Assessment of EMI and Power Quality in Mains Power Distribution Using a Low-Cost Breakout Box for EMC Education

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Abstract—Ensuring measuring safety during electromagnetic compatibility (EMC) and power quality (PQ) measurements is crucial, especially when students are involved. To enable utilization of low-cost digitizers, a measurement breakout box was designed to measure the mains voltage via a 1:1000 resistive divider, and via a high pass filtered output (from 2 kHz to 1 MHz). Also, a current measuring Hall-Element was added to reduce the cost of performing electromagnetic interference (EMI) and PQ measurements. This paper describes measurements that students can do in the laboratory using simple, low-cost, and safe measurement devices. As an assignment, students can for instance calculate total harmonic distortion (THD), apparent, reactive, and real powers. Additionally, using Fourier, the EMI present in the mains voltage can be observed via the high pass filter outputs. The breakout box was designed to enable EMC education by means of experiments and demonstrations at a low cost.

Keywords— Crest factor, current, power, power quality, voltage, total harmonic distortion (THD).

I. INTRODUCTION

All home appliances must meet the basic criteria for electromagnetic compatibility (EMC) regulations. In-site measurements are extremely difficult and risky, particularly for big stationary equipment, because these items cannot be turned off to place the measuring instruments [1]. In that situation, the fundamental testing for the appliances must be completed prior to their release to the market. The electromagnetic interference (EMI) test in the laboratory is regarded as one of the most important tests for the appliances that will be utilized on the market.

Doing these tests in the laboratory for EMC is expensive and time consuming; however, they may be done by employing line impedance stabilization networks (LISNs) [2], which have certain limitations in terms of cost, weight, and so on. As shown in [3]-[5], there are also alternate approaches for applying the tests to big devices without the needs for the LISN.

Measuring nonsymmetrical line and neutral voltages on live mains wire is difficult and dangerous for students. The addition of loads to the power mains has an effect on the voltage distortion of the mains, which affects power quality (PQ) since these devices are regarded a source of noise. These noises may have an impact on the functioning of other equipment connected to the mains. The PQ becomes increasingly prominent when non-linear loads are put to the grid [6].

All the devices used in daily life are directly linked to the power supply, i.e., 230 V/115 V, which is not permitted for students to make measurements in the laboratory for safety concerns. As a result, it is critical to build a simple and easy-to-use device that has all the capabilities for tests to evaluate the performance of the mains after addition of loads and assessment of the EMI and PQ combined in one case and performs its operation securely for educational purposes. The paper's major goal is to target high school or low technical students for making safe, simple, compact measurements for low rated appliances for EMC investigation.

This paper will simply demonstrate a compact suitcase that may be utilized for instructional purposes. In this study, the authors conducted a few measurements to examine the purpose of the device for evaluating the mains’ voltage and current drawn by different loads, EMI created by different loads and demonstrating the distortion caused by adding these devices for mains operation. All of these measurements serve the same purpose: to perform it as safely as possible so that the students may do it without any precautions.

The following sections will provide brief explanations of the device used for simply showing many measurements securely for students to utilize in the laboratory, supported by measurements for different loads. This paper is structured as follows: Section II provides a detailed explanation of the suitcase as well as the measurement device employed. Section III contains measurements and discussions for various types of loads, followed by the conclusion in section IV.

II. COMPLETE DESCRIPTION OF THE SUITCASE

Because this article is intended for instructional purposes, the entire description of the suitcase and its contents is offered in this section. The suitcase is divided into three sections that are completely compact, low cost, and safe for students to use. It includes the breakout box, as well as a low-cost digitizer and current probe. The following subsections provide a summary of each part.

A. The breakout box:

A breakout box for hand-on educational purposes has been developed, which combines voltage and current measurements in a single box.
A schematic overview can be seen in Fig. 1 and the result in Fig. 2. Relatively expensive current and differential voltage probes aren’t required to safely perform mains voltage (230V/115V) connected measurements. The box consists of two PCB’s stacked together (as shown in Fig. 2), which is eventually enclosed in a plastic box, so no live parts can be touched.

The box has 3 distinct measurement options:
- 1:1000 voltage measurement.
- 1:50, high-pass voltage measurement.
- Current measurement of a connected device.

The 1:50 high pass voltage measurement is described in [7]. In case of the current measurements, a Commercial Off-The-Shelf (COTS) hall effect current transducer is utilized. The current sensor output has been buffered and amplified to offer two distinct ranges, 80 mV/A and 800 mV/A. Note that for EMC education, one would like to be able to measure differential mode (DM) and common mode (CM) currents as well. For this purpose as one can see in Fig. 2, the line, neutral and protected earth wires are looped outside of the box, so an external current probe can be connected.

B. PicoScope:

As previously mentioned, the setup is entirely built on a low-cost design, thus all the supplementary instruments utilized are similarly low-cost purchases. Note that many alternatives exist, however in this case the two channel PicoScope 2204A, shown in Fig. 3, was used. It has an 8 bit vertical resolution, 10 MHz bandwidth and a 1 MΩ input impedance, which indicates that it is not a top of the line product, with limited dynamic range and bandwidth which is representative for student equipment. A benefit is that its software contains numerous features, including the ability to calculate the RMS and average values, as well as the total harmonic distortion (THD) of the two signals. Which could also be done via postprocessing, if the waveforms were recorded, but this requires some additional knowhow that might be not suitable in case of for instance high-school students. Utilizing readily available features for the Picotech software, it is possible to subtract, add and multiply the two signal during a measurement. These capabilities will be shown in the results section, where it will assist students in determining apparent power, active or reactive power, and even THD. Which is regarded as one of the most basic tools for students for displaying and preserving signal data.

C. External current sensors:

The last element is an AC current sensor SCT-013 (15A max) as shown in Fig. 4, which is used to measure the DUT’s CM, DM, and line or neutral currents [8]. In a single phase system the DM and CM current can be calculated as follows:

$$I_{DM} = \frac{I_L - I_N}{2}$$  \hspace{1cm} (1)

$$I_{CM} = \frac{I_L + I_N}{2}$$  \hspace{1cm} (2)

Utilizing the super positioning effect of fields inside the current sensor, one can directly measure them by measuring the line and neutral current in the same direction (CM), and by twisting the wire in opposite direction (DM). Students can also compare the direct measurement with a digital signal processing version by utilizing two channels to measure line and neutral current separately. In this study, the authors measured the current of the DUT and compared it to the output from the breakout box's BNC ports for simplicity and demonstrating the limited sensitivity of the Hall-element.
III. MEASUREMENTS AND RESULTS

In this section, the authors will show the measurements that were taken with various types of loads directly connected to the distorted mains to demonstrate the usage of the box. As an example of exercises for the students, processing was performed on the mains voltage, the load current and eventually combining both for power calculations.

The first measurements are of the mains voltage and the current drawn by various types of loads used as a DUT. The second set of measurements are the box's characteristics that measure the NM line/neutral voltage and the DM voltage before and after adding different loads. The final measurements are based on the scope's built-in capability for determining power, using basic formulas.

A. Voltage and current:

Fig. 5 sketches the measurement setup, including images of the loads that were used. The four different loads that were investigated are:

- an incandescent lamp.
- a light emitting diode (LED) lamp.
- a compact fluorescent lamp (CFL).
- a switched mode power supply (SMPS).

Except for the incandescent light, all these loads are non-linear. The major goal of adding different types of loads is to demonstrate that switching from linear to non-linear loads influences emissions and its effect on the mains. The aggregation of many of these power efficient loads will also have an impact on the distortion of the mains' waveform. The quality of the power can be examined for instance with crest factor (CF), power factor (PF), and THD. These non-linear loads cause a lagging factor in relation to the mains voltage, which has a detrimental impact on the PF and PQ of the mains [9].

The waveforms for the voltage and current, as measured from the breakout box together with the current sensor are shown in Fig. 6. With the voltage resulting from the 1:1000 resistive divider inside the breakout box. It can be clearly seen that it is not a perfect sinewave as one (students) might expect. The waveform is distorted, as most people within the EMC community will attest, but for students this might be a good hands-on insight. Since the voltage has been scaled to down to safe levels, the measurement box can now be connected directly to a digitizer of choice and can done in conjunction with a current.

As can be seen in Fig. 6(a), the incandescent lamp’s current exhibits a linear relationship with the input voltage, and therefore also being distorted, without a phase shift. Fig. 6(b) shows a unipolar current draw by the LED, while the CFL lamp is utilizing a full-bridge rectification, thus showing bipolar current. Both are only drawing current in a very short time period.

B. Current processing:

Typical exercises for students include extracting PQ parameters from waveform data. Here it is shown that the results for the CF and THD. Of course the calculation of THD can also be extended to the voltage, but demonstrative purposes this is omitted here.

\[ CF = \frac{i_{pk}}{i_{RMS}} \]  

\[ THD = \frac{i_{RMS}}{i_{RMS}} \]  

CF can be calculated from the current via Eq. (3). It is the ratio of the peak to the RMS value:

The parameter gives an indication if the waveform has a sharp peak. As is well known, the CF of a non-distorted sinusoidal signal is \( \sqrt{2} \), as it is the conversion factor between the peak and RMS values. From the values in Table I as predicted, the incandescent bulb has a CF of 1.41, while both LED and CFL have the sharpest waveforms. A CF value of 6.0 and 3.7 for LED and CFL respectively. This agrees with the qualitative observation from Fig. 6, but as just shown, it can easily be quantified by students. Connecting qualitative observations with quantifiable results is considered to be a key educational tool in EMC.

Next to the CF, the distortion of the current can also be calculated (as well in case of the voltage). There are multiple definitions for distortion, but in the PQ domain of EMI, the most commonly used is THD. THD can be calculated via a Fast Fourier Transform (FFT) or Fourier Series and comparing the harmonical content with the content at the fundamental frequency according to Eq. (4). In our case \( i_1 \), which is the fundamental value, is at 50 Hz. Table I displays these calculated THD values for all currents drawn by the loads, as well as the fundamental values of the current.

\[ THD = \sqrt{\frac{\sum_{n=2}^{\infty} i_n^2}{i_1^2}} \]  

It can be qualitatively observed from the waveform that the current drawn by LED lamps is the largest distorted signal, which is supported by the quantitative data in the table. The current from an incandescent lamp, on the other hand, is the least distorted since it is a linear load, thus it gives an indication about the distortion present in the mains distribution network.

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TABLE I. RMS, THD\( \delta \), AND CF FOR THE CURRENTS DRAWN BY LOADS

<table>
<thead>
<tr>
<th>Load type</th>
<th>( i_{RMS} ) (mA)</th>
<th>( i_{RMS} ) (mA)</th>
<th>THD( \delta ) (%)</th>
<th>( i_{pk} ) (mA)</th>
<th>CF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incandescent lamp</td>
<td>119</td>
<td>118.9</td>
<td>3.8</td>
<td>168</td>
<td>1.41</td>
</tr>
<tr>
<td>LED</td>
<td>10.2</td>
<td>4</td>
<td>236.8</td>
<td>60.8</td>
<td>6.0</td>
</tr>
<tr>
<td>CFL</td>
<td>34.8</td>
<td>23.7</td>
<td>107.6</td>
<td>127.6</td>
<td>3.7</td>
</tr>
<tr>
<td>SMPS</td>
<td>24.5</td>
<td>22</td>
<td>49.5</td>
<td>47.4</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Note that our digitizer of choice (PicoScope) provided this calculation in their software (similar to other oscilloscope manufacturers), which could be useful for students that are less familiar with processing raw waveform data, or even to give a validation for their own calculation.

Fig. 7 compares the currents from obtained by the internal (the box) and external sensors (additional sensor) for CFL. As can be observed, as the load draws hardly any current. The Hall-element used, has a sensitivity of 800 mV/A. This lack of sensitivity together with the EMI being generated by the on-board power module low currents will be highly distorted. The main objective of the box is to be used with higher power loads, that can be found in typical industrial or household environment. Students can for instance get acquainted with the power drawn (and EMI generated) by a washing machine, a dishwasher, TV, personal desktop computer, Wi-Fi router etc. etc. For ease of demonstration we show here how the box functions even with low power rated loads. Fig. 8 Clearly shows the high frequency noise that is expected from the measurement box.

C. EMI above 2 kHz:

PQ concerns itself with the fundamental frequencies of 50/60 Hz and approximately 50 of their harmonics. Therefore the domain ranges approximately up until 3 kHz, however an increase in reports of inference cases happening in the from 2 kHz to 150 kHz range was observed [7]. As was also previously explained in [7], a breakout box was created to observe and analyze the low frequency EMI that already exist in the mains distribution network. As was described in Sec. II, the educational tool developed here also incorporates that particular measurement technique.

As stated before, in the description of the box, it allows for the measurement of unfiltered NM line voltage, filtered NM line voltage and DM voltages. Fig. 8 (a) shows the produced noise for the mains voltage before filtering, whereas Fig. 8 (b) and (c) show the NM filtered voltage and DM voltage, respectively.

The most noteworthy aspect to note here is that the noise generated before and after the loads is the same in all
scenarios. As a result, the influence of these various loads is minor and may be ignored, apart from the results for the mains voltage shown in Fig. 8 (a) for the unfiltered voltage where the low order harmonics (noises) cause small changes when compared to the filtered voltage shown in Fig. 8 (b) by about 20 dBV. This signifies that the source's noise is the most prominent. In that circumstance, the main goal of LISN is necessary, which isolates the noise from the source to measure the load's noise properly which in our case still very low.

Since we know the NM and DM noises, we can calculate the CM noise by subtracting DM from NM. However, because both sounds are almost identical as seen from Fig. 8 (b) and (c), the CM noise will be close to zero.

D. Power calculations

Power measurement and calculation can be done utilizing the PicoScope's software capabilities, or by processing the digitized waveforms, which is also a great student exercise with a validation possibility. Using the scope, the RMS value of both voltage and current can be determined internally using the signal's RMS value computation. The apparent power \( S \) can then be calculated by multiplying both values. The active power \( P \) of the load may be calculated using the scope by determining the phase shift between the two signals. As a result, the load's power factor (PF) and reactive power \( Q \) may be calculated using both apparent and active powers. The active and reactive power may then be computed using the calculations below.

\[
S = V_{\text{rms}} \cdot I_{\text{rms}} \quad (5)
\]

\[
P = V_{\text{rms}} \cdot I_{\text{rms}} \cdot \cos(\theta) \quad (6)
\]

\[
Q = V_{\text{rms}} \cdot I_{\text{rms}} \cdot \sin(\theta) \quad (7)
\]

In this subsection, \( S \), \( P \), and \( Q \) are computed to assess the PQ of the mains when a CFL is added as a load. The PF must first be calculated, which may be done using the following equation:

\[
\text{PF} = \frac{\cos(\alpha)}{i_{\text{rms}}} \quad (8)
\]

Here, \( \cos(\alpha) \) is defined as the displacement factor (DF) which is the phase difference between the fundamental 50/60 Hz for both voltage and current. FFT may be used to calculate DF by displaying the phase angle for the fundamental values. After performing FFT, it was discovered that the DF is about '1', indicating that there is no phase angle between the two fundamental values. Then, in this case, DF is simply determined by two factors: the RMS value of the current and its fundamental, as presented in Table. I. It should be noted that PF is the same as \( \cos(\theta) \), which is used to calculate active power. Referring to the data in Table. I, \( \text{PF} = 0.68 \), hence the angle will be 47.1°. Using the same method as for obtaining the RMS value of the current, the FFT results reveal that the RMS value of the voltage is 237 V. These data yield apparent, active, and reactive powers of 8.2 VA, 5.6 W, and 6 VAR, respectively.

Because the FFT results show that there is no phase angle between the fundamental values of both voltage and current, the phase shift between the two signals may be found using the scope and the findings can be compared to estimated approaches conducted using FFT. The scope output for these values is 238.9 V for voltage and 36.7 mA for current. The phase difference between the two signals is 45°. These values are almost exactly the same as the computed value. The apparent power is 8.76 VA, the active power is 6.2 W, and the reactive power is 6.2 VAR, according to the scope findings.

The breakout box is a very valuable tool, especially for undergraduate students who have started an EMC course that may be linked with the lectures, because it broadens their understanding of addition of loads that contaminate the power mains and how it can be monitored. The results showed that the mains have a distorted sine wave, and even some electrical engineers are unaware that we have such voltage in the power mains. Finally, differential voltage probes are too expensive to employ, thus this box assists in keeping measurements affordable, and tangible.
IV. CONCLUSION

This study provided a safe and low-cost educational tool for investigating the power quality based on fundamental voltage and current measurements, with the extension towards low frequency EMI. It can easily be used for instructional purposes (even by non-technical students) with the goal of showcasing the disturbances that are introduced by different loads and the effect on the mains power supply it has. As was shown, the breakout box can be used with simple low power loads when it is combined with a more sensitive current probe. The box allows for safe and easy measurement of the NM line voltage, NM line current, filtered NM voltage, and filtered DM voltage. It was also shown that the measurement results can be analyzed with software, resulting in THD and CF values.

REFERENCES


