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CHARACTERISTIC OF HARMONIC DISTORTION IN FREQUENCY 9-150 KHZ GENERATED BY HOUSEHOLD APPLIANCES

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Abstract

The use of household appliances equipped with inverter technology is growing rapidly. As result of using inverters in household appliances, it causes voltage distortion in the electricity network. In induction hobs, the main distortion is in the 20-25 kHz frequency range. Other voltage distortions also exist in the 40-50 kHz frequency range. Since the voltage distortion is seen in the frequency range of integer multiplication of the principal voltage distortion, this can be categorized as a harmonic behavior of the voltage distortion. The second voltage distortion is also known as the 2nd order harmonic distortion. This study aims to determine the behavior of the magnitude of the 2nd order harmonic distortion. To test this phenomenon, measurements using a picoscope with several electronic types of equipment that use inverter technology, such as induction cookers and microwave inverters with various load operating configurations and interconnections between loads against 2nd order harmonic distortion. The results of testing and analysis of the 2nd order harmonic distortion in the load with inverter technology show that the interconnection load affects the magnitude of the 2nd order harmonic distortion. This condition will depend on the characteristic impedance of the distortion source device, neighboring devices, and the main network.

Keywords: Inverter, Voltage Distortion, 2nd Order Harmonic Distortion, Induction Cooker, Microwave

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Introduction

Electrical appliances for households today use a lot of power electronic components to save electricity. This is in accordance with the Presidential Instruction of the Republic of Indonesia (INPRES) Number 10 of 2005 concerning energy saving (Presiden Republik Indonesia, 2005). The impact of the development of power electronics technology has an impact on some equipment that uses inverter technology, where one of the advantages is to make energy consumption more efficient (Savetlana & Andriyanto, 2012).

Inverters are nonlinear devices in which there are power electronics components that function as high-frequency switching components (Ramadhan & Sudiarto, 2019), (Kurniawan & Sudiarto, 2020). As a result of its switching properties, an inverter can

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cause interference in the form of harmonic distortion, namely a sinusoidal voltage or current that has an integer frequency multiple of the fundamental frequency (50 or 60 Hz) (Dugan, McGranaghan, & Beaty, 1996). Voltage distortion appears in the frequency range of 2 – 150 kHz for household appliances that use inverter technology. Induction hobs have voltage distortion in the range of 2 – 150kHz (Dugan et al., 1996), (Rönnberg et al., 2017), (Muhammad & Sudiarto, 2019).

The characteristics of the current generated in some household appliances are non-linear due to the use of inverters and other power electronic components (Marganda & Sudiarto, 2020). Non-linear devices are devices whose current is not proportional to the applied voltag. Inverters usually use a switching frequency in the 9-150 kHz range, which can cause harmonic distortion and interference in the AC power output (Sudiarto, Widyanto, & Hirsch, 2014) (Sudiarto, Zahra, Jufri, Ardita, & Hudaya, 2019). This disturbance can be either harmonic or supraharmonic (Mendes et al., 2021). Harmonic is a distortion in the low-frequency range (50 Hz – 2.5 kHz) and supraharmonic is a disturbance in the high-frequency range (9 kHz – 150 kHz) (Kurniawan & Sudiarto, 2020). Both interferences can negatively impact the performance of the equipment, as well as other equipment connected to the shared network (Sudiarto et al., 2014) (Vinayagam et al., 2019). However, these international standards do not adequately cover the emission limits in the 9-150 kHz frequency range (Bollen, Olofsson, Larsson, Rönnberg, & Lundmark, 2014).

For an induction cooker, the main distortion is at a frequency of 20-25 kHz, but other voltage distortions are also at a frequency of 40-50 kHz and other distortions are at a frequency of 65-75 kHz. Because the voltage distortion seen in the frequency range is an integer multiplication of the frequency of the first voltage distortion, it can be categorized as a harmonic behavior of voltage distortion.

The voltage distortion appears three times, which is then referred to as the main distortion for the first order harmonic distortion, the 2nd order harmonic distortion for the second voltage distortion, and the 3rd order harmonic distortion for the third voltage distortion.

This research is focused on knowing how the behavior of the magnitude of the second-order harmonic distortion is and analyzing the effect of induction cooker and microwave inverter as electronic equipment that uses inverter technology on the behavior of harmonic distortion in the 9-150 kHz frequency range. The characteristics of harmonic distortion and voltage disturbance at a frequency of 9-150 kHz will be observed by varying the level of power consumption of induction cookers and microwave inverters with various load operations. The results of this study are expected to provide a reference in minimizing the impact of harmonic distortion on household appliances that use inverter technology.

Measurement Methodology

This study used a picoscope. The picoscope is connected to the side of the device under test (Device Under Test) to measure 2nd order harmonic distortion (Nikitin, Gorshkov, Nikitin, & Ksenevich, 2005). The measurements carried out in this study are used to investigate the behavior of the 2nd order harmonic distortion magnitude in the main network, when there are two tested devices (DUT) connected to the main network. Measurements will be made in 10 Cycles. The tested devices (DUT) or loads in this study are induction cooker A, microwave inverter B, and induction cooker C. The tested devices are used to describe the effect of interconnection loads that affect 2nd order harmonic distortion in the main network. To illustrate how large the variation of the 2nd order harmonic distortion is, the measurement is divided into three interconnect load configurations, namely:

1. Single load operation
2. Single load and one standby operation
3. Two-load operation

The single load operating configuration uses only primary load (induction cooker A) at level 3 and level 5 with various secondary load levels (microwave inverter B and induction cooker C). For single load and one standby operation, the main load is still induction cooker A, but for standby, load using induction cooker C and Microwave Inverter B. For the third operation, namely the two-load operation, the load is the same as before, except for load operation (Patel et al., 2013).

All measurements were carried out 20 times. Measurements are made in the time domain signal and use 10 cycles to sample the signal. The signal captured through the Picoscope is then converted into a frequency domain signal via Matlab. Since 10 cycles are used to sample the signal, the FFT has an interval of about 5 Hz. Signals are grouped in a 200Hz bandwidth for easy inspection and to comply with the 200Hz clustering standard in the IEC/EN 61000-4-7 standard (IEC, 2012).

The next step is to identify at which frequency and to what extent the voltage distortion is. Due to the small magnitude of the voltage distortion (in mV) and the voltage source being greater than 220 V, the magnitude is observed in decibels (dB).

$$Magnitude\ A_{(dB\mu V)} = 60 + 20 \log A$$

To study the behavior of 2nd order harmonic distortion in the range 2 – 150 kHz for household appliances, the measurement scheme, and instrument for measuring harmonic distortion can be seen in Figures 1 and 2 below

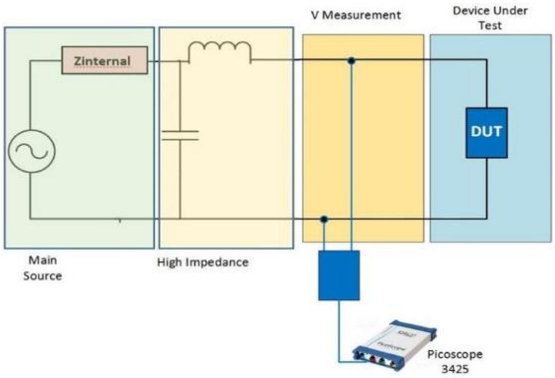

Figure 1 Measurement Scheme

Figure 2 Picoscope 3425

Measurement Result And Analysis

A. The Behavior of 2nd order harmonic distortion

To get a general idea of the harmonic distortion behavior, the results use the average value of 20 measurements. The results of the 2nd order harmonic distortion behavior can be seen in tables 1 and 2 below.

Table 1

Behavior Of The Voltage Distortion Harmonics On Cooker A Level 3

Load Configuration	Main Distortion		2nd order Harmonic Distortion			
	in mV	in dBμV	In mV	In dBμV	2nd order Harmonic Percentage in (mV)	2nd order Harmonic Percentage in (dBμV)
Single Operation	1978.45	125.92	15.73	83.93	0.70	43.15
With Cooker C (Standby)	158.69	104.01	21.52	86.66	13.10	17.66
With Microwave B (Standby)	205.32	106.25	12.89	82.21	5.94	24.53
With Cooker C level 7 (Operating)	202.76	106	21.09	86.48	10.25	19.93
With Microwave B (Operating)	350.66	110.9	13.39	82.54	3.52	29.07

Table 2

Behavior Of The Voltage Distortion Harmonics On Cooker A Level 5

Load Configuration	Main Distortion		2nd order Harmonic Distortion			
	in mV	in dBμV	In mV	In dBμV	2nd order Harmonic Percentage in (mV)	2nd order Harmonic Percentage in (dBμV)
Single Operation	5335.03	134.54	21.58	86.68	0.37	48.72
With Cooker C (Standby)	474.34	113.52	30.26	89.62	6.18	24.18
With Microwave B (Standby)	353.55	110.97	17.12	84.67	4.53	26.88
With Cooker C level 7 (Operating)	499.54	113.97	29.27	89.33	5.61	25.02
With Microwave B (Operating)	1294.68	122.24	17.51	84.87	1.28	37.85

In Tables 1 and 2, the calculation results use the distortion voltage (mV) and magnitude (dBµV). From the table above, it can be seen that when the second load is in standby or operating, the main distortion tends to decrease while the 2nd order harmonic distortion varies depending on the type of load. Because the main distortion is reduced When both loads (in standby and operating), and 2nd order harmonic distortion occurs, the percentage of 2nd order harmonic distortion will be greater than that of a single operating load (Induction Cooker A). It can also be seen that the primary distortion will be reduced to about 80% of the initial single load operation when connected to a secondary load. This happens for both A level 3 and level 5 induction cookers.

For induction cooker C as a secondary load in standby and operation, the main distortion is greater with the operation of induction cooker C. The 2nd order harmonic distortion also increases during both loads operating compared to the standby mode of induction cooker C. The percentage of 2nd order harmonic distortion to the main distortion tends to decrease. This happens for both A level 3 and level 5 induction cookers which serve as the main load.

For microwave inverter B as a secondary load in standby and operation, the primary distortion increases when the microwave is operating. The 2nd order harmonic distortion also increases as the microwave operates. The percentage of 2nd order harmonic distortion to the main distortion is smaller when the microwave is operating compared to the microwave in standby mode. This happens for both A level 3 and level 5 induction cookers which serve as the main load.

B. Impedance Analysis for 2nd Order Harmonic Distortion

Based on the measurement results using maximum voltage distortion, the frequency of a certain voltage distortion is known, so that the relationship between load configuration and harmonic quantities can be known. Because the main network is connected to a 700µH high impedance serial which is equivalent to ±219.8 in the 40-50kHz frequency range. Therefore, the circuit analysis will only discuss the characteristic impedance of the device under test (DUT).

The characteristic impedance is described in terms of magnitude and phase; phase will describe the type of load whether the load is capacitive (negative phase) or inductive (positive phase). The magnitude is obtained from measuring the current and voltage within a certain frequency range, then the voltage is divided by the current, resulting in impedance. The phase is obtained from modeling and simulation of the circuit, by injecting the harmonic frequency to determine the behavior of the load at that frequency. Since the characteristic DUT impedance of the three DUTs does not change much in frequency during operation and Standby, the characteristic impedance of the DUT in operation can be used. For different DUTs, the impedance can be seen graphically in Figures 3,4, and 5 below.

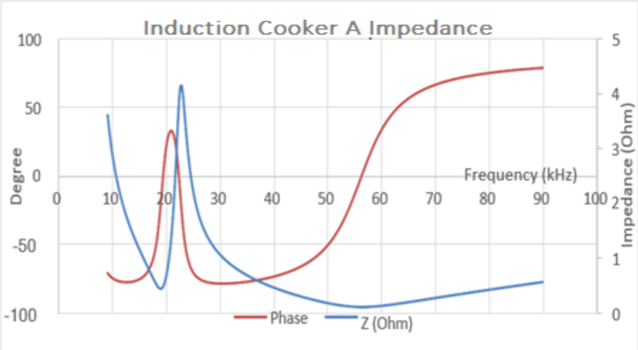

Figure 3 Impedance Characteristic of Induction Cooker A

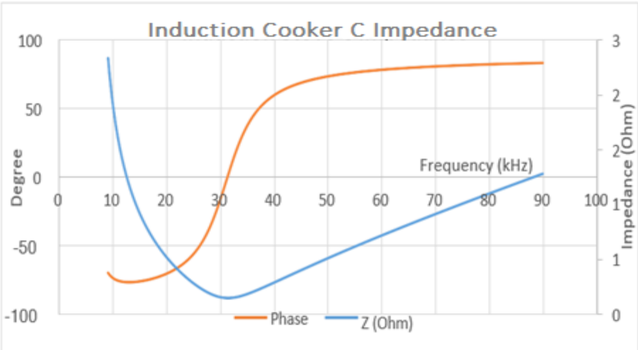

Figure 4 Impedance Characteristic of Induction Cooker C

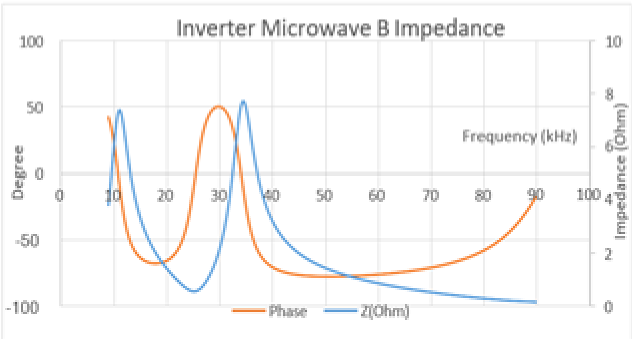

Figure 5 Impedance Characteristic of Inverter Microwave B

In induction cooker A level 5 and induction cooker C level 5 during both load operations, 2nd order harmonic distortion occurs at a frequency of 44.6 kHz. By using these frequencies, the impedance for induction cooker A and induction cooker C can be determined. At this frequency, the impedance of the induction cooker A is 0.318Ω -66.51˚, which means the impedance is capacitive. The impedance of the induction cooker C is 0.40Ω 68.89˚, which means the impedance is inductive. The main Z is the impedance for the main network because it is connected to a high impedance (700µH), 219.8Ω is being used.

The induction cooker A has a negative angle impedance which means it is capacitive and induction cooker C has a positive angle impedance which means it is inductive, the impedance for each DUT can be described as a combination of resistive-capacitive and resistive-inductive loads. From the above explanation that the main network and the secondary DUT (Induction cooker C) are connected in parallel. which means that the voltage source is the same as the addition of voltage distortion on the mains and the voltage on the induction cooker A. The equivalent circuit for this configuration can be seen in Figure 6 below.

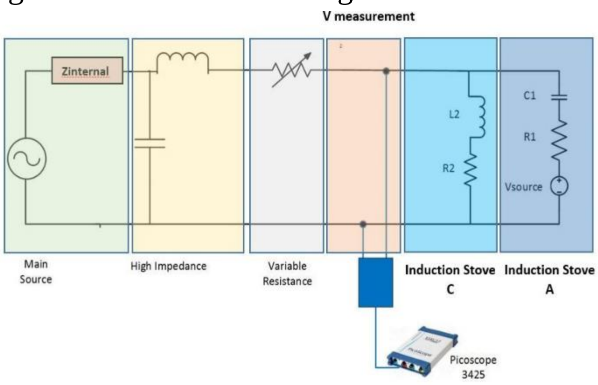

Figure 6 Equivalen Circuit during both operations

In Figure 6 it can be seen that the main network and the secondary device (Induction cooker C) are connected in parallel. which means that the voltage source (V source) is equal to the addition of the distortion voltage on the mains and the voltage on the induction cooker A. The formula is explained as follows.

Tables 3 and 4 below are the results of measurements of 2nd order harmonic distortion and voltage distortion calculated using circuit analysis for various configurations.

Table 3 Circuit Analysis Induction Cooker A Level 3

Induction Cooker A level 3 (Single Operation)				Vcalculation (Vsource – Vstove A)			
Harmonic Distortion	Freq. [kHz]	V measured [mV]	V source [mV]	Magnitude	angle	real	imajinary
2nd order	47	15,73	15,73	15,71	0	15,71	0
Induction Cooker A level 3 and Induction Cooker C (Standby)				Vcalculation (Vsource – Vstove A)			
Harmonic Distortion	Freq. [kHz]	V measured [mV]	V source [mV]	Magnitude	angle	real	imajinary
2nd order	47	21,52	15,73	20,99	33,35	17,53	11,54
Induction Cooker A level 3 and Microwave Inverter B (Standby)				Vcalculation (Vsource – Vstove A)			
Harmonic Distortion	Freq. [kHz]	V measured [mV]	V source [mV]	Magnitude	angle	real	imajinary
2nd order	47	12,89	15,73	13,78	-2,05	13,77	-0,49
Induction Cooker A level 3 and Induction Cooker C (Operation)				Vcalculation (Vsource – Vstove A)			
Harmonic	Freq.	V	V	Magnitude	angle	real	imajinary

Distortion	[kHz]	measured [mV]	source [mV]				
2nd order	47	21,09	15,73	20,99	33,35	17,53	11,54
Induction Cooker A level 3 and Microwave Inverter B (Operation)				Vcalculation (Vsource – Vstove A)			
Harmonic Distortion	Freq. [kHz]	V measured [mV]	V source [mV]	Magnitude	angle	real	imajinary
2nd order	47	13,39	15,73	13,76	-1,97	13,75	-0,47

Table 4 Circuit Analysis Induction Cooker A Level 5

Induction Cooker A level 5 (Single Operation)				Vcalculation (Vsource – Vstove A)			
Harmonic Distortion	Freq. [kHz]	V measured [mV]	V source [mV]	Magnitude	angle	real	imajinary
2nd order	44,6	21,58	21,58	21,55	0	21,55	0
Induction Cooker A level 5 and Induction Cooker C (Standby)				Vcalculation (Vsource – Vstove A)			
Harmonic Distortion	Freq. [kHz]	V measured [mV]	V source [mV]	Magnitude	angle	real	imajinary
2nd order	44,6	30,26	21,58	30,43	52,70	18,44	24,21
Induction Cooker A level 5 and Microwave Inverter B (Standby)				Vcalculation (Vsource – Vstove A)			
Harmonic Distortion	Freq. [kHz]	V measured [mV]	V source [mV]	Magnitude	angle	real	imajinary
2nd order	44,6	17,12	21,58	18,72	-1,24	18,71	-0,40
Induction Cooker A level 5 and Induction Cooker C (Operation)				Vcalculation (Vsource – Vstove A)			
Harmonic Distortion	Freq. [kHz]	V measured [mV]	V source [mV]	Magnitude	angle	real	imajinary
2nd order	44,6	29,27	21,58	30,43	52,70	18,44	24,21
Induction Cooker A level 5 and Microwave Inverter B (Operation)				Vcalculation (Vsource – Vstove A)			
Harmonic Distortion	Freq. [kHz]	V measured [mV]	V source [mV]	Magnitude	angle	real	imajinary
2nd order	44,6	17,51	21,58	18,66	-1,20	18,66	-0,39

Using circuit analysis data, the 2nd order harmonic distortion is calculated at 30.43 mV∠52.70˚ , while the 2nd order harmonic distortion measurement for the induction cooker A level 5 and the induction cooker level C during both DUT operations is measured 29, 27mV. The results are different because in this calculation the current entering the main network is assumed to be zero. Using circuit analysis, it can be seen that the magnitude of the harmonic distortion will depend on the characteristic impedance of the load.

To calculate the percentage of 2nd order harmonic distortion for various configurations, the following formula is used:

$$\%Config. = \frac{(Vmeasured - Vsource)}{Vsource} \times 100 \qquad (3)$$

The results of the percentage of 2nd order harmonic distortion for various configurations can be seen in Table 5 below.

Table 5 Percentage Of 2nd Order Harmonic Distortion For Various Configurations For The Single Operating Mode

Configuration	Percentage (%)	
	Level 3	Level 5
Single Operation	-	-
With Cooker C (Standby)	36,86	40.20
With Microwave B (Standby)	-18.05	-20.70
With Cooker C level 7 (Operating)	34.14	35.63
With Microwave B (Operating)	-14.83	-18.90

Table 5 is used to illustrate how the value of 2nd order harmonic distortion with various configurations is compared to a single load operation. From table 5 it can be seen that when an inductive load (induction cooker C) is connected to the circuit, the 2nd order harmonic distortion will increase by an average of about 36.81% when compared to the single operating mode. For induction cooker C in standby or in operation, 2nd order harmonic distortion has increased and occurs for level 3 and level 5 induction cooker configurations.

When induction cooker A is connected to a capacitive load (microwave inverter B), the 2nd order harmonic distortion is decreased by an average of 18.05% when compared to the single operating mode. For microwave inverter B in standby or operating, the 2nd order harmonic distortion has increased and occurs for the configuration of the induction cooker level 3 and level 5.

The difference between the impedance analysis for the 2nd order harmonic distortion and the observed value for the 2nd order harmonic distortion of the measurement is measured as an error. The percentage of errors can be seen in Table 6 below.

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Measured as an error. The percentage of errors can be seen in Table 6 below.

Table 6 Error Percentage for induction Cooker A measurement and impedance analysis

Cooker A Level 3			
Configuration	2nd Order Distortion		Error (%)
	Measurement (mV)	Calculation (mV)	
Single Operation	15.73	15.71	0.11
With Cooker C (Standby)	21.52	20.99	2.50
With Microwave B (Standby)	12.89	13.78	6.93
With Cooker C level 7 (Operating)	21.09	20.99	0.52
With Microwave B (Operating)	13.39	13.76	2.74

Cooker A Level 5			
Configuration	2nd Order Distortion		Error (%)
	Measurement (mV)	Calculation (mV)	
Single Operation	21.58	21.55	0.14
With Cooker C (Standby)	30.26	30.43	0.57
With Microwave B (Standby)	17.12	18.72	9.36
With Cooker C level 7 (Operating)	29.27	30.43	3.96
With Microwave B (Operating)	17.51	18.66	6.59

Conclusion

Based on the results of measurements of harmonic distortion at a frequency of 9-150 kHz produced by household appliances, the following conclusions are obtained The interconnected loads can affect the 2nd order harmonic distortion. They can increase or decrease the 2nd order harmonic distortion that occurs in the shared network. This condition will depend on the characteristic impedance of the distortion source device, neighboring devices, and the main network. Based on the measurement results, when the microwave inverter B is connected to the power grid, because it has capacitive behavior, the 2nd order harmonic distortion will be reduced by 18.12% compared to the single operation result of induction cooker A. On the other hand, when induction cooker C is connected to the power grid, because it has inductive behavior, the 2nd order harmonic distortion will increase by 36.71% compared to the single operation result of induction cooker A.

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