Sensitivity of static energy meter reading errors to changes in non-sinusoidal load conditions

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Abstract— **Previous studies regarding static energy meter errors under non-sinusoidal load conditions have shown that these meters can produce erroneous readings. This paper describes an investigation done using loads consisting of a commercial lighting dimmer in combination with either a resistive heater or an array of various energy-saving lamps. Dimmer impedance and phase firing angle were gradually adjusted to change load conditions. Several meters showed dramatic variations in metering error under different load conditions. In the most extreme case, metering errors ranged from five times the energy consumed by the load to registering almost no energy. Though perhaps not typically found in households, the load combinations used in this study were able to highlight sensitivities of different static energy meters to changes in load conditions.**

Keywords — static energy meter; metering error; electromagnetic interference; accuracy; impedance; phase firing angle.

I. BACKGROUND

A. Static energy meter reading errors

Some household static energy meters are known to give erroneous energy readings when exposed to certain extremely non-sinusoidal current signals. Studies conducted by the University of Twente (UTwente) highlight the fact that energy meters can produce considerable errors when exposed to certain types of interference [1], [2]. These tests have been reproduced by Van Swinden Laboratory (VSL) on a larger variety of meters with similar results [3]. In these investigations, resistive and non-linear loads were used in combination with a phase firing dimmer. Meters from different manufacturers and meters using different current sensor technologies appear to produce errors under a range of conditions, with meters employing Rogowski coils for current measurements being the most susceptible.

The magnitude of the energy metering error depends on external factors, such as load current amplitude and rise time of the current variations [3]. Little information on the exact mechanisms causing these errors is available, as details of the internal working principle of static energy meters is kept confidential by manufacturers. The investigation documented in this paper attempts to characterize static energy meter reading errors under different load conditions.

B. Conducted electromagnetic interference of household loads

Compact fluorescent lamps (CFL) and light emitting diode (LED) lamps make use of rectifiers and switch-mode converters to convert the grid voltage to required levels. Non-linear operation of the electronic components results in harmonic currents and other unwanted high frequency emissions [4].

To improve the current waveform, energy saving lamps implement various forms of power factor correction, smoothing out the current drawn by the lamps into a shape better resembling the applied voltage waveform. This power factor correction reduces harmonic emissions, improves current crest factor and may be required for electromagnetic compatibility compliance.

The shape of the current waveform withdrawn by an energy-saving lamp depends on the type of power factor correction applied [5]. It is also sensitive to the impedance of the supply system, the voltage total harmonic distortion and to the type of other loads connected onto the same network [6].

European standards, such as the IEC 61000-3-2 [7], require household loads up to 16 A per phase to comply to harmonic emission limits that depend on the type of load and load size. These limits are in place to contain voltage waveform distortion. Electronic loads that consume less than 75 W (excluding lighting equipment) are excluded from these harmonic limits, as their impact on voltage and current distortion is assumed to be negligible due to low power consumption. However, harmonic emissions resulting from multiple poorly compensated rectified loads are often in phase [8]. If a sufficient number of these loads are present, then the resulting harmonic emissions, fast transients and high peak currents could negatively impact energy meter accuracy. In addition, electronic loads with high switching frequencies, and devices that employ power line communication also produce 2 kHz to 150 kHz emissions that could also influence accuracy of static energy meters [4].

II. INVESTIGATION

A. Aim of the investigation

Previous work has shown a correlation between loads with high peak currents or fast current transients and metering errors in static energy meters [3]. Sensitivity of non-linear load characteristics to network conditions implies that the same load connected under different supply conditions could result in different static energy meter errors. Loads replicated under laboratory conditions, or identical loads connected to different power sources may not be able to replicate these errors, which is concerning for meter compliance tests based on replicated load
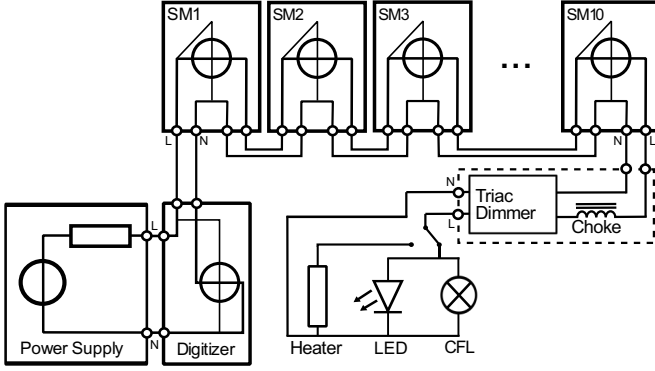
Fig. 1. VSL household energy meter test setup for non-linear loads

Fig. 2. Photograph of the dimmer choke inductor

conditions. To investigate the sensitivity of meter errors to load conditions, the input impedance of a dimmed load was systematically varied. The impact of dimmer phase firing angle and the impact of additional load current on metering error was also investigated in separate tests.

B. Test Setup

The VSL test setup for evaluating EMI effects of non-linear loads on energy meters [3] is based on the test setup used in the UTwente studies [1], [2]. A schematic of this setup is shown in Fig. 1. A series of static energy meters measure energy consumed by a non-linear load when supplied by a 230 V, 50 Hz sinusoidal voltage from a 4.5 kVA precision AC power supply with a steady-state output impedance of 7 mΩ.

Measurements are benchmarked against a wideband reference energy meter, which consists of a wideband digitizer sampling at 1 MSa/s [9] using a wideband shunt [10] for current measurement and a wideband voltage divider. Uncertainty of the measurement setup is less than 0.02% for voltages and currents at 50 Hz and less than 0.5% for the non-sinusoidal waveforms used in this investigation [3].

The static energy meters emit a pulse of light each time a preset number of watt hours is recorded. These pulses are logged using optical sensors and can be counted to calculate the accumulated watt hours measured by each meter. Pulse measurements are time stamped and the accumulated energy compared to the energy measured by the reference meter (digitizer) within the same period. The resulting energy metering error becomes apparent within minutes.

C. Static energy meters tested

Ten different household static energy meters of accuracy class A were selected. These meters come from various manufacturers and a number of them have produced erroneous results in previous studies. They make use of different current sensing technologies including Rogowski coils (4), Hall effect sensors (2), shunt resistors (2) and current transformers (2). To ensure that tests are conducted under comparable load conditions, all ten meters are measured simultaneously under the same test conditions.
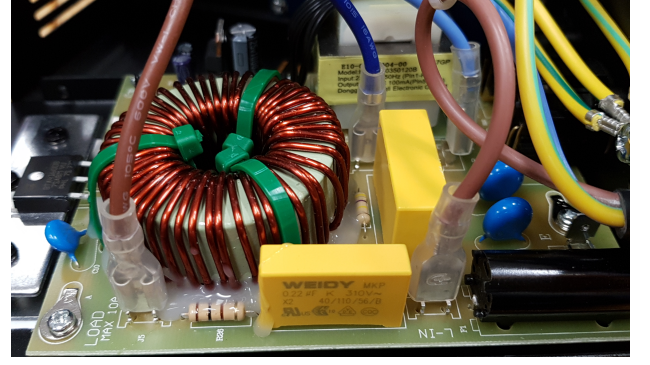
D. Energy metering error

Metering error was defined as the difference between the measurements of the static meter energy E_{MUT} and the reference meter energy E_{ref}. Since the static meters do not register energy consumed by the meter itself, E_{ref} is corrected for static meter energy consumption by subtracting the energy consumed by each subsequent energy meter (typically between 1 W and 2 W per meter) from the energy measured by the reference instrument. This results in an average meter reading error ε_{MUT} over the measurement period:

$$\varepsilon_{MUT}(n) = \frac{E_{MUT}(n) - E_{ref}(n)}{E_{ref}(n)} \times 100\% \qquad (1)$$

Where n denotes the meter number and $E_{ref}(n)$ the reference energy corrected for meter energy consumption.

E. Load

A leading-edge phase-firing dimmer connected to either a non-linear load of multiple energy saving lamps (CFL and LED) or an 800 W heater (resistive load) was used. These load combinations are similar to those previously used in the UTwente and VSL studies [1], [3] and although not typically found in European households, are proven to cause static energy meter reading errors.

The dimmer used is a commercially available leading-edge phase-firing dimmer for incandescent lamps, rated at 10 A. Internal switching is done by a TRIAC and the input is filtered by a 373 µH inductor shown in Fig. 2. Firing angle is digitally controlled and accurate to within 1° of the 50 Hz phase angle.

For the first set of tests, supply impedance was varied by changing the filter (also referred to as a choke) inductance. The number of windings around the core was systematically reduced which resulted in measured inductances of 373 µH, 221 µH, 147 µH, 113 µH, 86 µH, 56 µH and 35 µH. After this, the inductor was removed completely.

For these tests, the dimmer phase-firing angle was set to 110° as this phase firing angle lies between 90° (50% phase firing) and 122° degrees, where insufficient energy causes the CFL and LED load combination to visually flicker. The same dimmer setting was used for both the resistive and non-linear load to
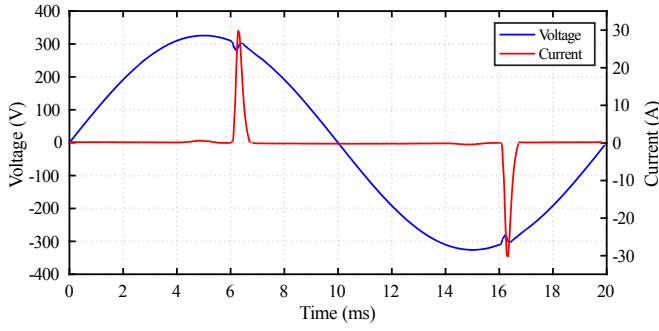
(a)
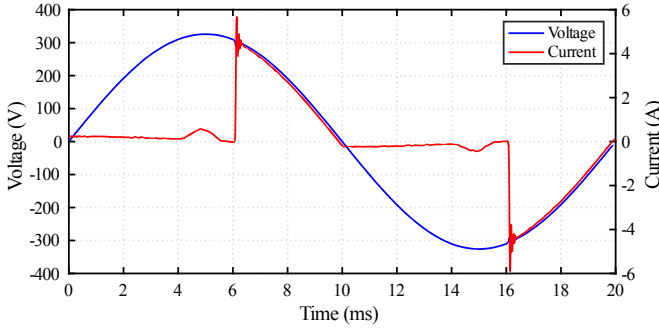
(b)

Fig. 3. Voltage and current waveforms for (a) 110° dimmed CFL + LED lamps and (b) 110° dimmed heater
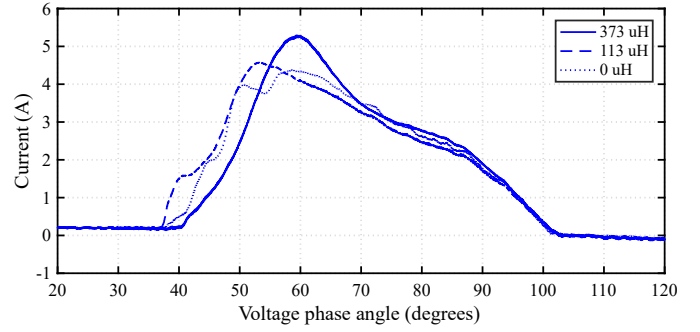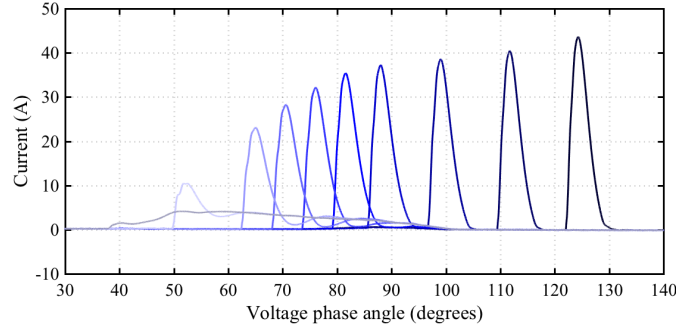

Fig. 4. Undimmed CFL + LED load waveform at different dimmer inductances

Fig. 5. CFL and LED current waveforms at dimmer phase firing angles between 35° and 122° with 56 µH dimmer inductance

isolate the effect of inductance from phase firing angle. At this dimmer setting, both load combinations consume approximately 270 W of active power.

A second set of tests were conducted using different phase firing angles for the CFL and LED load combination at a fixed inductance of 56 µH. These tests were then repeated using a similar dimmer with a choke inductance of 26 µH as additional comparison.

F. Load waveforms

Voltage and current waveforms of all tests were recorded by the wideband reference energy meter. This section illustrates how changes in load parameters changes the load current waveform.

Fig. 3(a) shows voltage and current waveforms for a CFL and LED load and in Fig 3(b) for a resistive load when the firing angle is set to approximately 110°. With this dimmer setting, the lamp current has a high peak and high crest factor. The resistive load current linearly relates to the dimmed voltage but oscillates at a higher frequency after switching. Current drawn due to the power consumption of the static energy meters is centered around the voltage peaks, as can be seen in Fig. 3(a) and Fig. 3(b). This additional power consumption is small compared to the connected load and has negligible influence on the calculated meter errors after correction.

Changes in dimmer inductance resulted in changes in load current characteristics for the non-linear lamp combination, even when not being dimmed. Fig. 4 shows the current waveforms of the undimmed CLF and LED load for three dimmer choke inductance levels (373 µH, 113 µH and 0 µH). The change in

waveform shape highlights the sensitivity of rectified non-linear loads to network conditions, as emulated with the changes to dimmer inductance.

Waveform characteristics are also influenced by the phase firing angle of the dimmer. Peak current amplitude increases as phase firing angle is increased, since the control circuits of the lamps attempt to regulate lumen production by keeping power consumption constant. Fig. 5 shows the load current of various firing angles for tests conducted with a dimmer choke inductance of 56 µH. Due to the dimming applied, the power factor correction of the individual lamps becomes ineffective. Once the firing angle is low enough that the load operates under grid voltage conditions (undimmed) for at least a part of the cycle where the load normally draws current, this negative effect is reduced and peak current decreases. At choke inductances less than 56 µH, the dimmer is unable to energize the CFL and LED combined load and only provides an undimmed voltage as output. For the resistive load, the dimmer functions for all inductor values and with the choke inductor removed.

Load currents of the CFL and LED lamp combination when dimmed at a phase firing angle of approximately 110° and connected with different dimmer choke inductances are shown in Fig. 6(a). Peak current increases and rise time decreases when reducing supply impedance. Fig. 6(b) shows the differential current of the same waveform. Higher levels in dI/dt are present and higher frequency currents increase in amplitude, which becomes notable for frequencies above approximately 1 kHz as shown in Fig. 6(c).

Similar to the CFL and LED load, the dimmed resistive load waveforms shown in Fig. 7 have increased peak current and a
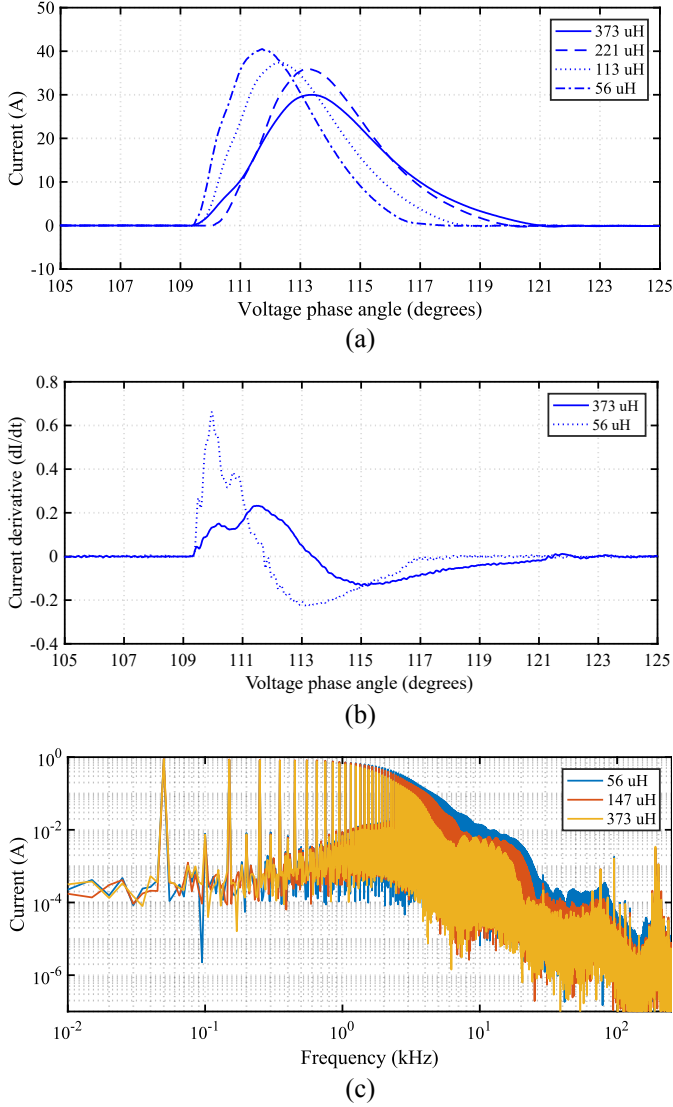
Fig. 6. Dimmed CFL+LED load current (a), current derivative (b) and FFTs (c) at different dimmer inductances and a 110° phase firing angle
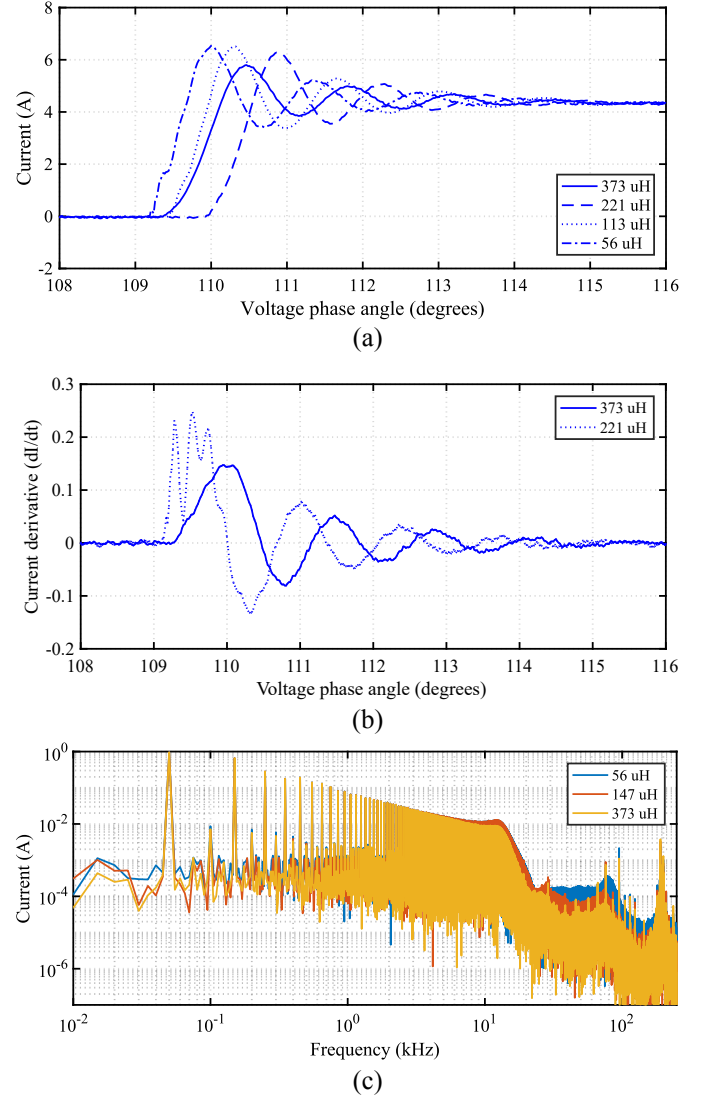

Fig. 7. Dimmed heater load current (a), current derivative (b) and FFTs (c) at different dimmer inductances and a 110° phase firing angle

shorter rise time when reducing the supply inductance. Peak current amplitude and maximum dI/dt are lower than that of the dimmed CFL and LED lamp combination. An increase in higher frequency currents is apparent above approximately 10 kHz. It is expected that the dimmed CFL and LED load combination will cause greater energy reading errors than the resistive load combination.

III. TEST RESULTS

A. Meter reading error for different impedances

Ten static energy meters where grouped based on the current sensing technology employed. Fig. 8(a) shows the static meter error for a range of dimmer choke inductance values for the resistive load and in Fig 8(b) for the CFL and LED lamps, both dimmed at a firing angle of 110°.

From Fig. 8(a) it can be observed that with the dimmed resistive load connected, two of the Rogowski-based energy meters have erroneous energy readings (Meter 3 and Meter 4). This error increases as dimmer impedance is reduced. The effect of impedance on metering error of the rest of the energy meters is negligible when connected to the dimmed resistive load for all inductance values investigated.

The dimmed CFL and LED load resulted in large positive or negative errors for eight of the ten static meters selected in this study, as shown in Fig. 8(b). Both energy meters using CTs (Meter 5 and Meter 6) measure energy up to 33 % less than the reference value. Hall effect meters (Meter 7 and Meter 8) are unaffected by the change in supply impedance. One shunt meter (Meter 9) recorded less than 20 % of energy consumed (80% error) at all dimmer inductances of 221 μH or lower, while the other shunt meter (Meter 10) was unaffected. Two Rogowski meters (Meter 1 and Meter 2) measured increasingly incorrect as supply impedance is reduced. A maximum error of 210 % was found at Meter 1. An active power measurement error of almost 300 W. Metering error for Rogowski coil energy meters are
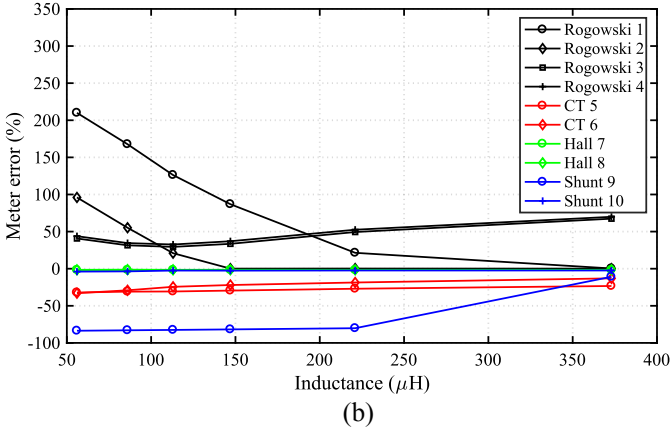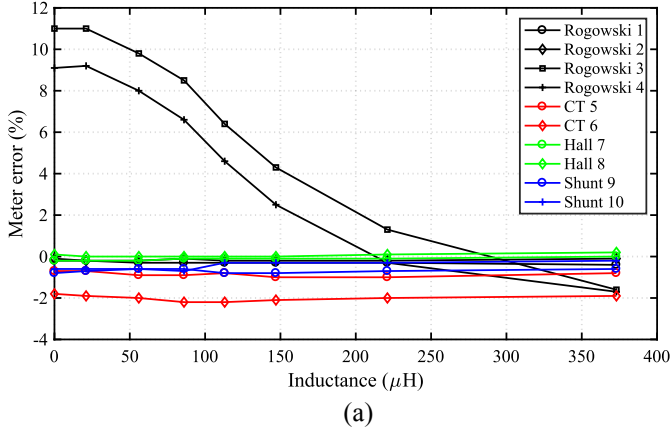
(a)

(b)

Fig. 8. Effect of dimmer inductance on static meter error for (a) resistive load and (b) CFL + LED lamps at a phase firing angle of 110°

(a)

(b)
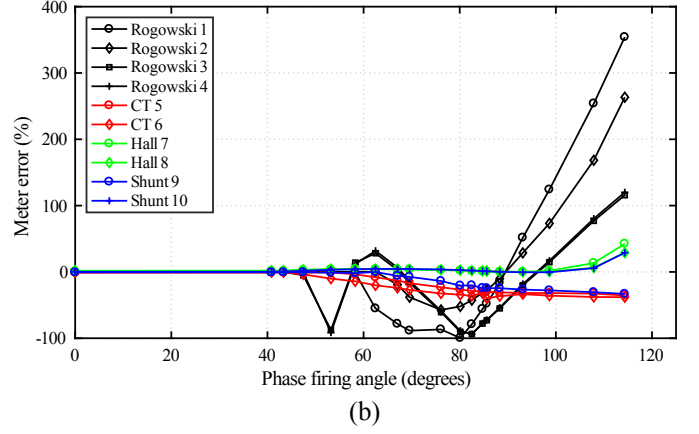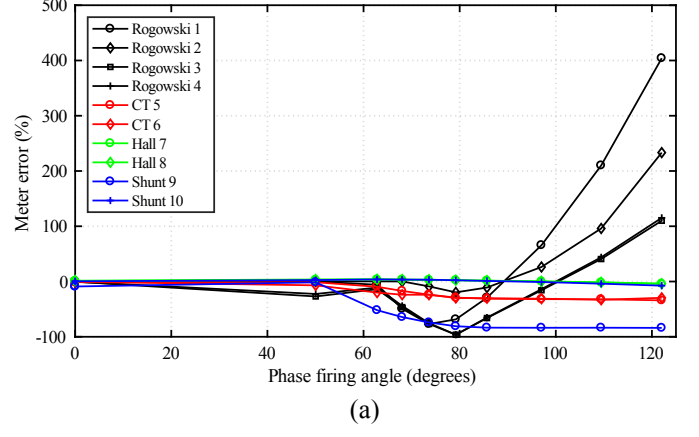
Fig. 9. Effect of dimmer phase firing angles on static meter error for two different dimmers with a choke inductance of (a) 56 uH and (b) 26uH

expected to increase at lower inductance levels for the dimmed CFL and LED load.

B. Effect of phase firing angle on meter error

Fig. 5 shows that the shape and amplitude of the current waveform changes significantly as the dimmer firing angle is varied. The impact of firing angle on metering errors was investigated using the CFL and LED load. As an additional comparison, the test was repeated on a second dimmer with a modified choke inductance of 26 µH. Fig. 9 compares the two test results.

Metering error trends for both dimmers are similar, but errors are more extreme for the second dimmer which has a smaller choke inductance. Errors also become larger as firing angle increases. The largest errors were obtained at a 122° firing angle for the energy meters using Rogowski coils. A measurement error in energy of 400 % was obtained by Rogowski meter 4 at a firing angle of 122°. This corresponds to an average error in active power measurement of 1350 W, five times the actual value for active power consumed in the load.

Metering errors reach a minimum for Rogowski meters 1 and 2 at a firing angle of approximately 90°, which is also the phase firing angle where compliance tests for phase fired waveforms

are conducted [11]. Rogowski meters 3 and 4 have near zero error at a firing angle of approximately 100°. At smaller firing angles (less dimming), the error changes from positive to negative until no energy is registered near 80°. For the second dimmer, this also happens near 55°. Meter 7 (Hall) and Meter 10 (shunt) only start to show metering error at firing angles larger than 100° when connected to the second dimmer. All other meters produced negative metering errors at firing angles larger than 40°, with errors increasing as firing angle is increased.

C. Metering error with and without additional resistive load

An 800 W resistive load (without dimmer) was connected in parallel with the dimmed CFL and LED load of approximately 270 W. To compare meter errors across power levels, the average power registered by each meter over the measurement time was calculated. Table I shows the difference in error for each meter (expressed in watt) when measured without and with the additional resistive load.

Minimal difference in metering error is seen in energy meters using Rogowski sensors. The energy meters using current transformers are the most affected by additional load. Energy meters 8 and 9 using Hall effect sensors and energy meter 10 using a shunt current sensor show negligible change in metering error.

TABLE I.   METER ERRORS WITH ADDITIONAL LOAD

Meter	Sensor type	Error without heater (W)	Error with heater (W)	Difference (W)
1	Rogowski	689	708	19
2	Rogowski	229	247	18
3	Rogowski	173	153	-20
4	Rogowski	181	163	-18
5	CT	-76	-104	-28
6	CT	-58	-11	47
7	Hall	-8	-10	-2
8	Hall	-8	-9	-1
9	Shunt	-63	-86	-23
10	Shunt	-15	-15	0

In practice, multiple linear and non-linear loads are connected simultaneously. If the combination of loads causes large peak currents or fast current transients similar to those seen in this investigation, energy metering errors could be present regardless of the linear portion of the load.

IV. CONCLUSION

The energy metering errors of ten different static energy meters with four different current sensing techniques were characterized under different load conditions. The meters were selected from a batch of more than 50 different meters, based on the metering errors they showed in previous studies. By systematically varying the test conditions, more insight has been gained on the behavior of the metering errors.

A reduction in impedance connected to the load resulted in more extreme errors. For the most extreme test conditions, meters from all four different current sensing techniques showed metering errors. At the impedance levels investigated, the dimmed CFL + LED load produced large errors, whereas the dimmed resistive load only affected the accuracy of two meters employing similar current sensor technologies at the phase firing angle investigated. The metering errors of affected meters connected to a specific load can be positive, negative or negligible depending on the meter technology and phase firing angle of the dimmer. Generally, an additional linear load is measured correctly, also in the presence of conducted EMI causing meter errors.

The high sensitivity of the energy metering errors to test conditions poses a challenge for the reproducibility of this type of meter accuracy tests. For reproduceable results, test conditions should be well documented, and ideally, voltage and current waveforms should be generated using amplifiers to eliminate any variation in loading conditions.

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