Significance of Non-Persistence on Waveform Parameters of Non-Linear Loads

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***Abstract*—In this thesis non-persistence is investigated for different non-linear loads and the effect it has on the waveform parameters. A waveform is non-persistent when the form differs from cycle to cycle. The waveform parameters are used to describe voltage and current in power quality, electromagnetic compatibility and research into faulty measurements of static electricity meters. Some commonly used parameters are investigated for non-persistence per cycle over one continuous minute. The different loads used were a dimmer, a water pump and a dimmed television. It was discovered that calculating the crest factor over multiple cycles could significantly increase the value compared to calculation over a single cycle. Using the IEC standard the found peak current could be 7% lower than the actual maximum value. The phase firing angle is the moment the current starts conducting and can be calculated for the positive and negative half, which could yield in different values. Based on the results an advise is given to check persistence, when working with parameters in non-linear loads.**

I. Introduction

Parameters are used to identify potential risks for e.g. electromagnetic compatibility (EMC) or power quality. These parameters are usually simplified to a single number, since it is expected to be the same for every cycles. Some loads however change their current waveform from cycle to cycle. Examples are a water pump [1] and a television connected to a dimmer [2]. Changing waveforms could mean that a single number for a parameter is not representative for the whole wave. During research into faulty measurements of static energy meters [3] waveforms, which could cause errors, are described using parameters. These parameters are used to find similar waveforms in the field that could potentially cause errors [4]. Non-persistence could cause these parameters to be non-representative, change for each measurement or change based on the method of measuring and processing.

The IEC standard [5] for assessment of power quality already dictates measuring over multiple cycles. However only a period of ten cycles is chosen, which is a trade off between more precision with extra cycles on one hand and needing more processing power and data storage on the other. Also parameters are calculated in a simple way by taking the average or an extreme. This is acceptable if the wave is the same every cycle, but could hide information for non-persistent waveforms.

This research will investigate the persistence of the current of different non-linear loads with measurements of one minute. The general shape and deviation of the waveform can be seen by plotting different cycles on top of each other. Additionally parameters are calculated to quantify the non-persistence. These parameters are plotted in e.g. a histogram to examine the spread, but also against time to identify periodicity and patterns. Lastly a comparison is made between calculating the parameters over single and multiple cycles to see if the current methods can cause errors.

First the paper will give a technical background discussing various parameters used in the research and the IEC standard for gathering data. Secondly the measurement plan and data processing are described. In the results some interesting findings for different parameters are highlighted. Recommendations for future research into persistence are given in the discussion. Lastly in the conclusion an advice is given to researchers, who are interested in using current parameters for non-linear loads.

II. Technical Background

A. Waveforms parameters

The investigated parameters are the same as the ones used in the research into the faulty measurements of static energy meters [6]. Since the load has a bigger impact on the current compared to the voltage, the current waveform will be less persistent and thus most interesting for this research. The studied current waveform parameters are rise time, fall time, current slope, crest factor, peak current, power factor, phase firing angle, energy and charge.

The rise time is the time it takes to go from 10% to 90% of the amplitude and the fall time is time going from 90% back to 10% [7]. The current slope is described as the slope during the rise and fall time. The crest factor (CF) is an indication on how narrow the pulse is. It is defined as the ratio between the peak current and the root mean square (RMS) of the current, as can be seen in Eq. 1, where the peak current is the maximum of the absolute of the waveform.

$$CF = \frac{I_{\text{max}}}{I_{\text{RMS}}} \tag{1}$$

The power factor (PF) is the ratio between the real power consumed and the apparent power, for which the latter can be found by multiplying the RMS of the current with the RMS of the voltage. The phase firing angle (FA) is defined as the phase difference between the previous zero crossing of the voltage and the moment the current start conducting. The energy can be calculated by taking the integral over the power, while the charge is the integral over only the current.

These parameters can vary from cycle to cycle, which is called non-persistence. The parameters however are not independent from each other. The current slope is depended on the rise and fall time and on the amplitude of the pulse, the crest factor is dependent on the peak current and the energy is dependent on all the other parameters. A non-persistence in one parameter could thus also be present in another parameter.

B. Present method

The IEC standard 61000-4-30 [5] for measuring power quality dictates capturing ten cycles for a 50 Hz grid. The measurements should be done in intervals of either three seconds, ten minutes or two hours depending on the purpose of the measurement. The described parameters could be extracted from the measurements, even though it is not described how for every parameter. The parameters are commonly calculated over the whole data set without first dividing into cycles. For persistent waveforms the parameters are the same calculated over ten or over one cycle, but this is not the case for non-persistent wave forms.

III. Method

A. Measurement plan

Different loads are tested, like a linear load, in the form of a heater. This is a baseline measurement, since it is expected that the load is persistent and the standards are based on this. Adding the dimmer will single out the non-persistence of the dimmer. Parameters to look out for are firing angle and current slope. Also two loads found to cause errors in static energy meters are investigated for persistence; a water pump and a dimmed television. These loads were already suspected to have non-persistence. All loads are powered using the power grid and measured by a PicoScope 4000 series with the current probe Keysight N2783B and differential voltage probe Pico TA043. Each measurement records the current and voltage simultaneously for one continuous minute at a sample frequency of 2 MHz. The data will thus contain approximately 3000 cycles with each cycle containing around 40000 samples.

The water pump has ten different levels, which differ mostly in firing angle, except for level 10, which has a longer pulse duration and two peaks. Fig. 1 shows the current and voltage of the water pump at level 5. The current is only drawn in the positive half with a firing angle of around 137.5°. It can also be seen that the load causes a drop in the grid voltage. For consistency and simplicity Level 5 is used in this report to described all first nine levels of the water pump.

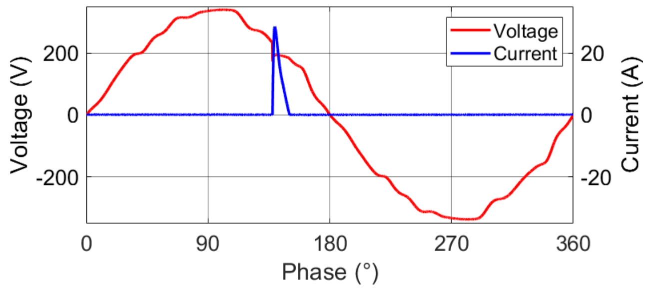

Fig. 1: Single cycle of current and voltage from a water pump

The television is dimmed with the same dimmer as the heater. The dimmer can be set to a FA of any value within a certain range. A narrow current pulse is drawn in both the positive and negative half, see Fig. 2. The FA has a great effect on the shape and the persistence of the waveform. The shape can have oscillations after the pulse or an extra pulse, which is wider and lower than the first. The non-persistence can be seen in different peak values, but also in changing shape between cycles.

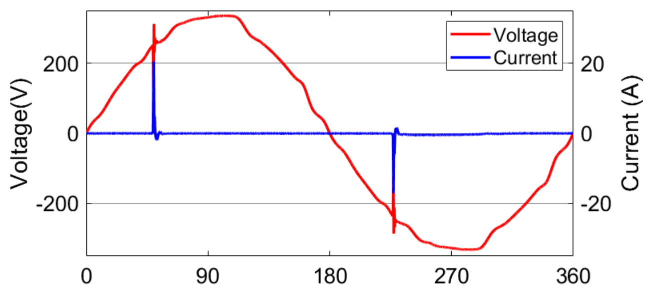

Fig. 2: Single cycle of current and voltage from a dimmed TV

B. Data processing

Besides plotting only one cycle, multiple cycles could be plotted on top of each other, which gives a visualization of the persistence. This way the general shape and obvious inconsistencies can be found, which could then be further investigated with parameters.

To make this visualization the start of every cycle need to be found, which cannot be done by cutting every 20 ms since the grid frequency is not constant and not perfectly 50 Hz. Zero crossings in the voltage are used to find the start, middle and end of every cycle. The sample position of those zero crossings were used to divide the voltage and current into cycles, which is possible since the samples for current and voltage were measured simultaneously. With the current divided into the cycles, the previously discussed parameters can be calculated for each individual cycle.

IV. Results

The non-persistence of the grid voltage will first be shortly touched upon and later the current will be discussed more thoroughly. A visualization is given of the non-persistence of the current drawn by the water pump. Next the firing angle of the dimmer will be discussed. Followed by the maximum current for both the water pump and the dimmed television and the crest factor. Lastly the periodicity is investigated with a Fourier transform.

A. Voltage waveform

A few results for voltage were remarkable: a difference in zero crossing in current and voltage for a linear load, a mean of 3.2 V and a difference in number of samples in the positive and negative half of the cycle, see Fig. 3. These results could however be explained by a bias in the voltage. A bias error in the voltage has an effect on some of the current parameters, since the cycles are based on the zero crossings in the voltage.

The mean voltage was deemed unsuitable to solve the bias problem, because the waveform of the positive and negative half could be different; if a load only draws its current in the negative half, like the water pump only draws current in the positive half, a voltage drop will only occur in that half. A better solution was considered to be subtracting a constant, which would minimize the difference in Fig. 3. This value was -2.5 V, which resulted in a eight sample difference in the mean, compared to 152 samples without correction. For each measurement this constant is subtracted, since the biasing was not changed between measurements.

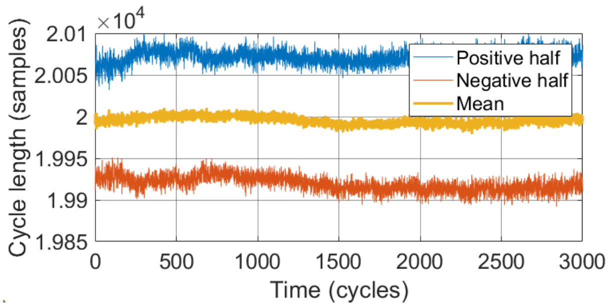

Fig. 3: Difference in half cycles caused by a bias in the voltage

B. Current waveform

Plotting different cycles on top of each other can show the general shape of the current and some of its non-persistence, which could be further looked into with parameters. In Fig. 4 the part of the waveform is shown, where the current is conducting. This is a zoomed in version of Fig. 1 with extra cycles added. The waveform is non-persistent in the firing angle and peak current, which has an effect on the RMS and CF as is shown later.

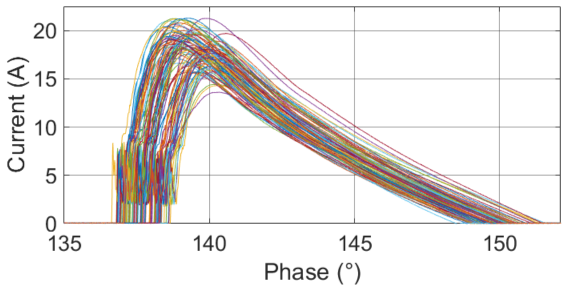

Fig. 4: 99 cycles of current from a water pump

C. Firing angle

The FA has an effect on the measurement error of the faulty measurements and could even change the sign of the error[8] [9]. For loads drawing current in the positive and negative half of the voltage, the computations could be done in both halves. This subsection will investigate if it is possible to measure one and assume the other is the same.

Two leading edge phase cut dimmers of the same kind are tested in combination with a linear load in the form of a heater. The dimmers could analogously be set to any firing angle with a single button, meaning it requires timing to get a certain firing angle. The positive firing angle was set for both dimmers at around 51°. This allows for comparing spread and relation between positive and negative firing angle, which is done in Fig. 5.

In the figure the spread for the firing angles in the positive and negative half can be seen for both dimmers, which are labelled as 1 and 2. The spread for each calculation of the FA is around 1°. The means for both measurements in the positive half are close, since for the set up these are set to the same value. There is a difference between the negative and positive half. It can be seen that dimmer 1 has a later firing angle in the negative half, while dimmer 2 has an earlier firing angle in the negative half. The difference between the means of the positive and negative side are 1.45° and -1.42° for dimmer 1 and 2 respectively. The same experiment is also done for a firing angle of around 112°, where similar results were found with 1.52° and -1.67° differences respectively.

When only looking at the positive FA, these two loads seem to have the same FA. While for same data, but looking at the negative FA, the loads seem to have a difference of 3° for FA.

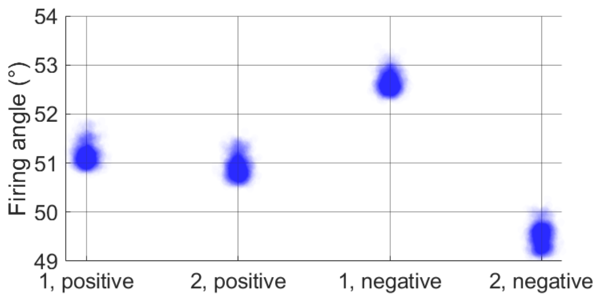

Fig. 5: FA of two leading edge phase cut dimmer of the same kind in the positive and negative half

D. *Maximum current*

An interesting aspect would be to see if the IEC standard is sufficient for non-persistent loads to determine peak current. The peak current is used for CF, but also for testing whether a current limits is exceeded, which could lead to interference or damage in the device.

The standard will find the peak current by taking the maximum of ten cycles every 150 cycles (three seconds) [5]. The standard will thus look at cycle 1 trough 11, 151 trough 161 etc., see Fig. 6. However the measurement could have started at any cycle. This way of finding the maximum is emulated with the one minute data set. The standard will find the maximum for twenty sets of ten cycles, which is done for the first 150 starting points. The maximum value for these two hundred cycles will be taken and compared to the maximum of the whole minute.

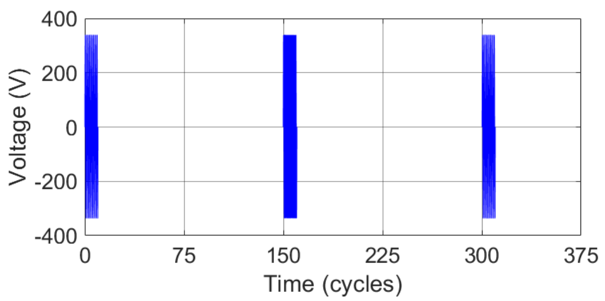

Fig. 6: Intervals measured by the IEC standard

1) Water pump: The maximum values found by the standard are compared in Fig. 7 to the maximum over the whole minute. The measurement can start at any moment, so in x-axis different starting points during the first three seconds are shown. Every starting point will contain 200 of the 3000 cycles. The minimum error is of course zero, since those starting points contain the absolute maximum. In other cases the maximum peak will be missed and the found maximum is lower, up to 1.67 A for a maximum peak of 23.46 A. Measuring for longer will increase the chances of finding a high value. However the found error could still increase, since a new absolute maximum can be found.

The standard only measures ten cycles every 150 cycles, so 6.67% of the waveform. The maximum peak could be outside the measured cycles, which could cause errors shown in Fig. 7. As the found maximum could be lower than the actual maximum, a load could wrongfully pass a current limit test.

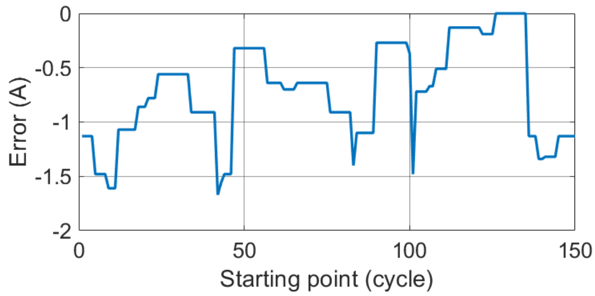

Fig. 7: Error in maximum current by using the standard method of capturing data compared to the maximum of the whole minute

2) Dimmed television: The same experiment with the standard as the previous section was done for the dimmed television, which yielded similar results. However, when looking at only ten cycles, the error was regularly more than 16 A. This result was further investigated by looking into the spread of the maximum current per cycle in Fig. 8. The absolute maximum over the whole minute was 38.12 A. The standard method will find a maximum, which was at most 1 A lower than this absolute maximum. Thus in this case the standard could catch a maximum close to the true value, even with only a small number of maximum current in that range. The regular error of over 16 A equates to a found maximum of 22 A. This can be expected from the histogram, where 69% is between 20 and 22 A and 82% is below the 22 A.

However it poses the question whether the absolute maximum is the important metric, since most of the times the current would not reach anywhere near it. In this example the mean, which is 22.20 A, would be more representative of all the cycles. The best way of characterizing the waveforms however is dependent on the purpose of the measurement. In some cases, like finding current which could damage a device, the absolute maximum is the best way. However in the case of the smart meters, where parameters are used to find patterns in the measurements, taking the absolute or even mean can hide important information.

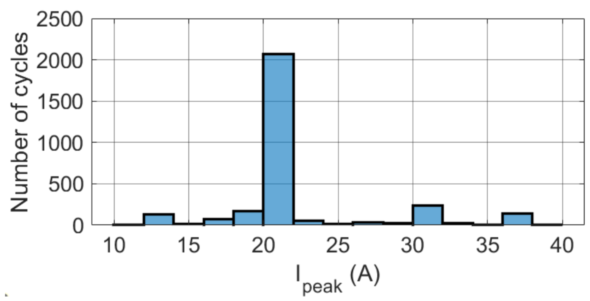

Fig. 8: Histogram on the peak current of individual cycles for a dimmed TV

E. Crest factor

The CF is defined as the ratio between the peak current and the RMS current. This seems straight forward, but it is dependent on how these parameters are determined. A common manner is taking the maximum value and the RMS over the whole data set of multiple cycles. Resulting in taking an extreme for peak current and an average for RMS. In Fig. 9 the RMS is plotted against the maximum current, which is equivalent for peak current for the water pump, which only draws current in the positive half. Also a black line is plotted, where each point has a CF of 9.5. In this case a cycle with a high maximum also has a high RMS. Result is the CF will be approximately the same for high or low peak currents, as can be seen the black line is followed.

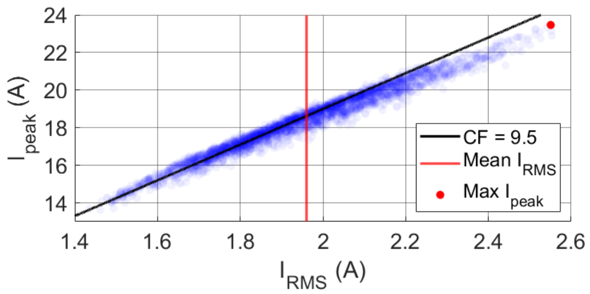

Fig. 9: Scatter plot for maximum and RMS current for single cycles

The CF is computed over a single cycle, ten cycles and the whole data set to show the effect of calculation over multiple cycles. Ten cycles is used like the IEC standard states. Fig. 10 show the spread for the CF calculations. The single cycle calculation are as expected from Fig. 9; the values are close to 9.5, which is indicated with the black line. Almost all ten cycle calculation are higher than any single cycle calculation. This is caused by taking extremes for the peak and an average for RMS. An example could be given for calculation of two cycles, e.g. a cycle with peak current of 16 A and one with 20 A and a RMS such that the CF is 9.5. The average RMS would be 1.9 A and the maximum peak would be 20 A; calculating the CF would give 10.55. The CF calculated over the whole minute of data was 11.96, using a peak of 23.46 A and a RMS of 1.96 A, which are indicated in Fig.9. When computing the CF, it is therefore necessary to divide the waveform into cycles for non-persistent waves.

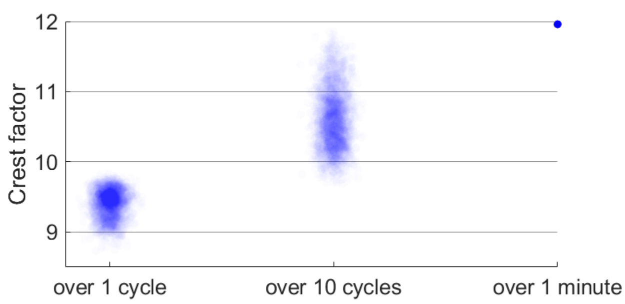

Fig. 10: Comparison for calculating CF over one or ten cycles

F. Periodicity

To determine the number of cycles needed to describe a non-persistent waveform, it is important to know if the non-persistence is periodic and with what frequency. Using fast Fourier transfer (FFT) on the parameters per cycle the periodicity can be examined. The FFT for maximum current of the water pump on level 5 can be seen in Fig. 11. Peaks can be seen at 0.24 Hz and 0.49 Hz, which equates to once every 4.1 and 2.0 cycles respectively. Both within the 10 cycles, meaning the current standard should find most variations in the maximum current. However, as can be seen in Fig. 7, this is not the case. Other levels for the water pump had peaks at different frequencies, but still within the ten cycles. The dimmed television is also examined. It showed no clear peaks and therefore the non-persistence is like white noise.

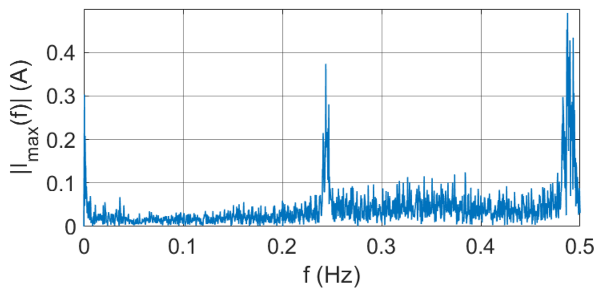

Fig. 11: FFT of maximum current, where 1/x-axis shows the number of cycles of a period

V. Discussion

No clear correlation was found between the results for the FFT in the section on periodicity and the other results. More research is needed to find the correlation, which might require a new method to determine periodicity. Periodicity will be an important part in determining the number of cycles needed to measure a non-persistent waveform. Even though it is expected to change for different loads.

This research covers only a limited number of loads. The non-persistence of the water pump could be caused by the movement of the water leading to different forces and thus energy needed. The dimmed television is likewise uncommon, because the load is not supposed to be dimmed. The small data set does not allow for clear recommendation for duration and intervals of testing. This will depend on periodicity and the allowed measuring error. Further research can go into the non-persistence of other loads and measure the loads for longer periods of time with intervals to find larger trends. The non-linearity of the loads seemed to be the cause of the non-persistence. With the increase of non-linear household appliances the problems with non-persistence will likely increase.

VI. Conclusion

Different parameters are calculated over single cycles. Investigated are the spread and comparison with calculation using the standard. The firing angle can have a difference between the positive and negative side of the current, so it would be best to calculate both. The maximum current shows larger data sets can still contain significant errors. For the dimmed TV the peak current of a cycle is most of the time not close to the maximum peak over the whole minute, which makes using the maximum for the peak not representative of the waveform.When calculating crest factor over multiple cycle, the value increases compared to the single cycle calculations.

The investigated loads, which were already known to have non-persistence, showed that non-persistence could have an effect on the waveform parameters. The non-persistence could cause an error in the peak finding by using the IEC standard. Crest factor should be calculated over a single cycle, since calculations over multiple cycles increases the value. No recommendation can be given for the measurement length in the standard, because periodicity results were ambiguous.

The advice is therefore to divide the gathered data into cycles, see how persistent the current is and based on that and the purpose of the data decide what the best way is to characterize the data.

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