Characterization Method Using Square Wave Signals for Testing Current Transducer Responses

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***Abstract*—The traditional testing of a frequency response using continuous waves has proven to be insufficient for characterizing current sensors. A new method is being developed that uses square waves and the Fourier transform to obtain a frequency response that more accurately represents the behaviour of the current transducer. In this paper, an example is given on how to obtain spread out measurement points by choosing the base frequency of the square waves. It is found that distributing the base frequencies of these square waves equally over the bandwidth of interest on the logarithmic scale gives a fairly good distribution.**

***Index Terms*—Frequency response, Square wave, Fourier transform**

I. Introduction

Energy meters are used to measure the power consumption of individual households. Cases in which these energy meters prove to be interfered by conducted electromagnetic interference generated by (non-linear) household equipment are described in [1] and [2]. The measured value can either be higher or lower than the actual used energy, resulting in under or over-billing of consumers. These issues occur when high power consuming or producing non-linear systems are connected to the energy meter. These systems produce pulsed currents, which is a superposition of several sine waves with different frequencies. However, this superposition only holds, when the system is linear and time-invariant. Because these energy meters are validated using frequency sweeps of continuous wave signals and deal with non-linear systems, they are not properly characterized for their task, which includes the measurement of these realistic pulsed currents. This is why a method is being developed to characterize current meters based on realistic pulsed signals instead of continuous waves. A proper frequency response was made in [3] by measuring a square wave with a certain current sensor and a reference. It was also shown in [3] that using pulsed signals instead of continuous waves can be a fast and cost-effective approach because fewer test signals are needed and square waves can be made with relatively cheap components. One drawback of that research is that only 2 frequencies of 50 Hz and 10 kHz were used. This gave a rather cluttered spread of measured frequencies. The purpose of this paper is to find a way to get the distribution of measurement points to look more like the spread of frequency points in a continuous wave test, where all measurement points are equally distributed on the logarithmic scale over the bandwidth of interest. This is done by simulating square waves with no distortion and finding how the harmonic frequencies relate to the base frequency of the square wave using the Discrete Fourier Transform (DFT). Based on these simulations, a set of square waves with different frequencies is selected to cover the bandwidth of interest. Measuring these square waves will verify the simulations.

The paper is structured as follows. In Section II, the theory about square waves and their frequency domain properties is discussed. The criteria of the measurement setup will be stated, and the simulations will be shown and elaborated upon. In Section III, the measurement setup will be shown and the measurement procedure will be described. Section IV shows the measurement results. The implications and meaning of the results will then be discussed in Section V and from this discussion a conclusion is made in Section VI. Finally, in Section VII, potential follow up research is discussed.

II. Analysis

A. Theoretical background

To mimic the real-life situation where consumers experience incorrect readings of their energy meters, square waves will be used to characterize the current transducers (CTs). These signals are easy to generate and resemble impulses created by household appliances well.

The Discrete Fourier transform (DFT) of a theoretical square wave looks like a series of peaks with exponentially decreasing magnitude as can be seen in Fig. 1. The frequencies of these peaks f_P are related to the base frequency f_b according to (1).

$$f_p = f_b * (2n+1), n \in \mathbb{Z} \tag{1}$$

This is a linear equation. The objective is to get these peaks to be spread out over a logarithmic scale because frequency analysis is often done on the logarithmic scale. In theory, n goes to infinity. But real-world limitations prevent the use of those high-frequency components because the amplitude gets too low to be measurable by the CT. The peak in the frequency response must have a magnitude above a certain threshold which is determined by the noise of the CT and the required signal to noise ratio (SNR). If the peak can not be distinguished from noise, it can not be used. Since the magnitude of the frequency components is exponentially decreasing, there is a point at which the magnitude of the peaks will barely decrease. If at this point the SNR is high enough, a single square wave will cover a large range of frequencies with high peak density. Even if this point cannot be reached, an effort should be made to make the highest possible harmonics usable. Because the magnitude of the frequency components is exponentially decreasing, each small increase in SNR will exponentially give more high frequency components. To obtain the best SNR, the amplitude of the square wave could be increased, and the parasitic inductance decreased, to name a few examples.

B. Setup Criteria

To obtain a good spread of measurement points, the points of several square waves have to be combined into one set. This set can be judged by the following parameters.

- Bandwidth
- Average measurement point density
- Largest difference between two consecutive measurement points
- Number of base frequencies

The bandwidth is the range of frequencies that can be tested with the chosen set of square waves. The average peak density is the logarithm of the bandwidth divided by the number of peaks in the bandwidth. This calculation results in how many peaks are present per decade on average. The largest difference between two consecutive peaks is calculated by taking the logarithm of the frequencies of all peaks and then find the largest difference between two consecutive peaks. This tells us how well the weakest part of the set of square wave frequencies works. The number of base frequencies is simply how many square waves are required to obtain the other properties. Obviously, lower is better. However, this is the least important property because having fewer frequencies only decreases the computing time and the time it takes to create the plot. But since this method will not be used in real-time data processing, this is not too important. Especially if a setup is made that measures a set of frequencies one after another automatically instead of manually measuring every square wave.

C. Simulations

To obtain a spread out distribution of peaks, not just the frequency but also the duty cycle of the square wave could be useful. In Fig. 1 the DFT of a 1 Hz, 50% duty cycle is shown. When comparing this to the DFT a 1 Hz, 35% duty cycle in Fig. 2 it can be seen that the lower duty cycle decreases the height of the peaks, and does not introduce new ones. This means that decreasing the duty cycle has no added value. Increasing the duty cycle will therefore not be beneficial either. Decreasing the duty cycle and multiplying the wave with -1 will give an increase in duty cycle, and multiplying a wave with -1 does not change its frequency domain properties. The magnitude responses of a 35% duty cycle or a 65% duty cycle square wave are therefore the same. Because of this, only 50% duty cycle square waves will be used from now on.

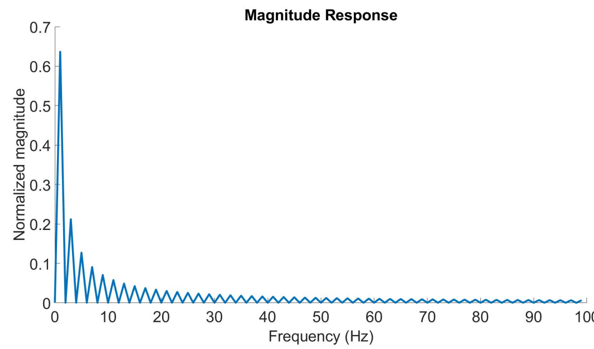

Fig. 1. Absolute value of the DFT of a 1 Hz, 50% duty cycle square wave

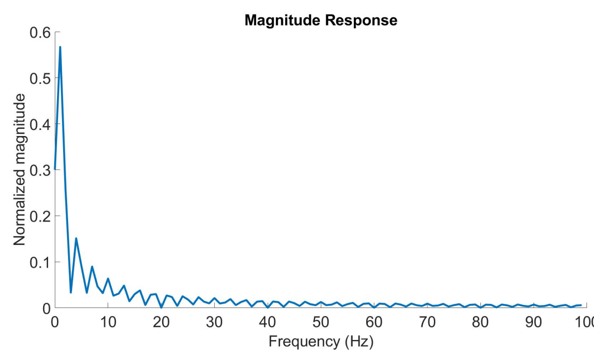

Fig. 2. Absolute value of the DFT of a 1 Hz, 35% duty cycle square wave

Before any measurements, a simulation is done. In this simulation, a near-perfect square wave is created and its DFT is computed. This gives a signal like in Fig. 1. Now, all peaks higher than a certain threshold can be used as measurement points for the characterization of CTs. This threshold is based on the noise of the CT and a chosen SNR. An SNR of 10 and noise with an RMS of 3 mA is assumed, which is found to be true based on the measurement results. Because different CTs have different noise values, a rough estimate is enough for the simulation to be useful. Once these computations are completed and only the peak locations are plotted on a logarithmic scale, Fig. 3 is obtained. What can be seen here is that the higher the harmonics go, the closer they appear on the logarithmic scale. This makes sense because the logarithmic scale increases exponentially while the frequency of the harmonics increases linearly. Important to note is that even though the highest usable peak of the simulated 1 Hz square wave in this simulation is around 40 Hz, this does not represent what the highest usable peak will be in measurements. This depends on several variables like the noise of the CT and the amplitude of the square wave. This is just a proof of concept.

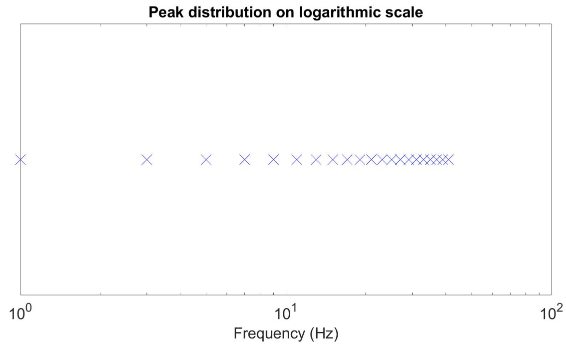

Fig. 3. Usable simulated measurement points of a 1 Hz square wave

To obtain the required bandwidth, more frequencies can be added. The result of this can be seen in Fig. 4. The colour of the marker represents the base frequency that specific harmonic belongs to. In this figure, it can be seen that the bandwidth is around 400 kHz. There are also some larger gaps when transitioning from a lower to a higher base frequency. This is not a problem because the highest usable harmonic of each base frequency does not necessarily correspond to what harmonics will be usable in the actual measurement, as stated before.

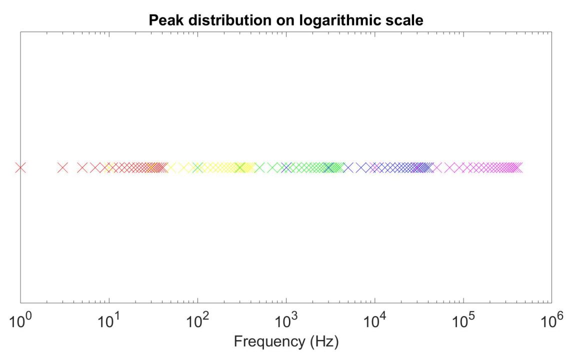

Fig. 4. Usable simulated measurement points of a 1, 10, 100, 1.000 and 10.000 Hz square wave

In Fig. 5. it can be seen that the largest gaps are about 0.15 decades, which is quite a lot. Something else that can be concluded from this figure is that the largest differences between measurement points do not occur where a new frequency base frequency is added but after a highest harmonic of a base frequency. This makes sense because the highest harmonics are very close together on the logarithmic scale. But at a certain frequency, these dense harmonics are no longer higher than the threshold and cannot be used. Now harmonics of a higher base frequency have to take over. And since the base frequency is higher, the harmonics are further apart. This effect can be reduced by choosing base frequencies that are closer together. In Fig. 5 it can also be seen that the

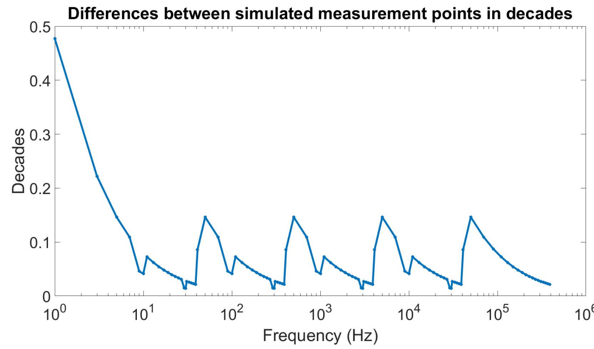

Fig. 5. Difference between consecutive peaks in decades when all peaks of the simulation are combined.

differences between the first few points are extremely large. This is because these points belong to the lowest frequency. That means there are no high harmonics of a lower frequency to reduce the difference between consecutive points.

III. Method

A. Measurement setup

To generate the square wave, a gallium-nitride half-bridge is used. It consists of a GS665EVBMB motherboard and a GSS66508/16T daughterboard. The half-bridge is controlled by the 3314A function generator by HP set to 3V square waves. The frequency of the function generator determines the frequency of the half-bridge. The motherboard is powered by a voltage of 12V which is supplied by a TENMA 72-2720 programmable DC power supply. The half-bridge is connected to an EA-PS 3080-20 C dc power supply which determines the amplitude of the square wave. The output of the half-bridge is connected to a 2,4 ohm power resistor. Parallel to this resistor is a TA043 differential voltage probe to measure the signal the half-bridge generates. In Fig. 6 a schematic of the measurement setup can be found. To create a clean square wave, parasitic inductances should be reduced as much as possible, as these will create distortion in the high-frequency components. For this research, the frequency set will be judged based on the properties of the TA-189 CT. According to the manufacturer, this CT has a bandwidth of 100 kHz. The noise was measured to be 3 mA RMS. Since the drop-off of the bandwidth is of interest, the bandwidth of the setup must be at least a decade higher than the bandwidth of the system it is trying to characterize. That is why the bandwidth of the setup must be at least 1 MHz.

B. Measurement procedure

First, a set of 5 base frequencies will be measured, starting at 1 Hz and increasing 10 fold up to 10 Khz, so 1, 10, 100, 1.000 and 10.000 Hz. This set will from now on be referred to as the 10x measurement set. Then, the DFT of all individual measurements will be calculated. After this, the peak values of the DFTs will be compared to a threshold. If the peaks are higher, they are deemed useful. If the peaks are lower they are not usable. This is similar to the calculation described in

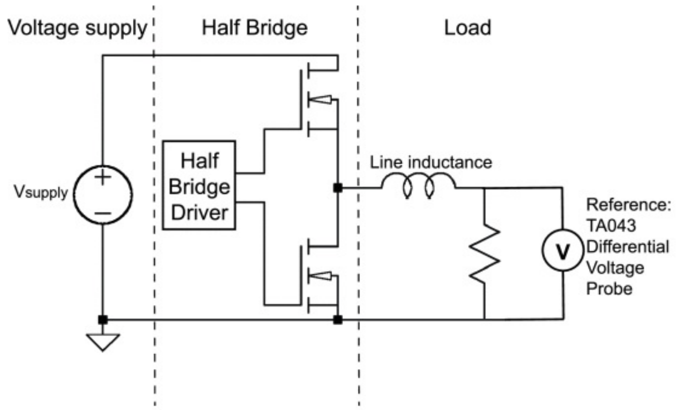

Fig. 6. Schematic of the measurement setup, based on the schematic in [3]

Section II-C. Based on these results of the 10x measurement set, an increment value other than 10 will be selected and measured. This value was chosen to be 8. The second set of measurements will use 6 base frequencies to still be able to cover the bandwidth of interest, starting at 1 Hz and increasing 8 fold up to 32.8 Khz. So 1, 8, 64, 512 4.960 and 32.800 Hz. This set will from now on be referred to as the 8x measurement set. The same signal processing will be done to this set as to the 10x measurement set. The threshold used to compare the peaks to will be determined based on the noise of the TA 189 and an SNR of 4. The SNR value is an estimated guess as figuring out what SNR is required for a good frequency response is not the main focus of this research. Furthermore, additional measurements are done to investigate the amplitude of the used square wave. Therefore the 32,8 kHz signal will also be measured with an input of 12V. This can then be compared to the 32,8 kHz signal with a 4V input to see if a higher voltage creates more distortion.

IV. Results

The measurements described in Section III-B have been executed. In Fig. 7 the measurement points provided by the 10x measurement set can be seen. In Fig. 8 the differences between the points of Fig. 7 are plotted to give a better overview of where the largest gaps in measurement points are. Note that the plot starts at 10 Hz. This is because the 1 to 10 Hz range looks the same as the simulation in Fig. 5. This means that the values between 1 and 10 Hz are much higher than the values after 10 Hz. Changing the scope to frequencies above 10 Hz makes sure the important part of the figure is in the full scope. In Fig. 9 the measurement points provided by the 8x measurement set can be seen. In Fig. 10 the differences between the points of Fig. 9 are plotted. This plot misses the first few hertz for the same reasons stated above. In Fig. 11, 12, 13 and 14 the measurement of a 10 Hz, 10 kHz and two 32,8 kHz square waves with different amplitude are plotted. In Fig. 15 the DFT of the square wave in Fig. 13 can be found. Finally, in Table I and Table II, some properties of the individual square wave measurements of both the 10x and 8x measurement set can be found.

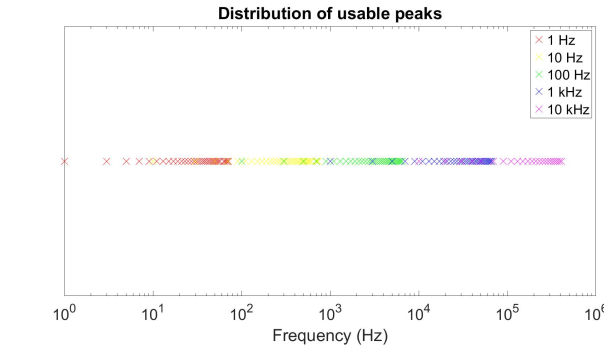

Fig. 7. Spread of all peaks of the 10x measurement set on logarithmic scale

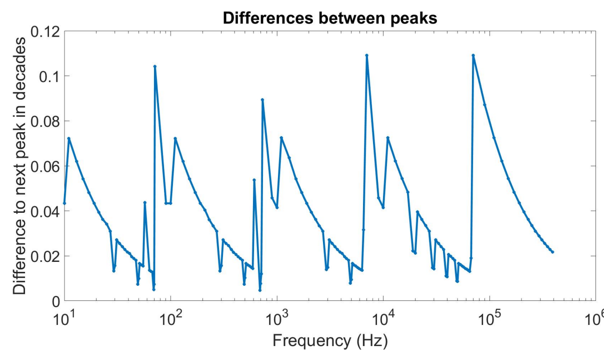

Fig. 8. Difference between consecutive peaks in decades when all peaks of the 10x measurement set are combined.

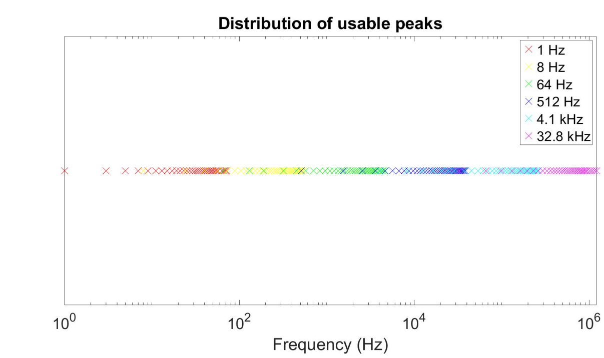

Fig. 9. Spread of all peaks of the 8x measurement set on logarithmic scale

V. Discussion

A. 10x measurement set

The 10x measurement set shows a pretty good distribution of peaks for an estimated guess of base frequencies. However, as you can see in Fig. 8, the gap to the next peak increases significantly around 70, 700, 7.000 and 70.000 Hz. This is because these are the upper limits of the usable frequencies of a specific square wave, as can be seen in Table I. So in the 70 Hz gap case, the 1 Hz square wave has a difference of 2

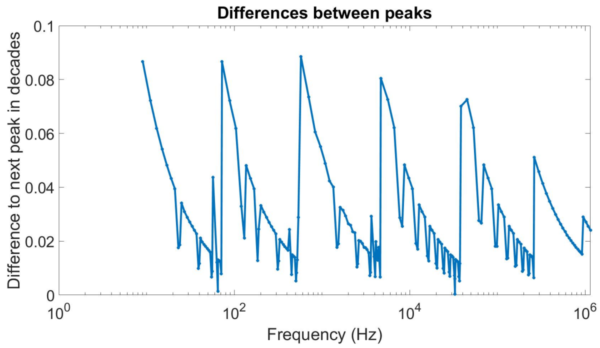

Fig. 10. Difference between consecutive peaks in decades when all peaks of the 8x measurement set are combined.

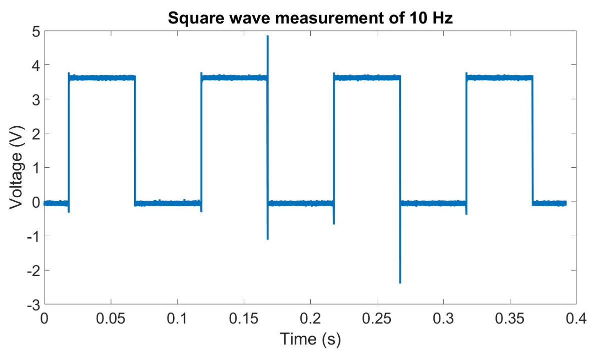

Fig. 11. Measured 10 Hz square wave with 4V input

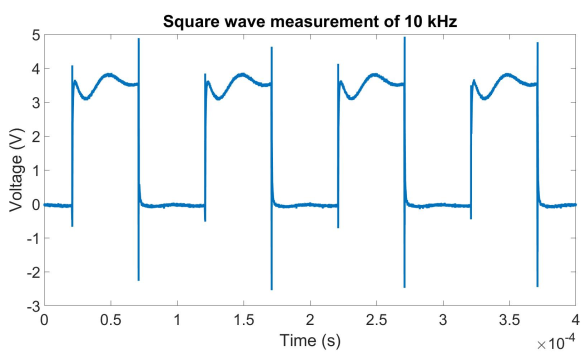

Fig. 12. Measured 10 kHz square wave with 4V input

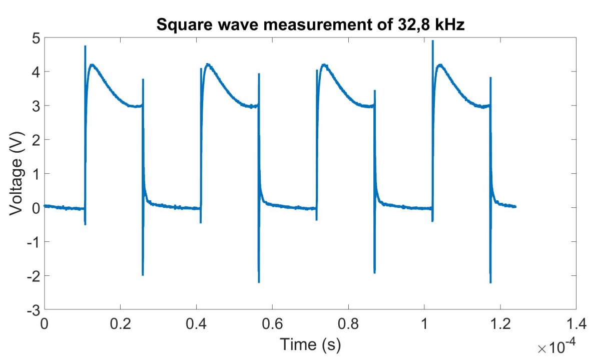

Fig. 13. Measured 32,8 kHz square wave with 4V input

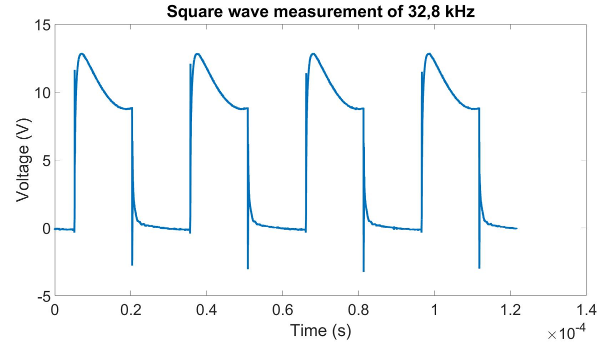

Fig. 14. Measured 32,8 kHz square wave with 12V input

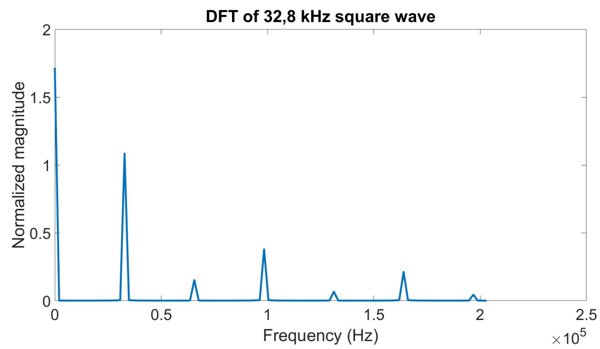

Fig. 15. Zoomed in frequency response of 32,8 kHz square wave

TABLE I
STATISTICS OF INDIVIDUAL BASE FREQUENCIES OF THE 10X MEASUREMENT SET

Base frequency	***Highest frequency***	***Number of frequencies***
1 Hz	71 Hz	34
10 Hz	732 Hz	34
100 Hz	6,5 kHz	33
1 kHz	67 kHz	34
10 kHz	410 kHz	23
		Total: 158

TABLE II
STATISTICS OF INDIVIDUAL BASE FREQUENCIES OF THE 8X MEASUREMENT SET

Base frequency	***Highest frequency***	***Number of frequencies***
1 Hz	71 Hz	34
8 Hz	538 Hz	33
64 Hz	4,7 kHz	35
512 Hz	38 kHz	38
4,1 kHz	258 kHz	36
32,8 kHz	1,21 MHz	33
		Total: 209

Hz between each peak. Once these peaks are no longer strong enough, the 10 Hz signal has to provide all the measurement points. This means that the peaks are 20 Hz apart instead of 2 Hz. Fig. 7 and Table I also show that the 10x measurement set does not reach the required bandwidth of 1 MHz as the highest usable frequency component is 410 kHz.

B. 8x measurement set

Fig. 10 shows that if the increase of frequency is lowered from a factor of 10 to a factor of 8, sudden increases in peak difference after a highest harmonic still exist, but the peak values are lower. Fig. 10 is basically a downscaled version of fig. 8. the average peak density is also higher for the 8x set compared to the 10x set. Since the 10x set did not have enough bandwidth, the 8x measurement set has 6 frequencies instead of 5. Now the bandwidth is 1,2 MHz, which is perfectly fine for measuring the TA 189.

What is interesting about the 32,8 kHz signal, is that it also has some peaks at even multiples of the base frequency as can be seen in Fig. 15, instead of only uneven multiples. This is because the square wave is distorted by the parasitic inductance introduced by the measurement setup which can be seen in Fig. 13. Fig. 11 shows an undistorted 10 Hz square wave for comparison. The distortion also causes the higher harmonics to have less magnitude, which means the bandwidth of this specific square wave is lower than that of lower frequency ones. In this case, this is beneficial since the bandwidth of 1 MHz is reached either way, and the peaks created by the distortion make sure that there are more peaks in the "transition range" from the 4 kHz to 32 kHz harmonics. This effect can be seen in Fig. 10. The last peak at around 100 kHz is significantly lower than the peaks before it, while the last peak in Fig. 8 has the same height as the others. This means that the 8x measurement set has a higher average measurement point density, and one of the largest differences between two measurement points has been reduced, meaning that distortion in this specific case is beneficial.

In Table I can be seen that the square wave of 10 kHz only provided 23 usable frequencies, which is significantly lower than all other measurements, including the 32,8 kHz square wave in Table II, which has a higher frequency and thus a higher distortion as can be seen in Fig. 12 and 13. The reason why the 32,8 kHz square wave has 33 points, is because its distortion is high enough such that the even harmonics that are introduced by the distortion are also usable. The 32,8 kHz square wave has 14 even harmonics, while the 10 kHz signal only has 2. The highest usable frequency of the 10 kHz square wave is 41 times its base frequency, while the highest usable frequency of the 32,8 kHz signal is 37 times its base frequency. Both of these values are lower than those of the lower frequencies, which can use harmonics of up 60 to 70 times their base frequency. The 10 kHz signal has enough distortion to decrease its highest frequency to 41 times the base frequency, but not enough distortion to introduce a relatively large number of new usable frequencies.

From the measurement results, it was found that distortion can be desirable in specific cases, but when trying to create a CT characterization setup, it is undesirable because it lowers the bandwidth of the higher frequency square waves. The magnitudes of the even harmonics introduced by the distortion are also unpredictable, which makes it even more difficult to implement in a standardized way. Finally, recreating the exact amount of parasitic inductance in different setups may also be somewhat troublesome. For these reasons, it is best to reduce the parasitic inductance as much as possible.

In Fig. 13 it can be seen that higher frequency components have a lot of distortion. However, when comparing Fig. 13 to Fig. 14 it can be seen that the shape of the wave does not change when increasing the voltage. The 4V signal decreases to 3V which is a 25% decrease. The 12V signal decreases to approximately 9V, which is also a 25% decrease. This means that an easy way to improve all properties of the setup without adding new square waves is to increase the supply voltage to the maximum the half-bridge can handle.

VI. Conclusion

In this paper, it is shown that for the characterization of CTs using square wave signals, a fairly good distribution of measurement points can be achieved by having each next base frequency be multiplied by a certain value. The lower this value is, the denser the measurement points. However, lowering this value also means more square waves are required to obtain the same bandwidth. Furthermore, it was found that increasing the amplitude of a square wave does not introduce more distortion, which means that increasing the input voltage will result in more measurement points per square wave. This paper also shows that some distortion can be beneficial in specific cases, but to have the most consistent results it should be avoided.

VII. Future research

This method of generating a frequency response has lots of room for improvement. Most importantly, the distortion of the high-frequency components of the square waves should be removed as much as possible. Finding out if the large difference in magnitude between individual measurement points could distort the measurements is also valuable. Another interesting topic is which frequency distribution type is best. The frequency distribution chosen in this research is linearly increasing on the logarithmic scale. However, it is also possible to add handpicked square waves to "patch" the transition range between two frequencies. The square waves are chosen such that their highest harmonics are located where the largest gaps in measurement points are. It could be interesting to find out if it is more effective to add these "patch frequencies" or if simply lowering the factor with which you increase the frequency works better. This likely depends on the requirements of the user. Finally, to optimize the system, the limit of how many accurate measurement points can be generated from a single square wave frequency can be found. This can be done by finding what SNR is required, increasing the voltage to the limit of the half-bridge and lowering the distortion in the square waves as much as possible.

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