POWER SYSTEM HARMONIC

FIELD MEASUREMENTS

PC SIMULATIONS

AND

STANDARDS

GARY ATKINSON-HOPE

DECLARATION

I hereby declare that the work for this thesis was done by myself, that I wrote it myself and that it has not been submitted to any other educational institution in order to obtain a qualification.

G. ATKINSON-HOPE SEPTEMBER 1996

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ABSTRACT

The research covered three main objectives:

Application of PC based harmonic penetration packages and a comparison of their simulation results.

Investigation and comparison of the IEEE, IEC and ESKOM power system harmonic standards.

Measurement of harmonics in two industrial networks and the application of the results to the regulatory limits provided by the standards.

The research makes use of two packages and uses parameters from an industrial network. Case studies were conducted using the same parameters so that the results obtained from each package could be compared. The standards have been individually investigated to determine each method for controlling harmonic distortion. The three standards have also been compared. Harmonic field measurements were conducted in industrial networks so that the limits imposed by the standards could be compared with real life operating conditions.

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ABBREVIATIONS AND SYMBOLS

A, B and C = Cases A, B and C

BR = Branch

CT = Current transformer

DF = Displacement power factor

DyOn = Delta, star transformer

EFF = Efficiency

EHV = Extra High Voltage

EQUIV = Equivalent Source impedance

ER = ERACS package

ESKOM = Electricity Supply Commission

EVEN % = Even harmonic percentage

FFT = Fast Fourier Transform

h = Individual harmonic component or number

HP = Horse power

HV = High Voltage

Hz = Frequency

I = Current

IEC = International Electrotechnical Commission

IEEE = Institute of Electrical, Electronic Engineers

I_L = Full load current

IPC = In Plant Point of Coupling

Isc = Short-circuit current

I THD % = Current Total Harmonic Distortion Percentage

kA = kilo-Amperes

kV = kilo-Volts

kVA = kilo-Voltamperes

kVARS = kilo-Voltamperes reactive

kW = kilo-Watts

LV = Low Voltage

MV = Mega-Volts

MVA = Mega-Voltamperes

n = Harmonic number (same as "h")

Odd % = Odd harmonic percentage

PC = Personal Computer

PCC = Point of Common Coupling

pu = Per-unit

$\% V_h$ = Percentage harmonic voltage

% V RMS = Percentage Voltage Root Mean Square value

% I_h = Percentage harmonic current

% I RMS = Percentage Current Root Mean Square value

q = pulse number

R = Resistance

Ref = Reference

RMS = Root Mean Square

Rsc = Ratio of Isc/I_L

SH = SUPERHARM package

SRC1 = Current name at source

SRCV = Bus name at source

TOP = Output Processor for "SH"

V = Voltage

Vry = Line voltage red to yellow

VT = Voltage Transformer

V THD % = Voltage Total Harmonic Distortion Percentage

X = Reactance

Yh = Admittance matrix for h harmonic

Zeq = Equivalent impedance

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CHAPTER 1

1. INTRODUCTION

Due to the increase in the use of nonlinear loads (e.g. convertors) in power systems, voltage and current waveforms are becoming distorted. The situation is expected to get worse as more nonlinear loads are installed.

Nonlinear loads cause harmonics to penetrate through distribution points within consumer installations and they cause the interface between utilities and end-users to loose power quality.

PC based harmonic analysis software packages are used to predict harmonic distortion levels in industry. They are particularly useful for newly designed installations or where installations are to be upgraded to include nonlinear loads.

Standards for controlling harmonic distortion levels exist. The standards control distortion by providing regulatory limits that may not be exceeded. They have been set up to prevent distortion from reaching unacceptable levels.

Research is needed to investigate how these packages and standards are applied to industrial networks.

1.1 AIMS OF RESEARCH

a. Application of two PC based industrial-grade harmonic software analysis packages and a comparison of their simulation results.

b. Investigate and compare the IEEE, IEC and South African standards that control harmonic distortion levels in power systems.

c. Measure harmonics in industrial networks and compare the results to the regulatory limits provided by the standards.

1.2 SCOPE OF DISSERTATION

The research investigates two industrial- grade harmonic software analysis packages.

The software investigated were the ERACS (UK) and the ELECTROTEK (USA) packages. The modelling used and the capabilities of each package were studied and compared.

Their applicability and suitability to South African industrial networks needed to be learned. Harmonic simulation studies were thus carried out using parameters from a local network.

Case studies were conducted using the same parameters so that the results obtained from each package could be compared.

Three power system harmonic standards were research.

The standards researched were the American (IEEE), the European (IEC) and the South African (ESKOM) standards.

Each standard has been individually investigated to develop an understanding of them and to learn their methods used to control harmonic distortion in power systems.

The three standards have also been compared to learn any similarities and/or differences which exist between them.

To better understand how standards are applied in industry, harmonic field measurements were conducted in industrial networks so that the limits imposed by the standards could be compared with real life operating conditions.

Measurements were conducted at a 11kV manufacturing plant and at a 33kV traction substation. Both networks contained convertors.

The effectiveness of the standards to control harmonics were also assessed.

1.3 SPECIFIC FACTORS USED IN HARMONIC STUDIES

In examining the effects of harmonics on power systems the following two specific **factors** are used. [1]

1.3.1 TOTAL HARMONIC DISTORTION

The total harmonic content of a waveform is measured in terms of the total harmonic distortion index. For voltage distortion, it is defined by:

$$V\ THD\ \% = \frac{\sqrt{\sum_{n=2}^{n} Vn^2}}{V_1} \quad x \quad 100\% \text{ - - - - - - - - - - - } (1.1)$$

where: V_1 is the fundamental component and V_2 to Vn are the individual harmonic components.

A similar index is used for total harmonic current distortion (I THD %).

When checking to decide if field measurements meet a standard it is traditional to first assess the THD %. As it is an index, it assesses the complete impact of the harmonic sources on a power system. It may however hide unacceptable individual harmonic component levels yet give the impression that the distortion is acceptable. Consequently, it is essential to assess individual harmonic component levels besides the THD %.

1.3.2 PERCENTAGE HARMONIC COMPONENT

Individual harmonic component levels are expressed as the ratio of the rms value of the individual harmonic component divided by the rms value of the fundamental.

For example:

(1) VOLTAGE

$$\% V_h = \frac{V_h}{V_f} x\ 100\% \text{ - - - - - - - - - - - - } (1.2)$$

(2) CURRENT

$$\% I_h = \frac{I_h}{I_f} x\ 100\% \text{ - - - - - - - - - - - - } (1.3)$$

Where: Vh and Ih are harmonic voltage and current components and V_f and I_f are the voltage and current values at the fundamental frequency respectively.

A percentage harmonic component shows how much each component contributes to the resultant distortion.

In this thesis reference is often made to these two factors. It is for this reason that a brief introduction into each is given.

2. APPLICATION OF PC BASED HARMONIC SOFTWARE ANALYSIS PACKAGES AND A COMPARISON OF THEIR SIMULATION RESULTS

Due to the rising levels of harmonic distortion in power systems it is necessary nowadays to conduct studies in this regard.

These effects can be detected by carrying out field measurements. This would only be possible in established installations. Any adverse effects would already exist. It would be better to predetermine these effects beforehand rather than having to correct by remedial steps.

In this regard computer simulation can be very useful. They are particularly useful for newly designed installations or where installations are to be upgraded to include nonlinear loads (e.g. convertors).

Harmonic analysis using PC based software packages are available and are used to predict harmonic distortion levels in industry.

Therefore it was decided to investigate and compare two packages and carry out simulations using parameters from an industrial network.

2.1. INDUSTRIAL NETWORK

Figure 6.1, Appendix 6 shows the schematic layout of the 11kV manufacturing plant used for harmonic simulation analysis.

Many harmonic problems occur at distribution voltage level. Therefore, a 11kV plant was chosen. Also, the highest THD% is normally found in this voltage range.

The plant comprises of an HV substation that supplies three main branches, a general office (linear load), a silica mill (group of motors) and a manufacturing section that includes two 6-pulse drives. Together they operate as a combined harmonic source in the plant.

The main components of the section, besides the harmonic source, are a transformer, cables, power factor correction capacitor banks and motors. The plant is supplied via an overhead line.

The combined drives operate with other loads at the S28 OFFTAKE MCC junction.

Figure 6.2, Appendix 6 shows the one-line-diagram of this plant.

The diagram has six buses. Bus 6, is a dummy bus and shows the combined drives separated from the other S28 OFFTAKE MCC loads. The reason for this is because the packages assume that harmonics are generated by a shunt load that does not absorb any harmonics. Therefore, during initialisation (injection) a program disconnects "ALL" shunts attached to an injection bus. If one wishes such shunts to be operative during an injection, then a dummy bus must be created. It should be connected between the desired injection point and the original bus via a low impedance line or cable (not a bus-section).

In our plant the harmonic source (combined drives) is connected to other shunts on a common bus. To prevent that these shunts become inoperative during injection a dummy bus 6 was created on the one-line-diagram. Bus 6 is connected to its original bus 5 via a low impedance cable. The rating of the combined two drives is 39.45 kVA, 0.79 lagging power factor.

The main parameters for the plant are given on the one-line-diagram.

Bus 1 is the 11kV point of common coupling (PCC).

A PCC is the interface between the utility supply and the consumer's installation.

Buses 2, 4 and 5 have been identified as in plant points of coupling (IPC's). They are IPC 1, IPC 2 and IPC 3 respectively.

Harmonic field measurements were conducted at three locations in the plant. See locations 1, 2 and 3 on Figure 6.1, Appendix 6.

These measurements were taken to determine the harmonic spectrums generated by the two drives individually and as a combined unit. Location 1 was for drive 1 and location 2 for drive 2. Location 3 was the measurement taken to obtain the spectrum for the combined drives.

A Fluke 41 Harmonic Analyser was used to take these measurements. See Appendix 5.

The measurements were downloaded to a PC using FLUKEVIEW software. See Appendix 6 for these results.

The reason for these measurements is so that real life spectrums can be used for harmonic injection during simulation studies rather than only using ideal (theoretical) spectrums.

2.2 HARMONIC ANALYSIS PACKAGES

The two packages selected were the ELECTROTEK [9] and the ERACS [10] packages.

The main purposes for the simulation studies are to compare the results of the two packages when:

a. an ideal (theoretical) 6-pulse drive spectrum is used as the harmonic source and injected at bus 6.

b. a real life 6-pulse drive spectrum is used as the harmonic source. This would enable a comparison to be made to the results obtained when an ideal spectrum was used. This comparison would show the error that arises if a theoretical rather than a real life spectrum is used.

c. the real life spectrum as measured at location 3 is used as the harmonic source. This spectrum combines the two drives and the other loads at the MCC together. In this case bus 5 would be used for injection. This enables a comparison to be drawn between the results obtained when two different injection points are used. If similar results are obtained, it will prove that the dummy bus method works. Buses 5 and 6 are both in the same radial branch, therefore it is expected that similar results should be obtained. This location for taking measurements has the advantage that the combined spectrum is easily measured. It is also the only way to determine the combined spectrum by measurement. It must be remembered that the other loads at the MCC do not contribute harmonic components. They only contribute towards the resultant at the fundamental frequency. If measurements are only taken at locations 1 and 2 then the combined spectrum can only be determined by calculations. To obtain the resultant fundamental for all the loads and drives combined, means measuring all of them individually. Their phase angles would also need to be ascertained. In practice this is a much more difficult task. To obtain the resultant fundamental for the combined drives only involves measuring the fundamental and its phase angle at location 3 and then subtracting therefrom all the fundamentals connected to this common junction. See page 18, Appendix 2 for this calculation.

2.2.1 ELECTROTEK PACKAGE

The ELECTROTEK package has a SUPERHARM and a TOP program.

SUPERHARM is a windows based package dedicated to harmonic penetration studies. A text editor is used to prepare a data file that describes the network to be simulated.

TOP is an abbreviation for "THE OUTPUT PROCESSOR".

It processes the simulation results produced by the SUPERHARM program and allows the output file to be viewed. It provides graphs and tables of the results that can be printed.

2.2.1.1 SIMULATION CASES

To achieve the main purposes for the simulation studies the following three cases were undertaken:

CASE A: COMBINED DRIVES AT BUS 6 MODELLED AS AN IDEAL 6-PULSE RECTIFIER (HARMONIC SOURCE) HARMONIC INJECTION AT BUS 6.

CASE B: COMBINED DRIVES AT BUS 6 MODELLED AS A 6-PULSE RECTIFIER USING THE HARMONIC SPECTRUM OF THE COMBINED DRIVES MEASURED IN THE FIELD AS THE HARMONIC SOURCE - INJECTION AT BUS 6.

CASE C: COMBINATION OF THE TWO DRIVES AND THE LINEAR LOAD 2 AT BUS 5 MODELLED AS A 6-PULSE RECTIFIER USING THE HARMONIC SPECTRUM MEASURED IN THE FIELD AT BUS 5 AS THE HARMONIC SOURCE - INJECTION AT BUS 5.

The network parameters are kept identical for each case study.

See paragraphs 1.1, 1.3 and 1.5, Appendix 1 for the input data file layout used for each case.

When carrying out simulations and no field measurements or data is available about a harmonic source an ideal model based on the expected fundamental current is used. The harmonic spectrum being based only on 6k±1 characteristic harmonics. This makes it an ideal rectifier. The harmonics generated are the 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th etc.

The harmonic spectrum used for Case A is as follows: (See page 1, Appendix 1).

HARMONIC SPECTRUM - CASE A			
h	Hz	AMPS	ANGLE
1	50	60.00	-38.0
5	250	12.00	-10.0
7	350	8.57	-266.0
11	550	5.45	-238.0
13	650	4.62	-134.0
17	850	3.52	-106.0
19	950	3.15	-2.0
23	1150	2.60	-334.0
25	1250	2.40	-230.0
29	1450	2.06	-202.0
31	1550	1.94	-98.0

TABLE 2.1

The SUPERHARM User Manual describes how to calculate the spectrum for a 6-pulse ideal convertor, namely:

(1) ESTABLISH "FUNDAMENTAL AND ITS POWER FACTOR"

From the combined two drives in the Plant,

$$KVA = 39.45 \text{ at } 0.79 \text{ pf (3-phase)}$$

$$I_{Fundamental} = \pm 60A \text{ at } 38° \text{ lagging}$$

(2) CALCULATE MAGNITUDES OF HARMONIC SPECTRUM CURRENTS

$$Ih - \frac{I_1}{h}$$

$$e.g.\ I\ (5th) - \frac{60}{5} - 12A$$

(3) CALCULATE PHASE ANGLES OF HARMONIC SPECTRUM CURRENTS

$$\theta h = \begin{cases} 0°, h = 1, 7, 13, 19, 25, 31 \\ 180°, h = 5, 11, 17, 23, 29 \end{cases}$$

e.g.

$\underline{h = 1}$

$$\theta h = 0 + [1(-38)] = -38°$$

$\underline{h = 7}$

$$\theta h = 0 + [7(-38)] = -266°$$

$\underline{h = 5}$

$$\theta h = 180 + [5(-38)] = -10°$$

(4) Using this method all the values for the "IDEAL RECTIFIER" are derived.

NB! The fundamental current component must be entered in the table.

CHAPTER 2

The harmonic spectrums used for Cases B and C were obtained from field measurements.(See pages 4 and 7, Appendix 1.

HARMONIC SPECTRUM - CASE B			
h	Hz	AMPS	ANGLE
1	50	60.00	-38.0
5	250	17.7	-17.0
7	350	2.6	-41.0
11	550	3.9	-68.0
13	650	1.0	-92.0
17	850	2.0	-113.0
19	950	0.8	-166.0
23	1150	1.4	-164.0
25	1250	0.7	-144.0
29	1450	0.9	-145.0
31	1550	0.6	-89.0

TABLE 2.2

HARMONIC SPECTRUM - CASE C			
h	Hz	AMPS	ANGLE
1	50	126.3	-39.0
5	250	17.7	-17.0
7	350	2.6	-41.0
11	550	3.9	-68.0
13	650	1.0	-92.0
17	850	2.0	-113.0
19	950	0.8	-166.0
23	1150	1.4	-164.0
25	1250	0.7	-144.0
29	1450	0.9	-145.0
31	1550	0.6	-89.0

TABLE 2.3

There is no difference in the spectrums between Cases B and C. This is because the linear loads at bus 5 contribute no harmonics. These loads only contribute to the resultant fundamental as stated previously.

Once prepared, the data files are used to execute the SUPERHARM program.

SUPERHARM can calculate both voltage and current at any bus in a network. The following results for buses 1 (PCC) and 4 (IPC 2) for all three cases were obtained:

1. The fundamental voltage and current.

2. The characteristic harmonic voltages up to the 25th harmonic.

3. The THD % for the voltage and current.

Also calculated were the characteristic currents up to the 25th harmonic in LINE 1 and BR 2.The reason for obtaining simulation results at the PCC is that harmonic distortion levels are usually defined by standards for this interface. This matter will be discussed in great detail in a subsequent chapter.

Results for IPC2 were chosen for three reasons. Firstly IPC 2 is the point most likely to display resonance as it is the bus to which pf correction capacitors are connected. Also, certain standards define distortion levels for IPC's. It also gives another point in the network at which comparisons can be drawn and shows harmonic penetration.

Also, the current spectrum in BR 1 will be the same as BR 2 except transferred via T1. Likewise the voltage spectrum at bus 2 will be very similar to that at buses 3 and 4.

2.2.1.2 SIMULATION RESULTS

The simulation results as calculated by SUPERHARM for the PCC and IPC 2 and processed by TOP for the three cases are given in Tables 1.1 (Case A), 1.2 (Case B), and 1.3 (Case C), Appendix 1.

A comparison of the results obtained for Cases A, B and C are given in Tables 1.4 and 1.5, Appendix 1.

2.2.2 ERACS PACKAGE

The ERACS package (Appendix 2) is not dedicated like SUPERHARM to harmonic analysis only but includes programs for Load Flow, Short-Circuit, Transient Stability and Protection Co-ordination studies besides its Harmonic Penetration program.

This package requires that before any other calculations (e.g. harmonic penetration, See paragraph 5.1, Appendix 5) are performed a successful loadflow analysis needs to be run.

2.2.2.1 LOADFLOW ANALYSIS

Paragraphs 2.1 to 2.3, Appendix 2 provides a summary of the input data particulars required to achieve a successful loadflow analysis.

Menus are provided for all types of circuit elements found in power systems. See Tables 2.1 to 2.10, Appendix 2 for the input data required by these menus.

A successful loadflow run was achieved. The results are shown on the one-line-diagram given in Figure 2.1 on page 8, Appendix 2.

For an interpretation of the loadflow results see paragraph 2.3.1, Appendix 2.

It could therefore be accepted that the modelling was correct.

The network is set up for harmonic penetration analysis.

2.2.2.2 SIMULATION CASES

The main objective of the simulation studies is to compare the SUPERHARM and ERACS results against each other.

In order to do this the same cases (Cases A, B and C) studied with the SUPERHARM package are studied with the ERACS package. That is, the same harmonic spectrums are used for both packages.

The same network and parameters are also used. The manner in which the parameters are entered is different as each package has its own method to input data. The SUPERHARM package makes use of a single input file per case while the ERACS package requires parameters to be entered via a range of different menus.

See paragraph 2.5, Appendix 2 for the step-by-step procedure used for the Case A harmonic penetration study. The same ideal rectifier harmonic spectrum as was used with SUPERHARM was injected into bus 6 except ERACS has a limitation that the harmonic phase angles must be within the 0° to 180° range. . See Table 2.14, Appendix 2 for the adjusted spectrum.

See paragraphs 2.6 and 2.7, Appendix 2 for the harmonic penetration details for Cases B and C.

A summary of the harmonic spectrums (with converted phase angles) for Cases B and C is given in Tables 2.16 and 2.17, Appendix 2 respectively.

2.2.2.3 SIMULATION RESULTS

The main advantage of the ERACS package is its ability to produce its simulation results directly onto one-line-diagrams. It produces a one-line-diagram for harmonic penetration for each harmonic making up the injection spectrum.

The results were extracted and are given in Tables 2.15 (Case A), 2.17 (Case B) and 2.18 (Case C), Appendix 2.

A comparison of the results obtained for Cases A, B and C are given in Tables 2.19 and 2.20, Appendix 2.

2.3 CASE STUDIES

As stated in Chapter 1 the two most important specific factors that need to be examined when considering the effects of harmonics in power systems are:

The amplitudes of the harmonic components, voltages and currents.

The total harmonic content, voltage and current, expressed as a THD %.

These will be the only harmonic factors used when simulation results are compared.

Comparisons will also be only made at the PCC and IPC 2 buses. An injected spectrum and the results at these two junctions will display the harmonic penetration taking place through the network.

Comparisons for each package will be drawn between Cases B and C. This will show if their results agree.

A comparison between the simulation results of the two packages on a case-by-case basis will be made. Case A results from SUPERHARM will be compared to the Case A results obtained by ERACS. The same will be done for Cases B and C. This will show how close the two packages are in predicting similar results.

A comparison will also be made between Cases A and B. This will show the error that will arise if an ideal spectrum is used rather than a real life spectrum.

2.3.1 SUPERHARM PACKAGE

Tables 1.4 and 1.5, Appendix 1 gives a summary of the results produced by the SUPERHARM package for the three cases studied.

Table 1.4 gives harmonic spectrum and THD % results for Cases A, B and C for both voltages and currents at the PCC bus 1 junction.

Table 1.5 gives results for the same factors but for the IPC 2 bus 4 junction instead.

Results for the fundamentals for all three cases are also given.

The SUPERHARM package only gives results for characteristic harmonics.

Similar results were expected between Cases B and C and are obtained. This proves that the linear loads at bus 5 contribute no additional harmonics and that the dummy bus 6 is an effective approach for simulation studies. It also confirms that it is only necessary to measure the input to a bus rather than carry out individual measurements of each load on a common junction. This latter approach is thus the recommended method to be used for harmonic penetration simulation studies.

2.3.2 ERACS PACKAGE

Tables 2.19 and 2.20, Appendix 2 gives a summary of the results produced by the ERACS package for the three cases studied.

As with SUPERHARM, results are given for the fundamentals, the harmonic spectrum 6k±1 up to the 25th harmonic and THD % values for all three cases studied and for the PCC and IPC 2 junctions.

Like SUPERHARM, similar results are expected for Cases B and C and are obtained by ERACS. This further supports the recommendation made above.

2.4 COMPARISON OF SUPERHARM AND ERACS SIMULATION STUDIES

The simulation results obtained by the two packages are firstly compared on a case-by-case basis.

This will be followed by a comparison between Cases A and B results obtained by the two packages.

2.4.1. CASE-BY-CASE COMPARISON

The three Cases, A, B and C are compared.

2.4.1.1 CASE A

The following tables are derived from the results obtained in Tables 1.4 and 1.5, Appendix 1 and Tables 2.19 and 2.20, Appendix 2.

<table>
<tr><th colspan="11">- CASE A -
COMPARISON BETWEEN SUPERHARM AND ERACS SIMULATION RESULTS
PCC LEVEL</th></tr>
<tr><th>h</th><th>1st</th><th>5th</th><th>7th</th><th>11th</th><th>13th</th><th>17th</th><th>19th</th><th>23rd</th><th>25th</th><th>THD</th></tr>
<tr><td colspan="11">PCC = BUS 1 (LINE VOLTAGE)</td></tr>
<tr><td>SH</td><td>10964</td><td>3.22</td><td>4.09</td><td>25.8</td><td>8.66</td><td>2.11</td><td>1.46</td><td>0.84</td><td>0.68</td><td>0.26</td></tr>
<tr><td>ER</td><td>10970</td><td>3.0</td><td>3.0</td><td>6.0</td><td>10.0</td><td>10.0</td><td>5.0</td><td>2.0</td><td>2.0</td><td>0.15</td></tr>
<tr><td colspan="11">BRANCH CURRENT LINE 1 - TO - BUS 1 (AMPS)</td></tr>
<tr><td>SH</td><td>94</td><td>0.41</td><td>0.38</td><td>1.51</td><td>0.43</td><td>0.08</td><td>0.05</td><td>0.02</td><td>0.02</td><td>1.77</td></tr>
<tr><td>ER</td><td>99</td><td>0.23</td><td>0.19</td><td>0.2</td><td>0.3</td><td>0.23</td><td>0.01</td><td>0.04</td><td>0.03</td><td>0.52</td></tr>
</table>

TABLE 2.4

<table>
<tr><th colspan="11">- CASE A -
COMPARISON BETWEEN SUPERHARM AND ERACS SIMULATION RESULTS
IPC2 LEVEL</th></tr>
<tr><th>h</th><th>1st</th><th>5th</th><th>7th</th><th>11th</th><th>13th</th><th>17th</th><th>19th</th><th>23rd</th><th>25th</th><th>THD</th></tr>
<tr><td colspan="11">IPC 2 = BUS 4 (LINE VOLTAGE)</td></tr>
<tr><td>SH</td><td>378</td><td>0.72</td><td>0.93</td><td>5.82</td><td>1.95</td><td>0.48</td><td>0.33</td><td>0.19</td><td>0.15</td><td>1.66</td></tr>
<tr><td>ER</td><td>372</td><td>0.0</td><td>0.0</td><td>1.0</td><td>2.0</td><td>2.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.83</td></tr>
<tr><td colspan="11">BRANCH CURRENT BR 2 - TO -BUS 4 (AMPS)</td></tr>
<tr><td>SH</td><td>849</td><td>12.3</td><td>11.3</td><td>45.5</td><td>12.9</td><td>2.41</td><td>1.48</td><td>0.71</td><td>0.53</td><td>5.92</td></tr>
<tr><td>ER</td><td>968</td><td>8.1</td><td>6.51</td><td>1.86</td><td>9.9</td><td>7.72</td><td>3.24</td><td>1.18</td><td>0.82</td><td>1.86</td></tr>
</table>

TABLE 2.5

Comparisons are drawn at PCC and IPC 2 junctions and a distinction is made between fundamentals, 6k±1 harmonics up to the 25th and THD % for voltages and currents.

For the fundamentals the two packages predict similar results except for the currents in branch BR2 where a large discrepancy is noted. (SH = 849A, ER = 968A).

In the harmonic component range at both junctions there are some similarities and differences.

Total harmonic distortion (THD) is an important criterion used in harmonic studies. It shows whether the distortion at a given junction is acceptable. Both packages predict THD % values for voltage and current in similar regions except a discrepancy is found at IPC 2 for the current BR2.

In general the individual harmonic components are small compared to the fundamental magnitudes. If each is compared as a percentage of the fundamental then the differences found between the results of the two packages are not that great. For example the 4.09V 7th harmonic predicted by the SUPERHARM package is only 0.04% of the 10964V PCC fundamental voltage. The 3V given by ERACS is only 0.03% of its fundamental. This shows only a small difference.

2.4.1.2 CASE B

- CASE B -
COMPARISON BETWEEN SUPERHARM AND ERACS SIMULATION RESULTS
PCC LEVEL

h	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
PCC = BUS 1 (LINE VOLTAGE)										
SH	10964	4.69	1.23	18.5	1.88	1.2	0.37	0.45	0.19	0.18
ER	10970	4.0	1.0	4.0	2.0	6.0	1.0	1.0	0.0	0.08
BRANCH CURRENT LINE 1 - TO - BUS 1 (AMPS)										
SH	94.2	0.6	0.11	1.08	0.09	0.05	0.01	0.01	0.001	1.32
ER	99.0	0.34	0.06	0.14	0.63	0.13	0.03	0.02	0.01	0.4

TABLE 2.6

- CASE B -
COMPARISON BETWEEN SUPERHARM AND ERACS SIMULATION RESULTS
IPC2 LEVEL

h	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
IPC 2 = BUS 4 (LINE VOLTAGE)										
SH	377.6	1.06	0.28	4.17	0.42	0.27	0.08	0.01	0.04	1.15
ER	372	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.44
BRANCH CURRENT BR 2 - TO -BUS 4 (AMPS)										
SH	849.2	18.1	3.44	32.5	2.79	1.37	0.37	0.38	0.15	4.42
ER	869.0	11.9	1.98	4.84	2.14	4.38	0.82	0.63	0.24	1.44

TABLE 2.7

The above tables are the Case B results obtained by the two packages. These are results obtained by using a real life harmonic spectrum.

The fundamentals at both junctions correlate except a large discrepancy is noted in the current at IPC 2 BR2 level.

Once again similarities and differences are found between the two packages in the 6k±1 harmonic range. The 11th harmonic results at both junctions, except for the LINE 1 current, show large discrepancies.

The THD % results are in similar regions except for the BR2 results where SUPERHARM predicts a much higher distortion level at bus 4 than does the ERACS package.

Like with Case A if the results are treated as percentages of the fundamentals then the differences are reduced.

2.4.1.3 CASE C

- CASE C - COMPARISON BETWEEN SUPERHARM AND ERACS SIMULATION RESULTS PCC LEVEL										
h	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
PCC = BUS 1 (LINE VOLTAGE)										
SH	10968	4.72	1.25	20.4	1.88	1.21	0.37	0.45	0.12	0.12
ER	10970	4.0	1.0	4.0	4.0	6.0	1.0	1.0	0.0	0.08
BRANCH CURRENT LINE 1 - TO - BUS 1 (AMPS)										
SH	90.41	0.61	0.12	1.12	0.09	0.05	0.01	0.01	0.01	1.49
ER	99.0	0.34	0.06	0.14	0.34	0.13	0.02	0.02	0.01	0.4

TABLE 2.8

- CASE C -
COMPARISON BETWEEN SUPERHARM AND ERACS SIMULATION RESULTS
IPC2 LEVEL

h	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
IPC 2 = BUS 4 (LINE VOLTAGE)										
SH	378.8	1.05	0.28	4.58	0.43	0.27	0.08	0.1	0.04	1.26
ER	372.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.44
BRANCH CURRENT BR 2 - TO -BUS 4 (AMPS)										
SH	857.9	18.2	3.47	35.96	2.82	1.38	0.38	0.38	0.16	5.36
ER	968.0	11.9	1.98	4.86	2.14	4.38	0.82	0.63	0.24	1.44

TABLE 2.9

Case C results are obtained when a spectrum which has been measured in the field is injected into bus 5.

The results show the same similarities and differences as were obtained for Case B studies. This is expected as the same harmonic spectrum is used. Once again if the results are treated as percentages of the fundamentals the differences found are not that great.

Case C to a large extent confirms Case B's results. The manner in which bus 5 and bus 6 have been modelled for harmonic penetration studies is confirmed as correct.

2.4.2 CASES A AND B COMPARISON

This comparison gives an indication of the error that can be expected if only ideal spectrums are used rather than real life spectrums. Cases A and B both use bus 6 for harmonic injection.

Tables 2.4 to 2.7 above have been summarised into a single table which compares Cases A and B. (See Table 2.21, Appendix 2).

The following observations between Cases A and B have been made.

The Case A result for the fundamentals are approximately equal to the Case B result.($A \approx B$).

The 5th harmonic results of Case B are higher than Case A results except at IPC 2 voltage level where "ER" predicts zero voltage for both cases. ($A<B$).

The 7th harmonic results of Case B are lower than Case A results except at IPC 2 voltage level where "ER" predicts zero voltage for both cases. ($A>B$).

The 11th harmonic Case B results are lower than Case A results except at IPC 2 current level where Case B "ER" results are higher. (A>B).

The 13th harmonic Case B results are lower than Case A except at PCC current level where "ER" predicts that the Case B results is higher. (A>B).

The 17th harmonic Case B results are lower than Case A (A>B).

The 19th harmonic Case B results are lower than Case A except at PCC current level and IPC 2 voltage level where the results are basically the same. (A>B).

The 23rd and 25th Case B harmonic results are higher than Case A except at IPC 2 voltage level where "ER" predicts zero voltage for both cases. (A>B).

The THD% results for Case B are lower than Case A results. (A>B).

From the above observations it is found that the ideal rectifier Case A component results are in **general higher** than the results of Case B except for the 5th harmonic.

The THD % Case A results are also found to be **generally higher** than Case B.

It is further found that besides the above trend SUPERHARM gives a higher THD % result than does the ERACS package.

In the harmonic range 5th, 7th, and 11th the SUPERHARM results are higher than the ERACS results while in the range 13th, 17th, 19th, 23rd and 25th the reverse is true.

If only ideal spectrums are to be used for engineering decisions then from the above findings it can be deduced that a conservative approach needs to be applied as results are higher than that expected in real life.

In general it is found that one cannot rely on simulations. Where possible field measurements should be used to check simulation results.

2.5 SUMMARY AND RECOMMENDATIONS

Computer simulations can be used for predicting harmonic distortion levels in industry.

PC based harmonic software packages are available and two such packages have been used for simulations.

Harmonic field measurements were conducted to measure the harmonic spectrum produced by an actual 6-pulse drive in the field.

A FLUKE 41 Harmonic Analyser was used to take these measurements and its associated

FLUKEVIEW software was used to download the results to a PC.

The reason for these measurements is so that real life spectrums can be used for harmonic simulation studies rather than only using ideal (theoretical) spectrums.

The two packages selected for harmonic penetration studies were the ELECTROTEK and ERACS packages. The ELECTROTEK comprises two programs. The SUPERHARM program is for simulation studies and the TOP program for processing the output results.

Three simulation cases were undertaken. Case A used an ideal 6- pulse rectifier 6k±1 harmonic spectrum as its harmonic source. The injection bus used was bus 6 in the industrial network. Cases B and C used the harmonic spectrum measured in the field. Their injections were at buses 6 and 5 respectively.

The packages can calculate the harmonic penetration at any bus in a network and were used to calculate results at the PCC and at IPC 2 within the plant.

The ELECTROTEK package is a dedicated package in that it only conducts harmonic studies.

The ERACS package is a power systems package and can conduct Loadflow, Short-Circuit, Transient Stability, Protection Co-ordination as well as Harmonic Penetration studies.

The SUPERHARM package requires input data to be entered via a single data file. All data pertaining to the network to be simulated is entered in this single file. The file is not user-friendly and requires a very specific layout format before a successful calculation can be made.

The ERACS package is different. It is menu driven. These menus are sophisticated and require input data values for many different parameters. This is because of the different kinds of studies that can be undertaken. Also before an ERACS harmonic penetration study can be performed the package requires a successful loadflow convergence.

A successful loadflow was conducted with the ERACS package. This however only proves that the modelling at 50Hz was correct.

The main objective was to compare simulation results.

For comparison studies the fundamental, the 6k±1 up to the 25th harmonic components and the THD % for both voltage and currents were the main criterion used for the evaluation. A distinction was also drawn between the PCC and IPC 2 junctions in the network.

Comparisons were made between the three case studies per package as well as a comparison between the simulation results of the two packages on a case-by-case basis. A comparison was also made between Cases A and Case B.

The Case A SUPERHARM results give results in a similar region to its Cases B and C results.

Although different results are obtained by the ERACS package its Case A results are also in the same region to its Cases B and C results.

From the case-by-case comparison between the two packages it was found that the Case A results for the harmonic component ranges at both the PCC and IPC 2 junctions were found to have similarities and differences. Both packages predicted THD % values for voltages and currents in similar regions. Similar results were found for Cases B and C studies. The Case C result to a large extent confirms Case B's results. This proved that the manner in which bus 5 and 6 were modelled for harmonic penetration studies was correct. It also shows that when real life spectrums are to be used then the **recommended** approach is that of Case C rather than using the dummy bus procedure.

A comparison was drawn between Cases A and B. The reason for the comparison is to obtain an indication of the error that can be expected if only ideal spectrums are used rather than real life spectrums. In general it was found that the Case A results are higher than those of Case B. If only ideal spectrums are used for engineering decisions then from these findings it is deduced that a conservative approach needs to be applied as the results are higher than that expected in real life.

It was also found that besides the above trends that the magnitudes for the 5th, 7th and 11th harmonic components were higher with the SUPERHARM package than with the ERACS package. For the remaining 6k±1 harmonics up to the 25th component the reverse was true.

In general it seems that one cannot rely on simulation results. A possible reason for discrepancies in simulation results could be because of incorrect modelling of the elements of the power system analysed. Where possible it is **recommended** that field measurements be conducted to check simulation results. This will not only confirm the effectiveness of a package but will also confirm which packages would give the best accuracy.

It is also **recommended** to use real life harmonic spectrums it they are available. They were found to give lower results than ideal spectrums. Thus more cost effective engineering decisions can be made.

From the results obtained it is **recommended** that at least two packages be used for harmonic penetration simulation studies. One package by itself cannot be relied upon. A second package can be used to confirm the other package results. Two packages will nevertheless establish a range of results which would give a better indication of the expected harmonic distortion levels.

CHAPTER 3

3. HARMONIC STANDARDS

The purpose of this chapter is to compare the IEEE, IEC and ESKOM standards on harmonics in power systems.

An explanation of how the standards are applied in industry will be provided in the next chapter.

Before proceeding with the comparison each standard will be introduced.

3.1 IEEE STANDARD 519

The official title of this standard is "The Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems"

It was approved in 1992 and published on the 12th April, 1993. [18].

The standard is used for guidance in the design of electrical power systems that include nonlinear loads under steady-state conditions. It recognises that the harmonic distortion problem is founded on a dual system. Distortion in power systems is caused by utilities and end-users together. Utilities being responsible for voltage distortion at PCC's while current distortion is caused by consumers.

The standard therefore includes two "Recommended Practices", one for individual consumers and another for Utilities.

3.1.1 RECOMMENDED PRACTICES FOR INDIVIDUAL CONSUMERS

This practice describes the current distortion limits that apply to individual consumers and focuses on the interface PCC with the utility.

The limits recommended by this practice establish the maximum allowable current distortion that a consumer may produce. See Tables 3.1, 3.2 and 3.3 Appendix 3.

Table 3.1 applies to the 120V to 69kV range. Table 3.2 to 69kV to 161kV range and Table 3.2 to the voltage range above 161kV. Each table lists the harmonic current limits based on the size of the load with respect to the size of the power system to which the load is connected. The ratio Isc/I_L = Rsc is the ratio of the short-circuit current available at the PCC to the fundamental load current. Thus, as the size of the user load current decreases with respect to the size of the system, the percentage of harmonic current that the user is allowed to inject into the utility system increases. For example:

If, Isc = 25kA and I_L = 1251A, Rsc = < 20 THD % = 5%

Isc = 13kA and I_L = 105A, Rsc = 125 THD % = 15%

Column 7 provides the THD % current limits that may not be exceeded by a user.

The limits increase as the Isc/I_L ratio increases.

The tables also provide limits according to different harmonic orders. (<11, $11 \leq h17$, $17 \leq h<23$, $23 \leq h<35$ and $35<h$). The limits also decrease as the harmonic order increases. For example the <11th limits are larger in value than those in the $35<h$ order.

The limits for each harmonic range increase as the Isc/I_L ratio increases.

The limits provided are for odd order harmonics. Even harmonics are limited to 25% of the odd order limits provided. For example the limit for a 2nd harmonic would be 0.25 x 4 % = 1 % when Isc/I_L <20. See Table 3.1, Appendix 3.

The tables apply mainly to power systems that include 6-pulse rectifiers which produce $6k\pm1$ characteristic harmonics. If non-characteristic or inter-harmonics are produced then the limits as provided by the tables are decreased to 25%, like for even harmonics. Inter-harmonics are harmonics which are neither odd nor even integer multiples of the fundamental. Non-characteristic components are other than $6k\pm1$ integer multiples of the fundamental.

When a power system includes convertors with pulse numbers higher than six, the limits for the characteristic harmonic order are increased by the follwing factor:

$$\sqrt{\frac{q}{6}}$$

where: q = pulse number

The characteristic harmonics for a 12- pulse convertor are $12k\pm1$.

The limits as provided by the tables are increased by a factor of:

$$\sqrt{\frac{12}{6}} \quad - \quad 1.414$$

The non-characteristic harmonic limits would be decreased to 25% of these newly calculated limits.

3.1.2 RECOMMENDED PRACTICES FOR UTILITIES

This practice describes the maximum voltage distortion limits that may exist at a PCC. It is the responsibility of the utility to ensure that these limits are not exceeded.

The recommended voltage distortion limits are given in Table 3.4, Appendix 3. It provides for three ranges of bus voltages at PCC's. They are for voltage ranges <69kV, 69kV to 161kV and 161kV and above.

Limits are provided for individual voltage distortion and for THD %. As the voltage ranges increase these limits decrease. They decrease from 3% to 1% and 5% to 1.5% respectively.

3.2 IEC STANDARD

The International Electrotechnical Commission (IEC) is a worldwide organisation for standardisation. Its object is to promote international cooperation on all questions concerning standards in the electrical field. To achieve its objective it publishes international standards.

3.2.1 IEC 1000 SERIES [16]

The IEC provides a set of standards termed its 1000 series to regulate the quality of supply in power systems. The series thus regulates not only harmonics but all quality of supply disturbances (e.g. voltage fluctuations, dips, unbalance, frequency variations, flicker etc.).

The IEC standards relevant to harmonics are:

a. IEC 1000 - 2 - 1
b. IEC 1000 - 2 - 2
c. IEC 1000 - 2 - 4
d. IEC 1000 - 3 - 2

3.2.1.1 IEC 1000 - 2 - 1 (1990)

"PART 2 SECTION 1" identifies power convertors, welding machines and arc furnaces as the main causes of characteristic harmonics and inter-harmonics in power systems. The IEC series provides "compatibility levels" to control harmonics. The standard uses the term "level" rather than "limit" as provided for in the IEEE standard.

Compatibility level is defined in this section as:

> "The specified maximum disturbance level expected to be impressed on a device, equipment or system operated in particular conditions."

Compatibility levels serve as reference values for trouble free operation of equipment.

3.2.1.2 IEC 1000 - 2 - 2 (1990)

This "PART 2 SECTION 2" provides compatibility levels for individual harmonic voltages in public low voltage power systems. Low voltage means ac distribution systems with nominal voltages up to 240V (1ph) and 415V (3ph). See Table 3.5, Appendix 3. This table provides levels for odd harmonics non-multiple of 3, odd harmonics multiple of 3 and for even harmonics.

Non-multiple of 3 odd harmonics have a harmonic order of 5, 7, 11, 17, 19, 23, 25 and >25. Their harmonic voltage % levels decrease from 6% to (0.2 + 12.5/n) %.

Multiple of 3 odd harmonics have a harmonic order of 3, 9, 15, 21 and >21. Their levels decrease from 5% to 0.2%.

The even harmonics (2, 4, 6, 8, 10, 12 and >12) levels decrease from 2% to 0.2%.

3.2.1.3 IEC 1000 - 2 - 4 (1994)

This "PART 2 SECTION 4" of the standard distinguishes between PCC's and IPC's. It provides compatibility levels for industrial and non-public networks and applies to low and medium voltage ac power supplies at 50/60Hz. Medium voltage typically means 1kV to 35kV.

Three classes are defined in this section.

CLASS 1.

This class applies to equipment which generally requires protection by such apparatus as uninterruptible power supplies (UPS's), filters or surge suppressors.

CLASS 2.

Class 2 applies to PCC's and IPC's in the industrial environment.

CLASS 3.

This class applies only to IPC's in industrial environments. This class is considered when any of the following conditions are met:

a. A major part of the load is fed through convertors.
b. Welding machines are present.
c. Large motors are frequently started.
d. Loads vary rapidly.

This standard is the most important IEC voltage standard as it regulates the industrial environment. It is also the most complex of all the IEC standards and provides five tables of compatibility levels. See Tables 3.6 to 3.10, Appendix 3.

Each table provides limits for the three different classes. Class 2 levels are the same as the IEC 1000 - 2 - 2 levels.

Table 3.6 provides compatibility levels for the total harmonic voltage distortion (THD %). The levels increase in percentage from 5% to 8% to 10% for the three classes. Class 3 being the most tolerant, allowing the most distortion.

Table 3.7 applies to non-multiple of 3 odd harmonics, Table 3.8 to multiple of 3 odd harmonics, Table 3.9 to even harmonics and Table 3.10 to inter-harmonic voltage components. The harmonic orders are the same as that used in the IEC 1000 - 2 - 2 standard. The inter-harmonic levels (not provided in IEC 1000 - 2 - 2) are arranged in <11, 11 to 13 included, 13 to 17 included, 17 to 19 included, 19 to 23 included, 23 to 25 included and for >25 harmonics.

3.2.1.4 IEC 1000 - 3 - 2 (1995)

This "PART 3 SECTION 2" standard provides compatibility levels for current harmonics. It regulates equipment which has input currents ≤ 16A/phase which are connected to public low voltage distribution systems (IEC 1000 - 2 - 2). Lighting equipment is typically the kind of equipment relevant to this section. See Tables 3.25 to 3.27, Appendix 3.

No current compatibility levels are as yet provided by the IEC for equipment (e.g. convertors) that will be used in the MV range and which will have currents >16A/phase.

In general, the IEC standard controls only voltage distortion in power systems. Harmonic current distortion is controlled by an equipment standard.

3.3 ESKOM STANDARD

Harmonics in South Africa are regulated by the Electrical Supply Commission (ESKOM).

This standard defines the maximum levels of voltage distortion that ESKOM would allow to exist on its Transmission, Distribution and Reticulation systems. [11].

The standard applies to steady-state balanced conditions and only to PCC's. The recommended limits (based on a five minute average value) provided by this standard are given in Table 3.11, Appendix 3.

The limits are arranged according to five PCC voltage ranges. Each range recommends maximum voltage limits for THD % and for odd, even and inter-harmonics in the < 14th, 14th to 25th and > 25th orders.

The standard thus provides limits for both voltage THD % and individual harmonic components.

The five PCC voltage ranges are:

Up to and including 1100V.
Above 1100V, up to and including 44kV.
Above 44kV, up to and including 132kV.
Above 132kV, up to and including 275kV.
Above 275kV.

The THD % has its highest level of 8% at the lowest voltage range and then decreases as the PCC voltage increases. Similarly the odd, even and inter-harmonics also decrease as the voltage ranges increase.

The standard is for voltage limits only. No current limits are recommended.

3.4 COMPARISON OF STANDARDS

The purpose of this section is to compare the IEEE, IEC and ESKOM standards on harmonics in power systems.

The IEEE and ESKOM standards are recommended practices whereas the IEC standards have the status of a "full standard". The IEC is an international standard covering European countries whereas the IEEE and ESKOM standards are national standards applying in the USA and SA respectively.

Limits provided by the IEEE standard are based on a 60Hz fundamental frequency. The IEEE levels are for both 50Hz and 60Hz whereas the ESKOM limits are on a 50Hz standard.

IEEE and ESKOM standards provide limits for PCC's only whereas the IEC standard provides compatibility levels for PCC's and IPC's.

Limits are provided by these standards for different voltage ranges. The IEEE provides for three ranges of voltages (See Table 3.4, Appendix 3) whereas ESKOM arranges their limits in five ranges (See Table 3.11, Appendix 3). Although there are differences in ranges both standards cover reticulation, distribution and transmission levels. The IEC provides levels only for the LV and MV voltage ranges.

3.4.1 THD % STANDARDS

All three standards prescribe maximum voltage THD % limits. They are compared in Table 3.12, Appendix 3.

The THD % limits for the IEEE and ESKOM voltage ranges decrease with increase in PCC voltage. The IEC standard which applies only to <35kV increases from class 1 to 3.

In the distribution voltage range, <69kV (IEEE), <44kV (ESKOM) and <35kV (IEC) the THD % = 5% for all three standards. Classes 2 and 3 for the IEC standard have higher levels of 8% and 10% respectively and are thus more tolerable of harmonic distortion.

No THD % levels are provided by the IEC for its HV voltage range at present.

Only the IEEE prescribes THD % limits for current, therefore no comparison can be drawn with the other two standards. See Tables 3.1 to 3.3, Appendix 3.

3.4.2 LIMITS FOR INDIVIDUAL HARMONIC COMPONENTS

THD % is a convenient index that is often used to assess the impact of harmonic sources on power systems. Caution should however be used when using THD % because it may hide unacceptable individual harmonic component levels. Because of this shortcoming all three standards specify THD % and limits for individual harmonic components.

This thesis concentrates on the comparison between the three standards in the distribution voltage range. This is because field measurements have been conducted in this range and they will be applied to the standards in the next chapter.

The distribution voltage range for this thesis is defined as the <69kV(IEEE), <44kV (ESKOM) and the <35kV (IEC) ranges. The voltage limits prescribed for individual harmonics within this defined range as prescribed by the different standards will be compared.

In the <69kV range (Table 3.4, Appendix 3) the IEEE prescribes a single limit of 3% and it is the limit that may not be exceeded by any individual harmonic, whether it is an odd, even or inter-harmonic.

The ESKOM limits for its <44kV range (Table 3.11, Appendix 3) are divided into three harmonic orders, namely:

Odd, even and inter-harmonics <14th harmonic.
Odd, even and inter-harmonic for the 14th to 25th harmonic.
Odd, even and inter-harmonic for >25th harmonics.

Within the <44kV ESKOM range there are also two ranges; <1.1kV and 1.1kV to <44kV.

The IEC limits (Tables 3.7 to 3.10, Appendix 3) are for the LV/MV voltage ranges. Limits are provided for three classes. Class 1 applies only to the LV range (<1kV) while classes 2 and 3 apply to the LV/MV range (<1kV and 1kV to <35kV). Limits are provided for odd harmonics (non-multiple of 3 and for multiple of 3), even harmonics and inter-harmonics. Limits are provided for harmonics according to these orders.

Of these three standards the IEC is the most intricate. The ESKOM approach is less complicated and the IEEE the simplest.

To ease the comparison of these three standards it was necessary to prepare nine comparative tables. (See Table 3.13 to 3.21, Appendix 3).

In each of the tables the IEEE <69kV limit was chosen as the reference column within a table followed by the two ESKOM voltage ranges and then by the more detailed IEC limits.

The tables have also been arranged in accordance with the ESKOM harmonic order approach.

The "h" in each table is used as a symbol to define individual harmonic components.

The limits provided in each table can be compared against each other. If a limit has a value greater than the reference level such limit is more tolerable of harmonic distortion. If the level is less, then the standard is stricter.

In an attempt to obtain a message from these comparative tables it was decided to derive a single table from these nine tables. Instead of using figures for the limits a non-numeric table was devised. (See Table 3.22, Appendix 3). The IEEE is used as the reference (Ref). Instead of using, for example 3%, the non-numeric abbreviation "Ref" is used in its place. Each limit or order of limits are then expressed as either being equal to the reference (= Ref), greater than the reference (>Ref) or less than the reference (<Ref).

For instance it can be seen (Column 1, Table 3.22) that for Table 3.16 the "h" range is <14th, the type of harmonic is even, the "h" components are 2, 4, 6, 8, 10 and >10 and when compared to the "Ref" it can be seen that the ESKOM limits are ≤Ref, that the classes 1 and 2 limits of the IEC are <Ref and the class 3 limits are <Ref except that the 2nd harmonic limit equals the reference (2nd = Ref).

The other limits can be compared in a similar manner. Table 3.22, Appendix 3 is thus a non-numeric summary of Tables 3.13 to 3.21. It was found that this table could be further summarized into a simpler table. (See Table 3.23, Appendix 3).

Table 3.23 is a quick guide as to the comparison of individual harmonic voltage limits provided by the three standards using the IEEE standard as a reference (Ref).

It is deduced from this table that only the ESKOM and IEC limits for odd harmonics <14th are >Ref and are thus more tolerable of voltage distortion than the IEEE standard.

All harmonic voltage limits (odd, even and inter-harmonic) prescribed by ESKOM and the IEC which are >14th harmonic are <Ref and are stricter limits than the IEEE standard.

Only the IEEE provides limits for individual harmonic **current** components. (See Tables 3.1 to 3.3, Appendix 3). The ESKOM and IEC standards do not provide direct limits, like the IEEE, for individual harmonic currents in power systems. The IEC controls distortion with its equipment standard. ESKOM has introduced an apportioning procedure for this control but it falls outside the scope of this thesis.[20].

3.4.3 ESKOM AND IEC STANDARDS

Both the ESKOM and IEC standards approach their limits in a similar manner. Both provide specific limits for odd, even and inter-harmonics.

The ESKOM standard is in terms of PCC voltage only. It can thus be compared to class 2 of the IEC 1000 - 2 - 4 standard which also uses the PCC as its reference point.

If the lowest and highest harmonic components of class 2 are used as a reference and it is compared to the 1.1kV to 44kV ESKOM limits then a table can be drawn up which compares these two standards. (See Table 3.24, Appendix 3).

The table follows the ESKOM harmonic orders (e.g. odd harmonics <14th, odd harmonics 14th to 25th etc.).

In the odd harmonic <14th order (Table 3.13, Appendix 3) the lowest and highest IEC limits are 1.5% (9th) and 6% (5th) respectively. The ESKOM limit for this range of harmonics is 4%. It can thus be seen that the 4% is within the IEC range of limits.

See the "COMMENTS ON LIMITS" column (Table 3.24, Appendix 3) for the comparative findings between these two standards.

It can be seen that five ESKOM limits are within the class 2 ranges and four limits are not.

The limits that are outside the IEC ranges are the >25th odd harmonics and the three inter-harmonic ranges. All these exceed the highest IEC limit and are thus found more tolerable towards distortion.

Besides a comparison between individual harmonic components a comparison can also be made in terms of THD %. Both of these standards provide voltage THD % limits for PCC's. See Table 3.12, Appendix 3.

It is found that the limit of 5% in the 1.1kV to 44kV ESKOM range is less than the <35kV IEC class 2 limit of 8%. The ESKOM limit is therefore more stricter than the IEC limit towards total harmonic distortion at a PCC.

3.5 SUMMARY AND RECOMMENDATIONS

With the increase of nonlinear loads in power systems, the voltage and current waveforms are becoming more distorted and the power quality is deteriorating.

Because of this development it has become essential to regulate the effects which harmonics produce in a system.

These effects are controlled by standards.

CHAPTER 3

Harmonic distortions are compared to a standard to evaluate whether it is harmful. Any distortion higher than a standard would be considered unacceptable.

In this regard international and national standards are in place. In America, Europe and South Africa the IEEE, IEC and ESKOM standards respectively regulate harmonic distortion levels.

These three standards are:

a. IEEE 519 - Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems.
b. IEC 1000 - Electromagnetic Compatibility.
c. ESKOM ESKASAA18 - Maximum Harmonic Voltage distortion in Electrical Networks.

The IEC standard is an international standard. The IEEE and ESKOM standards are national standards.

In this chapter each standard was first reviewed. This was followed by a comparison of these three standards. A comparison was also made between the IEC and ESKOM standards.

The IEEE standard controls distortion in power systems caused by utilities and end-users. Utilities being responsible for voltage distortion at PCC's while current distortion belongs to consumers.

The standard therefore includes two "Recommended Practices". One for individual consumers and another for utilities.

The consumer practice controls current distortion and focuses on the interface PCC with utilities.

Limits are recommended by the practice which may not be exceeded by consumers. The limits vary mainly according to three voltage ranges, 120V to <69kV, 69kV to <161kV and >161kV. These limits are provided in three tables. The limits within each table are based on the size of the load with respect to the size of the power system to which the load is connected. This is expressed as a Isc/I_L ratio where Isc is the short circuit current available and I_L is the fundamental load current.

As this ratio increases the limits provided by each table also increases.

Two main limits are provided for within each table. They are THD % and limits for individual harmonic components expressed as percentages. The individual harmonic currents are further subdivided into harmonic orders. (<11, $11 \leq h < 17$, $17 \leq h < 23$, $23 \leq h35$ and $35 < h$).

The limits provided are for odd harmonics. Even and inter-harmonics are limited to 25% of the odd order limits provided.

The tables of limits mainly apply to power systems which include 6- pulse rectifiers and ideally produce 6k±1 characteristic harmonics. If the system includes convertors with pulse numbers (q) higher than six, the limits have to be increased by the following factor:

$$\sqrt{\frac{q}{6}}$$

For 12- pulse convertors which produce ideally 12k±1 characteristic harmonics the limits are increased by a factor = 1.414.

The limits decrease as the voltage range increases.

The second IEEE practice prescribes the maximum allowable voltage distortion limits that may exist at a PCC. It is the responsibility of the utility to ensure that these limits are not exceeded.

The limits are provided for in a single table which provides for three ranges of bus voltages at PCC's. The same voltage ranges as are used for controlling current distortion apply.

Like the current distortion practice this voltage practice prescribes two different limits for regulating distortion, namely, THD % and limits for individual voltage components. In this practice the individual harmonic voltages are not subdivided into harmonic orders like the current practice. One limit is provided for all harmonics within a given voltage range. The limits also decrease as the voltage range increases.

The IEC provides a set of standards termed its 1000 series to control the quality of supply in power systems. The series thus not only regulates harmonic distortion but all quality of supply disturbances. It is thus a much broader standard than the IEEE that regulates harmonics only.

The IEC does not have a current practice like the IEEE but regulates the quantity of harmonics generated by equipment having phase currents ≤16A.(IEC 1000 - 3 - 2). This is not a power system standard but an equipment standard.

The IEC voltage standard provides "compatibility levels" and uses the term "level" rather than "limits" as provided for in the IEEE standard.

The IEC standard like the IEEE standard regulates harmonic distortion in terms of THD % and levels for individual harmonic components.

The IEC 1000 - 2 - 4 is the main standard regulating harmonic distortion in power systems. It thus applies to industrial networks. The standard also only applies to LV and MV systems. LV are voltages less than 415V and MV typically means 1kV to 35kV. No standard is at present in place for the HV voltage range.

This standard distinguishes between classes 1, 2 and 3.

Class 1 applies to the LV range and to environments which normally contain equipment which requires protection (e.g. UPS's , filters or surge suppressors.).

Class 2 applies specifically to LV and MV industrial environments and regulates harmonic distortion at PCC's and IPC's.

Class 3 applies only to LV and MV IPC's in industrial environments and specifically to loads that vary rapidly.

This IEC 1000 - 2 - 4 standard is complex in that it provides five tables of compatibility levels. Each table provides levels for all three classes. The class 2 levels in each of these tables are the same as the levels provided by the IEC - 2 - 2 standard. This latter standard regulates harmonic distortion in LV ac distribution systems. This means equipment designed for application in ac distribution systems may be used in this class of industrial environment. Each table further provides levels for individual harmonic components.

Each table however regulates different types of harmonics. This standard controls odd harmonics non-multiple of 3, odd harmonics multiple of 3, even harmonics and inter-harmonics. This is different from the IEEE that makes no specific provision for different types of harmonics but regulates all types with a single limit.

Harmonics in South Africa are controlled by the ESKOM standard.

The standard like the IEEE and IEC applies to PCC's. It does not regulate distortion at IPC levels.

It is also like the IEC standard in that it is only a voltage standard.

Like the IEEE, ESKOM provides recommended limits whereas the IEC standard is law and prescribes levels and not limits.

The ESKOM limits are provided in a single table which is subdivided into five PCC voltage ranges and covers like the IEEE the reticulation, distribution and transmission voltage levels. The IEC only provides levels for the LV and MV ranges.

Like the IEC standard, the ESKOM standard provides limits specifically for odd, even and inter-harmonics. They are similar to the IEC in that the limits are also arranged in terms of harmonic orders. The orders are however different. They are <14th, 14th to 25th and >25th orders. No mention is made of multiple of 3 and non-multiple of 3 orders.

The table also includes limits for THD %. These limits, like the limits for individual harmonics change as PCC voltage ranges alter. Like the IEC, no current limits are provided by the standard.

The IEC approach is the most intricate of the three standards. The ESKOM standard is less detailed and the IEEE the simplest.

The three standards were compared using nine comparative tables with the IEEE limit used as the reference (Ref). The comparison was made for limits in the <69kV range only. To obtain a message from all these tables a single non-numeric table was deduced and the limits were compared to the "Ref" as being either = Ref, >Ref or <Ref. This table in turn was further simplified into a quick reference guide. With this guide the individual voltage limits provided by the three standards are easily compared.

It was found that only the ESKOM and IEC limits for odd harmonics <14th are >Ref and are thus more tolerable of voltage distortion than the IEEE standard. All the other limits are stricter.

It was also found that the THD % limit of the IEEE, ESKOM and class 1 of the IEC were all the same in the <69kV range. The class 2 and 3 limits were more tolerable to distortion.

It was further found that a great similarity existed between the IEC Class 2 and ESKOM standards. Because of this these two standards were specifically compared to each other.

They were compared in a table which was prepared according to the ESKOM harmonic orders. The lowest and highest IEC limits as a range of limits were compared to the single limit provided by ESKOM. This was done for each harmonic order.

It was found that five ESKOM limits were within the class 2 ranges and four were not. Those outside were >25th odd harmonic order as well as all three inter-harmonic orders. All these ESKOM limits that were outside the IEC ranges had limits higher than the highest IEC limits and are thus more tolerable towards distortion.

Besides these differences it is found that the IEC and ESKOM voltage standards are similar and it is therefore **recommended** that these two standards be made identical in terms of limits. This will tighten the ESKOM standards in terms of individual voltage component limits and in this way be prepared for the increasing levels of distortion that are anticipated for the future as more nonlinear loads are installed. ESKOM should also extend their voltage limits to IPC's.

In terms of current distortion it is **recommended** that ESKOM implement the IEC standard which regulates harmonics produced by specific equipment rather than bringing in a complex current practice as provided by the IEEE.

CHAPTER 4

4. APPLICATION OF FIELD MEASUREMENTS TO STANDARDS

4.1 FIELD MEASUREMENTS

Measurements were carried out to provide experimental data and to compare the results against the regulatory levels provided by the IEEE, IEC and ESKOM standards.

As one of the standards researched is the ESKOM standard, installations which received an ESKOM supply were selected for the conduction of measurements. It is also known that harmonic distortion has its highest levels at harmonic source interfaces. In industrial plants harmonic sources are generally connected to IPC's. In manufacturing plants harmonic sources are usually connected at LV level even though their PCC's are at MV level. In traction substations a similar situation is found except that harmonic sources are usually connected closer to the MV PCC and their IPC's are also at MV level. Therefore distortion at PCC level is usually higher in traction substation than that found in manufacturing plants. (See paragraph 5.1, Appendix 5).

To obtain a contrast, measurements were conducted at a 11kV Manufacturing Plant and at a 33kV Traction Substation. (See Appendices 6 and 7 respectively).

Figures 6.1 and 6.2, Appendix 6 and Figures 7.1 and 7.2, Appendix 7 show the schematic layouts and one-line-diagrams respectively for these two industrial networks.

4.1.1 LOCATIONS

A FLUKE 41 Harmonic Analyser was used to take measurements (See Appendices 5, 6 and 7). Readings were taken at six locations in the plant and at three locations in the traction substation. These locations were chosen to give measurements to reflect the harmonic penetration taking place through these networks. Also because measurements were needed which could be compared to the three standards. All three standards prescribe PCC limits. The IEC however regulates PCC and IPC distortion levels. Measurements had therefore to be taken at both PCC and IPC levels.

4.1.1.1 11kV PLANT

See Figures 6.1, Appendix 6 for the six locations at which measurements were conducted in the plant.

Table 6.1, Appendix 6 summarises these locations and gives the CT and VT ratios that applied. Locations 1 to 4 were at LV and 5 to 6 were at HV levels.

Table 6.2, Appendix 6 gives a summary of the results obtained. These results include waveforms, bar charts and tables of numeric results. For these results see the attachments to Appendix 6.

The harmonic source in the plant is a 6-pulse convertor.

4.1.1.2 33 kV TRACTION SUBSTATION

Two measurement locations were at HV (PCC) level and the third was measured at the 3kV(IPC) level.

Table 7.2, Appendix 7 gives a summary of the results obtained. See the attachments to the appendix for the waveforms, bar charts and numeric results.

The harmonic source was a 12- pulse convertor.

4.1.2 RESULTS

From these results the required values needed for the comparisons had to be identified. See Table 4.1, Appendix 4.

It can be seen from this table that the results required for the application of the IEEE standards are the numeric values for V, I, V THD % and I THD % at PCC level only.

For the IEC application only V and V THD % are needed, but values are needed for PCC and IPC levels. ESKOM like the IEC only requires V and V THD % results and then only for PCC's.

The tables in the appendices from which the results need to be extracted are also identified.

Tables 4.2 to 4.7, Appendix 4 give the extracted results. These tables include results for individual harmonics up to the 31st component. Included after the 31st component are results for V THD % and I THD %.

For the plant, results have been extracted for Bus 1 (PCC), Bus 2 ((IPC1) and Bus 4 (IPC2). Results for the traction substation have been extracted for buses 1, 2 and 3.

These tables have been arranged according to the ESKOM harmonic orders, <14th, 14th to 25th and >25th up to the 31st harmonic.

4.2 COMPLIANCE OF MEASUREMENTS TO STANDARDS

When checking to decide if field measurements comply with a standard it is traditional to first assess the THD %. As it is an index, it assesses the total impact of harmonic sources on a power system. It may however hide unacceptable harmonic component levels yet giving the impression that the distortion is acceptable.

4.2.1 THD %

The THD %'s for the voltages and currents measured at PCC and IPC levels in the plant and traction substation are compared to the regulatory levels provided by the three standards in Table 4.8, Appendix 4.

The regulatory levels used are the ESKOM (1.1 to 44kV), IEEE (<69kV) and the IEC (1 to 35kV) ranges.

A distinction is also made between class 2 and 3 with the IEC standards. Class 2 applies to PCC's and IPC's. However when convertors are in operation and the load is expected to vary rapidly the standard recommends that class 3 is used. Class 3 only applies to IPC's. It can thus be seen that class 2 is applied to IPC 1 in the plant while class 3 is applied to IPC 2. In the substation however class 3 has been applied to both IPC 1 and IPC 2.

In terms of current only the IEEE provides regulatory levels. These regulatory levels depend upon the ratio:

$$Rsc = \frac{Isc}{I_L} \quad - - - - - - - - - (1)$$

where: Rsc is the ratio of the short-circuit current to the full load current at the PCC.

The applicable IEEE standards are 15% (Rsc = 125) and 5% (Rsc = <20). See paragraph 3.1.1, Chapter 3.

The standard most relevant to the installations is the ESKOM standard. In terms of PCC voltage THD % it is found that the field measurements are well within the limits prescribed and are therefore adequate to regulate these two installations at present. Both installations have room in terms of voltage THD % for the addition of extra harmonic sources.

As a further assessment the field measurements are checked against the IEEE and IEC standards.

In terms of voltage THD % it is found that the field measurements at neither the plant nor the substation exceeds any of the regulatory levels provided by these latter standards.

It can therefore be said that the regulatory levels provided by all three standards are adequate for voltage THD % even though their approaches are different. This is true for PCC's and IPC's.

Neither ESKOM nor IEC standards regulate current THD %. Though the installations are South African and no standards apply it was considered necessary to assess them in terms of current distortion. As the IEEE is the only standard providing current limits, the field measurements were compared to these limits.

The current THD % was found more than adequate at the 11kV plant PCC but inadequate at the 33kV traction substation PCC where the 10% field measurement exceeded the 3% limit provided by the standard.

The IEEE current standard does not apply in South Africa conformity. It is nevertheless recommended that the user take the necessary steps to decrease its current THD % distortion.

4.2.2. INDIVIDUAL COMPONENTS

4.2.2.1 HARMONIC VOLTAGES

The next stage after THD % assessment is to check the individual harmonic components measured in the field to the limits provided by each standard for such components.

The individual harmonic voltage components % V RMS measured in the plant and traction substation are given in Tables 4.2 to 4.7, Appendix 4.

These measurements have been applied to the standards in six tables. See Tables 4.9 to 4.14, Appendix 4.

Three tables apply to the plant and three to the substation.

Each set of three tables is arranged into:

1. Odd and even components <14th harmonic.
2. Odd and even components 14th to 25th harmonic.
3. Odd and even components >25th harmonic.

Inter-harmonics are not measured by the FLUKE 41 Analyser therefore only odd and even components of the field measurements are compared to the standards.

Each table includes field measurements for PCC's and IPC's enabling all three standards to be applied for comparative purposes simultaneously.

These standards apply to both the plant and the traction substation as their PCC's fall within the <69kV (IEEE), 1.1 to <44kV (ESKOM) and the 1 to 35kV (IEC) voltage ranges.

The applicable <69kV IEEE standard of 3% is derived from Table 3.4, Appendix 3. This standard provides a single percentage limit and does not distinguish between odd and even components.

The ESKOM limits are derived from Table 3.11, Appendix 3. This standard provides a single percentage limit for each of its three orders:

1. <14th - 4% (odd) and 2% (even).
2. 14th to 25th - 2% (odd) and 1% (even).
3. >25th - 1% (odd) and 0.5% (even).

Class 2 and 3 are the applicable IEC standards. They are derived as follows from Appendix 3:

1. Even Harmonics (2, 4, 6 etc.) - Table 3.9
2. Odd Harmonics non-multiple of 3 (5, 7, 11 etc.) - Table 3.7
3. Odd Harmonics multiple of 3 (3, 9, 15 etc.) - Table 3.8

The comparative tables are applied as follows:

EXAMPLE

In the <14th harmonic order in the plant the field measurements at Bus 1 (PCC) are all less than the levels provided by the three standards. The table is read row by row. For example, the 2nd harmonic field measurement is 0.1 % at PCC level and is compared to the 3 % (IEEE), 2 % even (ESKOM) and 2% class 2 (IEC). The IPC 1 (Bus 2) measurement of 0.0 % is compared to the class 2 IPC 2 % (IEC) level. The IPC 2 (Bus 4) 0.0 % measurement is compared to the class 3 IPC 2 (IEC) level of 3%.

The other measurements are compared in a similar manner.

It is found that the field measurements at both the plant and substation are all less than the levels provided by the three standards. Therefore, neither installation in terms of individual harmonic voltages at PCC's nor IPC's has any component having an unacceptable magnitude.

From this analysis it can be concluded that the regulatory levels provided by all three standards for harmonic voltage components whether odd or even are adequate even though their approaches are different.

The results also support the voltage THD % findings and it can be concluded that standards in the voltage range studied (<69kV) are adequate.

The results also show that the South African ESKOM standard, although different in its approach, achieves the same as the other two major regulatory bodies. (IEEE and IEC).

The findings also further support ESKOM's approach to regulating harmonics by providing limits for voltages only. This means that even if currents are distorted it makes no difference so long as the voltage supplies are within limits. If utilities provide voltage waveforms to their customers that are largely undistorted then their obligation has been satisfied. The responsibility for current distortion then passes to the client.

4.2.2.2 HARMONIC CURRENTS

Although there are no standards regulating harmonic currents in power systems in South Africa the IEEE provides a recommended practice.

Because this standard is in place in the USA it was considered necessary to find out how it regulates their industries and then to apply it to South African conditions and to assess its effectiveness.

The standard only applies to PCC's

The individual harmonic current components % I RMS measured in the plant and traction substation are given in Tables 4.2 to 4.7, Appendix 4.

These measurements have been applied to the IEEE standard in two tables. One for the plant and the other for the substation. See Tables 4.15 and 4.18, Appendix 4.

Each table is arranged into the four harmonic orders recommended by the IEEE. (<11th, 11h<17, 17≤h23 and 23≤h<35). Each order compares the harmonic components measured in the field to the standard.

Only odd and even harmonics up to the 31st are compared. The analyser used for field measurements is not able to measure inter-harmonic currents.

The <69 kV standard (Table 3.1, Appendix 3) applies as both PCC's fall within this range.

A 6-pulse harmonic source is used in the plant whereas in the substation it is a 12-pulse. The limits are therefore different for the two installations.

The plant has a Rsc = 125 therefore the limits for odd harmonics are 12% (<11th), 5.5% (11≤h<17), 5% (17≤h<23) and 2% (23≤h<35). Even harmonics are 25% of the odd harmonic limits (e.g. 0.25 x 12% = 3%).

In order to obtain the limits applicable to the 33kV traction substation a certain procedure needs to be followed. See paragraph 4.3.1.2, Appendix 4.

As q = 12, the characteristic harmonics need to be increased by a factor of 1.414. See Table 4.16, Appendix 4 for these adapted limits.

The non-characteristic limits, 5th, 7th, 17th, 19th, 29th, 31st etc are 25% of the odd limits provided in Table 3.1, Appendix 3. The Rsc = < 20. See Table 4.17 for these adapted limits.

All other harmonics are also adapted to 25% of the limits provided by Table 3.1, appendix 3.

These derived limits are applied in Table 4.18, Appendix 4.

It is found in the plant (Table 4.15, Appendix 4) that none of the measured harmonic currents exceed the limits recommended by this standard. The plant at present therefore has room for the addition of further harmonic sources.

The picture is however different in the traction substation (Table 4.18, Appendix 4). The 2nd, 3rd, 4th, 5th, 6th, 8th, 10th, 11th, 12th, 14th and 16th and all the harmonics in the order 23rd to 31st all exceed the limits provided by the standard.

The responsibility therefore lays with the end user and it is recommended that they take the necessary steps to decrease the individual harmonic current to below the recommended limits.

4.3 SUMMARY AND RECOMMENDATIONS

Field measurements were carried out to obtain experimental data and to provide results which can be applied to the regulatory levels provided by the IEEE, IEC and ESKOM standards to determine their effectiveness in controlling harmonic distortion.

Two installations were selected, both with incoming ESKOM supplies. This was essential as one of the standards researched is the ESKOM standard. Its effectiveness towards two major standards could be evaluated. As the IEC standards only apply to the <35kV voltage range the networks chosen had to be within this constraint. Also the IEEE levels are adapted as convertor pulse number increases, it was necessary to include measurements to demonstrate the effects of this change.

A 11kV manufacturing plant and a 33kV traction substation were chosen to provide the desired contrasts. The harmonic source in the plant is a 6-pulse whereas that in the substation is a 12-pulse convertor.

Measurement locations within each installation were chosen to determine the harmonic penetration taking place and to obtain results for the application of the standards. The IEEE and ESKOM standards apply only to PCC's while the IEC applies to both PCC's and IPC's. Measurements were thus taken at both these levels within each installation.

A FLUKE 41 Harmonic Analyser was used to take the measurements.

The harmonic measurements required for the application of the IEEE standard are %V, % I, V THD % and I THD % at PCC level only as it regulates both voltage and current distortion in power systems.

For the application of the IEC and ESKOM standards only %V and V THD % are needed as these standards only control voltage distortion. They differ in that the IEC controls harmonic levels at both PCC's and IPC's whereas ESKOM is only for PCC distortions.

All three standards require odd, even and inter-harmonic measurements. The FLUKE 41 Analyser only measures up to the 31st harmonic and is also unable to measure inter-harmonics. Measurements were thus limited to this range and only to odd and even harmonics and to THD %'s.

When checking to determine if field measurements comply to a standard it is usual to first assess THD % levels. This is because THD % is an index and gives an indication of the total impact of harmonic sources on power systems. It is for this reason that all three standards have these requirements.

The THD % regulatory levels used for the application of these measurements are those prescribed by the IEEE (<69kV), ESKOM (1.1 to 44kV) and IEC (1 to 35kV) voltage ranges. A distinction is also needed between class 2 and 3 with IEC standards. Class 2 applies to PCC's and IPC's in industrial installations and particularly when harmonic sources (e.g. convertors) are connected to IPC's which are distant from their PCC. This is the case with the 11kV plant. The IEC however recommends that class 3 is applied when the loads vary rapidly and their IPC is in close proximity to its PCC. Class 3 was thus applied to IPC measurements in the traction substation.

All three standards provide regulatory limits for V THD %. The V THD %'s measured at both installations have been applied to the regulatory limits to determine their compliance to the standards.

It was found that the measured V THD %'s at neither the plant nor the substation exceeded any of the regulatory levels provided by these standards.

The regulatory V THD % levels provided by all three standards are adequate even though their approaches are different. This is true for both PCC's and IPC's.

If the field V THD % are applied only to the ESKOM limits it is found that their limits regulate these two installations adequately at present. The impact of the harmonic sources do not distort the PCC voltages beyond that which is allowed by this standard.

In terms of I THD %, only the IEEE provides regulatory levels. Its levels depend upon a Rsc ratio. There are five Rsc ranges within the <69kV range. As both installations in which measurements were conducted have different Rsc ratios the regulatory limits for I THD % are not the same. The lower the Rsc ratio the higher is the limits prescribed.

When the field measured I THD %'s were applied to the IEEE standard it was found that its regulatory limits were adequate at the plant but inadequate at the traction substation PCC. The current distortion was found to be twice that which is allowed by the standard.

As the I THD % does not apply in South Africa conformity to it is not a requirement. The IEEE standard is however a recommended practice and should be followed. It is **recommended** that the traction substation take the necessary steps to decrease its I THD % distortion to below the limit provided by this standard.

After field measured THD %'s have been applied to standards, it is further required that %V and % I levels of individual harmonics are also compared to regulatory levels provided by these standards.

Where a field measured THD % exceeds a regulatory level it is essential to determine which individual harmonics are causing the excessive distortion so that the necessary corrective steps can be taken.

Field measurements for individual odd and even harmonics for both installations have been applied to the regulatory limits to assess their compliance to the standards.

It is found in terms of harmonic voltage components that those measured at both the plant and substation comply with the levels provided by the three standards. Therefore, neither installation has any harmonic voltages at its PCC's or IPC's which have unacceptable magnitudes. This agrees with the V THD % findings. The V THD %'s for these installations thus do not hide any problem components.

All three standards for odd and even components are adequate even though their approaches are different.

The ESKOM standard provides the same findings as the IEEE and IEC. Its approach to regulating individual harmonic voltages at PCC's is proven to be equally as good as the two other recognised standards.

The findings also supports ESKOM's approach by providing limits for voltages only. Even if currents are distorted it makes no difference so long as the voltage supplied is within the limits prescribed. If utilities provide voltage waveforms to their customers that are largely undistorted then their obligation has been satisfied. The responsibility for current distortion then passes to the client.

In South Africa there are no standards that directly regulate harmonic currents in power

CHAPTER 4

It is found from the standards compared that there are three different approaches to controlling harmonic distortion:

(1) Solely by systems standards (IEEE).

(2) By a voltage system standard supported by an equipment standard to control current distortion (IEC).

(3) By providing solely a systems voltage standard (ESKOM).

By a **systems standard** is meant that limits are provided for either voltage or current distortion and that they apply to power systems. The IEEE thus controls distortion by means of a voltage systems standard as well as by a current systems standard. The IEC and ESKOM are solely voltage system standards.

An **equipment standard** means the responsibilty for controlling current distortion falls on the manufacturer and not on the end-user.

In South Africa there are no standards that directly regulate harmonic currents in power systems. The IEC also does not directly control such harmonics. It through its IEC 1000 - 3 - 2 standard regulates harmonic currents generated by pieces of equipment. It is an equipment standard rather than a systems standard. The IEEE regulates harmonic currents as a systems standard rather than as an equipment standard.

The IEEE standard is the only systems standard in the world and it is a recommended practice. For this reason the individual harmonic currents, odd and even measured in the two installations have been applied to the regulatory limits prescribed by the IEEE to assess their compliance to the standard.

The two installations have different pulse numbers. Different IEEE limits apply. The 6-pulse limits are adapted to 12-pulse limits for use with the traction substation measurements. The standard provides a procedure for this adaption. The higher a pulse number the greater are the odd harmonic limits that apply. Even and inter-harmonic limits for any pulse number are 25% of the original values prescribed by the standard.

It is found that none of the measured harmonic currents in the plant exceed the limits recommended by the IEEE standard. The plant at present has room for the addition of further harmonic sources.

The picture is different for the traction substation where it is found that virtually all the harmonics exceed the limits provided by the standard. It is therefore **recommended** that the end-user take the necessary steps to decrease the unacceptable individual harmonic currents to below the recommended limits.

CHAPTER 5

5. SUMMARY AND CONCLUSIONS

The preceding chapters have described a number of investigations into harmonics in power systems. These are summarised in this chapter followed by conclusions and future work.

5.1 SUMMARY OF INVESTIGATIONS

PC based harmonic penetration software packages are used to determine distortion levels in industry.

Standards are provided by authorities to control harmonic distortion levels.

The research covered three main aspects:

a. Application of PC based harmonic penetration packages and a comparison of their simulation results.

b. Investigation and comparison of the IEEE, IEC and ESKOM standards.

c. Measurement of harmonics in two industrial networks and the comparison of the results with the regulatory limits provided by the standards.

5.1.1 SOFTWARE APPLICATIONS

The ELECTROTEK and ERACS packages were used for the application studies. This enabled comparisons to be drawn from their results.

Rather than use theoretical parameters for simulation studies parameters from a 11kV Manufacturing Plant were used. For a similar reason the harmonic spectrum generated by the 6- pulse convertor in the plant was used.

Three harmonic penetration cases were studied by each package. Case A used an ideal 6-pulse convertor $6k\pm1$ spectrum as its harmonic source. Case B made use of the spectrum measured in the field. Case C used a spectrum that combined the harmonics generated by the convertor with the currents produced by shunts loads which were connected to the same bus as the drives. The spectrum represented a combination of linear and nonlinear loads.

The same input parameters were used so that the simulation results could be compared. The packages are able to calculate the harmonic distortion at any bus in a network. For the three cases results were extracted only for the PCC and for the IPC2 within the plant. The harmonic distortion at three points within the network is thus known. The third is the point at which the spectrum is injected. These three points give an indication of the penetration taking place.

For the comparison studies the fundamental, the 6k±1 up to the 25th harmonic component and the THD % were the criteria used for the evaluation.

Comparisons were made between the three case studies per package as well as a comparison between the simulation results of the two packages on a case-by-case basis. A comparison was also made between Cases A and B. This latter comparison was drawn to obtain an indication of the error that can be expected if only ideal spectrums are used rather than practical spectrums.

5.1.2 COMPARISON OF STANDARDS

The IEEE, IEC and ESKOM standards were selected for investigation and comparison. The IEC is an international standard whereas the IEEE and ESKOM are national standards. The IEC provides regulatory limits for controlling harmonic distortion in Europe whereas the IEEE and ESKOM provides control in the USA and South Africa respectively.

In this study each standard has been individually investigated followed by a comparison of all three standards. A comparison was also made only between the IEC and ESKOM standards.

All three standards control harmonics by providing regulatory limits for THD % and for individual harmonic components.

5.1.2.1 IEEE 519

The IEEE standard provides recommended practices for utilities and for individual consumers. Both control distortion at the PCC. The utilities practice controls voltage distortion while the consumer practice prevents harmonic currents from exceeding regulatory limits. The IEEE 519 is thus a system standard. By a **systems standard** is meant that limits are provided for either voltage or current distortion and that they apply to power systems. The IEEE thus controls distortion by means of a voltage systems standard as well as by a current systems standard. The standard covers the LV, MV, HV and EHV voltage ranges for both practices.

The current limits are based on the size of the load with respect to the size of the power system to which the load is connected. This is expressed as a Rsc ratio and the limits decrease within a given voltage range as the ratio increases. Both THD % and limits for individual harmonic currents are provided. The limits are further adapted according to harmonic orders. A distinction is also made between odd, even and inter-harmonic limits. The limits are also adapted as the pulse numbers of harmonic sources increases. The limits increase as the pulse number increases.

The utilities practice prescribes maximum allowable voltage distortion limits. Like the current practice limits are provided for THD % and for individual harmonic components. In this practice the individual harmonic component limits are not subdivided into orders like the current practice and only one is provided for a given voltage range. The limits decrease as the voltage range increases.

5.1.2.2 IEC 1000

The IEC provides a set of standards termed its 1000 series.

Unlike the IEEE the IEC provides power system regulatory limits for voltage distortion only. Current distortion is controlled by an **equipment standard.** This means the manufacturers and not the end-users are responsible for current distortion. Categories of equipment are defined and limits are provided which may not be exceeded.

The IEC 1000 - 2 - 4 is the main system standard and provides regulatory limits for only the LV and MV voltage ranges. It also distinguishes between three classes. Class 1 controls equipment sensitive to harmonic distortion whereas classes 2 and 3 control mainly convertors.

Unlike the IEEE the IEC class 2 standard extends its control from PCC's to IPC's. Class 3 controls loads which vary rapidly at IPC's.

The standard provides THD %'s and limits for individual harmonic components. It also distinguishes between odd, even and inter-harmonic limits but subdivides its odd harmonics into non-multiple of 3 and multiple of 3 harmonics. The limits are also arranged according to harmonic orders.

5.1.2.3 ESKOM ESKASAA18

Harmonics in power systems in South Africa are controlled by the ESKOM standard.

The standard like the IEEE and IEC applies to the PCC. Like the IEEE it does not extend to IPC's. It is also like the IEC in that it is only a voltage standard. It differs from the IEEE and IEC in that no limits are prescribed for current distortion either as a system standard or as an equipment standard.

Like the IEEE, the ESKOM standard provides regulatory limits which covers the LV to EHV ranges.

Unlike the IEEE but like the IEC standard, ESKOM provides limits for odd, even and inter-harmonics. The odd harmonics are not subdivided into non-multiple of 3 and multiple of 3 harmonics. The limits are also arranged in harmonic orders. The orders are however different to the IEC orders.

Limits are also provided for THD %'s and decreases as the voltage range increases.

5.1.3 APPLICATION OF MEASUREMENTS TO STANDARDS

Field measurements were carried out to provide results that could be applied to the standards.

To obtain a contrast between all three standards, measurements were conducted at a 11kV Manufacturing Plant and at a 33kV Traction substation. Both installations have ESKOM PCC's and their harmonic sources are at IPC's. This enabled the IEC standard to be applied as well as the IEEE and ESKOM standards.

Only odd and even harmonics were investigated as the analyser used for measurements is unable to measure inter-harmonics.

The harmonic measurements required for the application of the IEEE standard are %V, % I, V THD % and I THD % at the PCC. For the IEC and ESKOM standards only %V and V THD% are needed as only voltage distortion is controlled.

When investigating the application of field measurements to standards it is customary to first assess the THD % levels. This is because THD % is an index and gives an indication of the impact of the harmonic sources on power systems. However it may hide unacceptable harmonic component levels, yet give an impression that the distortion is acceptable, therefore these levels need also to be investigated. It is for this reason that all three standards have these requirements. Therefore both THD % and levels of individual harmonic components have been investigated in this study.

5.2 CONCLUSIONS

a. In the first simulation investigation three cases per package were conducted. Its purpose was to establish results for different injecting harmonic spectrums which could subsequently be used for case-by-case studies between packages. From these initial investigations it was found that the Case A SUPERHARM results are close but not close enough to its Cases B and C results. The ERACS package results for its Case A were also found to be close to its Cases B and C results. The Case C results per package confirms the Case B results and from this comparison it can be concluded that the manner in which the harmonic sources and shunt loads were modelled for buses 5 and 6 was correct. It also confirms that it is only necessary to measure the input to a bus rather than carry out individual measurements of each load on a common junction. The Case C approach is thus the recommended method to be used for harmonic penetration simulation studies especially when more than one drive is connected to a common junction and also when real life rather than ideal spectrums are to be used.

b. From the comparison between the Case A results of the two packages it was found that for the harmonic component range studied at both the PCC and IPC levels were found to be close but not close enough. Both packages for this case predicted similar voltage and current THD %'s. Similar findings were obtained between the results of the two packages for Cases B and C. In terms of harmonic penetration it can be concluded that the two packages give inconsistent results and cannot be relied upon. If however assessment is based solely on THD %'s then the two packages can be considered reasonably consistent.

c. A comparison was also only made between Cases A and B. This investigation was to obtain an indication of the error that could be expected if only an ideal spectrum is used rather than a real life spectrum. When harmonic components are compared it was found that the Case A results were larger than the Case B results. A similar finding was obtained for voltage and current THD %'s. The magnitudes for the 5th, 7th and 11th components were higher with the SUPERHARM package than with the ERACS package. For the remaining 6k±1 harmonics up to the 25th component the reverse was found to be true. It can be concluded that the results obtained from using an ideal spectrum are in general higher than those obtained when a real life spectrum was used. These results are higher because the harmonic component magnitudes in an ideal spectrum were found to be larger than those measured in the field. If only ideal spectrums are to be used for engineering decisions then from the above findings it can be deduced that a conservative approach needs to be applied as results are higher than that expected in real life.

d. From the differences found in the simulation results it can be concluded that at least two packages should be used as both will establish a range of results which will give a better indication of the expected harmonic distortion levels. As higher results are obtained when using an ideal spectrum it is concluded that real life spectrums are rather used. It is further concluded that field measurements should be conducted to check simulation results if this is possible. This would not only confirm the effectiveness of a package but will confirm the package giving the best accuracy. If neither are correct then the measurements would atleast establish the range of distortion. Only one measurement need to be taken (e.g at a PCC) and this could be used for as a control point.

e. In terms of harmonic standards it was found that the IEEE controls both voltage and current distortion in power systems. It is a systems standard. The IEC controls only voltage distortion in power systems. It controls current distortion by an equipment standard. It thus provides only a system standard for voltages. The ESKOM standard like the IEC only controls voltage distortion in power systems. It provides no direct controls for current distortion. From this it can be concluded that there are three different approaches to controlling harmonic distortion:

(1) Solely by system standards.

(2) By a voltage system standard supported by an equipment standard to control current distortion.

(3) By providing solely a systems voltage standard

f. It is concluded that all standards control harmonics by providing regulatory limits for THD % and limits for individual harmonic components.

g. Of the three standards compared it can be concluded that the IEC systems standard is the most intricate because it provides regulatory limits for non-multiple of 3 and multiple of 3 odd harmonics besides limits for even and inter-harmonics. It also distinguishes between three classes. The ESKOM standard is less complicated as it does not subdivide its odd harmonics but like the IEC standard distinguishes between odd, even and inter-harmonic limits. The IEEE standard does not distinguish directly between types of harmonics.

h. In terms of individual harmonic component distortion standards it can be concluded that:

(1) The ESKOM and IEC <14th harmonic component limits are in general more tolerable to distortions than the IEEE standard. The reverse is true for odd harmonics in the 14th to 25th range.

(2) The ESKOM and IEC even and inter-harmonic limits are less tolerable to distortion than the IEEE standard.

i. With regard to THD % it can be concluded that the Class 2 and 3 IEC limits are more tolerable to distortion than the Class 1, ESKOM and IEEE limits. The latter three limits were found to be the same.

j. It can be concluded that a similarity exists between the IEC Class 2 and ESKOM standards. It was found that five ESKOM limits were within the Class 2 range of harmonics and four were not. Those outside the range were found to be >25th odd harmonics and the three inter-harmonic ranges <14th, 14th to 25th and >25th. It was further found that these limits that are outside the IEC ranges were greater than the highest IEC limit and are more tolerable towards distortion. Nevertheless the two standards are similar and it is recommended that in terms of individual harmonic component limits that they be made identical. ESKOM should maintain its THD % level as it is more stricter than the IEC class 2 level.

k. From the application of field measurements to the three standards studied it was found that the measured voltage THD %'s at neither the plant nor the traction substation exceeded the regulatory limits provided by these standards. This is true for both PCC's and IPC's. It also shows that the ESKOM limits achieve the same objectives. It can thus be concluded that even though each standard approaches harmonic distortion in a different way all are effective.

l. Only the IEEE standard provides regulatory limits for current THD %. When the field measurements were applied to this standard it was found that the current distortion in the plant was less than the recommended limits but in the traction substation the limits were exceeded. It can be concluded that the standard would for most purposes suffice except for traction substations. Even though the IEEE standard does not apply in South Africa it is persuasive and it is recommended that the substation take the necessary steps to decrease its distortion. The plant on the other hand can add extra harmonic sources.

m. In terms of individual harmonic voltage components it was found that neither of the two installations studied has any unacceptable distortion at either its PCC nor IPC levels. This agrees with the voltage THD % findings. It can be concluded that for odd and even components all three standards are effective even though their approaches to controlling distortion are different. It can also be concluded that the ESKOM standard is as effective as the IEEE and IEC standards. As the harmonic analyser used for measurements is unable to measure inter-harmonics no conclusions in this regard can be made.

n. With regard to individual current components it was found that none of the measured currents in the plant exceeded the limits recommended by the IEEE standard. The distortion is however unacceptable in the traction substation. Almost all component magnitudes exceed the IEEE limits. These results support the current THD % findings. It can thus be concluded that the IEEE component limits would suffice for most installations except traction substation.

o. In general it can be concluded that ESKOM's approach to controlling voltage distortion is effective from a utilities point of view. ESKOM's drawback is that it does not have a current standard that can be directly applied. End-users are thus able to pollute systems. They have however instituted an apportioning procedure.

5.3 RESEARCH PAPER

The author has prepared and presented a research paper at the South African Universities Power Conference in January 1996. The paper has also been accepted for presentation at the 7th IEEE International Conference on Harmonics which is to be held in October 1996. The paper was also accepted for the North American Power Symposium (NAPS) to be held in November 1996. It however will not be presented due to the clash with the IEEE Conference. A copy of the paper is attached at the end of this thesis.

5.4 FUTURE WORK

a. In order to prove that PC based harmonic penetration packages are effective in predicting results similar to field measurement, further case studies involving other installations needs to be investigated. Newly developed packages (post 1995) need also to be investigated and their results applied to field measurements to test their effectiveness. The use of more than two packages will also give an indication as to whether the programs are deficient or the field measurements are incorrect.

b. A study to be made of available harmonic measuring equipment and the best technique to be used for measurements needs to be undertaken.

c. The development of a current standard for ESKOM.

The thesis is a contribution to the field of research in harmonics in power systems and provides a base for further work and will be useful to other researches.

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APPENDIX 1

1. ELECTROTEK'S POWER SYSTEM HARMONIC ANALYSIS PACKAGES AND THEIR SIMULATION OF THE 11kV MANUFACTURING PLANT

1.1. INPUT DATA FILE LAYOUT CASE A (EVO13 . SHA)

```
TITLE
TITLE1="11KV MANUFACTURING PLANT"
TITLE2="HARMONIC SOURCE"
TITLE3="INJECTION AT BUS6"
! Case A: 11kv 3PH system modelled as 1ph circuit
!
OPTIONS
FBASE=50
!
!  Harmonic simulation case
!
!
!  Utility source
!
VSOURCE NAME=VSRC BUS=SRCV MAG=6350.853
!
!
! Harmonic Source FOR CASES WITH RECTIFIER MODELED AS AN IDEAL
!
! RECTIFIER,  6  PULSE,
!
ISOURCE NAME=SRC1 BUS=BUS6
!
TABLE=  {  {  50,   60.00,  -38.0},
           { 250,   12.00,  -10.0},
           { 350,    8.57, -266.0},
           { 550,    5.45  -238.0},
           { 650,    4.62, -134.0},
           { 850,    3.52, -106.0},
           { 950,    3.15,    -2.0},
           {1150,    2.60, -334.0},
           {1250,    2.40, -230.0},
           {1450,    2.06, -202.0},
           {1550,    1.94,   -98.0}
        }
!
```

APPENDIX 1

```
! BRANCHES WHICH ARE UNDERGROUND CABLES EXCEPT EQUIV Zeq
!
BRANCH NAME=EQUIV FROM=BUS1 TO=SRCV R=0.0 X=0.9
BRANCH NAME=BRANCH1 FROM=BUS1 TO=BUS2 R=0.058 X=0.0196
BRANCH NAME=BRANCH2 FROM=BUS3 TO=BUS4 R=0.00115 X=0.00134
BRANCH NAME=BRANCH3 FROM=BUS4 TO=BUS5 R=0.015 X=0.0134
BRANCH NAME=BRANCH4 FROM=BUS5 TO=BUS6 R=0.1 X=0.0
!
! CAPACITOR BANKS ON THE SYSTEM
!  ALL CAPACITORS ARE IN SERVICE
!
CAPACITOR NAME=BANK01 FROM=BUS4 KV=0.22 KVA=41.67

CAPACITOR NAME=BANK02 FROM=BUS4 KV=0.22 KVA=4.167
CAPACITOR NAME=BANK03 FROM=BUS4 KV=0.22 KVA=20.0
!
!
! LOAD REPRESENTING GENERAL OFFICE INSTALLATION
!
LINEARLOAD NAME=LOAD1 FROM=BUS1 KVA=140.34 KV=6.350853 DF=0.94
LINEARLOAD NAME=LOAD2 FROM=BUS5 KVA=13.3 KV=.22 DF=0.76
!
! TRANSFORMER 11KV/380V Dy0n AS A 1PH TRANSFORMER
!
TRANSFORMER NAME=T1 MVA=0.6667
H.1=BUS2 X.1=BUS3
KV.H=6.350853 KV.X=0.22
%R.HX=0.31 %X.HX=5.94
!
!
! INDUCTION MOTORS LUMPED AND TREATED AS 1PH MOTORS
!
INDUCTIONMOTOR NAME=MOTOR1 FROM=BUS1 DF=0.94 KV=6.350853 HP=282.938
%EFF=80
INDUCTIONMOTOR  NAME=MOTOR2  FROM=BUS4  DF=0.944  KV=0.22  HP=202.97
%EFF=80
!
!
!
!
RETAIN CURRENTS=YES
!
! END OF FILE
```

1.2 SIMULATION RESULTS CASE A

The following harmonic spectral and THD% results were obtained:

HARMONIC SPECTRAL SIMULATION RESULTS FOR 11kV MANUFACTURING PLANT - CASE A -										
h	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
Hz	50	250	350	550	650	850	950	1150	1250	%
PCC = BUS1 (LINE VOLTAGE - HV)										
V	10964	3.22	4.09	25.86	8.66	2.11	1.46	0.84	0.68	0.26
BRANCH CURRENT LINE 1 - TO - BUS1 NODE (AMPS)										
A	94	0.41	0.38	1.51	0.43	0.08	0.05	0.02	0.02	1.77
IPC 2 = BUS4 (LINE VOLTAGE - LV)										
V	378	0.72	0.93	5.82	1.95	0.48	0.33	0.19	0.15	1.66
BRANCH CURRENT BR2 BUS3 - TO - BUS4 NODE										
A	849	12.3	11.3	45.5	12.9	2.41	1.48	0.71	0.53	5.92

TABLE 1.1

NB! Single phase voltage results are obtained but have been converted to line values in above table.

1.3 INPUT DATA FILE LAYOUT CASE B (EVO14.SHA)

```
TITLE
TITLE1="11KV MANUFACTURING PLANT"
TITLE2="HARMONIC SOURCE"
TITLE3="INJECTION AT BUS6"
! Case B: 11kv 3PH system modelled as 1ph circuit
!
OPTIONS
FBASE=50
!
! Harmonic simulation case
!
! Utility source
```

APPENDIX 1

```
!
VSOURCE NAME=VSRC BUS=SRCV MAG=6350.853
!
!
! Harmonic Source FOR CASES WITH RECTIFIER MODELED USING
! HARMONIC SPECTRUM MEASURED IN THE FIELD FOR
!
! RECTIFIER, 6 PULSE,
!
ISOURCE NAME=SRC1 BUS=BUS6
!
TABLE= { {  50,   60.0,  -38.0},
         { 250,   17.7,  -17.0},
         { 350,    2.6,   41.0},
         { 550,    3.9,  -68.0},
         { 650,    1.0,  -92.0},
         { 850,    2.0, -113.0},
         { 950,    0.8, -166.0},
         {1150,    1.4, -164.0},
         {1250,    0.7,  144.0},
         {1450,    0.9,  145.0},
         {1550,    0.6,   89.0}
       }
!
! BRANCHES WHICH ARE UNDERGROUND CABLES EXCEPT EQUIV Zeq
!
BRANCH NAME=EQUIV FROM=BUS1 TO=SRCV R=0.0 X=0.9
BRANCH NAME=BRANCH1 FROM=BUS1 TO=BUS2 R=0.058 X=0.0196
BRANCH NAME=BRANCH2 FROM=BUS3 TO=BUS4 R=0.00115 X=0.00134
BRANCH NAME=BRANCH3 FROM=BUS4 TO=BUS5 R=0.015 X=0.0134
BRANCH NAME=BRANCH4 FROM=BUS5 TO=BUS6 R=0.1 X=0.0
!
! CAPACITOR BANKS ON THE SYSTEM
!  ALL CAPACITORS ARE IN SERVICE
!
CAPACITOR NAME=BANK01 FROM=BUS4 KV=0.22 KVA=41.67
CAPACITOR NAME=BANK02 FROM=BUS4 KV=0.22 KVA=4.167
CAPACITOR NAME=BANK03 FROM=BUS4 KV=0.22 KVA=20.0
!
!
! LOAD REPRESENTING GENERAL OFFICE INSTALLATION
!
LINEARLOAD NAME=LOAD1 FROM=BUS1 KVA=140.34 KV=6.350853 DF=0.94
LINEARLOAD NAME=LOAD2 FROM=BUS5 KVA=13.3 KV=.22 DF=0.76
!
```

APPENDIX 1

```
! TRANSFORMER 11KV/380V Dy0n AS A 1PH TRANSFORMER
!
TRANSFORMER NAME=T1 MVA=0.6667
H.1=BUS2 X.1=BUS3
KV.H=6.350853 KV.X=0.22
%R.HX=0.31 %X.HX=5.94
!
!
! INDUCTION MOTORS LUMPED AND TREATED AS 1PH MOTORS
!
INDUCTIONMOTOR NAME=MOTOR1 FROM=BUS1 DF=0.94 KV=6.350853 HP=282.938
%EFF=80
INDUCTIONMOTOR NAME=MOTOR2 FROM=BUS4 DF=0.944 KV=0.22 HP=202.97
%EFF=80
!
!
!
!
RETAIN CURRENTS=YES
!
!
! END OF FILE
!
!
....
```

1.4 SIMULATION RESULTS CASE B

The following harmonic spectral and THD % results were obtained.

HARMONIC SPECTRAL SIMULATION RESULTS FOR 11kV MANUFACTURING PLANT - CASE B -										
h	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
HZ	50	250	350	550	650	850	950	1150	1250	%
PCC = BUS1 (LINE VOLTAGE - HV)										
V	10964	4.69	1.23	18.5	1.88	1.2	0.37	0.45	0.19	0.18
BRANCH CURRENT LINE 1 - TO - BUS1 NODE (AMPS)										
A	94.2	0.6	0.11	1.08	0.09	0.05	0.01	0.01	0.001	1.32
IPC 2 = BUS4 (LINE VOLTAGE - LV)										
V	377.6	1.06	0.28	4.17	0.42	0.27	0.08	0.1	0.04	1.15
BRANCH CURRENT BR2 BUS3 - TO - BUS4 NODE										
A	849.2	18.1	3.44	32.5	2.79	1.37	0.37	0.38	0.15	4.42

TABLE 1.2

NB! Single phase voltage results are obtained but have been converted to line values in above table.

1.5 INPUT DATA FILE LAYOUT CASE C (EV015.SHA)

```
TITLE
TITLE1="11KV MANUFACTURING PLANT"
TITLE2="HARMONIC SOURCE"
TITLE3="INJECTION AT MCC"
! Case C: 11kv 3PH system modelled as 1ph circuit
!
OPTIONS
FBASE=50
!
! Harmonic simulation case
!
!
! Utility source
```

APPENDIX 1

```
!
VSOURCE NAME=VSRC BUS=SRCV MAG=6350.853
!
!
! Harmonic Source FOR CASES WITH RECTIFIER MODELED USING
! HARMONIC SPECTRUM MEASURED IN THE FIELD AT INPUT TO BUS5
! AND REPRESENTS A COMBINATION OF THE DRIVES AT BUS6 AND
! THE LINEARLOAD LOAD2
!
! RECTIFIER, 6 PULSE,
!
ISOURCE NAME=SRC1 BUS=BUS6
!
TABLE= {  {   50,   126.3,    -39.0},
          {  250,    17.7,    -17.0},
          {  350,     2.6,     41.0},
          {  550,     3.9,    -68.0},
          {  650,     1.0,    -92.0},
          {  850,     2.0,   -113.0},
          {  950,     0.8,   -166.0},
          { 1150,     1.4,   -164.0},
          { 1250,     0.7,    144.0},
          { 1450,     0.9,    145.0},
          { 1550,     0.6,     89.0}
       }
!
! BRANCHES WHICH ARE UNDERGROUND CABLES EXCEPT EQUIV Zeq
!
BRANCH NAME=EQUIV FROM=BUS1 TO=SRCV R=0.0 X=0.9
BRANCH NAME=BRANCH1 FROM=BUS1 TO=BUS2 R=0.058 X=0.0196
BRANCH NAME=BRANCH2 FROM=BUS3 TO=BUS4 R=0.00115 X=0.00134
BRANCH NAME=BRANCH3 FROM=BUS4 TO=BUS5 R=0.015 X=0.0134
BRANCH NAME=BRANCH4 FROM=BUS5 TO=BUS6 R=0.1 X=0.0
!
! CAPACITOR BANKS ON THE SYSTEM
!  ALL CAPACITORS ARE IN SERVICE
!
CAPACITOR NAME=BANK01 FROM=BUS4 KV=0.22 KVA=41.67
CAPACITOR NAME=BANK02 FROM=BUS4 KV=0.22 KVA=4.167
CAPACITOR NAME=BANK03 FROM=BUS4 KV=0.22 KVA=20.0
!
!
! LOAD REPRESENTING GENERAL OFFICE INSTALLATION
!
LINEARLOAD NAME=LOAD1 FROM=BUS1 KVA=140.34 KV=6.350853 DF=0.94
```

APPENDIX 1

```
!
! TRANSFORMER 11KV/380V Dy0n AS A 1PH TRANSFORMER
!
TRANSFORMER NAME=T1 MVA=0.6667
H.1=BUS2 X.1=BUS3
KV.H=6.350853 KV.X=0.22
%R.HX=0.31 %X.HX=5.94
!
!
! INDUCTION MOTORS LUMPED AND TREATED AS 1PH MOTORS
!
INDUCTIONMOTOR NAME=MOTOR1 FROM=BUS1 DF=0.94 KV=6.350853 HP=282.938
%EFF=80
INDUCTIONMOTOR  NAME=MOTOR2  FROM=BUS4  DF=0.944  KV=0.22  HP=202.97
%EFF=80
!
!
!
!
RETAIN CURRENTS=YES
!
!
! END OF FILE
!
!
....
```

1.6 SIMULATION RESULTS CASE C

The following harmonic spectral and THD% results were obtained.

HARMONIC SPECTRAL SIMULATION RESULTS FOR 11kV MANUFACTURING PLANT HARMONIC SOURCE MODELLED FROM HARMONIC CURRENT FIELD MEASUREMENTS - CASE C -										
h	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
HZ	50	250	350	550	650	850	950	1150	1250	%
PCC = BUS1 (LINE VOLTAGE - HV)										
V	10968	4.72	1.25	20.4	1.88	1.21	0.37	0.45	0.12	0.12
BRANCH CURRENT LINE 1 - TO - BUS1 NODE (AMPS)										
A	90.41	0.61	0.12	1.12	0.09	0.05	0.01	0.01	0.01	1.49
IPC 2 = BUS4 (LINE VOLTAGE - LV)										
V	378.8	1.05	0.28	4.58	0.43	0.27	0.08	0.1	0.04	1.26
BRANCH CURRENT BR2 BUS3 - TO - BUS4 NODE										
A	757.9	18.27	3.47	35.96	2.82	1.38	0.38	0.38	0.16	5.36

TABLE 1.3

NB! Single phase voltage results are obtained but have been converted to line values in above table.

1.7 COMPARISON OF SIMULATION RESULTS CASE A, B AND C

A comparison will be made between the three cases studied.

The following tables will compare the amplitudes of harmonic components and the THD % of the voltages and currents. The first table will be at PCC (HV) level and the second at IPC 2 (LV) level. The results are extracted from Tables 1.1, 1.2 and 1.3.

SUPERHARM PACKAGE
HARMONIC SPECTRAL AND THD% RESULTS - CASES A, B AND C
- PCC LEVEL -

Case	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
PCC = BUS 1 (LINE VOLTAGES)										
A	10964	3.22	4.09	25.86	8.66	2.11	1.46	0.84	0.68	0.26
B	10964	4.69	1.23	18.5	1.88	1.2	0.37	0.45	0.19	0.18
C	10968	4.72	1.25	20.4	1.88	1.21	0.37	0.45	0.12	0.12
BRANCH CURRENT LINE 1 - TO - BUS 1 (AMPS)										
A	94	0.41	0.38	1.51	0.43	0.08	0.05	0.02	0.02	1.77
B	94.2	0.6	0.11	1.08	0.09	0.05	0.01	0.01	0.001	1.32
C	90.41	0.61	0.12	1.12	0.09	0.05	0.01	0.01	0.01	1.49

TABLE 1.4

APPENDIX 1

SUPERHARM PACKAGE HARMONIC SPECTRAL AND THD% RESULTS - CASES A, B AND C - IPC 2 LEVEL -									
Case	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
IPC 2 = BUS 4 (LINE VOLTAGES)										
A	378	0.72	0.93	5.82	1.95	0.48	0.33	0.19	0.15	1.66
B	377.6	1.06	0.28	4.17	0.42	0.27	0.08	0.1	0.04	1.15
C	378.8	1.05	0.28	4.58	0.43	0.27	0.08	0.1	0.04	1.26
BRANCH CURRENT BR 2 - TO - BUS 4										
A	849	12.3	11.3	45.5	12.9	2.41	1.48	0.71	0.53	5.92
B	849.2	18.1	3.44	32.5	2.79	1.37	0.37	0.38	0.15	4.42
C	857.9	18.2	3.47	35.96	2.82	1.38	0.38	0.38	0.16	5.36

TABLE 1.5

Case B's spectrum is injected at bus 6 while Case C's spectrum is injected at bus 5. Similar results are expected between these two cases and are obtained. This proves that the linear load at bus 5 contributes no additional harmonics and that the dummy bus, bus 6 is effective.

The Case A results for the ideal rectifier spectrum gives results in the similar region to the other cases.

APPENDIX 2

2. THE ERACS POWER SYSTEM HARMONIC ANALYSIS PACKAGE AND ITS SIMULATION OF THE 11kV MANUFACTURING PLANT

2.1 LOADFLOW MODELLING, PARAMETERS, DATA ENTRY BOX FORMATS AND ONE-LINE-DIAGRAM DEVELOPMENT

2.1.1 BASE DATA

STUDY BASE, MVA 100.00
STUDY FREQUENCY 50.0

NB! 3 phase values are used.

2.1.2 BUSBARS

BUSBAR, MODELLING, PARAMETERS AND DATA ENTRY BOX FORMAT	
DATA ITEM	PARAMETER
BUSBAR NAME	BUS 1
RATED BUSBAR VOLTAGE, kV	11.0
BUSBAR FREQUENCY, Hz	50.0

TABLE 2.1

The one-line-diagram is simultaneously developed as input data is entered.

2.1.3 SHUNTS

SHUNT MODELLING, PARAMETERS AND DATA ENTRY BOX FORMAT						
Data Item	SHUNT PARAMETERS					
Shunt Identifier	Shunt-1	Shunt-2	Shunt-3	Shunt-4	Shunt-5	2 Drives combined
Busbar	4	4	4	4	5	6
Shunt Type 5	kW,kVAR	kW,kVAR	kW,kVAR	kW,kVAR	kW,kVAR	kW,kVAR
Rated kV	11	0.38	0.38	0.38	0.38	0.38
kW	395.75	0	0	0	10.108	31.165
kvar (Cap)	-	-125	-12.5	-60.0	-	
kvar (Ind)	143.64	-	-	-	8.643	24.187

TABLE 2.2

2.1.4 CABLES

CABLE MODELLING PARAMETERS AND DATA ENTRY BOX FORMAT					
DATA ITEM		BRANCH PARAMETERS			
		1	2	3	4
1st Connected bus		Bus1	Bus3	Bus4	Bus5
2nd Connected bus		Bus2	Bus4	Bus5	Bus6
Branch Identifier		BR1	BR2	BR3	BR4
Length of Cable	200m	1.0pu			
	10m		1.0pu		1.0pu
	100m			1.0pu	
Rating Selector		High	High	High	High
Cable Rating kA	70mm^2	0.226			
	185mm^2		0.331	0.331	0.331
Nominal kV Rating		11	0.38	0.38	0.38
Conversion Indicator		ohm/ ohm/μF	ohm/ ohm/μF	ohm/ ohm/μF	ohm/ ohm/μF
+ve, -ve series resistance		0.058	0.00115	0.015	0.1
+ve, -ve series resistance		0.0198	0.00134	0.0134	0.0
+ve, -ve shunt susceptance		0.0	0.0	0.0	0.0
Zero sequence series resistance		0.268	0.268	0.268	0.268
Zero sequence series reactance		0.11	0.11	0.11	0.11
Zero sequence shunt susceptance		0.0	0.0	0.0	0.0

TABLE 2.3

LINE MODELLING, PARAMETERS AND DATA ENTRY BOX FORMAT	
DATA ITEM	LINE PARAMETERS
FIRST BUSBAR	SRCV
SECOND BUSBAR	BUS 1
IDENTIFIER	LINE 1
LENGTH OF LINE	1.0
CONVERSION INDICATOR	ohm/mH/μF
+ve, -ve sequence series resistance pu of length	0.1
+ve, -ve sequence series reactance pu of length	0.9
+ve, -ve sequence shunt susceptance pu of length	0.6
Zero sequence series resistance pu of length	0.1
Zero sequence series reactance pu of length	0.9
Zero sequence shunt susceptance pu of length	0.6

TABLE 2.7

2.1.8 GENERATORS

GENERATOR MODELLING, PARAMETERS AND DATA ENTRY BOX FORMAT	
DATA ITEM	GENERATOR PARAMETERS
GENERATOR IDENTIFIER	GEN - 1
GENERATOR TYPE	INFINITE
VOLTAGE MAGNITUDE,(pu)	1.0
VOLTAGE ANGLE DEGREES	0.0
RATED VOLTAGE, kV	11.0
RATED FREQUENCY, HZ	50.0

TABLE 2.8

This completes the modelling and the production of the one-line-diagram.

2.2 SIMULATION PROCESS - LOADFLOW ANALYSIS

Various study parameters need to be defined. The most common being:

STUDY PARAMETERS	
DATA ITEM	PARAMETER
P MULTIPLIER	1.0
Q MULTIPLIER	1.0
CONVERGENCE TOLERANCE	0.00005
OVERFLOW FLAG SET LEVEL	0.8
LINE RATING SELECTOR	SUMMER
INITIAL ITERATION COUNT	25
BUS LOWER VOLTAGE LIMIT, pu	0.8
BUS UPPER VOLTAGE LIMIT, pu	1.1
AUTOMATIC TAP CHANGER	YES/NO

TABLE 2.9

Before the results can be displayed on the one-line-diagram the results wanted need to be selected.

The following results were selected.

LOADFLOW RESULTS	
SELECTION	PARAMETER
BUSBARS	kV Voltages at buses
SHUNTS	Currents in kA at all shunts
LINES/CABLES	Currents in kA (1C and 2C) through lines/cables
TRANSFORMERS	Currents in kA at HV/LV buses (1C and 2C)
MOTORS	Terminal Voltage (VT) and Currents (CT)
GENERATOR	Terminal Voltage (VT) and Currents (CT)

TABLE 2.10

2.3 LOADFLOW RESULTS

The results for the fundamental loadflow are shown on the following one-line-diagram.

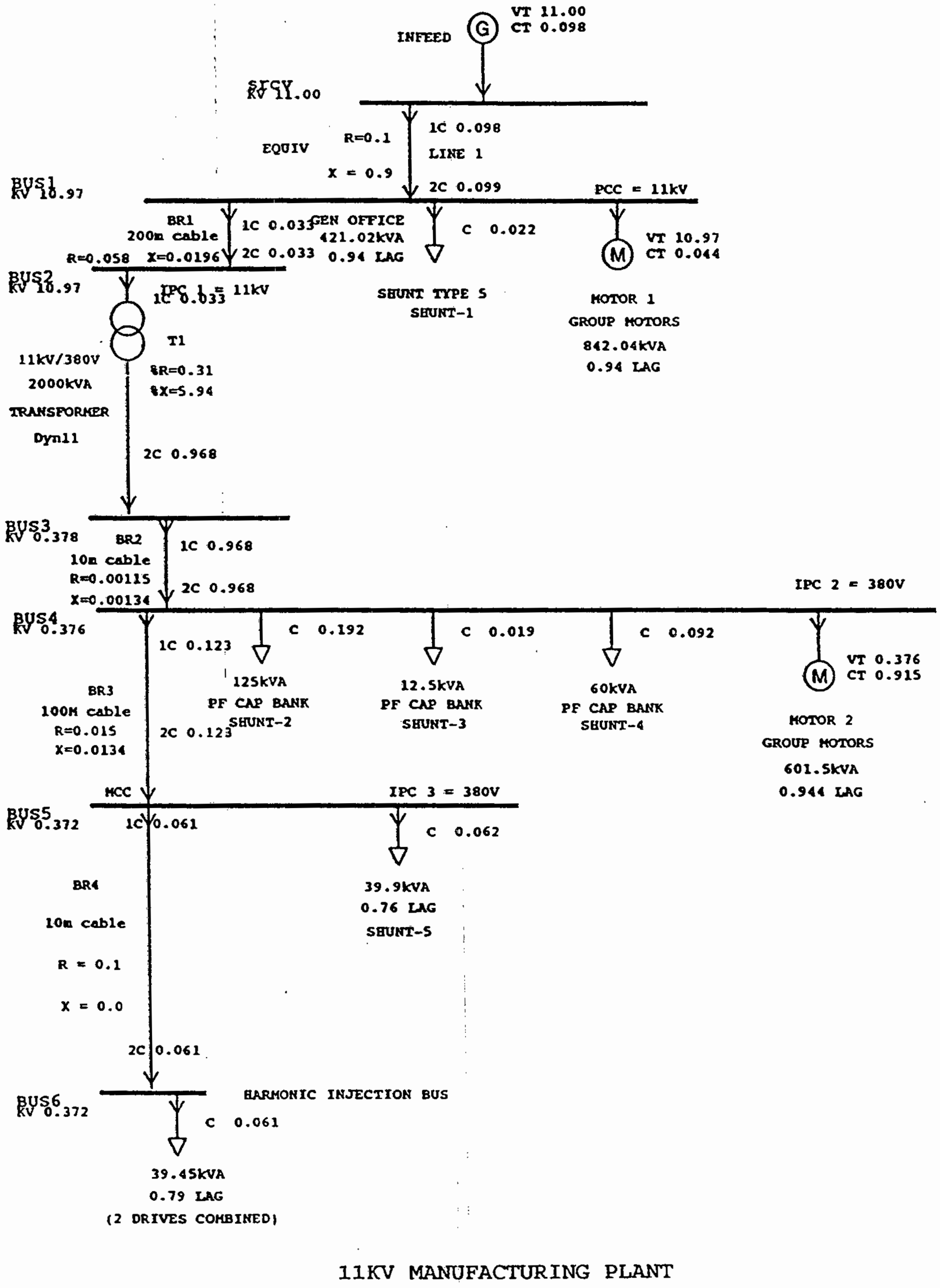


FIGURE 2.1

APPENDIX 2

2.3.1 INTERPRETATION OF LOADFLOW RESULTS

Convergence in itself is not the sole indication of the success of a loadflow analysis. The results should be correct values. Control points should be selected. The selected points were:

LINEARLOAD 1 AT BUS 1 = 22 AMPS
LINEARLOAD 2 AT BUS 5 = 60.2 AMPS

It can be seen from the one-line-diagram (Figure 2.1) that:

LINEARLOAD SHUNT - 1 = 0.022 kA
LINEARLOAD SHUNT - 5 = 0.062 kA

NB!

Current results were set to be displayed as kA

therefore: 0.022 kA = 22A
0.062 kA = 62A

<u>Other modelling checks are:</u>

(1) <u>MOTORS</u>	<u>EXPECTED</u>	<u>LOADFLOW RESULTS</u>
Group Motor 1 =	44A	44A

$I_L = 842.04 \text{ kVA} \div \sqrt{3}\ 11000 = 44.12 \text{ A}$ (Expected)

	<u>EXPECTED</u>	<u>LOADFLOW RESULTS</u>
Group Motor 2 =	913.8 A	914 A

$I_L = 601.5 \text{ kVA} \div \sqrt{3}\ 380 = 913.8 \text{ A}$ (Expected)

NB!

Results thus approve the motor modelling.

(2) <u>CAPACITORS</u>

	<u>EXPECTED</u>	<u>LOADFLOW RESULTS</u>
125 kVA (Shunt -2) =	189.9A	192A
12.5 kVA (Shunt-3) =	18.9A	19A

60 kVA (Shunt -3)	=	91.16A	92A

(3) 2 COMBINED DRIVES

	EXPECTED	LOADFLOW RESULTS
2 Drives =	59.93A	61A

$I_L = 39.45 \text{ kVA} \div \sqrt{3}\ 380 = 59.93\text{A}$ (Expected)

(4) FIELD MEASUREMENTS (FUNDAMENTAL FREQUENCY)

The current in BR3 as measured in the field = 126.3A
(Measurement 3 Table 6.5 Appendix 6)

Loadflow Analysis = 123A

The current in LINE 1 as measured in the field = 2.48 x (200 ÷ 5) = 99.2A
(Measurement 6 Table 6)
Loadflow Analysis = 99A

NB!

The loadflow not only converged but also provided the same results as the hand calculated results. It could thus be accepted that the modelling was correct. The network could thus be seen to be set up for harmonic penetration studies.

2.4 HARMONIC INJECTION MODELLING

HARMONIC NUMBER INPUT TABLE			
Selection	Harmonic Number	Selection	Harmonic Number
1	5.0	11	35.0
2	7.0	12	37.0
3	11.0	13	41.0
4	13.0	14	43.0
5	17.0	15	47.0
6	19.0	16	49.0
7	23.0	17	
8	25.0	18	
9	29.0	19	
10	31.0	20	

TABLE 2.11

These are typical characteristic numbers for rectifiers. A typical rectifier data box is:

HARMONIC INJECTION Nº 1 AT BUSBAR BUS 1 TOTAL DELAY ANGLE: 0.0					
HarmonicNº	Amplitude	Angle	HarmonicNº	Amplitude	Angle
Fundamental	1.00	0.0			
5.00	0.200	0.0	35.00	0.0286	0.0
7.00	0.143	0.0	37.00	0.0270	0.0
11.00	0.0909	0.0	41.00	0.0244	0.0
13.00	0.0769	0.0	43.00	0.0233	0.0
17.00	0.0588	0.0	47.00	0.0213	0.0
19.00	0.0526	0.0	49.00	0.0204	0.0
23.00	0.0435	0.0			
25.00	0.0400	0.0			
29.00	0.0345	0.0			
31.00	0.0323	0.0			

TABLE 2.12

The box lists the harmonics which have been defined and the busbar selected for the injection.

2.5 CASE A: HARMONIC ANALYSIS - IDEAL RECTIFIER INJECTION AT BUS 6 (MTH - 4.2)

The following is the step-by-step procedure used for CASE A.

```
C:\ > cd \ MYDIR

C:\ MYDIR > ERACS
```

(1) Select "LOAD SYSTEM"

(2) Choose File - "MTH"

(3) Select state - "4" (X = 0.9)

(4) One-line-diagram appears

(5) Run loadflow (MTH - 4 X = 0.9) from "CALCULATION" menu.

  a) Select state number

  b) Run study using same parameters

  c) One-line diagram re-appears after loadflow converged.

(6) Select "Harmonic" from "CALCULATION" menu to commence injection study.

  a) Select "New Study"

  b) Set up panel appears.

  c) Enter study number "2" (MTH - 4.2)

  d) Verify that run should use same parameters as loadflow run

  e) Enter study title "11kV MANUFACTURING PLANT"

  f) Use <TAB> to select "study option"

  g) Select "RECTIFIER/NON-RECTIFIER

  h) Select default for harmonic offset, triple indicator and output options

(7) Harmonic Number Input Table appears (Same as Table 2.11)

a) No harmonic numbers need to be added.

HARMONIC NUMBER INPUT TABLE			
Selection	Harmonic Number	Selection	Harmonic Number
1	5.0	11	
2	7.0	12	
3	11.0	13	
4	13.0	14	
5	17.0	15	
6	19.0	16	
7	23.0	17	
8	25.0	18	
9	29.0	19	
10	31.0	20	

TABLE 2.13

NB!

The harmonic spectrum to be injected will comprise only of 10 selections and is the same as was used for the CASE A SUPERHARM PACKAGE simulation.

b) Press <ctrl end> to finish selections.

(8) Select busbar for injection number 1. Point with mouse to bus 6 on one-line-diagram and select bus by pointing to top left hand corner of bus.

(9) Harmonic injection data box (same as Table 2.12) appears. The harmonic numbers of Table 2.13 above appear already in the data box.

HARMONIC INJECTION DATA BOX HARMONIC INJECTION: IDEAL RECTIFIER AT BUS 6 CASE - A -					
HarmonicNº	Amplitude	Angle	HarmonicNº	Amplitude	Angle
Fundamental	60.0	-38.0	31	1.94	-98.0
5	12.0	-10.0			
7	8.57	94.0			
11	5.45	122.0			
13	4.62	-134.0			
17	3.52	-106.0			
19	3.15	-2.0			
23	2.6	26.0			
25	2.4	130.0			
29	2.06	158.0			

TABLE 2.14

Enter an angle for each harmonic number within the range 0° to 180°. Larger angles need to be converted within this range. The following were converted.

-266° to 94°, -238° to 122°, -334° to 26°, -230° to 130° and -202° to 158°

The magnitudes are automatically calculated using;

$$I_h - \frac{I_1}{h}$$

once the magnitude for the fundamental is entered.

The harmonic spectrum represents and ideal rectifier (6k± 1) and is the same spectrum as that used for the CASE A SUPERHARM package simulation.

(10) Running Program

a) Once harmonic magnitudes and angles have been entered, press <Ctrl- end > to finish.
b) Set up panel reappears prompting "OK" to continue. Select "Yes".

c) End of study prompt appears. Press any key to proceed.

(11) One-line-diagram re-appears with the harmonic penetration for the fundamental results shown therein.

a) Use < + > = next harmonic, < - > previous harmonic to view results of each harmonic number. Each time a one-line-diagram appears with results shown thereon. The 11 selections can only be viewed individually.

b) Once viewing complete select <ESC> = FINISH. The 7 pull down menus appear on top of the screen.

(12) Select "RESULTS" menu then "HARMONICS", then "SHOW SELECTED RESULTS", Select one-line-diagram harmonic number of choice and it appears on the screen.

(13) Select "UTILITIES" menu and "PRINT DIAGRAM" menu to print one-line-diagrams chosen. Label diagram before printing with the "harmonic number thereon".

(14) Select "UTILITIES" menu and "PRINT LIST FILE" to print all the results in table format. The file MTH - 4.2 must be selected by pressing "spacebar" to obtain a print out.

2.5.1 SIMULATION RESULTS CASE A

Results are produced for the 5th to 25th harmonic as was done with the SUPERHARM cases.

The following harmonic spectral and THD % results were obtained:

HARMONIC SPECTRAL SIMULATION RESULTS FOR 11kV MANUFACTURING PLANT HARMONIC SOURCE MODELLED AS AN IDEAL RECTIFIER INJECTION BUS 6 - CASE A -										
h	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
HZ	50	250	350	550	650	850	950	1150	1250	%
PCC = BUS1 (LINE VOLTAGE - HV)										
V	10970	3.0	3.0	6.0	10.0	10.0	5.0	2.0	2.0	0.15
BRANCH CURRENT LINE 1 - TO - BUS1 NODE (AMPS)										
A	99.0	0.23	0.19	0.2	0.3	0.23	0.01	0.04	0.03	0.52
IPC 2 = BUS4 (LINE VOLTAGE - LV)										
V	372.0	0.0	0.0	1.0	2.0	2.0	0.0	0.0	0.0	0.83
BRANCH CURRENT BR2 BUS3 - TO - BUS4 NODE										
A	968.0	8.1	6.51	1.86	9.9	7.72	3.24	1.18	0.82	1.86

TABLE 2.15

2.6 CASE B: HARMONIC ANALYSIS - RECTIFIER MODELLED USING HARMONIC SPECTRUM MEASURED IN THE FIELD - INJECTION AT BUS 6 (MTH-4.3)

HARMONIC INJECTION DATA BOX
HARMONIC INJECTION: RECTIFIER MODELLED ON FIELD MEASUREMENTS INJECTION BUS 6
- CASE B -

HarmonicNº	Amplitude	Angle	HarmonicNº	Amplitude	Angle
Fundamental	60.0	-38.0	31	0.6	89.0
5	17.7	-17.0			
7	2.6	41.0			
11	3.9	-68.0			
13	1.0	-92.0			
17	2.0	-113.0			
19	0.8	-160.0			
23	1.4	-164.0			
25	0.7	144.0			
29	0.9	145.0			

TABLE 2.16

The harmonic spectrum is the same spectrum as that used for CASE B SUPERHARM package simulation.

The above spectrum represents the combination of the two spectrums produced by the two drives which were measured in the field. (See Measurement points 1, 2 and 3 and Tables 6.3, 6.4 and 6.5 attached to Appendix 6).

Measurement point 3 (Table 6.5 Appendix 6) gives the harmonic spectrum for the two drives plus the shunt load (Shunt - 5) together. As the linear shunt load (Shunt - 5) contributes nothing to the spectrum all the harmonics originate from the two drives combined together. The fundamental measured at point 3 however is the combination of the linear loads (Shunt- 5's) fundamental and the combined fundamentals from the two drives. The latter fundamentals (i.e. two drives) are represented on the one-line-diagram figure 2.1 above as a shunt load on Bus 6. The value is 61A. This can be checked as follows:

$I_{FUNDAMENTAL}$ (Point 3) = 126.3A at an angle of -39°
= (98.1 - j 79.48)A

The linear load at bus 5 = 39.9 kVA at pf 0.76 lag

V phase measured = 217 V per phase

$I_{FUNDAMENTAL}$ = 13300 ÷ 217
= 61.29A angle -40.2°
= (46.8 - j 39.56)A

$I_{FUNDAMENTAL}$ (Drive 1 + Drive 2) = (98.1 - j 79.48) - (46.8 - j 39.56)
= 65A angle -38°

It was decided to use 60A as was done with CASE B SUPERHARM simulation. .

2.6.1 SIMULATION RESULTS CASE B

The following harmonic spectral and THD % results were obtained:

<table>
<tr><th colspan="11">HARMONIC SPECTRAL SIMULATION
RESULTS FOR 11kV MANUFACTURING PLANT
HARMONIC SOURCE MODELLED FROM HARMONIC CURRENT
FIELD MEASUREMENTS INJECTION BUS 6
- CASE B -</th></tr>
<tr><td>h</td><td>1st</td><td>5th</td><td>7th</td><td>11th</td><td>13th</td><td>17th</td><td>19th</td><td>23rd</td><td>25th</td><td>THD</td></tr>
<tr><td>HZ</td><td>50</td><td>250</td><td>350</td><td>550</td><td>650</td><td>850</td><td>950</td><td>1150</td><td>1250</td><td>%</td></tr>
<tr><td colspan="11">PCC = BUS1 (LINE VOLTAGE - HV)</td></tr>
<tr><td>V</td><td>10970</td><td>4.0</td><td>1.0</td><td>4.0</td><td>2.0</td><td>6.0</td><td>1.0</td><td>1.0</td><td>0.0</td><td>0.08</td></tr>
<tr><td colspan="11">BRANCH CURRENT LINE 1 - TO - BUS1 NODE (AMPS)</td></tr>
<tr><td>A</td><td>99.0</td><td>0.34</td><td>0.06</td><td>0.14</td><td>0.63</td><td>0.13</td><td>0.03</td><td>0.02</td><td>0.01</td><td>0.40</td></tr>
<tr><td colspan="11">IPC 2 = BUS4 (LINE VOLTAGE - LV)</td></tr>
<tr><td>V</td><td>372.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>1.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.44</td></tr>
<tr><td colspan="11">BRANCH CURRENT BR2 BUS3 - TO - BUS4 NODE</td></tr>
<tr><td>A</td><td>968.0</td><td>11.9</td><td>1.98</td><td>4.84</td><td>2.14</td><td>4.38</td><td>0.82</td><td>0.63</td><td>0.24</td><td>1.44</td></tr>
</table>

TABLE 2.17

NB! The voltages are line voltages.

2.7 CASE C: HARMONIC ANALYSIS - RECTIFIER MODELLED USING HARMONIC SPECTRUM MEASURED IN THE FIELD - INJECTION BUS 5 (MTH - 4.4)

HARMONIC INJECTION DATA BOX HARMONIC INJECTION: RECTIFIER MODELLED ON FIELD MEASUREMENTS INJECTION BUS 5 - CASE C -					
HarmonicNº	Amplitude	Angle	HarmonicNº	Amplitude	Angle
Fundamental	126.3	-39.0	31	0.6	89.0
5	17.7	-17.0			
7	2.6	41.0			
11	3.9	-68.0			
13	1.0	-92.0			
17	2.0	-113.0			
19	0.8	-160.0			
23	1.4	-164.0			
25	0.7	144.0			
29	0.9	145.0			

TABLE 2.17

The harmonic spectrum is the same spectrum as that used for CASE C SUPERHARM package simulation (See paragraph 1.10 Appendix 1).

The injection is at the MCC (bus 5) and the fundamental measured at the input to bus 5 is used.

$I_{\text{FUNDAMENTAL}}$ 126.3 A at 39° lagging

The harmonic spectrum is the same as CASE B above. The shunt load (SHUNT -5) on bus 5 contributing no harmonics. All the harmonics coming from the two combined drives on bus 6.

2.7.1 SIMULATION RESULTS CASE C

The following harmonic spectral and THD % results were obtained:

HARMONIC SPECTRAL SIMULATION RESULTS FOR 11kV MANUFACTURING PLANT HARMONIC SOURCE MODELLED FROM HARMONIC CURRENT FIELD MEASUREMENTS INJECTION BUS 5 - CASE C -										
h	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
HZ	50	250	350	550	650	850	950	1150	1250	%
PCC = BUS1 (LINE VOLTAGE - HV)										
V	10970	4.0	1.0	4.0	4.0	6.0	1.0	1.0	0.0	0.08
BRANCH CURRENT LINE 1 - TO - BUS1 NODE (AMPS)										
A	99.0	0.34	0.06	0.14	0.34	0.13	0.02	0.02	0.01	0.4
IPC 2 = BUS4 (LINE VOLTAGE - LV)										
V	372.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.44
BRANCH CURRENT BR2 BUS3 - TO - BUS4 NODE										
A	968.0	11.9	1.98	4.86	2.14	4.38	0.82	0.63	0.24	1.44

TABLE 2.18

NB! The voltages are line voltages.

2.8 COMPARISON OF SIMULATION RESULTS CASE A, B AND C

The same comparisons as were drawn with SUPERHARM are made for the ERACS package. The same table format is also used.

The results are extracted from Tables 2.15 (Case A), 2.17 (Case B) and 2.18 (Case C).

ERACS PACKAGE
HARMONIC SPECTRAL AND THD% RESULTS - CASES A, B AND C
- PCC LEVEL -

Case	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
PCC = BUS 1 (LINE VOLTAGES)										
A	10970	3.0	3.0	6.0	10.0	10.0	5.0	2.0	2.0	0.15
B	10970	4.0	1.0	4.0	2.0	6.0	1.0	1.0	0.0	0.08
C	10970	4.0	1.0	4.0	4.0	6.0	1.0	1.0	0.0	0.08
BRANCH CURRENT LINE 1 - TO - BUS 1 (AMPS)										
A	99.0	0.23	0.19	0.2	0.3	0.23	0.01	0.04	0.03	0.52
B	99.0	0.34	0.06	0.14	0.63	0.13	0.03	0.02	0.01	0.40
C	99.0	0.34	0.16	0.14	0.34	0.13	0.02	0.02	0.01	0.40

TABLE 2.19

ERACS PACKAGE
HARMONIC SPECTRAL AND THD% RESULTS - CASES A, B AND C
- IPC 2 LEVEL -

Case	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
IPC 2 = BUS 4 (LINE VOLTAGES)										
A	372.0	0.0	0.0	1.0	2.0	2.0	0.0	0.0	0.0	0.83
B	372.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.44
C	372.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.44
BRANCH CURRENT BR 2 - TO - BUS 4 (AMPS)										
A	968.0	8.1	6.51	1.86	9.9	7.72	3.24	1.18	0.82	1.86
B	968.0	11.9	1.98	4.84	2.14	4.38	0.82	0.63	0.24	1.44
C	968.0	11.9	1.98	4.86	2.14	4.38	0.82	0.63	0.24	1.44

TABLE 2.20

Similar results are expected for Cases B and C and are obtained.

The Case A results give results in the similar region to the other cases.

2.9 COMPARISON BETWEEN SIMULATION RESULTS OF CASE A AND B FOR SUPERHARM AND ERACS PACKAGES

COMPARISON BETWEEN CASE A AND B SIMULATION RESULTS
SUPERHARM = "SH" ERACS = "ER"

Case	1st	5th	7th	11th	13th	17th	19th	23rd	25th	THD
PCC = BUS 1 (LINE VOLTAGE)										
A(SH)	10964	3.22	4.09	25.8	8.6	2.1	1.46	0.84	0.68	0.26
B(SH)	10964	4.69	1.23	18.5	1.88	1.2	0.37	0.45	0.19	0.18
A(ER)	10970	3.0	3.0	6.0	10.0	10.0	5.0	2.0	2.0	0.15
B(ER)	10970	4.0	1.0	4.0	2.0	6.0	1.0	1.0	0.0	0.08
BRANCH CURRENT LINE 1 - TO - BUS 1 (AMPS)										
A(SH)	94.0	0.4	0.38	1.51	0.43	0.08	0.05	0.02	0.02	1.77
B(SH)	94.2	0.6	0.11	1.08	0.09	0.05	0.01	0.01	0.0	1.32
A(ER)	99.0	0.23	0.19	0.2	0.3	0.23	0.01	0.04	0.03	0.52
B(ER)	99.0	0.34	0.06	0.14	0.63	0.13	0.03	0.02	0.01	0.4
IPC 2 = BUS 4 (LINE VOLTAGE)										
A(SH)	378	0.72	0.93	5.82	1.95	0.48	0.33	0.19	0.15	1.66
B(SH)	377.6	1.06	0.28	4.17	0.42	0.27	0.08	0.1	0.04	1.15
A(ER)	372.0	0.0	0.0	1.0	2.0	2.0	0.0	0.0	0.0	0.83
B(ER)	372.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.44
BRANCH CURRENT BR 2 - TO - BUS 4 (AMPS)										
A(SH)	849	12.3	11.3	45.5	12.9	2.41	1.48	1.71	0.53	5.92
B(SH)	849.2	18.1	3.44	32.5	2.79	1.37	0.37	0.38	0.15	4.42
A(ER)	968	8.9	6.51	1.86	9.9	7.72	3.24	1.18	0.82	1.86
B(ER)	968	11.9	1.98	4.84	2.14	4.38	0.82	0.63	0.24	1.44

TABLE 2.21

APPENDIX 3

3. COMPARISON OF IEEE, IEC AND ESKOM STANDARDS

3.1 IEEE STANDARD-CURRENT DISTORTION LIMITS

<table>
<tr><td colspan="7">TABLE 10.3 (IEEE TABLE NUMBER)
Current Distortion Limits for General Distortion Systems (120 V through 69 000 V)</td></tr>
<tr><td colspan="7">Maximum Harmonic Current Distortion in percent of IL</td></tr>
<tr><td colspan="7">Individual Harmonic Order (Odd Harmonics)</td></tr>
<tr><td>Isc/IL</td><td><11</td><td>$11 \le h < 17$</td><td>$17 \le h < 23$</td><td>$23 \le h < 35$</td><td>$35 < h$</td><td>THD</td></tr>
<tr><td><20*</td><td>4.0</td><td>2.0</td><td>1.5</td><td>0.6</td><td>0.3</td><td>5.0</td></tr>
<tr><td>20<50</td><td>7.0</td><td>3.5</td><td>2.5</td><td>1.0</td><td>0.5</td><td>8.0</td></tr>
<tr><td>50<100</td><td>10.0</td><td>4.5</td><td>4.0</td><td>1.5</td><td>0.7</td><td>12.0</td></tr>
<tr><td>100<1000</td><td>12.0</td><td>5.5</td><td>5.0</td><td>2.0</td><td>1.0</td><td>15.0</td></tr>
<tr><td>>1000</td><td>15.0</td><td>7.0</td><td>6.0</td><td>2.5</td><td>1.4</td><td>20.0</td></tr>
<tr><td colspan="7">Even harmonics are limited to 25% of the odd harmonic above.</td></tr>
<tr><td colspan="7">Current distortions that result in a d.c. offset, e.g. half-wave converters, are not allowed.</td></tr>
<tr><td colspan="7">* All power generation equipment is limited to these values of current distortion, regardless of actual Isc.IL.</td></tr>
<tr><td colspan="7">where:
Isc = maximum short-circuit current at PCC
IL = maximum demand load current (fundamental frequency component at PCC).</td></tr>
</table>

TABLE 3.1

APPENDIX 3

TABLE 10.4 (IEEE TABLE NUMBER)
Current Distortion Limits for General Sub-transmission Systems
(69 001 through 161 000 V)

Maximum Harmonic Current Distortion in percent of IL

Individual Harmonic Order (Odd Harmonics)

Isc/IL	<11	11≤h<17	17≤h<23	23≤h<35	35<h	THD
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4.0
50<100	5.0	2.25	2.0	0.75	0.35	6.0
100<1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a d.c. offset, e.g. half-wave converters, are not allowed.

* All power generation equipment is limited to these values of current distortion, regardless of actual Isc.IL.

where:
Isc = maximum short-circuit current at PCC
IL = maximum demand load current (fundamental frequency component at PCC).

TABLE 3.2

TABLE 10.5 (IEEE TABLE NUMBER)
Current Distortion Limits for General Transmission Systems
(> 161 kV), Dispersed General and Co-generation

Individual Harmonic Order (Odd Harmonics)

Isc/IL	<11	11≤h<17	17≤h<23	23≤h<35	35<h	THD
<50	2.0	1.0	0.75	0.3	0.15	2.5
>50	3.0	1.5	1.15	0.45	0.22	3.75

Even harmonics are limited to 25% of the odd harmonic limits above.

where:
Isc = maximum short-circuit current at PCC
IL = maximum demand load current (fundamental frequency component at PCC).

TABLE 3.3

3.2 VOLTAGE DISTORTION LIMITS

TABLE 11.1 (IEEE TABLE NUMBER)
Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD(%)
69 kV and below	3.0	5.0
69.001kV through 161kV	1.5	2.5
161.001 kV and above	1.0	1.5

TABLE 3.4

3.3 IEC STANDARD

3.3.1 COMPATIBILITY LEVELS FOR HARMONICS

Compatibility levels for individual harmonics in "public low voltage power supply systems " are provided in the standard as follows:

TABLE 1 (IEC TABLE NUMBER)
Compatibility levels for individual harmonic voltages in low voltage networks

Odd harmonics non-multiple of 3		Odd harmonics multiple of 3		Even harmonics	
Harmonic order n	Harmonic voltage %	Harmonic order n	Harmonic voltage %	Harmonic order n	Harmonic voltage %
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,3	6	0,5
13	3	21	0,2	8	0,5
17	2	>21	0,2	10	0,5
19	1,5			12	0,2
23	1,5			>12	0,2
25	1,5				
>25	0,2+(0,5x25/n) (See Note)				

TABLE 3.5

NOTE: 0.2 + (0.5 x 25/n) = 0.2 + 12.5/n . See Table 3.7 below.

3.3.2 TABLES OF COMPATIBILITY LEVELS - CLASSES 1,2 AND 3

TABLE 2 (IEC TABLE NUMBER)
THD - Compatibility levels for harmonics

	Class 1	Class 2	Class 3
Total harmonic distortion (THD)	5%	8%	10%

TABLE 3.6

TABLE 3 (IEC TABLE NUMBER) - Compatibility levels for harmonics-harmonic voltage components (**excluding multiple of 3, odd order**)

Order h	Class 1 Un (%)	Class 2 Un (%)	Class 3 Un (%)
5	3	6	8
7	3	5	7
11	3	3,5	5
13	3	3	4,5
17	2	2	4
19	1,5	1,5	4
23	1,5	1,5	3,5
25	1,5	1,5	3,5
>25	0,2+12,5/h	0,2+12,5/h	5x√11/h

TABLE 3.7

TABLE 4. (IEC TABLE NUMBER)
Compatibility levels for harmonics-harmonic voltage components
(multiple of 3, odd order)

Order h	Class 1 Un (%)	Class 2 Un (%)	Class 3 Un (%)
3	3	5	6
9	1,5	1,5	2,5
15	0,3	0,3	2
21	0,2	0,2	1,75
>21	0,2	0,2	1

TABLE 3.8

APPENDIX 3

TABLE 5 (IEC TABLE NUMBER) Compatibility levels for harmonics-harmonic voltage components **(even order)**			
Order h	Class 1 Un (%)	Class 2 Un (%)	Class 3 Un (%)
2	2	2	3
4	1	1	1,5
6	0,5	0,5	1
8	0,5	0,5	1
10	0,5	0,2	1
>10	0,5	0,2	1

TABLE 3.9

TABLE 6 (IEC NUMBER) Compatibility levels for **inter - Harmonics** - inter -harmonic voltage components			
Order h	Class 1 Un (%)	Class 2 Un (%)	Class 3 Un (%)
<11	0,2	0,2	2,5
11 to 13 included	0,2	0,2	2,25
13 to 17 included	0,2	0,2	2
17 to 19 included	0,2	0,2	2
19 to 23 included	0,2	0,2	1,75
23 to 25 included	0,2	0,2	1,5
>25	0,2	0,2	1

TABLE 3.10

3.4 ESKOM STANDARD

3.4.1 TABLE OF LIMITS

The recommended limits (based on a 5 minute average value) provided by this standard are given in the following table:

APPENDIX 3

TABLE 1 (ESKOM TABLE NUMBER)
Limits for steady state voltage harmonics

Nominal voltage at PCC			Recommended limits (% of nominal supply frequency component)	
Up to and including 1 100V	THD		8.0	
	odd		5.0	Limits on
	even	<14th	3.0	
	inter		1.5	individual
	14th ------------ 25th		0.5 x <14th	
	>25th		0.25 x <14th	harmonics
Above 1 100V, up to and including 44 kV	THD		5.0	
	odd		4.0	Limits on
	even	<14th	2.0	
	inter		1.0	individual
	14th ------------ 25th		0.5 x <14th	
	>25th		0.25 x <14th	harmonics
Above 44 kV, up to and including 132 kV	THD		3.0	
	odd		2.1	Limits on
	even	<14th	1.2	
	inter		0.6	individual
	14th ------------- 25th		0.5 x <14th	
	>25th		0.25 x <14th	harmonics
Above 132kV, up to and including 275 kV	THD		2.5	
	odd		1.8	Limits on
	even	<14th	1.0	
	inter		0.5	individual
	14th ------------- 25th		0.5 x <14th	
	>25th		0.25 x <14th	harmonics
Above 275kV	THD		2.0	
	odd		1.4	Limits on
	even	<14th	0.8	
	inter		0.4	individual
	14th ------------ 25th		0.5 x <14th	
	>25th		0.25 x <14th	harmonics

TABLE 3.11

3.5 COMPARISON OF STANDARDS

3.5.1 VOLTAGE THD% STANDARDS

COMPARISON OF VOLTAGE THD% STANDARDS							
IEEE		ESKOM		IEC			
PCC	THD%	PCC	THD%	PCC & IPC	THD%		
					CLASSES		
		<1.1kV	8.0%	L&MV	1	2	3
<69kV	5%	1.1 to 44kV	5.0%	<35kV	5%	8%	10%
69 to 161kV	2.5%	44 to 132kV	3.0%	HV	NO STANDARD		
>161kV	1.0%	132 to 275kV	2.5%				
		>275kV	2.0%				

TABLE 3.12

3.5.5 ODD HARMONIC TABLES

3.5.5.1 ODD HARMONICS <14TH HARMONIC TABLE

ODD HARMONIC % COMPONENT LIMITS <14TH HARMONIC IN THE IEC (LV/MV) AND ESKOM (<44kV) VOLTAGE RANGES COMPARED TO IEEE <69kV LIMIT USED AS REFERENCE										
IEEE	ESKOM		IEC (LV/MV)							
<69 kV	<1.1 kV	1.1 to 44kV	Non - multiple of 3				Multiple of 3			
			CLASSES							
			h	1	2	3	h	1	2	3
3.0	5.0	4.0	5	3	6	8	3	3	5	6
			7	3	5	7	9	1.5	1.5	2.5
			11	3	3.5	5				
			13	3	3	4.5				

TABLE 3.13

3.5.5.2 ODD HARMONICS 14TH TO 25TH HARMONICS TABLE

ODD HARMONIC % COMPONENT LIMITS FOR THE 14TH TO 25TH HARMONICS IN THE IEC(LV/MV) AND ESKOM (<44kV) VOLTAGE RANGES COMPARED TO IEEE <69kV LIMIT USED AS REFERENCE										
IEEE	ESKOM		IEC							
<69 kV	<1.1 kV	1.1 to 44kV	Non - multiple of 3				Multiple of 3			
			CLASSES							
3.0	2.5	2.0	h	1	2	3	h	1	2	3
			17	2	2	4	15	0.3	0.3	2
			19	1.5	1.5	4	21	0.2	0.2	1.75
			23	1.5	1.5	3.5	>21	0.2	0.2	1.0
			25	1.5	1.5	3.5				

TABLE 3.14

3.5.5.3 ODD HARMONICS >25TH HARMONICS TABLE

ODD HARMONIC % COMPONENT LIMITS FOR >25TH HARMONICS IN THE IEC (LV/MV) AND ESKOM (<44kV) VOLTAGE RANGES COMPARED TO IEEE < 69kV LIMIT USED AS REFERENCE						
IEEE	ESKOM		IEC			
<69kV	<1.1 kV	1.1 TO 44kV	NON - MULTIPLE OF 3 (MULTIPLE OF 3 LIMITS COVERED IN TABLE 3.14)			
			CLASSES			
			h	1	2	3
3.0	1.25	1.0	>25	$0.2 + 12.5/h$	$0.2 + 12.5/h$	$5\ X\ \sqrt{11/h}$
			FOR EXAMPLE			
			29	0.63	0.63	3.1
			31	0.6	0.6	2.98
			35	0.56	0.56	2.8

TABLE 3.15

APPENDIX 3

QUICK REFERENCE COMPARISON OF INDIVIDUAL HARMONIC VOLTAGE LIMITS USING IEEE STANDARD AS REFERENCE (REF)			
HARMONIC ORDER	IEEE	ESKOM	IEC
ODD HARMONICS <14TH	Ref (3%)	>Ref	≥ Ref (except 9th<Ref)
ODD HARMONICS, EVEN HARMONICS AND INTER-HARMONICS >14TH		<Ref	≤ Ref

TABLE 3.23

COMPARISON OF INDIVIDUAL VOLTAGE COMPONENT LIMITS OF THE IEC CLASS 2 AND ESKOM (1.1 TO 44kV) STANDARDS				
HARMONIC ORDER	IEC CLASS 2 COMPONENTS		ESKOM (1.1 to 44kV) %	COMMENT ON LIMITS
	LOWEST %	HIGHEST %		
Odd harmonics <14th	1.5	6.0	4.0	YES within range
Odd harmonics 14th to 25th	0.2	2.0	2.0	YES within range
Odd harmonics >25th	0.56	0.63	1.0	NO not in range
Even harmonics <14th	0.2	2.0	2.0	YES within range
Even harmonics 14th to 25th	0.2	2.0	1.0	YES within range
Even harmonics >25th	0.2	2.0	0.5	YES within range
Inter-harmonics <14th	0.2	0.2	1.0	NO not in range
Inter-harmonics 14th to 25th	0.2	0.2	0.5	NO not in range
Inter-harmonics >25th	0.2	0.2	0.25	NO not in range

TABLE 3.24

APPENDIX 3

3.7 CURRENT DISTORTION LIMITS - IEC 1000 - 3 - 2

TABLE 1 (IEC TABLE NUMBER)
LIMITS FOR CLASS A EQUIPMENT

HARMONIC ORDER n	MAXIMUM PERMISSIBLE HARMONIC CURRENT A
ODD HARMONICS	
3	2.30
5	1.14
7	0.77
9	0.40
11	0.33
13	0.21
15≤ n≤ 39	0.15(15/n)
EVEN HARMONICS	
2	1.08
4	0.43
6	0.30
8≤ n ≤ 40	0.23 (8/n)

TABLE 3.25

TABLE 2 (IEC TABLE NUMBER)
LIMITS FOR CLASS C EQUIPMENT

HARMONIC ORDER n	MAXIMUM PERMISSIBLE HARMONIC CURRENT EXPRESSED AS A PERCENTAGE OF THE INPUT CURRENT AT THE FUNDAMENTAL FREQUENCY %
2	2
3	30(λ)
5	10
7	7
9	5
11≤ n ≤ 39 (odd harmonics only)	3
Where: λ = circuit power factor	

TABLE 3.26

APPENDIX 3

TABLE 3 (IEC TABLE NUMBER) LIMITS FOR CLASS D EQUIPMENT		
HARMONIC ORDER n	MAXIMUM PERMISSIBLE HARMONIC CURRENT PER WATT mA/W	MAXIMUM PERMISSIBLE HARMONIC CURRENT A
3	3.4	2.3
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
$13 \leq n \leq 39$ (odd harmonics only)	$\frac{3.85}{n}$	see table 1

TABLE 3.27

APPENDIX 4

4.APPLICATION OF FIELD MEASUREMENTS TO STANDARDS

Before drawing up a detail summary of the numeric values of field measurements required for the application of standards the "**locations**" at which the standards are to be applied and what "**numeric values**" need to be extracted must be identified.

IDENTIFICATION OF RESULTS REQUIRED FOR THE APPLICATION OF STANDARDS								
11 kV MANUFACTURING PLANT								
Standard	PCC/ IPC	Location	Measurement Point	Numeric Values				APPENDIX TABLES
				UNIT		THD		
				V	I	V	I	
IEEE	PCC	BUS1	6	✓	✓	✓	✓	Appendix 6 Table 6.10
IEC	PCC	BUS1	6	✓		✓		As above
	IPC 1	BUS2	5	✓		✓		Appendix 6 Table 6.9
	IPC2	BUS4	4	✓		✓		Appendix 6 Table 6.6
ESKOM	PCC	BUS1	6	✓		✓		Appendix 6 Table 6.10
33kV TRACTION SUBSTATION								
IEEE	PCC	33kV Bus	1	✓	✓	✓	✓	Appendix 7 Table 7.3
IEC	PCC	33kV BUS	1	✓		✓		As above
	IPC1	33kV Bus	2	✓		✓		Appendix 7 Table 7.5
	IPC2	3kV AC Bus	3	✓		✓		Appendix 7 Table 7.6
ESKOM	PCC	33kV Bus	1	✓		✓		Appendix 7 Table 7.3

TABLE 4.1

4.1 NUMERIC VALUES OF FIELD MEASUREMENTS FOR THE APPLICATION OF STANDARDS

4.1.1 11kV MANUFACTURING PLANT

NUMERIC VALUES OF FIELD MEASUREMENTS <14th HARMONIC FOR APPLICATION OF STANDARDS - 11kV MANUFACTURING PLANT				
Harmonic Information	BUS NUMBER AND MEASURING POINTS			
	BUS 1 (6)		BUS 2 (5)	BUS 4 (4)
	Appendix 6 Table 6.10		Appendix 6 Table 6.9	Appendix 6 Table 6.6
	% V RMS	% I RMS	% V RMS	% V RMS
DC	0.0	1.5	0.0	0.0
1	100.0	99.9	100.0	100.0
2	0.1	0.1	0.0	0.0
3	0.4	0.6	0.2	0.4
4	0.1	0.0	0.1	0.1
5	0.5	0.5	0.5	1.3
6	0.1	0.0	0.0	0.0
7	0.0	0.5	0.1	0.2
8	0.0	0.1	0.0	0.0
9	0.0	0.1	0.0	0.1
10	0.0	0.0	0.0	0.0
11	0.1	0.5	0.1	0.2
12	0.0	0.1	0.0	0.0
13	0.0	0.2	0.1	0.0

TABLE 4.2

APPENDIX 4

NUMERIC VALUES OF FIELD MEASUREMENTS 14th TO 25TH HARMONIC FOR APPLICATION OF STANDARDS - 11kV MANUFACTURING PLANT				
Harmonic Information	BUS NUMBER AND MEASURING POINTS			
	BUS 1 (6)		BUS 2 (5)	BUS 4 (4)
	Appendix 6 Table 6.10		Appendix 6 Table 6.9	Appendix 6 Table 6.6
	% V RMS	% I RMS	% V RMS	% V RMS
14	0.0	0.0	0.0	0.0
15	0.0	0.1	0.0	0.0
16	0.0	0.1	0.0	0.0
17	0.0	0.1	0.0	0.0
18	0.0	0.1	0.0	0.0
19	0.0	0.1	0.0	0.0
20	0.0	0.1	0.0	0.0
21	0.0	0.1	0.0	0.0
22	0.0	0.0	0.0	0.0
23	0.0	0.1	0.0	0.0
24	0.0	0.0	0.0	0.0
25	0.0	0.1	0.0	0.0

TABLE 4.3

APPENDIX 4

NUMERIC VALUES OF FIELD MEASUREMENTS >25th HARMONIC FOR APPLICATION OF STANDARDS - 11kV MANUFACTURING PLANT				
Harmonic Information	BUS NUMBER AND MEASURING POINTS			
	BUS 1 (6)		BUS 2 (5)	BUS 4 (4)
	Appendix 6 Table 6.10		Appendix 6 Table 6.9	Appendix 6 Table 6.6
	% V RMS	% I RMS	% V RMS	% V RMS
26	0.0	0.1	0.0	0.0
27	0.0	0.1	0.0	0.0
28	0.0	0.1	0.0	0.0
29	0.0	0.1	0.0	0.0
30	0.0	0.1	0.0	0.0
31	0.0	0.1	0.0	0.0
V THD %	0.7		0.6	1.4
I THD %	-	1.1		-

TABLE 4.4

4.1.2 33kV TRACTION SUBSTATION

NUMERIC VALUES OF FIELD MEASUREMENTS <14th HARMONIC FOR APPLICATION OF STANDARDS - 33kV TRACTION SUBSTATION				
Harmonic Information	BUS NUMBER AND MEASURING POINTS			
	33kV Bus 1 (1)		33kV Bus 2 (2)	3kV Bus 3 (3)
	Appendix 7 Table 7.3		Appendix 7 Table 7.5	Appendix 7 Table 7.6
	% V RMS	% I RMS	% V RMS	% V RMS
DC	0.0	21.2	0.1	0.1
1	100.0	98.8	100.0	99.9
2	0.1	3.3	0.1	0.1
3	0.2	3.3	0.1	0.3
4	0.1	1.1	0.0	0.0
5	0.3	4.0	0.7	2.3
6	0.0	2.6	0.0	0.1
7	0.5	0.7	0.5	1.4
8	0.0	1.8	0.0	0.1
9	0.0	0.7	0.0	0.1
10	0.0	0.4	0.0	0.0
11	1.0	3.3	0.4	2.2
12	0.0	0.7	0.0	0.0
13	0.9	3.3	0.3	1.5

TABLE 4.5

NUMERIC VALUES OF FIELD MEASUREMENTS 14th TO 25TH HARMONIC FOR APPLICATION OF STANDARDS - 33kV TRACTION SUBSTATION				
Harmonic Information	BUS NUMBER AND MEASURING POINTS			
	33kV Bus 1 (1)		33kV Bus 2 (2)	3kV Bus 3 (3)
	Appendix 7 Table 7.3		Appendix 7 Table 7.5	Appendix 7 Table 7.6
	% V RMS	% I RMS	% V RMS	% V RMS
14	0.0	1.5	0.0	0.0
15	0.0	2.2	0.0	0.1
16	0.0	1.8	0.0	0.1
17	0.2	0.0	0.2	1.2
18	0.0	1.1	0.0	0.0
19	0.1	1.5	0.1	1.1
20	0.1	0.7	0.0	0.0
21	0.1	1.1	0.1	0.1
22	0.0	1.5	0.0	0.0
23	1.2	0.7	0.5	0.7
24	0.0	0.7	0.0	0.1
25	1.0	0.4	0.5	1.1

TABLE 4.6

APPENDIX 4

NUMERIC VALUES OF FIELD MEASUREMENTS >25th HARMONIC FOR APPLICATION OF STANDARDS - 33kV TRACTION SUBSTATION				
Harmonic Information	BUS NUMBER AND MEASURING POINTS			
	33kV Bus 1 (1)		33kV Bus 2 (2)	3kV Bus 3 (3)
	Appendix 7 Table 7.3		Appendix 7 Table 7.5	Appendix 7 Table 7.6
	% V RMS	% I RMS	% V RMS	% V RMS
26	0.0	0.4	0.1	0.0
27	0.0	2.2	0.0	0.1
28	0.0	0.4	0.1	0.0
29	0.3	0.7	0.7	1.1
30	0.0	0.4	0.0	0.1
31	0.1	0.4	0.5	0.8
V THD %	2.2	-	1.6	4.5
I THD %	-	10.0	-	-

TABLE 4.7

APPENDIX 4

THD% COMPARISON OF FIELD MEASUREMENTS TO STANDARDS FOR THE 11kV MANUFACTURING PLANT AND THE 33kV TRACTION SUBSTATION						
BUS Number and Location	ESKOM Standard 1.1 to 44kV PCC only	IEEE Standard <69kV PCC only	IEC Standard 1 to 35kV PCC/IPC		FIELD MEASUREMENTS	
			Class 2	Class 3	PLANT	SUB-STATION
VOLTAGE COMPARISONS						
11kV MANUFACTURING PLANT						
BUS1 PCC 11kV	5%	5%	8%	-	0.7%	-
BUS2 IPC1 11kV	-	-	8%	-	0.6%	-
BUS4 IPC2 380V	-	-	-	10%	1.4%	-
33kV TRACTION SUBSTATION						
BUS1 PCC 33kV	5%	5%	8%	-	-	2.2%
BUS2 IPC1 33kV	-	-	-	10%	-	1.6%
BUS3 IPC2 3kV	-	-	-	10%	-	4.5%
CURRENT COMPARISONS						
11 kV MANUFACTURING PLANT						
BUS1 PCC 11kV	-	15% Rsc=125	-	-	1.1%	-
33 kV TRACTION SUBSTATION						
BUS1 PCC 33kV	-	5% Rsc= <20	-	-	-	10%

TABLE 4.8

4.2 VOLTAGE COMPARISON OF INDIVIDUAL HARMONIC COMPONENT LEVELS MEASURED IN THE FIELD TO STANDARDS

4.2.1 11kV MANUFACTURING PLANT

4.2.1.1 ODD AND EVEN COMPONENTS <14TH HARMONIC

COMPARISON OF INDIVIDUAL ODD AND EVEN VOLTAGE COMPONENTS <14TH HARMONIC MEASURED IN THE FIELD TO < 69kV STANDARDS 11kV MANUFACTURING PLANT								
FIELD MEASUREMENTS				IEEE Standard	ESKOM Standard		IEC Standard	
h	BUS1	BUS2	BUS4	<69kV	1.1 to 44kV		1 to 35kV	
	PCC	IPC1	IPC2	PCC only	PCC only		PCC/ IPC1%	IPC2%
no	%	%	%	%	Odd%	Even %	Class 2	Class 3
2	0.1	0.0	0.0	3	-	2	2	3
3	0.4	0.2	0.4	3	4	-	5	6
4	0.1	0.1	0.1	3	-	2	1	1.5
5	0.5	0.5	1.3	3	4	-	6	8
6	0.1	0.0	0.0	3	-	2	0.5	1
7	0.0	0.1	0.3	3	4	-	5	7
8	0.0	0.0	0.0	3	-	2	0.5	1
9	0.0	0.0	0.1	3	4	-	1.5	2.5
10	0.0	0.0	0.0	3	-	2	0.2	1
11	0.1	0.1	0.2	3	4	-	3.5	5
12	0.0	0.0	0.0	3	-	2	0.2	1
13	0.0	0.1	0.0	3	4	-	3	4.5

TABLE 4.9

4.2.1.2 ODD AND EVEN COMPONENTS 14TH TO 25TH HARMONIC

COMPARISON OF INDIVIDUAL ODD AND EVEN VOLTAGE COMPONENTS 14TH TO 25TH HARMONICS MEASURED IN THE FIELD TO <69kV STANDARDS 11kV MANUFACTURING PLANT								
FIELD MEASUREMENTS				IEEE Standard	ESKOM Standard		IEC Standard	
h	BUS1	BUS2	BUS4	<69kV	1.1 to 44kV		1 to 35kV	
	PCC	IPC1	IPC2	PCC only	PCC only		PCC/ IPC1%	IPC2%
no	%	%	%	%	Odd%	Even %	Class 2	Class 3
14	0.0	0.0	0.0	3	-	1	0.2	1
15	0.0	0.0	0.0	3	2	-	0.3	2
16	0.0	0.0	0.0	3	-	1	0.2	1
17	0.0	0.0	0.0	3	2	-	2	4
18	0.0	0.0	0.0	3	-	1	0.2	1
19	0.0	0.0	0.0	3	2	-	1.5	4
20	0.0	0.0	0.0	3	-	1	0.2	1
21	0.0	0.0	0.0	3	2	-	0.2	1.75
22	0.0	0.0	0.0	3	-	1	0.2	1
23	0.0	0.0	0.0	3	2	-	1.5	3.5
24	0.0	0.0	0.0	3	-	1	0.2	1
25	0.0	0.0	0.0	3	2	-	1.5	3.5

TABLE 4.10

4.2.1.3 ODD AND EVEN COMPONENTS >25TH HARMONIC

COMPARISON OF INDIVIDUAL ODD AND EVEN VOLTAGE COMPONENTS >25TH HARMONIC MEASURED IN THE FIELD TO <69kV STANDARDS 11kV MANUFACTURING PLANT								
FIELD MEASUREMENTS				IEEE Standard	ESKOM Standard		IEC Standard	
h	BUS1	BUS2	BUS4	<69kV	1.1 to 44kV		1 to 35kV	
	PCC	IPC1	IPC2	PCC only	PCC only		PCC/ IPC1%	IPC2%
no	%	%	%	%	Odd%	Even %	Class 2	Class 3
26	0.0	0.0	0.0	3	-	0.5	0.2	1
27	0.0	0.0	0.0	3	1	-	0.2	1
28	0.0	0.0	0.0	3	-	0.5	0.2	1
29	0.0	0.0	0.0	3	1	-	0.63	3.1
30	0.0	0.0	0.0	3	-	0.5	0.2	1
31	0.0	0.0	0.0	3	1	-	0.6	2.98

TABLE 4.11

APPENDIX 4

4.2.2 33kV TRACTION SUBSTATION

4.2.2.1 ODD AND EVEN COMPONENTS <14TH HARMONIC

COMPARISON OF INDIVIDUAL ODD AND EVEN VOLTAGE COMPONENTS <14TH HARMONIC MEASURED IN THE FIELD TO <69kV STANDARDS
33kV TRACTION SUBSTATION

	FIELD MEASUREMENTS			IEEE Standard	ESKOM Standard		IEC Standard	
h	BUS1	BUS2	BUS3	<69kV	1.1 to 44kV		1 to 35kV	
	PCC	IPC1	IPC2	PCC only	PCC only		PCC%	IPC1/ IPC2%
no	%	%	%	%	Odd%	Even %	Class 2	Class 3
2	0.1	0.1	0.1	3	-	2	2	3
3	0.2	0.1	0.3	3	4	-	5	6
4	0.1	1.1	0.0	3	-	2	1	1.5
5	0.3	0.7	2.3	3	4	-	6	8
6	0.0	0.0	0.1	3	-	2	0.5	1
7	0.5	0.5	1.4	3	4	-	5	7
8	0.0	0.0	0.1	3	-	2	0.5	1
9	0.0	0.0	0.1	3	4	-	1.5	2.5
10	0.0	0.0	0.0	3	-	2	0.2	1
11	1.0	0.4	2.2	3	4	-	3.5	5
12	0.0	0.0	0.0	3	-	2	0.2	1
13	0.9	0.3	1.5	3	4	-	3	4.5

TABLE 4.12

4.2.2.2 ODD AND EVEN COMPONENTS 14TH TO 25TH HARMONIC

COMPARISON OF INDIVIDUAL ODD AND EVEN VOLTAGE COMPONENTS 14TH TO 25TH HARMONICS MEASURED IN THE FIELD TO <69kV STANDARDS 33kV TRACTION SUBSTATION								
FIELD MEASUREMENTS				IEEE Standard	ESKOM Standard		IEC Standard	
h	BUS1	BUS2	BUS3	<69kV	1.1 to 44kV		1 to 35kV	
	PCC	IPC1	IPC2	PCC only	PCC only		PCC%	IPC1/ IPC2%
no	%	%	%	%	Odd%	Even %	Class 2	Class 3
14	0.0	0.0	0.0	3	-	1	0.2	1
15	0.0	0.0	0.1	3	2	-	0.3	2
16	0.0	0.0	0.1	3	-	1	0.2	1
17	0.2	0.2	1.2	3	2	-	2	4
18	0.0	0.0	0.0	3	-	1	0.2	1
19	0.1	0.1	1.1	3	2	-	1.5	4
20	0.1	0.0	0.0	3	-	1	0.2	1
21	0.1	0.1	0.1	3	2	-	0.2	1.75
22	0.0	0.0	0.0	3	-	1	0.2	1
23	1.2	0.5	0.7	3	2	-	1.5	3.5
24	0.0	0.0	0.1	3	-	1	0.2	1
25	1.0	0.5	1.1	3	2	-	1.5	3.5

TABLE 4.13

APPENDIX 4

4.2.2.3 ODD AND EVEN COMPONENTS >25TH HARMONIC

COMPARISON OF INDIVIDUAL ODD AND EVEN VOLTAGE COMPONENTS >25TH HARMONIC MEASURED IN THE FIELD TO <69kV STANDARDS 33kV TRACTION SUBSTATION								
FIELD MEASUREMENTS				IEEE Standard	ESKOM Standard		IEC Standard	
h	BUS1	BUS2	BUS3	<69kV	1.1 to 44kV		1 to 35kV	
	PCC	IPC1	IPC2	PCC only	PCC only		PCC%	IPC1/ IPC2%
no	%	%	%	%	Odd%	Even %	Class 2	Class 3
26	0.0	0.1	0.0	3	-	0.5	0.2	1
27	0.0	0.0	0.1	3	1	-	0.2	1
28	0.0	0.1	0.0	3	-	0.5	0.2	1
29	0.3	0.7	1.1	3	1	-	0.63	3.1
30	0.0	0.0	0.1	3	-	0.5	0.2	1
31	0.1	0.5	0.8	3	1	-	0.6	2.98

TABLE 4.14

4.3 CURRENT COMPARISON OF INDIVIDUAL HARMONIC COMPONENT LEVELS MEASURED IN THE FIELD TO THE IEEE STANDARD

4.3.1 11kV MANUFACTURING PLANT

4.3.1.1 ODD AND EVEN COMPONENTS <31ST HARMONIC

COMPARISON OF INDIVIDUAL ODD AND EVEN CURRENT COMPONENTS
<31ST HARMONIC MEASURED IN THE FIELD TO <69kV IEEE STANDARD
Rsc = 125 PULSE Nº = 6 FOR BUS 1 (PCC)
11kV MANUFACTURING PLANT

h	<11th		h	11≤h<17		h	17≤ h <23		h	23≤ h<35	
Nº	Field %	Odd Even %	Nº	Field %	Odd Even %	Nº	Field %	Odd Even %	Nº	Field %	Odd Even %
2	0.1	3	11	0.5	5.5	17	0.1	5	23	0.1	2
3	0.6	12	12	0.1	1.375	18	0.1	1.25	24	0.0	0.5
4	0.0	3	13	0.2	5.5	19	0.1	5	25	0.1	2
5	0.5	12	14	0.0	1.375	20	0.1	1.25	26	0.1	0.5
6	0.0	3	15	0.1	5.5	21	0.1	5	27	0.1	2
7	0.5	12	16	0.1	1.375	22	0.0	1.25	28	0.1	0.5
8	0.1	3							29	0.1	2
9	0.1	12							30	0.1	0.5
10	0.0	3							31	0.1	2

TABLE 4.15

4.3.1.2 33 kV TRACTION SUBSTATION

The 33kV Traction Substation includes 12-pulse convertors.

The "**standards**" given in Table 3.1 Appendix 3 applies to 6-pulse convertors only and needs to be adapted for 12-pulse convertors.

PROCEDURE FOR ADAPTING 6-PULSE TO 12-PULSE STANDARDS

(a) 33kV PCC is in <69kV range.

(b) Rsc = <20

(c) Characteristic harmonics for a 12-pulse convertor are 12k± 1, namely 11, 13, 23, 25, 35 etc.

(d) Adapt characteristic harmonic standards by factor

$$\sqrt{\frac{q}{6}} = \sqrt{\frac{12}{6}} = 1.414$$

CHARACTERISTIC HARMONICS				
Characteristic Harmonics 6-Pulse Limit	11th	13th	23rd	25th
	2%	2%	0.6%	0.6%
Multiplication Factor	1.414	1.414	1.414	1.414
New 12-Pulse Limit	2.8%	2.8%	0.85%	0.85%

TABLE 4.16

(e) The non-characteristic harmonics for a 12-pulse convertor are : 5, 7, 17, 19, 29, 31 etc.

(f) Adapt non-characteristic harmonics to 25% of the values.

APPENDIX 4

NON-CHARACTERISTIC HARMONIC STANDARDS				
Harmonic Standards	<11th	11≤h<17	17≤h<23	23≤ h <3 5
6-Pulse Limit	4%	2%	1.5%	0.6%
Multiplication Factor	0.25	0.25	0.25	0.25
New 12-Pulse Limit	1%	0.5%	0.38%	0.15%

TABLE 4.17

The following comparative table for the 33kV 12-pulse Traction Substation has been derived using the above procedure.

COMPARISON OF INDIVIDUAL ODD AND EVEN CURRENT COMPONENTS <31ST HARMONIC MEASURED IN THE FIELD TO <69kV IEEE STANDARD
Rsc = 20 PULSE Nº = 12 FOR BUS 1 (PCC)
33 kV TRACTION SUBSTATION

h	<11th		h	11≤h<17		h	17≤h<23		h	23≤h<35	
Nº	Field %	Odd Even %	Nº	Field %	Odd Even %	Nº	Field %	Odd Even %	Nº	Field %	Odd Even %
2	3.3	0.25	11	3.3	2.8	17	0.0	0.38	23	0.7	0.85
3	3.3	1	12	0.7	0.13	18	1.1	0.1	24	0.7	0.04
4	1.1	0.25	13	3.3	2.8	19	1.5	0.38	25	0.4	0.85
5	4	1	14	1.5	0.13	20	0.7	0.1	26	0.4	0.04
6	2.6	0.25	15	2.2	0.5	21	1.1	0.38	27	2.2	0.15
7	0.7	1	16	1.8	0.13	22	1.5	0.1	28	0.4	0.04
8	1.8	0.25							29	0.7	0.15
9	0.7	1							30	0.4	0.04
10	0.4	0.25							31	0.4	0.15

TABLE 4.18

APPENDIX 5

5. HARMONIC PENETRATION AND MEASURING EQUIPMENT

5.1 HARMONIC PENETRATION

Harmonic propagation or penetration means the flow of harmonic currents and voltages throughout an ac system in the presence of one or more current harmonic sources. [1].

The harmonic voltage distortion diminishes in magnitude because the equivalent impedance decreases the closer one comes to the voltage source. An harmonic source is treated as a constant current device. Therefore as voltage measurements are taken closer to a voltage source (e.g. very high short-circuit level; very low equivalent impedance) the harmonic voltage distortion will approach zero. See equation 5.1 below.

The above assumes that the ac system is "linear" and passive and therefore the principle of superposition may be applied to enable each harmonic to be considered independently. The resultant system harmonic voltages for a balanced harmonic penetration are calculated by direct solution of the linear equation. [2].

$$[Ih] = [Yh]\ [Vh] \text{ -- } (5.1)$$

where: [Yh] is the system admittance matrix.

On the assumption of a balanced ac system, the model will only include the positive sequence component impedances.

The above equation is for steady state behaviour and will only change as loads, generators and line configurations alter.

The above is true only when the system distributed capacitance or other power factor correction capacitor banks are not in a resonant condition at another location in the system. [21].

An electrical network which includes capacitors are prone to parallel and series resonances. Generally this does not present a problem unless the resonance falls near one of the significant harmonics. In this case, harmonic amplification could take place causing dangerously high harmonic levels. Thus a relatively harmless harmonic current caused by a customer may be converted into an excessive harmonic voltage if the supply network resonates at the corresponding frequency. A consumer should thus limit his harmonic current injection. [23].

5.2. MEASURING EQUIPMENT

5.2.1 NEED FOR HARMONIC MEASURING INSTRUMENTS

In order to obtain an efficient and effective electricity supply, standards which control levels of harmonic distortion have been defined. This has resulted in the need to develop harmonic measuring instruments with the following purpose:

(1) To check system harmonic levels against a standard.
(2) To solve a problem of which harmonics are suspected as the cause.
(3) To provide background information on system harmonic levels.

The modern instrument used for harmonic analysis is a digital spectral analyzer.

5.2.2 BASIC OPERATING PRINCIPLES OF HARMONIC ANALYZERS

5.2.2.1 HARMONIC ANALYSIS

Harmonic analysis is the process of calculating the magnitudes and phases of the fundamental and higher order harmonics of a periodic waveform. The resulting series is known as the Fourier series and establishes a relationship between a time domain function and that function in the frequency domain.

5.2.2.2 BANDWIDTH

Spectrum analyzers provide a measurement of signal amplitude at all frequencies within a given range. Harmonic analyzers measure signal amplitudes at harmonic frequencies only and therefore cover only the frequency range containing the harmonics. They therefore have a narrow bandwidth. If the bandwidth is too narrow errors are introduced into the analysis.

ESKOM recommends for harmonic measurement purposes a digital, FFT instrument. The harmonic components must be calculated to at least the 50th harmonic. [4].

5.2.2.3 VOLTAGE AND CURRENT TRANSFORMERS

The first stage in the measuring process consists of measuring the signal to be analysed.

As both voltage and current needs to be analysed simultaneously, modern instrumentation uses a dual channel digital signal analyser with a built in FFT to gather information about harmonic waveforms. [13].

At low voltage levels a direct connection of the instrument may be possible. Current is usually measured using a clamp-on CT.

As the system current and voltage levels increase so the need arises for VT's and CT's.

Commercial instrument VT's and CT's installed in power systems can be adequately used for field measurements. It should be noted that should they be connected to any relays or recorders while harmonic measurements are being recorded, the results will be inaccurate due to additional distortion being introduced by such relays or recorders. If it is not possible to disconnect such apparatus great care should be taken in the interpretation of the measurements especially at lower levels of amplitudes. [25].

Only electromagnetic VT's and CT's may be used.

Under no circumstances should harmonic measurements be conducted utilizing CVT's (capacitive voltage transformers) as their bandwidth are extremely restrictive. The required accuracy can only be obtained from measurement transformers.

5.3 THE FLUKE 41 HARMONIC ANALYSER

5.3.1 ANALYSER USED FOR FIELD MEASUREMENTS

5.3.2 TRADEMARKS

The **"Fluke 41 Harmonic Analyser"** is a modern digital FFT analyser developed by the Fluke Corporation in the USA and communicates with a PC.

The measured data being displayed on a PC using **"FLUKEVIEW"** software. "Fluke 41" and "Flukeview" are both registered trademarks.

Details concerning the Fluke 41 Harmonic Analyser have been included in this thesis as it was the analyser used to carry out the field measurements which forms the experimental part of the research. Its application is demonstrated in the next chapter.

5.3.3. REASONS FOR SELECTING FLUKE41 ANALYSER

This measuring tool combines the ease of use of a digital multimeter with that of the visual feedback of an oscilloscope as well as having the power of an analyser. The tool provides common single phase testing techniques and provides information about a power system which used to only be obtainable in the past with very expensive and hard to use analyzers.[12].

It is a portable tool (234 x 100 x 64) mm in size. It only weighs 1kg and is battery operated with a minimum 24 hour continuous use life. Operating instructions are provided in the user manual.

These analyzers are powerful, versatile and accommodating to the way you work. They show you exactly what is happening in your electrical distribution system with display updates three times per second providing a real time response to changing circuit conditions. They fit in the palm of your hand making for easy trouble shooting. They go anywhere, slipping into tight spots and standing or hanging in any position that suits you.

This display tells you exactly what you need to know. Measurements can be displayed in three ways. If a system has harmonic distortion, you see the distorted waveform on the display. It is a dual channel instrument so that, voltage and current measurements are taken simultaneously enabling, inter alia, power factor and power to be obtained. Press a button and see a bar graph (harmonic spectrum) that displays the harmonics that are present. Another button press reveals the numeric value of the measurement.

The analyser meets international safety standards for measurement, control and laboratory use of electrical equipment.

The tool is very suitable for field measurements as is rugged, resistant to water (drip proof) and dustproof.

A harmonic measuring instrument had to be selected and purchased. The cost of the instrument had to be within the research budget constraint yet meet basic essential specifications.

For these above reasons the FLUKE41 ANALYSER was obtained. Its specifications now follow.

5.4 SPECIFICATIONS OF FLUKE 41 ANALYSER

5.4.1 TABULAR SUMMARY OF SPECIFICATIONS

The following Table 5.1 summarises some of the analyser's most important specifications:

APPENDIX 5

TABLE OF SPECIFICATIONS
FOR THE FLUKE 41 HARMONIC ANALYSER

PARAMETER	SPECIFICATION
VOLTAGE	
INPUT RANGE	5V to 600V(rms), 5V to 933V(peak)
FUNDAMENTAL	5-65Hz (0,3% accurate - rms)
INPUT IMPEDANCE	
IMPEDANCE	1M Ω BALANCED
CURRENT	
INPUT RANGE	1.00 to 1000A (rms), 1 to 2000A(peak)
FUNDAMENTAL	5 - 65 Hz (0.3% accurate)
80i - 5005 Current Probe	1 to 20A ac (±5%)
	20 to 100A ac (±5%)
	100 to 500A ac (±2%)
POWER	
RANGE	0 to 600 kW (average), 0 to 2000kW(peak)
ACTIVE POWER	±1%
HARMONIC ACCURACY	
VOLTS FUNDAMENTAL	±1%
PHASE	±2 degrees
16TH TO 31ST HARMONIC VOLTS	±2%
PHASE	±10 degrees
AMPS AND WATTS FUNDAMENTAL	
TO 15TH HARMONIC	±2%
16TH TO 31ST HARMONIC	±3%
BANDWIDTH	
INPUT RANGE (-0.5db)	DC, 5Hz to 2.1 kHz
POWER FACTOR	
RANGE (PF)	0 to 1.0
(DPF)	0 to 1.0
WAVEFORM MEMORY	
Eight memories each store waveform data for both voltage and current inputs for later recall or sending to a computer.	

TABLE 5.1

5.4.2 REMARKS ON SPECIFICATIONS

It can be seen that the FLUKE 41 can measure voltage and current harmonics up to 31st harmonic only. **No inter-harmonics are measured.**

Its standard current clamp-on accessory 80i - 500s can measure up to 500A (rms). For larger currents an 80i - 1000s Clamp-on is available for measuring current up to 1000A (rms) conditions. The 500A clamp-on has a frequency range of 5Hz to 10kHz while the 1000A has a range of 5Hz to 100Hz. Both are adequate for 600V rms voltages and have built in filters to eliminate high frequency noise and have minimal amplitude and phase angle errors . They therefore add the minimum of distortion to harmonic waveforms being measured.

It is a digital instrument operating on the FFT principle and its specifications compare favourably with the ESKOM requirements.

5.5 SINGLE VERSUS 3-PHASE MEASUREMENT

A single FLUKE 41 provides single phase measurements in 3-phase circuits. Included as an accessory (besides a current clamp-on probe) are test leads (TL 20) and test clips (AC 80) for voltage measurements. These allow for hands free voltage measurements. Line-to-line and line-to neutral voltage measurements are possible, provided they are within the 933Vpeak value. Therefore both delta and star connected systems can be measured.

The **measurement technique** used was to measure harmonic currents throughout the system all on the *"Same phase"* to obtain consistency. Voltage measurements were simultaneously taken using the "same line-to-line" voltages throughout each location.

5.6 COMMUNICATION WITH A PC

Model 41 communicates with a PC or directly to a Printer through a RS232 port. A 9 pin interface cable, 9 pin to 25 pin adaptor, and 25 pin to 25 pin adaptor allow for a variety of connections. Data can be down loaded from the analyser or a command can be sent from the PC.

Flukeview 41 software is provided with the FLUKE 41 analyser.

5.7 FLUKEVIEW SOFTWARE

The software can be used in DOS or Windows.

Flukeview software makes it easy to transfer data (both graphics and text) from the analyser to the PC and then to a word processing package for inclusion in any written document.

Operating instructions on how to use the software are provided in the users software manual. Hardware requirements are also provided therein. Adequate ram is required for pasting graphics.

APPENDIX 6

FIELD MEASUREMENTS

6. 11kV MANUFACTURING PLANT

6.1 SCHEMATIC LAYOUT OF PLANT

Figure 6.1 shows the schematic layout of the 11kV Manufacturing Plant in which harmonic measurements have been taken.

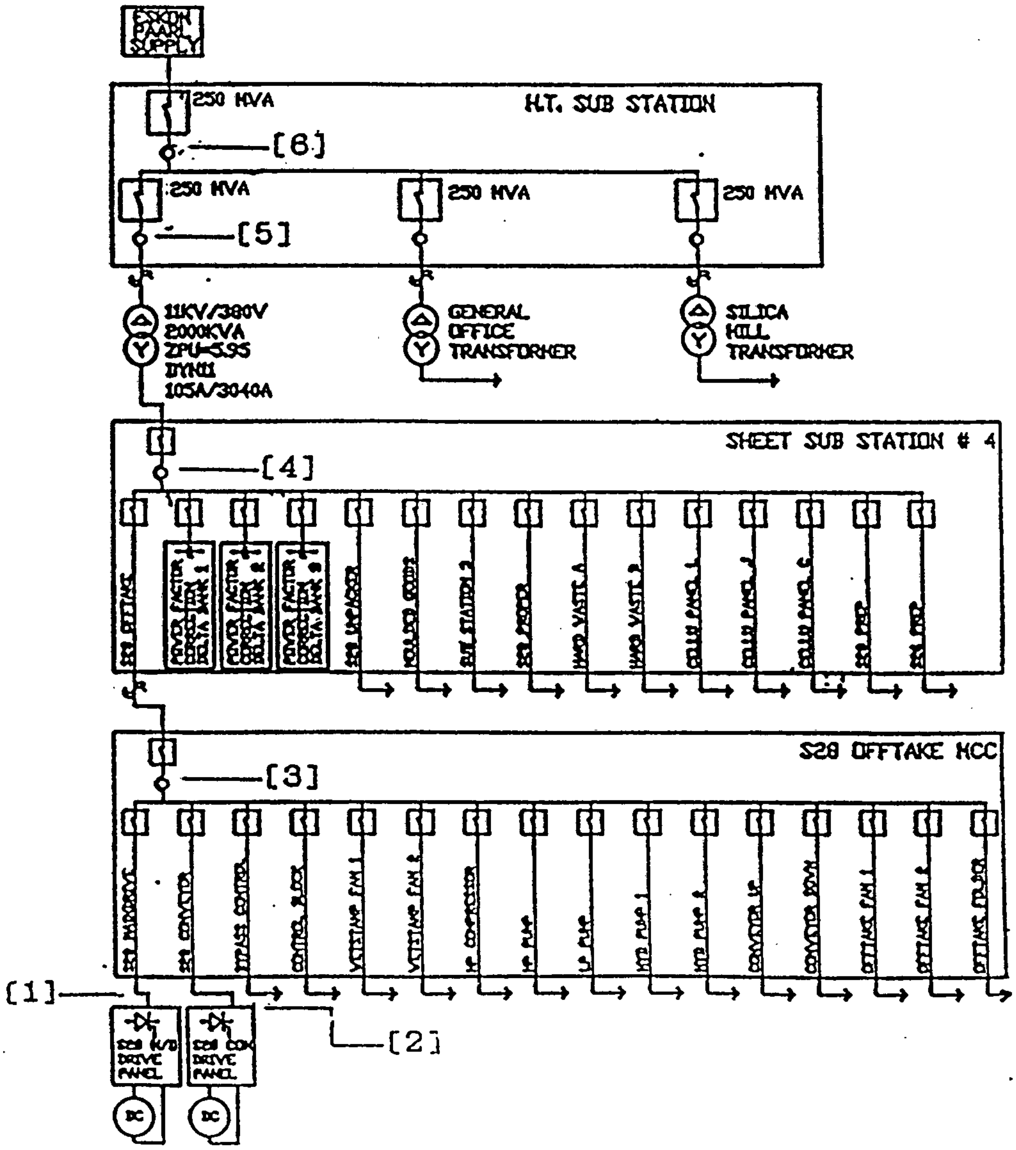


FIGURE 6.1

6.2. REASONS FOR SELECTION OF PLANT FOR MEASUREMENTS

As one of the standards researched is the ESKOM standard, a plant had to be selected which received an ESKOM supply.

Many harmonic problems occur at distribution voltage level, therefore a 11kV ESKOM supplied plant was chosen. Also the highest THD % distortion is expected in this voltage range.

The plant was chosen as it includes two 6-pulse convertors which would give rise to harmonic penetration (See Appendix 5 paragraph 5.1). As the plant also includes banks of power factor correction capacitors it has the potential for a harmonic resonance problem.

6.3 DESCRIPTION OF THE PLANT

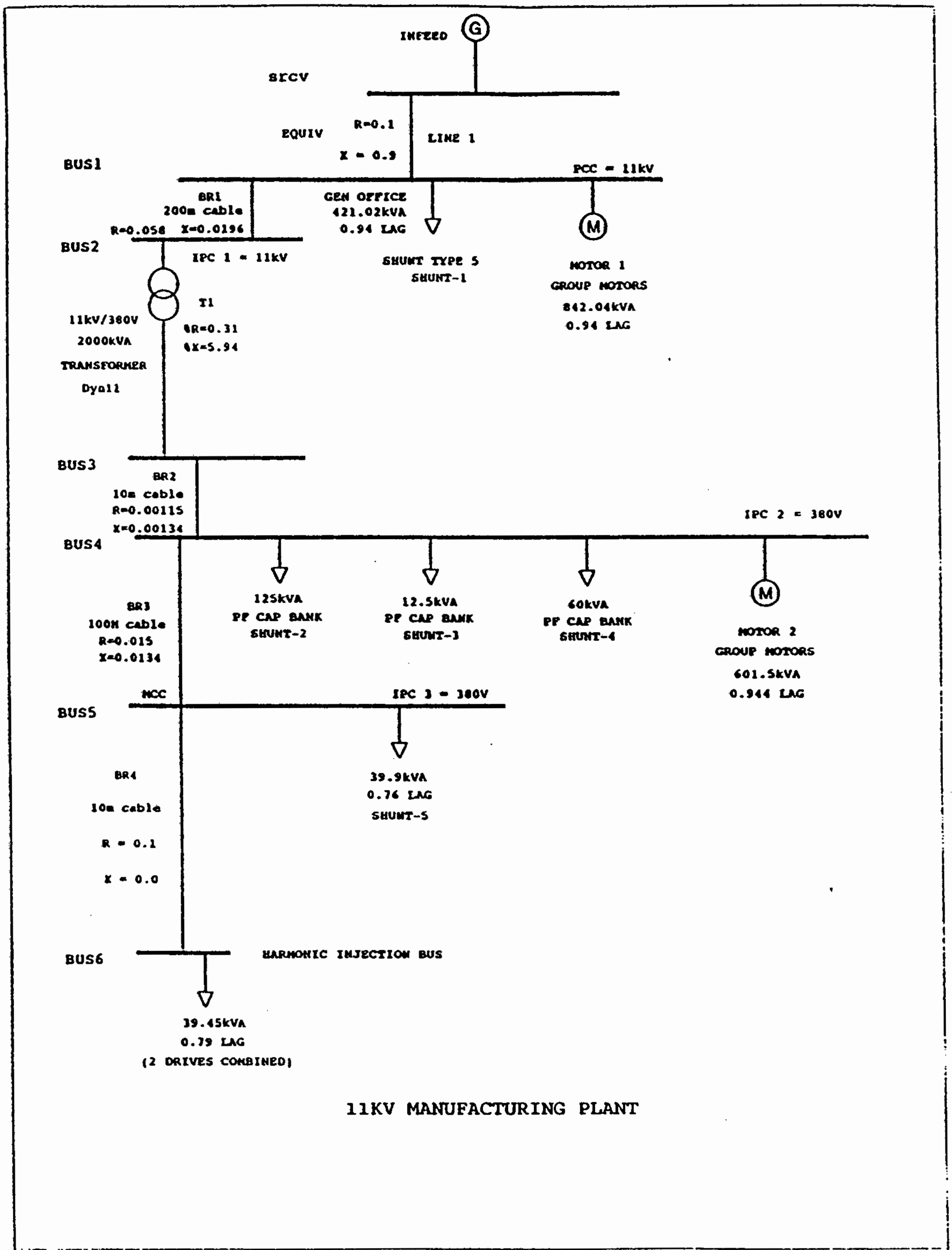
The plant comprises an HT substation having a main 250MVA (rupturing capacity) breaker supplying three other HT breakers, each of which supply their own loads. The general office and Silica Mill transformers supply ordinary loads whereas the 2000kVA transformer supplies the section of the plant which includes the harmonic sources.

The full load current at the PCC is 105A. The short-circuit current is 13kA.

6.4 ONE LINE DIAGRAM AND PLANT PARAMETERS

The **ONE LINE DIAGRAM** for the plant in Figure 6.1 and its **PARAMETERS** as shown in Figure 6.2 were determined:

APPENDIX 6



Produced on ERACS software from ERA TECHNOLOGY LTD., ENGLAND, KT22 7SA.

11kV Manufacturing Plant			MTH 951024-4 · Date: 10-06-96
ERA Technology Ltd., Cleeve Road, Leatherhead, Surrey, KT22 7SA, England	Tel: (44)372 374151 Tlx: Fax: (44)372 374496	Project: 11KV PLANT ONE-LINE-DIAGRAM 2 DRIVES COMBINED	Drn:GAH · Chkd:GAH · IssNo : 1 Drg No.: MT1

FIGURE 6.2

The diagram has 6 buses. Bus 1 is the 11kV PCC bus. Bus 2 and Bus 4 have been identified as IPC 1 (11kV) and IPC 2 (380V) respectively. Bus 6 being the harmonic injection bus.

The kVA and power factor loads are also identified as well as the impedance parameters for the transformer T 1 and the three cables BR1, BR2 and BR3.

The power factor correction capacitor bank ratings are also ascertained and indicated on the diagram.

The ERACS software from ERA Technology Ltd.,was used to generate the one-line diagram.

6.5 MEASUREMENT LOCATIONS IN PLANT

Measurements were taken at the following locations in the plant on the "red phase" for current and " V_{RY}" under steady-state conditions. See Figures 6.1 and 6.2 for location positions:

TABLE OF LOCATIONS OF MEASUREMENTS IN 11kV MANUFACTURING PLANT				
MEASURE-MENT POINT	LOCATION	BUS NUMBER	CT RATIO	VT RATIO
1 (LV)	S 28 Main Drive	Drive Terminals	-	-
2 (LV)	S 28 Conveyor Drive	Drive Terminals	-	-
3 (LV)	S 28 Off take MCC	Bus 5 (IPC 3)	-	-
4 (LV)	Sheet Substation 4	Bus 4 (IPC 2)	3000:5	-
5 (HV)	HT Substation	Bus 2 (IPC1)	125:5	11kV to 110V
6 (HV)	HT Substation	Input to Bus 1 (PCC)	200:5	11 kV to 110V

TABLE 6.1

The above table of measurement locations includes besides the measurement points, bus numbers, CT and VT ratios. Commercial CT's and VT's **do not** introduce appreciable distortions and any effect which they may produce can be ignored.

CT's were used to measure currents at measurement points 4, 5 and 6. VT's were used at hv points 5 and 6 to measure voltages.

The measurements were recorded and stored in the Fluke 41 Harmonic Analysers memory. Measurements can be displayed in three ways on the instrument screen, the distorted waveform, bar graph (harmonic spectrum) and numeric values of results. The three displays form a **"set of measurement results".**

These sets can be recalled and are available for sending to a computer (PC).

6.6. COMMUNICATION WITH PC

The **"sets"** of measured results were down loaded to a PC using the **FLUKEVIEW** software and stored in files. The following table, Table 6.2, displays these file's names and makes reference to **"Figures and Tables"** which accompany this appendix as **"ATTACHMENTS"**. See attachments.

These figures display the **waveforms measured** and their **harmonic spectrums** while the tables display their **numeric values.**

The following is a table of the sets of measurements for measurement locations. The table is subdivided into the following sets of measurements, each set having a figure for voltage and current waveforms on which is also shown bar graphs. Each set also has a table of numeric results:

a. Measurement Point 1.

b. Measurement Point 2.

c. Measurement Point 3.

d. Measurement Point 4:

  Case 1 with pf correction

  Without pf correction.

  Case 2 with pf correction

e. Measurement Point 5.

f. Measurement Point 6.

The table now follows:

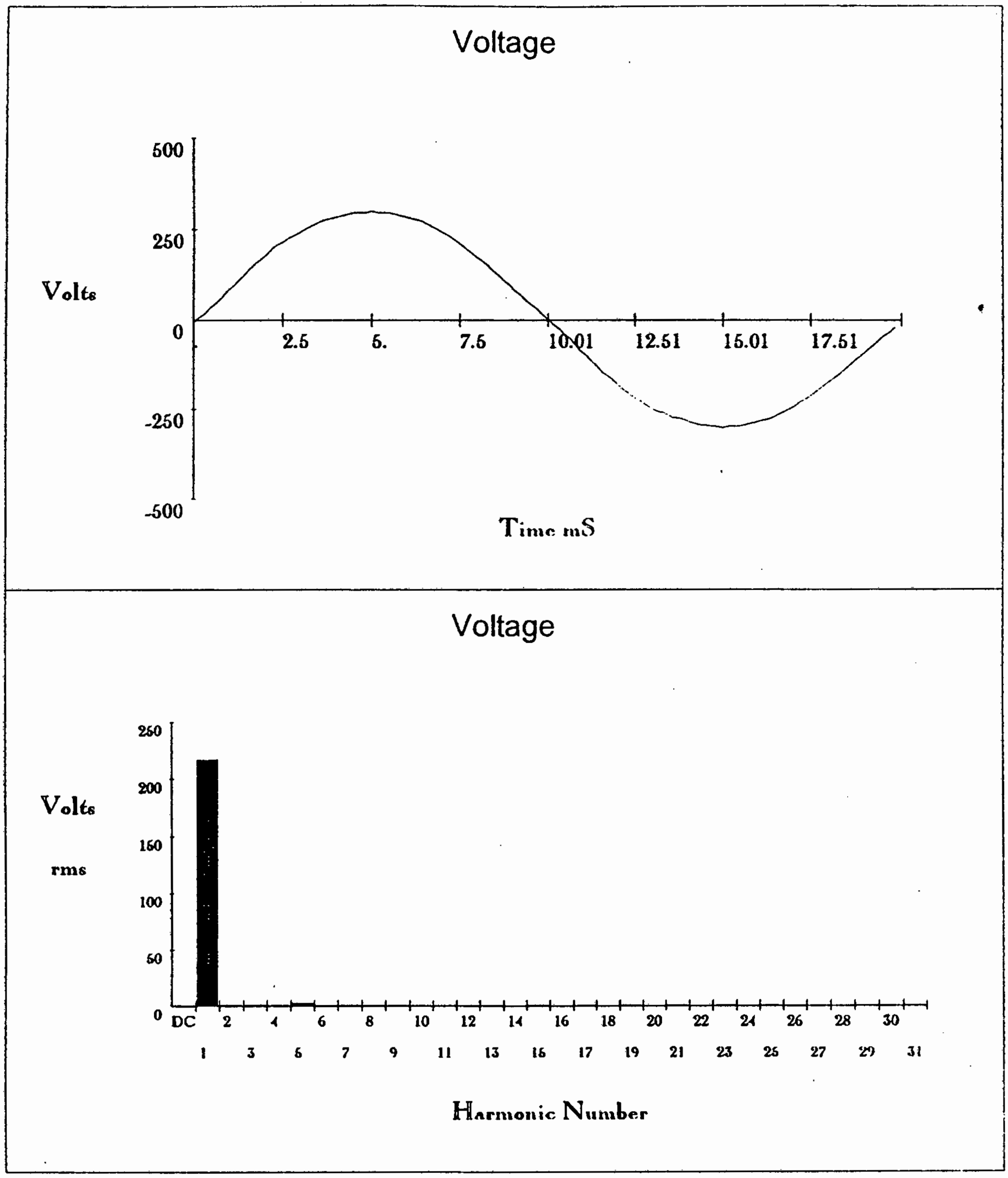
APPENDIX 6

<table>
<tr><th colspan="4">TABLE OF SETS OF MEASUREMENTS
FOR MEASUREMENT LOCATIONS</th></tr>
<tr><th colspan="2">WAVE FORMS AND HARMONIC SPECTRUMS</th><th>NUMERIC VALUES</th><th rowspan="3">FILE NAMES</th></tr>
<tr><th>VOLTS</th><th>AMPS</th><th rowspan="2">ATTACHED TABLES</th></tr>
<tr><th colspan="2">ATTACHED FIGURES</th></tr>
<tr><td colspan="4">SET OF MEASUREMENTS - MEASUREMENT POINT 1</td></tr>
<tr><td>Figure 6.3</td><td>Figure 6.4</td><td>Table 6.3</td><td>S28 MDR</td></tr>
<tr><td colspan="4">SET OF MEASUREMENTS - MEASUREMENT POINT 2</td></tr>
<tr><td>Figure 6.5</td><td>Figure 6.6</td><td>Table 6.4</td><td>S28 CBR</td></tr>
<tr><td colspan="4">SET OF MEASUREMENTS - MEASUREMENT POINT 3</td></tr>
<tr><td>Figure 6.7</td><td>Figure 6.8</td><td>Table 6.5</td><td>S28 MCCR</td></tr>
<tr><td colspan="4">SET OF MEASUREMENTS - MEASUREMENT POINT 4</td></tr>
<tr><td colspan="4">WITH PF CORRECTION - CASE 1</td></tr>
<tr><td>Figure 6.9</td><td>Figure 6.10</td><td>Table 6.6</td><td>SS 401</td></tr>
<tr><td colspan="4">WITHOUT CORRECTION</td></tr>
<tr><td>Figure 6.11</td><td>Figure 6.12</td><td>Table 6.7</td><td>SS 402</td></tr>
<tr><td colspan="4">WITH PF CORRECTION - CASE 2</td></tr>
<tr><td>Figure 6.13</td><td>Figure 6.14</td><td>Table 6.8</td><td>SS 403</td></tr>
<tr><td colspan="4">SET OF MEASUREMENTS - MEASUREMENT POINT 5</td></tr>
<tr><td>Figure 6.15</td><td>Figure 6 16</td><td>Table 6.9</td><td>SS 4HT2</td></tr>
<tr><td colspan="4">SET OF MEASUREMENTS - MEASUREMENT POINT 6</td></tr>
<tr><td>Figure 6.17</td><td>Figure 6.18</td><td>Table 6.10</td><td>HTISB 1</td></tr>
</table>

TABLE 6.2

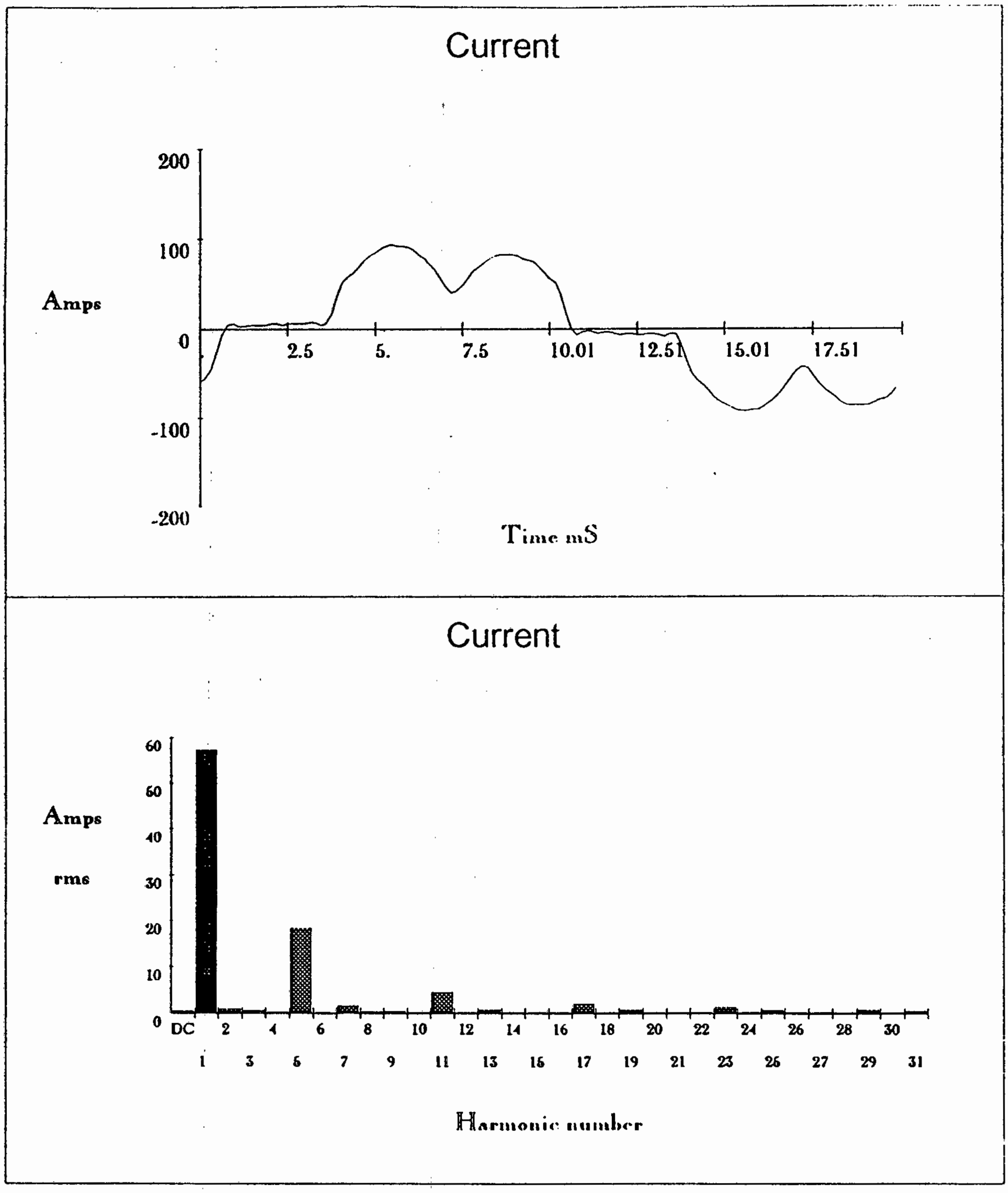
The attachments that follow are the results of field measurements measured. See attached Figures 6.3 to 6.18 and Tables 6.3 to 6.10.

Readings - 07/07/95 09:48:01



MEASUREMENT POINT 1 -- S28MDR
FIGURE 6.3

Readings - 07/07/95 09:48:01



MEASUREMENT POINT 1 -- S28MDR
FIGURE 6.4

Readings - 07/07/95 09:48:01

Summary Information

			Voltage	Current
Frequency	50.0	RMS	217	60.6
Power		Peak	306	94.7
KW	10.1	DC Offset	0	-0.4
KVA	13.1	Crest	1.41	1.56
KVAR	7.3	THD Rms	1.5	32.1
Peak KW	28.8	THD Fund	1.5	33.9
Phase	36° lag	HRMS	3	19.4
Total PF	0.77	KFactor		5.1
DPF	0.81			

Record Information

	Max	Average	Min
V RMS			
A RMS			
V Peak			
A Peak			
V THD-R%			
A THD-R%			
KWatts			
KVA			
TPF			
DPF			
Frequency			

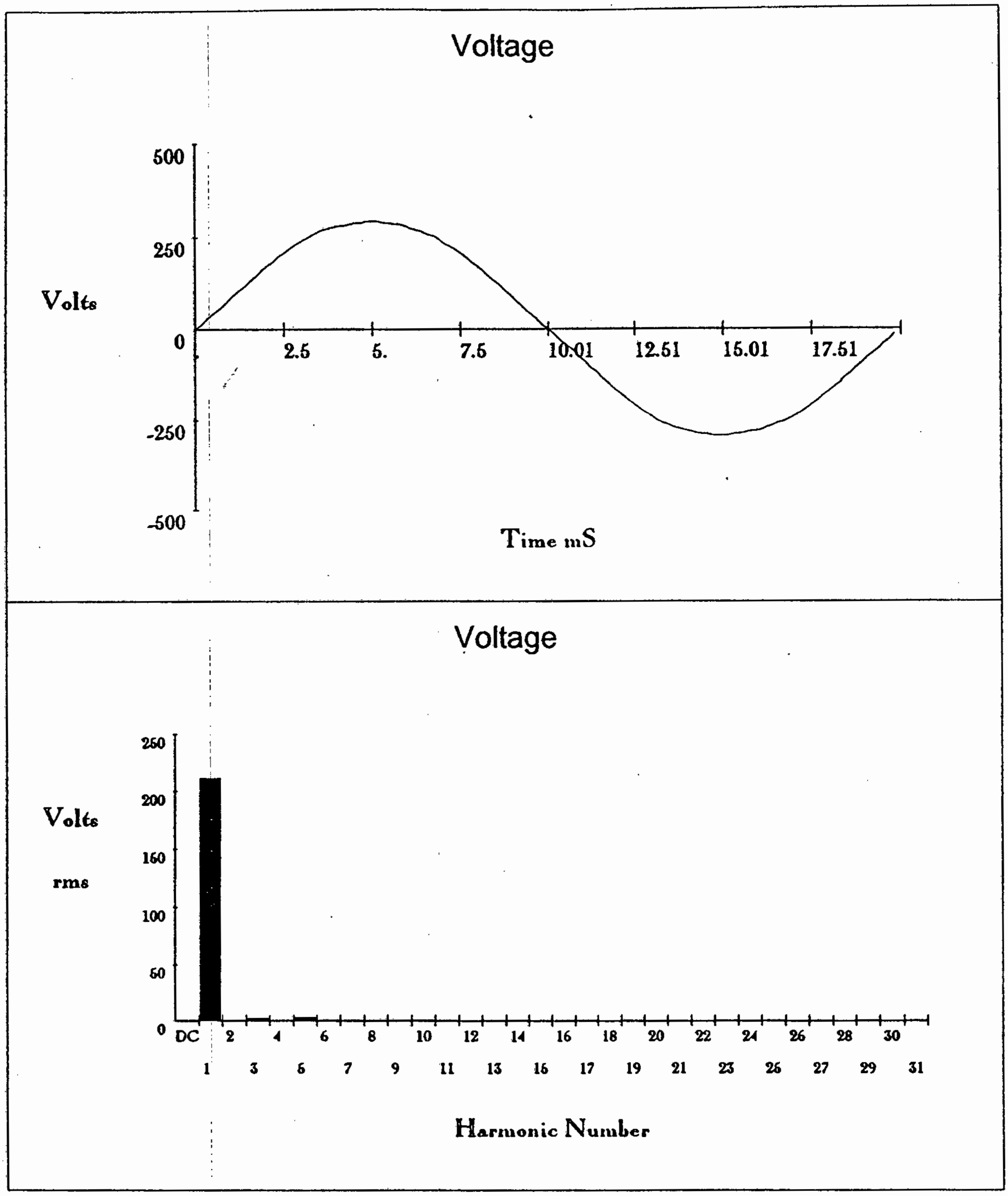
Harmonic Information

	Freq.	V Mag	%V RMS	V Ø°	I Mag	%I RMS	I Ø°	Power (KW)
DC	0.0	0	0.1	0	0.4	0.7	0	0.0
1	50.0	217	99.9	0	57.3	94.6	-36	10.1
2	99.9	1	0.2	-118	1.0	1.7	-54	0.0
3	149.9	1	0.6	-110	0.6	0.9	123	0.0
4	199.9	0	0.2	-165	0.3	0.5	-33	0.0
5	249.8	3	1.3	-143	18.5	30.5	-20	0.0
6	299.8	0	0.1	75	0.1	0.2	-165	0.0
7	349.8	1	0.5	-165	1.7	2.7	60	0.0
8	399.7	0	0.2	-180	0.3	0.6	-133	0.0
9	449.7	0	0.0	-125	0.5	0.8	-167	0.0
10	499.7	0	0.0	110	0.2	0.3	-144	0.0
11	549.6	0	0.2	-169	4.6	7.6	-74	0.0
12	599.6	0	0.0	40	0.1	0.2	143	0.0
13	649.6	0	0.1	46	0.8	1.3	-109	0.0
14	699.6	0	0.0	-176	0.3	0.5	167	0.0
15	749.5	0	0.0	-180	0.1	0.2	105	0.0
16	799.5	0	0.0	32	0.2	0.3	141	0.0
17	849.5	0	0.1	146	2.2	3.6	-126	0.0
18	899.4	0	0.0	40	0.1	0.2	96	0.0
19	949.4	0	0.1	44	0.7	1.2	169	0.0
20	999.4	0	0.0	9	0.2	0.4	109	0.0
21	1049.3	0	0.0	136	0.2	0.3	80	0.0
22	1099.3	0	0.0	-79	0.2	0.3	70	0.0
23	1149.3	0	0.1	85	1.4	2.3	177	0.0
24	1199.2	0	0.0	-34	0.1	0.2	39	0.0
25	1249.2	0	0.1	-8	0.7	1.1	113	0.0
26	1299.2	0	0.0	-72	0.2	0.4	46	0.0
27	1349.1	0	0.0	48	0.1	0.2	8	0.0
28	1399.1	0	0.0	-93	0.2	0.3	9	0.0
29	1449.1	0	0.1	28	0.9	1.4	125	0.0
30	1499.0	0	0.0	-129	0.1	0.2	-22	0.0
31	1549.0	0	0.0	-72	0.6	0.9	56	0.0

MEASUREMENT POINT 1 – S28MDR

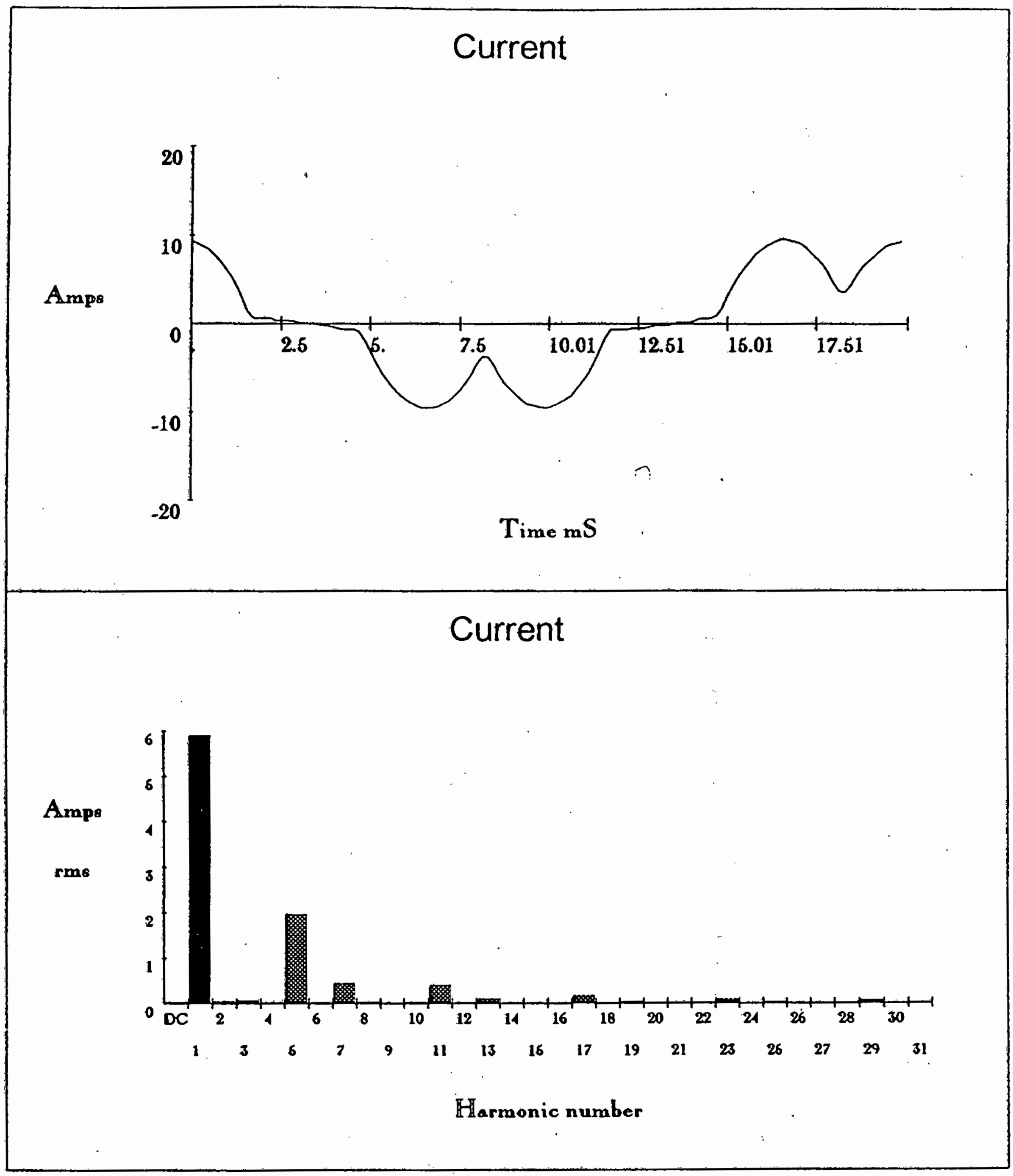
TABLE 6.3

Readings - 07/07/95 09:53:48



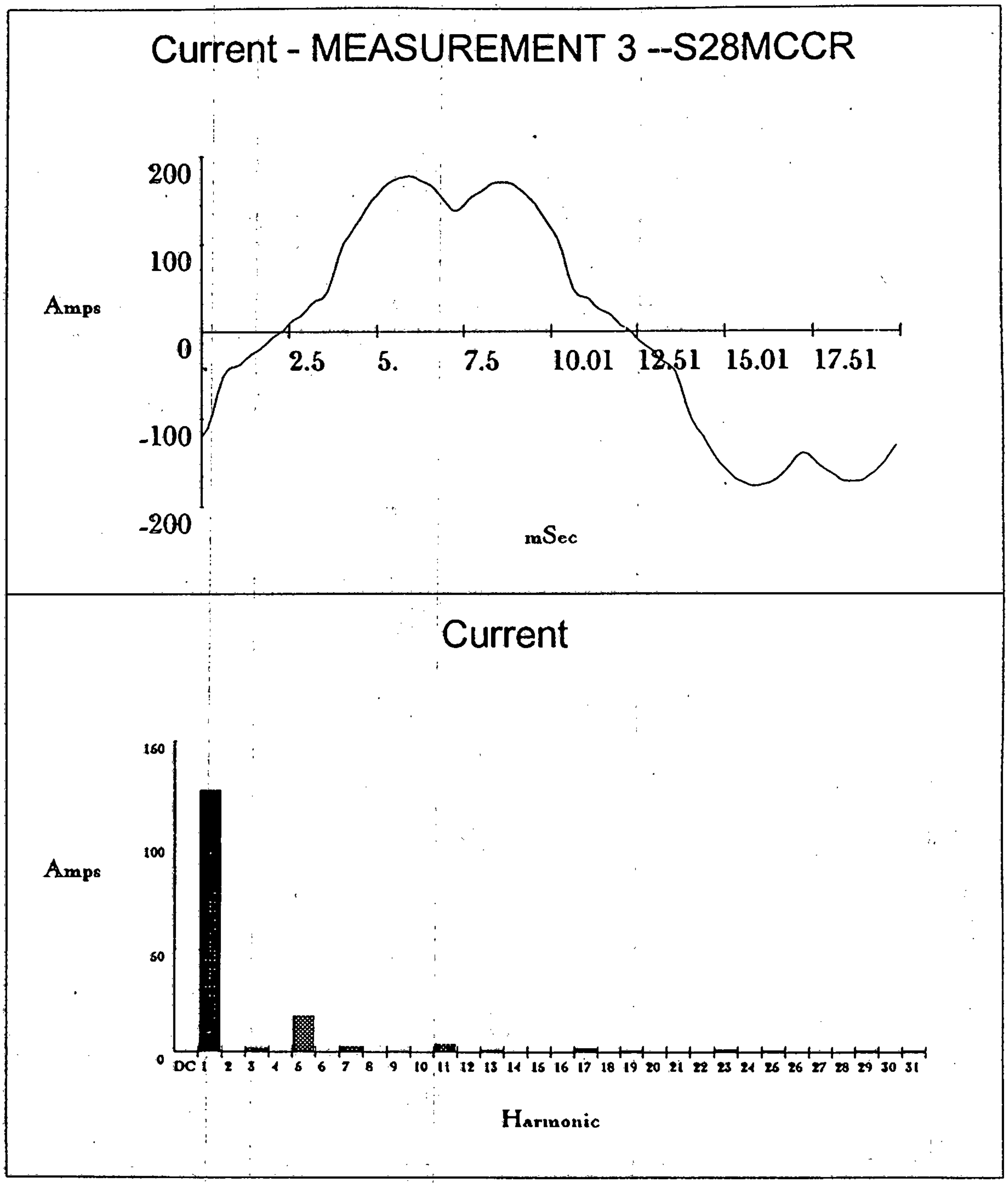
MEASUREMENT POINT 2 -- S28CBR
FIGURE 6.5

Readings - 07/07/95 09:53:48



MEASUREMENT POINT 2 -- S28CBR
FIGURE 6.6

Readings - 07/07/95 09:58:28



MEASUREMENT POINT 3 -- S28MCCR
FIGURE 6.8

Readings - 07/07/95 09:58:28

Summary Information

			Voltage	Current
Frequency	50.0	RMS	217	127.7
Power		Peak	306	181.4
KW	21	DC Offset	0	-0.3
KVA	28	Crest	1.41	1.42
KVAR	17	THD Rms	1.7	14.6
Peak KW	54	THD Fund	1.7	14.8
Phase	39° lag	HRMS	4	18.7
Total PF	0.77	KFactor		1.8
DPF	0.78			

Record Information

	Max	Average	Min
V RMS			
A RMS			
V Peak			
A Peak			
V THD-R%			
A THD-R%			
KWatts			
KVA			
TPF			
DPF			
Frequency			

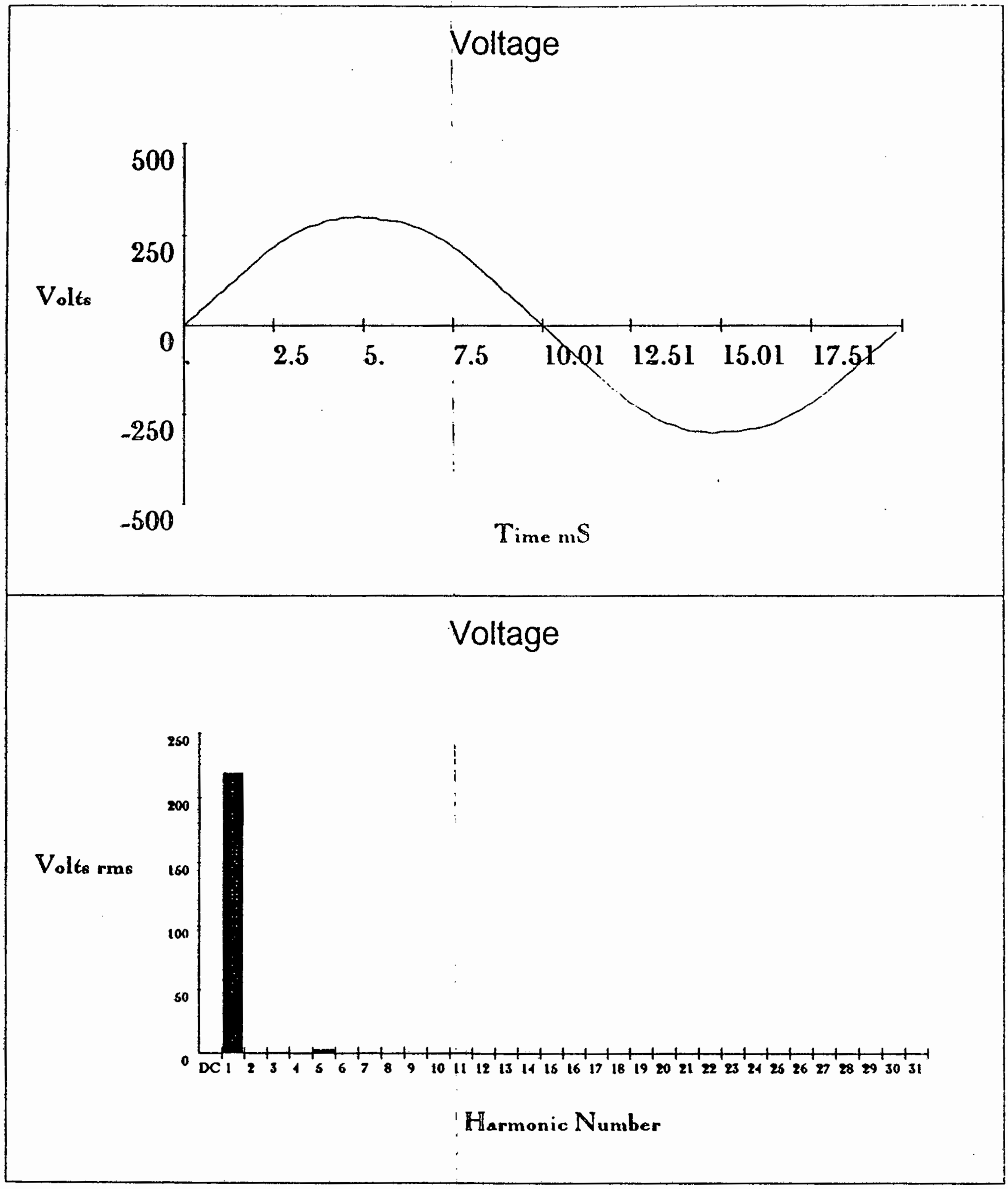
Harmonic Information

	Freq.	V Mag	%V RMS	V Ø°	I Mag	%I RMS	I Ø°	Power (KW)
DC	0.0	0	0.0	0	0.3	0.3	0	0
1	50.0	217	100.0	0	126.3	98.9	-39	21
2	99.9	0	0.0	75	0.4	0.3	-81	0
3	149.9	2	1.0	-162	2.0	1.5	150	0
4	199.9	0	0.1	-29	0.1	0.1	0	0
5	249.8	3	1.4	176	17.7	13.9	-17	0
6	299.8	0	0.1	-108	0.1	0.1	152	0
7	349.8	1	0.3	169	2.6	2.1	41	0
8	399.7	0	0.0	-150	0.1	0.1	-128	0
9	449.7	0	0.1	-111	0.5	0.4	85	0
10	499.7	0	0.0	-7	0.1	0.1	-39	0
11	549.6	0	0.1	-126	3.9	3.0	-68	0
12	599.6	0	0.0	-180	0.0	0.0	22	0
13	649.6	0	0.0	64	1.0	0.8	-92	0
14	699.6	0	0.0	-20	0.1	0.1	-177	0
15	749.5	0	0.0	156	0.1	0.1	76	0
16	799.5	0	0.0	135	0.0	0.0	-148	0
17	849.5	0	0.1	104	2.0	1.6	-113	0
18	899.4	0	0.0	140	0.0	0.0	-46	0
19	949.4	0	0.0	39	0.8	0.6	-166	0
20	999.4	0	0.0	47	0.1	0.0	122	0
21	1049.3	0	0.0	-175	0.1	0.1	13	0
22	1099.3	0	0.0	22	0.0	0.0	3	0
23	1149.3	0	0.1	49	1.4	1.1	-164	0
24	1199.2	0	0.0	110	0.0	0.0	-97	0
25	1249.2	0	0.1	29	0.7	0.5	144	0
26	1299.2	0	0.0	64	0.0	0.0	76	0
27	1349.1	0	0.0	126	0.1	0.1	-76	0
28	1399.1	0	0.0	-126	0.0	0.0	-112	0
29	1449.1	0	0.1	4	0.9	0.7	145	0
30	1499.0	0	0.0	56	0.0	0.0	171	0
31	1549.0	0	0.0	-46	0.6	0.5	89	0

MEASUREMENT POINT 3 – S28MCCR

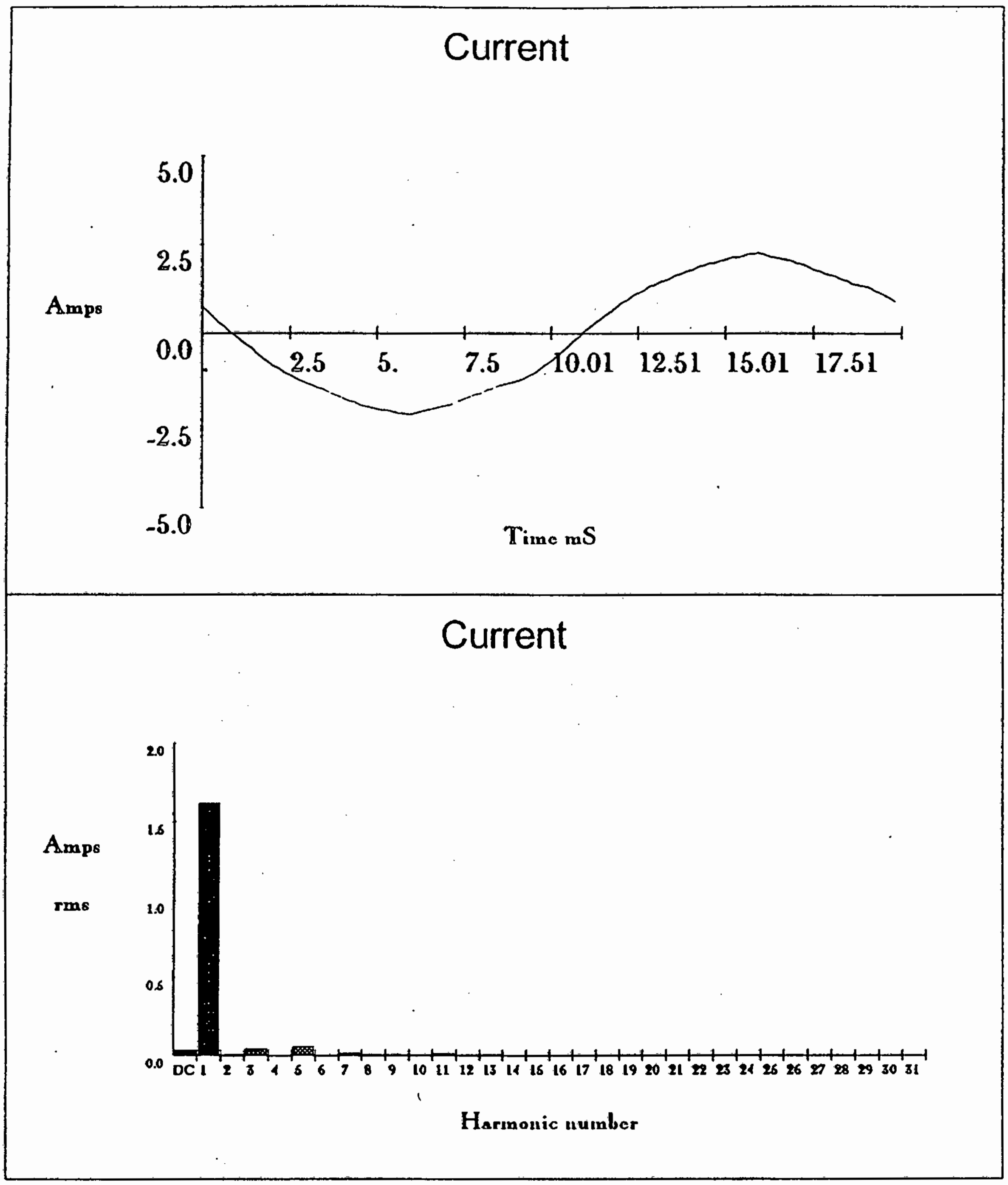
TABLE 6.5

Readings - 10/23/95 02:38:10



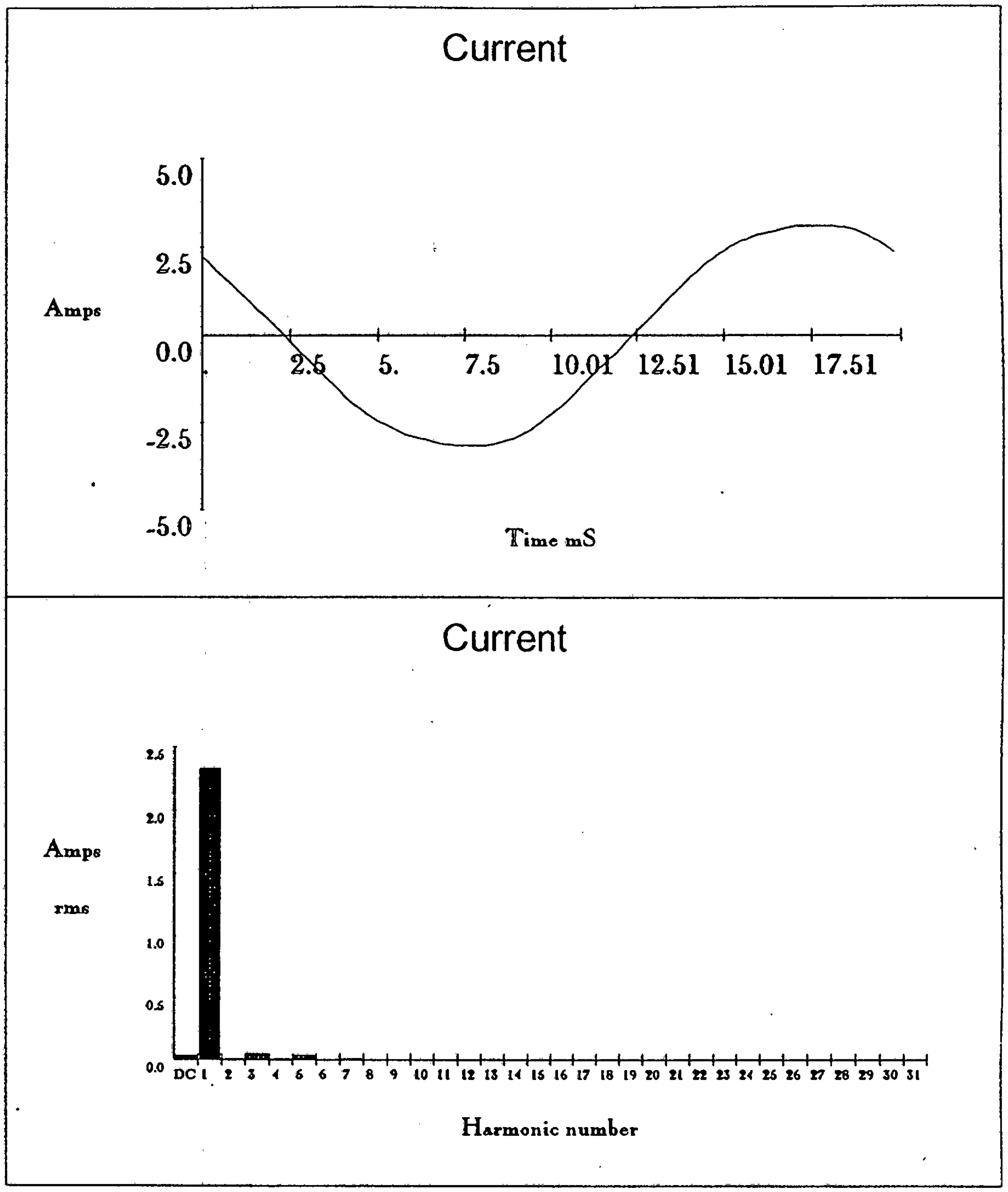
MEASUREMENT POINT 4 -- SS401
WITH PF CORRECTION --- CASE 1
FIGURE 6.9

Readings - 10/23/95 02:38:10



MEASUREMENT POINT 4 -- SS401
WITH PF CORRECTION — CASE 1
FIGURE 6.10

Readings - 10/23/95 02:44:40



MEASUREMENT POINT 4 -- SS402
WITHOUT PF CORRECTION
FIGURE 6.12

Readings - 10/23/95 02:44:40

Summary Information

			Voltage	Current
Frequency	50.0	RMS	215	2.33
Power		Peak	301	3.22
KW	-0.37	DC Offset	0	-0.04
KVA	0.50	Crest	1.4	1.38
KVAR	0.34	THD Rms	1.1	2.6
Peak KW	-0.86	THD Fund	1.1	2.6
Phase	138° lead	HRMS	2	0.06
Total PF	-0.74	KFactor		1.0
DPF	-0.74			

Record Information

	Max	Average	Min
V RMS			
A RMS			
V Peak			
A Peak			
V THD-R%			
A THD-R%			
KWatts			
KVA			
TPF			
DPF			
Frequency			

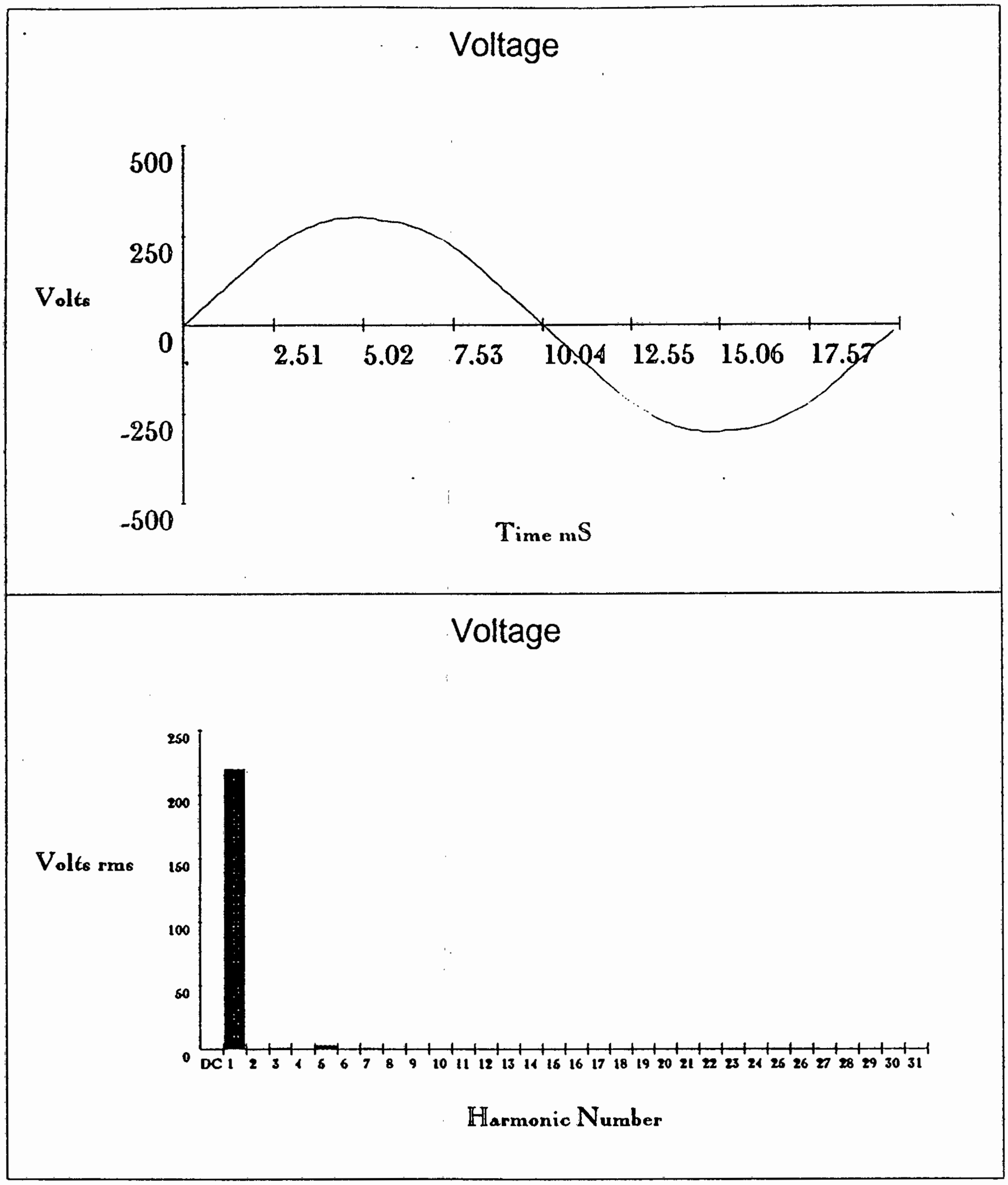
Harmonic Information

	Freq.	V Mag	%V RMS	V Ø°	I Mag	%I RMS	I Ø°	Power (KW)
DC	0.0	0	0.1	0	0.04	1.5	0	0.00
1	50.0	215	99.9	0	2.33	99.9	138	-0.37
2	99.9	0	0.1	-74	0.00	0.2	90	0.00
3	149.9	1	0.3	-58	0.05	2.1	84	0.00
4	199.9	0	0.1	-75	0.00	0.2	27	0.00
5	249.8	2	1.0	174	0.03	1.5	-176	0.00
6	299.8	0	0.0	27	0.00	0.1	-148	0.00
7	349.8	0	0.1	-82	0.00	0.2	101	0.00
8	399.7	0	0.0	163	0.00	0.0	104	0.00
9	449.7	0	0.0	-83	0.00	0.1	-167	0.00
10	499.7	0	0.0	-94	0.00	0.0	-88	0.00
11	549.6	0	0.2	91	0.00	0.1	35	0.00
12	599.6	0	0.0	103	0.00	0.0	68	0.00
13	649.6	0	0.0	-83	0.00	0.2	-7	0.00
14	699.6	0	0.0	0	0.00	0.0	108	0.00
15	749.5	0	0.0	-135	0.00	0.1	-120	0.00
16	799.5	0	0.0	-42	0.00	0.0	11	0.00
17	849.5	0	0.0	-7	0.00	0.1	-51	0.00
18	899.4	0	0.0	68	0.00	0.0	68	0.00
19	949.4	0	0.0	27	0.00	0.1	162	0.00
20	999.4	0	0.0	-51	0.00	0.0	166	0.00
21	1049.3	0	0.0	-96	0.00	0.1	83	0.00
22	1099.3	0	0.0	176	0.00	0.0	-111	0.00
23	1149.3	0	0.0	42	0.00	0.1	11	0.00
24	1199.2	0	0.0	-94	0.00	0.1	-29	0.00
25	1249.2	0	0.0	-43	0.00	0.1	-44	0.00
26	1299.2	0	0.0	-75	0.00	0.1	84	0.00
27	1349.1	0	0.0	4	0.00	0.1	17	0.00
28	1399.1	0	0.0	-100	0.00	0.1	12	0.00
29	1449.1	0	0.1	-48	0.00	0.1	-93	0.00
30	1499.0	0	0.0	167	0.00	0.1	-172	0.00
31	1549.0	0	0.0	-92	0.00	0.1	-56	0.00

MEASUREMENT POINT 4 – SS402
WITHOUT PF CORRECTION

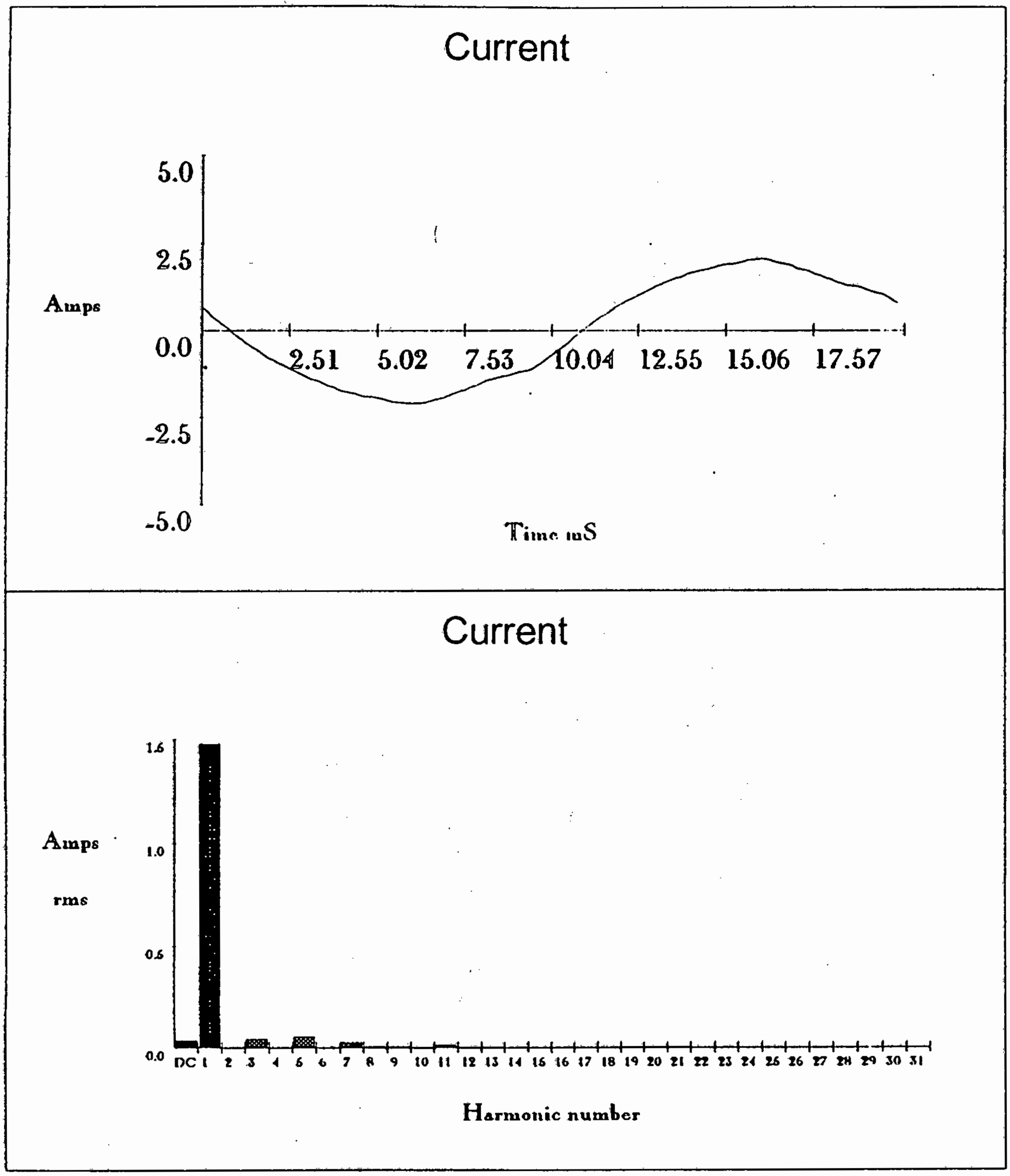
TABLE 6.7

Readings - 10/23/95 02:47:31



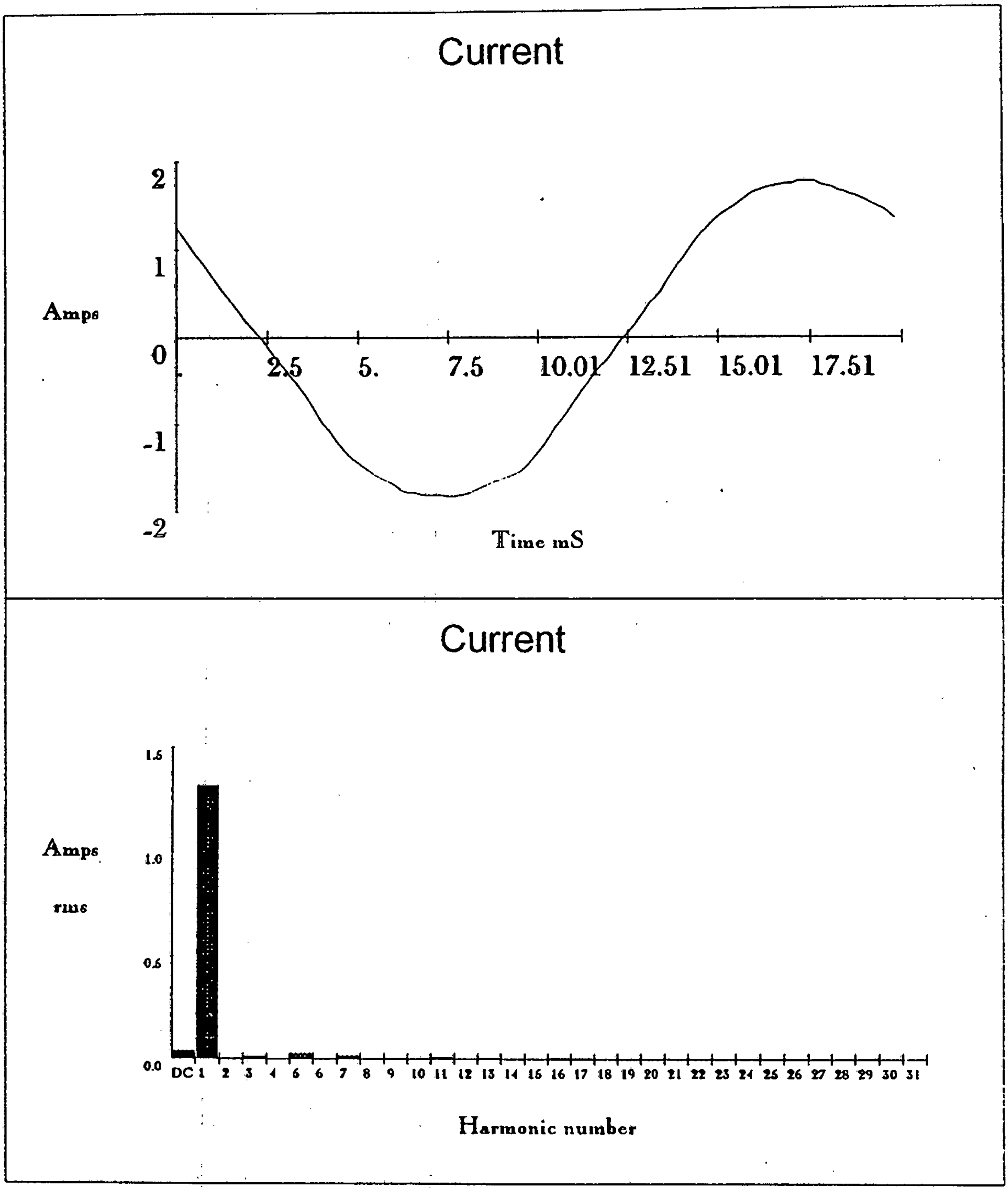
MEASUREMENT POINT 4 -- SS403
WITH PF CORRECTION --- CASE 2
FIGURE 6.13

Readings - 10/23/95 02:47:31



MEASUREMENT POINT 4 -- SS403
WITH PF CORRECTION --- CASE 2
FIGURE 6.14

Readings - 07/13/95 09:33:50



MEASUREMENT POINT 5 -- SS4HT2
FIGURE 6.16

Readings - 07/13/95 09:33:50

Summary Information

			Voltage	Current
Frequency	50.0	RMS	111.2	1.32
Power		Peak	156.7	1.83
Watts	-108	DC Offset	0.0	-0.04
VA	146	Crest	1.41	1.39
Vars	95	THD Rms	0.6	2.8
Peak W	-262	THD Fund	0.6	2.8
Phase	139° lead	HRMS	0.7	0.04
Total PF	-0.74	KFactor		1.0
DPF	-0.76			

Record Information

	Max	Average	Min
V RMS			
A RMS			
V Peak			
A Peak			
V THD-R%			
A THD-R%			
Watts			
Volt * Amps			
TPF			
DPF			
Frequency			

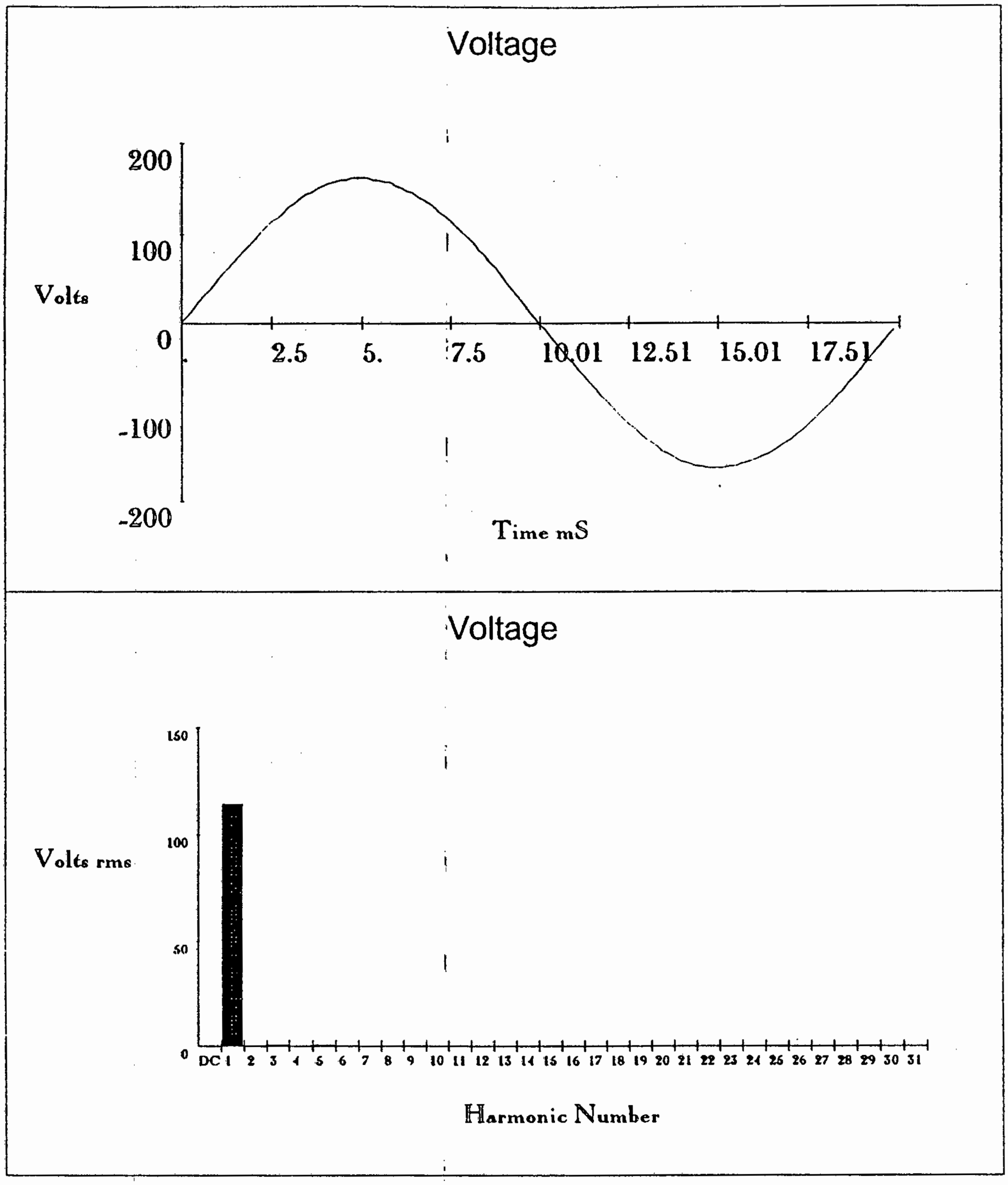
Harmonic Information

	Freq.	V Mag	%V RMS	V Ø°	I Mag	%I RMS	I Ø°	Power (W)
DC	0.0	0.0	0.0	0	0.04	2.9	0	0
1	50.0	111.2	100.0	0	1.32	100.0	139	-111
2	99.9	0.0	0.0	121	0.00	0.2	16	0
3	149.9	0.2	0.2	103	0.01	0.9	56	0
4	199.9	0.1	0.1	172	0.00	0.1	-70	0
5	249.8	0.6	0.5	111	0.03	2.2	146	0
6	299.8	0.0	0.0	-154	0.00	0.1	75	0
7	349.8	0.1	0.1	27	0.02	1.2	88	0
8	399.7	0.0	0.0	99	0.00	0.1	-51	0
9	449.7	0.1	0.0	117	0.00	0.3	167	0
10	499.7	0.0	0.0	-11	0.00	0.0	-180	0
11	549.6	0.1	0.1	37	0.01	0.5	130	0
12	599.6	0.0	0.0	-133	0.00	0.1	-34	0
13	649.6	0.1	0.1	127	0.00	0.3	-123	0
14	699.6	0.0	0.0	155	0.00	0.1	68	0
15	749.5	0.0	0.0	-83	0.00	0.1	-177	0
16	799.5	0.0	0.0	115	0.00	0.2	130	0
17	849.5	0.0	0.0	-180	0.00	0.2	153	0
18	899.4	0.0	0.0	25	0.00	0.1	50	0
19	949.4	0.0	0.0	51	0.00	0.0	27	0
20	999.4	0.0	0.0	0	0.00	0.0	-32	0
21	1049.3	0.0	0.0	-159	0.00	0.1	155	0
22	1099.3	0.0	0.0	-89	0.00	0.1	-110	0
23	1149.3	0.0	0.0	-145	0.00	0.1	180	0
24	1199.2	0.0	0.0	156	0.00	0.1	124	0
25	1249.2	0.0	0.0	-34	0.00	0.1	13	0
26	1299.2	0.0	0.0	-27	0.00	0.1	124	0
27	1349.1	0.0	0.0	180	0.00	0.1	140	0
28	1399.1	0.0	0.0	68	0.00	0.1	9	0
29	1449.1	0.0	0.0	-76	0.00	0.1	21	0
30	1499.0	0.0	0.0	-70	0.00	0.1	-154	0
31	1549.0	0.0	0.0	-32	0.00	0.1	-13	0

MEASUREMENT POINT 5 – SS4HT2

TABLE 6.9

Readings - 07/13/95 09:40:03

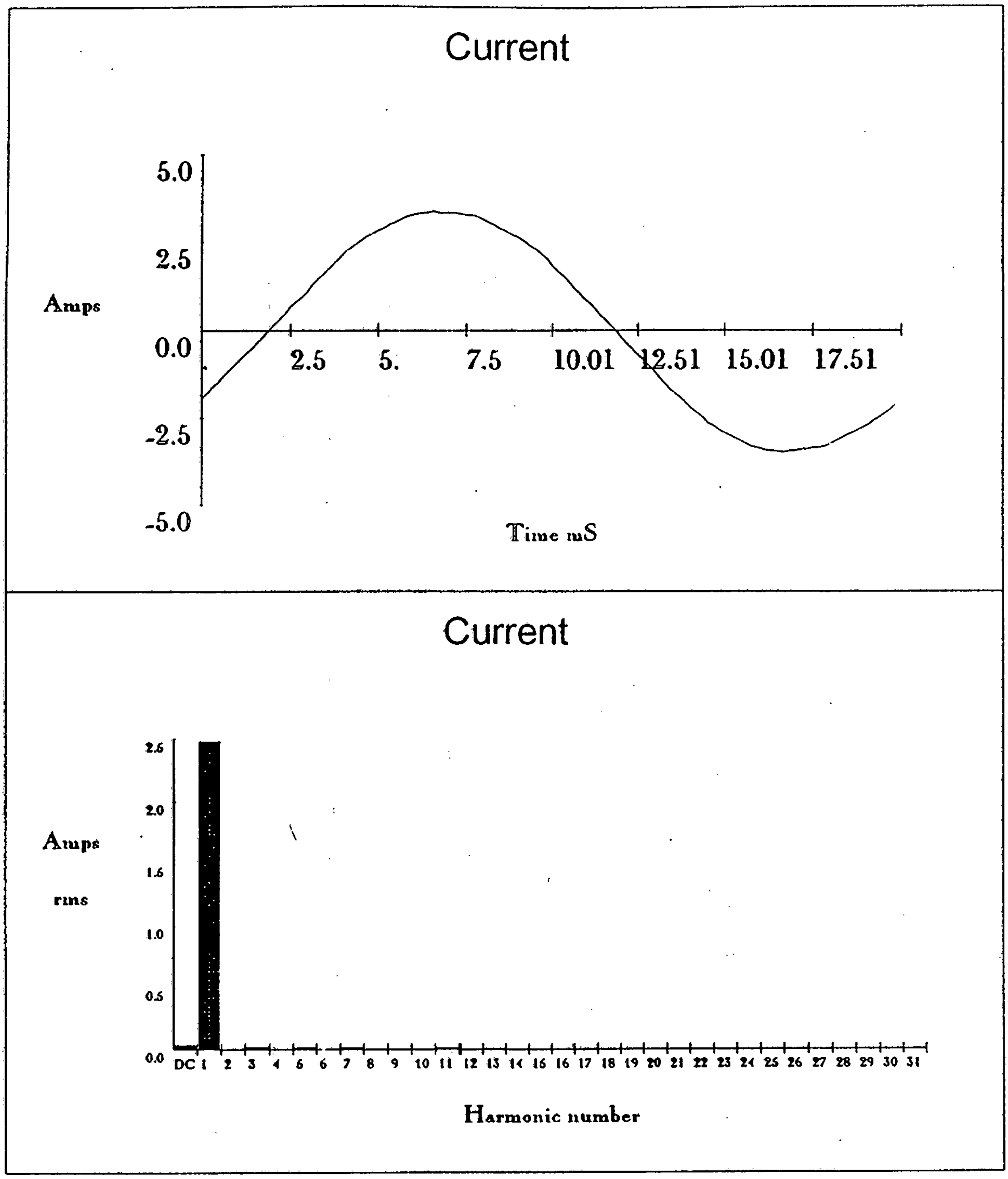


Voltage

Voltage

MEASUREMENT POINT 6 -- HTISB1
FIGURE 6.17

Readings - 07/13/95 09:40:03



MEASUREMENT POINT 6 -- HTISB1
FIGURE 6.18

7.2. ONE-LINE-DIAGRAM OF TRACTION SUBSTATION

The traction substation in which field measurements were conducted comprised of two 12-pulse rectifiers each being supplied by its own convertor transformer instead of a 3 winding transformer as shown in Figure 7.1 above.

The two separate 12-pulse rectifiers are labelled "RECTIFIER A" and "RECTIFIER B" in the substation studied and are identical.

These rectifiers are supplied from a 33 kV Switchroom that receives two separate incoming supplies from ESKOM. (ESKOM 1 and ESKOM 2). The Switchroom is a separate building from the building which houses the rectifiers.

The one-line-diagram of the substation in which measurements were carried out is given in Figure 7.2:

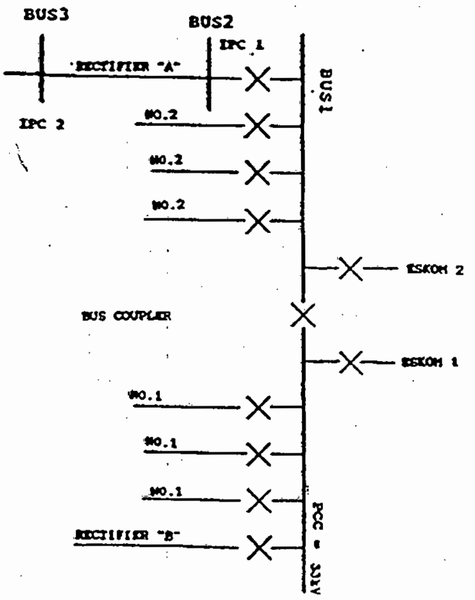


FIGURE 7.2

The switchroom has a bus coupler linking two bus sections together.

Each bus section supplies a 12-pulse convertor as well as ring feeds, namely:

"RECTIFIER A" AND 3 RING FEEDS EACH LABELLED "2"

"RECTIFIER B" AND 3 RING FEEDS EACH LABELLED "1"

Each rectifier and each ring feed has its own circuit breaker. Each bus section which receives an ESKOM supply (ESKOM 1 and ESKOM 2) also has its own main circuit breaker.

All these breakers have *"symmetrical breaking capacities"* of 25kA

The **"rated current"** is 1251 A.

7.3. REASONS FOR SELECTING A TRACTION SUBSTATION FOR MEASUREMENTS

The traction substation receives direct supplies from ESKOM and all three standards researched provide limits for harmonic distortion at PCC's. In plants harmonic sources are not generally directly connected to PCC's but rather to IPC's. In traction substations however, the harmonic source is directly connected via its transformers to a PCC. Harmonic magnitudes are thus expected to be larger.

7.4 HARMONIC MEASUREMENTS

Harmonic current measurements were measured on the "Blue phase" and the voltage measurements were between "Yellow and Blue phases". (Line-to-Line V_{YB}).

7.5 MEASUREMENTS LOCATIONS IN TRACTION SUBSTATION

Measurements in the substation were at three locations. Two locations were at HV measuring points (PCC) and the third was measured at an AC LV side (IPC).

7.5.1 MEASUREMENT POINT 1

The first HV location at which measurements were taken was at instrument transformers (VT's and CT's) at the ESKOM 1 incoming point to the substation. The CT ratio was 1200:1 and the VT ratio 33kV:110V.

7.5.2 MEASUREMENT POINT 2

The second HV location was on the HV side of "RECTIFIER A". The CT ratio was 50:5 and the VT ratio was 33 kV:110V. (See Figure 7.1 above).

7.5.3 MEASUREMENT POINT 3

The third location was on the LV side of "RECTIFIER A" taken as an IPC. As no CT's or VT's were available at this ± 3kV (RMS) level, measurements were conducted on the LV side (380V side) of the 3kV/380V auxiliary transformer. (See Figure 7.1 above for position of auxiliary transformer).

7.5.4 TABLE OF MEASUREMENT LOCATIONS

The following table, Table 7.1 summarises these locations:

TABLE OF LOCATIONS OF MEASUREMENTS IN 33 kV TRACTION SUBSTATION				
MEASURE-MENT POINT	LOCATION	BUS TYPE	CT RATIO	VT RATIO
1(HV)	ESKOM 1 INCOMING	PCC	1200:1	33kV:110V
2(HV)	HV SIDE OF RECTIFIER "A"	PCC	50:5	33kV:110V
3(LV)	LV SIDE OF AUXILIARY TRANSFORMER RECTIFIER "A"	IPC	-	-

TABLE 7.1

7.6 COMMUNICATION WITH PC

All in all, four sets (voltage, current and numeric data) of measurements were conducted and down loaded to a PC using the FLUKEVIEW software and stored in files.

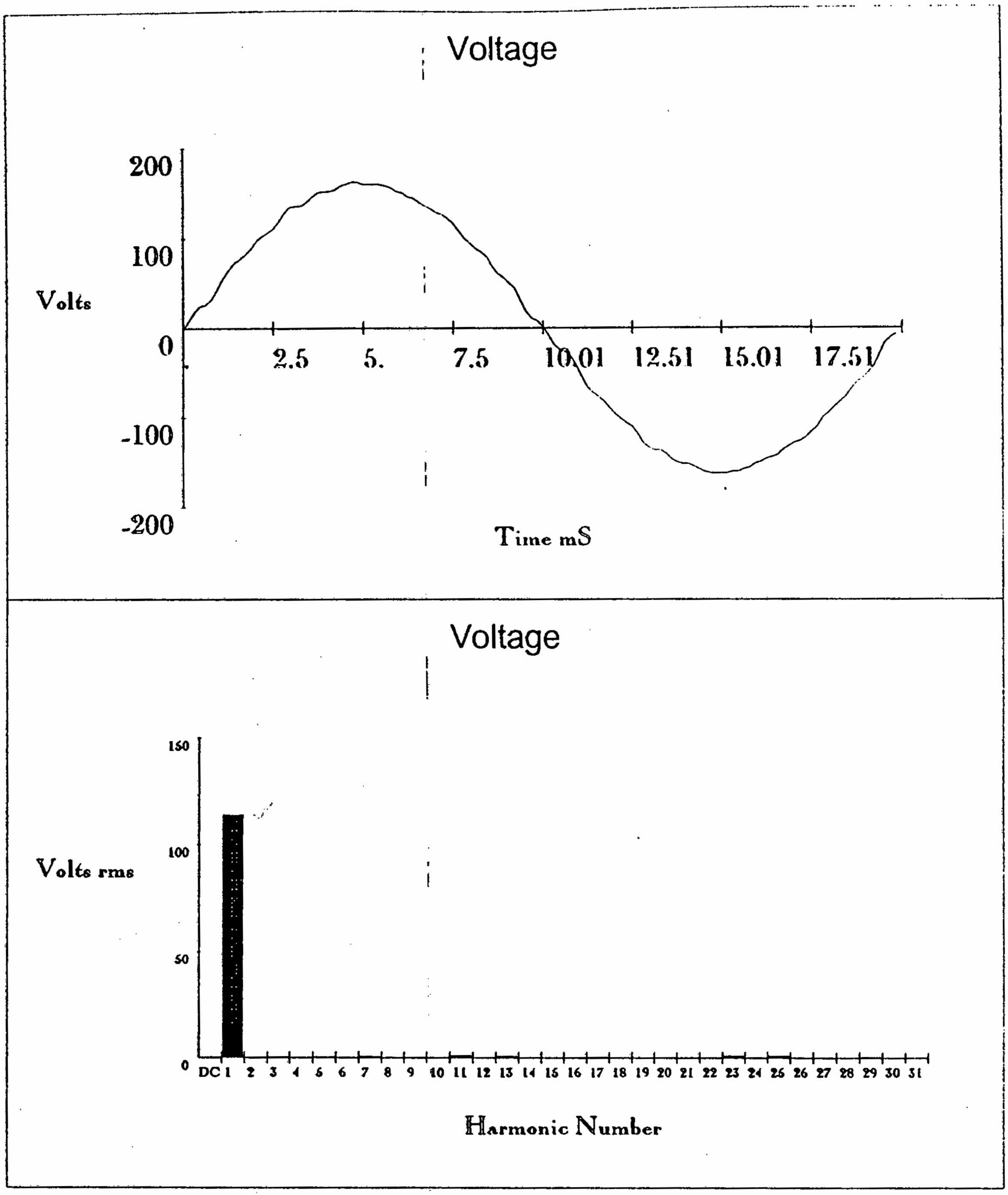
The following table, Table 7.2, displays these five file names and refers each one of them to figures and tables which accompany this appendix as "**ATTACHMENTS**". These figures display the **waveforms measured** and their harmonic spectrums while the tables display their numeric values.

<table>
<tr><th colspan="5">TABLE OF SETS OF MEASUREMENTS
FOR MEASUREMENTS LOCATIONS</th></tr>
<tr><th rowspan="3">SWITCHING CONFIGURATION</th><th colspan="2">WAVE FORMS AND HARMONIC SPECTRUMS</th><th>NUMERIC VALUES</th><th rowspan="3">FILE NAMES</th></tr>
<tr><th>VOLTS</th><th>AMPS</th><th rowspan="2">ATTACHED TABLES</th></tr>
<tr><th colspan="2">ATTACHED FIGURES</th></tr>
<tr><td colspan="5">SET OF MEASUREMENTS - MEASUREMENT POINT 1</td></tr>
<tr><td>Bus Coupler Closed Eskom 2 open</td><td>Figure 7.3</td><td>Figure 7.4</td><td>Table 7.3</td><td>TSO 1</td></tr>
<tr><td>Bus Coupler Open Eskom 2 closed</td><td>Figure 7.5</td><td>Figure 7.6</td><td>Table 7.4</td><td>TSO 3</td></tr>
<tr><td colspan="5">SET OF MEASUREMENTS - MEASUREMENT POINT 2</td></tr>
<tr><td>Bus Coupler Closed Eskom 1 & 2 are closed</td><td>Figure 7.7</td><td>Figure 7.8</td><td>Table 7.5</td><td>TSO 4</td></tr>
<tr><td colspan="5">SET OF MEASUREMENTS - MEASUREMENT POINT 3</td></tr>
<tr><td>Bus Coupler Closed Eskom 1 & 2 are closed</td><td>Figure 7.9</td><td>Figure 7.10</td><td>Table 7.6</td><td>TSO 5</td></tr>
</table>

TABLE 7.2

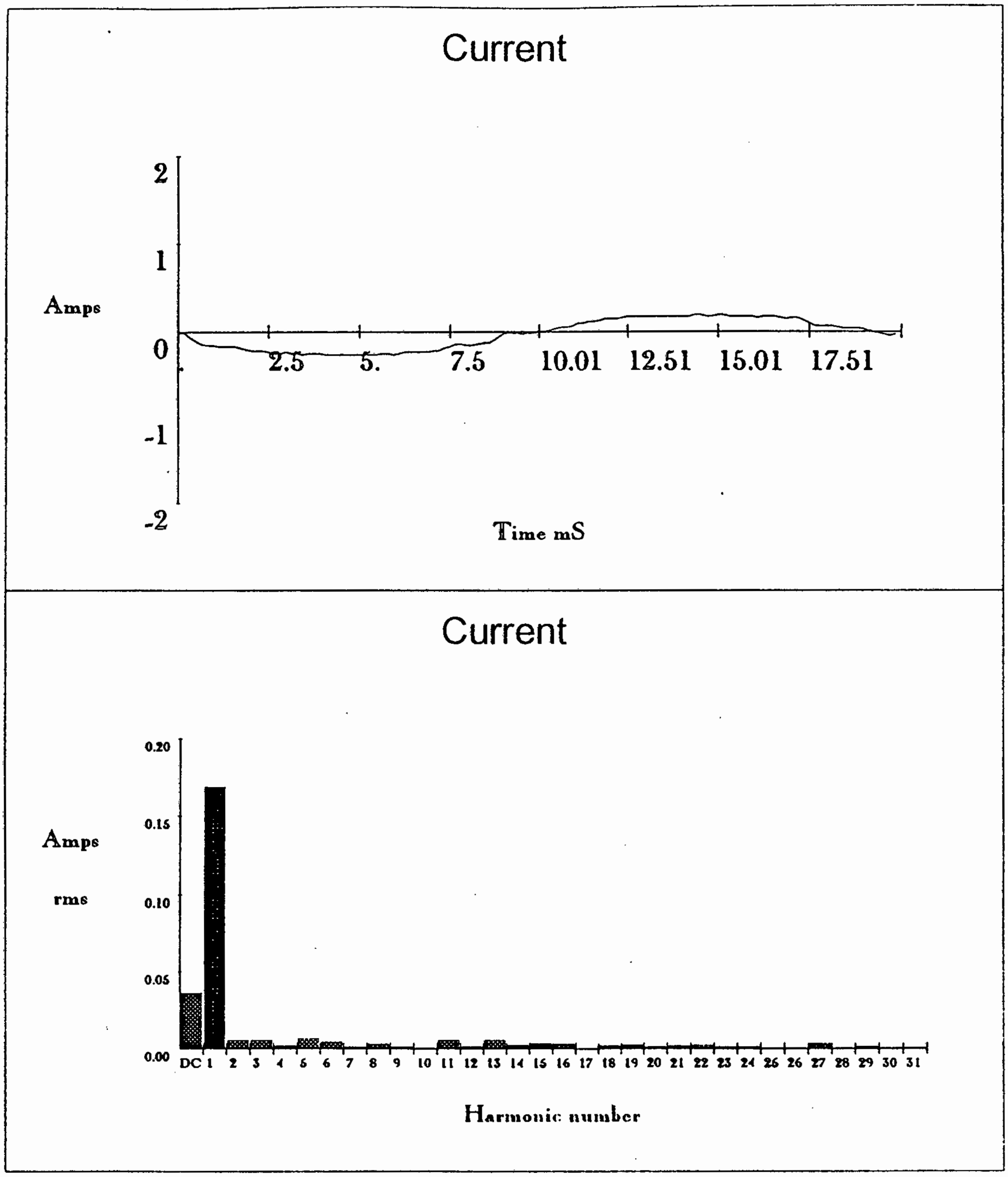
The attachments that follow are the results of field measurements measured. See attached Figures 7.3 to 7.10 and Tables 7.3 to 7.6.

Readings - 08/29/95 13:58:30



MEASUREMENT POINT 1 -- TSO1
FIGURE 7.3

Readings - 08/29/95 13:58:30



MEASUREMENT POINT 1 -- TSO1
FIGURE 7.4

APPENDIX 7

Readings - 08/29/95 13:58:30

Summary Information

			Voltage	Current
Frequency	50.0	RMS	113.7	0.17
Power		Peak	161.9	0.23
Watts	-19	DC Offset	0.0	-0.04
VA	19	Crest	1.42	1.33
Vars	2	THD Rms	2.2	9.9
Peak W	-43	THD Fund	2.2	10.0
Phase	172° lag	HRMS	2.5	0.02
Total PF	-0.96	KFactor		2.5
DPF	-0.99			

Record Information

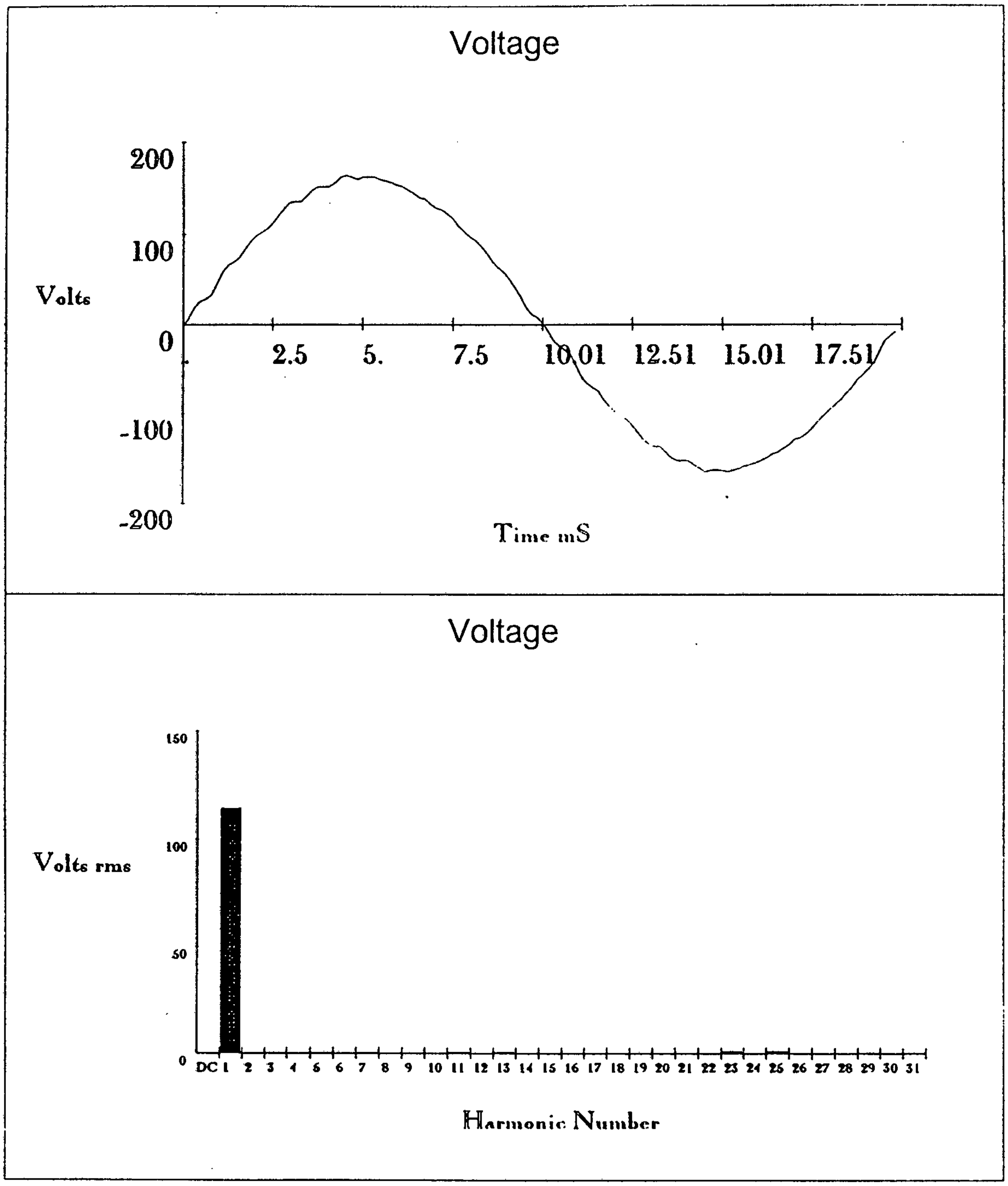
	Max	Average	Min
V RMS			
A RMS			
V Peak			
A Peak			
V THD-R%			
A THD-R%			
Watts			
Volt * Amps			
TPF			
DPF			
Frequency			

Harmonic Information

	Freq.	V Mag	%V RMS	V Ø°	I Mag	%I RMS	I Ø°	Power (W)
DC	0.0	0.0	0.0	0	0.04	21.2	0	0
1	50.0	113.6	100.0	0	0.17	98.8	-172	-19
2	99.9	0.1	0.1	96	0.01	3.3	97	0
3	149.9	0.3	0.2	-112	0.01	3.3	-158	0
4	199.9	0.2	0.1	147	0.00	1.1	117	0
5	249.8	0.4	0.3	120	0.01	4.0	67	0
6	299.8	0.0	0.0	133	0.00	2.6	148	0
7	349.8	0.6	0.5	161	0.00	0.7	91	0
8	399.7	0.0	0.0	57	0.00	1.8	172	0
9	449.7	0.0	0.0	70	0.00	0.7	105	0
10	499.7	0.0	0.0	104	0.00	0.4	163	0
11	549.6	1.1	1.0	138	0.01	3.3	53	0
12	599.6	0.0	0.0	-160	0.00	0.7	53	0
13	649.6	1.0	0.9	125	0.01	3.3	74	0
14	699.6	0.0	0.0	-163	0.00	1.5	-2	0
15	749.5	0.0	0.0	49	0.00	2.2	113	0
16	799.5	0.0	0.0	-155	0.00	1.8	31	0
17	849.5	0.3	0.2	-32	0.00	0.0	98	0
18	899.4	0.0	0.0	12	0.00	1.1	49	0
19	949.4	0.1	0.1	-86	0.00	1.5	28	0
20	999.4	0.1	0.1	50	0.00	0.7	60	0
21	1049.3	0.1	0.1	-134	0.00	1.1	60	0
22	1099.3	0.1	0.0	39	0.00	1.5	79	0
23	1149.3	1.4	1.2	-68	0.00	0.7	-136	0
24	1199.2	0.0	0.0	-91	0.00	0.7	164	0
25	1249.2	1.1	1.0	-104	0.00	0.4	-165	0
26	1299.2	0.0	0.0	68	0.00	0.4	-107	0
27	1349.1	0.0	0.0	-119	0.00	2.2	15	0
28	1399.1	0.0	0.0	40	0.00	0.4	49	0
29	1449.1	0.4	0.3	-50	0.00	0.7	22	0
30	1499.0	0.0	0.0	0	0.00	0.4	-145	0
31	1549.0	0.1	0.1	-55	0.00	0.4	76	0

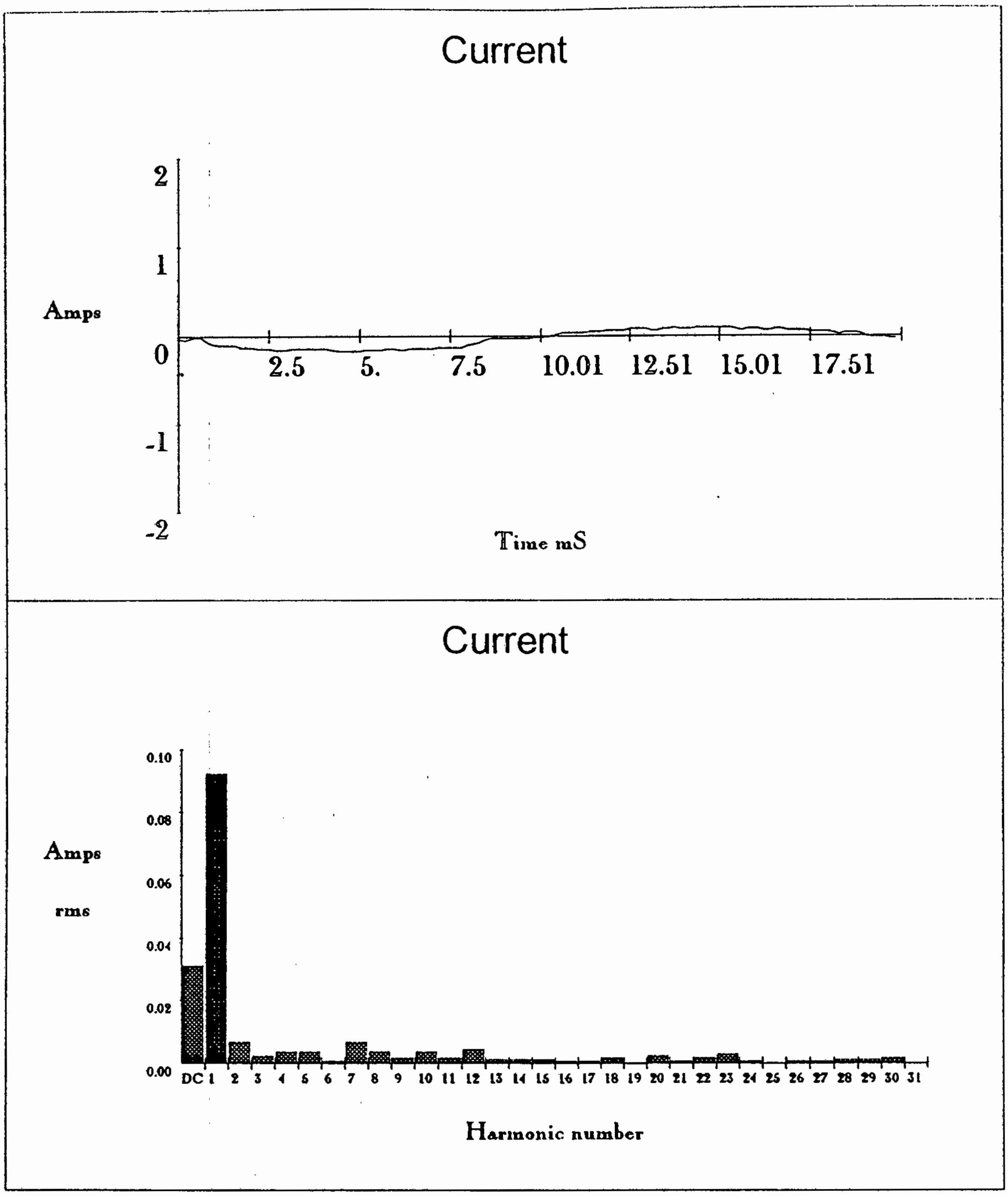
MEASUREMENT POINT 1 – TSO1
TABLE 7.3

Readings - 08/28/95 15:28:16



MEASUREMENT POINT 1 -- TSO3
FIGURE 7.5

Readings - 08/28/95 15:28:16



MEASUREMENT POINT 1 -- TSO3
FIGURE 7.6

Readings - 08/28/95 15:28:16

Summary Information

			Voltage	Current
Frequency	50.0	RMS	114.5	0.10
Power		Peak	163.5	0.14
Watts	-10	DC Offset	0.1	-0.03
VA	11	Crest	1.43	1.43
Vars	0	THD Rms	1.9	15.8
Peak W	-28	THD Fund	1.9	16.0
Phase	174° lag	HRMS	2.2	0.01
Total PF	-0.92	KFactor		4.3
DPF	-0.99			

Record Information

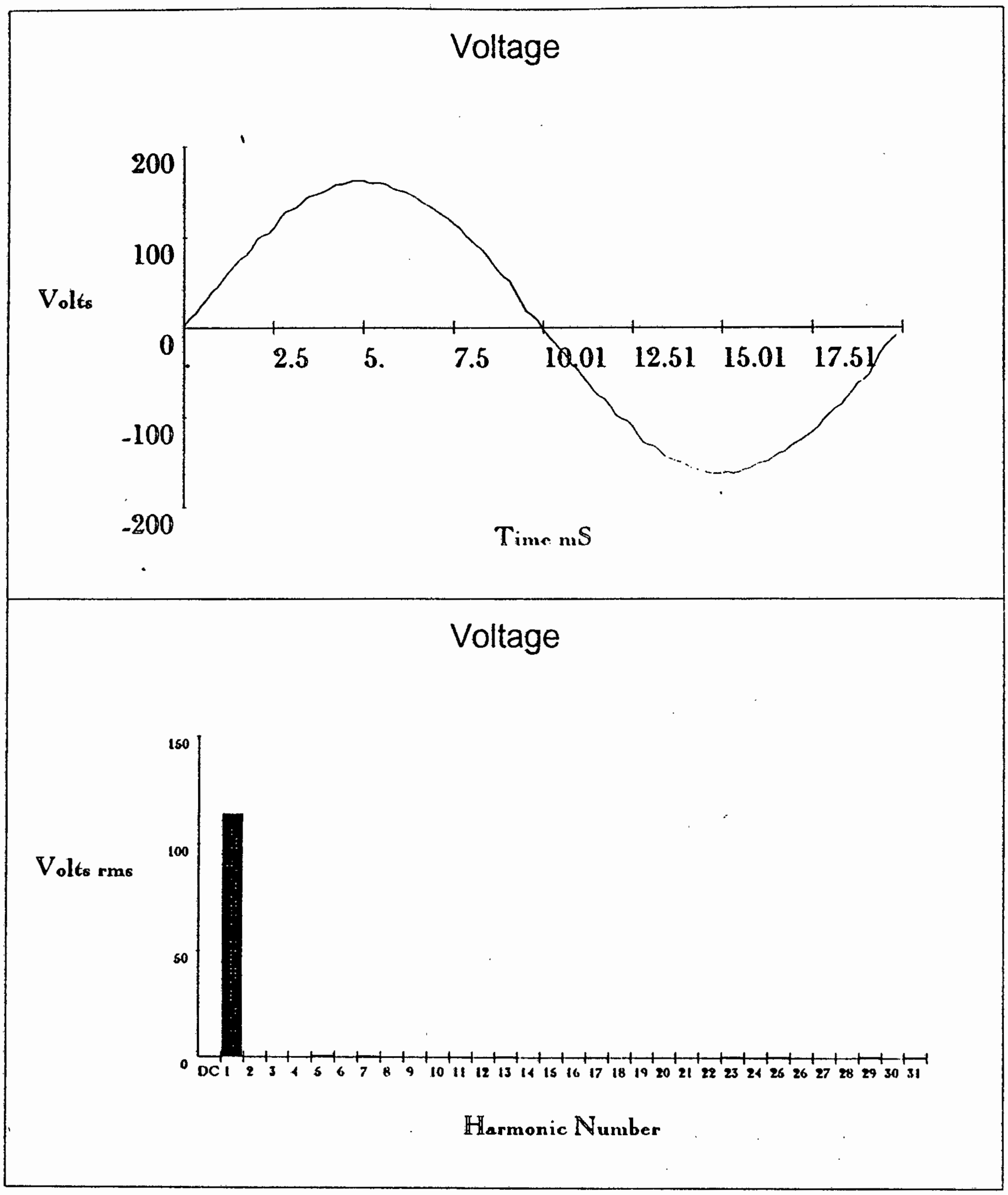
	Max	Average	Min
V RMS			
A RMS			
V Peak			
A Peak			
V THD-R%			
A THD-R%			
Watts			
Volt * Amps			
TPF			
DPF			
Frequency			

Harmonic Information

	Freq.	V Mag	%V RMS	V Ø°	I Mag	%I RMS	I Ø°	Power (W)
DC	0.0	0.1	0.1	0	0.03	34.0	0	0
1	50.0	114.5	100.0	0	0.09	100.6	-174	-11
2	99.9	0.1	0.1	76	0.01	7.5	104	0
3	149.9	0.2	0.2	-47	0.00	2.7	-151	0
4	199.9	0.1	0.1	151	0.00	4.1	141	0
5	249.8	0.5	0.4	53	0.00	4.1	58	0
6	299.8	0.0	0.0	151	0.00	0.7	67	0
7	349.8	0.4	0.4	162	0.01	7.5	34	0
8	399.7	0.0	0.0	-13	0.00	4.1	-54	0
9	449.7	0.0	0.0	81	0.00	2.0	127	0
10	499.7	0.0	0.0	27	0.00	4.1	-34	0
11	549.6	0.7	0.6	148	0.00	2.0	55	0
12	599.6	0.0	0.0	-120	0.00	4.8	13	0
13	649.6	0.8	0.7	136	0.00	1.4	-30	0
14	699.6	0.0	0.0	-165	0.00	1.4	-18	0
15	749.5	0.0	0.0	42	0.00	1.4	-25	0
16	799.5	0.0	0.0	-108	0.00	0.7	62	0
17	849.5	0.0	0.0	-77	0.00	0.7	-115	0
18	899.4	0.0	0.0	180	0.00	2.0	-127	0
19	949.4	0.0	0.0	-90	0.00	0.0	-10	0
20	999.4	0.0	0.0	-174	0.00	2.7	-127	0
21	1049.3	0.1	0.1	-112	0.00	0.7	-86	0
22	1099.3	0.0	0.0	28	0.00	2.0	-134	0
23	1149.3	1.2	1.0	-38	0.00	3.4	-139	0
24	1199.2	0.0	0.0	22	0.00	0.7	-115	0
25	1249.2	1.2	1.1	-85	0.00	0.0	-103	0
26	1299.2	0.1	0.1	-86	0.00	0.7	154	0
27	1349.1	0.0	0.0	-56	0.00	0.7	-103	0
28	1399.1	0.0	0.0	-174	0.00	1.4	85	0
29	1449.1	0.5	0.4	-110	0.00	1.4	84	0
30	1499.0	0.0	0.0	-158	0.00	2.0	133	0
31	1549.0	0.2	0.2	-156	0.00	0.0	89	0

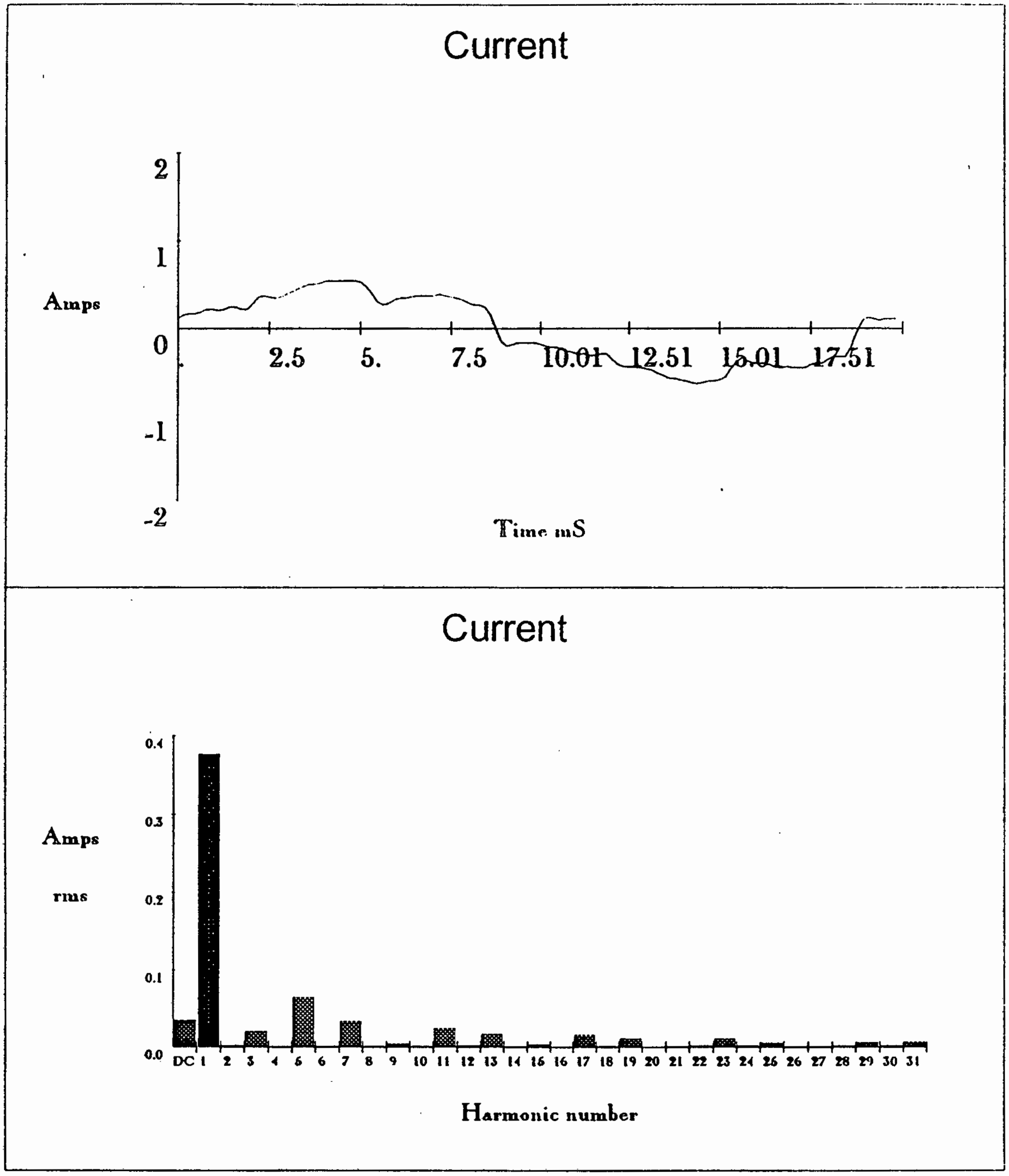
MEASUREMENT POINT 1 – TSO3
TABLE 7.4

Readings - 08/28/95 16:08:34



MEASUREMENT POINT 2 -- TS04
FIGURE 7.7

Readings - 08/28/95 16:08:34



MEASUREMENT POINT 2 -- TS04
FIGURE 7.8

Readings - 08/28/95 16:08:34

Summary Information

			Voltage	Current
Frequency	50.0	RMS	113.9	0.39
Power		Peak	162.4	0.61
Watts	42	DC Offset	-0.1	-0.04
VA	44	Crest	1.43	1.56
Vars	8	THD Rms	1.6	22.3
Peak W	102	THD Fund	1.6	22.9
Phase	12° lead	HRMS	1.8	0.09
Total PF	0.95	KFactor		5.0
DPF	0.98			

Record Information

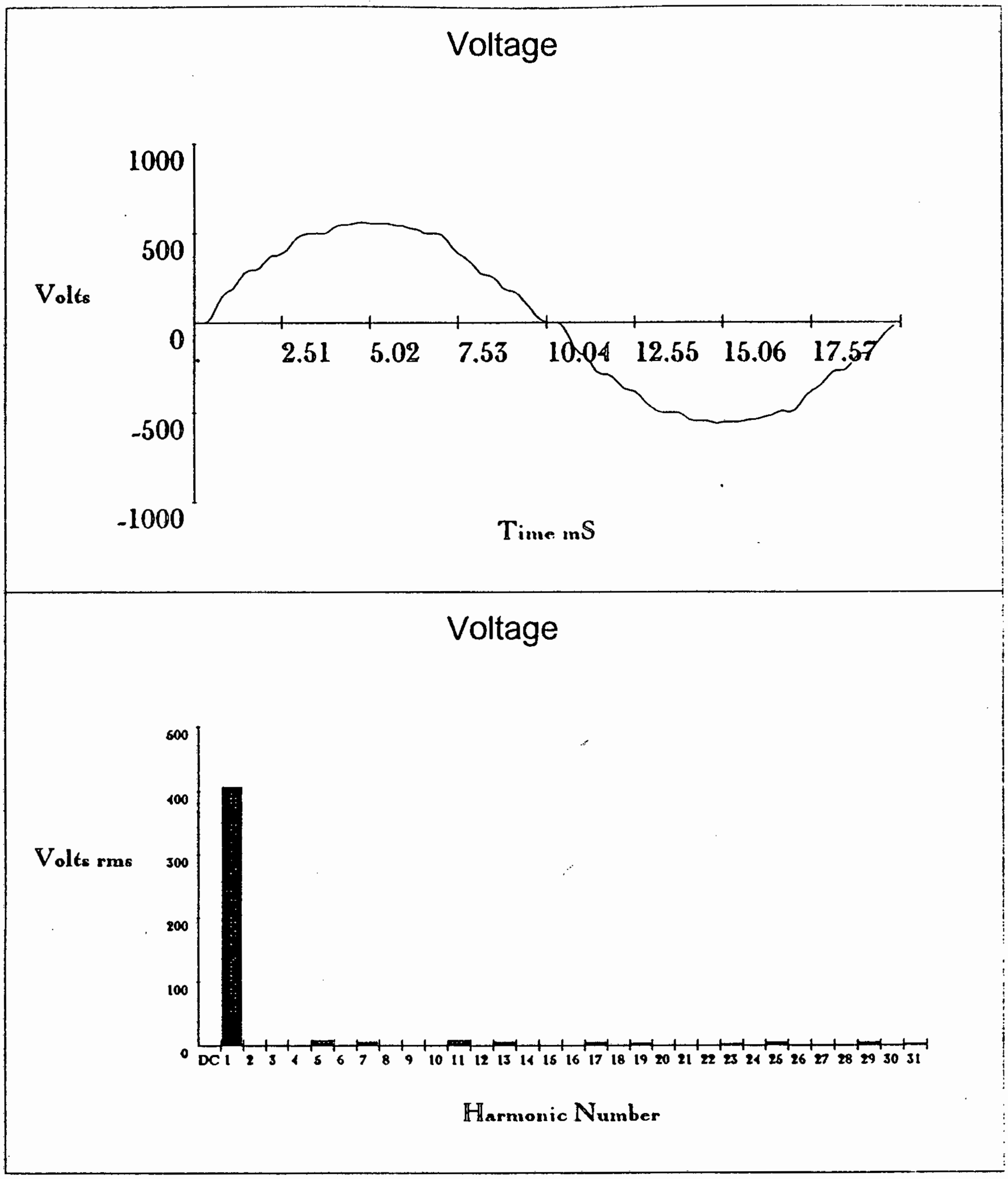
	Max	Average	Min
V RMS			
A RMS			
V Peak			
A Peak			
V THD-R%			
A THD-R%			
Watts			
Volt * Amps			
TPF			
DPF			
Frequency			

Harmonic Information

	Freq.	V Mag	%V RMS	V Ø°	I Mag	%I RMS	I Ø°	Power (W)
DC	0.0	0.1	0.1	0	0.04	9.2	0	0
1	50.0	113.9	100.0	0	0.38	97.4	12	42
2	99.9	0.1	0.1	26	0.00	0.5	112	0
3	149.9	0.2	0.1	-42	0.02	5.5	95	0
4	199.9	0.0	0.0	146	0.00	0.3	77	0
5	249.8	0.8	0.7	72	0.06	16.8	112	0
6	299.8	0.0	0.0	180	0.00	0.3	21	0
7	349.8	0.5	0.5	126	0.03	8.7	-141	0
8	399.7	0.0	0.0	-16	0.00	0.2	-133	0
9	449.7	0.0	0.0	-180	0.00	1.0	160	0
10	499.7	0.0	0.0	51	0.00	0.2	39	0
11	549.6	0.5	0.4	163	0.02	6.5	-104	0
12	599.6	0.0	0.0	-94	0.00	0.5	73	0
13	649.6	0.4	0.3	141	0.02	4.4	-41	0
14	699.6	0.0	0.0	79	0.00	0.3	-22	0
15	749.5	0.0	0.0	168	0.00	0.8	-86	0
16	799.5	0.0	0.0	89	0.00	0.0	-53	0
17	849.5	0.2	0.2	-108	0.02	4.2	34	0
18	899.4	0.0	0.0	72	0.00	0.2	-167	0
19	949.4	0.2	0.1	-115	0.01	2.9	77	0
20	999.4	0.1	0.0	34	0.00	0.0	-165	0
21	1049.3	0.1	0.1	-96	0.00	0.2	60	0
22	1099.3	0.0	0.0	4	0.00	0.5	-110	0
23	1149.3	0.6	0.5	-46	0.01	2.9	167	0
24	1199.2	0.0	0.0	-117	0.00	0.5	-171	0
25	1249.2	0.6	0.5	-59	0.01	1.5	-144	0
26	1299.2	0.1	0.1	117	0.00	0.2	48	0
27	1349.1	0.0	0.0	-126	0.00	0.3	148	0
28	1399.1	0.1	0.1	107	0.00	0.5	8	0
29	1449.1	0.8	0.7	68	0.01	1.8	-39	0
30	1499.0	0.0	0.0	-66	0.00	0.5	0	0
31	1549.0	0.6	0.5	4	0.01	1.9	-11	0

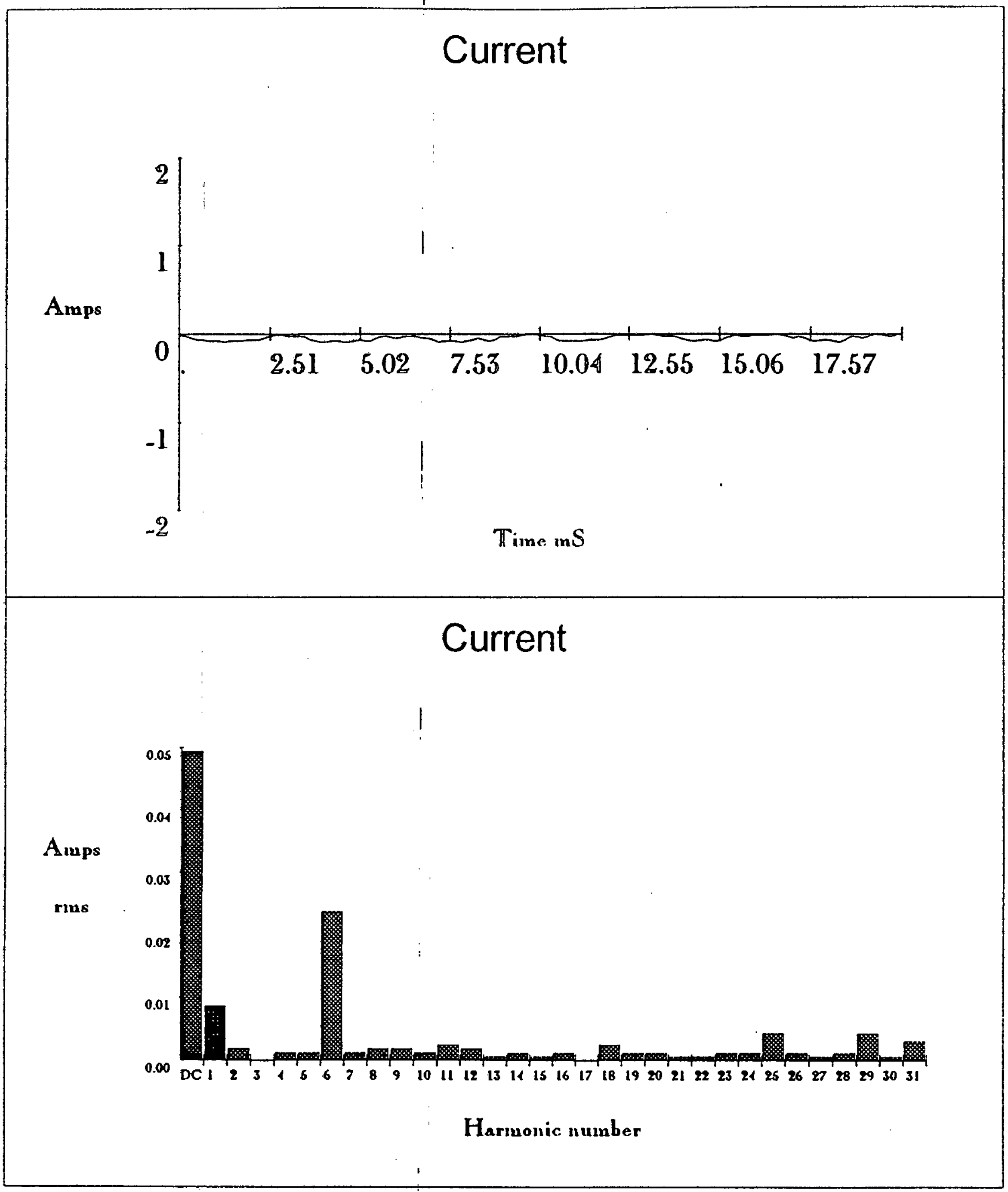
MEASUREMENT POINT 2 -- TS04
TABLE 7.5

Readings - 08/29/95 14:18:16



MEASUREMENT POINT 3 -- TSO5
FIGURE 7.9

Readings - 08/29/95 14:18:16



MEASUREMENT POINT 3 -- TSO5
FIGURE 7.10

Readings - 08/29/95 14:18:16

Summary Information

			Voltage	Current
Frequency	49.8	RMS	408	0.07
Power		Peak	573	0.05
Watts	-3	DC Offset	1	-0.05
VA	28	Crest	1.41	0.73
Vars	0	THD Rms	4.5	94.8
Peak W	-57	THD Fund	4.5	296.6
Phase	175° lag	HRMS	18	0.03
Total PF	-0.13	KFactor		**OL**
DPF	-1.00			

Record Information

	Max	Average	Min
V RMS			
A RMS			
V Peak			
A Peak			
V THD-R%			
A THD-R%			
Watts			
Volt * Amps			
TPF			
DPF			
Frequency			

Harmonic Information

	Freq.	V Mag	%V RMS	V Ø°	I Mag	%I RMS	I Ø°	Power (W)
DC	0.0	1	0.1	0	0.05	98.8	0	0
1	49.8	407	99.9	0	0.01	17.5	-175	-4
2	99.6	0	0.1	56	0.00	3.8	83	0
3	149.4	1	0.3	-116	0.00	0.0	-172	0
4	199.3	0	0.0	74	0.00	2.5	174	0
5	249.1	9	2.3	-129	0.00	2.5	39	-1
6	298.9	0	0.1	111	0.02	47.5	141	0
7	348.7	6	1.4	-76	0.00	2.5	154	-1
8	398.5	0	0.1	23	0.00	3.8	91	0
9	448.3	0	0.1	139	0.00	3.8	-97	0
10	498.1	0	0.0	-60	0.00	2.5	105	0
11	548.0	9	2.2	172	0.00	5.0	-81	-1
12	597.8	0	0.0	-70	0.00	3.8	112	0
13	647.6	6	1.5	163	0.00	1.3	29	-1
14	697.4	0	0.0	-12	0.00	2.5	115	0
15	747.2	1	0.1	71	0.00	1.3	-8	0
16	797.0	0	0.1	-42	0.00	2.5	7	0
17	846.8	5	1.2	146	0.00	0.0	95	0
18	896.7	0	0.0	-101	0.00	5.0	99	0
19	946.5	4	1.1	136	0.00	2.5	-106	-1
20	996.3	0	0.0	-144	0.00	2.5	-82	0
21	1046.1	0	0.1	-2	0.00	1.3	121	0
22	1095.9	0	0.0	-23	0.00	1.3	63	0
23	1145.7	3	0.7	175	0.00	2.5	-165	0
24	1195.5	0	0.1	-110	0.00	2.5	78	0
25	1245.4	5	1.1	158	0.00	8.8	-4	-1
26	1295.2	0	0.0	117	0.00	2.5	-4	0
27	1345.0	1	0.1	-10	0.00	1.3	87	0
28	1394.8	0	0.0	20	0.00	2.5	0	0
29	1444.6	5	1.1	29	0.00	8.8	65	0
30	1494.4	0	0.1	102	0.00	1.3	60	0
31	1544.2	3	0.8	13	0.00	6.3	169	-1

MEASUREMENT POINT 3 -- TSO5
TABLE 7.6

POWER SYSTEM HARMONIC FIELD MEASUREMENTS AND THE APPLICATION OF STANDARDS INCLUDING SIMULATION

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ABSTRACT

In this paper international and local power system harmonic standards are compared and applied to field measurements taken at a 11 kV manufacturing plant and in a 33 kV traction substation. The 11 kV plant was simulated using two industrial grade harmonic software packages and their results compared to the actual values measured.

1 INTRODUCTION

With the increase of non-linear loads in power systems, the voltage and current waveforms are becoming more distorted and the power quality is deteriorating. Because of this development it has become essential to assess any adverse effects which harmonics may produce in a system. These effects are best ascertained by carrying out field measurements. Computer simultations can be used to check field measurements and are particularly useful for newly designed installations or where installations are to be upgraded to include non-linear loads. Any adverse effects can be pre-determined and remedial steps taken.

These measurements need to be compared to a standard to evaluate whether or not they are harmful.

Certain international and local standards governing permitted levels are in place. In the USA an American Standard (IEEE) applies whereas in Europe a different standard (IEC) applies. South Africa (ESKOM) tends to follow the European standard but has slightly different limits for distortion levels. Measured harmonics significantly higher than the recommended levels would be considered unacceptable.

These standards are applied to a South African 11 kV manufacuring plant and to a 33 kV traction substation to demonstrate their differences.

The 11 kV plant is also simulated using two leading international industrial grade software analysis packages to ascertain the harmonic penetration being caused by a 6 pulse dc drive. The results of the simulation being compared to the actual field measurements taken.

2 HARMONIC STANDARDS

Three standards are compared, namely:

a. IEEE519 Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems [1].

b. IEC1000 series standard [2].

c. ESKOM - ESKASAA18 standard [3].

These standards all make use of the total harmonic distortion (THD) voltage or current, defined as:

$$\mathrm{THD} = \frac{100\sqrt{\sum_{n=2}^{k} U_n^{\,2}}}{U_1} \quad \ldots\ldots (1)$$

where: U_1, is the fundamental component, U_2 to U_n are the harmonic components.

IEEE STANDARD

This standard sets limits for percentage "individual harmonic component distortion" and "THD". It limits both utility voltage and end user current distortions at the point of common coupling (PCC).

Voltage

Tabel 1 lists the limits to ensure quality of voltage and decrease with PCC voltage increase.

NEW IEEE STD 519 VOLTAGE DISTORTION LIMITS		
Bus voltage at PCC	Individual voltage distortion (%)	Total harmonic distortion (%)
Below 69 kV	3.0	5.0
69 kV to 161 kV	1.5	2.5
161 kV and above	1.0	1.5

Table 1

Current

This standard also limits PCC current. Table 2 lists the limits for systems below 69 kV and increase as the ratio of the short circuit current to load current (I_{SC}/I_L) increases. The standard provides similar tables for PCC's above 69kV.

NEW IEEE STD 519 CURRENT DISTORTION LIMITS FOR NONLINEAR LOADS						
Maximum Harmonic Current Distortion in % of fundamental						
Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	h<11	11≤h < 17	17≤h<23	23≤h<35	35≤h	THD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
≥1000	15.0	7.0	6.0	2.5	1.4	20.0

Table 2

Table 2 applies to 6 pulse convertors, but can be adapted for higher pulse numbers. See application examples in the standard.

IEC STANDARD

The following is a brief outline of the IEC standards:

a. IEC555-I (1982) Definitions of disturbances caused by household appliances.

b. IEC1000-1-1 (1992) Definitions used in IEC1000.

c. IEC1000-2-1 (1990) Disturbances in public power supply systems.

d. IEC1000-2-2 (1990) Defines the compatibility levels for individual harmonic voltages in public low voltage power supply systems.

e. IEC1000-2-4 (1994) Prescribes the compatibility levels for industrial and non-public networks. It applies to low and medium voltage supplies. It distinguishes between the *"Point of common coupling (PCC)"* and the *"In Plant point of coupling (IPC)"*. This standard defines 3 classes:

CLASS 1: Relates to equipment very sensitive to disturbances. (e.g. equipment using UPS, filters etc.)

CLASS 2: Applies to PCC's and IPC's in industrial environments. The compatibility levels are identical to those of public networks. (see 1000-2-2). Therefore components designed for application in public networks may be used in this class.

CLASS 3: Applies only to IPC's in industrial environments. It has higher compatibility levels than Class 2. This class should be considered when loads are fed through convertors.

Compatibility levels (THD %) for these classes are:

Compatibility levels for harmonics			
	Class 1	Class 2	Class 3
Total harmonic distortion (THD)	5%	8%	10%

Table 3

They are for harmonic voltage components only. No limits are specified for currents. They apply to line voltages, class 1 to LV, classes 2 and 3 to LV and MV. Standards for HV and higher are not yet in place. See application examples in the standard.

f. IEC1000-3-2 (1995) This standard replaces IEC555-2 (1982). It refers to equipment having input currents ≤16A/phase connected to public low voltage distribution systems. (e.g. lighting).

ESKOM STANDARD

This standard sets limits for percentage "individual harmonic distortion" and "THD" at PCC's for Transmission, Distribution and Reticulation voltage ranges. It is based on IEC standards and on experience in South African Systems.

Table 4 lists the limits for the 1,1 to 44 kV PCC voltage range. The standard also provides limits for PCC ranges below 1.1kV and above 44 kV.

Limits for steady state voltage harmonics			
Nominal voltage at PCC		**Recommended limits (% of nominal supply frequency component)**	
Above 1 100V, up to and including 44 kV	**THD**	**5,0**	
	odd	**4,0**	**limits on individual harmonics**
	even <14th	**2,0**	
	inter	**1,0**	
	14th – 25th	**0,5 x <14th**	
	>25th	**0,25 x <14th**	

Table 4

3. COMPARISON OF STANDARDS

In brief the IEEE standard limits both voltage and current distortion at a PCC. The voltage limits are sub-divided into three voltage ranges (Table 1). The current limits are categorized in accordance with typical I_{SC}/I_L ratio found in power systems. (Table 2.) In contrast the IEC and Eskom limits are for harmonic voltages only. No limits are specified for currents.

The IEC limits do not vary in accordance with voltage ranges but apply singularly to the LV and MV range. They however are grouped in classes (Table 3). Unlike the IEEE and Eskom standards, the IEC standard caters for both PCC's and IPC's. The Eskom standard differs from the IEC standard in that its limits vary like the IEEE in voltage ranges. The IEEE has 3 ranges (Table 2) whereas Eskom has 5 voltage ranges. (Table 5).

In terms of voltage "THD" the 3 standards can be summarised as follows.

IEEE		ESKOM		IEC	
PCC	THD %	PCC	THD%	PCC/IPC	THD%
		<1,1kV	8%	LV/MV	
<69kV	5%	1,1 to 44kV	5%	CLASS 1	5%
69 to 161kV	2,5%	44 to 132kV	3%	CLASS 2	8%
>161kV	1,0%	132 to 275kV	2,5%	CLASS 3	10%
		275kV	2,0%		

Table 5

4. FIELD MEASUREMENTS AND THE APPLICATION OF STANDARDS

Figure 1 shows the one-line diagram for the 11 kV Plant in which harmonic field measurements were taken:

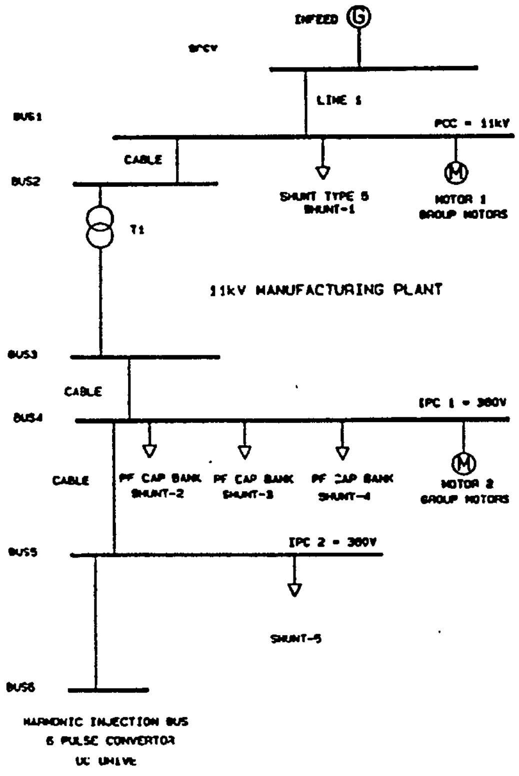

Figure 1

Measurements were taken at inputs to buses 1(PCC), 2,4(IPC1), 5(IPC2) and 6. The following results *inter alia*, were measured at the PCC and IPC1.

FIELD MEASUREMENTS					
NO	FREQ	PCC = BUS 1(HV)		IPC1 = BUS 4 (LV)	
	HZ	V(v)	C(A)	V(v)	C(A)
1 5 7 11	50 250 350 550	11 410 60.0	99.2 0.4 0.4 0.4	380 5.2 1.7	888.0 36.0 18.0 6.0
THD %		0,7	1.1	1.4	5.2

Table 6

11 kV MANUFACTURING PLANT

IEEE (PCC ONLY)

The full load current at PCC = 105 A, I_s = 13 kA, I_s/I_L = 125, ∴ From Table 2 the THD% = 15%. The 1,1% (Table 6) is well within the current standard. The voltage "THD" measured is 0,7% and is also well within the 5% standard (Table 1).

IEC (PCC and IPC1)

In terms of Table 3 Class 2 (PCC's) voltage "THD" must not exceed 8%. Class 3(IPC's) is 10%. The measured THD's of 0,7% (PCC) and 1,4% (IPC1) are both well within these standards.

ESKOM (PCC ONLY)

The 11 kV PCC falls within the 1.1 to 44 kV, 5% THD range (Table 4). The measured "THD" of 0,7% is well within this standard.

33 kV TRACTION SUBSTATION

Measurements were taken under two different switching configurations:

SWITCHING CONFIGURATION	THD%			
	PCC		RECTIFIER"A"	
	VOLTS	CURRENT	VOLTS	CURRENT
Bus coupler closed Eskom 2 open	2.2	9.9		
Bus coupler open Eskom 2 closed	1.9	15.8	4.5	94.8

Table 7

Figure 2 shows the one-line diagram of the 33kV Switchroom for the traction substation.

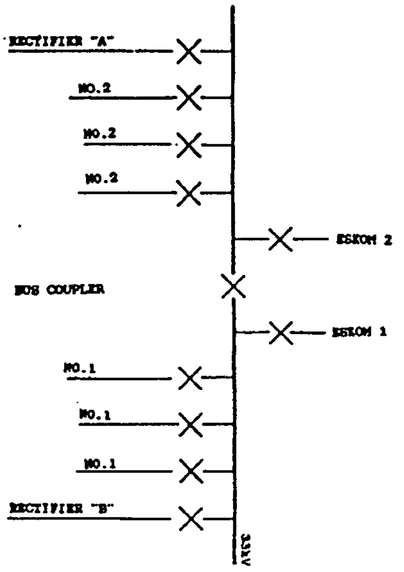

Figure 2

IEEE (PCC ONLY)

I_S/I_L = 25000/1250 = 20, from Table 2 THD% = 5%. The measured THD's of 9,9% and 15,8% exceed the standard limits. The limit for the voltage (Table 1) is 5%. The 2,2% and 1,9% are within the limits.

IEC (PCC ONLY)

Class 2 (Table 3) prescribes 8% as the limit. The 2,2% and 1,9% are within standard.

IEC (IPC - RECTIFIER A)

Class 3 prescribes 10%. The 4,5% is within the range.

ESKOM STANDARD (PCC ONLY)

The 33 kV voltage standard is 5% THD (Table 4). The 2.2% and 1,9% are within the standard.

5. FIELD MEASUREMENT RESULTS COMPARED TO SIMULATION RESULTS

The 11 kV Plant has been simulated using the ERACS [4] and the SUPERHARM [5] industrial grade harmonic analysis packages. The following results have been obtained and are listed in Table 8.

COMPARISON OF HARMONIC FIELD MEASUREMENTS
TO SIMULATION RESULTS - CASE B

No	1	5	7	11	13	17	19	23	25	THD
freq	50	250	350	550	650	850	950	1150	1250	
PCC = Bus 1 (HV)										
V	11410	60.0								0.7
V1	10924	4.7	1.2	18.5	1.9	1.2	0.4	0.5	0.2	0.2
V2	10970	4.0	1.0	4.0	2.0	6.0	1.0	1.0		0.1
C	99.2	0.4	0.4	0.4						1.1
C1	94.2	0.6	0.1	1.1	0.1	0.1	0.01	0.01		1.3
C2	99.0	0.4	0.1	0.1	0.6	0.1	0.03	0.02	0.01	0.4
IPC1 = Bus 4 (LV)										
V	380	5.2	1.7							1.4
V1	377	1.1	0.3	4.2	0.42	0.3	0.1	0.1	0.04	1.2
V2	372					1.0				0.5
C	888.0	36.0	18.0	6.0						5.2
C1	849.2	18.1	3.5	32.5	2.8	1.4	0.4	0.4	0.2	4.4
C2	968.0	11.9	2.0	4.9	2.2	4.4	0.8	0.6	0.2	1.4

FIELD MEASUREMENTS
V = VOLTAGE,
C = CURRENT

SIMULATION PACKAGE
V1 and C1 = SUPERHARM
V2 and C2 = ERAC PACKAGE

Table 8

6. CONCLUSION

From the results obtained it can be concluded that all three voltage standards are adequate. They may be different in their approaches but their applications lead to similar findings.

The simulation results are encouraging and it is considered that if measurements are taken under defined conditions and under conditions where simultaneous measurements are taken at different points in a network, then a closer correlation should be obtained. The packages indicate the presence of the same harmonics as were measured.

7. REFERENCES

[1] "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems", IEEE-519, 1992.

[2] "IEC 1000 Electromagnetic Compatibility series" 1992.

[3] "Eskom Handbook Power Quality", March 1994.

[4] ERACS Power System Analysis Package, ERA Technology Ltd, England.

[5] SUPERHARM Harmonic Analysis Package, Electrotek Concepts, Inc., USA.

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