parameters are given in the Appendix. It was found that exact phase balance could in general be obtained with appropriate choice of values of phase converters, subject to the limitations inherent in each phase-balancing scheme. Figs. 3 shows the variation of the phase converter conductances/susceptances that result in perfect phase balance when the IG is operating on a 220-V single-phase power system. Very good agreement between the computed and experimental results is observed, thus verifying the theory developed before.

As shown in Fig. 3, perfect phase balance can be achieved over the practical operating speed range of the IG (1500 r/min to 1570 r/min). The susceptance B_2 increases approximately linearly with speed and remains capacitive over the whole speed range. On the other hand, B_1 decreases with speed. At speeds below 1539 r/min, B_1 is capacitive and above this speed B_1 is inductive. At 1539 r/min, phase balance can be achieved with a single capacitance across B-phase.

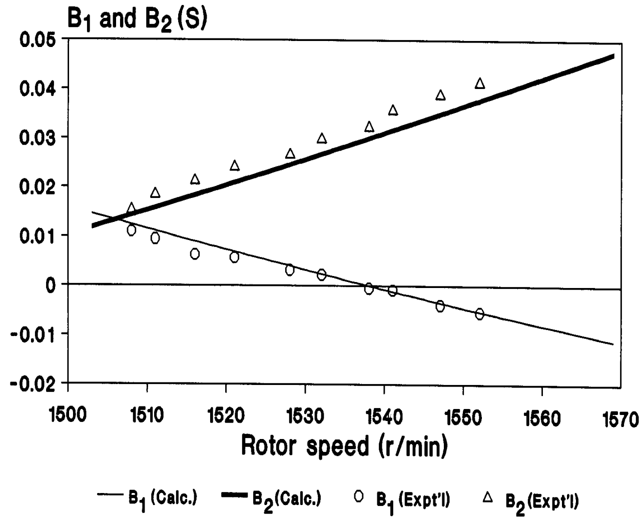

Fig. 3 Values of B_1 and B_2 to give phase balance at different speeds in $C_1(L_1)$-C_2 scheme.

IV. CONCLUSIONS

This paper has presented the general principle of phase balancing for a three-phase IG operating on a single-phase power system. A practical phase-balancing scheme has been proposed. The feasibility of the phase-balancing scheme has been verified by laboratory experiment on a small induction machine.

V. APPENDIX

TECHNICAL DATA OF INDUCTION GENERATOR

Three-phase, four-pole, 220-V, 9.4-A, 50-Hz, delta-connected, squirrel-cage induction machine. The equivalent circuit parameters (in per-unit values) are:

Stator resistance R_1	=	0.0965
Stator leakage reactance X_1	=	0.102
Postive-sequence rotor resistance R_{2p}	=	0.0731
Negative-sequence rotor resistance R_{2n}	=	0.0847
Rotor leakage reactance X_2	=	0.102
Core loss resistance R_c	=	29
Friction and windage loss P_{fw}	=	0.013
Stray-load loss	=	1.8% of power output

Variation of positive-sequence air-gap voltage E_1 with magnetizing reactance X_m of the machine is modelled by the following describing equations:

$$E_1 = \begin{cases} \dfrac{0.928X_m}{X_m - 0.121}, & X_m \le 1.829 \\ 1.264 - 0.211X_m, & 0.7469 \le X_m < 1.829 \\ 1.985 - 0.605X_m, & 1.829 \le X_m < 2.143 \\ 4.223 - 1.649X_m, & 2.143 \le X_m < 2.334 \\ 145.85 - 62.33X_m, & 2.334 \le X_m < 2.34 \\ 0, & 2.34 \le X_m \end{cases} \tag{12}$$

VI. REFERENCES

[1] R. Ramakumar, "Emerging options for integrated renewable energy systems," in *Proceedings of IEEE Power Engineering Society Winter Power Meeting 2000*, 23-27 January 2000, Singapore.

[2] Loi Lei Lai (Editor), *Power System Restructuring and Deregulation: Trading, Performance and Information Technology*. London: John Wiley & Sons, August 2001.

[3] N. Jenkins, "Embedded generation," *IEE Power Engineering Journal*, Vol. 9, No. 3, pp. 145-150, June 1995.

[4] R.L. Nailen, "Watts from waste heat - induction generators for the process industries," *IEEE Transactions on Industry Applications*, Vol. IA-19, No. 3, pp. 470-475, May/June 1983.

[5] P.G. Holmes, "Single- to 3-phase transient phase conversion in induction motor drives," *IEE Proceedings*, Part B, Vol. 132, No. 5, pp. 289-296, September 1985.

[6] M.O. Durham and R. Ramakumar, "Power system balancers for an induction generator," *IEEE Transactions on Industry Applications*, Vol. IA-23, No. 6, pp. 1067-1072, November/December 1987.

[7] M.G. Say, *Alternating Current Machines*. London: Pitman (ELBS), 5th Ed., pp. 333-336, 1983.

[8] J.E. Brown and O.I. Butler, "A general method of analysis of 3-phase induction motors with asymmetrical primary connections," *IEE Proceedings*, Vol. 100.

VII. BIOGRAPHIES

T. F. Chan (M '95) received the B.Sc. (Eng.) and M.Phil. degrees in electrical engineering from the University of Hong Kong, in 1974 and 1980, respectively. He received the PhD degree in Electrical Engineering from City University, London, UK, in 2005. Currently, he is an Associate Professor with the Department of Electrical Engineering, the Hong Kong Polytechnic University, where he has been since 1978. His research interests are self-excited a.c. generators, brushless a.c. generators, and permanent-magnet machines.

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5. Insurance Issues for Energy Risk

Harald Braun, City University, London, Xchanging, UK, Loi Lei Lai, City University, London, UK

Abstract—This paper is a survey of insurance options for the deregulated energy market. Decision makers and engineers in the energy sector have a need for risk management and require up-to-date information of available risk transfer options from the insurance industry. This paper is summarising the risks energy companies are facing and what cover is available. It also outlines some options that risk managers have, how deregulation is affecting the insurance industry and how new energy technologies are impacting the insurance market.

Index Terms—Deregulation, Energy Risk, Insurance, Investor Owned Utilities (IOU), Risk Analysis, Risk Management.

I. INTRODUCTION

THE initiation of deregulation in the energy sector, which introduced competition to the electric power industry, has triggered the creation of Investor-Owned Utilities (IOUs). For IOUs to be profitable, they require good risk management, good strategy and reduction of overheads. Because of this, energy companies have been subject to significant restructuring programmes, acquisitions and mergers, asset divestitures and other forms of corporate restructuring [1].

Energy prices are volatile and following the introduction of the European Emission Trading Scheme (EU ETS) in January 2005 energy generators were attempting to diversify into low emission energy resources such as wind, hydro and nuclear faculties. Most of the low emission energy resources are based on proven technology but are difficult to insure since not much historical data is available. The insurance industry, on the other hand, has been somewhat slow with the amendment of their insurance products to follow the trends in the energy sector. As a result, the insurance sector is losing money with out-of-date insurance products in terms of underwriting profitability and new products that are required for new technology in the energy sector e.g. fuel cell power plants [2].

It can be costly for insurers to calculate premiums bases on underwriting procedures that have been used for similar equipment but where significant differences exist. For example, new wind power generation companies have no claims history and little experience with new turbines, which have similar design as proven products but differ internally. For precise underwriting it is critical to monitor technological changes and ensure experienced staff is available [3].

Furthermore, energy companies vary in their business strategies and are therefore vertically and horizontally integrated businesses. Vertically integrated energy companies e.g. transmission can be served by the insurance industry with a single line of business written or risk group. Companies that are horizontally integrated and possess their own generation, transmission and distribution companies require a mix of business lines from a single or multiple insurers.

With this, the risk manager of an energy company needs to understand what types of insurances are available on the market place and which part of their risk portfolio can be covered by risk transfer to insurers. The shortfall of suitable insurance cover in the energy sector has forced the formation of industry specific mutual insurance companies that offer coverage not available in the insurance sector or with favourable conditions. Such lack of insurance cover opens the doors for Alternative Risk Transfer (ART) products that are often not as stringently regulated as the insurance sector [4].

II. RISKS TO ENERGY COMPANIES

Energy companies are exposed to a multitude of risks, therefore good risk management is required. The first steps required for risk management are risk identification, assessment, avoidance, reduction, retention and risk transfer. Not all risks are transferable to insurance companies since an insurer can only accept “pure risks” [5]. In order to transfer risks, risk managers need to identify insurable risks within their operation. To choose from a portfolio of available insurance policies, possible events and their likelihood need to be identified. With this, policies that guard events that give rise to an insurable primary cause need to be bought [6]. There are several risk categories to consider [7, 8]:

A. Property Risk

Energy companies may own pipelines, refineries and buildings or invest into real estate or property developers.

B. Legal Risk

Energy companies are exposed to corporate governance, joint venture disputes, contract risk negotiation, directors' and officers' liability, pollution liability, and exposure to third party contracts.

C. Political and Regulatory Risk

There are sovereign or political risk factors to deal with such as confiscation, nationalization, expropriation, kidnap and ransom, antitrust/collusion, transmission confiscation, currency inconvertibility, war and civil disturbance.

D. Operational Risk

Maintain security, guards, fences, CCTV, fire, well blow-out, explosion, business interruption, reputation, supplier failure, industrial espionage, and shutdown risks.

E. Environmental Risk

Exposure to climatic changes, population explosion and pandemics, changes in the legal system, nuclear proliferation and geological affects such as earthquakes and tsunamis need to be evaluated.

F. Intellectual Property Risk & Keyman Insurance

Losing a key employee and their specialised knowledge, failure to comply with best employment practices, and incidents involving gross misconduct at the workplace can have a profound effect on your company's performance.

G. Financial Risk

An IOUs operation is also affected by a range of financial and economic risks such as fluctuations in the stock market, commodity prices and GDP, interest and exchange rates. Market risks are evaluated by economists as well as evaluation of the fiscal regime that the host country is offering.

III. OPTIONS FOR COVER

Energy companies have several options on how to manage their risk portfolio [9]. This section illustrates the four basic options risk managers have for transferring insurable risks.

A. Do Nothing

Keep uninsured risk with investors and shareholders. Cover losses from current revenue stream account as operating costs. Of use for large companies that have multiple $billion turnover. As a result, cash flow can be interrupted and expensive short term loans may be required. If the risk is retained issues relating to risk avoidance and risk reduction should be addressed.

B. Buy Insurance

Pay insurance premium to a direct insurer, mutual insurer or via broker to insurance company. Claim on insurance cover if loss occurs. Investors like to protect their capital and many banks require insurance cover for their investment. Note that cover is cheaper if it has high excess amounts but investors may disapprove and request lower excess.

C. Capital Build up

Energy companies can build up capital reserves as part of a risk management contingency plan. This works well for smaller amounts and where the maximum amount of the risk is known and can be calculated.

D. Self Retention

Absorb the first part of the loss via capital build up and cash flow and pass on losses exceeding a limit to reinsurance companies [10]. This is referred to as self insurance or captive insurance and can be considered for large risks. Captives can purchase reinsurance and have tax benefits on cash build up.

IV. INSURANCE COVER FOR ENERGY COMPANIES

The purposes of an insurance cover is to reduce risk exposure to investors, keep the company focused on their core business, avoid diversification, and increase the cash flow by reducing loss reserves and to cover for unexpected events that lie outside core activities [11]. As well as providing cover, insurance companies give expert advice for identifying and managing risks with insurance experts that can suggest changes to business operation for BI risk reduction [5]. They may suggest keeping spares on site to reduce delivery times to remote sites e.g. remote transformer sites keep spare fuses, cables and connectors.

Multiple-line insurance companies or energy brokers have energy insurance divisions that are measuring exposure to potential loss of energy companies. They are able to make suggestions on how to minimise liability exposure through transfer of risk to an energy underwriter. Once the business is placed, periodic reviews of the insurance portfolio will be carried out since legal and technological changes may require contract alterations. Insurance professionals will also audit policies for accuracy to ensure adequate coverage.

A. *Insurable Risks*

Traditionally, “pure risks” are beyond the core competencies of the subject-matter possessor. They should not offer an opportunity of gain and, in case of a loss, the possessor should be indemnified to the value of the subject-matter at a point in time [6]. However, some insurance companies now cover speculative risks that were traditionally not insurable, such as the exchange of currency, weather insurance, environmental impact and damage assessment [12].

B. *Uninsurable Risks*

Speculative, non-financial and fundamental risks are uninsurable risks because the insured would gain from a claim. While speculative and non-financial risks are uninsurable as a matter of principle, fundamental risks are uninsurable because of lack of willingness or capacity. Thus, fines are uninsurable because it is against public interest.

In some countries failure to deliver power or congestion mismanagement is fined by the regulator. Imposed fines caused by power blackouts or improper congestion management will have to be paid by the energy company [13]. As far as liability goes, energy companies are currently not liable for the widespread havoc and losses to business and individuals. Therefore businesses that rely heavily on energy supply should consider business interruption cover.

V. INSURANCE AND DEREGULATION

Prior to deregulation, contracts between generation and transmission companies did not exist since both entities belonged to the same governmentally owned institution. Since more and more energy companies are now private and located in different countries, some contracts require insurance cover for business interruption and political risks.

Manipulative traders using criminal tactics are another risk energy companies should protect themselves against by means of risk transfer. Rogue energy traders have the potential to take part in fraudulent reporting of sales transactions, megawatt "laundering", fake power delivery scheduling, conspiracy and price fixing.

By purchasing D&O cover, energy trading companies can protect themselves from claims made by victims of market manipulations. With the recent upsurge of corporate scandals and insider trading, e.g. Enron, and directors being sued more frequently, premium rates of D&O cover had increased. But the recent introduction of International Accounting Standards (IAS) and the increased transparency of financial reporting have seen D&O premiums fall back to competitive levels.

Increased energy trading in a deregulated market causes transmission line congestion and thus frequency and voltage unreliability that in extreme cases can cause damage or loss of distribution infrastructure. Such damage, combined with rogue trading, may not be recoverable from an insurance contract.

State owned energy companies had little requirement for private insurance to secure their business. This has saved costs since the government has the financial capabilities to supply support in case of an accident. Privatised energy companies are no longer under the umbrella protection of the government and therefore require insurance cover from the commercial or mutual sector. Governmental energy companies were largely self insured via means of a captive.

The total cost of insurance coverage for an energy company which operates its own generation, transmission and utility company is usually smaller compared to individual companies. One of the reasons for this lays in the inherent contract uncertainty between separate companies cannot avert business interruption to any of the partners caused by a supplier. Additionally, basic, non-specialist cover that is required by all companies, such as employer’s liability, needs to be purchased for each entity, thus raising the overall cost caused by duplication compared to a single entity. The separation of large state-owned companies will introduce duplication and therefore increase overheads. Businesses are now reducing their cost base via mergers and acquisitions to lessen overheads and duplication. Such enterprises use this as a means for diversification and growth opportunity. Nevertheless, services and functions have been separated into entities by generation, transmission and distribution that resemble part of the enterprise. With this, each entity has now unique needs in terms of their insurance portfolio.

Energy companies that retain their risk are referred to as captives. Captives are wholly owned insurance subsidiaries of non-insurance parents that are permitted to write admitted cover of the parent in many or all EU countries. Their advantages are that the insured has no need to expose sensitive information to an external third party, profits during a soft market will remain in the enterprise, storing funds in pools without paying for risk transfer, investment income from funds, direct access to reinsurance and tailored XL programme and potential tax advantages if a loss occurs.

Disadvantages are the up front and running costs of an insurance company subsidiary, funds for initial capitalization, fees, taxes, reinsurance and wages.

There are covers a captive cannot provide e.g. workers compensation, automobile liability and general liability. Such risks can be insured via a fronting arrangement. In Fronting, an external licensed insurance company provides the cover and the unlicensed captive will provide reinsurance to the fronting company, gaining large policy discounts.

VI. RELEVANT COVER TYPES

Insurance covers are very complex and contain many clauses on the primary cause and the insured subject matter. This section summarises a few cover types that are common in the energy sector. Each cover type listed outlines its basics and is subject to variations in their policy wordings.

A. Property and Casualty (PC, PI)

Classes that are generally covered range from utilities and chemical operations to alternative energy sources, oil and gas, and pipeline and refinery risks. Additionally risks such as construction, property damage (PD), transportation, equipment breakdown and communications can be included.

Casualty insurance is generally segmented by the class of business clients operate since there are distinct differences in their insurance needs, for example Mining, Oil and Gas and Power Utilities all have different cover requirements.

B. Statutory Liability

Companies require Employer’s Liability (EL) insurance in many countries. It protects the insured against liability arising from bodily injury or disease sustained by their employees out of and in the course of their employment in the business. Many companies have Public and Product liability and Professional Indemnity insurance to protect against claims arising from third parties.

C. Business Interruption (BI)

The purpose of BI policies is to protect an operation from loss of revenue. This cover is beneficial as part of a risk management portfolio because lost income in a monetary form during a predetermined period of time after the loss occurrence can be recovered. Many insurance policies are limited by the sum insured or the policy’s limit of liability. Therefore BI will stop paying when normal operation resumes or the limit has been reached.

D. Boiler & Machine (B&M)

Industrial boilers are generally excluded from all cover types and must be insured separately.

The electrical machinery insurance contract covers losses caused by the breakdown of electrical machines. It is primarily to indemnify loss resulting from property damage to the insured and others for which the insured may be liable.

E. Advance Loss of Profits (ALOP)

ALOP cover is usually used to protect anticipated revenue from projects when their completion has been delayed. This cover is beneficial when construction work or machinery or equipment is delayed e.g. for a new power plant or transmission lines. Anticipated revenue from the electricity generation can be recovered from the insurance company. The claim amount is difficult to calculate since no past income figures are available. This policy terminates when construction has been completed. E.g. to protect an operating plant from loss of anticipated income, a BI policy is required. ALOP can be part of a Construction All Risks (CAR) or Erection All Risks (EAR) policy.

F. Sabotage and Terrorism

This cover is excluded in many insurance covers, especially in property policies. Only a few insurers are offering this cover which can protect against Malicious Damage (terrorism), Mutiny, Revolution, Strikes and War and protects Property, BI, CAR and PD. UK insurers will reinsure terrorism cover with the Pool Re insurance scheme [14]. Pool Re will ensure that terrorism insurance availability for commercial property would continue after the withdrawal of reinsurers from the market. The HM Treasury is the reinsurer of last resort for Pool Re in the event that all funds are exhausted. Similar State Compensation Funds have been set up in the US.

G. Directors & Officers (D&O)

Directors and Officers policies will protect director’s personal assets from claims to the organisation. In UK law, companies are allowed to indemnify director’s legal costs if they have been found not guilty. Such costs can be recovered from a D&O policy.

H. Nuclear Cover

Operators of nuclear power plants in the EU are liable for any damage caused by them, regardless of fault. Their liability is limited by both international conventions and by national legislation, so that beyond their financial limit the 1998 Paris/Brussels Convention dictates how claims responsibility is handled.

The 1998 Paris/Brussels Convention operates in three tiers of compensation payable to claimants. The 1st tier corresponds to the operator's liability amount of 700 million euro. This is followed by a payment by the state in which the liable operator's installation is located for up to 500 million euro. Followed by the 3rd tier where the contributions from all of the contracting parties must pay up to 300 million euro. With this, the Paris/Brussels regime will provide for up to 1.5 billion euro of compensation [15].

I. Forced Outage Cover

All players in a deregulated wholesale power prices environment that buy and sell electric power are exposed to an outage risk. If an outage occurs when spot market power prices for replacement power are high, the financial loss can be covered by electricity outage insurance.

J. Weather Risk Programs

***Amount of Rainfall*:** Protect hydro electric companies from draught. Money is paid for every inch below expected rainfall average up to a certain point.
***Demand Management*:** Protect utilities by paying fixed amount for every degree below average thresholds to offset lost revenue caused by low demand.
***Generator Start-up*:** Fixed amount is paid if temperature change causes power demand.
***Wind Generation*:** Pays if wind speeds fall below threshold levels so that power can be bought from the spot market.

VII. OBTAINING COVER

Energy companies have several options on how to obtain cover for insurable risks.

A. Private or Governmental Cover

The following factors may be used to support a decision for a national or multilateral insurance policy. Consider private insurance cover from an insurer or via a broker if there is a nationality requirement for governmental cover. If a project does not represent a new investment, private insurers are most likely to offer coverage since governments generally insure only new investments. Additionally, private cover is more flexible when it comes to negotiating contract wording but governmental contracts often have a higher contract certainty.

The government insurance is usually cheaper and solvency is assured but it may take longer to process an insurance policy from negotiation to inception and settlement of claims. Claims from a governmental insurance company can be easier to recover given that private companies are more aggressive when it comes to claims payment. And because both governments, host and foreign, will be aware of the insurance contract, claims non-payment or intent to instigate damage may lead to conflict between governments.

The government insurance companies will usually write a policy for a longer period, fifteen or twenty-year term, while private ones will write policies as short as annual. This is particularly important for long-term projects to avoid escalation of insurance costs.

It is important to be aware of the fact that a private insurance contract will be invalidated if disclosed to the foreign government since it may lead to a claim caused by the foreign government (de facto principle).

B. Mutual Insurer

Mutual insurance companies have been formed for risks that are difficult to insure or cannot be placed elsewhere. Such insurers are referred to as industry mutuals such as Aegis (casualty, management liability and property), Energy Insurance Mutual (excess casualty and management liability), Nuclear Electric Insurance Limited (NEIL) (nuclear property) and Oil Insurance Limited (OIL) (energy property). They were formed to fill needs not met by commercial insurers and require clients to be members of their organisation. Problem is that increase in members does not guarantee long term stability or success and that some companies do not wish to pass on their earnings to some of their rivals if they claim.

C. Partnerships

Insurance companies are working in partnership with energy companies, their clients. Such partnerships are a pragmatic way to confront challenges that are too big and risks that are too complex for any one energy company to go it alone.

Partnership is in effect an insurance contract that can be created by strategic partnering or planning. If a claim occurs and damage needs to be repaired, a partner may offer favourable terms or fast response times to minimise their own affects from the claim. If the partners are located in the foreign country where the project is based, the political risk is reduced since they are more aware of the local law and political developments.

VIII. NEW TECHNOLOGIES

Energy underwriters had massive losses because they did not understand the impact of new technology to their business. With the introduction of new gas turbines, business interruption and machinery breakdown cover was not correctly adjusted and cover started after a very short period of interruption e.g. 7 days. With increased complexity of machinery, specialist materials and long delivery distances, a relatively simple fault on a turbine took up to 6 weeks to repair. This has caused large losses on business interruption and machinery breakdown policies.

As a consequence, insurers now have a better understanding of the new technology they insure and store hard-to-get items locally and ensure that staff is appropriately trained.

With the onset of new technology in the alternative energy line of business, new hi-tech products require insurance to protect against losses arising from mechanical breakdown, fire, damage and theft.

With generating technology being more proven with fewer defects, rate reductions can be negotiated for 2006. But price increases or defect clauses in contacts are expected for new unproven generation technology e.g. renewables.

IX. RECENT DISASTERS

The number of major disasters may have dropped but their severity has increased. With the hurricane disasters, 2005 has been the most expensive year for the insurance industry [16].

After the losses in energy lines in 2005, the market can still accommodate demand but the combination of increasing volatility and exposure has resulted in a hard market and there may be no viable alternative to self-insurance or going captive for many. Without changes to pricing and contracts, the direct and mutual insurance market may lose some of its bigger and better clients for good.

This development has been seen as a start-up opportunity for new reinsurance companies with a clean balance sheet to provide reinsurance contracts as they do not have the loss experience from the past years. Such reinsurers offer short tail coverage (1 year) with high deductibles to take advantage of possible high earning from increased rates. Established reinsurers that have been in business for many years and lost money are now increasing their capital base to benefit from the hard market to recoup previous losses. This competition between old and new is good news for cedants [17].

X. CLAIMS PAYMENTS

With insurance, the quality of service cannot be evaluated until a claim is made, therefore claims processing in terms of speed and accuracy is paramount. Insurance companies can settle a claim via cash, repair or replacement.

The amount of the loss is generally the net book value of the insured investment. The book value is an important factor in determining how much will be recovered in the event of a loss e.g. the book value to be utilised can be from a foreign entity or a local parent company.

XI. IMPACT ON ENERGY PRICE

Commercial insurance has a significant impact on energy companies risk management strategy and cost base. Many energy companies have cited the availability and cost of insurance as negatively impacting their business profitability. Increase in running costs of an energy company is reflected in the price of energy, thus driving energy costs up [18, 19].

Energy companies with captives that buy reinsurance should be aware that reinsurance pricing is not regulated and therefore can increase by several factors for high risk energy lines [20]. Such increases should be part of their risk management during the annual renewal season.

Energy companies can avoid this annual insurance renewal cycle with its unpredictable pricing [21] by joining mutual insurance organizations and gain more stable pricing as a long-term alternative risk funding strategy.

The sheer size of the 2004/2005 Hurricane season [22] and the World Trade Centre (WTC) in 2001 has meant that many reinsurers have had to reconsider the acceptance and pricing of single large risks. E.g. Munich Re has increased its premium rates for oil platforms in the Gulf of Mexico by 400% in November 2005 [17].

Premium increase in BI and other turnover related covers can be expected for electricity companies since electricity is connected to the overall energy price. Energy companies should try to base BI on transmission volume, not pricing and lock such covers.

Insurers that had losses on the upstream market will try to retrieve the losses in the downstream energy market, creating a competitive environment that can drive 2006 renewal prices for electricity utilities down. In the past years, rate reductions of 40-50% compared to 2002 have been achieved.

XII. CONCLUSION

The deregulated energy sector can manage some of its risks by means of risk transfer via insurance. In an environment of global climate change, hurricanes, floods, false accounting and volatile energy prices they must compose innovative risk management portfolios at competitive terms. Before deregulation, state owned utilities had the financial support from governments to cover losses, now with smaller IOUs that large capital base has become unavailable and energy suppliers are forced to pursue their own risk management solutions [23].

Professional risk management, preparation and presentation of risks, can pay dividends on insurance contract renewal.

XIII. REFERENCES

[1] L.L. Lai (editor), Power System Restructuring and Deregulation: Trading, Performance and Information Technology, John Wiley & Sons, ISBN: 0 471 49500-X, Sept. 2001.

[2] R. Dixon, “Prospects for Hydrogen and Fuel Cell Technologies,” International Energy Agency, 5 December 2005.

[3] T. Stenzel, “Offshore Wind Experiences,” International Energy Agency, 17 August 2005.

[4] M. Lane, “Alternative Risk Strategies,” Published by Risk Books, ISBN: 1 899332 63 4, 2002.
[5] Chartered Insurance Institute “Legal and Regulatory,” Exam Preparation Guide Number IF1, ISBN: 1 85369 364 2, 2004.
[6] Chartered Insurance Institute “Underwriting process,” Exam Preparation Guide Number IF3, ISBN: 1 85369 369 3, 2004.
[7] A.M. Best, “Bests Underwriting Guide,” 2005.
[8] A.M. Best. (2005, 12). Best Week. *Journal*. Volume (12), Available: http://www.bestweek.com
[9] S. Otten, “Customer Portfolio Management,” The IEE International Conference on Energy Trading and Risk Management, City University London, ISBN: 9 78086 341591 3, 21-22 Nov 2005.
[10] Chartered Insurance Institute “Principles of Reinsurance,” Exam Preparation Guide Number 785, ISBN: 1 85369 487 8, 2005.
[11] N. Roberts, “Management of Energy Risks,” The IEE International Conference on Energy Trading and Risk Management, City University London, ISBN: 9 78086 341591 3, 21-22 Nov 2005.
[12] M. S. Row, “Impact of Seasonal Forecasting on Energy Trading,” The IEE International Conference on Energy Trading and Risk Management, City University London, ISBN: 9 78086 341591 3, 21-22 Nov 2005.
[13] Energy and Power Management. (2004, 10). Blackout, Demand Growth Point to Need for Legislation. *Journal*, Available: http://www.energyusernews.com/CDA/Archives
[14] H.M. Treasury UK. (2004, 12). Pool reinsurance arrangements: technical notice to industry. Available: www.hm-treasury.gov.uk
[15] World Nuclear Association. (2005, 12). Civil Liability for Nuclear Damage. Available: http://www.world-nuclear.org
[16] Willis. (2006, 01). Re-View. *Journal*. Available: http://www.willis.co.uk/news/Publications/Willis_Re-View_06.pdf
[17] Willis. (2006, 06). Energy Market Review. *Journal*. Available: http://www.willis.co.uk/news/Publications/EMR June 2005.pdf
[18] O Treceno, “Maintaining Technical Expertise in the Insurance and Reinsurance Industries,” The International Association of Engineering Insurers (IMIA), 37th annual conference, September 2004.
[19] J. Taber, D. Chapman, T. Mount, “Examining the Effects of Deregulation on Retail Electricity Prices,” Cornell University Department of Applied Economics and Management, 14 June 2005.
[20] A. Pincott “The Regulation of Reinsurance,” Kluwer's Insurance & Reinsurance Law Briefing, vol. 53, 12 March 2001.
[21] H. Braun, “A Neural Network Linking Process,” Ph.D. dissertation, School of Engineering and Mathematical Sciences, City Univ., London, UK, 2003.
[22] Insurance Journal. (2005, 11). Atlantic Hurricane Season. *Journal*. Available: www.insurancejournal.com/news/southeast/2005/11/30/62594.htm
[23] L.L. Lai and H. Braun, Opening plenary, The IEE International Conference on Energy Trading and Risk Management, City University London, ISBN: 9 78086 341591 3, 21-22 Nov 2005.

IX. BIOGRAPHIES

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6. Evolutionary Computation Techniques for Power Market Equilibrium Determination

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ABSTRACT

This paper reviews the application of some evolutionary computation techniques for power market equilibrium determination. Competitive power markets are formulated as a Cournot game. Genetic algorithm and coevolutionary computation techniques are adapted to numerically solve the optimization problem of finding the market equilibrium. Numerical example shows that the evolutionary computation approach is effective and it provides a powerful means for electricity market analysis.

Index Terms: Cournot game, power market, equilibrium, genetic algorithm

I. INTRODUCTION

Power industries in many countries are undergoing restructuring and deregulation. In the competitive market environment, consumers and producers of power can make transactions with prices and volumes traded being determined by market mechanisms. The equilibrium prices and volumes reached by the market are a function of the participants' characteristics as well as the structure of the market.

To engineer appropriate structures for the emerging markets, it is necessary to predict the kind of equilibrium a market can naturally arrive at, given the inherent characteristics of the participants. Game theory has a history of application in analysis of market equilibrium [1]. Cournot games are often applied to determine equilibrium production and consumption volumes in markets. Using Cournot game to analyze power markets results in an unwieldy system of nonlinear differentiable equations. To simplify the problem, past applications conjectured about how certain producers would behave or, alternatively, costs and demand characteristics were simplified to affine functions, which are linear functions with an extra additive constant. More realistic but still limited models used quadratic costs, resulting in the solvable linear-complementary problem and the quadratic programming problem [2].

This paper reviews the application of evolutionary computation techniques including genetic algorithm and coevolutionary computation methods for determination of the Cournot game equilibrium.

II. POWER MARKET EQUILIBRIUM DERTERMINATION

A. Modeling the power market [3,4]

A competitive power market with known supply, but generally unknown demand characteristics is best modeled as a single consumer multiple producers market with a uniform market price, where I producers act independently and the single consumer represents the aggregated behavoiur of all consumers. The ith producer, where $1 \le i \le I$, is characterized by a cost $c_i(q_i) = a_i(q_i^2) + b_i q_i + d_i > 0$ to produce q_i MWh of electricity. Producer i's objective is to maximize its profit in (1), subject to capacity constraints in (2), by choosing acceptable optimal volume q_i^* for a given market price p.

$$\pi_i(q_1,\ldots,q_I) = pq_i - c_i(q_i) \qquad (1)$$

$$q_{i\min} \le q_i \le q_{i\max} \qquad (2)$$

If it is assumed that there is negligible transmission loss, then the aggregate demand Q will be equal to the total output of all the producers in the market as shown below.

$$Q = \sum_{i=1}^{I} q_i \qquad (3)$$

When operating in a market that is in a state of disequilibrium, producers will adjust their individual production levels in response to changes in price p. In doing so, they collectively determine a new Q, the change in Q in turn causes the aggregated consumer to adjust p according to its demand characteristics. The affine demand function in (4) is assumed in this paper.

$$p = A - B \cdot Q \qquad (4)$$

where A and B are the positive coefficients.

The change in p in turns prompts producers to collectively readjust Q, and thus the cycle of reactive adjustments is continued until equilibrium is reached when

(i) The aggregated consumer operates at a price $p = p_{equ}$ and volume $Q = Q_{equ}$ where dp/dQ is such that the consumer and producers' tendency to change Q is balanced, that is $dp/dQ=p'(Q_{equ})$.

(ii) Every producers' trading volume converges to some individual volumes $q_i = q_i^*$s which is collectively optimal for all producers, but not necessary collusively optimal in that the producers' aggregated profit is a maximum.

B. Genetic algorithm solution method [3,4]

The operation of the market in subsection A above can be modeled as a non-cooperative Cournot game where there is no collusion between producers [3]. The non-collusive Cournot-Nash equilibrium for production occurs when all producers simultaneously but individually maximize their profits. Mathematically, this condition can be described as $d\pi_i/dq_i = 0$. This in turn implies the simultaneous differential equation set in (5). By differentiating (3) with respect to Q and substituting the results into (5), the condition for equilibrium can be expressed by (6).

$$\frac{dq_i}{dQ} = \frac{q_i p'}{c_i' - p} \qquad (5)$$

$$1 = \sum_{i=1}^{I} \frac{q_i p'}{c_i' - p} \qquad (6)$$

The equilibrium system described by (6) is an underconstrained systems since there are I unknown q_i's and only I inequality constraints in (2). Consequently, solutions of (6) are not unique and so the market will in general have multiple dynamic equilibria. This underconstrained nature requires the solution method to be capable of finding multiple solutions. The genetic algorithm (GA) is a guided stochastic search paradigm capable of finding multiple solutions [5]. GA mimics the process of biological evolution by recursively operating on a set of candidate solutions (CS), to produce a better set with each iteration. Many variants of GA exist. The work in [3] makes use of the basic GA (BGA) with universally sampled proportional fitness selection and two-point crossover [6]. Besides, the mutation scheme in [4] is employed. The fitness F of a CS ($q_1, q_2, \ldots q_I$) is defined to be $F=E^{-1}$, where E is the CS's error in solving (6) and is given by

$$E = \left| 1 - \sum_{i=1}^{I} \frac{q_i p'(Q)}{c_i'(q_i) - p(Q)} \right| \quad (7)$$

For each market scenario 50 trials are conducted. For each trial 100 CSs are randomly initialized and evolved for 100 iterations. The best solution of the evolved CS set is taken as the trial's solution. Of the 50 trial solutions, those with error $E > 10^{-15}$ are rejected from the final solution set. Further, due to the stochastic nature of the algorithm and finite sampling (50 trials), outliers in any attributes are removed from the solution set to obtain a representative solution distribution. A CS is considered to be an outlier if it lies greater than one standard deviation from the mean.

C. Coevolutionary computation solution method [7]

Coevolutionary computation is developed from traditional evolutionary algorithms (EAs), which simulates the evolutionary mechanism in nature and adopts the notion of ecosystem. Multiple species in the ecosystem coevolve and interact with each other and result in the continuous evolution of the ecosystem. Fig. 1 shows the fitness evaluation phase of the EA from the perspective of species 1. To evaluate individuals from one species, collaborations are formed with representatives from each of the other species. There are many possible methods for choosing representatives with which to collaborate. An obvious one is to simply let the current best individual from each species be the representative, and an alternative one is to randomly select an individual from each species to be the representative. The evolution of each species is handled by a standard GA.

A population of GA is used to represent one producer in the market, and thus I GA populations exist in the ecosystem. In Cournot oligopoly, a producer i only needs to optimize its own profit π_i expressed by (1), with the quantity q_i as the decision variable. A binary code chromosome is used to encode the quantity, and the profit is used as the fitness of the chromosome directly. It is noted that in the procedure of fitness evaluation, the market price p is to be determined using the producers' quantities in the market first obtained from (3) and (4). When the market price has been evaluated and the profit of the producer has been calculated using (1), the fitness of the chromosome can be found.

From the calculation process above, it can be observed that the populations are coordinated by the common market price p. When producer i changes its quantity q_i to gain more profit in (1), it will change the market price according to the inverse demand function in (4), and in turn changes the profits of other producers. The adjustment process will continue until no producer can get more profit by changing its quantity without changing the quantities of other producers, that is when the market reaches Cournot-Nash equilibrium.

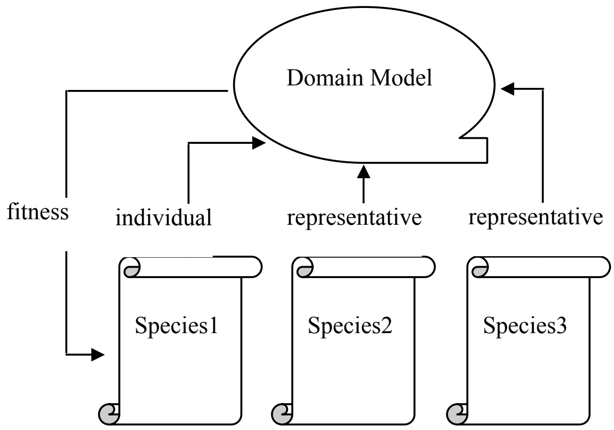

Figure 1. Framework of coevolutionary computation model

III. A NUMERICAL EXAMPLE

To illustrate the effectiveness of the evolutionary computational techniques for the power market equilibrium determination, the GA solution method in Section II.B is studied using a test case [4] with the familiar quadratic costs and affine demand market. Other demand functions for GA and coevolutionary computation solution methods can be referred to [7-8]. In [4], two situations are examined, one with demand price close to marginal cost, $p \to c'$, and the other with the price much higher than the marginal costs, $p >> c'$. This seemingly extreme situation often occurs in real market as price spikes. The effects of demand variations on market equilibrium are also examined. Variations in demand are modeled by changing the demand parameters for each market scenario. The generation cost parameters summarized in Table I are obtained from [4]. The B^{-1} values in Table II are selected to span the feasible range that give solutions within the system's minimum and maximum capacity.

The solutions of market equilibrium are shown in Fig. 2. For the situation of $p \to c'$, the market price is bounded below by the producers' minimum marginal cost, and there is a dispersed distribution of market equilibrium states. Dispersed market equilibrium states for each distinct demand function implies that the market has multiple equilibria. In contrast, market equilibrium with $p >> c'$, is governed by demand parameters instead of the producers' marginal costs, and there is one market equilibrium state, with generally many dynamic sub-states, for each demand function. From analysis, the distribution of equilibrium states for $p >> c'$ is found to be approximately governed by the condition of unit demand elasticity, $\varepsilon = 1$. Demand elasticity, defined as $\varepsilon = -(p/Q)(dQ/dp)$, becomes $\varepsilon = (A/BQ) - 1$ for affine demand. Unit elasticity implies that $p = A/2$ and $Q = A/2B$ which are indeed the approximate co-ordinates of the equilibrium states for $p >> c'$.

The $\varepsilon = 1$ condition is commonly known as the point of zero marginal revenue; at this point a unit increase in volume is matched by a unit decrease in demand price. If production volumes are less than those at $\varepsilon = 1$, then producers are inclined to increase production since total profit can be improved by increasing volumes and hence revenue. For producers, trading beyond the $\varepsilon = 1$ point is unjustified since the gain from additional volumes is less than the loss from additional lower price. Thus, in the limits when c' becomes insignificant, $\varepsilon = 1$ can be considered as a condition for market equilibrium. This condition is only approximate because with the usual constraints on p and c', (6) can only be mathematically satisfied if $\varepsilon > 1$. The approximation becomes an equality only in the limit that $p \to \infty$ or if non-positive marginal costs are contemplated.

The existence of market equilibrium with high price and low volume such as $(p_{equ}, Q_{equ}) \approx (500,690)$, indicates that if demand is unresponsive to price signals, then high prices will persist even though there is plenty of space capacity in the system. Equally, the existence of market equilibrium with low price and high volume, such as (p_{equ}, Q_{equ}) ≈ (9.3,2960), indicates that producers can be economically margins are minimal. The lack of equilibrium states with simultaneous low price and volume indicates that producers simply cannot operate in a state where their total revenue ($p_{equ} \times Q_{equ}$) is too low to cover costs.

TABLE I. Parameters For Generation Cost Models

No of	Type	a \$/MWh^2	b \$/MWh	d \$	$q_{\max}$ MW	q_{min} MW
1	base	2.80×10^{-4}	8.10	550	680	0.00
1	base	5.60×10^{-4}	8.10	309	360	0.00
1	base	5.60×10^{-4}	8.10	307	360	0.00
6	shoulder	32.4×10^{-4}	7.74	240	180	60.0
2	peak	28.4×10^{-4}	8.60	126	120	55.0
2	peak	28.4×10^{-4}	8.60	126	120	55.0

TABLE II. Parameters For Aggregated Demand Models

Case	Parameter	Settings
'$p \to c_{min}$'	A, \$ B^{-1}, MWh/\$	10 1000, 1500, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 5500
'$p >> c_{min}$'	A, \$ B^{-1}, MWh/\$	1000 1.50, 2.00, 2.50, 3.00, 3.50, 4.00, 4.50, 5.00, 5.50, 5.80

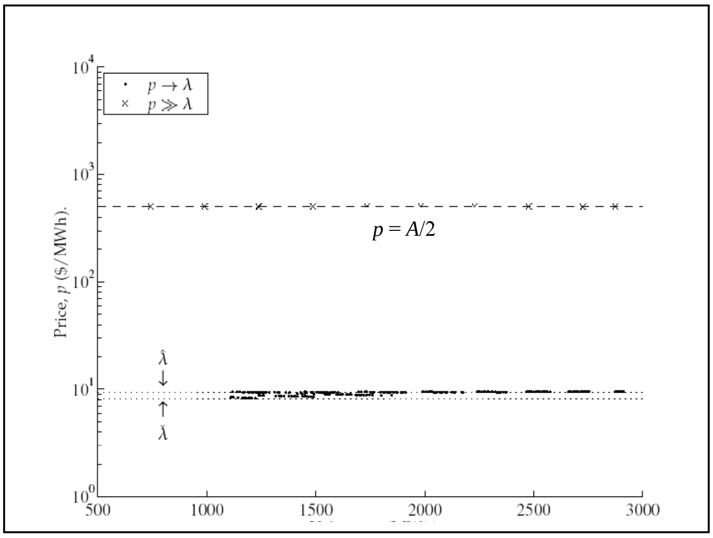

Figure 2. Equilibrium market price and volume

IV. CONCLUSION

This paper has reviewed the genetic algorithm method and a coevolutionary computation approach for finding the market equilibrium based on the Cournot game model. The solution methods do not rely on conjectures about participants' behaviour. The dynamic equilibrium or multiple equilibria solutions can be obtained. The new methods are very promising for monitoring competitive operations and assessing potential restructuring options in power markets.

V. ACKNOWLEDGMENT

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VI. REFERENCES

[1] E. Ramusen, "Games and information an introduction to game theory", 2nd Edn., Blackwell Cambridge, 1994.
[2] B.F. Hobbs, "LCP models of Nash-Cournot competition in bilateral and POOLCO-based power markets", IEEE Proceedings: Power Engineering Society 1999 Winter Meeting, New York, January 1999, CDRom.
[3] D.H.M. Nguyen and K.P. Wong, "Determining equilibrium of competitive power markets", IEEE Conference Proceedings, Power Utility Deregulation, Restructuring and Power Technologies 2000, London, UK, April 2000, pp. 119-124.
[4] D.H.M. Nguyen and K.P. Wong, "Natural dynamic equilibrium and multiple equilibria of competitive power markets", IEE Proc., Gener. Transm. Distrib., March 2002, 149, (2), pp. 133-138.
[5] K.P. Wong and Y.W. Wong, "Genetic and Genetic/Simulated-Annealing approaches to economic dispatch", IEE Proc. Gener. Transm. Distrib., 1994, 141, (5), pp. 507-513.
[6] D.E. Goldberge, "Genetic algorithms in search, optimization and machine learning", 1st Edn, Addison-Wesley, Reading, 1989.
[7] H.Chen, K.P. Wong, D.H.M. Dguyen and C.Y. Chung, "Analysing Oligopolistic electricity market using coevolutionary computation", accepted by IEEE Trans. on Power Systems.
[8] D.H.M. Nguyen and K.P. Wong, "Analysis of competitive power market with constant elasticity function", IEE Proc., Gener. Transm. Distrib., 2003, 150, (5), pp. 595-603.

BIOGRAPHIES

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7. Wind Power Trading Options in Competitive Electricity Market

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Abstract: Integration of wind power into the competitive electricity market presents challenges to power system planners and operators. It is not possible for wind generators to bid into the competitive electricity market due to high cost and intermittent nature of available power. This paper analyses and proposes the pricing mechanism for wind power in the competitive electricity market. The both demand and supply side bidding scenarios with case studies are presented in the paper. The impact of wind power in market mechanism such as market collusion, ancillary series and market power are also discussed. This paper could be a guide-line for the policy makers and market operators to promote the wind power with system reliability and security.

I. INTRODUCTION

Due to decreasing oil and coal reserve, environmental concerns and fear of nuclear disasters, it is believed that future power generation will not be limited to the conventional power plants. Despite rapidly climbing prices for natural gas and oil, the simple fact is, alternative energy in all its forms is not yet competitive on the price front for everyday users. Alternative energy is generally defined as any power source that is not based on fossil fuels or nuclear reactions. That includes electricity generated from wind, solar, geothermal, biomass or plant matter, and hydro power. Alternative fuels also can include ethanol from corn, bio-diesel made from vegetable crops and methane made from waste or other sources. Wind power is a potential candidate in non-conventional power generation family.

Wind farms are becoming an increasingly common sight on off-shore and on-shore. Their large scale integration in the electricity system presents some planning and operational difficulties due to mainly the intermittent and difficult to predict nature of wind which is considered at unreliable energy sources. However, the percentage of energy provided by wind is increasing due to technology and efficiency improvements, government financial support and energy policies. Wind turbines have become more efficient and their costs have dropped about 80 percent since 1980 to about four to eight cents per kilowatt-hour today, vs. about 38 cents to 40 cents 25 years ago.

An economic analysis often reveals that wind power is competitive with conventional power. But such an analysis strips out distortions such as input fuel subsidies, taxes and cross-subsidies between different class of consumers and uses the opportunity cost of capital as the discount rate. It also includes valuations for environmental externalities associated with burning fossil fuels. The wind power without government subsidy is still not competitive to the conventional energy sources. The energy production cost issue becomes more challenging due to ongoing restructuring process motivated to provide competition wherever possible for the cheap and choice of energy to the customers.

Competitive power market opens the room for playing the generators and retailers/consumers in their bid prices. The price formation is an internal decision of sellers and buyers. Bidding at both sides (supply and demand) are equally important from the market point of view. Competition in supply is concerned with how generators price their commodities so as to be commercially successful in the supply-demand market. The plural term commodities is used to emphasize that a supplier may have several types of plants (thermal, hydro, combine cycle etc.) and the pricing, and consequently the dispatch strategies, will reflect numerous technical and commercial particularities.

In the competitive electricity market, wind power is assumed as non-competitive as it has higher cost and uncertainty of availability of power [1]-[3]. To fit the non-conventional energy sources into liberalized electricity market, these generators are taken into the market differently than the dispatchable generators [5]-[6]. In some countries [7], wind generation is accommodated in day-ahead and hour-ahead energy markets without imbalance penalties. Imbalance (scheduled generation minus actual production) penalties are imposed to prevent gaming and to secure better system operation. In some electricity market, wind generators are not allowed to bid and they are taken into the system as and when these powers are available. Normally, wind generators are paid at the actual energy market price plus a fixed premium [1]. Even at these prices, wind generators can only recover the cost if they get some subsidy from the governments. With the removal of subsidies from these generators, it would be very difficult for them to survive in the emerging electricity market unless a suitable market mechanism is devised to take care of their output powers as and when available.

With rising environmental concerns, the wind energy is a better choice. But wind might run into competitive trouble against emerging clean coal technologies. Moreover the impacts of wind' s variability on the system operating costs are not negligible [8]. In most cases, the costs are less than 10% of wholesale energy value and in some cases substantially less. For power systems with a substantial natural gas component, wind actually provides a hedge against fluctuations and spikes in gas costs. It can be a hedging tool of system operators against the gamming and market power in the electricity market.

Due to oligopoly nature of market and electricity as a special commodity, there are fair chances of having the market power and market abuse. A good trading mechanism is a basic need which may reduce the market inefficiency. The assessment of cost associated with wind generation prediction errors in an electricity market is presented in [1]. A case of Spanish electricity market has been considered to show the effect of forecasting error. Trading of wind generation in short term market for UK with different window blocks have been considered in [4].

This paper analyses and proposes the pricing mechanism for wind power integrated into the electricity market. The both demand and supply side bidding scenarios are illustrated with examples. Several other considerations in market mechanism such as market collusion, ancillary series and market power are also highlighted. This paper could be guide line for the policy makers and market operators to promote the wind power with system reliability and security.

II. BIDDING STRATEGIES

In genuinely competitive conditions, several producers compete to win a share of the market and bid against each other to supply electricity to the grid. The prices bid by suppliers for the blocks of generation offered to the grid would reflect what portions of the load curve a supplier hopes to win for each type of plant in its possession. This, in turn, depends on production cost estimates, temporal considerations of system demand variation, unit commitment costs and commercial considerations such as profit or economic utility maximization and expectations of competitors' behavior.

The sealed bid auction is widely used in the pool type electricity market. Each supplier submits a sealed bid to the pool to compete for the supply of the forecasted load that is broadcasted by the pool. Theoretically, in perfectly competitive market, suppliers should bid at, or very close to, their marginal production costs to maximize returns. However, the electricity market is not perfectly competitive, and power suppliers may seek to benefit by bidding a price higher than marginal production cost. Each supplier's objective is to maximize benefit, therefore, given its own costs and constraints and its anticipation of rival and market behavior by constructing its offer (bid) price. On the other side, the pool operator will use a dispatch strategy that minimizes customers' payments given the supply costs represented in the suppliers' bids.

There are two type of market exists based on the bidding mechanism. If bidding is done by only suppliers, it is termed as single-sided bidding whereas if both suppliers and costumers are allowed to bid into the market, it is known as double-sided bidding mechanism.

III. MARKET CLEARING PROCESS

Each generator bids to sell its available supplies at some offer price and each utility (or other load serving entity) bids to purchase electricity at some offer price**.** Once the market-clearing price is determined, all bids to sell with offer prices lower than or equal to the market clearing price and all bids to purchase with offer prices greater than or equal to the market-clearing price is accepted. All sales bids with higher offer prices or purchase bids with lower offer prices would be rejected.

3.1 Single Price Market Clearing Process

In uniform market clearing price mechanism, all the sellers would receive the market-clearing price for their electricity, even if they bid less than that price and all buyers would pay the market-clearing price, even if they bid more than that price. The theory behind such a bidding system is that all bids to sell electricity would be priced at the marginal cost of that electricity. Bidding at a lower price than marginal cost would also not change the revenues if the bid were lower than the market-clearing price. However, such a bid could result in the firm selling electricity at a price lower than its marginal cost and thus losing money. Therefore, for a firm operating competitively, bidding a price equal to its marginal cost would lead to the greatest profit. In theory, such a competitive market would be desirable for the wholesale electricity markets and would result in the lowest total cost to generate a given amount of electricity.

3.2 Pay-as-Bid Market Clearing Process

A second alternative would be to design the system to pay bidders just what they bid, rather than to pay them the market-clearing price. The total cost of all purchases would be averaged, and each buyer would pay the average bid price. Many have argued that a system of paying on pay- as-bid basis, rather than on a market-clearing basis, would result in smaller total payments by the buyers of electricity. Under pay-as-bid system, each firm makes the most profit by guessing the cut-off price and bidding at or just below that price, as long as the cut-off price is at least as high as its marginal cost. Thus, even in a competitive market, suppliers would not bid at their marginal costs. If all firms could guess the cut-off price perfectly, each firm whose marginal cost was no larger than the cut-off would bid the cut-off price and each would be paid the cut-off price. The cutoff price would be the same as the market-clearing price.

The advantage often postulated for such a system would disappear under the best circumstance: perfect guessing. Although each firm would learn much from observing the results of the hourly bids, twenty-four a day, there would undoubtedly be mistakes, and to compensate, firms would bid somewhat below their estimate of the cut-off price. Some lower-cost firms would guess incorrectly and bid above the cut-off price, thereby leading to increases in the cut-off price. Thus, some higher-cost firms would generate electricity and some lower-cost firms would remain idle. The total cost of generating the given quantity of electricity would, therefore, be increased above the cost in a market-clearing system. The net result would be some variability in the prices paid for electricity at any hour, with some prices higher than what would have been the market-clearing price and some possibly lower. Whether such a system would increase or decrease the total payments for obtaining a given quantity of electricity would depend on the precise bidding strategies of the various market participants. However, pay-as-bid system could be expected to increase the total cost of generating electricity and would therefore be less efficient than a one-price market-clearing system.

There is another difficulty with the auction system, arising because the system is based on hourly or half-hourly bidding and market clearing. Some generating plants, typically operating as base-load plants, have very long and very costly periods for ramping up from no production to full capacity. These plants might be profitable to operate if they received at least a particular price for a large fraction of the day or for all of the peak period of a day. However, if they were operating only a few hours, even at a higher price, they might not be profitable to operate, since the fixed costs of ramping up could be greater than the profit earned during those more limited hours. For such plants, their offer price at any hour must depend on whether they would be generating electricity at the other hours of the day.

IV. DETERMINATION OF MARKET CLEARING PRICE

The market-clearing price is the lowest price that would provide enough electricity from accepted sales bids to satisfy all the accepted purchase bids. This market-clearing price setting can also be understood in other way. The sales bids would be ranked from the lowest offer price to the highest offer price i.e., in their merit order. The purchase bids would be ranked from their highest offer price to the lowest offer price, in their merit order. Equivalently, for purchasers that simply offered to buy a fixed quantity, the quantities would just be added up. At some price, the total of sales bids up to that point in their merit order would be equal to the total of purchase bids down to that point in their merit order. That price would be the market-clearing price.

The bidders can be allowed to bid their outputs or demands either in the blocks or as linear form as shown in Fig. 1. In a market, both the supply and demand bids are of the same type i.e. either block or linear bids. The detail analysis of wind energy payment in the liberalized market is presented for linear bid cases.

4.1 Single Side Bid Market

In a linear bid model, a supply curve which is a function of market price (p) of any bidder-i can be expressed as

$$q_i(p) = p / m_{si} \tag{1}$$

where m_{si} is the slope of the supply curve as shown in Fig. 1. If there are Ng suppliers who bid into the market, the combined supply curve will be

$$q(p) = p\sum_{i=1}^{Ng}\frac{1}{m_{si}} \tag{2}$$

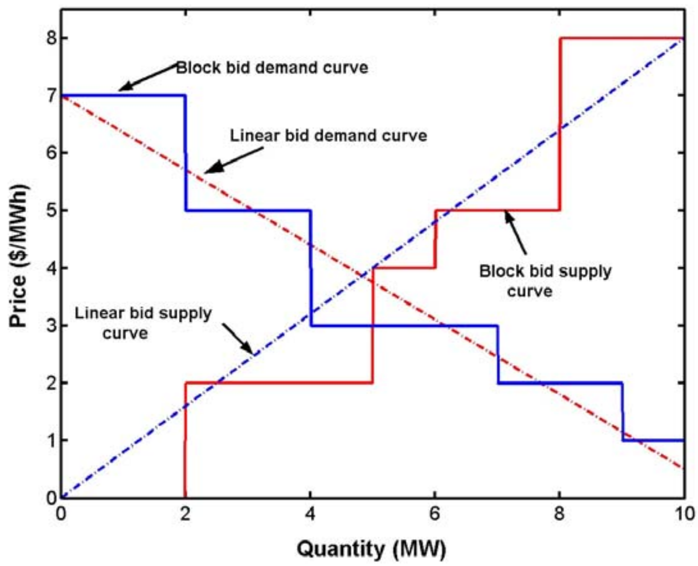

Fig. 1: Demand and supply bid curves

For the fixed demand D, the market clearing price (p^*) will be obtained by solving following equation.

$$p^*\sum_{i=1}^{Ng}\frac{1}{m_{si}} = D \tag{3}$$

In this, it is assumed that bidders have enough capacity. With limited capacity of any individual supplier can be included accordingly. If the i^{th} generator has the minimum (q_i^{min}) and maximum (q_i^{max}) power output limits, the supply curve defined in equation (1) will become

$$q_i(p) = \left(\frac{p}{m_{si}}\right)\left[u(q_i, q_i^{\min}) - u(q_i, q_i^{\max})\right] \tag{4}$$

where $u(q, q_0)$ is the unit function defined as

$$u(q, q_0) = \begin{cases} 1 & if \quad q \geq q_0 \\ 0 & otherwise \end{cases} \tag{5}$$

The combined supply curve would be

$$q(p) = \sum_{i=1}^{Ng}\left(\frac{p}{m_{si}}\right)\left[u(q_i, q_i^{\min}) - u(q_i, q_i^{\max})\right] \tag{6}$$

Thus the market clearing price can be determined by equating equation (6) with total demand.

4.2 Double Side Bid Market

In single side bidding, the demand is assumed to be fixed irrespective of the market price. Also single side bidding is a special case, where demand bidder is inelastic to the price. Demand curve for any individual in linear bid mode can be expressed as,

$$d_i(p) = (p_{i0} - p)/m_{di} \tag{7}$$

where m_{di} is the slope of the demand curve and p_{i0} is the intercept on price axis as shown in Fig. 1. If there are Nd consumers who bid into the market, the combined demand curve will be

$$d(p) = \sum_{i=1}^{Nd}\frac{p_{i0}}{m_{di}} - p\sum_{i=1}^{Nd}\frac{1}{m_{di}} \tag{8}$$

The market clearing price (p^*) can be obtained by solving the following equation.

$$p^*\sum_{i=1}^{Ng}\frac{1}{m_{si}} = \sum_{i=1}^{Nd}\frac{p_{i0}}{m_{di}} - p^*\sum_{i=1}^{Nd}\frac{1}{m_{di}} \tag{9}$$

or

$$p^* = \frac{\sum_{i=1}^{Nd}\frac{p_{i0}}{m_{di}}}{\left(\sum_{i=1}^{Ng}\frac{1}{m_{si}} + \sum_{i=1}^{Nd}\frac{1}{m_{di}}\right)} \tag{10}$$

The effect of generator output and consumption limits can be taken appropriately.

4.3 Market Clearing Price with Wind Generators

There are two possibilities for integration of wind generators in the competitive electricity market. In option one, they will be allowed to bid into the market and take the market clearing price with some premium. Moreover, they must not be charged the output variability penalty as other dispatchable generators are charged for the same. The risk of getting dispatched in the pay-as bid market is more. Due to government' s commitments for green energy this option is not suitable. Moreover, wind generators are not competitive without the government subsidy and in future government would like to remove the subsidies.

Another option, which is more appealing, is that the outputs of wind generators can be taken into the system whenever and wherever, they are available. In this condition the market clearing price (MCP) is to be determined to take care of wind generation output and the variability of wind power as well. With the different types of biding options, the MCP is to be effectively determined which is discussed in the case studies.

The effect of non-availability of wind power is the same as the non-availability of conventional power plant which have less probability of the same and they are penalized with huge revenue. Since the wind power depends on the availability of wind, the forecasting error is higher and therefore its effect on the market price and system operation is to be minimized. With proper pricing mechanism, the efficiency of market can be improved.

V. OTHER ASPECTS OF WIND POWER TRADING

5.1 Mitigation of Market Power

With introduction of competition in electricity market, there are several situations where market does not operate in a fair and transparent manner by the network constraints and also due to gaming by the market participants. Market power, in economics aspect, is the ability to profit by moving the market price away from the competitive level. In regulatory aspects, market power to a seller is the ability profitably to maintain price above competitive levels for a significant period of time. According to economics, any ability to do this, no matter how fleeting or minimal, is still market power. Most firms have some market power and this causes no significant problems provided the amount is small. Market power is harmful to the competition and it is necessary to identify the potential for its abuse, and to take steps to mitigate the market power.

Market power can be exercised by withholdings the output of generators. Withholding can be accomplished financially by bidding a high price, or physically by not bidding at all. If a high bid does not result in withholding, it is not an exercise of market power, even though it profitably raises the market price. In most markets, other than power markets, it is impossible to raise the market price without withholding, so this anomaly never occurs.

The most obvious effect of market power is the transfer of wealth from consumers to all the suppliers in the market, not just to the supplier who is exercising the power. This is not a major concern of economist which usually ignores the problem of wealth transfer. Economists are more concerned with efficiency, and in this case, are concerned with that high monopoly prices will lead to inefficiently low levels of consumption. The resulting loss of benefit to the consumers will be greater than the increase in profits. Strictly speaking, market power in electric power industry is due to following.

- Large share of generation or market dominance
- Network constraints
- Additional opportunity to create intentional congestion.

Wind power outputs can be used by market operators (MOs) for mitigating the market power exercised by the dispatchable generators. In normal cases, MOs are mitigating the market power abuse by using the dispatchable loads which is more expensive than the wind power because the cost of non-served energy is more than the cost of energy to be supplied. Since the wind power is intermittent and other generators do not know the exact amount of output from the wind power, their market power capability will be reduced.

5.2 Market Collusion

Collusion or horizontal merger of potential competitors can create or strengthen the market power. For collusion of suppliers to be successful, suppliers must be able to reach terms that are mutually profitable. Factors that tend to facilitate collusion are:

- A frequently repeated action for a homogeneous product under similar demand and supply conditions,
- Intimate knowledge of rival’s operating costs and behavior, and
- Almost immediate knowledge of a rival’s actions.

Generally, several aspects of electricity markets discourage collusive behavior. First, demand conditions vary considerably throughout the day and the actual demand levels experienced can vary significantly associated with these variables compounded by the uncertainty associated with predicting the amount and prices offered by all rivals with given forced outages and system operating constraints. Second, while information regarding power suppliers' operating cost in the past has been publicly available, this historical information is not necessarily indicative of suppliers' likely bid prices, since these operating cost do not reflect startup cost and are in many instances, average costs for an entire power plant.

Wind power with pump storage hydro power plant can have much effect on the market price setting. To recover the cost, wind power may try to get associated with other types of generators and may create the market power. Any such type of merger/collusion should be avoided by allowing the wind power to generate power as and when available.

5.3 Ancillary Service Provisions

Ancillary services such as reactive power support, spinning reserve, load frequency control (AGC), black start capability, energy imbalance etc. can be procured through auction based competitive markets similar to energy market. These ancillary services required for maintaining the quality and security/reliability of supply. Due to intermittent output of wind power coupled with uncertainty of wind, there is a possibility of higher cost of market due to greater imbalance of power, if wind generators are allowed to bid into the market. On the other hand, if wind power is with MOs, it can be used to provide the real power either in ancillary service or primary energy market to reduce the cost of electricity.

VI. STUDY CASES

Different biding scenarios of wind power in the electricity market are illustrated. In this study, the uniform pricing approach is considered. For sake of simplicity, only three generators other than a wind generator have been considered to bid into the market. For more bidding generators, the combined supply curved is to be obtained as explained in section IV. The output of wind generator is assumed to be 5 MW. Following cases are studied:

Case-A: Linear supply bid with fixed demand
Case-B: Linear supply bid with linear demand bid

Table I shows linear bidding parameters, at any unit time, of three supply bidders as defined in (1). The lower and upper limits of these generators are also given in the Table I. The cumulative supply curve is obtained using (2) and shown in Fig. 2.

Table I: Linear Bid Data

	m_{si} ($/MW^2)	q_g^{max} (MW)	q_g^{min} (MW)
Bidder-1	0.10	20	100
Bidder-2	0.25	10	50
Bidder-3	0.20	10	100

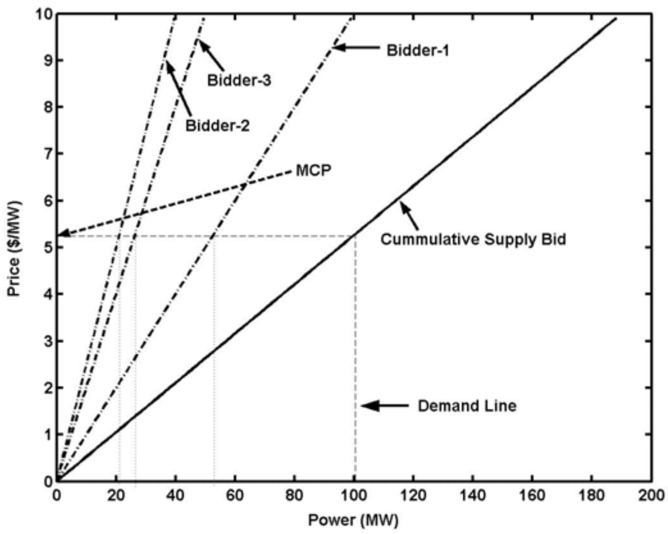

Fig.2: Linear supply bid with fixed demand

Case-A: In this case, a constant demand of 100 MW is considered. If wind power would not be available, the total demand would have been met by the three supply bidders 1, 2, and 3. The market clearing price (MCP), which is the intersection of demand curve and total supply curve, is \$5.26/MWh. The scheduled output powers of the supply bidders is obtained by intersection of MCP line to the individual supply bid lines as shown in Fig. 2. The bidders 1, 2 and 3 must generate 52.63 MW, 21.05 MW and 26.32 MW, respectively.

Consider wind power is available. Now it must be absorbed without knowing its actual price of output. With the availability of wind power (5 MW), the bidders can share the total dispatch of 95 MW (=100-5 MW). The corresponding MCP is now \$5.0/MWh. Since the MCP is reduced, it may not possible to recover the cost of wind power and also the excess cost during the non-availability of wind power. Thus the market price is to be fixed to the value obtained without considering the wind generation which is \$5.26/MWh. The output of bidders will be reduced according to the bidding characteristics which can be obtained by reducing the output by (Δq_i) as

$$\Delta q_i = \frac{\Delta p}{m_{si}} \tag{11}$$

where Δp is the change in MCP with and without wind power.

To see the bidding impact of wind generators, let wind generator be allowed to bid into the electricity market. The variations of wind output and the MCP with the different bidding rates are shown in Fig. 3. From Fig. 3, it can be seen that for its complete dispatch, wind power can bid any value less than \$5.0/MWh which is the market clearing price obtained by the total demand minus the wind power. It also shows that if wind power bids at zero, it will be completely dispatched and the MCP will be \$5.00/MWh. At zero bid of wind power, the cumulative supply curve will be parallel line below the total supply curve (without the wind power bidding).

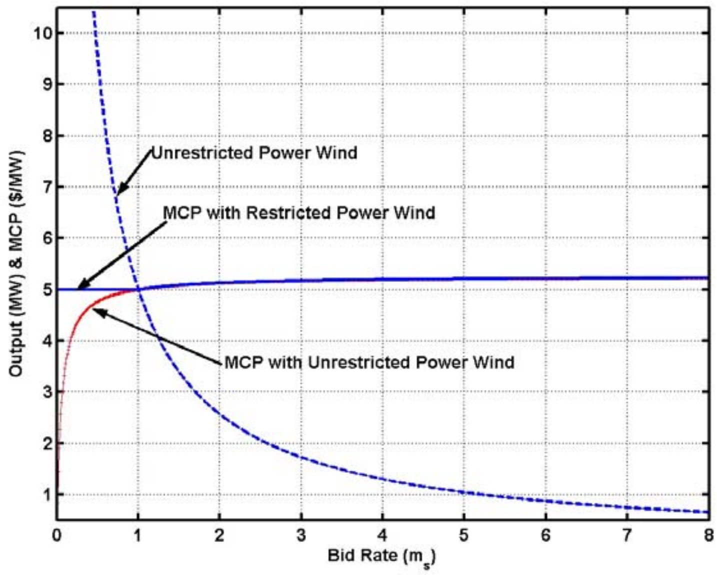

Fig. 3: Market clearing price with different bidding rate of wind power

The MCP with unrestricted wind power (having large wind power output) is the same as MCP at the restricted wind power (5MW in this case) at bidding rate of 1.0. It can be mathematically proved. For the maximum market clearing price *p*, the m_s for wind would be infinite and for minimum MCP, the m_s should be zero which can be obtained solving following equation.

$$\frac{\partial p}{\partial m_s} = \frac{\partial}{\partial m_s}\left(\frac{D}{\sum_{i=1}^{Ng}\frac{1}{m_{si}}}\right) = 0 \qquad (12)$$

There are two options available with market operator to decide the market clearing price. In option-I, the MCP can be calculated with reduced load (demand minus wind power availability during that period). It is $5/MW in this example. Since the wind power has reduced the MCP, a premium can be given to the wind power over and above MCP. To benefit wind power, and of course other generators, in option-II, MCP can be calculated without considering the wind power for total demand and the output of the bidding generators are adjusted using (11). The revenue collected from the market is $526.32 (=MCP*Demand) which can be seen from Table II. Bidding rate (m_s) from 1 to 10 will be reduced the wind power dispatch. In option II, even in the case of non-availability of wind power due to absence of wind, the market operator is not going to have deficit of money. And also wind power, if available, gets more revenue compared to bidding into the market without any risk.

Table II: Output Power and Payments (Case-A)

	Output (MW)		Payments ($)		Payment in Option II
	m_s>10	m_s <1	m_s>10	m_s<1	
Bidder-1	52.63	50.0	277.01	250.00	263.16
Bidder-2	21.05	20.0	110.80	100.00	105.26
Bidder-3	26.32	25.0	138.51	125.00	138.58
Wind Power	0.00	5.0	0.00	25.00	26.32
Total	100.0	100.0	526.32	500.00	526.32

Case-B: In most of the electricity market, instead taking the constant forecasted demand, the demand side participants are also allowed to bid into the market with their demand elasticity. Two different demand bidders are considered in this work for simplicity. Their bid data are given in Table III. The Total demand curve of the two demand bids along with a cumulative supply curve of three bidders as given in Table I are shown in Fig. 4.

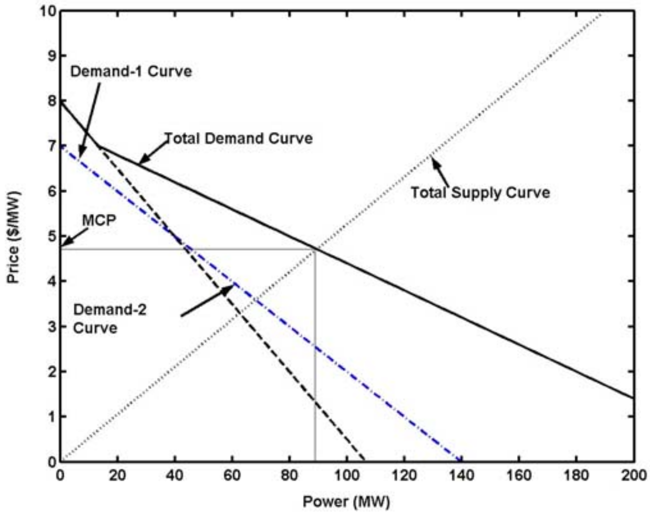

Fig. 4: Linear supply and demand bid curves

The MCP, which is the intersection of cumulative supply and total demand curves as shown in Fig. 4, is found to be $4.713 /MWh. The demand requirements of both bidders would be 45.73 MW and 43.82 MW, respectively. If wind generator bids at zero (Option-I), the MCP will be the intersection of a new supply curve parallel below (5 MW in x-axis) to the cumulative supply curve of three supply bidders. It is similar to the intersection of a parallel line below the demand curve to the total supply curve without the wind power. The MCP is found to be $4.618/MWh. Mathematically, it can also be obtained as

$$p^* = \frac{\sum_{i=1}^{Nd} \frac{p_{i0}}{m_{di}} - 5}{\left(\sum_{i=1}^{Ng} \frac{1}{m_{si}} + \sum_{i=1}^{Nd} \frac{1}{m_{di}} \right)} \tag{13}$$

Table III: Linear Demand Bid data

Data	m_{di} ($/MW/MW)	p_{i0} ($/MW)
Demand-1	0.050	7.0
Demand-2	0.075	8.0

Due to the elasticity of demand bidders, there is reduction in the spot price which causes the increased in the consumption of demand bidders and it is 47.64 MW and 45.09 MW, respectively. The effect on the variation of bidding of wind generator on wind output and the MCP is shown in Fig. 5. It can be noted that bidding rate less than 1.0 will have no impact on the MCP with restricted wind power of 5 MW (considered maximum output). However, with higher bidding rate, the MCP increases but the power dispatched from the wind power is less.

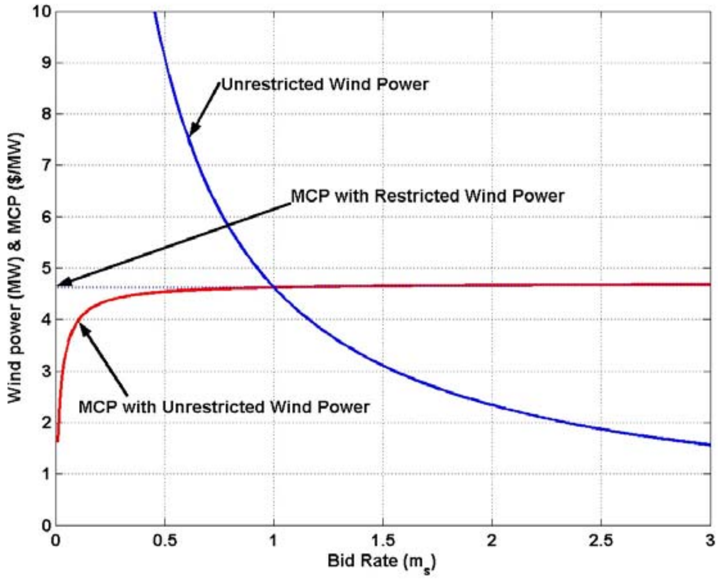

Fig. 5: MCP with restricted and unrestricted wind power bids

Table IV shows the payments made/received from the bidders at different MCP. Negative sign shows the payment received from the demand bidders. It can be seen from Table IV that the money given to the wind generation is higher with MCP calculated at zero wind power. If market provision has the imbalance penalties for down loading, the generators can be paid at actual MCP (i.e. $4.618/MWh) with zero bid of wind power whereas wind power can be paid at maximum MCP. The payment to be collected from the demand bidder will be at the maximum MCP rate (column 6). In the event of non-availability of wind power, the suppliers will be asked to increase their output and the wind power money will be given to them.

Table IV: Output Power and Payments (Case-B)

	Without wind power		With wind power		
	Power (MW)	Payment (at 4.713)	Power (MW)	Payment (at 4.618)	Payment (at 4.713)
Bidder-1	47.13	222.14	46.18	213.26	217.64
Bidder-2	18.85	88.86	18.47	85.32	87.05
Bidder-3	23.57	111.10	23.08	106.63	108.81
Wind	0.00	0.00	5.00	23.09	23.56
Demand-1	45.73	-215.56	47.64	-220.00	-224.53
Demand-2	43.82	-206.54	45.09	-208.20	-212.53

VII. CONCLUSION

A suitable market mechanism is required to accommodate the non-conventional energy sources due to several technical and non-technical reasons. Having intermittent nature of availability, a proper trading option must be used for these sources to recover their costs in competitive power market. This paper presents the various market strategies in competitive power market having wind generators.

A proper use of these sources can also avoid the abuse of competitive power market by which the efficiency of the market can be increased. Wind power can play a vital role in mitigating the market power, ancillary services but their costs must be recovered for successful promotion of wind power energy. The trading with wind power must be transparent for free and fair trade of electricity. This paper could be guide line for the policy makers and market operators to promote the wind power with system reliability and security.

VIII. REFERENCES

[1] A. Fabbri, T. G. S. Roman, J. R. Abbad and V. H. M. Quezada, ‘Assessment of the cost associated with wind generation prediction errors in a liberalized electricity market’, *IEEE Trans on Power Systems*, Vol. 20, No. 3, pp. 1440-1446, August 2005.

[2] Wind Energy Manual, Iowa Energy Center, USA, [on-line], **http://www.energy.iastate.edu/renewable/wind/wem/wem-02_toc.html**

[3] R. Spencer, ‘Untapped Potential of Wind Power’, IEEE Power Engineering Review, pp. 10-11, September 2002.

[4] G.N. Bathurst, J. Weatherill and G. Strbac, ‘Trading Wind Generation in Short Term Energy Market’, IEEE Trans. On Power Systems, Vol. 17, No. 3, pp. 782-789, August 2002.

[5] J. Kabouris and C.D. Vournas, ‘Application of Interruptible Contracts to Increase Wind Power Penetration in Congested Area’, IEEE Trans on Power Systems, Vol. 19, No. 3, pp-1642-1649, August 2004.

[6] C. Chompoo-inwai, W.J. Lee, P Fuangfoo, M. Williams and J.R. Liao, ‘System Impact Study for the interconnection of Wind Generation and Utility System’, IEEE Trans on Industry Application, Vol. 41, No. 1, pp. 163-168, January/February 2005.

[7] R. Piwko, D Osborn, R Gramlich, G Jordan, D Hawkins and K Porter, ‘Wind energy delivery issues’, IEEE Power & Energy Magazine, Vol.3, No.6, pp.47-56, November/December 2005.

[8] E. A. DeMeo, W Grant, MR. Milligan and M.J. Schuerger, ‘Wind plant intergration: Cost, Status & Issues’, IEEE Power & Energy Magazine, Vol.3, No.6, pp.38-46, November/December 2005.

IX. BIOGRAPHIES

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I. Erlich received his Dip.-Ing. Degree in electrical engineering from the University of Dresden, Germany in 1976. After his studies, he worked in Hungary in the field of electrical distribution networks. From 1979 to 1991, he joined the Department of Electrical Power Systems of the University of Dresden again, where he received his PhD degree in 1983. In the period of 1991 to

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8. The Effect of DG using Fuel Cell under Deregulated Electricity Energy Markets (Paper 06GM1321)

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***Abstract* —** The electricity supply industry is undergoing deregulation around the world. A free market approach to buying and selling electricity is forecasted to drop the cost and introduce choice into what has been a monopoly industry. Deregulation has accelerated the development of smaller generators and fuel cells will gradually become more attractive to mainstream electricity users as they improve in capability and decrease in cost. Some of the operating conflicts and the effect of distributed generation (DG) on power quality are addressed. Molten Carbonate Fuel Cell (MCFC) stack dynamic model was developed to analyze a spectrum of dynamic responses from slow to fast transients and a simplified process flow diagram (PFD) of the Santa Clara Demonstration Project is presented. The integration of Direct Carbonate Fuel Cell (internally reformed carbonate fuel cell) with a gas turbine is an emerging technology. Fuel cell-microturbine hybrid power plant can be interfaced with the utility grid via a three-phase inverter, controlling active and reactive power.

***Index Terms* --** Deregulation, distributed generation, fuel cells, hybrid power plant.

I. INTRODUCTION

Small scale power generating technologies, such as gas turbines, small hydro turbines, photovoltaics, wind turbines and fuel cells, are gradually replacing conventional generating technologies in various applications in the electric power systems. These distributed technologies have many benefits, such as high fuel efficiency, short construction lead time, modular installation, and low capital expense, which all contribute to their growing popularity. The prospect of independent ownership for distributed and other new generators, as encouraged by the current deregulation of the generation sector, further broadens their appeal. In addition, the industry restructuring process is moving the power sector in general away from the traditional vertical integration and cost-based regulation and toward increased exposure to market forces. Competitive structures for generation and alternative regulatory structures for transmission and distribution are emerging from this restructuring process [1].

In this process of transformation, the Federal and State regulatory agencies are imposing regulations on deregulation and restructuring with the intention of protecting the average consumer by providing open competition. In response to these regulations, there are a host of acquisitions and mergers by the private sector to position themselves to take advantage of new business opportunities. However, while everybody is concerned about the regulatory and financial issues, many of the technical and environmental challenges to be faced by this new development appear to be ignored.

The US National Science Foundation (NSF) had the first of a series of national workshops called "Vision 21: Environmental Electric Energy Opportunities for the Next Century," on the future technologies to support the Nation's electric supply, delivery and consumption for the 21st century [2]. These workshops hope to present the prospects for leading energy technologies, provide a lasting vision of our energy future and give the attendees a window to the needs and opportunities to the next century. Followings are the major themes and objectives:

- Anticipate and explore the science, technology and security needs for the restructured electric supply systems of the next century,
- Educate technologists about the coming trends in emerging generation, storage and delivery systems, control and communication systems needs, energy efficiency, load matching, advanced power delivery and conversion concepts, etc.,
- Understand the impact of the US electric power industry on global climate change,

- Discuss and contrast several diverging expert views of the electric utility of the future and search for common technical and polish themes and directions,
- Provide suggestions for academic researchers regarding valuable energy technology investigation areas.

As the second workshop, the NSF, Department of Energy (DOE), and Electric Power Research Institute (EPRI) jointly sponsored the workshop "Future Research Directions for Complex Interactive Electric Networks" in Washington, DC, U.S.A. [3]. The workshop concentrated the R&D needs in the following four areas:

1. Power system economics,
2. Real-time wide area sensing, communications and control of large scale networks,
3. Distributed generation, fuel cells and new technology,
4. Prescriptive and predictive model development.

In this paper, distributed generation technologies and their effects on deregulation in electricity energy market are introduced. Among those new technologies, fuel cells are presented as a promising technology in the future.

II. DEREGULATION IN ELECTRICITY ENERGY MARKETS

It has been a surprise to many Californians that the most prosperous state in the U.S. is in power shortage and the Silicon Valley is not exempt from black out.

Electricity demand is projected to grow sharply over the next twenty years. Based on current estimates, the United States will need about 393,000 MW of new generating capacity by 2020 to meet the growing demand. If the U.S. electricity demand continues to grow at a high rate it has had recently, we will need even more generating capacity. To meet the future demand, the United States will have to build between 1,300 and 1,900 new power plants; that averages out to be more than 60 to 90 plants a year, or more than one plant a week [4].

A. Electricity Restructuring

One of the most important energy issues facing the Administration and Congress is electricity restructuring. The electricity industry is going through a period of dramatic change. To provide ample electricity supplies at reasonable prices, states are opening their retail markets to competition. This is the most recent step in a long transition from reliance on regulation to reliance on competitive forces.

The electricity industry has undergone considerable changes in the last two decades. These changes affect how our electricity infrastructure operates. Major industry restructuring has separated once vertically integrated electric utilities that supplied generation, transmission, and distribution services into distinct entities. To facilitate competition at the wholesale level, in 1996, the Federal Energy Regulatory Commission (FERC) required transmission-owning utilities to "unbundle" their transmission and power marketing functions, and provide nondiscriminatory, open access to their transmission systems by other utilities and independent power producers. At the retail level, some states have required utilities to divest their generation assets as part of restructuring. These utilities currently supply only transmission and distribution services for customers who purchase electricity (i.e., generation services) from other firms.

B. Change in Wholesale Electricity Market

This transition from regulation to competition began in 1978 with enactment of the Public Utility Regulatory Policies Act, which promoted independent electricity generation. Open-access transmission policies adopted by the Federal Energy Regulatory Commission (FERC) in the late

1980s further promoted competition in wholesale power markets.

Congress largely ratified these polices with enactment of the Energy Policy Act of 1992, which further promoted non-utility generation. FERC took another large step to promote competition with its open-access rule in 1996, which provided greater access to the transmission grid, the highway for interstate commerce in electricity.

C. Change in the Retail Electricity Market

Increased competition in wholesale power markets encourages states to open retail electricity markets. Under current law, FERC has jurisdiction over the wholesale power market, while states have jurisdiction over retail markets. Beginning in 1996, states began opening their retail markets to competition in order to lower electricity prices.

Most new electricity generation is being built not by regulated utilities, but by independent power producers. These companies assume the financial risk of investment in new generation, and their success rides on their ability to generate electricity at a low cost. These dramatic changes affecting the industry led to important structural changes. Independent power producers, which were once infant industries, now dwarf many utilities. Utility mergers, which were once rare, are now commonplace. While utilities had service areas that were limited to a single state or region, independent power producers are international companies that can build power plants across the globe. Many utilities that were once vertically integrated divested themselves of generation, either voluntarily or because of the state law.

III. DISTRIBUTED GENERATION

The concept of DG has a variety of meanings, often resulting in some confusion. DG will refer to any modular generation located at or near the load center. These small, self-contained, decentralized power systems are categorized as photovoltaic, mini-hydro, and wind systems or in the form of fuel-based systems, such as fuel cells and microturbines [5].

A shift in the economies of scale recently took place where smaller power plants with a few dozens of MW’s, instead of few GW’s, became more economical. Also, generators with renewable sources as wind or solar energy became more economically and technically feasible. This has resulted in the installation of small power plants connected to the distribution side of the network, close to the customers and hence referred to as “distributed” generation.

Recently, power market liberalization in Europe and North America has resulted in an increase in the number of smaller power producers participating in the electricity market giving rise to a renewed interest for DG. This led to a considerable increase in the proportion of DG in the network. A study by the Electric Power Research Institute (EPRI) indicates that by 2010, 25% of the new generation will be distributed [6].

The introduction of DG to the distribution system will have a significant impact on the flow of power and voltage conditions at the customers and utility equipment. These impacts might be positive or negative depending on the distribution system operating characteristics and the DG characteristics. Positive impacts include:

1. Voltage support and improved power quality.
2. Diversification of power sources.
3. Reduction in transmission and distribution losses.
4. Transmission and distribution capacity release.
5. Improved reliability.

However, some operating conflicts related to over-current protection, voltage regulation, power quality problems, ferroresonance and others might result when the distributed generators are to operate in parallel with the utility distribution system.

A. DG Technologies

There are various types of distributed generation technologies ranging from the well established reciprocating engines and gas turbines to more recent types of renewable sources such as wind farms and photovoltaic. Emerging technologies such as fuel cells and micro-turbines are recently commercialized. DG technologies can generally fall under two main categories:

1. Combined Heat and Power (CHP). CHP plants or cogeneration are power plants where either electricity is the primary product and heat is used as a byproduct, or where heat is the primary product and electricity is generated as a byproduct. The overall energy efficiency is then increased. Many DG technologies, such as Reciprocating engines, Micro-turbines and Fuel cells can be used as CHP plants.

2. Renewable Energy Generation. This refers to distributed generation that uses renewable energy resources such as the heat and light from the sun, the wind, falling water, ocean energy and geothermal heat. The main DG technologies falling under this category are wind turbines, small and micro hydro power, photovoltaic arrays, solar thermal power, and geothermal power [6].

By relying on dispersed small-scale generators, combined with other distributed resources such as flywheel storage devices and sophisticated control equipment, utilities can avoid costly investments in large, often the polluting central plants. They can also deploy generating assets more flexibly as needed, and at the same time reduce transmission and distribution losses.

B. Interface to the Utility System

Distribution generators are interconnected with the utility to operate in parallel with its distribution system. There are three types of the electrical system interfaces [6].

1. Synchronous Machines. The majority of DG interconnected for parallel operation with the utility distribution system are three phase synchronous machines. Synchronous generators use DC field for excitation, and hence they can produce both active and reactive power.

2. Asynchronous (Induction) Machines. Induction generators are induction motors driven slightly faster than the synchronous speed. Unlike synchronous generators, induction generators are capable only of producing active power and not reactive power.

3. Power Electronic Inverters. An inverter is a solid state device that converts DC electricity to AC electricity at a desired voltage and frequency. DG technologies that generate either dc (wind, fuel cell and photovoltaic) or non-power frequency ac (micro turbines) must use an inverter to interface with the power system.

C. Operating Conflicts

The introduction of DG to the utility distribution system might create some operating conflicts such as over current protection, voltage regulation and others [6].

1. Fault Clearing. With DG, there are multiple sources. Therefore, opening only the utility breaker doesn't guarantee fault clearance. All DG protection devices must then detect the fault and separate to allow the normal fault-clearing process to proceed.

2. Reclosing. DG must disconnect early in the reclose interval to allow time for the arc to dissipate in order to have a successful reclose. If the DG is still connected upon reclosing, the DG equipment itself is subject to damage.

3. Interference with Relaying. DG connection can reduce the current seen by the relay and hence shortening its reach. High impedance (low current) faults will go undetected until they burn into larger faults with more damage to the utility equipment and more risk of sustained interruption to

customers.

4. Islanding. DG relaying might fail to detect that the utility breaker has opened and continue to energize a portion of the feeder forming what is called “island”. The following problems might take place:

1. Low power quality for customers on the island.
2. Reclosing.
3. Safety concern of a generator accidentally energizing the line resulting in injuries to the public and the utility personnel.
4. Ferroresonance. Requiring the DG to disconnect at the first sign of trouble will leave the service transformer isolated without load and served with an open phase. This is a classical ferroresonance condition where the capacitance of the cable appears in series with the magnetizing inductance of the transformer. This results in very irregular high voltage and currents.

D. Power Quality Issues

The effect of the DG on power quality depends on many factors including:

1. Type of DG.
2. Its interface with the utility system
3. The size of the DG unit, its intended mode of operation and expected output fluctuation.
4. The total capacity of the DG relative to the system.
5. Size of generation relative to the load at the interconnection point.
6. Feeder voltage regulation practice.

In general, back-up generation and on-site power supply provided by DG improve the system power quality. However, some issues might arise when distributed generators, with different types and technologies, are interconnected to the utility distribution system [6].

1. Sustained Interruptions. When the DG is interconnected in parallel with the utility distribution system, some operating conflicts might arise that affect the system reliability. An example is the incompatibility between instantaneous reclosing and DG, or the interference with utility relaying and reducing the devices’ reach.

2. Voltage Regulation. Generator controls are much faster and smoother than conventional tap-changing transformers and switched capacitor banks. The conflict might, however, arise due to the interference of these generators with the existing utility voltage regulation equipment. Special communications and control are then required to overcome this conflict and allow these generators to work properly with the utility voltage regulating equipments.

3. Voltage Flicker. DG may cause voltage flicker as a result of starting a machine (induction generator) or step change in the DG output which results in a significant voltage change on the feeder. In case of wind and solar energy systems, the output fluctuates as the intensity of wind and sun changes. Mitigation approaches include reduced voltage starts on induction generators, tighter synchronization for synchronous DG. Inverters are controlled to limit inrush currents and the change in output levels.

4. Voltage Sags. The ability of a DG to counteract voltage sags depends on its type and location. Large synchronous generators can help support the voltage and reduce voltage sags on local facility. Inverter-based distributed generators can be controlled to supply reactive power for voltage support during a sag.

5. Harmonics. DG might introduce harmonics in the network to which it is connected. The type and

severity will depend on the power converter technology and interconnection configuration. Synchronous DGs can also be a source of harmonics (mainly triplen) depending on the design of the generator windings and grounding. The grounding arrangements of the DG and the step-up transformer play a major role here where an interface transformer connection with a delta winding, that can suppress the triplen harmonics, might be a solution.

E. Types of Distributed Resources

In principle, any of the alternative or renewable energy sources, from biomass to photovoltaics, is suitable for inclusion in the kind of "microgrid" as devising for the "virtual utility" of the future. But wind and biomass are constrained by the availability of wind and land, and photovoltaics will become cost-competitive only if gas prices double. Partly for those reasons, the two candidate technologies for distributed generation that are arousing the most excitement right now are fuel cells and microturbines.

As for miniature gas-fired turbines, they are arousing just as much excitement. More or less arbitrarily defined as micro (30-200 kW and above), mini (500-1000 kW), and small (up to 15 MW), such turbines are generally expected to be reliable (even though their rotation rates are high), quite efficient (albeit less so than large combined-cycle plants), and readily produced and deployed (despite the concerns about grid interoperability). Microturbines and fuel cells can be deployed not only in isolation but also in combination. Marrying the two technologies could have prodigious advantages. Among the gains are overall system efficiency and recovery of pollutants, including greenhouse gases. Many of these revolutionary technologies seem not ready for prime time. In the end the impression is that the more substantial developments in distributed generation are evolutionary, and come largely from firms already well-established in their fields of endeavor [7].

Just about any smaller-scale energy source has the potential to help reduce reliance on natural gas: by providing peaking power where needed, cutting losses and costs associated with distribution and transmission, and providing a backup to centrally generated electricity. Distributed generation and storage also can yield greater trustworthiness than the "three nines" (99.9 percent reliability) that has been the power industry standard.

A major limitation of the distributed-generation concept, however, is that the most promising technologies – both fuel cells and microturbines – almost always rely on natural gas as the preferred feedstock. Thus they can do little to cut back on the use of gas beyond improving distribution efficiencies – by reducing line losses, for example, and allowing for energy to be used more flexibly [7].

In Europe (where the weather conditions are really variables and the forecast are available for limited period ahead of time), the Photovoltaic (PV) system needs to be over-dimensioned and integrated with batteries and Diesel Generator Set (DGS) for back-up purpose. Because of these limits the PV has been rarely chosen as energy supply in the off-grid industrial application which requires more than few kWh/day. The wind Generator (WG), despite of its reduced cost comparing to the PV solution, is not so diffused in Europe because of the weather conditions.

The European weather conditions do not allow designing PV only and/or WG only stand alone plants, despite of these technologies being available for energy supplying in the off-grid system. The High Integrated Hybrid System (HIHS) instead permits to design a power supply system able to guarantee the continuity of the supply mixing the different renewable energy sources – like PV, WG (even micro-hydro if possible) – limiting the DGS use for back-up purpose only. A way to increase sustainability of the system consists of substituting the DGS backup set with a fuel cell (FC). In this way, it is possible to use the energy surplus to produce, by a hydrolysis process, the hydrogen needed from the FC. In the case of FC, the costs are higher because of the absence of a real market for FC maintenance. FC cost will be reduced in the next years because of the increase of the FC production. In particular, the possibility of substituting the Diesel Generator backup group with a fuel cell for supplying isolated telecommunication devices is investigated both through the energy balance and an economic investment. Using the fuel cell technology as backup device the need of periodic maintenance and refueling operation is limited or removed. Accounting environmental cost, the photovoltaic-wind-fuel cell configuration permits an increasing of environmental sustainability and then a decreasing of external costs in the electric power generation [8].

IV. FUEL CELLS

Fuel cells generate electricity through an electrochemical process in which the energy stored in a fuel is converted into DC (direct current) electricity. The process is similar to that of a battery. Because fuel cells generate electric energy without combusting fuel, they have many advantages. Some are as follows:

- High energy conversion efficiency
- Modular design
- Very low emissions
- Low noise
- Fuel flexibility
- Cogeneration capability

All fuel cells have the same operating principle: an input fuel is chemically transformed in the fuel cell to create an electric current. Fuel cells consist of an electrolyte material, which is sandwiched in between two thin electrodes, in this case, a cathode and an anode. The oxygen (i.e., air) passes over the cathode and the input fuel passes over the anode where it catalytically splits into ions and electrons [9].

A. Types of Fuel Cells

There are four main types of fuel cells currently being developed and/or distributed. They include Phosphoric Acid Fuel Cells (PAFC), Molten Carbonate Fuel Cells (MCFC), Solid Oxide Fuel Cells (SOFC), and Proton Exchange Membrane Fuel Cells (PEMFC). Technological comparisons between these four fuel cells are outlined in Table I. Zinc Air, Alkaline Fuel Cells, and Regenerative Fuel

TABLE I. TECHNOLOGY COMPARISON [9]

	PAFC	**MCFC**	**SOFC**	**PEMFC**
Electrolyte	Phosphoric Acid	Molten Carbonate Salt	Ceramic	Polymer
Operating Temperature	375°F (190°C)	1200° F (650°C)	1830°F (1000°C)	175°F (80°C)
Fuels	Hydrogen (H2) Reformate	H2/CO/ Reformate	H2/CO2 /CH4 Reformate	H2 Reformate
Reforming	External	External Internal	External Internal	External
Oxidant	O2/Air	CO2/O2/Air	O2/Air	O2/Air
Efficiency	40-50%	50-60%	40-80%	40-50%

Cells are other technologies that are similar in design or output to fuel cells.

B. Specific Applications

Fuel cells allow for a number of different types of applications, including stationary power sources, portable power sources, micro power sources, and those found in vehicles.

1. Stationary Power Sources. Stationary power sources are connected to the utility grid. However, these types of fuel cells have the capability of providing premium power quality that the utility grid and momentaries cannot, especially in the cases of voltage sags. Premium power can be cleaner, less polluting, more secure, and more reliable. For these reasons, hospitals, plastic extruders, data centers, telecommunication switching centers, and cell phone towers will find fuel cell technology valuable.

Fuel cells may be used in residential homes, small commercial businesses, and larger commercial or industrial companies for emergency backup electricity, baseload / lifeline electricity, high-power quality requirements (i.e., in-home office connections), energy self-sufficiency, and remote off-grid locations. Utilities and other energy providers may also use fuel cells to ensure high customer power quality, meet transmission upgrade deferrals, and fit in with the "Green Power" market. Such distributed generation is modular, provides ease of sitting, and ensures lower capital cost.

2. Portable Power Sources. Portable power sources are not connected to the utility grid. These fuel cells allow consumers the opportunity for portable power for emergency equipment, hand-held power tools, and road signs.

3. Micro Power Sources. Like portable power sources, micro power sources are not connected to the utility grid either. These types of fuel cells have the capability of being manufactured in sizes that will comply with the smallest power requirements. Hand-held computers (i.e., 3 Whr), notebook computers (i.e., 40 Whr), and cellular telephones (i.e., 3 Whr) are a few such examples.

4. Vehicles. Fuel cells are currently being tested and marketed by many of the major automobile manufacturers. They provide an alternative to internal combustion engines, and because of their efficiency, will help reduce dependence on imported oil. Fuel cells also offer reduced vehicle emissions.

C. Molten Carbonate Fuel Cell (MCFC)

The Direct Carbonate Fuel Cell (DFC) is a type of molten carbonate fuel cell (MCFC) that internally reforms methane-containing fuels within the anode compartment of the fuel cell. This technology, as a mature product, has a projected net fuel-to-electricity efficiency of 55-60% and a total thermal efficiency approaching 85%. 16 fuel cell stacks were used in the Santa Clara Demonstration Project (SCDP) with each stack rated at 125-kW and consisting of 258 cells. The cells and stacks were based on "direct fuel-cell technology" developed by Fuel Cell Energy (FCE). Natural gas is internally reformed into hydrogen, partially in an internal reforming unit and partially at the cells. The approach, Fig. 1, is a combination of indirect internal reforming (IIR) and direct internal reforming (DIR), which provides for better thermal management.

An MCFC stack dynamic model was developed to analyze a spectrum of dynamic responses from slow to fast transients [10]. Several assumptions were made in this work: a single stack temperature, representation of mass inventory, water-gas shift reaction at equilibrium, and inclusion of appropriate kinetics for the reforming reaction. These latter assumptions relate directly to the fast dynamics of the fuel cell stack. In [11] the model is extended by first deriving an explicit differential equation set and then representing polarization losses and temperature-dependent terms in the cell voltage. This is done by combining the basic lumped-parameter dynamic model with results from a three-dimensional cell performance model, correlated with experimental data.

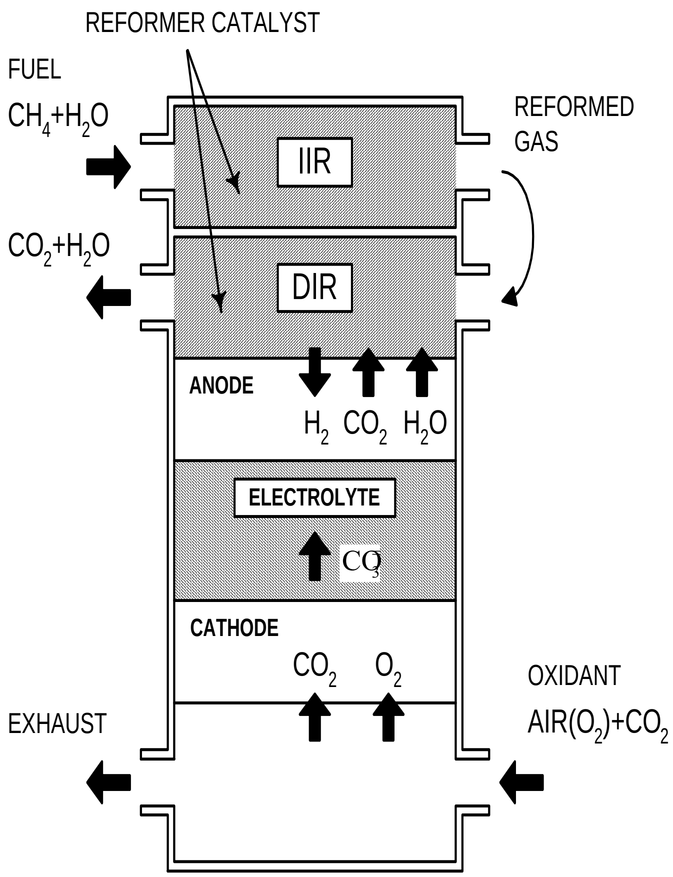

Fig. 1. IIR/DIR structure of MCFC stack.

A simplified process flow diagram (PFD) of the Santa Clara Demonstration Project is shown in Fig. 2. This consists of a lumped representation of all sixteen stacks together with the balance-of-plant (B.O.P.). A dynamic model for the SCDP including B.O.P. has been described in [12]. The principle components in the PFD are:

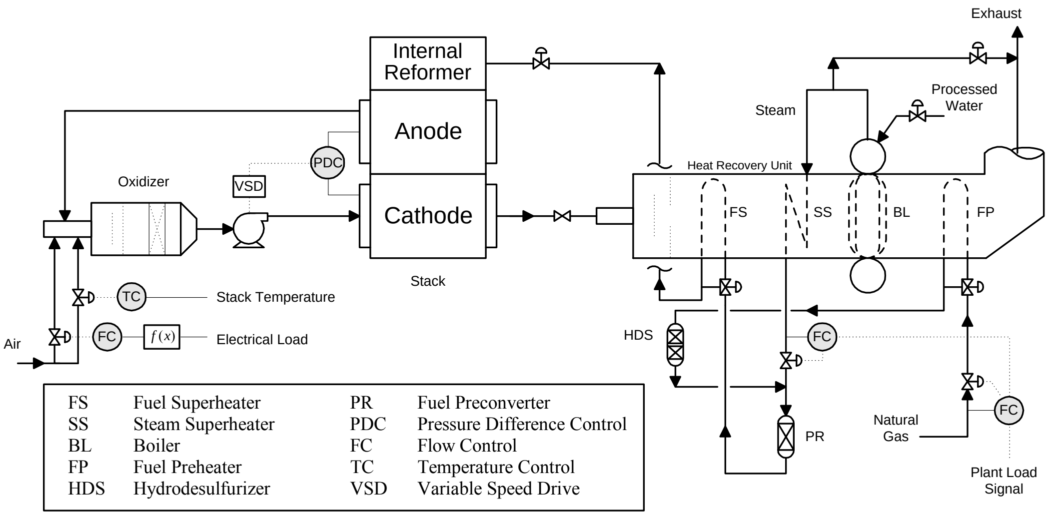

Fig.2. Simplified process flow diagram for the Santa Clora Demonstration Project

- Cathode gas preparation including anode exhaust oxidizer and booster blower
- Fuel processing including fuel preconverter and hydrodesulfurizer
- Heat recovery including steam generation and fuel and steam preheating
- Direct reforming (lumped) fuel cell stack

The stack cathode electrochemical reaction requires both O_2 and CO_2:

$$\tfrac{1}{2}O_2 + CO_2 + 2e^- \longrightarrow CO_3^{=} \qquad \textit{Cathode} \qquad (1)$$

where carbonate ions $CO_3^{=}$ then migrate to the anode electrode through the electrolyte. The O_2 required is made available by injection of air into the oxidizer to control stack temperature while CO_2 is made available by recycling the CO_2 from the anode electrochemical reaction:

$$H_2 + CO_3^{=} \longrightarrow H_2O + CO_2 + 2e^- \qquad \textit{Anode} \qquad (2)$$

In (1) a small percentage of the CO_2 is contributed by oxidation of CO (also present at the anode) within the oxidizer. According to Fig. 2, air flow into the oxidizer is under stack temperature feedback control. Due to the large stack thermal time constant, there is also feedforward flow control of air using plant electrical load as the measurable disturbance. The function $f(x)$ represents a static mapping between electrical load and desired air flow, with the advantage that a rapid change in air flow is possible, enabling a much tighter control of stack temperature than with slow feedback alone. Under the combined feedforward/feedback control scheme O_2 is well in excess of CO_2, with the possibility of CO_2 becoming the limiting reactant at the cathode.

The anode electrochemical reaction (2) requires hydrogen and there are several sources:

1. Hydrogen introduced into the Reforming Unit (RU) from upstream chemical reactions. RU is used to convert hydrocarbon into gas mixture of hydrogen and carbon compounds called "reformate."
2. Internal production of hydrogen from the reforming reaction in both RU and cell anode.
3. Internal production of hydrogen from the water-gas shift reaction in both RU and cell anode.

The reforming and water-gas shift (WGS) reactions are:

$$CH_4 + H_2O \longrightarrow CO + 3H_2 \qquad \textit{Reforming} \qquad (3)$$

$$CO + H_2O \longrightarrow CO_2 + H_2 \qquad \textit{Water-Gas Shift} \qquad (4)$$

Also part of the cathode gas preparation is a variable speed-driven booster blower for controlling differential pressure between anode and cathode.

Fuel processing consists of both the hydrodesulfurizer and the fuel preconverter. The hydrodesulfurization reactor removes odorants and impurities from natural gas to the level required for fuel cell operation. This reactor has minimal effect on key operating conditions such as temperature and pressure because it is primarily used to remove trace amounts (parts per million, ppm) of sulfur compounds. The preconverter in the system removes higher hydrocarbons from the gas to preclude the formation of carbon in the stack during temperature transients. This is **ACCOMPLISHED BY STEAM REFORMING, (3) AND (4), AT LOWER TEMPERATURE.**

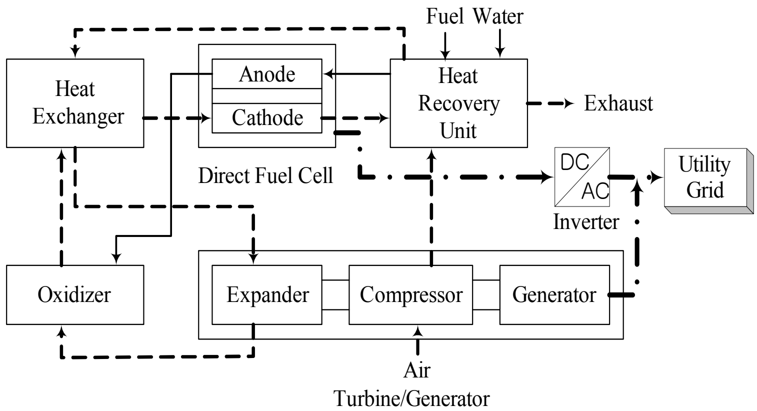

Fig. 3. Fuel cell/turbine hybrid system.

V. HYBRID POWER PLANT

The direct carbonate fuel cell (DFC) is a variant of MCFC in that it internally reforms methane-containing fuels within the anode compartment of the fuel cell. The integration of Direct Carbonate Fuel Cell with a gas turbine (DFC/T) is an emerging technology. The impetus for the integration is achieving ultra high efficiencies especially in large-scale power markets where the traditional combined cycles are approaching the sixty percent efficiency mark. The DFC/T cycle incorporates innovative design concepts for generation of clean electric power with very high efficiencies. One of the key features of the DFC/T combined cycle is the independency of the gas turbine pressure and the fuel cell pressure, which overcomes many of the operational issues during system transients [13].

Integration of a high temperature fuel cell with a gas turbine has recently been the focus of development by various organizations. The DFC/T hybrid system concept is based on integration of an atmospheric pressure internally reforming Direct FuelCell with a gas turbine. The power plant design utilizes a heat recovery approach for extraction of heat from the balance-of-plant. The fuel cell plays the key role by producing the larger share of the power (>80%). The gas turbine is utilized for generation of additional power by recovering the fuel cell byproduct heat, as well as for providing the air for the fuel cell operation. The DFC/T system concept is schematically shown in Figure 3. The feed water humidifies natural gas in a waste heat recovery unit (HRU). The mixed fuel and steam are then preheated to about 550°C prior to entering the fuel cell anode. The methane in the natural gas is reformed in the fuel cell and its chemical potential is converted to electrical energy. The anode

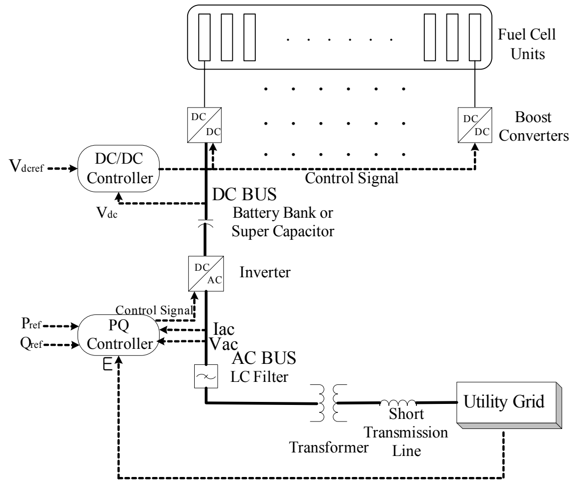

Fig. 4. Interface to the utility grid.

exhaust, containing some unreacted fuel, is mixed with air and then oxidized completely in a catalytic oxidizer. In the turbine cycle, air is compressed to the operating pressure of the gas turbine and heated in a recuperator using waste heat from the fuel cell. The compressed air is then heated further to the operating temperature of the gas turbine expander by a heat exchanger (HE) located between the oxidizer and fuel cell cathode [14]. The hot compressed air is then expanded in the turbine providing additional electricity. The expanded air flows into the oxidizer, into the HE, and subsequently into the fuel cell cathode. At the cathode, the oxygen in the air and the CO2 from the anode are reacted to complete the electrochemical fuel cell reaction. The cathode exhaust provides the heat for preheating the air and fuel, and for generation of steam in the HRU before exiting the power plant.

Figure 4 shows a block diagram of a FC power plant interfaced with the utility grid via boost dc/dc converters and a three-phase pulse width modulation (PWM) inverter. An energy storage device, e.g., a battery bank or super capacitor, is used to improve the performance of the FC power system under transient disturbances such as motor starting. An LC band pass filter is used to eliminate (or at least reduce) undesired harmonics. A short transmission line is used to connect the MCFC power system to the utility grid [15].

FC can deliver the desired real and reactive power to the grid, when a utility is operating under heavy load. With a FC power system, a certain amount of power may be scheduled to be delivered to a load center from the utility grid and the rest to be supplied by the FC system. A proper load-tracking controller can be used to ensure that the scheduled power is delivered from the grid, and that the FC system follows the remainder of the load demand.

VI. CONCLUSION

Since its inception, the nature of producing electricity has favored large central-station generators, all interconnected in a vast web of transmission lines. Distribution lines carried this electricity to the homes, businesses and factories of the world. Years of technology research and development have produced smaller generators that can approach the low cost of grid-supplied electricity. In some cases, these smaller devices provide superior solutions to supplying electricity.

In recent years, deregulation has accelerated the development of these types of alternative technologies, as inventors see the opportunity to compete in market niches that did not exist a few short years ago. While DG may greatly improve reliability, some problems concerning power quality and system reliability may arise under certain circumstances. Control systems and communication possibilities would be necessary to protect the distribution network and maximize the use of active and reactive power generated by DG.

Fuel cells will start out as a high-cost technology, supplying electricity (and heat) to these niches and gradually become more attractive to mainstream electricity users as they improve in capability and decrease in cost. Fuel cells, used to generate electricity, are an up-and-coming solution to the energy problem, and may increase in popularity as the world moves toward the deregulation of the utility industry. Among several types of fuel cells, an MCFC stack dynamic model was developed to analyze a spectrum of dynamic response from slow to fast transients. The integration of Direct Carbonate Fuel Cell with a gas turbine is an emerging technology to achieve high efficiencies in large-scale power markets. Fuel cell-microturbine hybrid power plant can be interfaced with the utility grid via boost dc/dc converters and a three-phase pulse width modulation (PWM) inverter, controlling active and reactive power.

Using new clean-energy options, such as hydrogen and fuel cells, will be an increasingly important part of the global energy mix in the coming decades. The potential benefits – economical and environmental – of a hydrogen economy are enormous. Hydrogen technology and fuel cells are innovations the world needs.

VII. REFERENCES

[1] M. Ilic, F. Galiana and L. Fink, Power Systems Restructuring, Kluwer Academic Publishers, M.A., 1998.

[2] Vision -21, Environmental Electric Energy Opportunities for the Next Century, NSF Workshop, Arlington, VA, April 27-29, 1998.

[3] Future Research Directions for Complex Interactive Electric Networks, NSF/DOE/EPRI Workshop, Washington, DC, November 16-17, 2000,

[4] Department of Energy, http://www.energy.gov/, Nov. 24, 2005.

[5] K. Tran and M. Vaziri, “Effects of dispersed generation (DG) on distribution systems.”, IEEE Power Engineering Society General Meeting, June 12-16, 2005, pp.748 – 753.

[6] I. El-Samahy and E. El-Saadany, “The effect of DG on power quality in a deregulated environment.”, IEEE Power Engineering Society General Meeting, June 12-16, 2005, pp.714 – 721.

[7] W. Sweet, "Networking assets.", IEEE Spectrum, Jan. 2001, pp.84 – 88.

[8] I. Iannone, S. Leva and D. Zaninelli, "Hybrid photovoltaic and hybrid photovoltaic-fuel cell system: Ecconomic and environmental analysis", IEEE Power Engineering Society General Meeting, June 12-16, 2005, pp.2289 – 2295.

[9] Wisconsin Public Service, http://www.wisconsinpublicservice.com/, Nov. 24, 2005.

[10] M. D. Lukas, K. Y. Lee, and H. Ghezel-Ayagh, “Development of a Stack Simulation Model for Control Study on Direct Reforming Molten Carbonate Fuel Cell Power Plant,” IEEE Transactions on Energy Conversion, Vol. 14, No. 4, pp. 1651-1657, 1999.

[11] M. D. Lukas, K. Y. Lee, and H. Ghezel-Ayagh, “An Explicit Dynamic Model for Direct Reforming Carbonate Fuel Cell Stack,” IEEE Transactions on Energy Conversion, Vol. 16, No. 3, pp. 289-295, Sep. 2001.

[12] M. D. Lukas, K. Y. Lee, and H. Ghezel-Ayagh, “Modeling, Simulation, and Control of Direct Reforming Molten Carbonate Fuel Cell Power Plant,” The Fourth IFAC Symposium on Power Plants & Power Systems Control 2000, pp. 127-134, April 26-29, 2000.

[13] H. C. Maru and H. Ghezel-Ayagh, “Direct Carbonate Fuel Cell – Gas Turbine Combined Cycle Power Plant,” European Fuel Cell Forum, A10-4, July 5-8, 2005.

[14] I. Jurado and J. R. Saenz “Adaptive Control of a Fuel Cell-Microturbine Hybrid Power Plant,” IEEE Trans. on Energy Conversion, vol. 18, No. 2, pp. 342-347, June, 2003.

[15] C. Wang, M. H. Nehrir, and S. R. Shaw, "Dynamic models and model validation for PEM fuel cells using electrical circuits," IEEE Trans. on Energy Conversion, vol. 20, No. 2, pp. 442-451, June, 2005.

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