Inverter Performance Comparison On Solar Panel Applications

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Abstract

In this study, the effects of harmonics on the quality of the electrical power produced by both types of inverters are compared in solar panel applications between pure sine wave and modified sine wave inverters. Additionally, a number of prior investigations into harmonics and inverters have been analyzed. This study was done to find the best kind of inverter to use with solar panels in order to increase the effectiveness and caliber of the electricity generated. Experimental research methodology is applied, with measurements of the electrical power quality produced by both types of inverters under the identical circumstances. According to the findings, the modified sine wave inverter has a higher THD power quality than the pure sine wave inverter. The modified sine wave's displacement power factor (DPF) cannot be more than one (one), but the pure sine wave's DPF is equal to the cos phi value. At a 200W load, the pure sine wave inverter has a power efficiency of 93.35% while the modified sine wave inverter has an efficiency of 81.50%. Given that modified sine waves have a higher harmonic influence, it may be said that pure sine wave inverters create electrical power of a higher quality. Therefore, it is highly advised to utilize a pure sine wave inverter for solar panel applications.

Keywords: *inverter, solar panel, pure sine wave*

Abstrak

Penelitian ini membahas perbandingan antara inverter pure sine wave dan modified sine wave pada aplikasi panel surya, dengan mempertimbangkan dampak harmonik pada kualitas daya listrik yang dihasilkan oleh kedua jenis inverter. Sejumlah penelitian sebelumnya yang terkait dengan harmonik dan inverter juga telah dikaji. Penelitian ini dilakukan untuk membantu menentukan tipe inverter yang lebih tepat untuk aplikasi panel surya, sehingga dapat meningkatkan efisiensi dan kualitas daya listrik yang dihasilkan. Metode penelitian yang digunakan adalah eksperimental, dengan pengukuran kualitas daya listrik yang dihasilkan oleh kedua jenis inverter pada kondisi yang sama. Hasil penelitian menunjukkan bahwa inverter pure sine wave memiliki kualiatas daya THD yang lebih kecil daripada modified sine wave. Displacement Power Factor (DPF) pada inverter pure sine wave sama besar dengan nilai cos phi, sedangkan nilai DPF pada modified sine wave tidak lebih dari 1 (satu). Efisiensi daya inverter pure sine wave 93,35% dibandingkan dengan inverter modified sine wave 81,50% pada beban 200W. dapat disimpulkan bahwa inverter pure sine wave menghasilkan kualitas daya listrik yang lebih baik daripada modified sine wave, karena memiliki dampak harmonik yang lebih rendah. Oleh karena itu, inverter pure sine wave lebih disarankan untuk digunakan pada aplikasi panel surya.

Kata kunci: inverter, panel surya, pure sine wave

Introduction

As time goes by, technology is becoming more and more important in our lives. One of the daily needs affected is the need for electricity. Recently, renewable energy has been discussed and developed into an alternative energy breakthrough. Renewable energy such as biomass, geothermal energy, solar energy, hydro energy, wind energy and so on (Tiwari, 2018). One of the renewable energies that is undergoing a lot of development is solar panels, which use sunlight as a power plant. Solar panels produce direct current (DC) electricity, which needs to be converted to alternating current (AC) by an inverter to meet load requirements.

Therefore, this study compares the power quality produced by pure sine wave and modified sine wave inverters in solar panel applications. Several studies discussing the harmonics of PV systems and the effects of inverters have been reviewed Fei Wang and others (2011) introduced a way to predict the resonant quasi network impedance between DG inverters and the grid. The harmonic interaction between the grid and a given DG inverter can be estimated in advance. By using a 4th order bandpass filter, the proposed harmonic detector can effectively extract the harmonic components without phase lag. A closed-form analytical approximation of the output harmonic spectrum of a single-phase, two-stage inverter under the effect of current control hysteresis was carried out (Albanna., et al, 2010). Selection of a harmonic elimination problem using Artificial Neural Networks (ANNs) to generate angular switching in an 11-level full-bridge inverter cascade supplied by multiple DC input sources (Aravind & Alexander, 2010). The resonance limitation of a standard current controller operating under abnormal grid conditions was analysed and a control scheme of a 3-phase PV inverter was presented (Castilla, et al, 2013). Dongare (2017), present a current control inverter design that mitigates under-order harmonics. The complete design has been validated with experimental results and good agreement with the theoretical analysis of the whole system is observed. The Selective Harmonic Elimination (SHE) selection technique is applied to determine the switching angle of a multilevel inverter in conjunction with specially connected transformers (Young, Wu and Liu, n.d)

A modified sine wave inverter has an efficiency of 2.5% and a power factor of 2.8%, which is lower than pure sine wave but has a simpler and more efficient system and can be trusted to produce a higher voltage magnitude than pure sine wave, according to Mohammed (2009), who conducted research on the comparison of inverters using power quality consisting of THD and DF. According to Cheema et al. (2015) and Ikhsan & Fachri (2023), applying a low pass L-C filter to a pure sine wave inverter can result in an output wave with a low THD. By incorporating L-C filters, Haider (2015) describes his work on creating pure sine wave inverters that are more efficient than earlier inverters and result in a system that is reasonably efficient with a relatively low level of efficiency for inputs less than 100W. Efficiency rises when power does as well.

Literature Review

In order to convert DC power into AC power sources that are compatible with the current power grid system, the inverter becomes one of the key components of the solar panel system (Kwang & Masri, 2010). Modified sine wave inverters and pure sine wave inverters are the two main types of inverters available today (Cheema, et al, 2015). Both types of inverters are cutting-edge technological innovations and commonplace electrical equipment. However, there is a disturbance in the electrical power quality during the power supply process that needs correction. Harmonics are among the most significant elements influencing power quality (Phannil, et al, 2017). Harmonics have been the subject of various studies (Ajeigbe, et al, (2018), Baitha & Gupta, (2015), Bierk, et al, (2011)).

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a. Harmonics

Power systems are made to run at either a 50 or 60 Hz frequency. Some loads, however, produce currents and voltages at frequencies that are integral multiples of the fundamental 50 or 60 Hz frequency. Power system harmonics, a type of electrical pollution, are these higher frequencies. The total harmonic distortion (THD), often known as the harmonic distortion factor, is the generally accepted unit of measurement for harmonics. The RMS value of the harmonics above the fundamental divided by the RMS value of the fundamental is referred to as THD (Grady & Grady, 2012).

The THD formula is$THD_i = \frac{\sqrt{\sum_{k=2}^{\infty} I_k{}^2}}{I_1} \cdot 100\%$ ....(1)

The formula THD_i is used to measure the total harmonic distortion (THD) of signal i. In this formula, the THD is calculated as the square root of the sum of the squares of the second harmonic values to infinity (I_k), then the result is divided by the fundamental (I_1). The result is then multiplied by 100% to give the percentage of THD.

The same applies to THDv:

$$THD_v = \frac{\sqrt{\sum_{k=2}^{\infty} V_k{}^2}}{V_1} \cdot 100\% \quad \text{...(2)}$$

The formula THD_v is used to measure the total harmonic distortion (THD) of a voltage signal (v). In this formula, THD is calculated as the square root of the sum of the squares of the second harmonic values to infinity (V_k), then the result is divided by the fundamental voltage value (V_1). The result is then multiplied by 100% to give the THD percentage of the voltage signal.

b. Power Factor

The concept of power factor is obtained to measure how efficiently the load uses the current from the AC system. Power factor can occur in two output waveform conditions (Grady & Gilleskie, 1993), namely:

1. Sinusoidal Condition

Sinusoidal is a type of wave formed by the repetition of curved lines with the mathematical pattern of sine or cosine. These waves have several important characteristics such as amplitude, frequency and phase. Sinusoids can be found in various natural phenomena, including sound waves, electrical signals and electromagnetic waves. In mathematical terms, sinusoids can be expressed by the equations sin(t) or cos(t), where t is the time variable. Sinusoidal waves have a repeating oscillation pattern with a regular shape consisting of identical cycles. Amplitude describes the height or size of the wave, while frequency refers to the number of cycles that occur in a unit of time, usually one second. Meanwhile, phase describes the relative position of the wave with respect to time. The true power factor (pf_{true}) of a load is defined as the ratio of mean power to apparent power or

$$pf_{true} = \frac{P_{avg}}{S} = \frac{P_{avg}}{V_{rms} I_{rms}} \quad \text{..(3)}$$

The formula pf_{true} is used to calculate the true power factor in an electrical system. The true power factor is calculated by dividing the average power (P_{avg}) by the product of the root mean square (RMS) values of voltage (V_{rms}) and current (I_{rms}). This formula allows us to determine how efficiently the system is using power by comparing the average power consumed with the effective power provided by the voltage and current.

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In the case of pure sinusoids, which are.

$$pf_{true} = pf_{disp} = \frac{P_{avg}}{\sqrt{P^2+Q^2}} \quad \text{...(4)}$$

The formula $pf_{true} = pf_{disp}$ is used to calculate the true power factor and the reactive power factor in an electrical system. The true power factor is calculated by dividing the average power (P_{avg}) by the square root of the sum of the squares of the active power (P) and reactive power (Q). This formula allows us to know the extent to which the average power uses the total power in the system, including the reactive power component.

$$pf_{true} = \frac{\frac{V_I}{\sqrt{2}}\frac{I_I}{\sqrt{2}}cos(\delta_1-\theta_1)}{\frac{V_I}{\sqrt{2}}\frac{I_I}{\sqrt{2}}} = cos(\delta_1-\theta_1) \quad \text{...(5)}$$

The formula pf_{true} indicates that the true power factor in an electrical system can be calculated as the cosine of the phase angle difference between voltage (θ_1) and current (δ_1), i.e., $cos(\delta_1 - \theta_1)$. In this formula, $\frac{V_I}{\sqrt{2}}$ and $\frac{I_I}{\sqrt{2}}$ represent the effective (RMS) values of voltage and current. Using this formula, we can see how much real power (cosine of the phase angle) is being used by the system to utilise the available voltage and current.

2. Non-Sinusoidal Condition

Non-sinusoidal refers to a certain kind of wave that is not sinusoidal in shape. Non-sinusoidal waves have waveforms that are more complicated and cannot be adequately characterized by a simple sine or cosine operation. Square waves, triangle waves, beat waves, and complex waves like musical sound waves are a few examples of non-sinusoidal waves. The waveform and its scientific character are where sinusoidal and non-sinusoidal vary most. Sinusoids can be represented by a single sine or cosine and have a predictable motion pattern. Non-sinusoidal waves, on the other hand, have waveforms that are more complicated and do not adhere to the conventional sinusoidal design.

Under non-sinusoidal conditions, the voltage and current relationships contain harmonics, mostly generated by non-linear loads such as speed controllers and diode bridge rectifiers. Harmonic oscillations are common in multiples of 3, 5 and 7 at 50/60 Hz. Substituting equations (2.1) and (2.2) gives the equation:

$$pf_{true} \approx \frac{P_{avg}}{V_{rms}I_{rms}} \cdot \frac{1}{\sqrt{1+(THD_I/100)^2}} = pf_{disp} \cdot pf_{dist} \quad \text{...(6)}$$

The formula pf_{true} approximates P_{avg} divided by the product of V_{rms} and I_{rms} multiplied by the inverse of the root of 1 plus the square of $(THD_I/100)$. In this formula, pf_{true} represents the true power factor, while pf_{disp} represents the displacement power factor and pf_{disp} represents the distortion power factor. Using this formula, we can calculate the true power factor by considering the apparent power factor and the distortion power factor affected by the harmonic distortion in the current signal.

c. Power

Non-sinusoidal refers to a certain kind of wave that is not sinusoidal in shape. Non-sinusoidal waves have waveforms that are more complicated and cannot be adequately characterized by a simple sine or cosine operation. Square waves, triangle waves, beat waves, and complex waves like musical sound waves are a few examples of non-sinusoidal waves. The waveform and its

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$$\eta = \frac{P_{out}}{P_{in}} \; x \; 100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

Methodology

In this study, the inverter is assembled according to the working system in the PV system application Figure 1 with battery components, solar charger controller, inverter and load. The system design of the inverter circuit Figure 2 is shown in the following figure:

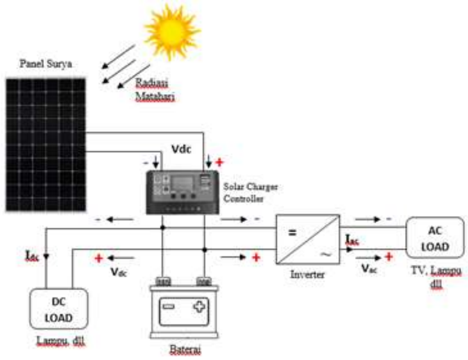

Figure 1: Solar System

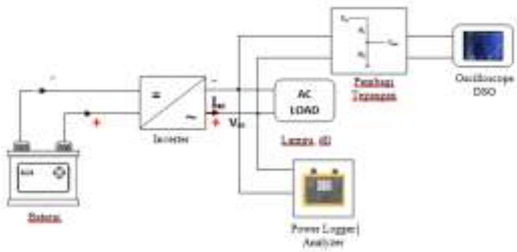

Figure 2. Inverter System in Solar Power Plant

The inverters compared based on their output waves are pure sine wave inverters and modified sine wave inverters with the specifications shown in Tables 1 and 2.

Table 1. Pure Sine Wave Inverter Specifications

Model FPC-500AL	***Parameters***	***Rated***
DC Input	*Rated Battery Voltage*	12VDC
	Rated Current	50Asdwe
	No-load current	< 600mA
	Efficiency	> 91 %
	Battery Type	Lead-acid battery
AC Output	*Rated power*	500W
	AC voltage	220VAC
	Frequency	50Hz
	Waveform	*Pure sine wave*

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Table 2: Specifications of Modified Sine Wave Inverter

Model SDA-500W	***Parameters***	***Rated***
Input	*Battery voltage*	48V
	High voltage cut-off	DC60±3V
	Low voltage alarm	DC41±1.5V
	Low voltage cut-off	DC40±2V
	Input voltage range	DC40V-DC60V
Output	*Rated power*	500W
	Power surge	≥*Rated power**2
	Output voltage	AC 220V ±10%
	Output frequency	50Hz+/- 5Hz 50Hz/60Hz *optional*

Preparing the necessary equipment, such as batteries, DC power meters, DC ampere-turns, inverters, AC power meters, voltage dividers, oscilloscopes, power logger analyzers, and loads, is the first stage in gathering inverter data. Additionally, all of the gear is set up as depicted in Figure 2. Data is gathered under settings of 100W, 200W, 300W, 350W, 400W, and 450W load fluctuations with no load. A 100W lamp, a 300W hairdryer, and a 350W iron are the loads that were employed, and the data that was gathered included inverter input and output, power, and THD. A power meter and an ampere meter are used to gauge the inverter's input and output. While a power logger analyzer is used to determine the inverter THD. Following data processing, power, THD, and power factor calculation values are compared. This is done to calculate the power efficiency value and the measurement instrument tolerance value.

Results and Discussion

Based on the tests carried out with pure sine wave and modified sine wave inverters, the output wave results are shown in Figures 3 and 4. The results of the pure sine wave inverter no-load data collection are as follows:

Battery Input before load = 12,45 Vdc
Inverter output before load = 222 Vac
Input current before load = 0,62 A
Output current before load = 0,07 A

Figure 3: Output Waveform of Pure Sine Wave Inverter

The measurement results of the pure sine wave inverter without using a load with an input voltage of 12.45V and a current of 0.62A gave an input power of 7.72W with a waveform as shown in Figure 3. The highest input voltage and current in the inverter occurs when using the smallest load of 100W, namely 11.96V and 8.89A. At the maximum load condition of 450W, the input voltage is 9.47V with a high current of 24.07A. Changes in the input voltage affect the size of the inverter output. Voltage and current are inversely proportional to each other. At the minimum load condition of 100W, the output voltage has the highest value of 224V with the lowest current of 0.45A. Whereas at the maximum load condition of 450W the lowest input voltage is 189V and the

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highest current is 1.77A. As the load used increases, the input capacity decreases, thus affecting the size of the inverter output. The results of the modified sine wave inverter no-load data collection are as follows:

Battery Input before load = 12,08 Vdc
Inverter output before load = 214 Vac
Input current before load = 0,92 A
Output current before load = 0,33 A

Figure 4. Modified Sine Wave Inverter Output Waveforms

With an input voltage of 12.08V and a current of 0.92A and no load, the modified sine wave inverter's measurement findings produced an input power of 11.11W and a waveform similar to that in Figure 4. When employing the minimum load of 100W, 11.58V and 8.97A, the inverter's highest input voltage and current, respectively, occur. The input voltage is 9.47V and the high current is 24.07A when the load is at its maximum of 450W. The size of the inverter output changes as the input voltage changes. Current and voltage have an inverse relationship. The output voltage is at its peak value of 203V and its lowest value of 0.51A at the minimal load condition of 100W. While the lowest input voltage and highest current are both 1.16A when the maximum load situation is 450W. The battery voltage drops as the installed load rises. This also has an impact on the inverter's output.

As the power increases, the power supplied to the inverter decreases in proportion to the output power. In this case, the efficiency decreases inversely to the condition when the load increases near the maximum limit. The full data of the inverter test results are shown in Table 3.

Table 3. Inverter Experiment Results

Parameters	**Load**											
	100W		**200W**		**300W**		**350W**		**400W**		**450W**	
	PS	MS	PS	MS	PS	MS	PS	MS	PS	MS	PS	MS
Vin(V)	11,96	11,58	11,50	11,14	11,23	10,75	10,91	10,51	10,75	10,15	10,42	9,47
Iin(A)	8,89	8,97	18,50	16,40	26,62	22,81	30,15	22,21	31,08	24,86	36,3	24,07
Vout(V)	224	203	224	189	212	174	203	161	199	157	189	116
Iout(A)	0,45	0,51	0,89	0,83	1,29	1,16	1,46	1,18	1,52	1,26	1,77	1,16
Pin(W)	106,3	103,8	212,7	182,6	298,9	245,2	328,9	233,4	334,1	252,3	378,2	227,9
Pout(W)	98,69	83,44	198,6	148,9	272,6	197,7	296	185,4	300,6	194,7	334,4	131,3
Cos phi	0,98	0,80	0,99	0,94	0,99	0,97	0,99	0,97	0,99	0,98	0,99	0,97
Efficiency (%)	92,82	80,33	93,35	81,50	91,18	80,63	89,99	79,43	89,97	77,16	88,41	57,6

Based on the experiments carried out, the values of THDv and THDi are obtained for each inverter. This is because the use of non-linear loads, of which the inverter is one [9], produces a lot of harmonics. The modified sine wave inverter has a higher THDv of more than

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40% compared to the THDv in the pure sine wave inverter of less than 5%. Then for THDi in the modified sine wave inverter more than 30%. In this condition, the THDi of the modified sine wave inverter is larger than that of the pure sine wave inverter. The amount of THD will affect the power quality of the system. The THD can be calculated using equation 2.1. The magnitude of each load THD on the inverter is shown in Figures 5 and 6.

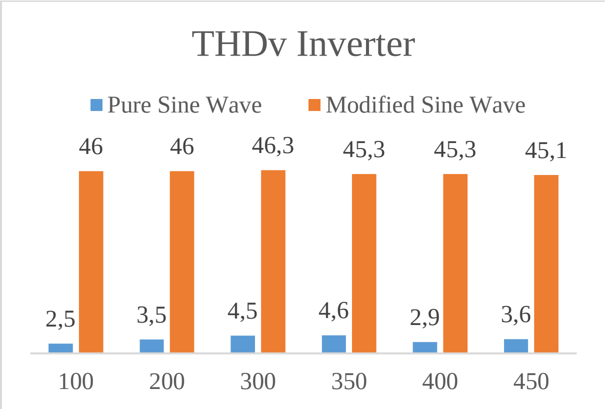

Figure 5. THDv Inverter

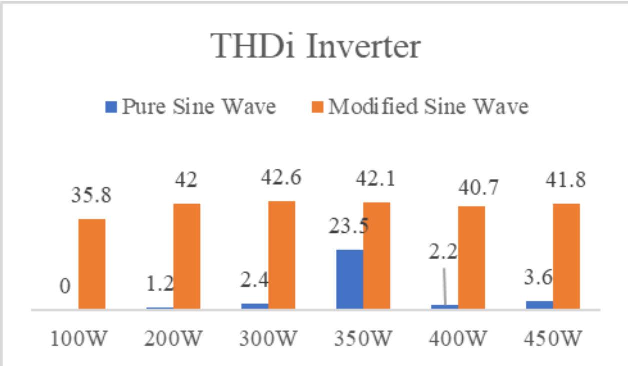

Figure 6. THDi Inverter

Voltage and current harmonics generated by non-linear loads can increase losses and therefore have a negative impact on components and electrical distribution systems. The relationship between harmonics and losses is very complex, so it can be compared by including harmonics from non-linear loads in the power factor as in equation 2.5.

Tabel 4. Power Factor Pure Sine Wave

Load	P	S	pfdisp	pfdist	pftrue
100W	98.78	100.8	0.98	1	0.98
200W	197.37	199.36	0.99	0.99	0.99
300W	270.75	273.48	0.99	0.99	0.99
350W	293.42	296.38	0.99	0.97	0.96
400W	299.46	302.48	0.99	0.99	0.99
450W	331.19	334.53	0.99	0.99	0.99

From the table above it can be seen that the DPF value on the pure sine wave inverter is equal to the PF value or the cos phi value displayed on the meter. Calculate the PFdisp value using equation 2.5.

Tabel 5. Power Factor Modified Sine Wave

Load	P	S	pfdisp	pfdist	pftrue
100W	82.82	103.53	0.8	0.94	0.75
200W	147.46	157.87	0.94	0.93	0.87
300W	195.78	201.84	0.97	0.92	0.89
350W	184.28	189.98	0.97	0.92	0.89
400W	193.86	197.82	0.98	0.93	0.91
450W	130.52	134.56	0.97	0.92	0.89

According to the results of the table above, the modified sinusoidal inverter has a PFdisp value that cannot be higher than 1, suggesting that PFtrue in non-sinusoidal situations has a maximum value [20] with equation 2.6. This inverter's PFtrue value is lower than its PFdist value. A pure sine wave inverter has the highest power factor, averaging 0.998 under varying load conditions. The modified sine wave inverter has an average power factor of 0.946. Experiments using a pure sine wave inverter gave a power efficiency of 92.82% at 100W load. The power efficiency increases to 93.35% at 200W load. Calculate the power efficiency using equation 2.8.

Vin = 11,96 V
Iin = 8,89 A
Vout = 224 V
Iout = 0,45 A
Cos θ = 0,98
Pin = Vin x Iin
= 11,96 x 8,89
= 106,32 W
Pout = V_{out} x I_{out} x cos θ
= 224 x 0,45 x 0,98
= 98,69 W

$$\eta = \frac{P_{out}}{P_{in}} \ x\ 100\% \qquad (2.7)$$

$$= \frac{98,69}{106,32} \ x\ 100\%$$

= 92,82%

Experiments using a pure sine wave inverter gave a power efficiency of 92.82% at 100W load. The power efficiency increases to 93.35% at 200W load. Power calculation using equation 2.8.

Vin = 11,58 V
Iin = 8,97 A
V_{out} = 203 V
I_{out} = 0,51 A
Cos θ = 0,8
Pin = Vin x Iin
= 11,58 x 8,97
= 103,87 W
Pout = V_{out} x I_{out} x cos θ
= 203 x 0,51 x 0,8
= 82,82 W

$$\eta = \frac{P_{out}}{P_{in}} \ x\ 100\% \qquad (2.7)$$

$$= \frac{82,82}{103,87} \ x\ 100\%$$

= 80,33%

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The inverter's power efficiency can be calculated from the voltage and current data recorded. The power efficiency of pure sine wave and modified sine wave inverters is shown in the graph below.

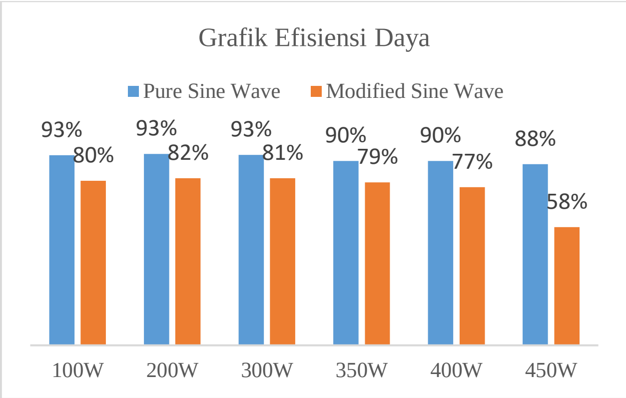

Figure 7. Inverter Power Efficiency

Conclusion

The pure sine wave inverter outperforms the modified sine wave inverter, with the highest THD values at THDv 4.6% and THDi 23.5%, according to comparison results utilizing THD parameters, DPF, and inverter power efficiency. Pftrue is the same as PFdisp. This inverter's efficiency can reach 93%. The improved sine wave inverter's THD values are THDv46.3% and THDi42.6%, which are significantly higher. Pftrue PFdisp and PFdisp is less than 1 for this inverter. The power efficiency rating is 82%. Pure sine wave inverters have a more complex circuit with a higher price than modified sine wave and the presence of PWM to reduce harmonics in the inverter output wave. This research can be continued by adding another type of inverter, namely square wave. Modelling is then carried out to reduce the harmonics generated in the inverter to improve the power quality of the inverter.

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