

The Effect of High Switching Frequency on Inverter Against Measurements of kWh-Meter

Isdawimah¹, Rudy Setiabudy¹, and Ridwan Gunawan¹

Abstract—In PV systems connected to the grid requires a kWh meter to measure the amount of power delivered to the grid, and an inverter to convert the DC voltage generated by PV into AC voltage. The latest generation of Inverter using the high switching frequency to obtain the inverter with good efficiency, small in sizes and lightweight. This led to the emergence of harmonics to the grid through the instrument of kWh meter, and caused the kWh-meter is not working properly. This study is intended to obtain the minimum value of the switching frequency which affect the results of measurement of Digital kWh meters. Kwh-meter tested by varying the switching frequency which is obtained from various types of inverters and from the simulator of switching of high frequencies.

Keywords—accuracy of measurement, digital kWh-meter, switching inverter, PV connected to the grid.

I. INTRODUCTION

Inverter one of electronic device which the function is to convert the DC voltage to AC voltage which the value of its amplitude and its frequency can be adjusted. The inverter is widely used in power generation system for renewable energy, such as on PV system, wind power, micro hydro and fuel cell. Various configuration of PV-inverter system shown in Figure 1 [1].

In general, the inverter uses a transformer to raise the voltage. Problems that appear to this kind of inverter which is using the transformer are the presence of core-iron losses and copper losses which affect the efficiency of the inverter and ultimately affect the efficiency of the system which is controlled by inverter [2]. Moreover, the usage of transformer caused the dimension of inverter become larger and heavier. One of ways to solve this problem is by using the high frequency up to 200 kHz on switching of inverter process (Figure 2), which is allows the size of transformer and losses of power become smaller [3]-[5]. However, high switching frequency will cause on-load harmonics.

Harmonics are defects on sinusoidal waves due to presence of another wave with frequencies of integer multiples of the fundamental frequency. The level of harmonics that exceed the standard (Table 1 and Table 2) could cause overheating of the equipment, permanent damage to some electronic equipment, reduced the lifetime of equipment and an error of energy measurement [6] - [8]. An example case of error in energy measurement of 15% occurred in the PV-inverter systems that supply power to the load and the grid [9].

In addition to harmonics, inverters with high switching frequency (3 kHz-150 kHz) causing electromagnetic distribution [10], where the standard for measuring electromagnetic compability (EMC) and immunity to harmonics in the frequency is not available yet [9].

Given the inverter which available in the market place has reached the switching frequency of 200kHz while kwh-meter test on PV-inverter system is just reached the inverter's switching frequency of 9kHz [10]. Therefore, the authors do the test up to 200 kHz by using common

inverter which available in the market and simulator switching frequency of the inverter for a particular frequency value which is not available in the market. By that way, obtained the correlation between the switching frequencies of the inverter (0-200kHz) with an error rate of measurement of digital kWh-meter, so it can determine a method to overcome them.

Switching frequency of the inverter is:

$$f_{osc} = \frac{1.1}{R_T C_T} \quad (1)$$

The effective voltage (V_{rms}) generated by inverter is :

$$V_{rms} = \frac{1}{2\pi} \int_0^{2\pi} v(\omega t) d\omega t$$

$$V_{rms} = \frac{V_{dc}}{2} \quad (2)$$

Total Harmonic Distortion is ratio between effective value of the harmonics against its fundamental effective wave, essentially expressed in % THD, is equal to:

$$THD_I = \frac{\sqrt{(I_2)^2 + (I_3)^2 + (I_4)^2 + \dots + (I_n)^2}}{I_1} \times 100\% \quad (3)$$

$$THD_V = \frac{\sqrt{(V_2)^2 + (V_3)^2 + (V_4)^2 + \dots + (V_n)^2}}{V_1} \times 100\% \quad (4)$$

The thresholds of harmonic of the voltage are classified based on the value of the applied voltage and regulated in IEEE STD 519-1992, as listed in Table 1. For voltages less than 69 kV, threshold of harmonic distortion of equipment (Individual Harmonic Distortion) is 3%, while threshold of overall harmonic distortion (Total harmonic distortion) is 5%. The threshold for current harmonics are classified based on ratio of the value of the maximum short circuit current with a maximum load current (Table 2).

Harmonics of the inverter output voltage can be obtained by outlining the voltage waveforms using Fourier series. A periodic function $2\pi f(x)$ that is integral to the area of $[-\pi, \pi]$, having the numbers (a_n and b_n) is referred to as the Fourier coefficients of f , that is [11]:

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos nx \, dx, n \geq 0 \quad (5)$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin nx \, dx, n \geq 1 \quad (6)$$

¹Isdawimah, Rudy Setiabudy, and Ridwan Gunawan are with Departement of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Depok, Indonesia. E-mail: atadawim@gmail.com; rudy@eng.ui.ac.id; ridwan@eng.ui.ac.id.

Configuration with the series formula is :

$$\sum f_n(x) = [a_0 \cos(0x) + b_0 \sin(0x)] + [a_1 \cos(x) + b_1 \sin(x)] + [a_2 \cos(2x) + b_2 \sin(2x)] + [a_3 \cos(3x) + b_3 \sin(3x)] + \dots + [a_n \cos(nx) + b_n \sin(3x)] \quad (7)$$

From the equation above, we see that at $n = 0$ has a value that does not depend on its sinusoidal part, so:

$$A_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) dx$$

$$f(x) = A_0 + \sum_{n=1}^{\infty} [a_n \cos(nx) + b_n \sin(nx)] \quad (8)$$

Basic components of the output voltage waveform (V_{fund}) inverter is:

$$v(\omega t) = \sum_{n=1,3,5,\dots}^{\infty} \frac{2V_{dc}}{n} \sin(n\omega t) = 0 \text{ untuk } n=2,4,\dots$$

$$V_{fund} = \frac{\sqrt{2}}{\pi} V_{dc} = 0.45V_{dc} \quad (9)$$

Writing the partial sum of the Fourier series f above and expansion it to the infinite value, can be formulated as follows:

$$\sum f_n(x) = A_0 + \sum_{n=1}^{\infty} a_n \cos(nx) + \sum_{n=1}^{\infty} b_n \sin(nx)$$

Thus harmonic at n on the waveform of output voltage (V_n) is:

$$V_n = \frac{V_{fund}}{n} \quad (10)$$

While the power absorbed by the load is:

$$P_{rms} = \frac{V_{rms}^2}{R} \quad (11)$$

$$P_{fund} = \frac{V_{fund}^2}{R} \quad (12)$$

$$v(n) = \frac{v_n}{\sqrt{2}} = \frac{2V_{dc}}{n\pi\sqrt{2}} = \frac{\sqrt{2}V_{dc}}{\pi n} \text{ untuk } n = 1,3,5$$

II. METHOD

The purpose of testing digital kWh-meter on PV-inverter system is to obtain an overview of the influence of inverter's switching frequency (0-200kHz) against the error rate of measurement on digital kWh-meter.

In this case, the testing was using a single phase digital kWh-meters which available in the market as the Device Under Tested (DUT kWh) with a Constant of 6000 pulses/kWh and a digital kWh-meter class 0.01 as a kWh-meter reference (REF kWh).

The testing also used two types of inverters which are available in the market, 6 units inverters with different kind of waveforms and switching frequency, as well as the simulator inverter with adjustable switching frequency (0-200kHz).

The type of the applied load is a resistive load, such as 100W/220V incandescent lamps. To meet the objectives, then three kinds of kWh-meter testing are applied, there are:

- Testing the kWh-meter with voltage source from the grid (Figure 3) to measure the level of kWh-meter accuracy.
- Testing the kWh-meter with PV-inverter system as a voltage source, using inverter which are available in the market with a wide range of switching frequency (Figure 4). The test aims to obtain a correlation between inverter's switching frequency with an error rate of measurement of digital kWh-meter.

- Testing the kWh-meter with voltage source from PV-inverters system, using a simulator inverter (Figure 5) with the variation of the switching frequency (0-200kHz). This simulator is used to complete the switching frequency value that could not be obtained from the inverter which available in the market. From the test obtained a minimum value of switching frequency in which affect the accuracy of kWh-meters.

The circuit of simulator inverter in Figure 5 consists of a pulse signal (derived from the signal generator) which the waveform, voltage and frequency could be adjusted. This signal is amplified by an amplifier circuit and a step-up voltage transformer. Pulse's signal is then superimposed on sinusoidal waves emanating from the grid, in order to obtain a new waveform resembles the waveform produced by the inverter with certain switching frequency.

III. RESULT AND DISCUSSION

In kWh-meter being tested there is LED that flashes with a certain time duration in accordance to the sum of energy measured in units of pulses / kWh. The kWh-meter requires 6000 pulses / kWh and duration of 100ms/pulse. This means the minimum of electrical energy that can be measured by the kWh-meter is 0.167Wh.

At first conducted the Testing #1 (Figure 3) to test the measuring grade of kWh-meter instruments, where kWh-meter is used to measure the power consumption of a resistive load (incandescent bulbs) which are supplied by a single-phase voltage source from the grid. From the test obtained the measurement of kWh-meters by 0.1 kWh (100Wh) within 61.5 minutes.

The results of these measurements indicate that the kWh-meter has been working in accordance to its measuring class (class 0.5).

kWh-meter then tested with second test (Testing #2 - Figure 4), where the kWh-meter is used to measure the power consumption of the resistive load which is supplied by a voltage source from the PV-inverter system. At a given period, the inverter replaced with another inverter from a different switching frequency. Prior to testing, the first stage is measuring switching frequency of each inverter using an oscilloscope. Value of inverter's switching frequency (F_s) is calculated based on the full-wave travel time (T) related to the time scale used (time/div), is equal to:

$$F_s = \frac{1}{T} \text{ where } T = n \times \text{time/div}$$

$$F_s = \frac{1}{n \times \text{time/div}}$$

Figure 5 is an example of the measurement results the inverter's switching frequency which are available in the market with the waveform of Quasi-square wave. The time scale (time / div) is 50 μ s with a pulse width (n) 2.6 div, the switching's frequency is:

$$F_s = \frac{10^6}{2.6 \times 50} = 7.7 \text{ kHz}$$

This test is using 6 units of single-phase inverter in various waveforms and switching frequency (Table 3), where the value of switching frequency of inverters which are available in the market is in the order of kHz,

the range of (6.7 kHz - 117 kHz). This becomes a constraint in testing the kWh-meter for low value of switching frequency (in the order of Hz).

Within the same value of the voltage, current and power factor, result of the Testing #2 compared to the Testing #1 (Table 4), in order to obtain the time difference (dt) and the energy difference (dWh). Data of measurement in Table 4 shown that in the Testing #2, kWh-meter measuring greater energy compared to Testing #1 and the longer the greater their energy difference. Difference in measurement caused by the presence of harmonics generated by the inverter (Table 3) exceeds the threshold (Table 1 and Table 2).

The Test #3 is testing kWh-meter with voltage source from PV-inverter systems. Inverters which are used in the form of simulator with adjustable switching frequency.

Figure 6 is an example of the process of formation of a new wave on the simulator-inverters, where a pulse signal with 277Hz switching frequency are superimposed on a sinusoidal wave with a frequency of 50Hz, resulting in a multilevel waveform with the switching frequency is 277Hz.

By adjusting the frequency of the pulse signal from the signal generator, will obtained the waves within various switching frequency. In addition to a low switching frequency ($F_s < 1000\text{Hz}$), this simulator can generate a high switching frequency, as shown in Figure 7.

The measurement results of Testing #3 in the form of a graph illustrating the relationship between the switching frequency and the measurement error (Figure 8). The testing is executed till the switching frequency reached at 200kHz and produced a significant measurement error (7.7% -17.2%), exceed the class of measuring instrument itself.

If the results of Testing #3 compared to the results of Testing #1 (Table 5), then it obtain the same conditions with the Testing #2, where the kWh-meter on Testing #3 measuring greater energy compared to kWh-meter in the Testing #1. This is caused by the presence of the THD on the inverter (Table 6).

IV. CONCLUSION

This study aims to get an optimum performance of kWh-meter when used to measure the electrical energy supplied by the PV-inverter system.

The method used was testing the kWh-meter with various voltage sources derived from the grid, the inverter from the PV system and from PV-inverter system but the inverter in the form of simulator. This simulator is used to expand the inverter's switching frequency becomes (71Hz-200kHz) in order to overcome the limitation of switching frequencies which are available in the market.

From the testing results obtained the minimum switching frequency that affecting measurement errors digital kWh-meter, that is as big as 556 Hz. Measurement error is decreased when the switching frequency is enlarged.

So it can be stated that the higher the inverter's switching frequency, the measurement errors are getting smaller. The measurement error is in a significant value (7.7% -17.2%), exceed the class of measuring instrument itself, even the switching frequency is enlarged to 200kHz. This is due to the harmonic distortion exceeds the allowable standard.

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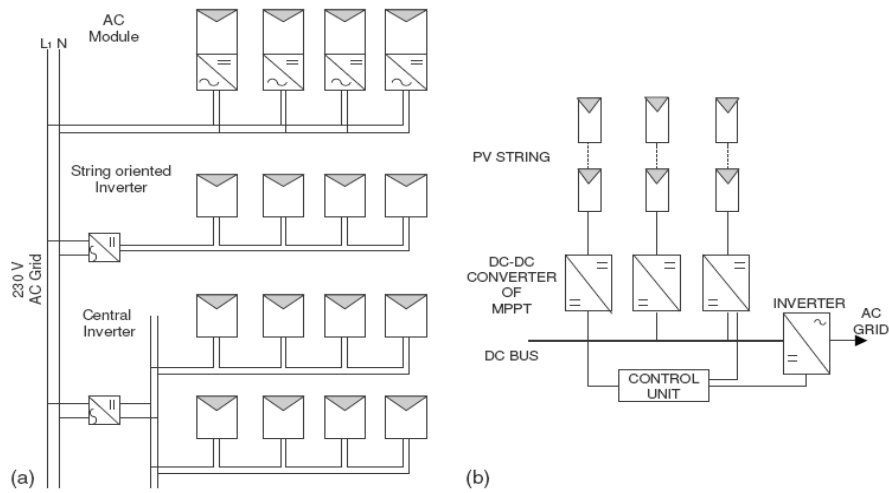


Figure 1. Configuration of PV-inverter [1]

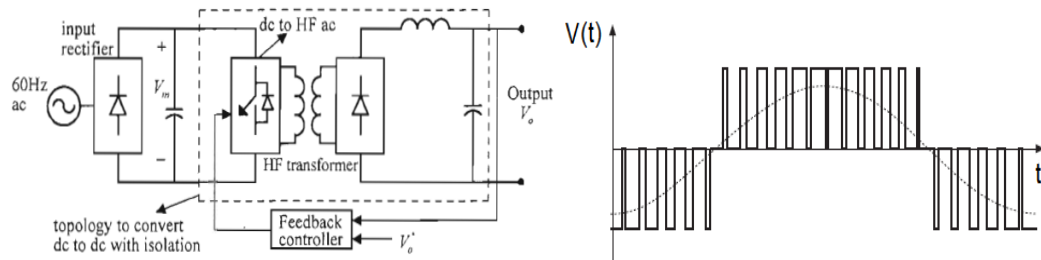


Figure 2. Inverter using the HF transformer (left) and HF signal modulation (right) [5]

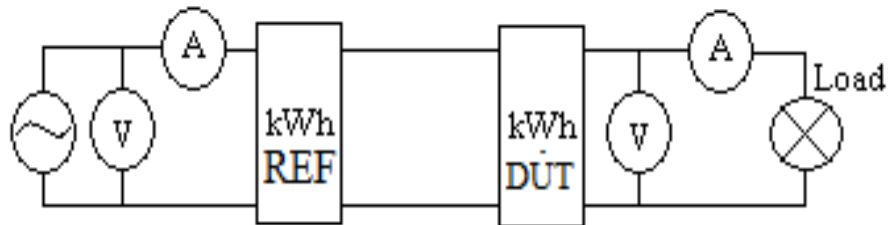


Figure 3. Testing the kWh-meter with voltage source from the grid

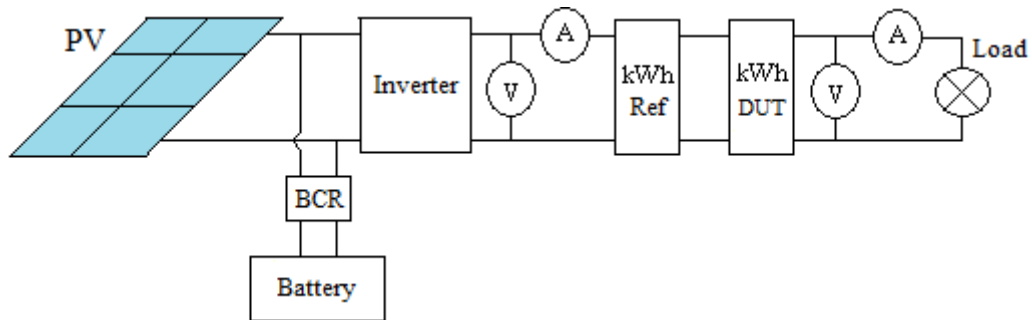
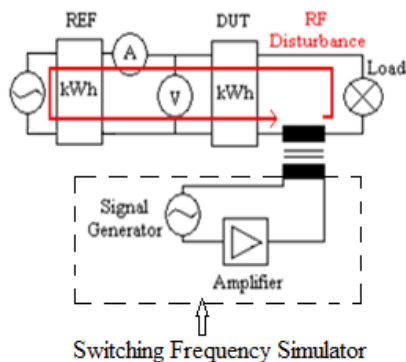


Figure 4. Testing the kWh-meter with PV-inverter system as a voltage source



← Amplifier
← Signal Generator

Figure 5. Testing the kWh-meter with voltage source from PV-inverters system, using a simulator inverter

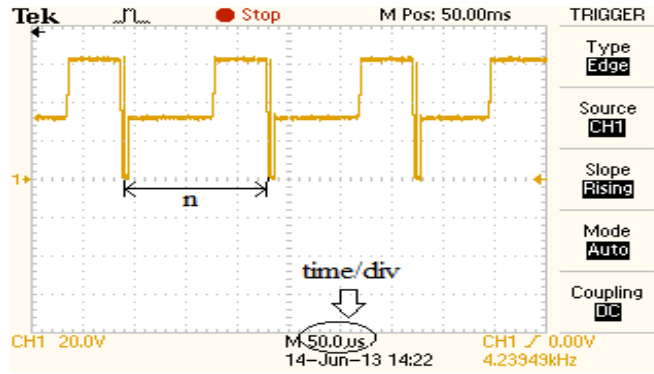


Figure 6. Switching frequency of inverter

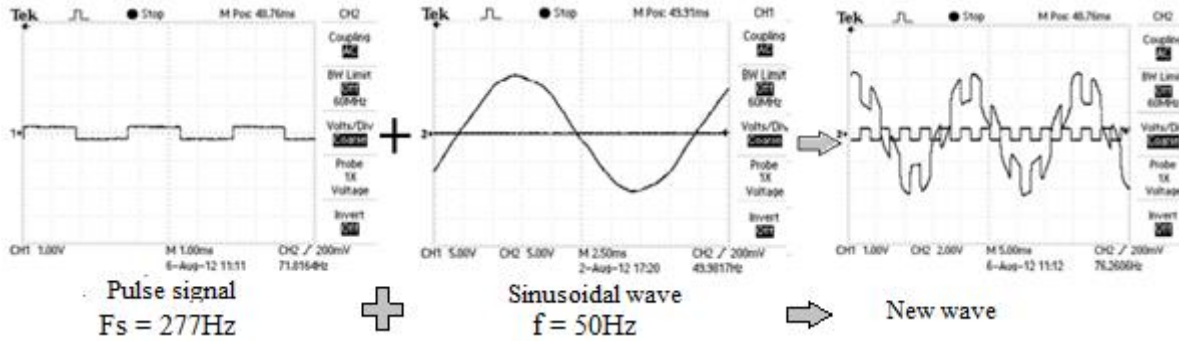


Figure 6. Process of forming a new wave in the simulator-inverter

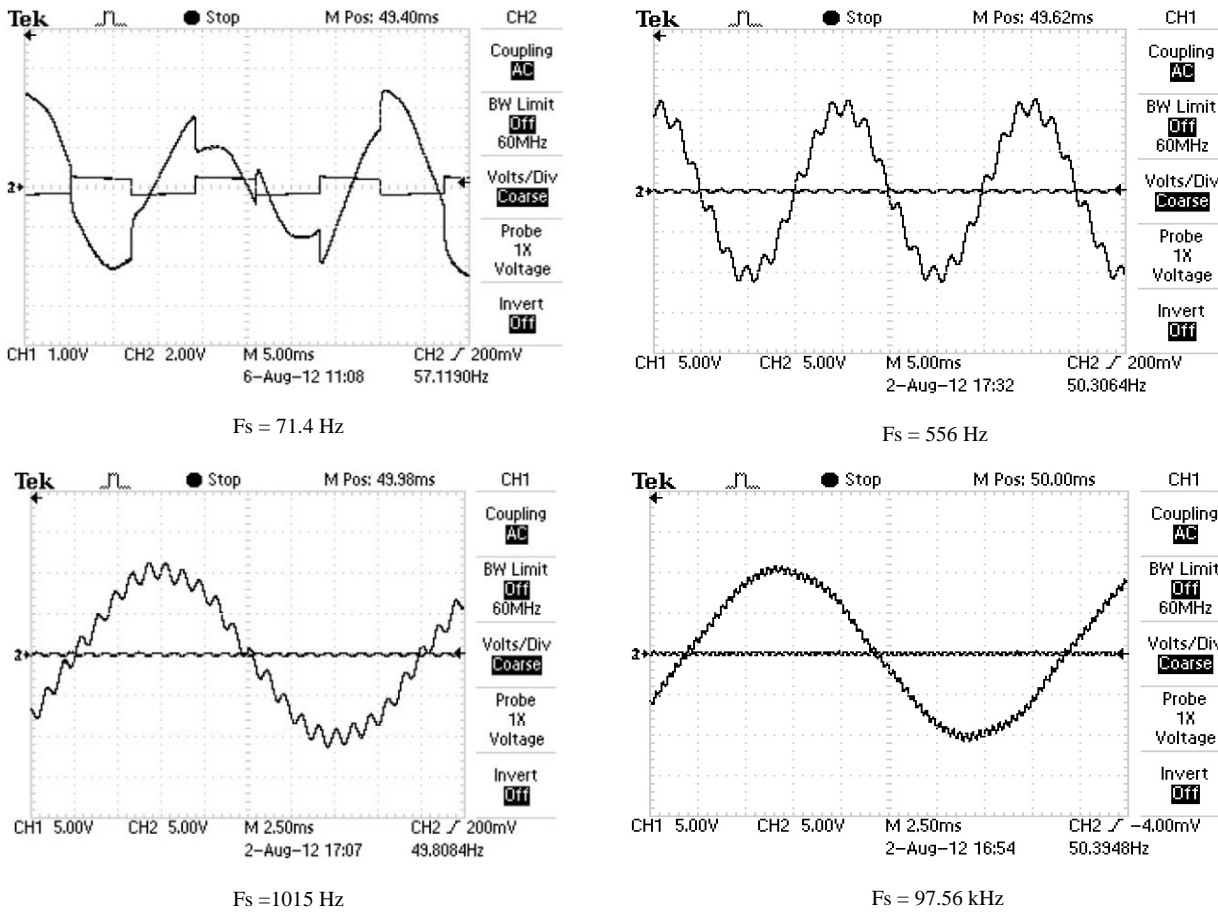


Figure 7. Various of switching frequencies generated by the simulator-inverter

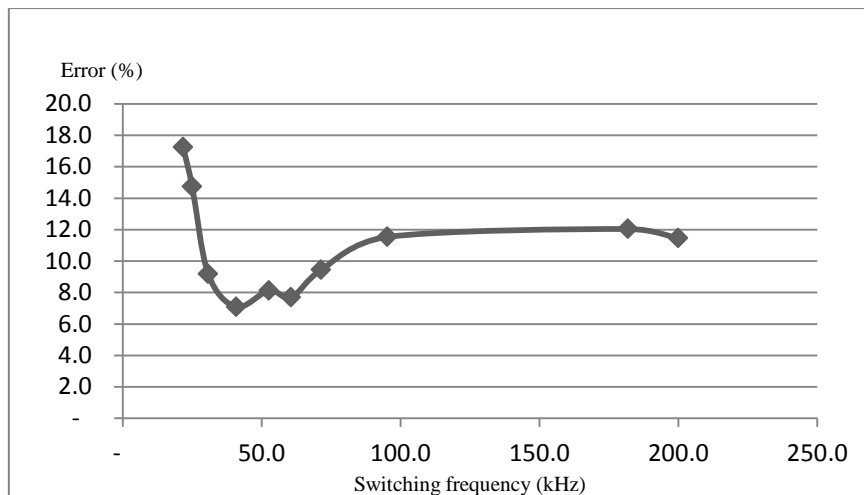


Figure 8. Graph of error energy meter measurement depend switching frequency inverter

TABLE 1.
VOLTAGE DISTORTION LIMITS

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC Terminal that will attenuate by the time it is tapped for a user.

Source: IEEE STD 519-1992

TABLE 2.
CURRENT DISTORTION LIMITS FOR GENERAL DISTRIBUTION SYSTEMS (120 V THROUGH 69,000 V)

I_{sc}/I_L	Maximum Harmonic Current Distortion in Percent of I_L					TDD
	Individual Harmonic Order (Odd Harmonics)					
	<11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	
$<20^*$	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above
Current distortion that result in a dc offset, e.g., half-wave converters, are not allowed.
*All power generation equipment is limited to these values of current distortion.

Regardless of actual I_{sc}/I_L

Where

I_{sc} = maximum short circuit current at PCC

I_L = maximum demand load current (fundamental frequency component) at PCC

Source: IEEE STD 519-1992

TABLE 3.
SWITCHING FREQUENCY (Fs) AND THD INVERTER

Wave Shape	F_s (kHz)	THD-V (%)	THD-I (%)
Sine wave	117	27,8	40,1
Quasi-square wave	50	22,3	23,5
Multilevel	40	2,4	19,6
Quasi-square wave	7,7	2,7	18,4
Quasi-square wave	7,1	2,0	20,0
Square wave	6,7	2,7	12,7

TABLE 4.
COMPARISON OF ENERGY MEASUREMENT FROM GRID (TESTING #1) AND PV-INVERTER (TESTING #2)

V(V)	Load I(A)	pf	Grid Wh1	Inverter Wh2	Wh1-Wh2 dWh	dWh (%)	t1-t2 dt
220	0,44	1	100.1	97.9	-2.2	-2.2	-1.2
220	0,44	1	200.1	216.0	16.0	8.0	9.2
220	0,44	1	300.0	330.2	30.2	10.1	17.4

TABLE 5.
COMPARISON OF ENERGY MEASUREMENT FROM GRID (TESTING #1) AND SIMULATOR (TESTING #3)

V(V)	Load		Grid	Inverter	Wh1-Wh2		t1-t2
	I(A)	pf	Wh1	Wh2	dWh	dWh (%)	dt
220	0,44	1	100.1	99.5	-0.6	-0.6	-0.2
220	0,44	1	200.1	216.0	16.0	8.0	9.2
220	0,44	1	300.0	330.2	30.2	10.1	17.4

TABLE 6.
THD ON VARIOUS INVERTER

Type of inverter	Switching frequency (kHz)	THD-V (%)	THD-I (%)
Simulator inverter	0,46	22,3	19,6
Simulator inverter	0,83	2,7	18,4
Simulator inverter	3,05	2,0	20,0
Simulator inverter	83,3	2,7	12,7