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Optimization of Power Loss Reduction in IGBT-based Three-Phase Rectifiers using Discontinuous Pulse Width Modulation Method: A Simulation-Based Analysis with QSpice and Fuji IGBT Simulator

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***Abstract*—The increasing demand for electricity supply is evident across various modern industrial sectors. Electrification advancements in the transportation industry aim to address environmental and energy issues and continue to evolve. Charging electric vehicles is one of the most important aspects of electrification in the transportation sector. This study develops and simulates a three-phase IGBT-based rectifier using the Discontinuous Pulse Width Modulation 60-degree (DPWM1) method to optimize power loss reduction in a 200-kW charging system. The DPWM method has been shown to reduce power losses by up to 44% compared to the conventional Sinusoidal Pulse Width Modulation (SPWM) method under full load conditions, resulting in reduced heat and cooling requirements for the devices. Simulations show that with the appropriate use of filters, the total harmonic distortion of current (THDi) of the AC input side is reduced to 2.267%, minimizing the negative impacts on the grid. In addition, implementing feedforward control maintains DC voltage stability despite load variations, improving system efficiency and reliability.**

Keywords: ***dpwm1, three phase rectifier, igbt, feed forward control, power quality***

I. Introduction

In various modern industrial applications, the importance of a reliable, efficient, and stable power supply is increasingly recognized. Many electrical systems are operated using AC power grids as the primary choice due to their capability to be transmitted efficiently over long distances [1]. In the 21st century, the industrial world has experienced rapid development as various equipment continues to evolve, such as electric motors and battery charging systems, which drive the reduction of air pollution. Electrification of the transportation sector is an effective way to address environmental and energy issues. Therefore, governments worldwide are striving to promote the use of electric vehicles [2]. Rectifier systems are needed to convert AC electricity into DC.

Three-phase rectifiers offer significant advantages over single-phase rectifiers, including the ability to produce a stable DC voltage with lower ripple and higher efficiency in high-power applications. However, this does not mean that three-phase rectifier systems are without drawbacks. One of the main issues is the disturbances introduced into the power grid system. Switching elements such as diodes, SCRs, IGBTs, and MOSFETs are used in the rectification process, along with active loads operating based on grid frequency, resulting in the injection of harmonics into the grid. The use of IGBTs and MOSFETs is more recommended for high-power applications because these semiconductor components are controllable and capable of high switching frequencies. Adding filters on the three-phase input side can reduce the harmonics generated. However, another issue arises when high switching frequencies are applied, namely, power losses in semiconductor components [3]. With the advancement of technology, innovations such as the Insulated Gate Turn-Off (IGTO) have emerged as an evolution of the IGBT. IGTO offers higher current density and better power efficiency with lower power losses [4]. In addition, there are also MOSFETs with Silicon Carbide (SiC) material that can operate at high switching frequencies but still have high efficiency. However, SiC MOSFET has a much higher price compared to IGBT. Since IGTO is still in the development stage and MOSFET has a high price, IGBT remains the main choice in this research.

In general, the control of semiconductor components such as IGBT and MOSFET is performed using Pulse Width Modulation (PWM) signals. The most straightforward and commonly used method is Sinusoidal Pulse Width

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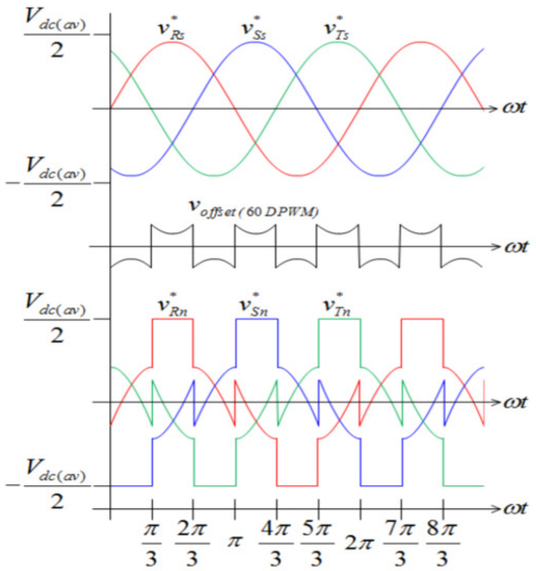


Figure 1. Modulation signal reflecting the DPWM1 method

Modulation (SPWM), a pulse width modulation technique in which a sinusoidal reference signal is compared to a triangular carrier signal. The semiconductor components are switched on and off alternately at every intersection of these two signals. This results in a significant issue: considerable power losses due to constant switching during each cycle [5]-[7]. Switching losses can be reduced when using SiC MOSFET because one of their advantages is the absence of tail current, which significantly reduces switching losses [12]. However, to build a power converter with high power capacity, the use of SiC MOSFETs will require a considerable cost. Therefore, it is necessary to develop a PWM modulation method to reduce switching losses in IGBT, one of which is by using the Discontinuous PWM (DPWM) modulation method.

DPWM is a modulation technique in which the modulation signal is clamped to the DC rail for one-third of each period, eliminating switching during that time. This significantly reduces the switching losses of power converters, especially at high switching frequencies. Moreover, the implementation of DPWM can enhance system reliability by reducing heat generation, thereby extending the lifespan of components and lowering maintenance requirements, with fewer cooling devices needed for the converter. This study aims to develop, design, and simulate a three-phase controlled rectifier with a resistive load using QSpice software, employing DPWM modulation, and to analyze the overall system efficiency improvement through power loss reduction using IGBT modules simulated with the Fuji Electric IGBT Simulator software.

II. Literature Review

A. DPWM 60 Degree (DPWM1)

This study presents the DPWM1 method to reduce switching losses in a three-phase rectifier. Figure 1 shows the modulation reference signal that reflects the DPWM1 method. Mathematically, the DPWM1 modulation in Figure 1 is expressed by the following equation,

$$\left.\begin{array}{ll} v_{offset}=\dfrac{V_{dc(avg)}}{2}-v_{Rs}^{*}; & \pi/3\le\omega t\le 2\pi/3 \\ v_{offset}=\dfrac{-V_{dc(avg)}}{2}-v_{Ts}^{*}; & 2\pi/3\le\omega t\le \pi \\ v_{offset}=\dfrac{V_{dc(avg)}}{2}-v_{SS}^{*}; & \pi\le\omega t\le 4\pi/3 \\ v_{offset}=\dfrac{-V_{dc(avg)}}{2}-v_{Rs}^{*}; & 4\pi/3\le\omega t\le 5\pi/3 \\ v_{offset}=\dfrac{V_{dc(avg)}}{2}-v_{Ts}^{*}; & 5\pi/3\le\omega t\le 2\pi \end{array}\right\} \tag{1}$$

$$\left.\begin{array}{l} v_{Rn}^{*}=v_{Rs}^{*}+v_{\text{offset}} \\ v_{Sn}^{*}=v_{Ss}^{*}+v_{\text{offset}} \\ v_{Tn}^{*}=v_{Ts}^{*}+v_{\text{offset}} \end{array}\right\} \tag{2}$$

with v_{Rn}^{*}, v_{Sn}^{*} and v_{Tn}^{*} are the modulation reference signals for the 60-degree three-phase DPWM. The formation of the DPWM signal is like SPWM, which involves comparing the reference signal with the triangular carrier signal [6]-[8].

B. Passive Filter Design

A high-power three-phase controlled rectifier must include an L or LCL filter. These filters are placed between the three-phase input voltage source and the controlled rectifier switching device. The L filter is simpler, while the LCL filter has better filtering capabilities. According to the German VDE standard, the minimum impedance for these filters is 5% of the base impedance, as formulated below [9].

$$L_{s1}=5\%\times\frac{V_{LL}/\sqrt{3}}{I_{s1}} \tag{3}$$

where L_{s1} is an inductor in each phase (H), V_{LL} is line-to-line voltage (V), and I_{s1} is current in each phase (A).

For the LCL filter, the value of L_r (the converter-side inductance) can be calculated as described in the following equation [10], [11], [13].

$$L_r=\frac{V_{DC}}{nf_sI_{\text{grid}_{rated}}\%ripple} \tag{4}$$

$$I_{grid_{rated}}=\frac{P_{load}}{\sqrt{3}V_{ac}} \tag{5}$$

In the equation above, for a 2-level converter, the value of n is 4, and for a 3-level converter, the value of n is 8. The fundamental reactive power absorbed by the filter capacitor must be less than 5% of the rated active power of the rectifier's voltage source to prevent excessive power factor reduction. The filter capacitor (C_f) for three phases can be calculated as shown in the following equation,

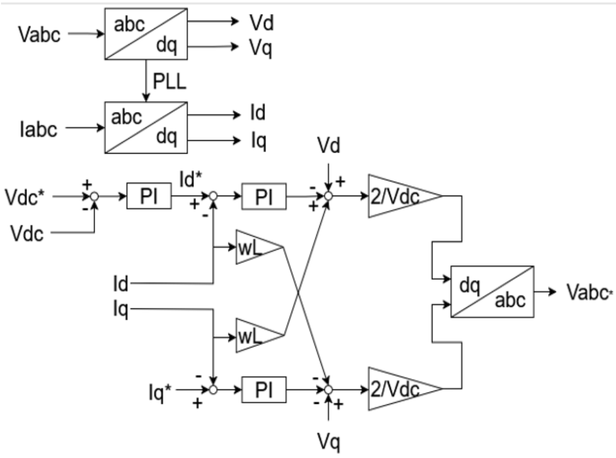


Figure 2. Control scheme of a three-phase PWM-controlled rectifier

$$C_f < 5\% C_b \tag{6}$$

which one,

$$Z_b = \frac{E_n^2}{P_{in}} \tag{7}$$

$$C_b = \frac{1}{\omega_g Z_b} \tag{8}$$

where E_n is the AC line-to-line RMS voltage, Z_b is base impedance, C_b is base capacitance and ω_g is the angular grid frequency. To achieve an attenuation factor of 10%, and using the previously derived values, the value of r can be calculated using the following equation,

$$r = \left| \frac{\frac{1}{10\%} - 1}{1 - L_r C_f \left(2\pi f_s\right)^2} \right| \tag{9}$$

The grid-side inductor (L_g) is defined as:

$$L_g = r \times L_r. \tag{10}$$

C. Control of Three-Phase PWM Controlled Rectifier

Control of a three-phase PWM-controlled rectifier can utilize Voltage Oriented Control (V_{OC}), which is one of the control methods for three-phase controlled rectifiers. This method is based on the transformation of the three-phase stationary reference system (*abc*) to the synchronous rotating reference system (*dq*) through the two-phase stationary reference system (alpha-beta). With this transformation, the control voltage remains constant and becomes a DC value, simplifying the entire control process. In this control scheme, the d-axis is aligned with the supply voltage vector, which is why it is referred to as voltage-oriented. The PWM control scheme for the three-phase rectifier is shown in Figure 2.

The function of the dq current controller is to control the reference current of the *d* component (I_d) to regulate the DC voltage (V_{DC}), while the reference current of the q component (I_q) is controlled to ensure a unity power factor. Thus, a unity power factor can be achieved by setting I_{qref}=0 [12], [14].

D. Clarke and Park Transformation

The Clarke transformation is used to convert a three-phase coordinate system (ABC) into an ($\alpha\beta$) system. From the three-phase system, only two phases are needed to transform into the ($\alpha\beta$) system, which, when implemented in hardware, reduces the need for sensors [15]-[17].

$$\alpha = a \tag{11}$$

$$\beta = \frac{1}{\sqrt{3}}(a + 2b) \tag{12}$$

To convert it back to the three-phase system, the following equation can be used.

$$a = \alpha \tag{13}$$

$$b = \frac{-\alpha + \sqrt{3} \times \beta}{2} \tag{14}$$

$$c = \frac{-\alpha - \sqrt{3} \times \beta}{2} \tag{15}$$

where *a, b, c* are three-phase quantities, α and β are stationary orthogonal reference frame quantities.

The Park transformation is used to convert the voltage and current from the two-phase orthogonal system ($\alpha\beta$) to the two-phase rotating reference system (*dq*).

$$\begin{bmatrix} d \\ q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \tag{16}$$

To convert it back to the ($\alpha\beta$) system, the following equation can be used,

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} d \\ q \end{bmatrix} \tag{17}$$

To obtain the value of theta (θ), the following equation can be used,

$$\theta = \operatorname{atan2}(\beta, \alpha) \tag{18}$$

where *d* and *q* are rotating reference frame quantities, θ is the rotation angle.

III. Method

A. Converter Parameter

The converter parameters must be calculated according to the requirements, as this will affect the performance of the converter itself. The parameter design of the three-phase controlled rectifier is shown in Table 1.

Table 1. Converter parameter design

Parameter	Value	Unit
Three-Phase Input Voltage	380	V
Fundamental Frequency	50	Hz
Output Power	200	kW
Switching Frequency	20	kHz
DC Output Current	250	A
DC Output Voltage	800	V
Inductor Filter	0.23	mH
DC link Capacitor	4.2	mF

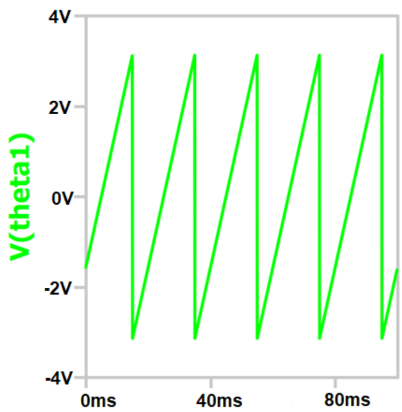


Figure 3. Theta values of the three-phase sinusoidal reference signal

B. DPWM1 Signal Generation

The output signal from the PWM rectifier control scheme shown in Figure 2 is a sinusoidal reference signal. When this reference signal is compared with a triangular carrier signal, it produces a PWM signal known as Sinusoidal Pulse Width Modulation (SPWM). This reference signal is v^*_{Rs}, v^*_{Ss} and v^*_{Ts} as shown in (1) and Figure 3. Equations (1) and (2) can be used to convert it into a DPWM1 signal. Below is the method to convert the sinusoidal reference signal into a DPWM1 signal using QSpice software:

1. Generate sinusoidal reference signals from three AC voltage sources, set the amplitude to be less than 1, and adjust the three signals to simulate three-phase voltages with a 120-degree phase difference.
2. Obtain the value of theta using (18) and the Clarke transformation. The purpose of obtaining theta is to determine the interval for calculating the value.
3. Since some theta values fall within the negative interval, they are adjusted by adding 2π. Once theta is obtained as shown in Figure 4, use (1) to calculate the v_{offset} value, but pay attention to the interval, as the numbers may differ while having the same value.
4. Pay attention to the starting point of the theta value in Figure 4. The theta value starts at 11π/6, and the first interval for v_{offset} is between 11π/6 and 13π/6. Referring to (1), the v_{offset} values for all intervals can be represented as shown in Figure 5.
5. Figure 6 shows the test circuit for generating the DPWM1 signal. The contents of the DPWM1 block in Figure 6 consist of the algorithm outlined in Figure 5, which is used to determine the offset value according to (1) and the modulation reference value for DPWM1 according to (2). The simulation results are shown in Figure 7, where the values of v^*_{Rn}, v^*_{Sn}, and v^*_{Tn} are used as reference signals for generating the DPWM1 signal by comparing them with a triangular carrier signal.

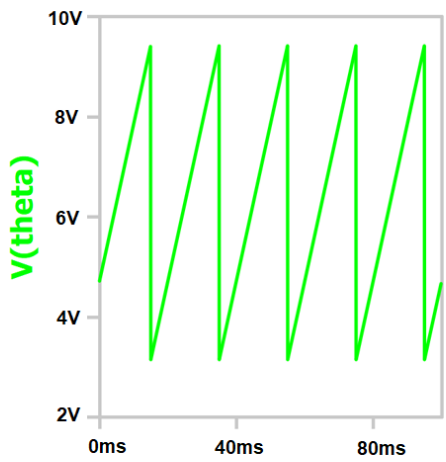


Figure 4. Theta values for the DPWM1 modulation method

```
if (11*M_PI/6 <= theta && theta <= 13 * M_PI / 6)
    {
        Voffset = 1 - a;
    }
    else if (13 * M_PI / 6 <= theta && theta <= 15 * M_PI / 6)
    {
        Voffset = -1 - c;
    }
    else if (15 * M_PI / 6 <= theta && theta <= 17 * M_PI / 6)
    {
        Voffset = 1 - b;
    }
    else if (17 * M_PI / 6 <= theta && theta <= 18 * M_PI / 6)
    {
        Voffset = -1 - a;
    }
    else if (M_PI <= theta && theta <= 7 * M_PI / 6)
    {
        Voffset = -1 - a;
    }
    else if (7 * M_PI / 6 <= theta && theta <= 9 * M_PI / 6)
    {
        Voffset = 1 - c;
    }
    else if (4 * M_PI / 3 <= theta && theta <= 6 * M_PI / 3)
    {
        Voffset = -1 - b;
    }
    else
    {
        Voffset = 0; // default value if theta is outside expected range
    }

   // Calculate final values
   Vr = a + Voffset;
   Vs = b + Voffset;
   Vt = c + Voffset;
```

Figure 5. DPWM1 signal generation algorithm

C. Proposed Control Scheme for Three-Phase PWM Controlled Rectifier

The control scheme in Figure 2 is a commonly used scheme for regulating three-phase controlled rectifiers.

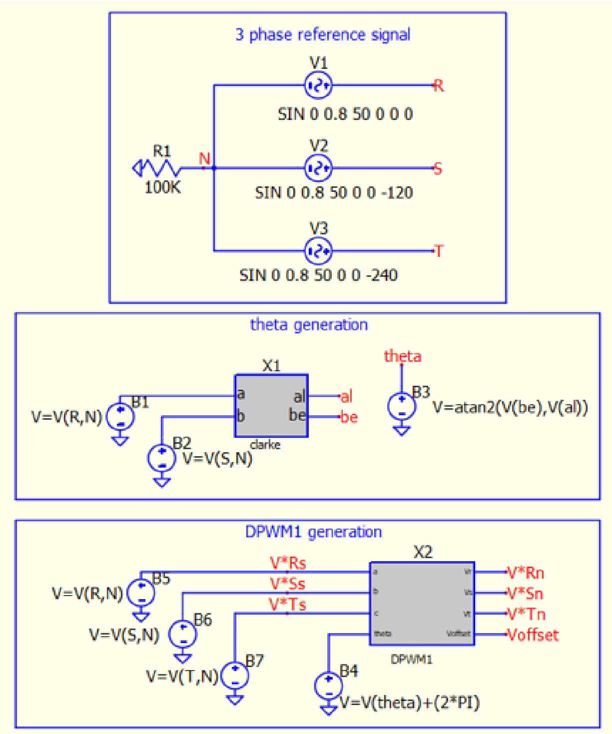


Figure 6. Test circuit for DPWM1 signal generation

In this study, a development was made by converting the sinusoidal reference signal into a DPWM1 signal. Additionally, feedforward control was implemented to reduce voltage deviations under changing conditions, such as load variations. Feedforward control helps maintain the voltage at the reference level despite fluctuating loads [18]. Therefore, the control scheme for the 3-phase PWM rectifier in Figure 2 is further developed in this study as shown in Figure 8.

IV. Results and Discussion

A. Simulation with QSpice Software

The main circuit of a three-phase controlled rectifier with an LCL filter is designed based on the parameters in Table 1. Subsequently, the control circuit is developed as illustrated in Figure 8. Before running the simulation, certain considerations need to be addressed, including the addition of a pre-charge circuit for the capacitor in the DC link. If no pre-charging is done, there will be a very high current surge in the capacitor, which could damage the equipment. Another important aspect can be seen in the control circuit in Figure 9, where the division involves Vdc as the denominator. If the simulation is run directly without modification, the control loop will produce an error because the initial value of Vdc is zero. Therefore, the solution is to define the value of Vdc first or, more easily, run the simulation in diode rectifier mode or turn off all IGBTs. Once the DC link voltage has stabilized, switch the control to closed-loop mode. To reduce the voltage transients, the initial reference value should be set slightly lower than the Vdc output when in diode mode.

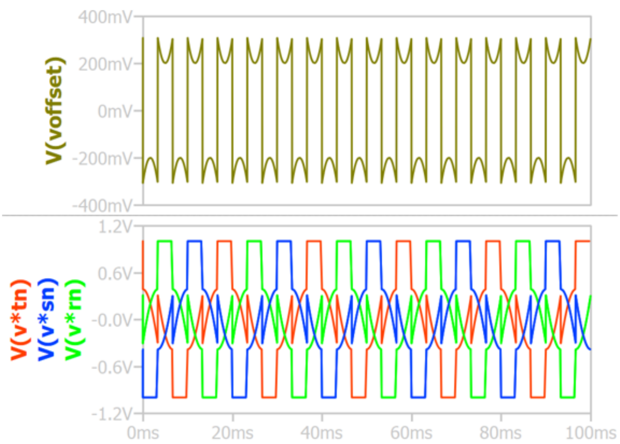


Figure 7. DPWM1 signal generation test results

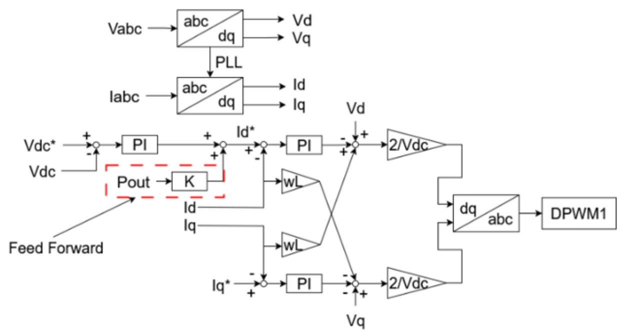
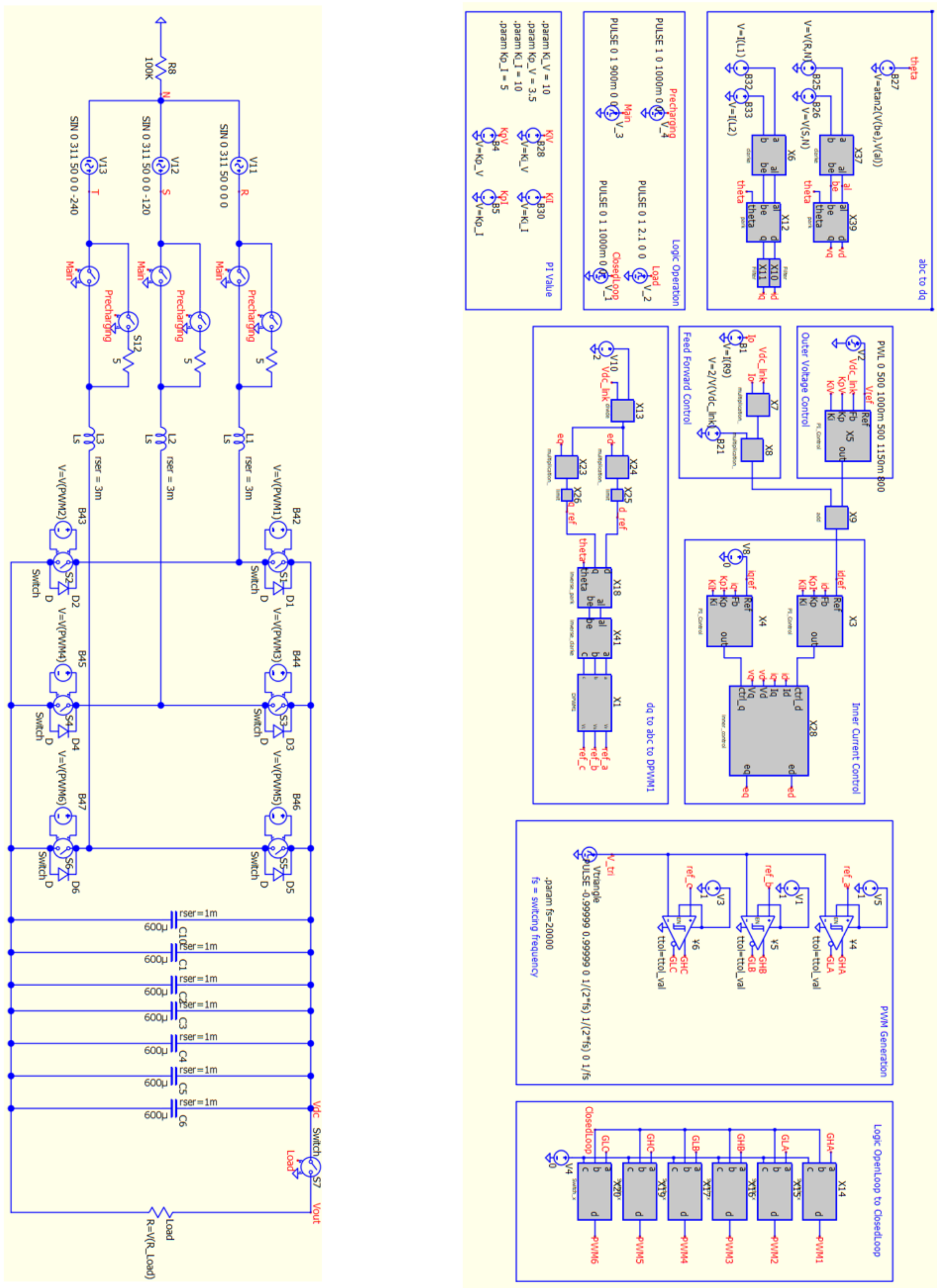


Figure 8. Proposed control scheme for three-phase PWM controlled rectifier

Figure 8 shows the simulation circuit of the 3-phase PWM rectifier in the QSpice software. The "Logic Open loop to Closed loop" block is used to disable the PWM signal, causing the rectifier to operate in diode mode. The "Logic Operation" block contains the simulation sequence, starting with the pre-charging process, i.e., the AC source will flow through the pre-charging circuit, which includes a resistor to limit the current. When charging the DC Link capacitor, do not initially connect the load. After the DC Link voltage has stabilized, switch to closed-loop mode and wait for the DC link voltage to match the reference. Do not connect the load until the voltage matches the reference.

The QSpice software results in Figures 10 and 11 show the DC output voltage from startup to full load. Figure 10 uses feedforward control, while Figure 11 does not. The difference is noticeable when there is a load change; with feedforward control, the voltage does not drop during load changes. The addition of an appropriate AC filter can also reduce the THD of the current, as shown by the simulation results in Figure 12, which shows a current THD of 2.267% (Nyquist frequency). The designed AC filter is intended to operate at full load. Therefore, in Figure 13, the grid current waveform at 50% load shows higher harmonics compared to the full load condition.

The value 1.23817% is the current THD calculated up to the observed harmonics, which is the 50th harmonic. The calculation is as follows [19],



(a) (b)

Figure 9. Simulation circuit (a) Topology, (b) Control

$$I_{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \times 100\% \tag{19}$$

where I_n is n^{th} harmonic current value (A), I_1 is fundamental current (A), and n is maximum observed harmonic components.

THD current value up to the 50th harmonic is,

$$I_{THD} = \frac{\sqrt{((2.718 \times 10^{(-3)} \times 305.608)^2 + \cdots + (5.569 \times 10^{(-4)} \times 305.608)^2)}}{I_1} \times 100\%$$

where 2.718×10^{-3} is the magnitude of the 2nd harmonic current, 305.608 is the magnitude of the fundamental

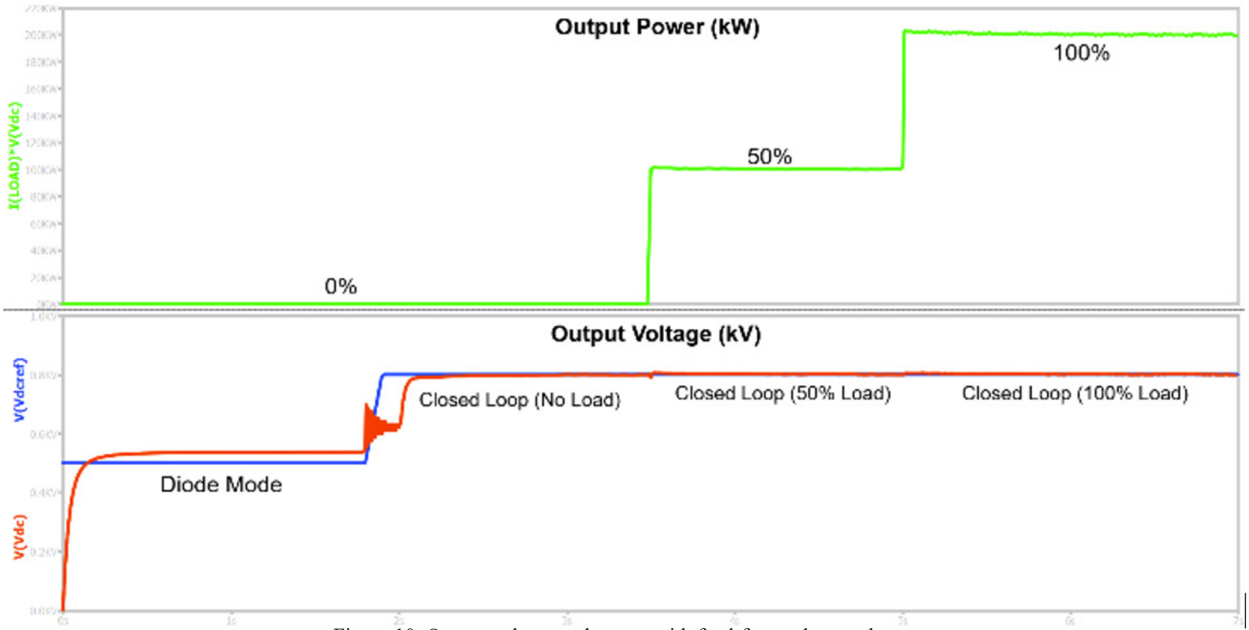


Figure 10. Output voltage and power with feed-forward control

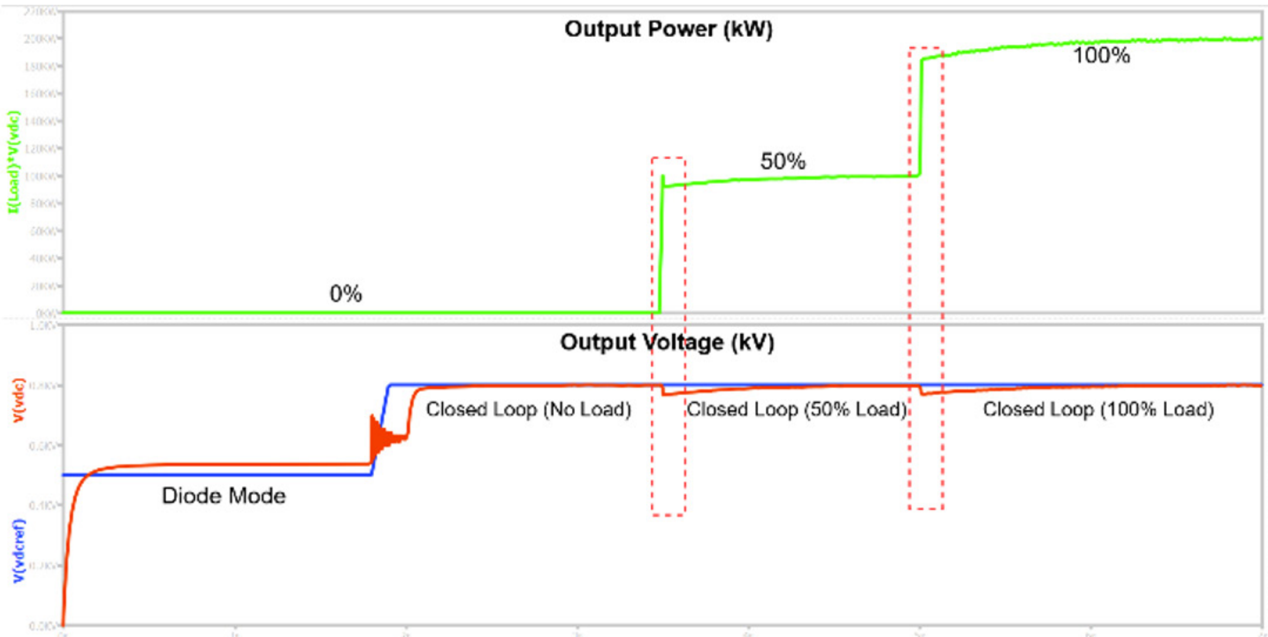


Figure 11. Output voltage and power without feed-forward control

current, and 5.569×10^{-4} It is the magnitude of the 50th harmonic current. so, the harmonic current obtained up to the 50th Orde is 1.23817%.

B. Simulation with Fuji IGBT Simulator Software

This simulation begins with the selection of the IGBT to be used according to the specifications in Table 1. The output voltage from the rectifier is 800Vdc, so the chosen IGBT must be capable of operating above 800Vdc. The output current is 250A, but the current on the AC side is 305 Arms, so an IGBT capable of withstanding up to 350 Arms is selected. Based on the specifications and simulation, the IGBT 2MBI450XEE120-50 is chosen. Ensuring the thermal, electrical, and mechanical setup complements the IGBT specifications is vital to maintaining optimal performance and reliability. Proper implementation will help minimize failures and extend the lifespan of a circuit.

The simulation is run by selecting the single mode in Figure 14 and then choosing the circuit according to its converter topology. For the three-phase rectifier circuit, it can be replaced with a three-phase inverter circuit. Next, select the PWM modulation method to be used. In this study, the DPWM1 and SPWM modulation methods are chosen. Also, fill in the parameters based on the converter's conditions under full load, including AC frequency, switching frequency, AC, DC voltage, power factor, and modulation index.

Figures 15 and 16 display the simulation results using the IGBT Simulator software from Fuji Electric.

```
.four 50 50 -i(v11):
 Fundamental: RMS Magnitude=305.608 Phase=-0.126227° DC=-0.629136
 Harmonic Frequency     Magnitude    Phase
     1      5.000e+01     1.000e+00     0.00°
     2      1.000e+02     2.718e-03   118.40°
     3      1.500e+02     1.490e-03  -118.90°
     4      2.000e+02     6.374e-03    44.54°
     5      2.500e+02     2.381e-03  -162.88°
     6      3.000e+02     6.015e-03  -159.14°
     7      3.500e+02     1.618e-03   162.94°
     8      4.000e+02     4.116e-03   -32.24°
     9      4.500e+02     7.025e-04   157.26°
    10      5.000e+02     2.256e-03   -25.66°
    11      5.500e+02     1.168e-03   116.41°
    12      6.000e+02     2.990e-03   130.77°
    13      6.500e+02     8.568e-04   114.23°
    14      7.000e+02     2.000e-03   -85.49°
    15      7.500e+02     3.986e-04   117.57°
    16      8.000e+02     1.415e-03   -66.96°
    17      8.500e+02     7.217e-04    86.61°
    18      9.000e+02     1.923e-03    85.07°
    19      9.500e+02     6.085e-04    82.54°
    20      1.000e+03     1.427e-03  -121.97°
    21      1.050e+03     3.661e-04    62.37°
    22      1.100e+03     1.019e-03  -105.50°
    23      1.150e+03     5.381e-04    45.58°
    24      1.200e+03     1.449e-03    46.41°
    25      1.250e+03     4.513e-04    40.61°
    26      1.300e+03     1.041e-03  -163.40°
    27      1.350e+03     2.891e-04    42.97°
    28      1.400e+03     7.723e-04  -139.47°
    29      1.450e+03     4.206e-04     9.56°
    30      1.500e+03     1.104e-03     9.05°
    31      1.550e+03     4.047e-04    11.22°
    32      1.600e+03     8.108e-04   157.20°
    33      1.650e+03     2.418e-04    -0.44°
    34      1.700e+03     6.094e-04  -178.72°
    35      1.750e+03     3.291e-04   -28.36°
    36      1.800e+03     9.289e-04   -30.38°
    37      1.850e+03     3.101e-04   -28.36°
    38      1.900e+03     6.995e-04   127.21°
    39      1.950e+03     1.871e-04   -34.31°
    40      2.000e+03     5.110e-04   144.56°
    41      2.050e+03     2.704e-04   -60.13°
    42      2.100e+03     7.435e-04   -64.20°
    43      2.150e+03     2.990e-04   -50.31°
    44      2.200e+03     6.111e-04    86.84°
    45      2.250e+03     1.680e-04   -80.78°
    46      2.300e+03     4.326e-04   110.39°
    47      2.350e+03     2.350e-04  -107.52°
    48      2.400e+03     7.010e-04  -101.02°
    49      2.450e+03     2.370e-04   -91.21°
    50      2.500e+03     5.569e-04    53.18°
 THD = 1.23817%(2.26709%)
```

Figure 12. Phase A current THD

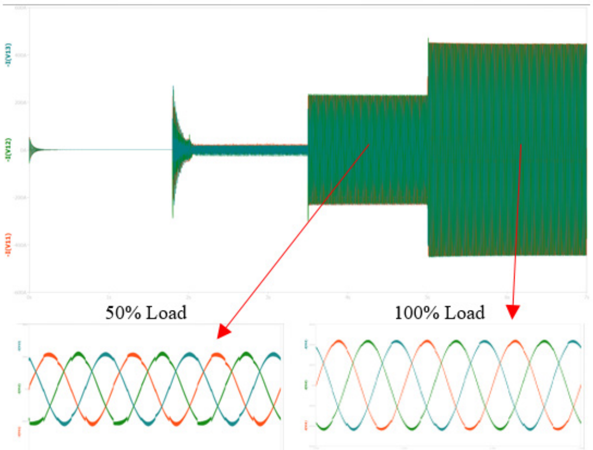


Figure 13. Grid currents

The selected IGBT module is the 2MBI450XEE120-50, which has a specification of 1200V 450A. When using DPWM1 modulation, the total power loss at full load is 3719.5 W, while using SPWM modulation, the total power loss reaches 6648.6 W. This demonstrates a power loss reduction of up to 44% when using DPWM1 modulation. Additionally, the temperature displayed on the IGBT module is lower, thereby reducing the cooling system issues.

The reduction in switching losses and temperature decrease in the IGBT module is due to the PWM formed, which has a time interval where it will always be on or off when the reference DPWM1 signal is at its maximum or minimum position for 60 degrees. Therefore, during this period, no switching process occurs in the IGBT as shown in Figure 17.

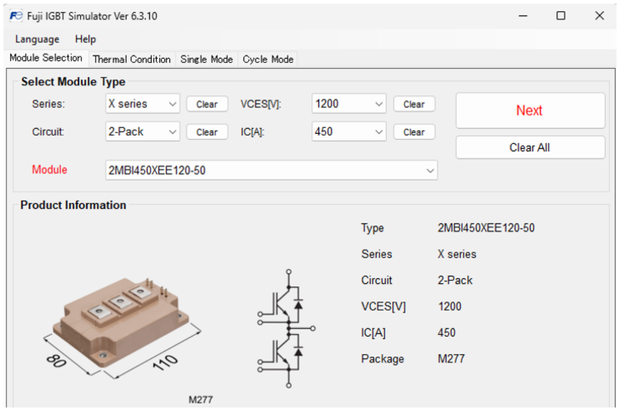


Figure 14. IGBT selection in the fuji IGBT simulator

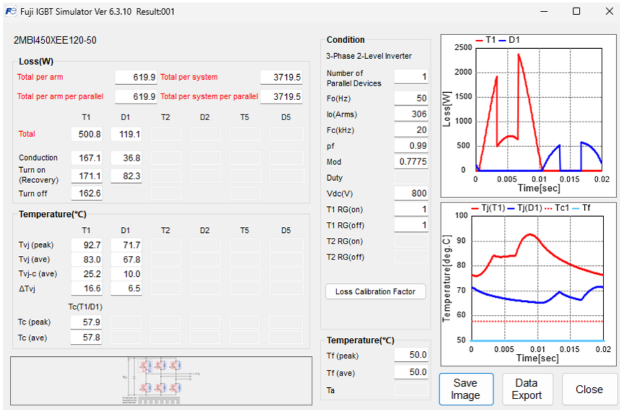


Figure 15. Power losses in the IGBT module at full load using DPWM1 modulation

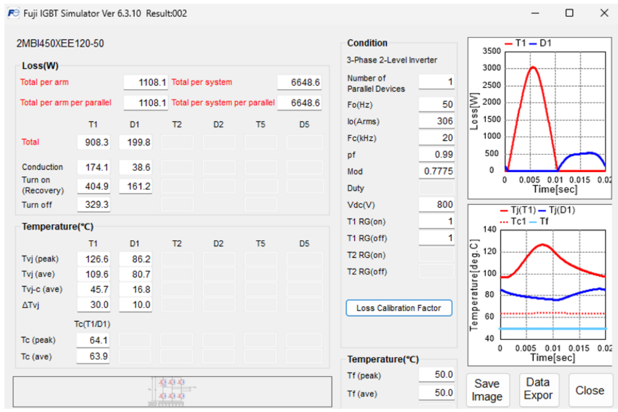


Figure 16. Power losses in the IGBT module at full load using SPWM modulation

V. Conclusion

The implementation of the 60-degree Discontinuous Pulse Width Modulation (DPWM1) method on a three-phase rectifier utilizing IGBT modules presents a significant advancement in power efficiency and thermal management compared to traditional Sinusoidal Pulse Width Modulation (SPWM). By applying DPWM1, a notable reduction in power losses of up to 44% has been achieved. This reduction is crucial for minimizing heat generation within the IGBT modules, consequently lowering the necessary cooling requirements, which can

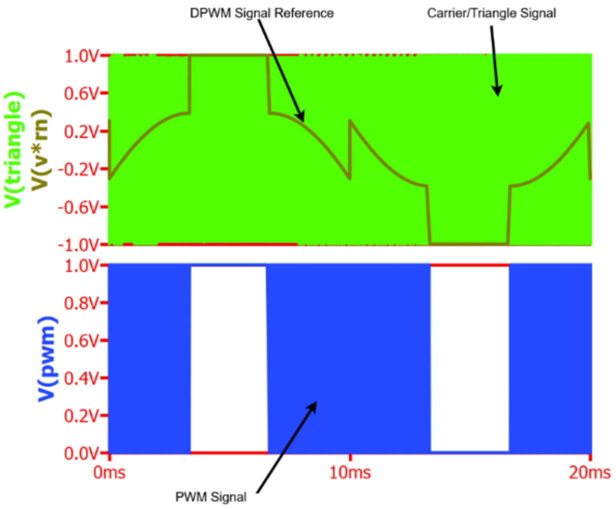


Figure 17. PWM signal with DPWM1 modulation

lead to improved overall system reliability and longevity. Furthermore, simulations conducted using QSpice software demonstrate the effectiveness of this method in maintaining a low Total Harmonic Distortion (THD) of current at 2.267%. This low THD is particularly important for ensuring the quality of power supplied to the load, as it minimizes the potential adverse effects on both the rectifier and other connected equipment. Additionally, the implementation of feedforward control in this design helps maintain the stability of the DC voltage during load changes, thus improving system efficiency and reliability.

This research opens up opportunities for further development in optimizing control and efficiency in converters for larger charging applications. The application of a DC-DC converter at the rectifier's output side can enhance system reliability because it can be controlled in constant voltage, constant current, and constant power modes, with all reference values starting from 0, which is not possible with an AC-to-DC rectifier. Although this study focuses on conventional IGBT devices, future work may consider newer semiconductor technologies with improved thermal characteristics, such as advanced IGBT structures or emerging devices (sometimes referred to as IGTO by certain manufacturers or researchers), which promise reduced power losses and more compact cooling systems.

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