18

Energy Issues under Deregulated Environment

18.1 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 [1].

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 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.

18.2 Harmonics Generated from Railway Operation

Nowadays, there are 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 [2].

The electric power supplies all over the world are becoming under 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, there are three 400kV connections to the National Grid Company (NGC); one of them is a dual connection. 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 centenary system. Due to these requirements, the need for load balancing and voltage regulating equipment are essential.

18.2.1 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 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 the firing pulse to the thyristors, which is the voltage across the reactor and 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 that 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.

18.2.2 Data Analysis

Measurements on performance were carried out on a typical railway operation. Figure 18.1 shows the variation of traction transformer catenary current that lasted for about 22 minutes and 30 seconds.

Fig. 18.1. 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 18.2 to 18.5 respectively below:

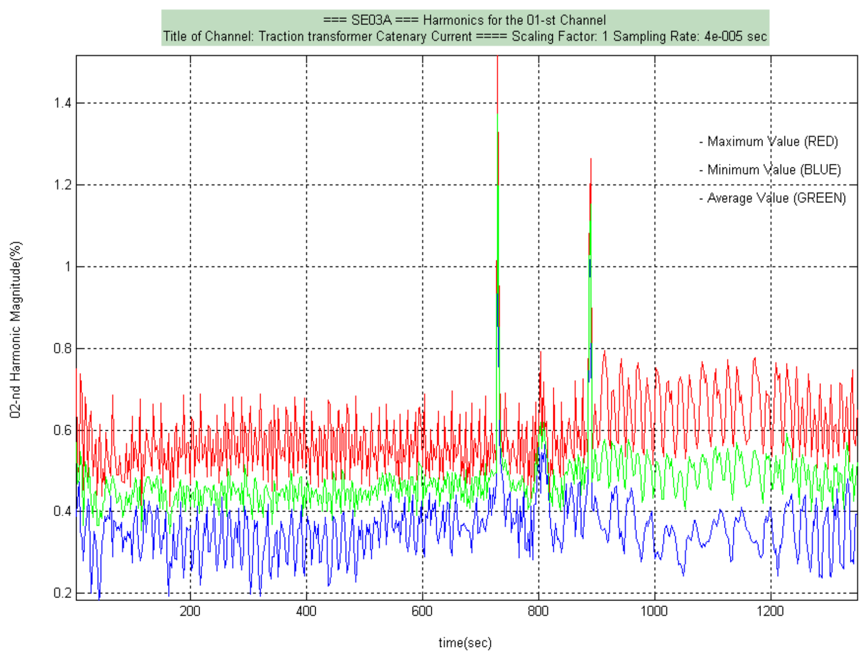


Fig. 18.2. Second harmonic

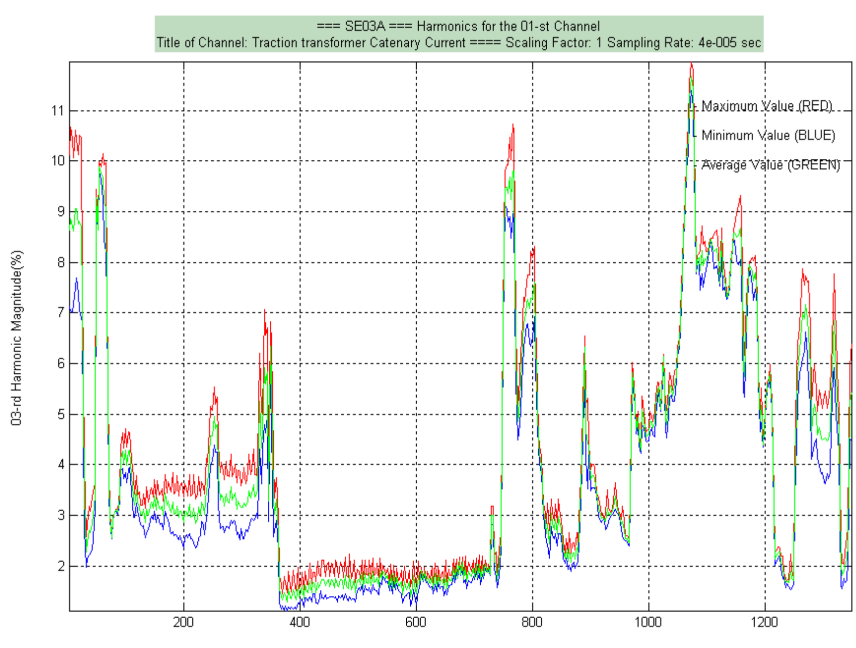


Fig. 18.3. Third harmonic

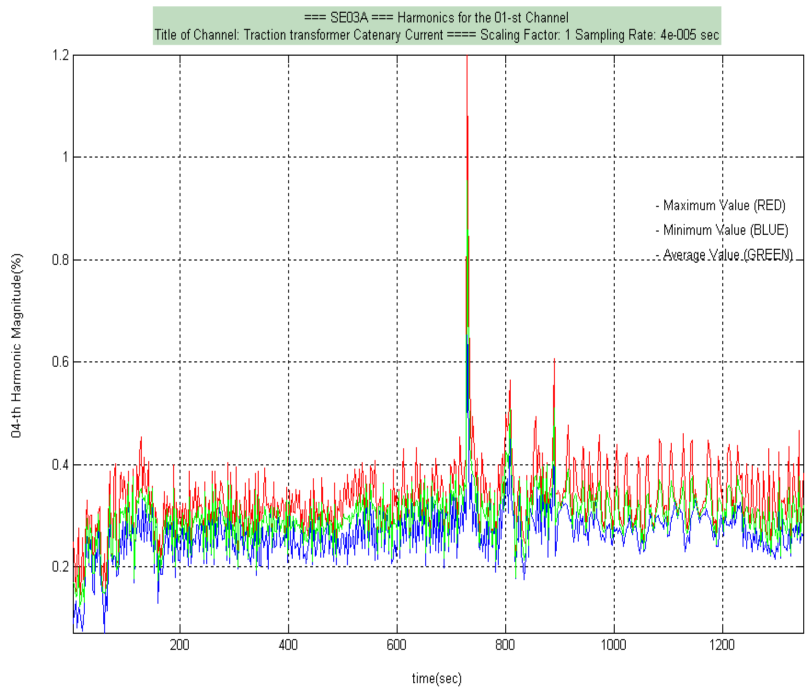


Fig. 18.4. Fourth harmonic

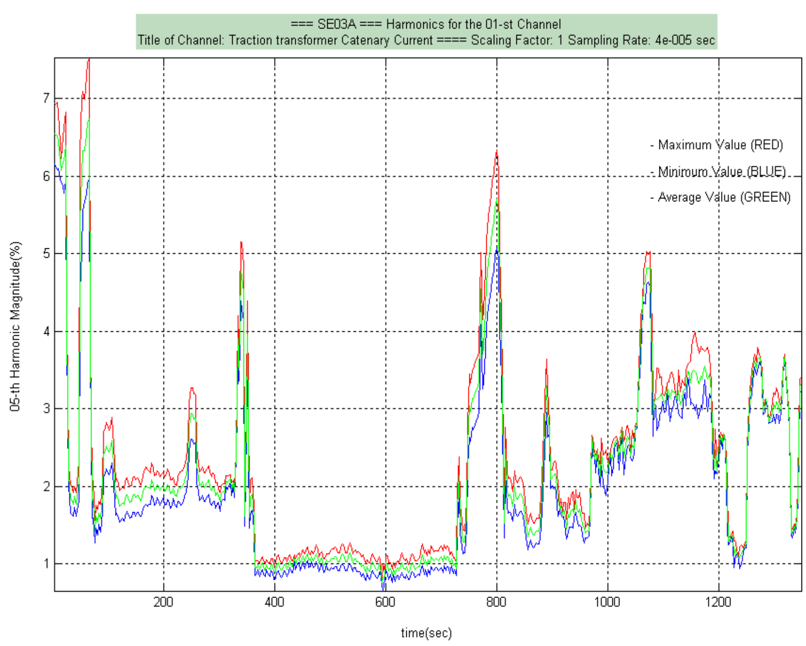


Fig. 18.5. Fifth harmonic

18.3 Practical Application of Wavelet to Power Quality Analysis

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 [3].

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 low voltage (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. 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 analyze harmonics contents contained in the power signal. The FFT has many attractive features. That theory of FFT has been fully developed and is well known; scientists and engineers are familiar with the computation procedures and find it convenient to use as many standard computation tools 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 Section attempts to develop an algorithm based on wavelet transform to identify power frequency variations, sub-harmonics, integer harmonics and inter-harmonics.

18.3.1 Wavelet Transform and Analyzing 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.

The wavelet transform of a continuous signal, f(t), is defined as:

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

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. These are

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

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

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

where f_b is the bandwidth parameter and;
f_c is the center 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 it 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. For example, the mean of the CMW in (3) with f_b=2 and f_c=1 is $2.6753\text{x}10^{-9}$ which is practically equal to zero. The frequency support of the CMW in (2) is the value of the entire frequency axis.

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

18.3.2 Harmonics Frequency Detection Algorithm

Given a signal f(t) represented as

$$f(t)=a(t)\cos\phi(t) \qquad (4)$$

The wavelet function in (2) can be represented as

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

The dilated and translated wavelet families 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

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

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 range of $\psi_{u,s}$ in (6) and if $\phi'(u) \geq \frac{\Delta\omega}{s}$. 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 so straightforward.

The instantaneous frequency is measured from wavelet ridges defined over the wavelet transform. The normalized scalogram is defined by [4] as:

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

It is calculated as:

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

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

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

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

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

18.3.3 Discrimination of Adjacent Frequencies

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

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

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

Suppose that (12) is represented as

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

where x represents an arbitrary magnitude to be defined later.

Combining (12) and (13) gives

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

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

Figure 18.6 shows the plot of the frequency support of two dilated CMW at scales s_1 and s_2 respectively.

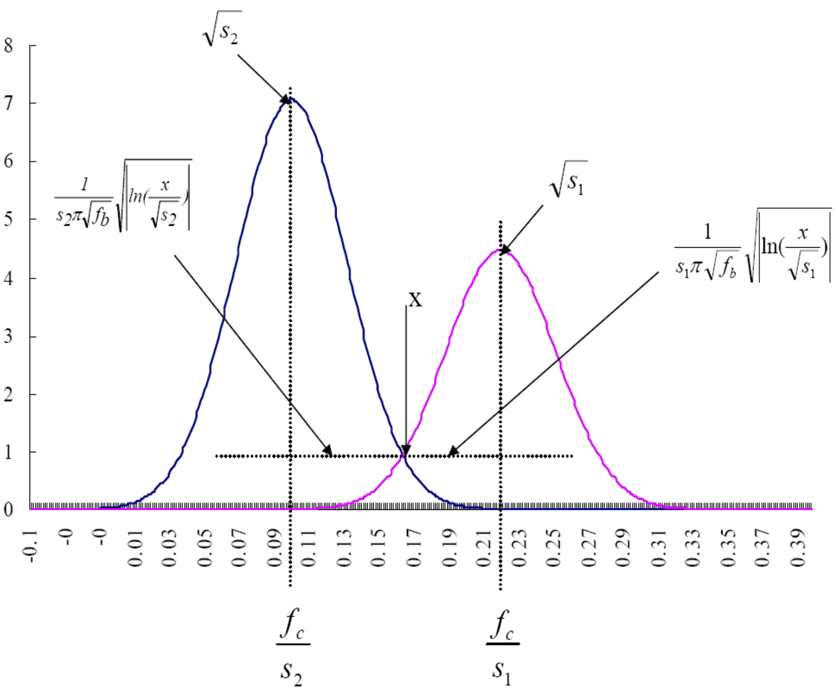


Fig. 18.6. Frequency plot of (14) for two CMWs at scales s_1 and s_2

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

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

where f_s represents the sampling frequency, then

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

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

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

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

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

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 that is a necessary condition to discriminate adjacent harmonic frequencies in the power signal.

18.3.4 Harmonics Amplitude Detection Algorithm

Theoretically, once the algorithms developed before identify the harmonic frequencies presented in the power signal, 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 harmonic frequencies ranging from 50Hz to 1000 Hz have errors of the order of ±5%. Figure 18.7 below shows a plot of the absolute coefficients generated by CWT for the harmonic frequency at 991.5Hz.

In Figure 18.7, 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.

Discrete Stationary Wavelet Transform (DSWT) is adopted to remove the fluctuations appeared as noise superimposed on the absolute coefficients plot in Figure 18.7.

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.

Figure 18. 8 shows the DSWT output of the absolute coefficients shown in Figure 18.7 which clearly shows that the superimposing fluctuations are removed resulting in an accurate detection of the harmonic amplitudes.

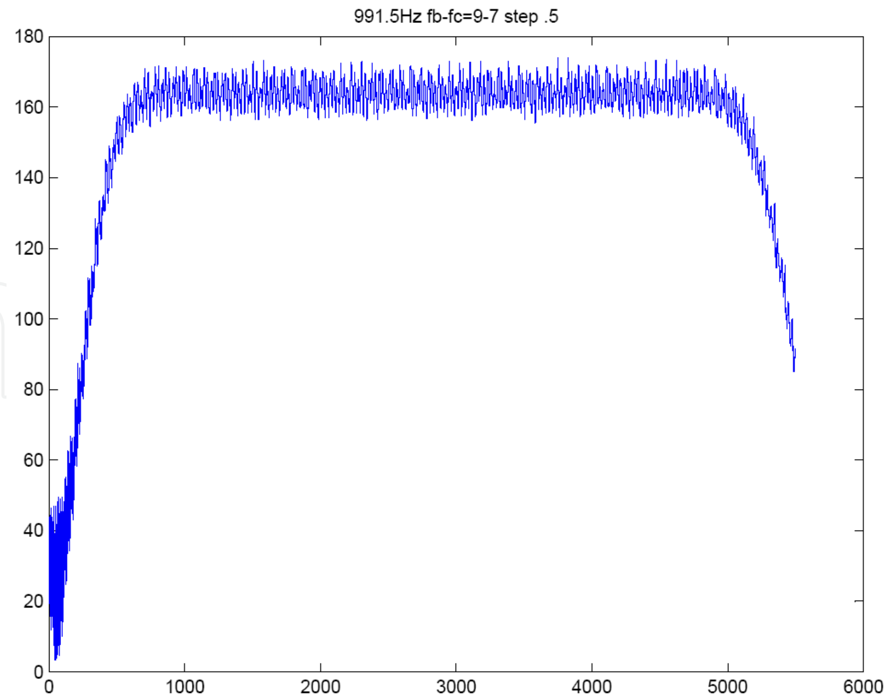


Fig. 18.7. Absolute coefficients plot generated by CWT (using Complex Morlet Wavelet, f_b=9, f_c=7) for harmonic frequency at 991.5 Hz

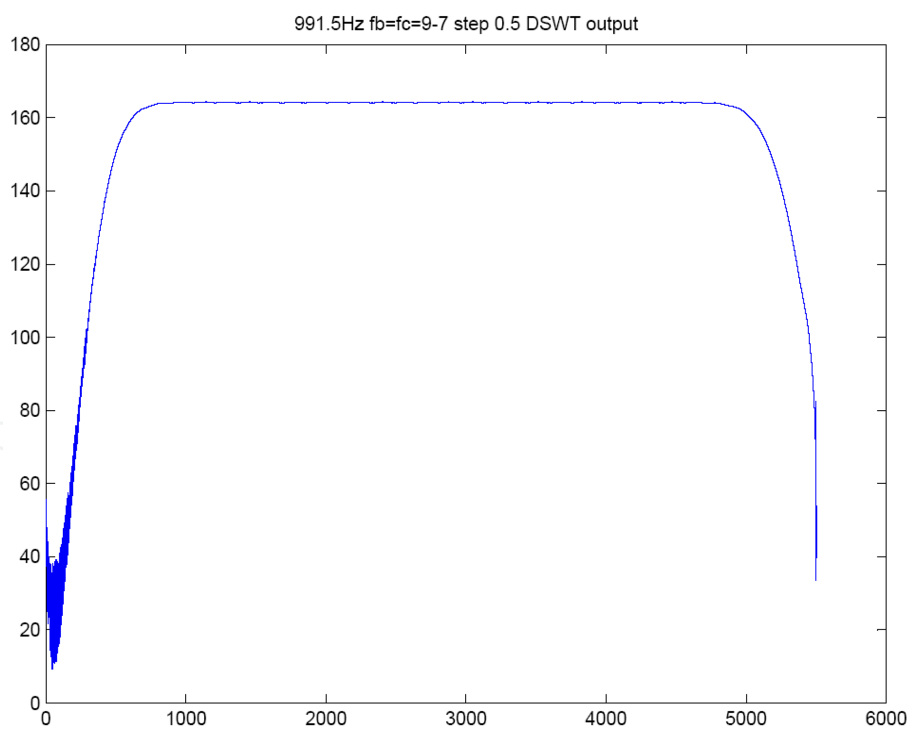


Fig. 18.8. Coefficients generated by discrete stationary wavelet transform (using Symlet2 wavelet, level 5 decomposition) from the absolute coefficients generated by CWT (using Complex Morlet Wavelet, f_b=9, f_c=7) for harmonic frequency at 991.5 Hz

18.3.5 Simulation Setting

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 18.1.

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

Table 18.1. Harmonic Frequency contained in the simulated signal

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 harmonic 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 18.2. In any case a minimum of 20 data per cycle is maintained. The data size for CWT computation is set at 5000.

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

Table 18.2. Sampling frequencies and sample data size for harmonic frequencies of the simulated signal

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

18.3.6 Simulation Results

The simulation results for harmonics detection is shown in Table 18.3. It can be seen that the frequency detection by the proposed algorithm is very promising, especially at high harmonic frequencies. 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 before is successful in distinguishing adjacent frequencies.

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%

Table 18.3. Harmonic frequencies detection results

The accuracy in the detection of harmonic amplitudes depends on the accuracy in harmonic frequencies detection. As seen from the results shown in Table 18.4, the harmonic 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%.

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%

Table 18.4. Harmonic frequencies amplitude detection results

The larger amplitude detection errors are found to have happened at 50.1 Hz and 249 Hz respectively. Table 18.5 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.

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%

Table 18.5. Comparison of detection errors in harmonic frequencies and harmonic amplitudes

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.

18.4 Energy Risk and the Management

Risk may be defined as the potential harm that may arise from some present process or decision or from some future event, the hazard to which we are exposed is uncertainty. Harm can take different forms in the electricity industry, whether one is an investor in generation, a sale organization, or an end-user.

Uncertainties could be due to some of the following items:

- Electricity price (volatility)
- Fuel price
- Fuel availability (uncertain availability)
- Economic conditions (inflation, floating exchange rates, interest rates)
- Volume (uncertain ability to balance supply and demand of electricity)
- Financial risk (credit and settlement)
- Weather load dependence
- Environmental constraints
- Transmission restrictions
- Technology changes
- Regulatory conditions (consistency and stability of regulations, transparency)
- Political decisions (political tariff setting).

There is a need to adequately assess and manage risk. Some risk analysis methods for energy include [5]:

- Position reporting – monitoring of portfolio positions
- Deterministic scenario analysis
- Sensitivity analysis
- Value-at-risk models
- Maximum loss model.

Risk management is the process of assessing risk and developing strategies to manage the risk.

There is a need for investment in new capacity due to electricity demand continues to grow and reserve margins have declined as markets have been liberalized.

For the UK, when extending System Operation to Scotland there were a number of differences. The two Scottish systems have been essentially vertically integrated since Nationalization – England and Wales has always split Supply and Distribution from Generation, Transmission and System Operation.

The Scottish demand is only 10% of GB demand but they have 10GW generation. Transmission is at 400/275 to the major stations and load centers but there is a lot of low capacity 132kV transmission supporting remote areas with a lot of small generating stations – hydro and new wind [6].

We need to observe Generation down to 5MW (30MW in South Scotland) to ensure secure operation of the Transmission system. This means modeling a number distributed stations (up to 100MW), exempted from having a generation license. This highlights the issues that arise with increased penetration of distributed generation to the system.

A change in any output or load will immediately affect all the others. The frequency controls the magnitude of each demand by direct relation to nominal (50Hz) and it will change immediately if a large demand or generation source changes magnitude.

Inertia on rotating synchronous generation will release extra output on falling frequency and vice versa, while frequency sensitive units will increase or decrease steam flow to turbine of a frequency change.

The balance has to be maintained at a level such that so that frequency does not go outside statutory limits (± 0.5Hz, 1%) or operational limits (± 0.2Hz 0.4%). To do this it is essential to know or predict the export and import of all elements of generation and demand.

At any time, the level of ordered plant may turn out to be insufficient and expensive but fast reacting generation must be used.

Observability and predictability of demand and Generation output is crucial to maintaining a viable balance, keeping spare and reserve levels and thus fuel burn and emissions down.

Conventional Plant is slow to start to compensate for market errors. Much expensive part loading is required to provide response and plant has to be warmed to be available as spare. Better and more frequent forecasting is being developed and use of frequent countrywide observation seems appropriate for better accuracy in market timescales. Also try and forecast when such errors are likely. The difference between the predicted and the actual output has a marked effect on the level of demand to be met by other plant.

The use of other flexible plant to cover renewable shortfall risk is inefficient; that capacity should be scheduled to help meet demand and reduce main generation. Large demand variations need to be tackled to improve efficiency of delivery and reduce capacity requirement. The energy efficiency argument for electricity is not just to reduce demand it is also to control when optional demand is used.

Modern ICT systems can improve information flow to and from large numbers of distributed locations. This can be used to improve observation and predictability. Work on demand side management (DSM) shows that such information systems can have major benefits in improving load factor and thus reducing emissions and unnecessary fuel burn.

The 21st century vision for information systems should have all the information (including 'real-time') to make sound asset management and investment decisions; a fully populated asset register linked to network management, financial, work management, SCADA, and other key information systems; comprehensive modeling, reporting, and decision support tools, ability to predict future performance accurately across short, medium and long timeframes; uncertainty (over asset condition and time-to-failure) reduced such that performance can be predicted within acceptable levels of confidence and last but not least a comprehensive network and asset knowledge to optimize risk and maximize business performance.

There are the risks and challenges, such as re-investment is not like green-field investment; managing outage risk is an enormous challenge**;** successfully integrating new technologies with old during the transition stage is another enormous challenge**.** But the greatest challenge is in deciding what exactly should be done, for example, to do something different or to take the 'safe' option and rebuild an infrastructure that was designed in the 19th and 20th centuries. It would be nonsense to apply the same approach for the same problem but to expect to have a different result.

Turning to the economic consideration, replacing like with like is always the easiest - and cheapest - option in the short-run, but the assets installed today will still be there in 50 to 70 years time. There is a big question that they meet future requirements for performance. Basically redesigning networks will require significant up-front costs and some existing assets may need to be retired early. Therefore incentives to invest for long-term sustainability rather than short-term gains are essential.

However, presently an inadequate core-skill base is a big issue [7]. Since 1996, the number of electrical engineering students on degree courses has fallen by 29%. Only 13% of these opt for power-related modules. Overall, less than 150 students graduate with a degree in power engineering in the UK each year - and most of these are overseas students (about 80% at the post-graduate level). Presently, more effort has been spent to encourage young (school-age) people such that they perceive engineering to be an exciting career/profession.

Liberalization also leads to uncoordinated cross-border trades; increased transmission distances and transmission systems run closer to their limits due to commercial pressure.

The future will have more decentralized but coordinated operation. Coordination requires effective IT tools to exchange of real-time information. Modern control room facilities should be able to provide accurate and sufficient system information for the operators' safety operating; all available remedies for different security issues and suggestion for operators for the best remedies. Monitoring system can be designed to display machine angle separations and damping factors for transient stability and dynamic stability, respectively. Secured network of sensors, communication links, information processors and dynamic algorithms are developed for intelligent grid.

Pricing Models are developed for mid-term, long-term or spot pricing deals. They must manage the risks of over/under production and buying/selling into unfavorable market condition.

In summary, factors that need to be taken into consideration for the electricity industry include asset age profiles and condition trends indicate the need for a sustained ramp-up in asset replacement - perhaps over 15 years. Electricity demand continues to grow and this has implications for plant ratings. Customer expectations regarding security, reliability, and quality are increasing. Environmental considerations are placing new constraints on network design and operating criteria. Networks must support the low greenhouse gas emission which means being accessible to distributed (renewables) generation. To achieve this, it is essential to have long-term national commitment to infrastructure investment and management, an effective incentive-driven regulation, a creation of appropriate skills and experience through the wider education system and the development of appropriate technologies by suppliers for demand-side management and smart metering.

18.5 Insurance Issues for Energy Risk

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.

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. 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.

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.

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 favorable 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.

18.5.1 Risks to Energy Complaints

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 transfer. Not all risks are transferable to insurance companies since an insurer can only accept "pure risks". 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 in mind, policies that guard events that give rise to an insurable primary cause need to be bought into consideration. There are several risk categories to consider [8] and they are summarized as follows:

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 blowout, 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 specialized 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. Economists as well as evaluation of the fiscal regime that the host country is offering evaluate market risks.

18.5.2 Option for Cover

Energy companies have several options on how to manage their risk portfolio. This section illustrates the four basic options that risk managers may have to transfer insurable risks.

A. Do Nothing
Keep uninsured risk with investors and shareholders. Cover losses from current revenue stream account as operating costs. This is useful 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 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 insurance companies. This is referred to as self-insurance or captive insurance and can be considered for large risks. Captives can purchase insurance and have tax benefits on cash build up.

18.5.3 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 unexpected events that lie outside core activities. 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. They may suggest keeping spares on site to reduce delivery times to remote sites e.g. remote transformer sites to 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 minimize 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. 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.

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

In some countries failing in 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. As far as liability goes, energy companies are currently not liable for the widespread losses to business and individuals. Therefore businesses that rely heavily on energy supply should consider business interruption cover.

8.5.4 Insurance and Deregulation

Prior to deregulation, contracts between generation and transmission companies did not exist since both entities belonged to the same government-owned institution. Since more and more energy companies are now in 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 that energy companies should protect themselves from them 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. Privatized 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 that 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 which 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.

18.5.5 Relevant Cover Types

Insurance covers are very complex and contain many clauses on the primary cause and the insured subject matter. This section summarizes 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 in 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. 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 organization. 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 euros. Followed by the 3rd tier where the contributions from all of the contracting parties must pay up to 300 million euros. With this, the Paris/Brussels regime will provide for up to 1.5 billion euros of compensation.

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 hydroelectric companies from draught. Money is paid for every inch or cm 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*:** Pay if wind speeds fall below threshold levels so that power can be bought from the spot market.

18.5.6 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 mutual 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 organization. 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 favorable terms or fast response times to minimize 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.

18.5.7 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. But price increases or defect clauses in contacts are expected for new unproven generation technology e.g. renewable.

18.5.8 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.

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 reinsures offer short tail coverage (1 year) with high deductibles to take advantage of possible high earning from increased rates. Established reinsures 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.

18.5.9 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 utilized can be from a foreign entity or a local parent company.

18.5.10 Impact of 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.

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. 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 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 and the World Trade Center (WTC) in 2001 has meant that many reinsurers have had to reconsider the acceptance and pricing of single large risks. E.g. Munich Re increased its premium rates for oil platforms in the Gulf of Mexico by 400% in November 2005.

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

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 current renewal prices for electricity utilities down. In the past years, there is rate reductions of 40-50% as compared to 2002 .

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

18.6 Wind Energy Generation System

18.6.1 Introduction

This section presents a unique Axial-Flux Permanent Magnet Synchronous Generator (AFPMSG), which is suitable for both vertical-axis and horizontal-axis wind turbine generation systems. An outer-rotor design facilitates direct coupling of the generator to the wind turbine, while a coreless armature eliminates the magnetic pull between the stationary and moving parts. The design and construction features of the AFPMSG are reviewed. The flux-density distribution is studied, with the aid of a finite element software package in order to predict the generated e.m.f. waveform. The performance equations of the AFPMSG are derived, and the condition for maximum efficiency is deduced for both constant-speed and variable-speed operations. The experimental results, in general, confirm the theory developed [9].

The past few decades have witnessed rapid development in the use of alternative energy resources for electrical power generation, which plays a key role in rural electrification and industrialization programs. Power generation utilizing wind energy, in particular, has received great attention in countries all over the world. In remote areas where a central grid connection is not feasible, small-scale autonomous wind-energy power-generation systems may be developed for supplying to local consumers, reducing the connection cost, and avoiding the transmission and distribution losses. The market potential of wind-energy generators is considerable in view of the surging power demands in China and Southeast Asia. Self-Excited Induction Generators (SEIGs) have been widely used for wind energy power generation. Although induction machines are robust and inexpensive, they need capacitors to provide excitation, and their satisfactory operation requires an excitation controller. Over-voltage and over-current are operational problems that need to be resolved under variable speed operation. The space-consuming capacitors are bulky and expensive.

Greater availability and decreasing cost of high-energy permanent-magnet (PM) materials, neodymium-iron-boron (NdFeB), in particular, has resulted in rapid permanent magnet generator development, especially for wind energy conversion applications. PM machine advantages include lightweight, small size, simple mechanical construction, easy maintenance, good reliability, high efficiency, and absence of moving contacts. More importantly, PM generators can readily deliver power without undergoing the process of voltage build-up and there is no danger of loss of excitation.

Many small wind-turbine manufacturers use direct-coupled PM generators. Compared with a conventional, gearbox-coupled wind turbine generator, a direct-coupled generator system eliminates mechanical reduction gear, reduces size of the overall system, lowers installation and maintenance costs, lessens component's rapid wear and tear, lowers noise, and quickens response to the wind fluctuations and load variations.

However, a direct-coupled generator has to operate at very low speeds (typically from 200 r/min to 600 r/min) in order to match the wind-turbine speed, and, at the same time, to produce electricity within a reasonable frequency range (25–70 Hz). The generator is physically bigger in size and must be designed with a large number of poles. Various PM machine topologies have been proposed for direct-coupled wind generator applications, namely outer-rotor design, modular design, axial-field machine, the TORUS generator and core-less generator.

These machines have been developed mainly for use with horizontal-axis wind turbines. In this section, a unique axial flux permanent-magnet synchronous generator (AFPMSG) that can be used in a horizontal-axis wind turbine (HAWT) or a vertical-axis wind turbine (VAWT) system will be investigated.

Application potentials include a power source for rural farms, villages, and home energy for remote-area weather monitoring equipment, and a portable power supply for nomadic people.

This section is organized as follows. Two direct-coupled wind turbine systems that may employ the proposed AFPMSG are introduced in sub-section 18.6.2. The design features and construction of the prototype generator are presented in sub-section 18.6.3. The analysis of the flux density distribution of an experimental AFPMSG using a two-dimensional finite element package is presented in sub-section 18.6.4. Steady-state performance analysis is discussed in sub-section 18.6.5. Experimental results are presented and discussed in sub-section 18.6.6.

18.6.2 Wind-Turbine Generator Systems

Two small-scale wind-turbine generator systems are proposed here. Figure 18.9 shows a horizontal-axis wind turbine system (HAWT) that employs the proposed direct-coupled AFPMSG. To facilitate direct coupling of the generator to the turbine blades, an outer-rotor machine configuration is used. The rotor rotates about a stationary shaft, which is supported on a tower by means of a yaw mechanism. The turbine blades are attached on the flange surface of the rotor. For simplicity in construction, a single-sided AFPMSG configuration is adopted. As shown in Figure 18.10, the disk armature winding is attached to the shaft via a metal coupler and is sandwiched between the two rotor frames, one of which carries surface-mounted magnets.

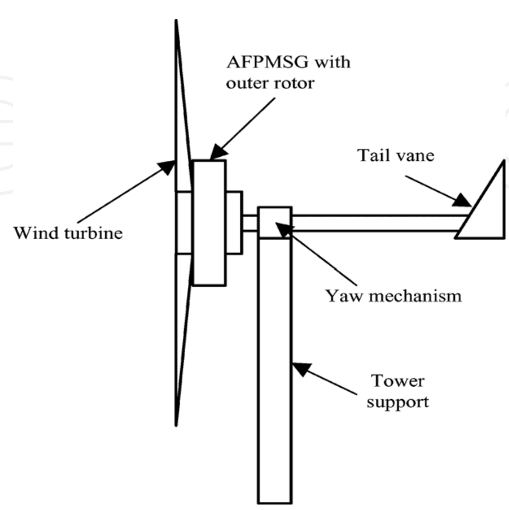


Fig. 18.9. Proposed arrangement of a micro-horizontal-axis wind turbine (HAWT) system using an outer-rotor AFPMSG

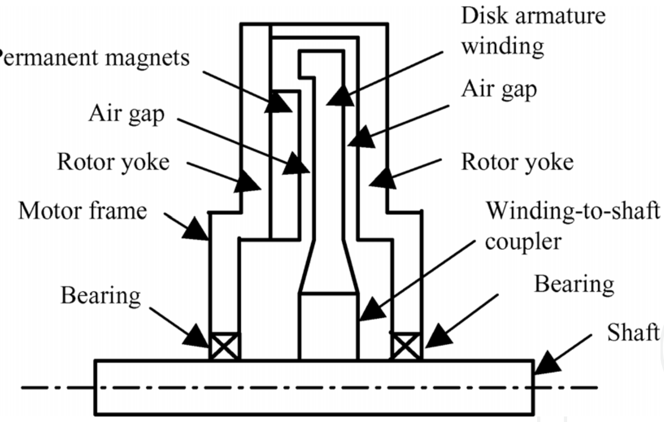


Fig. 18.10. Cross-sectional view of the proposed outer-rotor AFPMSG

The totally enclosed design will keep off rain, dirt, and foreign matter, therefore, a nacelle is not required, and system cost and weight is minimized. The rotor frames also serve as the yokes by completing the magnetic circuit. The proposed outer-rotor AFPMSG design may also be applied to a form of vertical-axis wind turbine (VAWT) system, as shown in Figure 18.11. This turbine has recently received some attention for possible deployment in a rooftop wind generation system. The turbine consists of a circular disk that spins on a stationary shaft. The rotatable shutters, when driven into the wind, will cause the circular disk to spin about the hollow shaft (shown shaded), thereby turning the rotor of the AFPMSG, which is attached to the disk.

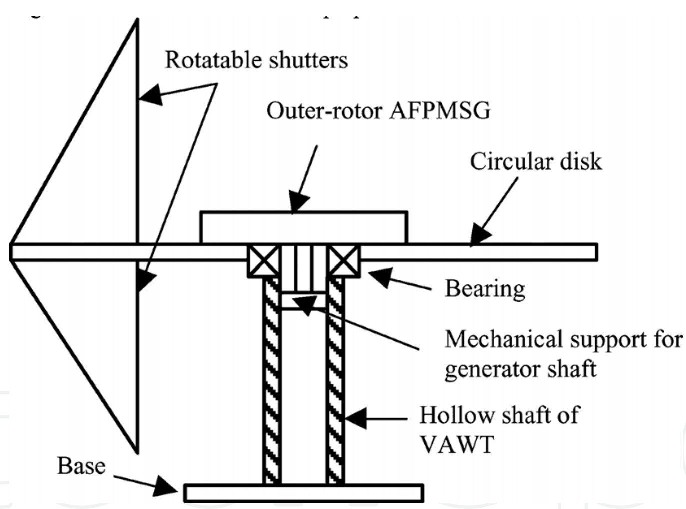


Fig. 18.11. Vertical-axis wind turbine (VAWT) using the proposed outer-rotor AFPMSG

18.6.3 Design and Construction of AFPMSG

A. General Design Considerations

The AFPMSG's weight is reduced by using a large number of poles and high-energy neodymium-iron-boron (NdFeB) magnets for the rotor field. When driven by a low-speed wind turbine, the poles enable generation at a reasonable frequency range. This also reduces yoke thickness and the length of armature coil overhang. The low-speed generator design poses a less stringent demand on the mechanical strength of the rotor magnets. Since high-energy

NdFeB magnets are used, an air gap disk winding design is feasible. The coreless armature design results in zero magnetic pull between the stator and rotor, eliminates iron loss, and improves generator efficiency. There is no cogging torque so smooth running is assured. The number of poles of the AFPMSG is determined by the intended operating speed of the wind turbine. Most small-scale wind turbines have nominal speeds in the range of 400–800 r/min. Hence, for an output voltage at a reasonable frequency, the number of poles will probably be in the range of 10–18. The NdFeB magnets, which are approximately trapezoidal-shaped and have a short length in the direction of magnetization, can be easily manufactured, and are readily available in the market.

B. Principal Machine Dimensions

For a given output power and operating speed, the AFPMSG principal dimensions may be determined using an approach similar to conventional machine design approaches, based on specific magnetic and electric loadings. For the special geometry of the AFPMSG, the output power *P* is given by:

$$P = 1.11\xi\sigma_f K_{w1} n\overline{B}ac\frac{\pi^2}{4}D_1(D_2^2 - D_1^2) \quad (20)$$

Where
ac specific electric loading at the inner circumference of
the armature;
*D*1 inner diameter of rotor magnet;
*D*2 outer diameter of rotor magnet;
*Kw*1 winding factor of armature;
B specific magnetic loading;
n rotor speed;
ξ ratio of output voltage *V* to open-circuit voltage *EF* ;
Of correction factor to account for flux fringing in the radial direction at the inner and outer peripheral regions.

For small machines supplying a pure resistive load, the ratio ξ may be chosen to be 0.7–0.8.

In order to maximize the output power for given values of specific loadings, the ratio of *D*2 to *D*1 should be chosen to be √3. From (20), the optimal output power of the AFPMSG may be expressed as:

$$P_{\text{opt}} = 1.11\xi\sigma_f K_{w1} n\overline{B}ac\frac{\pi^2}{2}D_1^3 \quad (21)$$

By equating *P*opt in (21) to the desired power output, *D*1 (and hence *D*2) can be determined.

The total axial length of the AFPMSG is given by:

$$l_{\text{axial}} = l_m + l_g + l_{y1} + l_{y2} \quad (22)$$

lm thickness of magnet along direction of magnetization;
lg effective air gap;
*ly*1 thickness of rotor yoke with magnets;
*ly*2 thickness of rotor yoke without magnets.

The proposed AFPMSG has a coreless armature configuration. For magnetic circuit computations, the effective air gap *lg* should include the axial thickness of the disk winding, i.e.

$$l_g = l_{\mathrm{wdg}} + 2g \tag{23}$$

where *l*wdg is the thickness of disk armature winding and, *g* is the physical clearance between disk armature winding and rotor surface (assumed to be equal on both sides of the winding).

For a given voltage and output power, the number of turns and cross-sectional area of armature conductors may be determined, subject to the limits of current density. The thickness of the armature winding may be determined from:

$$l_{\mathrm{wdg}} = \frac{Z_c A_c}{\zeta \pi D_1} \tag{24}$$

where *Zc* is the total number of armature conductors, *Ac* is the cross-sectional area of each conductor, and ξ is the space utilization factor.

The factor ξ should allow for the space occupied by the epoxy resin to form a disk armature of sufficient mechanical strength.

A sufficiently large physical clearance *g* between the armature winding and the rotor yoke should be chosen in order to avoid physical contact between the winding and the rotor during normal operation. For small machines *g* is in the range of 0.5–0.8 mm.

To minimize the weight of the magnets, one should aim for an operating point that gives the maximum energy product. This is achieved when the magnet flux density *Bm* is equal to one-half of the remnant flux density *Br*. From a consideration of the magnetic circuit and assuming no fringing, the magnet length *lm* and the effective air gap *lg* are related by:

$$l_m = \frac{A_m l_g}{\alpha A_g} \tag{25}$$

where *Am* is the area of magnetic pole, *Ag* is the area of air gap, and *a* is the magnetic flux leakage factor (i.e., ratio of the flux in magnet to the flux in air gap).

If the maximum allowable yoke flux density is Bmax, the thickness of yokes ly1 and ly2 may be determined as follows:

$$l_{y1} = \frac{\Phi_{y1}}{(D_2 - D_1)B_{\max}} \tag{26}$$

$$l_{y2} = \frac{\Phi_{y2}}{(D_2 - D_1)B_{\max}} \tag{27}$$

where Φy1 and Φy2 are the total flux entering each rotor yoke.

Equations (20)–(27) enable the principal dimensions of the AFPMSG to be determined in a machine design program.

C. Prototype AFPMSG

A 16-pole design was adopted for the prototype AFPMSG built in accordance with Figure 18.10. An output frequency of 60 Hz is obtained when the machine operates at a nominal speed of 450 r/min. The pertinent technical details are given in the Appendix.

Figure 18.12 shows the shape of NdFeB magnets and their positions on the rotor back-plate (which is part of the motor frame). To facilitate assembly of the magnet poles, two circular arrays of nonmagnetic spacers were fitted onto the back-plate at the interpolar axes. The magnets were then inserted into the regions between adjacent radial rows of spacers. A bonding adhesive was next applied to the edges between each magnet and the rotor back-plate for better mechanical strength.

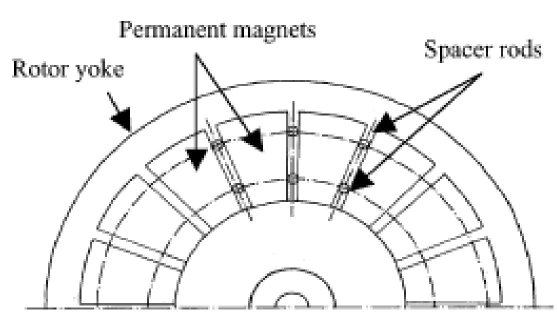


Fig. 18.12. Schematic diagram showing the layout of rotor magnetic poles

A star-connected, double-layer, full-pitch armature winding with 48 coils was used. Construction of the disk armature winding required a special technique. A total of 48 pegs were arranged, equally spaced, as a circular array on a winding workbench as shown in Figure 18.13. The armature coils were then assembled, the pegs providing proper positioning. The wire used has a special coating, which softens and becomes an adhesive when treated with a solvent. As the coils were laid, the solvent was applied and the coils were pressed together.

The coil ends were then connected to produce the phase windings, after which the whole winding was put into a circular mold and impregnated with epoxy resin.

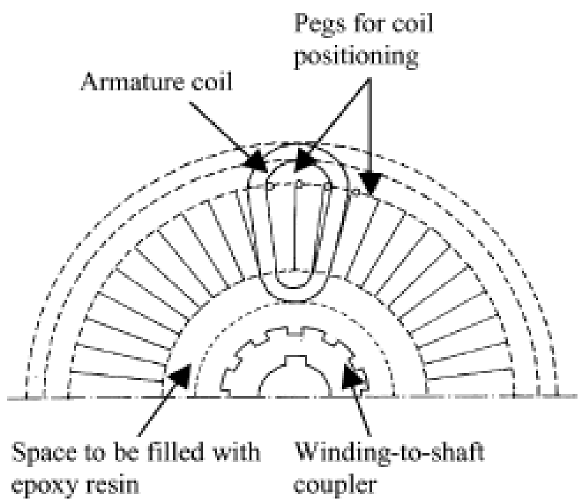


Fig. 18.13. Schematic diagram showing construction of the disk armature winding

During the impregnation stage, the winding-to-shaft coupler was also placed in the mold with its axis coincident with that of the armature winding. The coupler was held in this position throughout the thermo-setting period so that the coupler and the disk winding became an integral unit. Finally, the inner bore of the shaft coupler was trimmed to ensure that the plane of the disk winding was normal to the shaft.

Assembly of the generator involved sandwiching the stator disk winding between the two rotor frames (one with surface mounted magnets and one without). Jacking bolts were used to control the separation between the rotor frames by using the screwed holes provided on each motor frame (which are visible in Figure 18.20 later). This prevented the two rotor frames from accidentally snapping into each other during the assembly process due to the strong magnetic pull.

18.6.4 Flux Density Distribution

The flux density distribution in the AFPMSG affects the voltage waveform and the losses, and hence the efficiency. Strictly speaking, magnetic field analysis of the AFPMSG is a three dimensional (3-D) problem and requires a 3-D finite element method (FEM) software. In order to save modeling time and computation time, a 2-D FEM package is used in this study instead. Since the prototype machine being investigated has a large number of poles, there is only a slight loss in accuracy if the 2-D analysis is performed on a cylindrical surface at the mean diameter of the AFPMSG. Figure 18.14 shows the 2-D model constructed for the analysis of the experimental machine's flux density distribution.

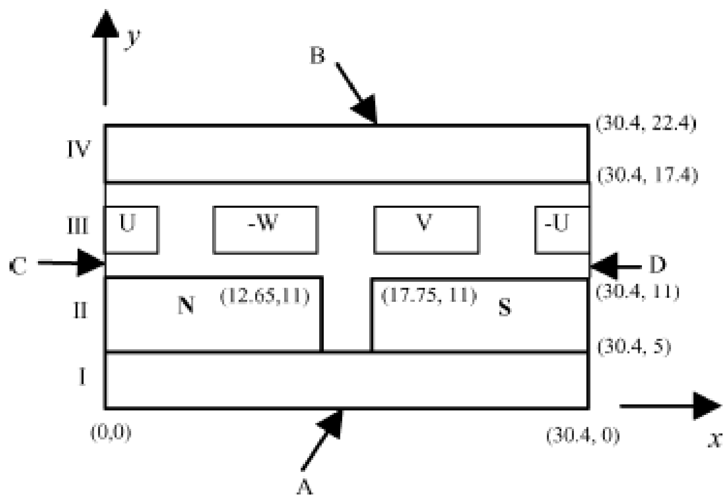
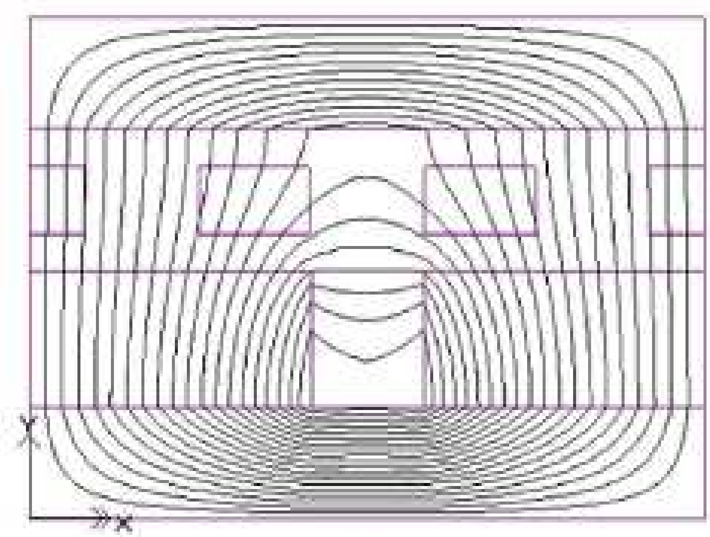
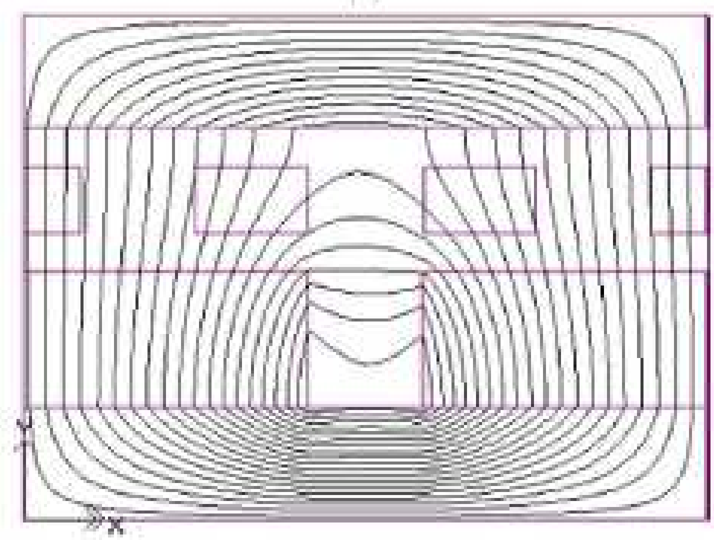


Fig. 18.14. Model for 2-D magnetic field computation of the experimental AFPMSG, all coordinates being expressed in millimeters (I, IV—steel yokes; II—NdFeB magnets, III—armature winding)

The variable x (Figure 18.14) denotes the circumferential distance measured from the centerline of a north pole, and the variable y denotes the axial distance from the bottom surface A of the lower rotor yoke with magnets. The magnetization of the rotor NdFeB magnets is in the axial direction. All the flux is assumed to be confined within the motor frame, hence tangential boundary conditions are assigned to surfaces A and B of the rotor yokes. In other words, the normal components of flux density are forced to zero at these surfaces. Periodic conditions are assigned to the surfaces C and D at the centerlines of the rotor magnets. The armature winding (region III) is modeled as rectangular conductor areas in the air space between the magnets and the upper rotor yoke. The machine phases are denoted by U, V and W, while the positive and negative signs indicate respectively a “go” and a “return” coil-side. For the time instant being modeled, the centerline of phase U coincides with the centerline of a rotor north pole. If the generator is on load, each conductor area is excited by the instantaneous value of phase current that corresponds to the specific rotor position shown in Figure 18.9. This model was solved using the 2-D static solver of the finite element software MagNet, Version 6.



(a)



(b)

Fig. 18.15. Flux plots of AFPMSG. (a) No load. (b) Full load at unity power factor

Figure 18.15(a) and 18.15(b) show the computed flux plot of the prototype AFPMSG on no load and full load at unity power factor, respectively. It is observed that the air gap flux density in general has an axial component By as well as a circumferential component Bx. The flux plot also reveals that there is considerable leakage flux between adjacent magnetic poles. Besides, the flux lines are most dense in the bottom rotor yoke on which the magnets are mounted.

As shown in Figure 18.16, the flux density in the bottom yoke (at y = 4.8 mm) reaches 1.8 T. In the prototype machine, however, the actual flux density is slightly low since the radial length of the rotor yoke is larger than that of the magnets (Figure 18.12). Due to the relatively long effective air gap, armature reaction effect is suppressed and the flux density distribution of the AFPMSG at full load differs only slightly from that at no load, as observed from Figure 18.15(a) and 18.15(b). The air gap flux density, leakage flux, and saturation level of the generator are thus primarily determined by the rotor magnetization, and these do not vary significantly with normal load current.

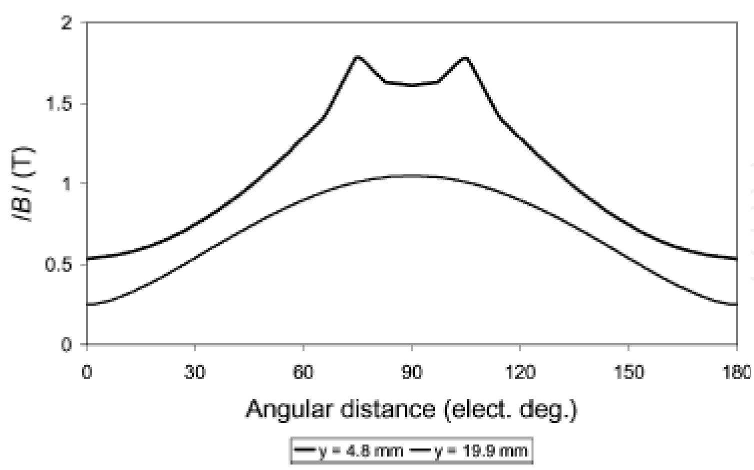


Fig. 18.16. Variation of absolute value of flux density with angular velocity with annual distance lower and upper rotor yokes

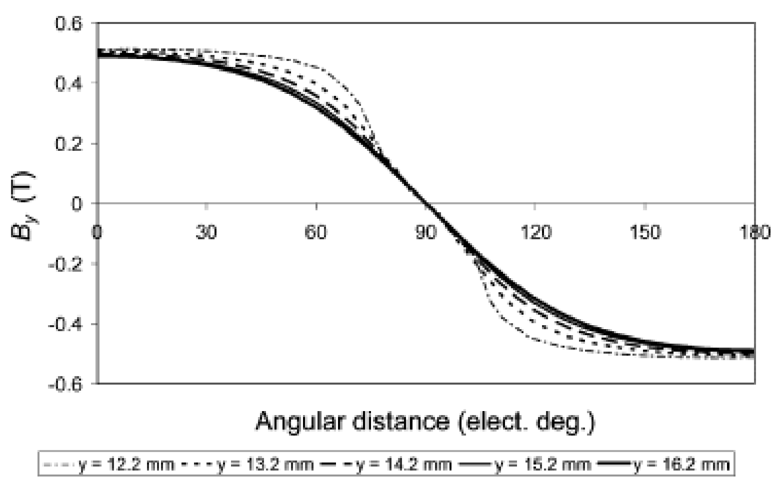


Fig. 18.17. Computed axial component (By of no-load air-gap flux density

Figures 18.17 and 18.18 show respectively the computed variation of *By* and *Bx* with angular distance along the circumferential direction. Both waveforms vary considerably with the axial distance *y*, measured from the lower surface A of the rotor yoke with magnets. It should be noted that *Bx* will not contribute to any rotation electromotive force (e.m.f.), but, together with *By*, will cause eddy currents to flow in the armature conductors and hence will result in eddy current losses. The eddy current loss *Pe* may be computed using the method discussed in [10].

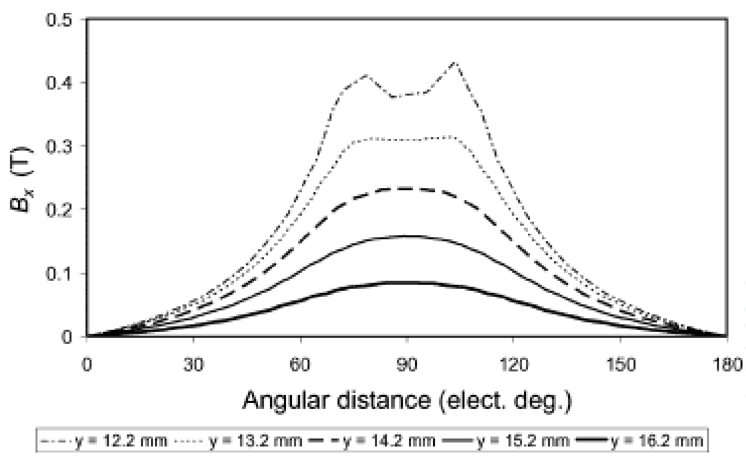


Fig. 18.18. Computed axial component (By of no-load air-gap flux density

An examination of the *By* waveform reveals that slot harmonics are absent. For smaller values of *y* (i.e., at axial positions closer to the rotor magnets), the waveform becomes approximately trapezoidal and there is considerable harmonic distortion.

From Table 18.6, it is observed that the fundamental of *By* decreases only slightly with the axial position *y*, but in the conductor region it is approximately equal to 0.56 T. The amplitudes of lower-order harmonics (up to the 11th) also decrease with *y*. At *y* = 14.2 mm (i.e., the center plane of the disk winding), *By* contains a 3rd harmonic component of 12.2%, a 5th harmonic of 1.6%, and a 7th harmonic of 0.5%, while higher harmonics are negligible. With triplen harmonics excluded, the total harmonic distortion (THD) in *By* is about 1.7%. In the experimental machine, the armature conductors are located in regions around the mean air gap plane. Hence, it is expected that the THD in the output line voltage will also be 1.7%, and the voltage waveform should be quite sinusoidal.

The results in Table 18.7 show that while *Bx* is comparatively small compared with *By*, the percentage harmonic contents are much larger. At the mean air gap plane (*y* = 14.2 mm), the 3rd, 5th and 7th harmonics in *Bx* are, respectively, 29.1%, 3.9%, and 1.3% of the fundamental.

Harmonic Order *n*	Axial position *y* (mm)				
	13.2	13.7	14.2	14.7	15.2
1	0.5822	0.5704	0.5603	0.5520	0.5448
3	0.0089	0.0077	0.0682	0.0609	0.0552
5	0.0143	0.0110	0.0091	0.0072	0.0063
7	0.0053	0.0040	0.0030	0.0023	0.0022
9	0.0061	0.0032	0.0019	0.0006	0.0002
11	0.0069	0.0037	0.0025	0.0019	0.0014
13	0.0018	0.0004	0.0003	0.0006	0.0007

Table 18.6. Principal harmonics in B_y at no-load

Harmonic Order n	Axial position y (mm)				
	13.2	13.7	14.2	14.7	15.2
1	0.2377	0.2080	0.1789	0.1502	0.1222
3	0.0765	0.0626	0.0521	0.0420	0.0330
5	0.0122	0.0093	0.0069	0.0051	0.0039
7	0.0048	0.0034	0.0024	0.0018	0.0012
9	0.0075	0.0047	0.0031	0.0020	0.0015
11	0.0056	0.0032	0.0020	0.0014	0.0008
13	0.0035	0.0019	0.0009	0.0008	0.0004

Table 18.7. Principal Harmonics in B_x at No-load

18.6.5 Steady-State Performance

A. Prediction of Terminal Voltage

Since the surface-mounted NdFeB magnets have recoil permeability close to that of air, the AFPMSG may be regarded as a cylindrical-rotor synchronous machine with a constant field excitation. Figure 18.19 shows the per-phase equivalent circuit of the generator when supplying an isolated resistive load, where *EF* is the no-load terminal voltage, *R* is the armature resistance, *Xs* is the synchronous reactance, *RL* is the load resistance, and *V* is the terminal voltage; all being per-phase quantities.

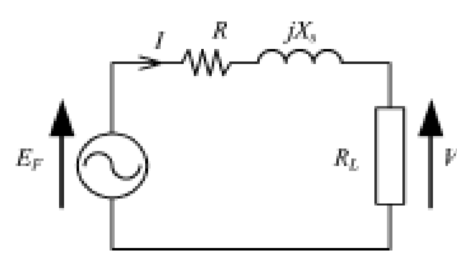


Fig. 18.19. Per-phase equivalent circuit of AFPSGM

From the circuit, the current, terminal voltage, and output power of the generator may be determined as follows:

$$I = \frac{E_F}{\sqrt{(R+R_L)^2 + X_s^2}} \quad (28)$$

$$V = E_F \frac{R_L}{\sqrt{(R+R_L)^2 + X_s^2}} \quad (29)$$

$$P_{\text{out}} = \frac{3E_F^2}{(R+R_L)^2 + X_s^2} R_L \quad (30)$$

By using (28) and (29), the load characteristics of the AFPMSG can be computed provided the synchronous impedance is known.

B. Determination of the Synchronous Reactance

The armature resistance *R* may be determined from a dc resistance test, while the e.m.f. *EF* due to PM excitation may be determined from an open-circuit test. Performance of a short-circuit test, however, may not be feasible due to thermal limitations and the possibility of irreversible demagnetization of the rotor magnets. A more convenient method to determine the synchronous reactance *Xs* is by carrying out an inductive load test. This test gives a fairly accurate prediction of the synchronous reactance without the need for load angle measurements. The AFPMSG is driven at constant speed and a variable three-phase inductive load is connected across the armature terminals. Readings of armature current *I* and terminal voltage *V* are taken. From the voltage phasor diagram, *Xs* may be determined as follows:

$$X_s = \frac{\sqrt{E_F^2 - (IR)^2} - V}{I}. \qquad (31)$$

C. Losses and Efficiency

Since the AFPMSG has no armature core, there is no armature iron loss and the losses mainly consist of the copper loss *Pcu*(= $3I^2R$), the friction and windage loss *Pfw*, and the eddy current loss *Pe* in the armature conductors. The sum of *Pfw* and *Pe* is equal to the mechanical power input to the generator shaft under no-load conditions. The efficiency of the AFPMSG is thus given by:

$$\eta = \frac{P_{\text{out}}}{P_{\text{out}} + \text{Losses}} = \frac{3I^2R_L}{3I^2R_L + 3I^2R + P_{fw} + P_e}. \qquad (32)$$

The efficiency of the AFPMSG may be increased by designing it with a small armature resistance *R*, i.e., by using conductors of a large cross-sectional area. Multiple-circuit coils may be used in order to minimize the eddy-current loss *Pe* [10]. For operation at a given speed, *Pfw* and *Pe* may be assumed to be constant. Under this condition, the maximum efficiency of the AFPMSG will occur at a load resistance *RL* given by:

$$R_L = \sqrt{\frac{3E_F^2R}{P_{fw} + P_e} + Z_s^2} \qquad (33)$$

For a given load resistance *RL*, the condition for maximum efficiency under variable speed operation may be estimated by assuming that the friction and windage losses *Pfw* vary linearly with speed over the speed range being considered. The eddy current losses *Pe*, on the other hand, vary as the rotor speed squared [10]. We can therefore write:

$$E_F = k\omega \tag{34}$$

and

$$P_{fw} + P_e = k_1\omega + k_2\omega^2 \tag{35}$$

where k, $k1$ and $k2$ are constants and ω is the angular frequency of output voltage. Equation (32) can thus be written as follows:

$$\eta = \frac{3k^2\omega R_L}{3k^2(R+R_L) + (k_1 + k_2\omega)\{(R+R_L)^2 + (\omega L_s)^2\}} \tag{36}$$

where Ls is the synchronous inductance per phase.

Maximum efficiency will occur when the derivative $d\eta/d\omega$ is equal to zero, from which the following equation may be derived:

$$2k_2\omega^3 + k_1\omega^2 - k_1\left(\frac{R+R_L}{L_s}\right)^2 = 0. \tag{37}$$

Equation (37) may be solved analytically or numerically to give the angular frequency at which maximum efficiency occurs, and, hence, the value of the maximum efficiency.

If, however, the armature winding is made of conductors with a small cross-sectional area, the eddy current losses may be ignored and maximum efficiency will occur at an angular output frequency given by:

$$\omega = \frac{R+R_L}{L_s}. \tag{38}$$

The value of maximum efficiency is

$$\eta_{\max} = \frac{R_L}{R+R_L}\left(\frac{3k^2}{3k^2 + 2k_1L_s}\right). \tag{39}$$

18.6.6 Experimental Results and Discussion

Figure 18.20 shows the setup for experimental investigations on the AFPMSG. The shaft of the machine was mounted on a special test rig so that the rotor frame can turn freely. Provisions were made on the motor frame for coupling the generator rotor to a dynamometer motor drive by means of a belt transmission. The turbine is therefore emulated by varying the speed of the dynamometer motor.

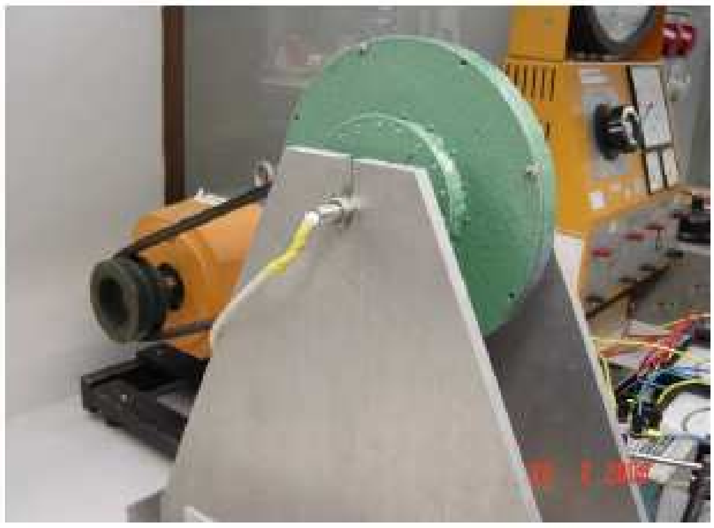


Fig. 18.20. Test rig for experimental investigations on the AFPMSG. The outer rotor being driven by a dynamometer motor via a belt transmission

The armature resistance of the AFPMSG was measured to be 0.58Ω from a dc resistance test. Table 18.8 gives the no-load test and inductive load test data obtained at a rotor speed of 450 r/min. From (31), the synchronous reactance *Xs* of the AFPMSG at 450 r/min (or 60 Hz) was determined to be 0.25Ω per phase. Due to the large effective air gap, armature reaction is relatively weak in the AFPMSG and hence *Xs* is small compared with the armature resistance *R*. The machine performance, such as the voltage drop, therefore depends primarily on *R* in this type of machine.

Test	Line voltage (V)	Line current (A)	Power Input (W)
No-load test	25.0	0	17.0
Inductive load test	21.7	5.9	–

Table 18.8. No-load and inductive load test data for AFPMSG

A check of the 2-D finite element computation is in order. Using the measured no-load line voltage, the fundamental component of *By* was found to be 0.564 T. This value agrees very well with the average value of *By* in the conductor region, computed at the mean radius of the machine (Table 18.6). This shows that the 2-D model is sufficiently accurate for obtaining a good engineering solution.

Figures 18.21(a)–(c) shows the variations of terminal voltage, output power, and efficiency of the experimental AFPMSG with line current under constant-speed operation. The voltage-current characteristics are practically linear from no load to full load. At a speed of 600 r/min, the voltage drop between no load and full load is 25% and an output power of 340Wcan be delivered at rated current. When the speed is reduced to 300 r/min, the voltage drop between no load and full load increases to 50%, and at rated current the output power is only 110 W. Due to the relatively large armature resistance, maximum efficiency of the machine occurs at low values of load current. A maximum efficiency of 79.0% can be achieved at 600 r/min.

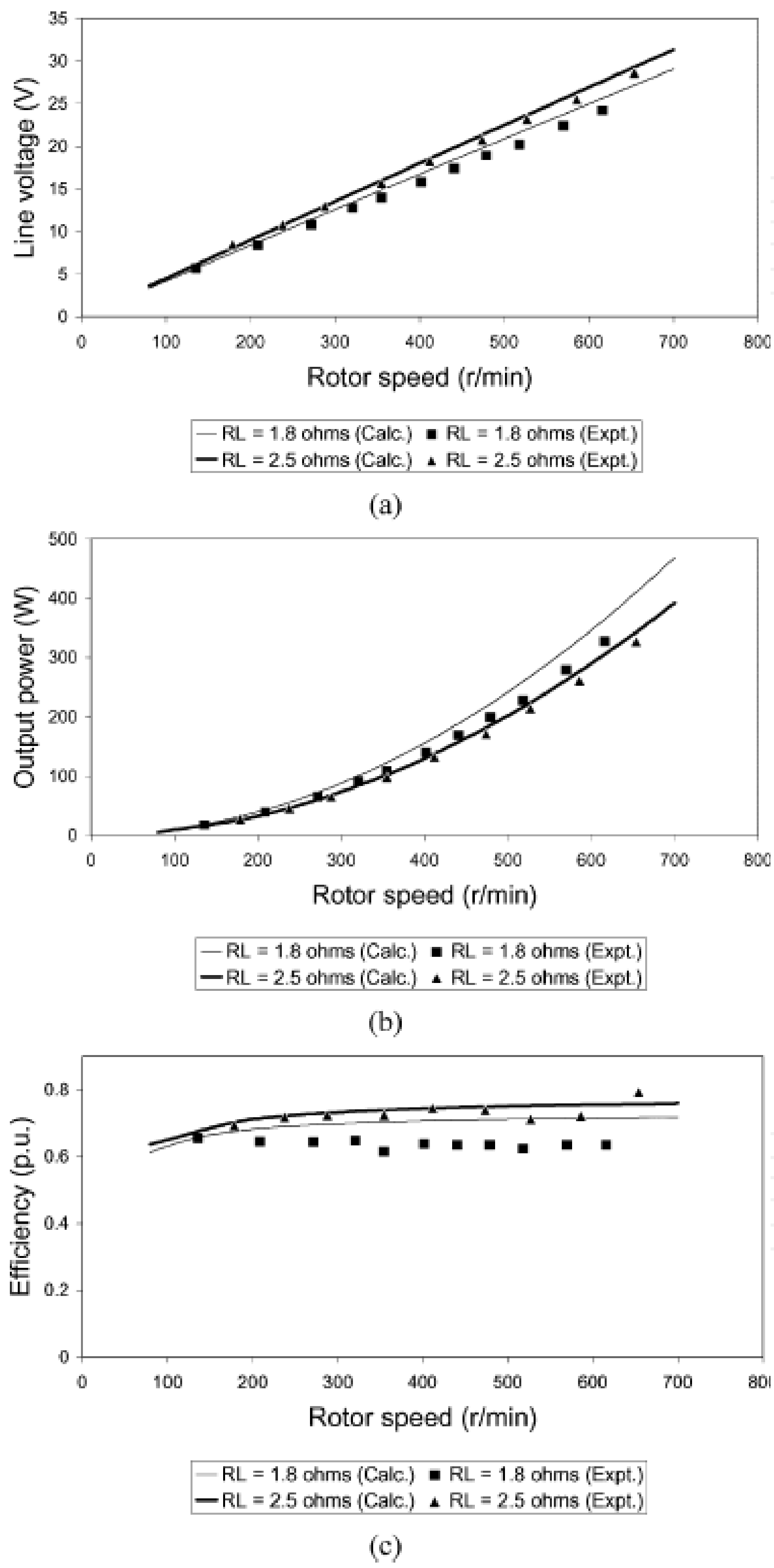


Fig. 18.21. Performance of AFPMSG under constant-speed operation (a) Variation of voltage with current. (b) Variation of output power with current. (c) Variation of efficiency with current

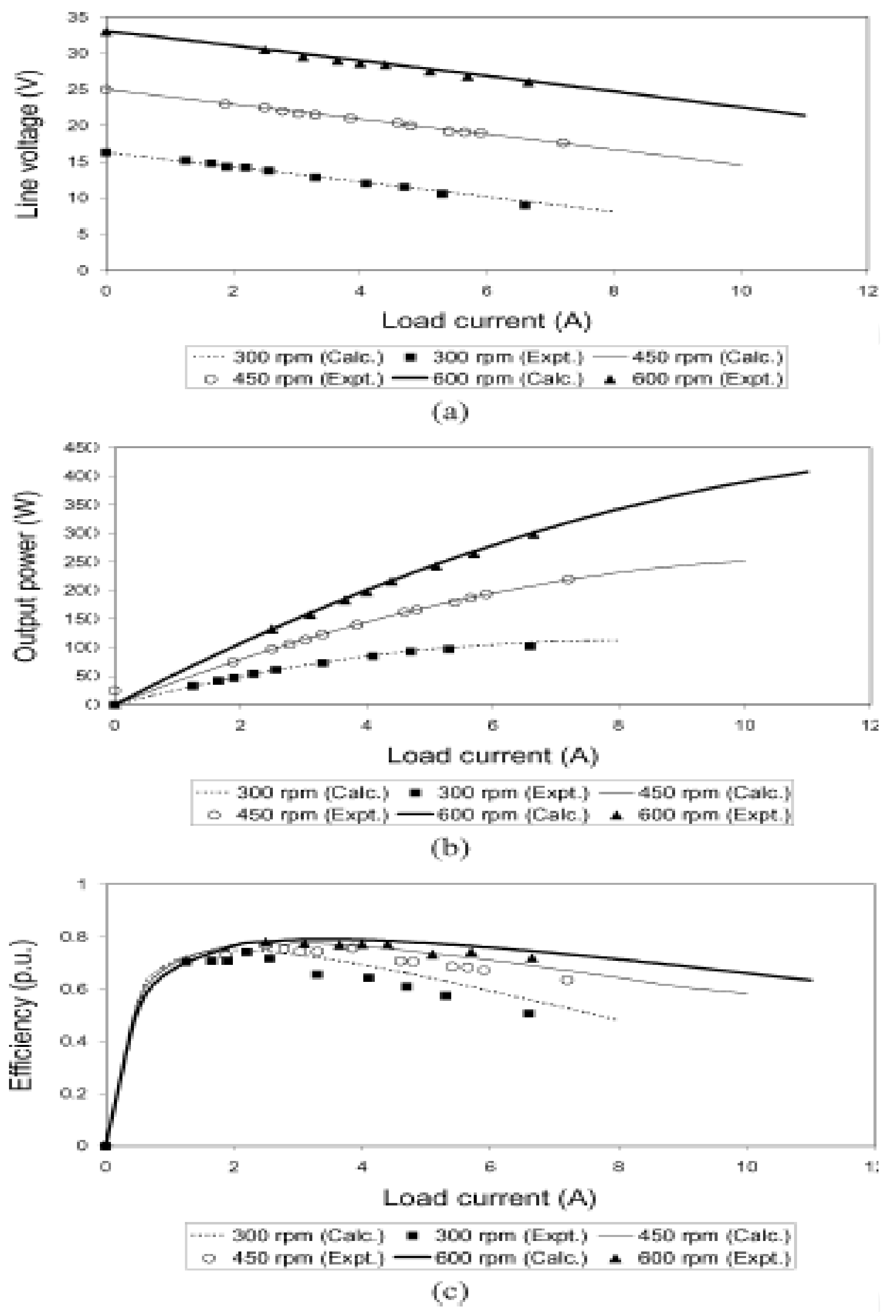
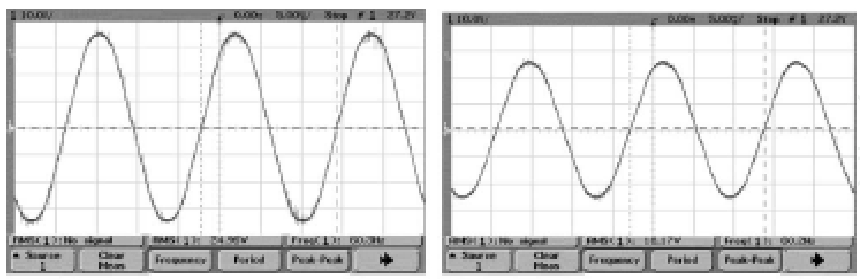


Fig. 18.22. Performance of AFPMSG: variable-speed operation (a) Variation of line voltage with rotor speed. (b) Variation of output power with rotor speed; (c) Variation of efficiency with rotor speed

Figures 18.22(a)–(c) shows the variations of terminal voltage, output power, and efficiency of the experimental AFPMSG with speed when the load resistance is constant. The output voltage varies almost linearly with the rotor speed, while the output power varies approximately with the square of the rotor speed. The efficiency, however, is only slightly affected by the speed. With RL = 2.5Ω, the computed efficiency varies from 74% to 76% when the speed increases from 350 to 700 r/min.

The close agreement between the voltage–current and power–current characteristics confirms the theory developed in sub-section 18.5 of this chapter. Experimental values of efficiency, however, correlate less well with the computed values due to the difficulty in accurately determining the losses in the belt transmission.



(a) (b)

Fig. 18.23. Line voltage waveforms of AFPMSG (a) At no load. (b) When delivering a current of 6.1 A to a resistive load (voltage scale: 10 V/div; time scale: 5 ms/div)

Figure 18.23(a) and 18.23(b) show, respectively, the line voltage waveforms of the AFPMSG at no load and when delivering a current of 6.1 A to a resistive load. The waveforms are practically sinusoidal.

From a measurement using a harmonic analyzer, it was found that in each case there was mainly a 1.4% 5th harmonic and a 0.2% 7th harmonic, with a total harmonic distortion of 1.6%. This experimental result is consistent with the harmonic analysis of the By waveform in Table 18.6, the slight reduction in THD being due to the spread of the conductors for each coil side. The voltage waveforms have confirmed that the proposed AFPMSG is an excellent source of sinusoidal power. The measurements also revealed that the total harmonic distortion was not sensitive to the variation of load. This is due to the fact that the armature reaction m.m.f. has only a slight effect on the resultant flux density distribution in the air gap, as observed from the flux plots in Figure 18.15.

18.7 Systematic Losses and Smart Electricity Use

The economic efficiency of today's Electricity Supply System (ESS) is driven by two mutually supporting key factors: the load factor; and fuel conversion efficiency. The higher the load factor, the more efficient the running of the plant and the more investment in generation efficiency is worthwhile. The higher the generation efficiency the more the plant will be called on and so the higher load factor.

This sub-section presents two ways by which smart appliances enhance both these factors, one quite rapidly but the other needing deeper change in the way we market electricity.

The role of refrigerators is in providing frequency response. In a population of refrigerators, there will at any instant be many that are on and many that are off. On average, in the UK, the average load from domestic refrigeration is over 1GW, although, if they were all replaced by the most efficient of modern appliances, it would be less than this. One technology, when fitted into new refrigerators, influences the numbers that are on or off depending on system frequency so as to balance the continuous small and occasional large fluctuations in supply and demand. In this, they displace the frequency response service largely supplied from thermal power stations.

The frequency service from power stations is particularly carbon intensive, creating significant losses or inefficiencies in the plant. To provide low frequency response, generation has to be operated at part load, but with capability to increase or reduce load very rapidly – typically within 5-10 seconds. While there is little published on how great are the resulting losses, they are significant, with resulting emissions perhaps in the order of over a million tons of CO_2 p.a. in the UK.

A population of refrigerators, on the other hand, can react to a change of frequency within about 1/10 of a second. While refrigerators shift their consumption by seconds and minutes, and this marginally reduces the need for peaking capacity, much bigger rewards are available if load can be shifted by hours or even days from the current peaks. In the UK (and in many other countries), the peak load (which is what dictates the needed generation capacity) arises at around 6.00 pm in winter, and is followed by a decline as the nation settles down for the evening and the night.

In an idealized example case, if the overall daily Great Britain load could be spread evenly across the day in the winter, then the peak generation need would be reduced by some 15GW. While this is, in practice, unrealizable, even a proportion of this would save many billions in new investment as existing plant reaches the end of its life and electricity consumption continues to grow. In addition, some of the plant that was run would be able to run at a constant output and so more efficiently. These are big rewards.

Nobody really knows how much peak load can be shifted to other times. What can be said is that many appliances, such as dishwashers, laundry machines and the like, have enough microprocessor intelligence to manage a shift of their consumption to when it would be cheaper, so long as the user's deadline for clean dishes or laundry is met. All they need is guidance and reward for doing so.

Smart tariff appliances do this by price, although one proposal using frequency where the frequency is deliberately run below its nominal level over peak periods is being investigated. It was proposed to use broadcasting, by suppliers, of a continuously varying expected price over the next day, days and even weeks. Appliances see this expected price, and so can optimize their consumption to meet the users' deadline at the minimum and cost, known and displayed when the users set the deadline. Smart meters also track the consumption and its cost at each moment, and add up the bill for presentation to the user and to the utility from time to time.

Of course, as more wind generation penetrates the system, the price will depend, in part, upon the weather, so as wind forecasts change, so can prices and therefore appliance plans and their consumption. You end up doing your laundry when the wind is blowing.

It does not know quite how big will be the rewards from this. It is assessed that a variant of the refrigerator technology, applied to water heating in South Africa, can lead to peak capacity reductions of around 3GW, and do so within about 3 years. Some work in the US (seemingly based on big appliances and big consumptions) suggests a saving of the order of $200 p.a. per household. Is this $200 p.a. per household an amount that could be afforded to waste?

18.8 Combined Heat and Power and District Heating with Thermal Storage

The combined production of heat and power (CHP) or put in another way, the utilization of the waste heat from power production for heating homes and buildings and meeting process heat demands are experiencing growing interest in the UK. CHP and District Heating (DH) or Community Heating (CH) as it is often referred to as in the UK, provide the following advantages: high flexibility of fuel usage; high efficiency; high environmental quality, less effluent/waste disposal problems; reduced air pollution and increased cost-efficiency.

Denmark decided to explore the opportunities and invest in CHP and DH almost 30 years ago. Today 60% of the Danish housing stock, whether privately owned or council dwellings is connected to a DH scheme and more than 95% of this heat comes from waste heat, i.e. from CHP. Over 50% of electricity production in Denmark is CHP. In the UK less than 3% of dwellings are connected to a DH scheme and only around 7% of electricity production is CHP.

Denmark has broadly seen three scales of CHP that were mainly implemented in the following chronological order:

- Large scale CHP in cities (>50 MWe).
- Small (5 kWe – 5 MWe) and medium scale (5 – 50 MWe).
- Industrial and small scale CHP.

Denmark's ten major cities (the smallest has a population of around 50k the largest around 1.1M) have citywide DH where most of the heat (95-98%) is produced by large CHP plants. The five largest are gas-fired combined cycle plants; the others are using natural gas, biomass, waste or biogas. Several hundred towns and communities are supplied with DH created by local initiatives back in the 1960s, which now have been modernized and are mostly supplied by CHP.

In a DH system, it includes the production, the distribution and the customers. A DH network can be split into three levels:

- Branches and connections to consumers
- Distribution heat network, e.g. 100 °C/40 °C
- Transmission heat network, e.g. 120°C/70°C.

A DH scheme can consist of a distribution network only or a combination of distribution and transmission. One reason for the transmission/distribution concept is that the transmis-

sion system can be run with a higher pressure level, the transmission network is often a 25 bar system, while the distribution system can be a 6, 10 or 16 bar.
The cost of installing the heating network depends on four factors:

- The design operating temperature and pressure
- The complexity of existing services
- The length of the network
- The peak heat demand.

Thermal storage has been used in DH systems for decades, the main aim being to separate time-dependent demand and occurrence of heat and electricity from one another.

Practically all CHP plants of the backpressure type, as well as small-scale plants only producing heat and electricity in fixed ratios are equipped with a thermal store. CHP plants of the extraction type have earlier only to a limited extent been operating with a thermal store.

Operating a CHP plant in a liberalized electricity market increases the need for more flexibility of the plant in order to operate in the most economical way, serving both the heat consumers as well as the electricity market.

The thermal store is used for short-term storage of water-based energy. Basically there are two main purposes for having a thermal store:

- To save operational cost in the form of heat production cost.
- To save investments (in the form of investments in peak load capacity and network capacity). The investment in a thermal store should be carefully compared to that of establishing a peak load unit in the network.

In Denmark the thermal stores are mainly installed in order to save heat production cost as most of the DH systems are supplied from CHP plants. This means that the heat production cost is not only related to the fuel cost but also to the selling price of electricity. For many years the selling price of electricity from decentralized CHP plants has been based on a triple tariff. Now the selling price of electricity may have many values during the day and may change hour by hour.

As the selling price of electricity reflects on the heat production cost, the heat storage tanks in Denmark are mainly utilized in order to optimize the power production and are mainly related to the power production in two ways:

- Back pressure production: The proportion between electricity production and heat production is fixed; an increase in electricity production will result in an increase in heat production. Typical production equipment is backpressure steam turbines or piston engine installations
- Extraction production: An increase in the heat production will decrease the power production. Typical production equipment is extraction steam turbines.

How the heat storage tank is utilized depends on the types of production units in the DH network.

Thermal stores in Denmark are centralized and connected to the DH system between the CHP plant and the network. Decentralized thermal stores have been implemented in the Netherlands. The purpose of these thermal stores can be to save heat production cost but the decentralized placement of the tanks indicates that the purpose of the tanks also has been to reduce the pipe diameters of the network and thereby the network investments. Furthermore, the decentralized placement of thermal stores may be a possibility if the space at the central production unit does not allow for a large storage tank.

Thermal storage does not generally reduce fuel consumption and therefore has no impact on CO_2 emissions. As the purpose of the tank is mainly of an economic nature, the specification of the size of thermal store must therefore be based on an economic analysis.

The following information is required in order to accurately size a thermal store:

- Daily load variations during the year over a number of years.
- The possible savings related to the production units due to the installation of the thermal store. The possible savings will typically be related to an optimized power production in relation to large changes in the selling price of electricity.
- Prices for the heat storage tank installation including pumps, pipes, valves etc.

Due to heat loss it is important that the surface area of the water in the thermal store is as little as possible in relation to its volume. The optimal would be a ball but due to considerations for the construction a cylinder where the diameter is equal to the height is ideal. Normally, a height/diameter ratio above 1.5 is used. It should be taken into account that there will be an unusable separation layer of typically one meter. In order to secure a good separation between hot and cold, diffusers should be placed at the top and bottom.

The connection of the thermal store to the DH system will depend on the type of DH system.

The main issue here is the maximum temperature of the DH system where there is a distinction between systems with supply temperature of up to 97 ^{o}C and systems with higher supply temperatures.

If the maximum temperature is lower than the boiling point of the water (in Denmark which is near the surface of the sea, this in practice means 95-97^{o}C) a non-pressurized tank can be used. A minor gauge pressure is maintained at the top of the tank as nitrogen or steam cushion prevents the oxygen from the air to penetrate into the DH water.

Sometimes a non-pressurized tank is also used for maintaining the static pressure in the DH system. The non-pressurized tank is often used in the smaller or medium sized systems and they will typically have a height of between 15 and 25 meters. Depending on the topography of the network and on whether the tank is placed either high or low compared to the other parts of the DH system, the water column in the tank may be sufficient to provide the required static pressure in the DH system.

In large DH transmission systems the maximum temperature is often above 100°C (typically up to 120°C). If water with that temperature should be stored in a non-pressurized tank, permanent boiling would take place at the top of the tank that is highly undesirable. In order to avoid this, temperature lowering installations or pressurized tanks may be used.

18.9 Conclusions

It is clear there are many issues in the energy sector. The energy field is fuelled with excitement. Public interest and awareness is heightened in topics like energy efficiency, global warming and climate change, the carbon footprint, smart metering, intelligent grids, renewable energy sources, distributed generation, power quality, risk management and asset management. Observation, predictability, and reliability are the key to efficiency. Predictability in Market timescales is key in efficient scheduling. Cheap advanced ICT systems to monitor distributed systems and communicate dynamic tariffs. Volatile energy prices are a fact of life. Regulatory stability and a clear energy policy are essential for future security of supply. Investment in new generating capacity is essential - not only in renewable. Some topics have been introduced with examples.

This chapter has also presented a form of axial-flux permanent magnet synchronous generator (AFPMSG) that is suitable for a direct-coupled wind turbine system. The application of this machine to horizontal-axis and vertical-axis wind turbine generator systems is discussed. An analysis of the magnetic flux density distribution in the AFPMSG has been made with the aid of commercial, finite element software. The computed results show that the output line voltage is practically sinusoidal for the proposed machine configuration. Experiments performed on a prototype generator have confirmed the feasibility of the AFPMSG design and the validity of the equivalent circuit model.

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Appendix

The prototype AFPMSG has the following design specifications:

1) Output at nominal speed
230 W, 16.7 V, 8.0 A, 60 Hz
2) Rotor field
Number of poles 16
Outer diameter 200 mm
Inner diameter 110 mm
Thickness of magnets 6 mm

Pole arc at mean radius 150°e
Remanent flux density 1.128 T
Recoil permeability of magnets 1.03
Thickness of each rotor yoke 5 mm
3) Armature winding and air gap
Winding type three phase star, double layer, full-pitch
Number of coils 48
Turns per coil 7
Armature resistance at 75°C 0.58 Ω
Thickness of winding 5 mm
Physical air gap length 2 × 0.7 mm
4) Mass of active materials
Copper 0.8 kg
Iron 2.0 kg
Magnets 0.56 kg

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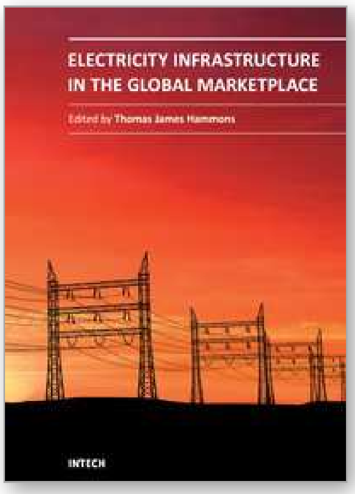

Electricity Infrastructures in the Global Marketplace
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This book discusses trends in the energy industries of emerging economies in all continents. It provides the forum for dissemination and exchange of scientific and engineering information on the theoretical generic and applied areas of scientific and engineering knowledge relating to electrical power infrastructure in the global marketplace. It is a timely reference to modern deregulated energy infrastructure: challenges of restructuring electricity markets in emerging economies. The topics deal with nuclear and hydropower worldwide; biomass; energy potential of the oceans; geothermal energy; reliability; wind power; integrating renewable and dispersed electricity into the grid; electricity markets in Africa, Asia, China, Europe, India, Russia, and in South America. In addition the merits of GHG programs and markets on the electrical power industry, market mechanisms and supply adequacy in hydro-dominated countries in Latin America, energy issues under deregulated environments (including insurance issues) and the African Union and new partnerships for Africa's development is considered.

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