Harmonic fingerprint measurement

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Chapter 1 Introduction

1.1 Background
This project is done as a master student traineeship. It is part of the KTI (Kwaliteit van toekomst infrastructuur). As the KTI is going on, harmonic fingerprint measurement for some household appliances is needed. Presented here is the harmonic fingerprint measurement for several household appliances (listed in Appendix 1). The measurement was done for individual appliance to find out its harmonic spectrum under various polluting grid conditions. Later, one combined measurement was done with various appliances together to see their mutual responses.

1.2 Goals of the measurements
More and more power electronics technology is applied in household appliances, and this leads to nonlinear characteristics. There are standards to limit network operator and appliances manufacturers. The standard IEC 61000-3-2 [1] provides individual harmonic current limits for appliances with a rated current ≤16 A per phase, while IEC 61000-3-12 [2] deals with all equipment having a rated input current >16 A and ≤75 A per phase. The standard EN 50160 limits the voltage at the point of connection (POC), which means the connection point between the household appliances and LV network. While regulation for household customers is a controversial topic and it needs more research work. The harmonic spectrum will be utilized for a model LV network developed for KTI project.

The goal of the measurements is to record the emission behavior of household devices at POC, including both harmonic current amplitude and phase shift. By recording the data at POC, it is possible to help to make regulations for customers.

The scheduled tasks are:

- Finding out typical device's harmonics spectrum (up to 25th harmonic) from the laboratory measurements and make simulation with LTspice.
- Finding out the mutual responses (up to 25th harmonic) when connecting different household appliances simultaneously to the grids.

1.3 Methodology
Several appliances' harmonic fingerprint measurement has been done. All the measurements are done between grid simulator and load as shown in Figure1-1 and this is the POC in practical situation. Fingerprints are shown in the appendix. Typical voltage and current wave form is recorded and simulation by LT-spice is done to verify it. Harmonic component analysis is also presented here.

1.4 Laboratory measurements
Laboratory measurement setup
The grid simulator will be adjusted to the nominal voltage of 230V / 50Hz in ideal situation. What is more, the simulator can produce the voltage containing one specific order of harmonic with required amplitude and phase shift. The harmonic fingerprint is a dataset that contains a large set of harmonic measurements for a single device. To establish a fingerprint, the device under test is first connected to an undistorted voltage. The harmonic current emission of the device is then measured. Subsequently, a specific odd order of harmonic voltage, from 3rd harmonic to 25th harmonic is added to the supply voltage with the amplitude and phase shift stepwise increasing, from 1% to 10% with 1% step and from 0° to 330° with a 30° step. Household appliance used in the measurement are listed in Appendix 1.

The output impedance of the grid simulator must be in accordance with IEC725, this means:

Phase: \[ R = 0.24 \text{ and } X = 0.15j \]

Neutral: \[ R = 0.16 \text{ and } X = 0.10j \]

Total: \[ R = 0.40 \text{ and } X = 0.25j. \]

The power analyzer will be used to sample a time series of \( U \) and \( I \) data with 10k samples per second, and the computer to store these samples. The time series of \( U \) and \( I \) will be used to build a Digsilent Power factory model. (Bhattacharyya & Heskes, 2008)[3] The work flow is shown in Figure 1-2.
1.5 Concept [4]

In order to analysis the harmonics of normal loads, especially the nonlinear loads. First a schema is introduced as shown in Figure 1-3.

The symbols used in the schema are:

\(U_g\) = the grid background harmonic voltage distortion
\[ Rg = \text{the grid resistance, including skin-effect} \]
\[ Lg = \text{the grid inductance} \]
\[ Io = \text{the harmonic current emission of the load without background distortion} \]
\[ C = \text{the capacitance of the load} \]
\[ G = \text{the total conductance of the load} \]
\[ P = \text{Active power connection point (for calculating} \ G) \]
\[ Q = \text{Reactive power at connection point (for calculating} \ C) \]

To explain the method and to show the response on harmonic voltage of passive components, the results of measuring a capacitor will be given. Figure 1-4 shows the results of a capacitor, corresponding with 1 kvar load at 230V. Picture a is the harmonic voltage put on to the capacitor. All bullets are harmonic voltages which are added to the fundamental voltage with the given amplitude and phase. The harmonic current response on this harmonic voltage is given in picture b. The thicker bullets in the two pictures correspond with each other. So, the harmonic current is linear with the harmonic voltage and with 90 degrees phase shift, as expected.

Due to the 90 degree phase shift, the harmonic active power is zero, what means that \( G(n) = 0 \), for each harmonic. By calculating the \( C(n)/C_{ref} \) it shows that this value is 1, for each harmonic. It is more practical to use a normalized value of the capacitance. Therefore \( C(n) \) will be divided by \( C_{ref} \), which is defined as the value of the capacitor that would carry the same current as the inverter at nominal power.

\[
\frac{C(n)}{C_{ref}} = \frac{-Q(n)}{\left|\frac{P_{nom}}{\omega \cdot U_{nom}}\right|^2} = \frac{-Q(n) \cdot U_{nom}^2}{n \cdot |P_{nom}| \cdot U_{(n)}^2}
\]
The most common model for harmonic sources is in the form of a harmonic current source, specified by its magnitude and phase spectrum. The phase is usually defined with respect to the fundamental component of the terminal voltage. The data used in this report is obtained from actual measurements. The net harmonic currents injected by large numbers of single phase electronic loads are significantly affected by both the attenuation and diversity.

Attenuation refers to the injection of voltage and current distortion. It is primarily due to the shared transformer impedance. When the non-linear loads are represented by a fixed harmonic current source, there will be an error on the voltage THD when compared to the simulation where the currents are dependent on the node voltage. The attenuation factor is represented by the ratio of the resultant current \( I_h^N \) for harmonic \( h \) for \( N \) units to the total harmonic current for \( h \) harmonics injected by \( N \) sources \( (N* I_h) \). \( I_h \) is the harmonic current injected by each non-linear device. When a system contains a single dominant source of harmonics, phase spectrum is not important. However, phase angles should be taken into consideration when multiple harmonic current sources are present. The distortion of an aggregate waveform might be limited because of the ‘diversity effect’. This effect is due to the possible harmonic cancellations among the non-linear loads because of the dispersion in harmonic current phase angles. Attenuation considers harmonic current from the amplitude point of view and diversity from the phase shift point of view. In the measurement, both the current amplitude and phase angle are necessary data, so both of the two effect can influence the measurement[5]

Chapter 2 Individual Measurement

In this chapter, several devices are being measured individually. The typical voltage and current waveform and fingerprint diagram have been analyzed.
2.1 Personal Computer

Nowadays, PC is a common used device in house consumer. So it is necessary to see its harmonics spectrum. In Figure 2-1 and Figure 2-2 is the shape of the current in case of different voltages.

![Figure 2-1: PC current and undistorted sinusoidal voltage](image)
Figure 2-2: PC current and voltage in case of 25th harmonic 5% distortion without phase shift

Figure 2-3: Fingerprint of PC for harmonic order 25
From the current wave shape, it is clear that PC behaves like typical rectifier which converts AC to DC. Of course it is not linear any more. A linear behavior means that a certain change of voltage will result in a proportional change of current. Definitely it is not the case of PC.

As is shown in Figure 2-3, for low amplitude of harmonics, PC behaves like a resistor while for high amplitude of harmonics, PC behaves like a capacitor. At low frequency, taking voltage harmonic number as 3, as shown in Appendix E-1, when the voltage harmonic increases from 1% to 10%, the current harmonic does not change too much. While for high frequency, for example N is 25, as shown in figure 2-3, the current harmonic increases from 0.026805 A to 0.338653 A (obtained from measurement), which is 10 times increase. From the fingerprint shown in Appendix E, it is obvious that at low frequency, there is no linear behavior, such as Appendix E-1 and Appendix E-2; with the increase of frequency, the fingerprint becomes more and more like a counter clock wise star shape, as shown in Appendix E-7. However, it is still not linear. But there is a trend that for high order harmonics, with the increase of harmonic voltage, the harmonic current shifts its phase from in phase with the voltage to leading the voltage. This means that for high order harmonics, the fingerprint can be regarded as sectionalized linearization.

2.2 Energy Saving Light

![Energy saving light current and undistorted sinusoidal voltage](image)
Figure 2-5: Energy saving lamp current and voltage in case of 25th harmonic 5% distortion without phase shift

Figure 2-6: Fingerprint of energy saving lamp for harmonic order 25
Energy saving light is widely used device in house consumer. Of course it becomes more and more important for the power grid and it will affect the harmonic in the POC (point of connection).

What differs from PC is, for high order harmonics, with the increase of harmonic voltage, the harmonic current decrease the leading angle compared to the voltage, as shown in Figure 2-6. This means that for high order harmonics, when the amplitude of harmonics is low, energy saving light behaves like a capacitor while for high amplitude; the inductive effect becomes more and more obvious.

This difference is shown also in the wave shape of voltage and current. The rectifier results in similar current, however, the phase shift is different. For PC, the fundamental current is in phase with the voltage as shown in Figure 2-1, while for energy saving light; the fundamental current is leading the voltage as shown in Figure 2-4.

Energy saving light also contains rectifier which leads to non-linear characteristic. Also similar with PC, energy saving light has no linear behavior at low frequency, as shown in Appendix B-1; with the increase of frequency, the fingerprint becomes more and more like a clock wise star shape, as shown in Figure 2-6. The current amplitude increase is also similar with PC, at low frequency, the current does not change too much, for example, when harmonic number N is 3, as shown in Appendix B-1. While with the increase of frequency, the current increase becomes more and more obvious. At high frequency(above 19th harmonic), the amplitude increase is almost 10 times, corresponding to the harmonic voltage increase from 1% to 10%.

2.3 LED

A light-emitting diode (LED) is another efficient light source which deserves research. The voltage and current wave shape is shown in Figure 2-7 and Figure 2-8.
Figure 2-7: LED lamp current and undistorted sinusoidal voltage
Figure 2-8: LED lamp current and voltage in case of 25th harmonic 5% distortion without phase shift

Figure 2-9: Fingerprint of LED lamp for harmonic order 13
In the LED circuit, also there is rectifier, but now the capacitor value is very small that it charges and discharges fast. So the current will follow, resulting in such a sinusoidal similar shape. Because of the capacitor voltage divider, the current is leading the voltage as shown in Figure 2-9. At low frequency (harmonic number is 3, 5, 7), as shown in Appendix D-1, Appendix D-2 and Appendix D-3, it is almost linear, behaving like a capacitor. At higher frequency, the fingerprint is becoming a clock wise star shape, as shown in Appendix D-4 to Appendix D-8. Above Appendix D-9, the fingerprint becomes more complicated. It is part clock wise, part linear.

One thing needs to be mentioned here is that the current amplitude increase is much bigger than PC and energy saving lamp. At low frequency (harmonic number is 3, Appendix D-1), the current increase is already 10 times. While for high frequency (harmonic number is 25, Appendix D-12), the current amplitude increase is up to 200 times. Taking the 21st harmonic measurement (amplitude from 1% to 10%, 0° phase shift) as an example, the current is shown in Figure 2-10.

![Figure 2-10: High increase of current at 21st harmonic](image)

2.4 Rectifier Characteristic[^6]

By comparing the simulation of personal computer, energy saving lamp and LED lamp, it is clear to see that many household devices are using AC-DC converters now. However, these rectifiers may behave differently from each other.

The typical circuit for an AC-DC converter is shown as below in Figure 2-11.

[^6]: [Personal Computer, Energy Saving Lamp, LED Lamp]
Now based on the typical circuit, simulation of PC, energy saving lamp and LED lamp has been done. The capacitor is charged by the rectified voltage.
Figure 2-14: Simulation for wave form of PC case of 25th harmonic 5% distortion without phase shift (in order to decrease the simulation time, the R, C value have been changed from figure 2-11)

Figure 2-15: Rectifier simulation circuit for energy saving lamp

Figure 2-16: Simulation wave form of voltage source, voltage on the capacitor and current before the rectifier for energy saving lamp
When the rectified voltage is higher than the voltage on capacitor, the capacitor will be charged and there is current flowing.

The most important difference for PC and energy saving light is the capacitor used in the rectifier. The capacitor used in PC is bigger than the one used in energy saving light. If the capacitor value is big enough that the voltage on it keeps almost constant, then the current will flow in phase with the voltage, just like the case of PC. While for the energy saving lamp, the capacitor value is smaller than the one in PC, from Figure 2-16, it is clear to see that the corresponding current is leading the voltage which matches the case in the fingerprint.

Then how about the phase shift for high order harmonics? It is clear from the fingerprint that for PC, when the amplitude of harmonic voltage is increased, the current is changing from in phase to leading. While for energy saving light, when the amplitude of harmonic voltage is increased, the current is changing from leading to in phase. Why this happens?

Taking the 25th harmonic as an example, source supplies 5% amplitude of 25th harmonic without phase shift to PC and energy saving light. The wave shape of voltage and current is shown in Figure 2-14 and 2-17.

It is clear to see that besides the current in phase with the peak value of voltage, there is current flowing in the sub peak value of voltage because of the harmonic. Of course, the reason is that the sub peak value of voltage is bigger than the voltage of capacitor.

For PC, when the voltage with 25th harmonic is applied, more current flows before the peak voltage value. So it is clear that the phase would be leading as shown in Figure 2-3.

For energy saving light, when source supplies the voltage with 25th harmonic, more current behind the current under clean voltage flows. So the phase is becoming less leading, as shown in Figure 2-6.
Figure 2-18: Rectifier simulation circuit for LED lamp

Figure 2-19: Simulation wave form of voltage source, voltage on the capacitor and current before the rectifier for LED lamp

Figure 2-20: Simulation for wave form of LED lamp case of 25th harmonic 5% distortion without phase shift
For the same reason as energy saving lamp, when high order harmonic voltage is applied to the LED lamp, with the increase of voltage amplitude, the phase will become less leading, as shown in Figure 2-9.

Table 2-1: Summary of rectifier characteristics

<table>
<thead>
<tr>
<th></th>
<th>Capacitor value</th>
<th>THD</th>
<th>Current phase compared to voltage under clean condition</th>
<th>Current phase compared to voltage with harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>Big</td>
<td>High</td>
<td>In phase</td>
<td>Leading</td>
</tr>
<tr>
<td>Energy saving lamp</td>
<td>Middle</td>
<td>Middle Leading</td>
<td>Less leading</td>
<td></td>
</tr>
<tr>
<td>LED lamp</td>
<td>Small</td>
<td>Low</td>
<td>Leading</td>
<td>Less leading</td>
</tr>
</tbody>
</table>

Summary of rectifier characteristics is shown in Table 2-1. From the wave form of voltage and current (Figure 2-1, Figure 2-4, Figure 2-7), it is clear now that all PC, energy saving lamp and LED lamp contain rectifier inside. Different capacitor value can be the reason for their difference behavior. Simulation proves this assumption, however, there is a pre-condition in the simulation that all the load after the rectifier is the same. While in reality, it is more complicated.

2.5 Refrigerator

Refrigerator is commonly used appliance in house all year long. It is necessary to do measurement about this device.

Figure 2-21: Fridge current and undistorted sinusoidal voltage
From Figure 2-21, it is easy to see that the fridge behaves like an inductor. The voltage phase is leading the current phase. This is understandable because the power source is connected to the motor directly for the refrigerator. And the motor appears inductive.

From the fingerprint shown in Appendix A, it is also clear to say that the refrigerator behaves as an inductor. When harmonic number is 3, the current amplitude changes only a little with the increase of harmonic voltage from 1% to 10%, while with the increase of frequency, the current grows faster. At the 25th harmonic, the current increases almost 200 times.

2.6 Inverter
Solar energy system, as a green energy source, is getting more and more attention these days. So more and more solar inverters are connected into grid, and they will bring some effects to the power system.

Figure 2-22: inverter current and undistorted sinusoidal voltage
From Figure 2-22 and Figure 2-23, it is clear to see that the harmonic component is pretty small, so the pollution that brings to the grid by solar inverters is not so serious.

While from the inverter fingerprint shown in Appendix C, it is clear to see that inverter has approximate linear behavior, especially for high order harmonics. There is an obvious phase shift between the voltage and the current, for small order harmonics (harmonic number N is 3 to 17, as shown in Appendix C-1 to C-8), the inverter appears like inductor because of the filter inside. While for high order harmonics (harmonic number N is 19 to 25, as shown in Appendix C-9 to C-12), the inverter behaves like a negative resistor. This is because the inverter measured in the experiment combines the reference source and the synchronization with the supply voltage by using the waveform shape of the supply voltage as a reference source. However, if this voltage is polluted with background distortion, the reference source will also be polluted and the current regulator of the inverter will pollute its own output current accordingly. Filtering of the pollution using such a controller is difficult. This kind of inverter has the character of a negative resistor. [7]

2.7 TV

TV is a common used household device. Making fingerprint for such a frequently used appliance is undoubtedly necessary.
From Figure 2-24 and Figure 2-25, it seems that in TV circuit; also there exists an AC-DC converter. As shown in Appendix F-1, when harmonic number is 3, there is no star shape. From the 5th harmonic to the 11th harmonic(Appendix F-2 to F-5), however, the linearity is much better; a star shape is formed in the fingerprint. The reason is that the capacitor behind the bridge is not quickly charged to the source value.
when the diode is conducting. So after the peak value of source voltage, still the source voltage is higher than capacitor voltage value for some time, and current flows which makes the current more in phase of voltage. Above the 13th harmonic, the linearity is not so good any more.

2.8 TV Problem for 25th Harmonic

When the measurement for TV was being done, there is a problem happening. When the harmonic order goes up to 25th and the amplitude goes up to 10 percent, the TV will shut down itself. This phenomenon does not happen in other devices. Then what is the TV problem?

Voltage was supplied to the TV with 10 percent amplitude harmonic; one harmonic each time and THD value is measured. (All figures are from FLUKE meter) The THD in this report is calculated with respect to fundamental component \(F_1\) as shown in (1)

\[
THD_P = \sqrt{\sum_{n>1} (F_n)^2} / F_1
\]  

(1)

Figure 2-26: THD value and harmonic component of TV in case of voltage with 3rd harmonic (10 percent, 0 phase shift)
Figure 2-27: THD value and harmonic component of TV in case of voltage with 7th harmonic (10 percent, 0 phase shift)

Figure 2-28: THD value and harmonic component of TV in case of voltage with 13th harmonic (10 percent, 0 phase shift)
Figure 2-29: THD value and harmonic component of TV in case of voltage with 17th harmonic (10 percent, 0 phase shift)

Figure 2-30: THD value and harmonic component of TV in case of voltage with 19th harmonic (10 percent, 0 phase shift)
From the Figure 2-26 to Figure 2-31, it is clear to see that with the increase of harmonic order, the corresponding harmonic current component is increasing from 40% to 70%. There is something happening at the 25th harmonic and this needs more research work. Also from the harmonic components in Figure 2-26 to Figure 2-31, it is clear to see that even if one harmonic is supplied in the voltage, many other order harmonic components appear in current.
Chapter 3  Combined Measurement

In this chapter, discussion about the device-combined situation is presented. As we know, in a house, usually there are some appliances on simultaneously. Because these devices have different behaviors, so when combined together, they may influence each other and the THD value of the POC may change.

In the measurement, one energy saving lamp, one fridge, one TV, one personal computer with monitor and one resistance (52.9 Ω) were chosen. Resistance stands for linear household devices in reality (such as cooking element, iron etc.). The THD of the POC and all the points connected to the individual appliance is measured. Voltage source supplies different voltage, one is clean voltage and the other is voltage with 5th harmonic with 3% amplitude and 180 degree phase shift. Also, the THD value of the POC is measured when single device is connected.

<table>
<thead>
<tr>
<th>Table 3-1: Current THD value for POC and each device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined measurement</td>
</tr>
<tr>
<td>POC</td>
</tr>
<tr>
<td>PC</td>
</tr>
<tr>
<td>Energy saving lamp</td>
</tr>
<tr>
<td>R</td>
</tr>
<tr>
<td>Fridge</td>
</tr>
<tr>
<td>TV</td>
</tr>
<tr>
<td>Single measurement</td>
</tr>
<tr>
<td>PC</td>
</tr>
<tr>
<td>Energy saving lamp</td>
</tr>
<tr>
<td>R</td>
</tr>
<tr>
<td>Fridge</td>
</tr>
<tr>
<td>TV</td>
</tr>
</tbody>
</table>

From Table 3-1, it is easy to see that the THD value for TV has been decrease by more than 10 percent. The reason is that the current harmonic from TV and current from other device canceled each other because they are opposite in phase. As shown in the appendix of fingerprint with harmonic order 5, it is clear to see that the harmonic current of energy saving lamp is leading the voltage while the harmonic current of fridge is lagging the voltage, so they can cancel each other and this makes the THD value smaller when they are combined together.

There is one thing seems abnormal in the table. It is the current THD value of R(Resistance). Under clean voltage condition, the THD value should be 0. However, it is more than 5 percent in the table. The error might come from the voltage source and the resistance. On one hand, even if the voltage is measured just after the clean voltage is programmed, it is hard to see a complete clean voltage. There is always some harmonics contained in the voltage. On the other hand, the resistance used in the experiment is apparently not a pure resistance. There may some inductance in the resistance. Both of them can result in the unexpected current THD value.
Chapter 4 Conclusion

For individual device measurement, fridge behaves like an inductor. Current THD value for clean grid is 14.2%. The fingerprint is quite linear. The current for inverter is quite sinusoidal and the THD value is very small. For the fingerprint, it behaves like a negative resistor. PC, TV, energy saving lamp and LED lamp all have rectifier inside which is AC-DC converter. The converters behave similar, however, there are some differences, and one reason for the difference could be the capacitance value behind the rectifier. The bigger the capacitor value is, the higher the current THD. THD for PC is 195.5% under clean voltage, for TV is 88.8%, while for energy saving lamp is 73.9%. For LED lamp, it is even lower. And these devices do not have linear fingerprints.

When different devices are combined together, some device's THD value may decrease. The reason is that the harmonic current may cancel each other because of the phase shift. So doing more research on the fingerprint of each device and to find out what combination is optimal for the POC is possible.

The measurement for this report considers only odd harmonics (3rd to 25th). Further study is to be done for even harmonics too. Moreover, more devices are required to be measured to see their influence on each other and overall impacts on current THD value at a POC.

Acknowledgement

My gratitude goes first to Professor Myrzik, for that she helped me find this traineeship. Second, I would like to express my gratitude to Shannistha, who offered me the chance to do my internship and led me into the topic. Last my thanks would go to Glenn. He gave me lots of help during the experiment and analysis. Also he helped me lot in other aspects rather than the academic field. Without his consistent and illuminating help, this report could not have been finished.

References


**Appendix**

**Appendix 1: Specifications of devices**

<table>
<thead>
<tr>
<th>Devices</th>
<th>Manufacturer</th>
<th>Type</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Saving Lamp</td>
<td>PHILIPS</td>
<td>GENIE 11W</td>
<td>220–240V, 50–60HZ</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>Whirlpool</td>
<td>ARC5754/2</td>
<td>Energy Consumption per Year in kWh: 270</td>
</tr>
<tr>
<td>TV</td>
<td>PHILIPS</td>
<td>32PFL5403D/12</td>
<td>32&quot;, 81cm LCD</td>
</tr>
<tr>
<td>LED</td>
<td>LEMNIS</td>
<td>E27</td>
<td>230V, 50HZ, 3.4W</td>
</tr>
<tr>
<td>Personal Computer</td>
<td>Retailer(aragorn)+Dell moniter</td>
<td>Monitor: 1703FPt</td>
<td>N/A</td>
</tr>
<tr>
<td>Inverter</td>
<td>SMA</td>
<td>Sunny Boy SWR 1100E</td>
<td>Nominal output: 1000W</td>
</tr>
</tbody>
</table>

N/A means not available
Appendix A

Harmonic Voltage for N = 3

Harmonic Current for N = 3

Appendix A-1

Harmonic Voltage for N = 5

Harmonic Current for N = 5

Appendix A-2
Appendix B

Harmonic Voltage for N = 3

Harmonic Current for N = 3

Appendix B-1

Harmonic Voltage for N = 5

Harmonic Current for N = 3

Appendix B-2
Appendix B-3

Appendix B-4
fingerprint of energy saving lamp

Appendix B-5

Appendix B-6
fingerprint of energy saving lamp

Appendix B-7

Appendix B-8
fingerprint of energy saving lamp

Appendix B-11

Appendix B-12
Appendix C

Harmonic Voltage for \( N = 3 \)

Harmonic Current for \( N = 3 \)

Appendix C-1

Harmonic Voltage for \( N = 5 \)

Harmonic Current for \( N = 5 \)

Appendix C-2
Appendix C.3

Appendix C.4
Appendix C-5

Harmonic Voltage for N = 11

Harmonic Current for N = 11

Appendix C-6

Harmonic Voltage for N = 13

Harmonic Current for N = 13
fingerprint of inverter

Appendix C- 7

Appendix C- 8
Appendix C-9

Harmonic Voltage for N = 19

Harmonic Current for N = 19

Appendix C-10

Harmonic Voltage for N = 21

Harmonic Current for N = 21
Appendix C-11

Appendix C-12
Appendix D

Harmonic Voltage for N = 3

Harmonic Current for N = 3

Appendix D-1

Harmonic Voltage for N = 5

Harmonic Current for N = 5

Appendix D-2

fingerprint of LED lamp
Appendix D-3

Appendix D-4
Appendix D-5

Harmonic Voltage for N = 11

Harmonic Current for N = 11

Appendix D-6

Harmonic Voltage for N = 13

Harmonic Current for N = 13
fingerprint of LED lamp

Appendix D-7

Appendix D-8
Appendix D-9

Appendix D-10

fingerprint of LED lamp
fingerprint of LED lamp

Appendix D-11

Harmonic Voltage for N = 23

Harmonic Current for N = 23

Appendix D-12

Harmonic Voltage for N = 25

Harmonic Current for N = 25
Appendix E

Harmonic Voltage for N = 3

Harmonic Current for N = 3

Harmonic Voltage for N = 5

Harmonic Current for N = 5
Appendix E-11

Appendix E-12
Appendix F

Harmonic Voltage for N = 3

Harmonic Current for N = 3

Harmonic Voltage for N = 5

Harmonic Current for N = 5

Appendix F-1

Appendix F-2
Appendix F-5

Appendix F-6
Appendix F-9

Appendix F-10
Appendix F-11

Appendix F-12