Implementation of Power Factor Correction using Asynchronous Boost Converter on Single Phase Full-Bridge Diode

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Abstract—In various industrial applications, the use of a power supply that uses a conventional diode single-phase rectifier topology results in high harmonic values in the electricity distribution system. One of the real impacts of this harmonic value is the heating of the electric power system equipment and power losses. High rms current values due to harmonics often cause problems in protection settings in addition to efficiency problems. The percentage value between the total harmonic component and the fundamental component is called THD (Total Harmonic Distortions). Therefore, in this study an asynchronous dc-dc boost converter is connected to the output side of a single-phase diode rectifier which is capable of improving power factor and low harmonics. So that a THD value of less than 15%, PF (Power Factor) = 0.92-1 and a sinusoidal input current can be obtained. The implementation results show that the PFC (Power Factor Correction) method can work well on single-phase diode rectifiers.

Index Terms— Boost converter, Power Factor Correction, Single phase rectifier, Total Harmonic Distortion.

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Abstrak—Pada berbagai aplikasi industri, penggunaan power supply yang menggunakan topologi penyearah satu fasa dioda konvensional mengakibatkan nilai harmonis yang tinggi pada sistem distribusi listrik. Salah satu dampak nyata dari nilai harmonis ini adalah pemanasan pada peralatan sistem tenaga listrik dan power losses. Nilai arus rms yang tinggi akibat harmonis seringkali memberikan masalah setting proteksi selain masalah efisiensi. Nilai prosentase antara total komponen harmonis dengan komponen fundamentalnya disebut THD (Total Harmonic Distortions). Oleh sebab itu, pada penelitian ini suatu konverter dc-dc boost asinkron dihubungkan pada sisi keluaran penyearah 1 fasa dioda yang mampu melakukan peningkatan faktor daya dan harmonis rendah. Sehingga dapat diperoleh nilai THD kurang dari 15%, PF (Power Factor) =0.92-1 dan bentuk arus masukan sinusoidal. Hasil implementasi menunjukkan bahwa metode PFC (Power Factor Correction) dapat bekerja dengan baik pada penyearah satu fasa dioda.

Kata Kunci— Boost converter, Power Factor Correction, Single phase rectifier, Total Harmonic Distortion.

I. INTRODUCTION

Modern electronic equipment does not always bring passive loads to the source or power line side. Initially, reasonable loads have one of the resistive characteristics such as lights or sinusoidal input current and experience phase interference such as an AC motor. Currently, most electronic systems use one or more power converters that cause the current on the source side or power line to become non-sinusoidal. These characteristics of the input current cause the current and possible voltage distortions that can cause problems on other electronic equipment connected to the source and reduce the capacity of such systems. This problem required the creation of a standard design with the aim of limiting harmonic distortion on the source or power line side. The solution to this problem is known as power factor correction (PFC) [1],[2].

From the influence of harmonic on the system, then some countries use the large standard harmonic that is still allowed on a system, i.e. with the standard IEC 61000-3-2. From the negative consequences caused by the harmony of the directional network, a power supply network that has very high quality such as high efficiency and small harmony is required. One additional topology used to assist the alignment performance is the dc-dc converter type boost [3]. The Boost topology itself has a variety of shapes, one of which is the bridgeless topology. Bridgeless topology has a fairly high complexity on the controller side and a poor EMI impact [4]-[7].

Based on previous research, on the three-phase alignment application, a cost analysis has been carried out to determine the power size and type of boost topology for the PFC application [8]. One method used for bridgeless topology is the interleaved method [9],[10]. On the other hand, the complexity of the network became increasing and less so in line with the demand for PFC features on various electrical devices, mainly battery charger on the latest electric car applications. Moreover, the demand for PFC rectifier features with broad voltage range capabilities is increasing [12].

To solve this problem, the author tried to design a series of “Boost Converters” as a Power Factor Correction. (PFC). The chosen topology is an asynchronous boost converter connected to a full-wave one-phase diode booster.

II. SINGLE PHASE RECTIFIER PROBLEM

The AC-DC converter or rectifier is a circuit that can convert an AC voltage into a DC voltage. The most widely used type of regulator topology in power supply applications is a full bridge diode one-phase regulator. The full bridge controller (full-bridge) uses 4 diodes as seen in Figure 1. When the input voltage undergoes a
positive cycle, power is supplied to the load through diodes D1 and D2. At the time of a negative cycle, the diodes D3 and D4 enter the conduction mode to transfer power to the load. The waveform for output voltage and input current can be seen as in Figure 2.

Figure 1. Single Phase Full-Bridge Rectifier

Figure 2. Single Phase Full-Bridge Diode Waveform (red: input current, green: input voltage, dan blue: output voltage)

The problem that arises on the single-phase bridge diode regulator is the non-sinusoidal form of the input current. This leads to the high value of harmonic on the input. Based on Figure 2, it can be seen that the input peak current value becomes high enough that the rms value of the input current also increases. It does not comply with the IEC 61000-3-2 standard relating to the limit of harmony values generated by a device to be connected to the electrical network.

The concept of PFC improvement is by connecting the boost converter to the output side of the rectifier. By controlling the PWM value, then the current on the boost converter inductor can be set as an absolute sinusoidal value with the same frequency as the source voltage. Figure 3 shows a PFC Boost Converter simulation. The source current waves that are not originally sinusoidal on conventional condensers can be fixed into sinusoid. Figure 4 shows a sinusoidal-shaped blue input current wave. This proves that a simulation of the improvement of the input side power factor from a conventional one-phase diode condenser can approach a value of 1.

III. DESIGN AND IMPLEMENTATION

Literature studies that carried out as references in this research are books / e-books, existing research journals, or accountables articles. This is done to obtain basic design, supplementary information and recommended laboratory setup to obtain valid data. The proposed measurement for this research can be described as follows:

• Output voltage of PFC Boost Converter.

A. Laboratory Experimental Setup

Figure 3. Simulation Circuit of Boost PFC Converter

Figure 4. Simulated Waveform of Single Phase Full-Bridge Rectifier with PFC Correction Circuit (red: conventional rectifier input current, green: input voltage, purple: output voltage dan blue: PFC rectifier input current)

B. Block Diagram of Proposed Circuit

Block diagram on Figure 5 can be explained as follows:

• Diode rectifier is used to rectify the sinusoidal input voltage.
• Current sensor is used to directly measure the input current for current loop control.
• Boost converter circuit is used to increase the output voltage.
• Voltage sensor is used to measure the output voltage in the voltage control loop.
• IC FA5502 is used as main controller to generate PWM switch into the MOSFET.
• Rheostat in forms of pure resistive load is connected to the output to test the performance of the proposed PFC correction circuit.

1) Circuit Specification
a. IC FA5502
b. IGBT 60N100
c. Dioda MUR 3060
d. PFC Boost Converter

• Input Voltage = 220 Vac
• Input Frequency = 50Hz
• Output Voltage = 380 Vdc
• Switching Frequency = 85 KHz
• Output Power = 2000 Watt

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C. Calculation of PFC Boost Controller Component

\[ I_{out} = \frac{P}{V_o} = \frac{2000 \text{ W}}{380 \text{ Vdc}} = 5.26 \text{ A} \]  \hspace{1cm} (2)

4) The inductor is a very important component of the PFC (Power Factor Correction) Boost Converter. Because it works to ensure that the load will get the current supply when the MOSFET is switched off. To determine suitable value, inductor calculation according to the equation on the IC data sheet FA5502 is performed.

\[
\frac{V_{in}^2(V_o - \sqrt{2} \cdot V_{in})}{\gamma \times f_s \times P_{in} \times V_o}
\]  \hspace{1cm} (3)

where

\[ V_{in}^2 = \text{AC input Voltage (Vrms)} \]
\[ \gamma = \text{Ratio of ripple content to peak input current. (Set to approx. 0.2)} \]
\[ f_s = \text{Switching frequency (Hz)} \]
\[ P_{in} = \text{Maximum input power} \]

\[ L \geq \frac{220^2(321 - \sqrt{2} \cdot 220)}{0.2 \times 85000 \times 2000 \times 321} \]  \hspace{1cm} (4)

\[ L \geq 43.783 \mu H \]

hence, L value should be greater than 43.783 \( \mu \)H

5) Capacitor

Capacitors is used not only as electric charge storage but also low pass filter on the output. On this boost PFC converter circuit, the main purpose of the output capacitor is to reduce the voltage ripple. The larger the capacitor value, the smaller the ripple, or vice versa. in this implementation stage 100 \( \mu \)F of electrolytic capacitor is used as output voltage filter.

\[ V_{rp} = \frac{I_o}{\omega_0 \times C_o} \]  \hspace{1cm} (5)
\[ C_o = \frac{I_o}{V_{rp} \times \omega_0} \]  \hspace{1cm} (6)

\[ I_o = \text{Output current [A]} \]
\[ \omega_0 = 2\pi f_0 (f_0: \text{AC Line Frequency (Hz)}) \]
\[ C_o = \text{Output smooting capacitance [F]} \]

6) \( R_s \) – Current Sense

\[ R_s \leq \frac{V_{in_{min}}}{\sqrt{2} \times P_{in_{max}}} \]  \hspace{1cm} (7)

where

\[ V_{in_{min}} = \text{Minimum AC input voltage [Vrms]} \]
\[ P_{in_{max}} = \text{Maximum input position [W]} \]

hence,

\[ R_s \leq \frac{220}{\sqrt{2} \times 2000} \Omega \]
\[ R_s \leq 0.07778 \Omega \]
Hence, a 5 Watt 0.05 resistor is used as current sense resistor in this experimental setup.

7) IGBT

The semiconductor switches that are commonly used on power applications >1000 W are IGBT. The IGBT type should be strong enough to withhold the PFC (Power Factor Correction) Boost Converter input voltage of 311 Vdc and 5 A of input current. Based on these values, the IGBT 60N100 was chosen as the primary semiconductor switch because it has a current rating of 60 A and a voltage rating of 1000 V.

8) Diode Bridge

The single phase full-bridge rectifier can be implemented by connecting 4 pieces of discrete package diode. This configuration has advantage such as high reliability because each of diode can be replaced immediately if there is any problem. However, for the sake of simplicity and EMI robustness, a bridge package is used in this experimental stage. The diode bridge has a voltage rating of 400 volts and a current rating of 50 ampere.

D. Hardware Implementation PFC Boost Converter

Setelah memperhitungkan komponen yang akan digunakan dan membuat skematik rangkaian PFC (Power Factor Correction) boost converter maka selanjutnya membuat desain PCB PFC (Power Factor Correction) boost converter. Figure 7 menunjukkan layout PCB untuk implementasi Boost PFC Converter.

IV. DISCUSSION AND ANALYSIS

This chapter will discuss the parameters measurement of each component, and test the performance and characteristics of the PFC Boost converter. The proposed circuit is expected to run in accordance with design in the previous chapter which will then be analyzed to determine the accuracy of the implementation between the design stage and the obtained results.

A. Loading Test of Single Phase Full-Bridge Diode

In this test, measurements of circuit parameter values such as input current and output voltage of the rectifier diode without using the PFC method have been carried out. Measurement of single phase rectifier without PFC Boost Converter is done by changing the load value. This aims to determine the effect of changes in load on the power factor, converter efficiency and output voltage.

Base on Figure 8, it can be seen that the circuit is working without power factor correction method, hence it is working as conventional single phase full-bridge diode. The waveform of measured input voltage and current can is provided on Figure 9. The shape of input current is not sinusoidal. This condition emphasizes the present of harmonic in the input current.

Detailed value of input current Total Harmonic Distortion (THD) can be seen in Figure 10. A Power Quality Analyzer FLUKE® 434 is used to measure the harmonic content of diode rectifier input current. High value of THD is generated in the input side due to interaction between switching cycle of the diode bridge and output capacitor filter. The conventional single phase full-bridge diode is switched based on the fundamental frequency of the input voltage.

Figure 10. Input Current Harmonic Spectrum of Conventional Single Phase Full-Bridge Diode @ 100 W Load
A pure resistive load in the forms of bulb lamp is used in both conventional diode bridge rectifier and PFC Boost Rectifier to ensure no input current waveform defect due to DC side load type. Based on Table 1, the input current THD value is more than a 100 % and getting worse as the load increased. The maximum measured input current THD value is 126 % when the diode rectifier is delivering 649 W of power to the load.

### Table 1

<table>
<thead>
<tr>
<th>No</th>
<th>Input Voltage (V)</th>
<th>Power Factor</th>
<th>Input Power (W)</th>
<th>Total Harmonic Distortion (%)</th>
<th>Output Voltage (V)</th>
<th>Output Power (W)</th>
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<td>117.2</td>
<td>300</td>
<td>111</td>
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<td>791</td>
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</table>

Table 2 shows the measurement results from Boost PFC Rectifier loading test. The measurement is carried out with the same maximum load around 650 W. The significant difference compared to the conventional diode rectifier is the input power factor value. The proposed circuit is able to improve the input PF value. The input power factor value is ranging between 0.99 to 0.92. As the load increased the input PF is decreased. However, the amount of THD still less than 20 % which is an indication of low distortion on input current waveform.

### Table 2

<table>
<thead>
<tr>
<th>No</th>
<th>Input Voltage (V)</th>
<th>Power Factor</th>
<th>Input Power (W)</th>
<th>Total Harmonic Distortion (%)</th>
<th>Output Voltage (V)</th>
<th>Output Power (W)</th>
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<td>740</td>
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<td>374</td>
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</table>

The captured waveform of input current and voltage at 250 W of output power is shown in Figure 12. The input current waveform has a sinusoidal wave shape. High frequency ripple is generated in the input waveform as a result of Boost PFC switching frequency. It is very small compared to the rms value of input current; hence it is negligible.

The input current also in phase with the input voltage. This condition verifies the measured PF value on Table 2. It is also emphasizing that the PFC controller IC FA5502 can detect the input current to generate a synchronized PWM in accordance with unity PF target. Not only the PF but also the output voltage is well regulated at 374 V.
Figure 13. Input Harmonic Spectrum of Boost PFC Rectifier

C. Output Voltage Regulation

IC FA5502 provide voltage loop control feature for regulated output voltage. In this experimental setup, the output reference voltage is set at 380 V DC. Based on the measured data at Table 2, the output voltage is kept constant at 374 V. The voltage drop can be caused by tolerance and parasitic effect of voltage reference resistor network.

The output voltage regulation of the proposed circuit can be calculated by using following equation:

\[
\text{Voltage Regulation} = \left(\frac{V_{NL} - V_{FL}}{V_{NL}}\right) \times 100\% = \left(\frac{380 - 374}{380}\right) \times 100\% = 1.57\%
\]

where:

- \( V_{NL} \) = No-load Voltage (V)
- \( V_{FL} \) = Full-load Voltage (V)

It can be concluded that the proposed Boost PFC Rectifier has 1.57% of voltage regulation at 650 W load.

D. Power Factor Correction Performance

Based on measured data on Table 2 and Figure 12, it can be concluded that the PFC controller (IC FA5502) is able to control the input PF value while maintaining the output voltage. The input power factor is almost unity (PF ≈ 1). To show significant power correction results, measured data between Boost PFC rectifier and diode rectifier is compared.

Let us recall the data from Table 1 which is shows the poor value of input PF (0.67) on diode rectifier. The main cause of this poor PF value is non sinusoidal input current waveform, hence high value of input current distortion. The consequence of this condition is very high peak input current. This high peak input current require further adjustment in terms of protection device sizing which is the major drawback when integrating a conventional diode rectifier into electrical network.

With the same amount of delivered output power, Boost PFC Rectifier has better value of input PF compared to the conventional diode rectifier. Suppose the conventional diode rectifier input PF is used as reference, then input PF improvement that is provided by Boost PFC Rectifier can be calculated as follows:

\[
\text{Input PF Improvement} = \left(\frac{PF_{PFC(ON)} - PF_{PFC(OFF)}}{PF_{PFC(OFF)}}\right) \times 100\% = \left(\frac{0.67 - 0.64}{0.64}\right) \times 100\% = 5.25\%
\]

Where:

- \( PF_{PFC(ON)} \) = input PF of Boost PFC Rectifier
- \( PF_{PFC(OFF)} \) = input PF of diode rectifier

and it can be concluded that the proposed circuit can significantly increase the input PF of diode rectifier.

Beside the input PF improvement, the propose design is able to fulfill the THD limit in accordance with IEC 61000-3-2. This standard is used to decide whether any power converter is suitable to be connected with electrical grid in terms of injected THD into network. Thus, the injected harmonic into network is equal with input current THD of rectifier. Figure 14 shows the comparison of input current THD between diode rectifier and PFC Boost Rectifier. Significant difference occurred at any output load values.

Similar with input PF, the input current THD improvement value relative to the diode rectifier THD can be expressed by using equation below:

\[
\text{THD Improvement} = \left(\frac{THD_{PFC(OFF)} - THD_{PFC(ON)}}{THD_{PFC(OFF)}}\right) = \left(\frac{12.6\% - 12.9\%}{12.6\%}\right) = 87.3\%
\]

where

- \( THD_{PFC(ON)} \) = input current THD of Boost PFC Rectifier
- \( THD_{PFC(OFF)} \) = input current THD of diode rectifier.

From those value, it can be concluded that the proposed Boost PFC Rectifier can reduce the input current THD of diode rectifier. Table 3 is provided to summarize the comparison between diode rectifier and Boost PFC Rectifier in terms of input current THD.
The second column on Table 3 shows the standard value for each harmonic order. Diode rectifier cannot fulfill the standard in all harmonic order; hence it is not recommended to be used in large power application because overheating of transformer or any other magnetic component is likely occurred. On other hand, the Boost PFC Rectifier can meet the criteria in all harmonic order except at 9th harmonic order. Possible causes are high switching frequency of MOSFET, resonance on input low pass filter configuration, and picked up noise by the measurement device. However, the total THD value of Boost Rectifier is still within the standard.

V. CONCLUSION

Based on the discussion and analysis in the previous chapter, it can be concluded that the Asynchronous Boost Converter is successfully implemented to improve the input power factor on single phase diode bridge. The PF improvement and input current THD reduction is verified with experimental results in laboratory. Boost PFC Rectifier performance can solve the major drawback of conventional diode rectifier. The measured input PF and current THD can meet the IEC 61000-3-2 THD standard.

VI. REFERENCES


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TABLE III
INPUT CURRENT THD BENCHMARKING WITH IEC 61000-3-2 THD STANDARD

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>IEC-61000-3-2 Standard (%)</th>
<th>Measured Diode Rectifier THD (%)</th>
<th>Measured Boost PFC Rectifier THD (%)</th>
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