EXPERT GROUP STUDY
ON

RECOMMENDED PRACTICES
FOR WIND TURBINE TESTING
AND EVALUATION

7. QUALITY OF POWER SINGLE GRID-CONNECTED WECS

Submitted to the Executive Committee
of the International Energy Agency Programme
for
Research and Development
on Wind Energy Conversion Systems

RECOMMENDED PRACTICES
FOR WIND TURBINE TESTING

7. QUALITY OF POWER.
SINGLE GRID-CONNECTED WECS

1. EDITION 1984

Edited by

Lionel J. Ballard
ERA Technology Ltd.
Cleeve Road
Leatherhead
Surrey KT22 7SA
UK

and

Roy H. Swansborough
ERA Technology Ltd.
Cleeve Road
Leatherhead
Surrey KT22 7SA
UK

Table of Contents

INTRODUCTION

The procedure needed for evaluation of wind turbines must encompass all aspects of a Wind Energy Conversion System (WECS) ranging from: energy production, quality of power, reliability, durability and safety, through to cost effectiveness or economics, noise characteristics, impact on the environment and electromagnetic interference. The development of internationally agreed upon evaluation procedures for each of these areas is needed now to aid in the development of the industry while strengthening confidence and preventing chaos in the market.

It is the purpose of the proposed recommendations for wind turbine testing to address the development of internationally agreed upon test procedures which deal with each of the above noted aspects for characterizing WECS. The IEA Expert Committee will pursue this effort by periodically holding meetings of experts, to define and refine consensus evaluation procedures in each of the areas:

1. Power performance.
2. Cost of energy from WECS.
3. Fatigue evaluation.
4. Acoustics.
5. Electromagnetic interference.
6. Safety and reliability.
7. Quality of power.

This paper addresses the seventh of these efforts. The expert committee will seek to gain approval of the procedures in each member country through the IEA agreements. The recommendations shall be regularly reviewed and areas in need of further investigation shall be identified.

SCOPE

This document describes the recommended practices for determining the quality of power delivered by a single grid-connected WECS. It provides a methodology for obtaining power quality data which can be used to compare WECS of different type and make. The following is noted:

1. The recommendations apply to WECS which are used for generating electricity and at present only considers single and three phase network connected machines.

2. The procedures and practices will generally be applicable to all sizes of WECS although a more detailed power quality assessment may be desired for larger WECS.

3. The procedures and practices are generally applicable to a single machine whose capacity is small compared with the network to which it is connected.

4. The recommendations in their present form are not applicable to wind farms, wind-diesel systems or large WECS with Power Conditioning Units. It is hoped to cover these in subsequent editions.

5. The recommendations do not attempt to quantify acceptable limits or standards of power quality.

The topics covered in these recommendations relate to the quality of power in terms of:

1. Power variation.
2. Reactive power demand.
3. Voltage variations during generation.
4. Voltage variations on cut-in.
5. Switching operations.
6. Harmonics.

RECOMMENDED PRACTICES FOR WIND TURBINE QUALITY OF POWER TESTING AND EVALUATION

1. DEFINITION AND UNITS

Net Power (P) – the power available from a WECS less any power needed for control, monitoring, display or maintaining operation, i.e. power available to the user. Unless otherwise specified, P will be 10 minute average values.

Net Reactive Power (Q) – the reactive power supplied by the power system or absorbed by the power system. Unless otherwise specified, Q will be 10 minute average values.

Maximum Power – the maximum net power delivered by WECS in normal operation.

Rated Power – the rated power of the electrical generator.

Rated Windspeed – the lowest wind speed at which rated power occurs.

Power Curve – a graph which depicts the net power of a WECS as a function of wind speed.

Cut in Wind speed – the minimum wind speed at which the WECS begins to produce power that is deliverable to a load.

Cut-out wind speed – the maximum wind speed at which the WECS produces energy.

Point of Common Coupling (PCC) – the point of common coupling with other consumers is the point in the supply network, electrically nearest to the consumer for whom the WECS is proposed, at which other consumer loads are, or may be connected.

Units – numerical values reported are to be given in metric international system (SI) units.

In this text the Wind Energy Conversion System will be called WECS, wind turbine, or machine under test.

2. THE MACHINE UNDER TEST

The WECS tested shall be thoroughly described and pertinent engineering and geometric data supplied. Photographs of the machine under test are desired.

In the case of testing of a standard production model WECS, the manufacturer should provide a clear description of the model and serial number of the machine tested.

Listed below is a sample of the typical data which should appear in the report where possible:

- Geometric data: rotor size and type, number of blades, blade airfoil section data, hub height of rotor and tower type. For propeller type turbines it shall be stated if the rotor is located upwind or downwind.

- Materials: blade and tower materials.

- Transmission: description of gear box arrangement if any; gearing ratio(s).

- Generator: complete specification including type, number of phases, number of poles, rating, voltage, frequency.

- Inverter (if used): complete specification including type, number of phases, rating, voltage, frequency etc.

- Grid interface: details of any terminal equipment, such as capacitors or series inductors, connected to the machine terminals.

- Control systems: description of cut-in and cut-out control, blade pitch angle control, regulation of rotor rotation speed, synchronising, voltage regulation etc.

Other information essential for the understanding of the operation of the WECS shall be included.

3. THE TEST SITE

A description and a map of the test site shall be provided. Selection of the site should minimise the possibility of the local topological features affecting the test results. In situations where topological features may affect test results for certain wind directions, it is recommended that these test results be deleted or reported separately with adequate explanation. Preferably, the description of the test site should include a series of photographs, taken from the place of the WECS, in all directions.

The electrical supply to the test site should be described and the power system resistance and reactance at the point of measurement quoted. The basis on which the power system resistance and reactance has been determined should be described.

The nominal voltage of the test supply shall be the rated voltage of the WECS.

Measurements described in these recommendations shall be made at a test voltage within ±5% of the nominal voltage.

4. TESTING AND ASSESSMENT METHODOLOGY

4.1. General

The purpose of the testing and assessment practices is to assess the quality of power delivered by a WECS at the test site, so that the quality of power delivered by the machine when installed at the users site can be predicted and to enable comparisons to be made with other WECS. The quality of power delivered by a WECS is described in terms of a number of parameters (as listed under 'Scope') each of which can vary from site to site depending on the wind regime and the local network characteristics. In order to make the results independent of the site wind regimes and transferrable from the test site to a prospective users site the power quality parameters have generally been measured or calculated as functions of the output power of the turbine. Thus the 'envelope' of variations has generally been determined rather than the variation of the power quality parameter within the envelope.

The recommendations that follow describe the test and assessment methodology. In order to make the results transferrable from the test site to a prospective user site many of the methods involve measurement and calculations. Both of these procedures are described.

Exceptions to this are the procedures recommended for harmonic assessment of WECS, power fluctuations and cut-in frequency.

4.2. Measurement of Power Variations

The purpose of the measurements described in this section is to determine the normalised standard deviation of net power variations with wind speed for the WECS at the test site.

The overall measurement accuracy of the power instrumentation used for the test shall be within 3% of full range over a range of 5% to 125% of the WECS maximum power.

Calibration of the instrumentation shall be conducted in such a way that it can be verified that the accuracy has been maintained during the test period. The calibration shall be traceable to international standards.

The measurement of power variations should be carried out at the same time as the power measurements for determining the power curve (Ref. 1). The criteria for data base requirements, elimination of erroneous data, the data acquisition system and the accuracy and period of wind speed measurements given in Ref. 1, shall apply here.

The net power (uncorrected for temperature and pressure) generated by the WECS should be measured using a sampling frequency of 1 Hz. After each 10 minute period the variance of the 600 samples shall be calculated and accumulated in bins, the corresponding 10 minute average wind speed determining the specific bin. Then the ensemble averages of the net power variances and wind speeds shall be determined by dividing the summed values of power variances and wind speeds by the number of data sets, ie:

$$\sigma_{pi}^2 = \frac{1}{N_i} \sum_{J=1}^{N_i} \sigma_{pij}^2$$

$$V_i = \frac{1}{N_i} \sum_{j=1}^{N_i} V_{ij}$$

where $\sigma_{pij}^2 = j^{th}$ 10 minute power variance in the ith bin

$V_i = j^{th}$ 10 minute average of wind speed in the ith bin

From the ensemble averages of the variance the normalised standard deviation should be determined as follows:

For the ith bin,
Normalised standard deviation $\sigma_{pui} = \dfrac{\sqrt{\sigma_{pi}^2}}{\text{rated power of the WECS}}$

Finally a curve of normalised standard deviation σ_{pui} of the power variation should be plotted against corresponding bin averages of the wind speed V_i. An example of this curve is shown in Fig. 1.
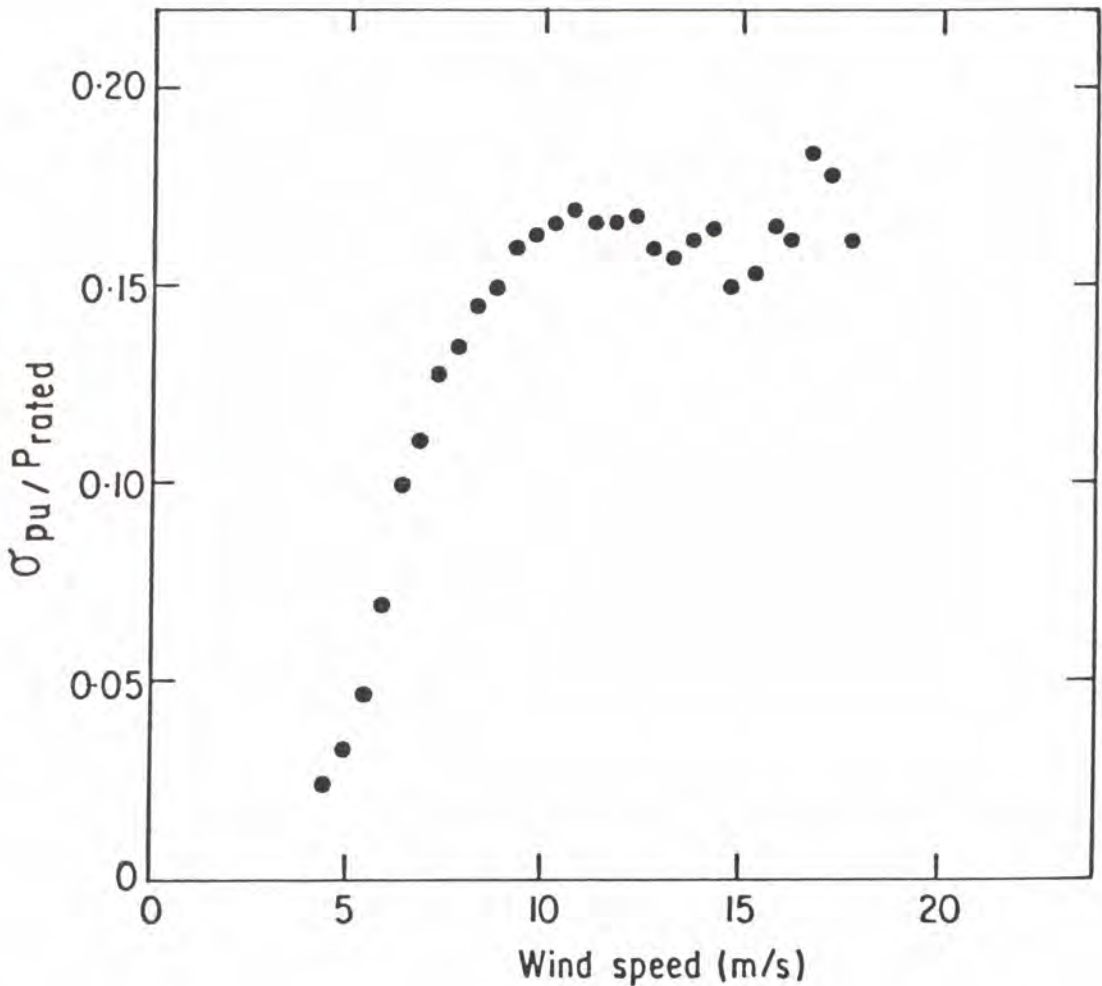
Fig. 1: Curve of normalised standard deviation of power variation against average wind speed.

4.3. Measurement of the Reactive Power Demand

4.3.1. WECS Incorporating Directly Connected Asynchronous Generators

The purpose of the measurements described in this section is to determine the relationship between net reactive power and net power.

The overall measurement accuracy of the power and reactive power instrumentation used for the test shall be within 3% of full range over a range of 5% to 125% of the WECS maximum power for the power measuring instrumentation and over a range of 5% to 125% of the WECS maximum reactive power for the reactive power measuring instrumentation.

Calibration of the instrumentation shall be conducted in such a way that it can be verified that the accuracy has been maintained during the test period. The calibration shall be traceable to international standards.

The reactive power measurements should be carried out in conjunction with the power measurements for determining the power curve (Ref. 1). The criteria for data base requirement, elimination of erroneous data and the data acquisition system given in Ref. 1 shall apply to the measurements made of net reactive power.

After the data reduction, but before the real power data has been corrected for temperature and pressure variations, real and reactive power data analysis will be performed using the method of bins. The procedure is described in Ref. 1, section 5.3., except that an additional register is required in each bin for the reactive power. Thus if the reactive power demand curve is required, each bin will have three cumulative registers, one for wind speed, one for net power and one for net reactive power.

The 10 minute averaged values of net reactive power shall be accumulated in the bins, the wind speed determining the specific bin. Then the ensemble average of the net power (uncorrected for temperature and pressure) and net reactive power shall be determined by dividing the summed value of the real and reactive power data sets by the number of data sets by the number of data sets, ie:

$$P_i = \frac{1}{N_i} \sum_{j=1}^{N_i} P_{ij}$$

$$Q_i = \frac{1}{N_i} \sum_{j=1}^{N_i} Q_{ij}$$

where P_{ij} = j[th] 10 minute average of net power in the ith bin

Q_{ij} = j[th] 10 minute average of net reactive power in the ith bin

N_i = number af data sets in i[th] bin.

The ensemble averages (P_i, Q_i) shall then be plotted and a curve drawn through the points. This curve describes the net reactive power demand (ordinate) of the WECS as a function of the net power (abscissa).

Although it is preferred that the determination of the net power, net reactive power curve is carried out on the WECS at the test site an alternative is to perform these measurements on the electrical generator separately under laboratory test conditions.

4.3.2. WECS Incorporating Line Commutated Inverter

Under consideration.

4.3.3. WECS Incorporating Directly Connected Synchronous Generators

Unlike the asynchronous generator the synchronous generator is self exciting and does not require reactive power supplied to it to enable it to excite. Thus the reactive power demand is a function of the reactive power demand of the connected system. A definitive curve of net power versus net reactive power is not therefore appropriate for this machine.

The maximum range of reactive power generation/demand for the machine can be determined by measurement but it is felt that the value calculated from the manufacturers figures for volt-amperes and watts for the synchronous generator is adequate.

4.4. Assessment of Voltage Variations During Generation

4.4.1. WECS Incorporating Directly Connected Asynchronous Generators

The purpose of the calculations described in this section are to predict the 'envelope' of voltage variation of the users site based on measurements already taken (Section 4.3.) of the net reactive power versus net power and a knowledge of the system resistance and reactance at the users site. The result is a curve of voltage variation versus net power which describes the envelope.

The voltage at the point of common coupling (PCC) with other consumers may be described by the quadratic equation:

$$(V^2)^2 + (2(QX_s - PR_s) - E^2)(V^2) + ((QX_s - PR_s)^2 + (PX_s + QR_s)^2) = 0 \qquad \ldots(1)$$

where   V is the line voltage at the PCC
P is the total net power generated by the WECS
Q is the total net reactive power demand of the WECS
R is the system phase resistance at the PCC
X is the system phase reactance at the PCC
E is the nominal source line voltage

Where the machine under consideration has a single phase generator the values of V and E used in the equation shall be the line to neutral values at the PCC.
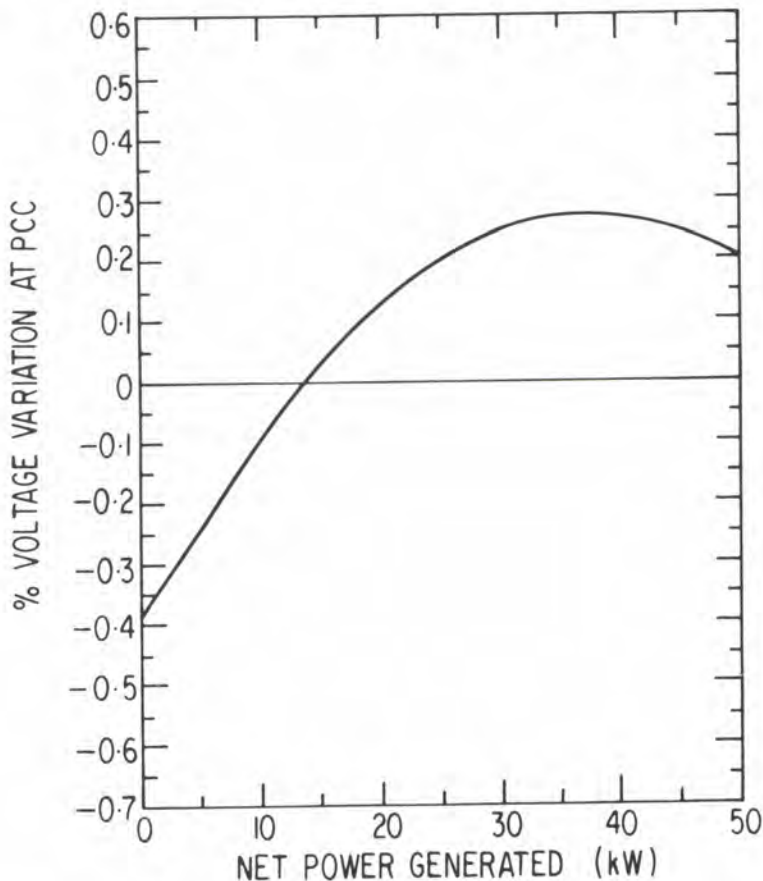

Fig. 2: Example of voltage variation curve.

Using the known value of R, X and E at the prospective site for the WECS, the quadratic equation should be solved for corresponding values of net power (P) and net reactive power (Q) taken from the measured curve (see section 4.3.). E should be taken as the nominal system source line voltage at the PCC.

The percentage variation (Δ V) of V should then be calculated for each of the solved values of V using:

$$\Delta V = \left(\frac{V}{E} - 1 \right) \times 100\% \qquad \qquad ...(2)$$

The percentage variation (Δ V) shall then be plotted (ordinate) against the delivered net power of the WECS (abscissa). If the variation become negative this should be shown on a negative going axis. An example is shown in Fig. 2.

The accuracy with which the voltage variation can be predicted is sensitive to the accuracy with which values of R and X can be determined for the network. It should also be noted that the effective values of R and X may vary depending on the system condition.

An example of the calculation is shown in Appendix A.

4.4.2. WECS Incorporating Commutated Inverters

Under consideration.

4.4.3. WECS Incorporating Directly Connected Synchronous Generators

Unlike the asynchronous generator the synchronous generator has self excitation and so the terminal voltage of the machine may be independently controlled to within a certain tolerance.

There exist National Standards relating to the response of various types of synchronous generator excitation systems. These standards set limits on the steady state error in the terminal voltage on no-load and on the transient response of the excitation system during a load change on the machine.

As these generators are already subject to the testing requirements of National Standards, the voltage variations expected can be predicted based on the test results of the present Standards.

4.5. Measurements and Assessments during Network Connection or during Change of Operation

The connection, disconnection or change of operation of a WECS can cause a disturbance on the network to which it is connected. Only the disturbance caused by connection and change of operation (such as change of generator in dual generator machines or winding switching through a star-delta transformation) are considered here as these are likely to cause the more severe disturbances. In practice, network connection can occur when wind speed increases to a level above the cut-in wind speed and at high wind speeds when reconnection is made following a decrease in wind speed to a level below the cut-out wind speed. For practical reasons the recommended measurement of electrical disturbances during network connection is restricted to cover the former case of connection during increasing wind speed.

The principle factors which affect the power quality in this respect are the magnitude of the disturbance and its frequency of occurrence. The sections that follow make recommendations for their measurements and assessment.

4.5.1. Measurement and Assessment of the Voltage and Current Variations for WECS that Incorporate Asynchronous Generators

The connection of an asynchronous machine to a power system will generally cause a current in-rush to flow momentarily which may be many times the rated current of the machine. This may occur on cut-in or change of operation when the generation mode is altered. The passage of such a high current will cause the voltage at the machine terminals, and at the PCC, to momentarily reduce.

Measurement of the in-rush current and the voltage depression should be carried out using a rapid response instrument to record the line current and line voltage waveforms on connection to the network and during change of operation. Total accuracy of the measurement of the current and voltage should be within 2% of full range. The line current and line voltage should be measured on the power system side of the cut-in switch. The form of the waveforms of line current and line voltage on the instant of connection to the network are illustrated in Fig. 3. With reference to the variables shown, the maximum line voltage depression V_{min} and maximum current I_{max} for a three phase machine are given by:

$$V_{min} = \frac{V'_{min}}{2\sqrt{2}} \text{ rms} \qquad \qquad ...(3)$$

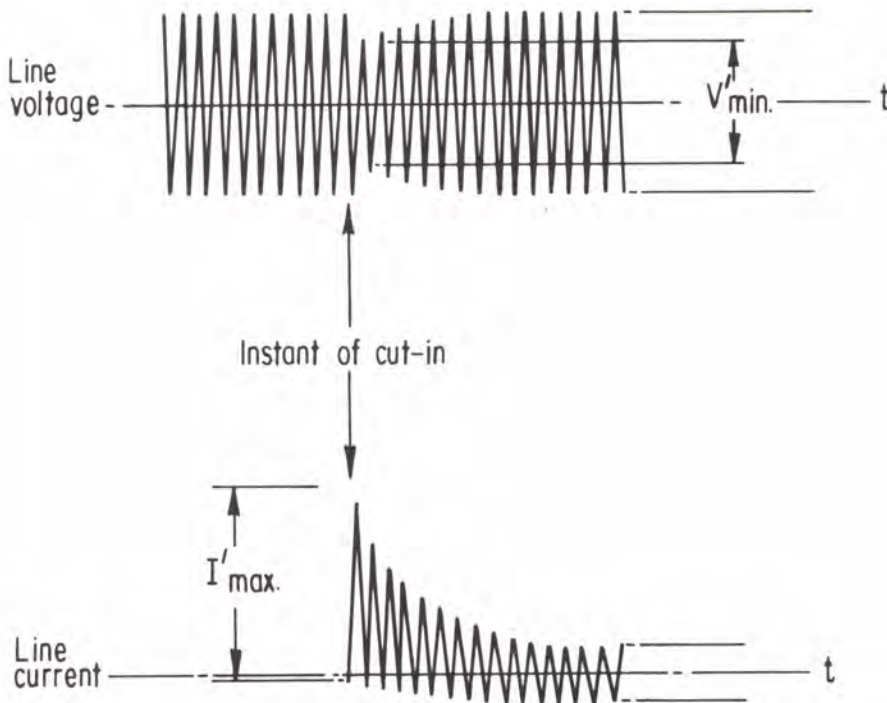$$I_{max} = \frac{I'_{max}}{2\sqrt{2}} \text{ rms} \qquad \qquad ...(4)$$

Fig. 3: Typical waveforms of line voltage and current during the connection of an asynchronous generator.

11

Using the known value of R, X and E at the prospective site for the WECS, the quadratic equation should be solved for corresponding values of net power (P) and net reactive power (Q) taken from the measured curve (see section 4.3.). E should be taken as the nominal system source line voltage at the PCC.

The percentage variation (Δ V) of V should then be calculated for each of the solved values of V using:

$$\Delta V = \left(\frac{V}{E} - 1 \right) \times 100\% \qquad\qquad ...(2)$$

The percentage variation (Δ V) shall then be plotted (ordinate) against the delivered net power of the WECS (abscissa). If the variation become negative this should be shown on a negative going axis. An example is shown in Fig. 2.

The accuracy with which the voltage variation can be predicted is sensitive to the accuracy with which values of R and X can be determined for the network. It should also be noted that the effective values of R and X may vary depending on the system condition.

An example of the calculation is shown in Appendix A.

4.4.2. WECS Incorporating Commutated Inverters

Under consideration.

4.4.3. WECS Incorporating Directly Connected Synchronous Generators

Unlike the asynchronous generator the synchronous generator has self excitation and so the terminal voltage of the machine may be independently controlled to within a certain tolerance.

There exist National Standards relating to the response of various types of synchronous generator excitation systems. These standards set limits on the steady state error in the terminal voltage on no-load and on the transient response of the excitation system during a load change on the machine.

As these generators are already subject to the testing requirements of National Standards, the voltage variations expected can be predicted based on the test results of the present Standards.

4.5. Measurements and Assessments during Network Connection or during Change of Operation

The connection, disconnection or change of operation of a WECS can cause a disturbance on the network to which it is connected. Only the disturbance caused by connection and change of operation (such as change of generator in dual generator machines or winding switching through a star-delta transformation) are considered here as these are likely to cause the more severe disturbances. In practice, network connection can occur when wind speed increases to a level above the cut-in wind speed and at high wind speeds when reconnection is made following a decrease in wind speed to a level below the cut-out wind speed. For practical reasons the recommended measurement of electrical disturbances during network connection is restricted to cover the former case of connection during increasing wind speed.

The principle factors which affect the power quality in this respect are the magnitude of the disturbance and its frequency of occurrence. The sections that follow make recommendations for their measurements and assessment.

4.5.1. Measurement and Assessment of the Voltage and Current Variations for WECS that Incorporate Asynchronous Generators

The connection of an asynchronous machine to a power system will generally cause a current in-rush to flow momentarily which may be many times the rated current of the machine. This may occur on cut-in or change of operation when the generation mode is altered. The passage of such a high current will cause the voltage at the machine terminals, and at the PCC, to momentarily reduce.

Measurement of the in-rush current and the voltage depression should be carried out using a rapid response instrument to record the line current and line voltage waveforms on connection to the network and during change of operation. Total accuracy of the measurement of the current and voltage should be within 2% of full range. The line current and line voltage should be measured on the power system side of the cut-in switch. The form of the waveforms of line current and line voltage on the instant of connection to the network are illustrated in Fig. 3. With reference to the variables shown, the maximum line voltage depression V_{min} and maximum current I_{max} for a three phase machine are given by:

$$V_{min} = \frac{V'_{min}}{2\sqrt{2}} \text{ rms} \qquad \qquad ...(3)$$

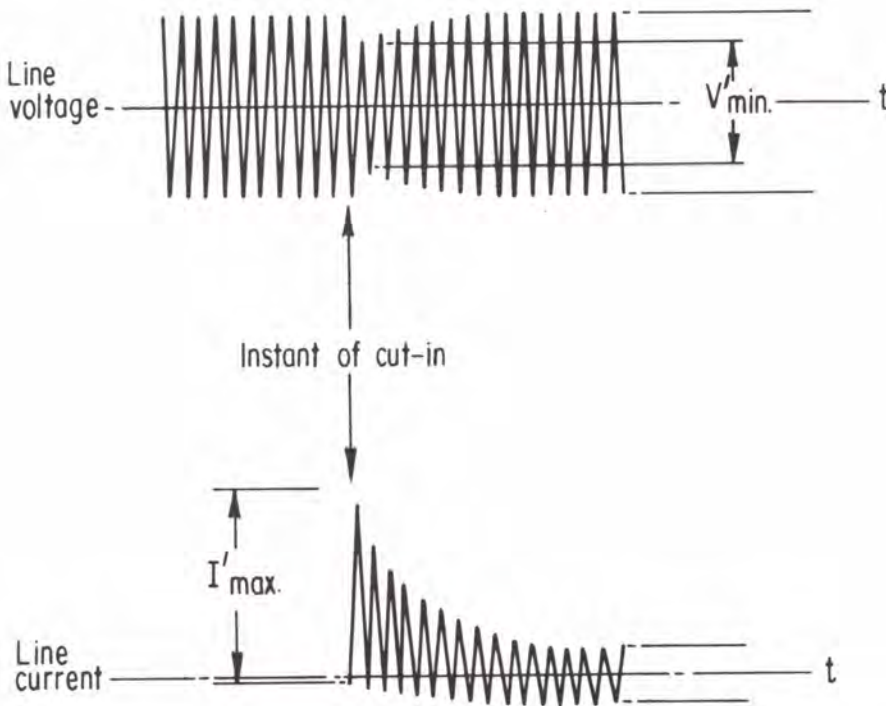$$I_{max} = \frac{I'_{max}}{2\sqrt{2}} \text{ rms} \qquad \qquad ...(4)$$

Fig. 3: Typical waveforms of line voltage and current during the connection of an asynchronous generator.

The measurement should be repeated at least ten times during connection and during other switching operations to account for differences in the magnitude of V_{min} and I_{max} due to non-consistent operation of the cut-in mechanism. The test should be carried out at any convenient wind speed above cut-in by a suitable means (eg. allowing the WECS to self start following the release of the parking brake).

The minimum value of V_{min} and maximum value of I_{max} determined should be quoted for connection to the network and for other switching operations.

The power factor of the machine at the instant of connection should be derived from the record of the waveforms remembering that the current and voltage are line values. If this proves difficult a value of 0.3 should be assumed as an approximation.

To assess the voltage depression which is likely to occur at the PCC when the WECS is used at the prospective users site, the following calculation is required.

The equivalent WECS phase resistance (R_w) and phase reactance (X_w) should be calculated at the instant of connection using the measured values of V_{min} and I_{max} and the measured or assumed value of power factor. The percentage voltage depression at the PCC is formed from

$$V_d = \sqrt{\frac{(R_s^2 + X_s^2)}{(R_s + R_w + R_L)^2 + (X_s + X_w + X_L)^2}} \times 100\% \qquad \text{...(5)}$$

where R_s is the system phase resistance at the PCC
 X_s is the system phase reactance at the PCC
 R_L is the total phase resistance of the transmission link between the WECS and the PCC
 X_L is the total phase reactance of the transmission link between the WECS and the PCC

4.5.2. Measurement of the Voltage and Current Variations for WECS that Incorporate Synchronous Generators

The synchronisation of a synchronous generator to a power system can cause fluctuations in the current and system voltage.

The voltage and current variations during synchronisation should be measured using a rapid response instrument to record the line current and voltage waveforms on cut-in and during change of operation. The line voltage and line current should be measured on the power system side of the cut-in switch.

The total accuracy of the measurement of the current and voltage should be within 2% of full range.

The measurement should be repeated at least ten times to account for differences in the magnitude of the synchronising voltages and currents due to non-consistent operation of the cut-in mechanism. The test should be carried out at any convenient wind speeds above cut-in by a suitable means. The tests should cover both cut-in operations from low wind speed and cut-in operations following shut-down of the WECS at high wind speeds.

The maximum peak to peak variation of the voltage and current recorded on synchronisation should be quoted in the test report along with the corresponding record of the measured current and voltage waveforms.

4.5.3. Measurement of Frequency of Occurrence

It is recognised that the frequency of occurrence of cut-in, cut-out and other switching operations will depend on the site wind regime as well as the WECS characteristics. Thus measurements recommended here are intended as a guide only to the likely magnitude of the frequency of occurrence.

It is recommended that the following are recorded during measurement of the power performance as recommended in Ref. 1. The measurement period should at least correspond to the operating time taken to meet the data requirements of the power performance recommendations.

1. Total number of connections made to the network due to a rise in wind speed above the cut-in wind speed during the measurement period.

2. Total number of connections made to the network due to a fall in wind speed below the cut-out wind speed during the measurement period.

3. Total number of any other relevant switching operations (eg. change of generators in dual generator WECS) during the measurement period.

The measurement period used together with the recorded number of switching operations should be stated in the test report.

4.6. Assessment of Harmonics

4.6.1. Waveform Distortion

Inherent in the definition of acceptable quality of electricity supply is that the waveforms of the supply voltage is sinusoidal with a nominal frequency of 50 to 60 Hz.

A small amount of distortion of the supply waveform is inevitable in practice because of the manufacturing tolerance inherent in generating plant. Limits are imposed on allowable levels of distortion caused in this way by the various national standards covering individual items of plant.

Conventional stationary and rotating electrical loads contribute little to waveform distortion since their characteristics are essential linear. However, some modern high efficiency electrical equipment employing thyristors for instance exhibit non-linear characteristics and can be a major source of waveform distortion.

Non-linear loads can also be considered as harmonic generators and will cause distortion of both current and voltage waveforms.

For practical purposes the degree of distortion present in a waveform is assessed by analysing the distorted waveform into is harmonic components which form a series of sinusoidal components having frequencies that are integer multiples of the fundamental frequency (50 to 60 Hz).

In the consideration of harmonic content in electrical power systems, upper harmonic frequency is usually restricted to 40 times the fundamental frequency (ie. 2.0 to 2.4 kHz).

Harmonic current and voltage magnitudes at a particular location in the electrical power system are not always constant and frequently vary erratically depending on the mode of operation and characteristics of the non-linear equipment.

Distortion of the supply voltage at the point of common coupling with other consumers is one of the most important parameters which must be contained within acceptable limits. The limits are usually imposed by national supply authorities.

Insufficient is known of the characteristics of the electrical power system at harmonic frequencies to enable calculation of harmonic content to be made with confidence. It is therefore recommended that harmonic assessment of WECS should be carried out solely by measurement. Even so the measurements taken at a test site cannot readily be translated to any other potential location. Check measurements should therefore be made on the installed WECS as part of the commissioning procedure if required.

4.6.2. Assessment of Harmonics by Measurement

If the assumption can be made that the harmonic content of the waveform remains constant, a harmonic analyser can be used to measure the amplitude and phase angle of each harmonic, relative to the fundamental (50 Hz or 60 Hz) harmonic, in turn. When using a harmonic analyser a measurement time of 10 seconds per harmonic is recommended which results in total measurement duration of at least 7 minutes if 40 harmonic frequencies are to be measured. A purpose built automatic harmonic analyser is to be preferred which can be set to make and record the sequence of harmonic measurements at preset intervals between 7.5 and 60 minutes.

The assumption of constant harmonic distortion may not be valid in those cases where very rapid bursts of harmonic current are generated by plant connected near the PCC. In this case an alternative and more rapid measurement method is necessary. A suitable harmonics analysis instrument, based on a microcomputer, is currently under development which records digitally the current or voltage waveform over consecutive periods of 10 seconds. Each recorded waveform is analysed by a fast Fourier Transform program to provide its harmonic content.

For cases where harmonic content is continually varying, more sophisticated equipment is available which carries out a special analysis of the recorded waveform.

Input to the above instruments for measuring harmonic currents can be via either measuring shunts or current transformers providing these introduce negligible impedance in series with the main circuit over the frequency range of the harmonics being measured. In the case of current transformers any DC component of the measured current introduced by their use shall not cause a measurement error greater than 5%.

In view of the variable nature of the harmonics expected from WECS it is recommended that recordings are made over a period to be determined during the tests to ensure that the maximum harmonic level is recorded. It is suggested that an initial series of recordings are made over a period of two hours to assess the variability or otherwise of harmonic content. If the harmonic readings indicate the occurrence of short duration burst of high harmonics which persist for less than 2 seconds and the interval between bursts is greater than 30 seconds these can be ignored.

It is recommended that over the recording period the highest three readings of a harmonic be identified and the lowest of these three, if they are not equal, is taken as the harmonic level to be recorded in the test report.

4.6.3. Harmonic Measurement Procedure

The following measurement procedure is recommended to assess harmonic content of voltage and current waveforms produced by WECS:

1. **Without WECS Connected**

   Measure harmonic content of network voltage waveform at the PCC. Amplitude and relative phase angle of each harmonic shall be recorded.

2. **With WECS Connected and Operating at or near Minimum Output**

   a) Measure harmonic content of the voltage waveform at the same PCC, as in 1 above. Amplitude and phase angle of each harmonic shall be recorded together with the measured power output from the WECS.

   Vectorial subtraction of each harmonic recorded in 1 above from that recorded in 2(a) will produce the contribution of WECS to the harmonic voltage distortion at the PCC. The calculated results shall be recorded.

   b) Measure harmonic content of the current waveform at any convenient point between WECS terminals and PCC. Amplitude and relative phase angle of each harmonic shall be recorded together with the measured power output from the WECS during the harmonics measuring period.

3. **With WECS Connected and Operating at or near Rated Output**

   Repeat measurements 2(a) and 2(b). Amplitude and relative phase angle of each harmonic shall be recorded together with the measured power output from the WECS during the harmonic measuring period.

5. TEST REPORT

The test report shall include, but not be limited to, the items listed below:

1. Description of the WECS including the major items listed in Section 2. In particular a full description should be given of the generator or inverter and any terminal equipment associated with the WECS.

2. Location and description of the test site and power system as detailed in Section 3.

3. Instrumentation, including type and location. If calibration is applicable the method of calibration used, the calibration time interval used. Clear diagrams should be included to indicate the point of measurement.

4. Description of the data acquisition system.

5. Deviation from recommended practices.

6. Test results, including where appropriate:

 i) Plot of power variation measurements.

 ii) Plot of net power vs net reactive power.

 iii) Minimum voltage and maximum value of in-rush current on cut-in should be stated for the asynchronous generator type WECS. Voltage and current should be expressed as percentages of the rated values.

 iv) Corresponding time history record of (iii) showing voltage and current waveforms.

 v) Maximum percentage (of rated value) variations of rms voltage and current during cut-in and synchronising of synchronous generator type WECS.

 vi) Occurrence of connections, disconnections and other switching operations in terms of their total number and period of measurement.

 vii) Harmonic content of voltage and current listing amplitude and phase angle for each harmonic.

6. REFERENCE

1. Frandsen, S., Trenka, A. R., Pedersen, B. Maribo: 'Recommended Practices for Wind Turbine Testing and evaluation', Part 1, Power Performance Testing.

APPENDIX A

EXAMPLE CALCULATION OF MAXIMUM VOLTAGE VARIATIONS OCCURING DURING GENERATION AT THE USERS SITE

In this example consider the connection of a 40 kW WECS which uses an asynchronous generator connected to a network which also supplies other consumers.

The network and generator details are as follows:

Network Details

Source fault level (33/11 kV substation)	150 MVA
HV network – 100 mm² ASCR 11 kV overhead line	10,000 metres long
– 500 mm² ASCR 11 kV overahead line	4,000 metres long
Transformer (11/0.415 kV)	
– 50 kVA 3 phase	
LV network – 100 mm² AC 415 V overhead line	200 metres long
– 50 mm² AC 415 V overhead line	150 metres long
– 35 mm² 415 V AL underground cable	100 metres long
Service cable from PCC	
– 35 mm² 415 V AL underground cable	100 metres long

Nominal system source line voltage at point of common coupling with other consumers: 440 V.

Generator Details

Generator type – three phase mains excited asynchronous.

Rating – 40 kW at rated speed.

Net reactive power characteristics – as figure A1 determined as described in section 4.3.1.

Calculation of Network Impedance

Using typical network impedance data and referring these values to the PCC voltage, the total network impedance is calculated as follows:

Plant		Impedance (R + jX)) ohms
Source (150 MVA) $\dfrac{(\text{Source Voltage at PCC})^2}{\text{Fault VA}} =$		0 + j 0.00130
HV Network:	10,000 m × 100 mm² OHL	0.00420 + j 0.00590
	4,000 m × 50 mm² OHL	0.00336 + j 0.00245
	50 kVA Transformer	0.08760 + j 0.14400
LV Network:	200 m × 100 mm² OHL	0.05400 + j 0.05520
	150 m × 50 mm² OHL	0.08120 + j 0.04460
	100 m × 35 mm² U/G	0.02760 + j 0.07330
	Impedance from source to PCC:	0.25800 + j 0.32680
Service:	100 m × 35 mm² U/G	0.05240 + j 0.00750
	Impedance at consumers supply terminals:	0.31040 + j 0.33430

Thus for determining the voltage fluctuation limits at the PCC use $R = 0.258$ and $X = 0.3268$. For determining the voltage fluctuation limit on the consumers premises use $R = 0.3104$ and $X = 0.3343$.

For the PCC

Substituting the values of R = 0.258, X = 0.3268 and E = 440 V (the nominal source voltage at the PCC) into equation (1) and solving for V for a range of values of P and corresponding values of Q taken from Fig. A1 gives the values in column 3 of Table 1.

Using equation (2), the percentage variation expected at the PCC of the site considered may be calculated, and for the example these values are shown in column 4 of Table 1. From these the overall voltage variation limits at the PCC may be extracted.

In the example, the overall voltage variation predicted is 2.4% at the PCC. The voltage variation with output power of the WECS is shown in Fig. A2.

TABLE 1: CALCULATED VALUES OF VOLTAGE VARIATION

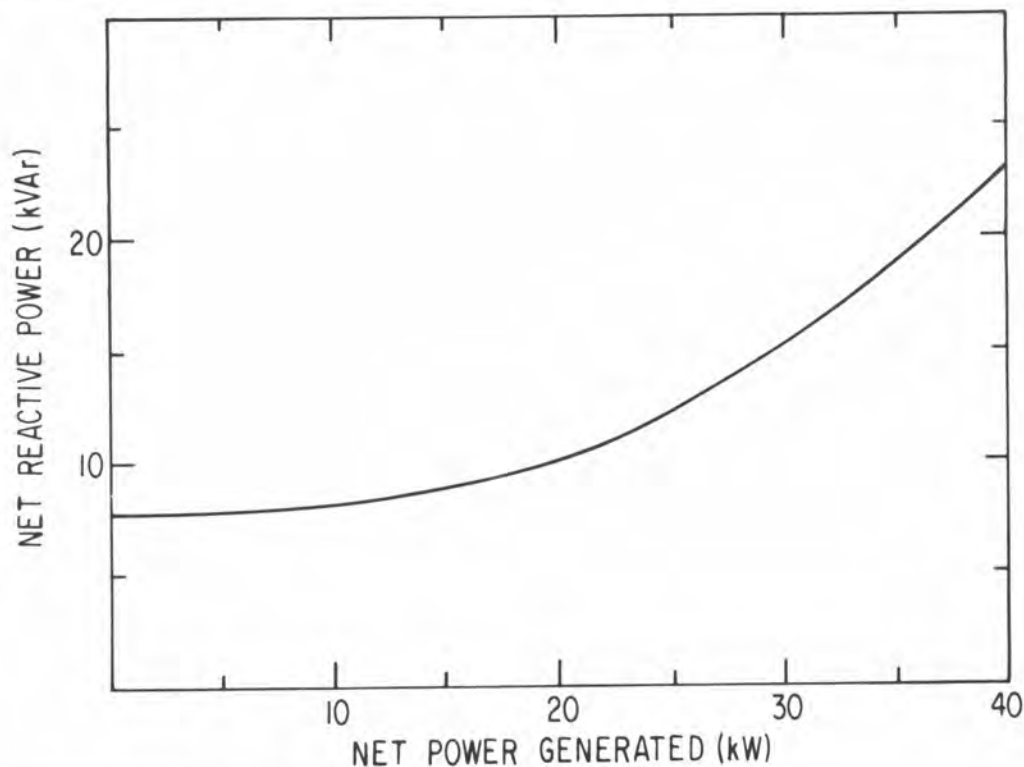| Net Power	Net Reactive Power	Voltage at PCC	Variation from Nominal
(kW)	(kVAr)	(V)	(%)
0	8	434.0	−1.4
5	8	436.9	−0.7
10	8.2	439.6	−0.1
15	8.6	442.1	0.5
20	9.7	444.5	1.0
25	11.9	445.0	1.1
30	14.9	445.4	1.2
35	18.6	445.1	1.2
40	23.0	444.2	1.0

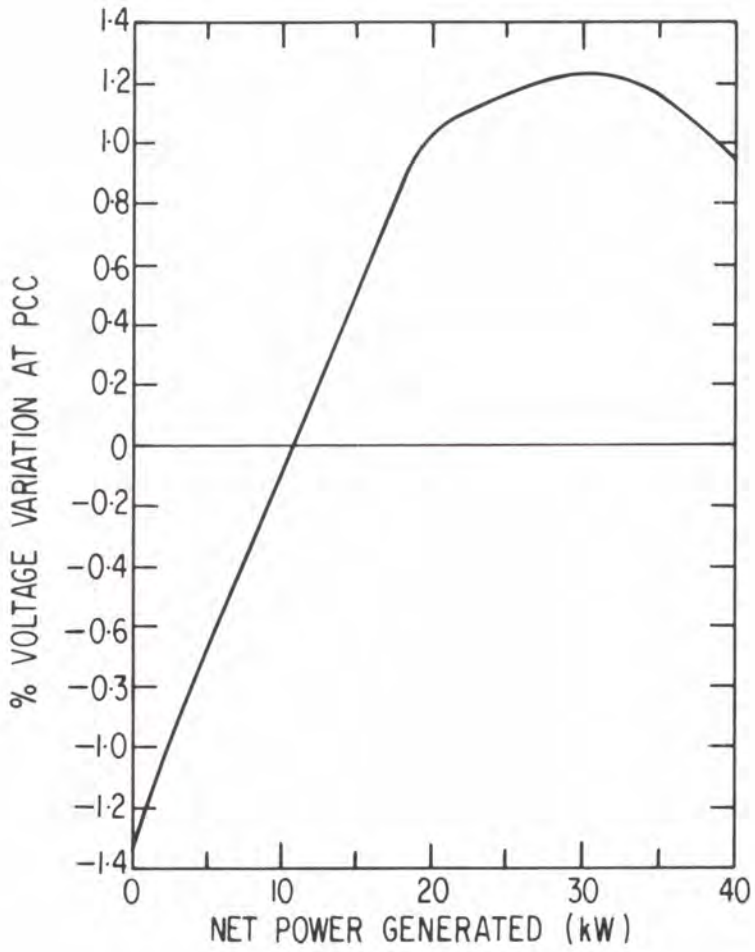*Fig. A1: Net reactive power versus net power for WECS used in example.*

Fig. A2: Voltage variation with generator net power.
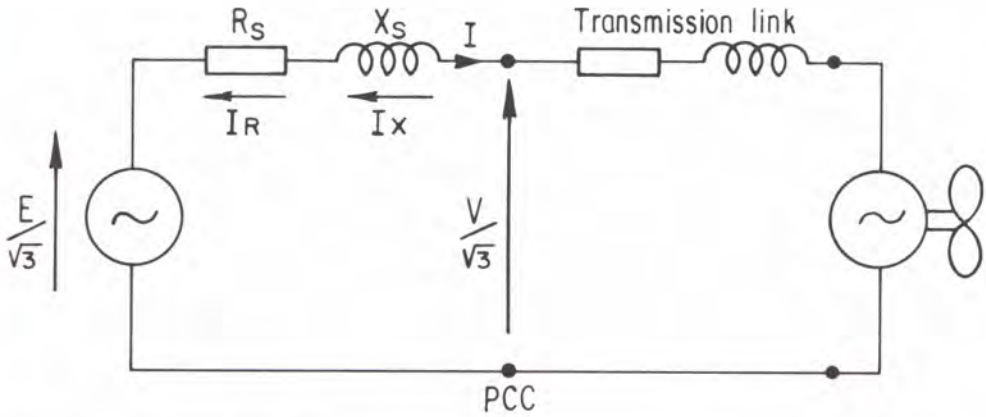
APPENDIX B

DERIVATION OF EQUATION (1)

Fig. B1: Equivalent single phase diagram.

For a WECS generating into the network which has a system phase impedance of $R_s + j X_s$ and a source line voltage of E, the phasor diagram of the system (exaggerated) will be as below:
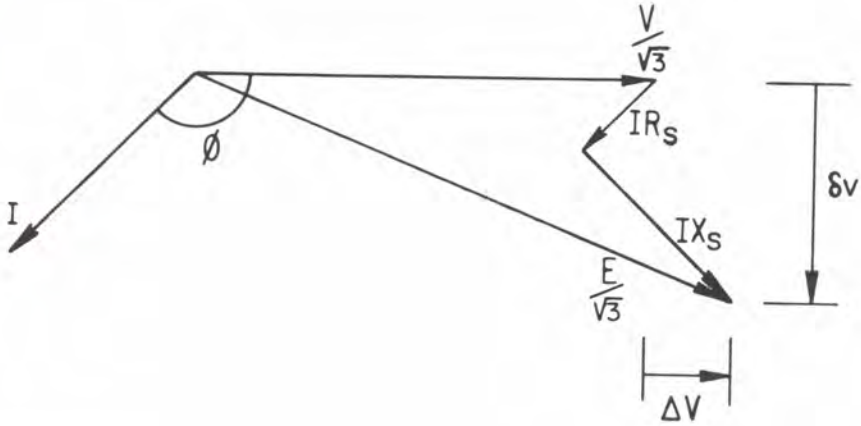

Fig. B2: Phasor diagram.

Resolving for δV and ΔV

$$\delta V = IR_s \operatorname{Sin} \varnothing + IX_s \operatorname{Cos} \varnothing$$
$$\Delta V = IX_s \operatorname{Sin} \varnothing - IR_s \operatorname{Cos} \varnothing$$

Now using the relationships

$$P = \sqrt{3} VI \operatorname{Cos} \varnothing \quad \text{the total real power}$$
$$Q = \sqrt{3} VI \operatorname{Sin} \varnothing \quad \text{the total reactive power}$$

we get

$$\delta V = (PX_s + QR_s) / \sqrt{3} V$$
$$\Delta V = (QX_s - PR_s) / \sqrt{3} V$$

vectorially

$$\frac{\overline{E}}{\sqrt{3}} = \frac{V}{\sqrt{3}} + \Delta V - j\delta V$$

or

$$\overline{E} = \frac{1}{V} (V^2 + QX_s - PR_s - j (PX_s + QR_s))$$

and rearranging:

$$(V^2)^2 + \{2 (QX_s - PR_s) - E^2\} (V^2) + (QX_s - PR_s)^2 + (PX_s + QR_s)^2 = 0 \qquad \dots (1)$$

APPENDIX C
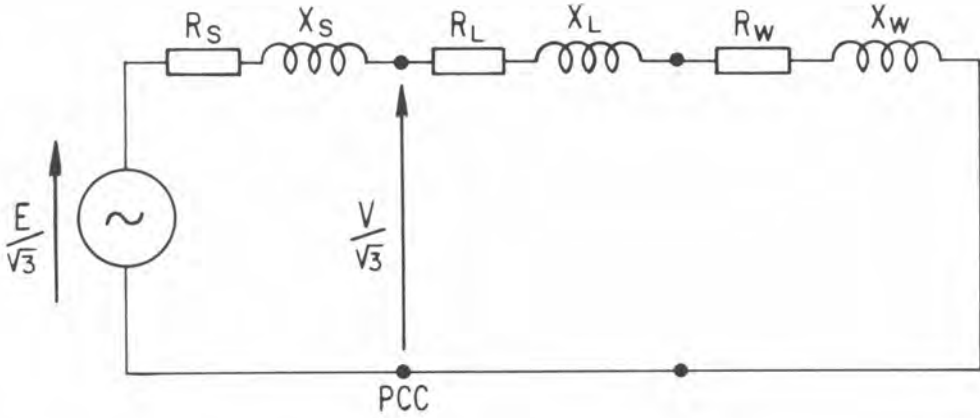
DERIVATION OF EQUATION (5)

Fig. C1: Equivalent single phase diagram.

The voltage depression V_d at the PCC is given to a good approximation by the voltage divider equation:

$$\overline{V}_d = \frac{R_s + j X_s}{R_s + R_L + R_w + j (X_s + X_L + X_w)}$$

and taking the modulus

$$V_d = \sqrt{\frac{R_s^2 + X_s^2}{(R_s + R_L + R_w)^2 + (X_s + X_L + X_w)^2}}$$

Available on request from:

B. Maribo Pedersen
Dept. of Fluid Mechanics
Technical University of Denmark
Building 404
Lundtoftevej 100
DK-2800 Lyngby
Denmark

H. J. M. Beurskens
ECN
Westerduinweg 3
Postbus 1
NL-1755 ZG Petten
The Netherlands

R. G. Youlton
MEE4C, Room 548
Dept. of Trade & Industry
Ashdown House
123 Victoria Street
London SW1E 6RB
England

A. R. Trenka
DOE/USA
Rockwell International
P.O. Box 464
Golden
Colorado 80401
USA

A. Gustafsson
FFA
Box 11021
S-161 11
Sweden