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Design of a High-Efficient Grid-Connected Three-Phase Three-Level T-Type PV Power System

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Abstract

This paper intends to design a high-efficient grid connected three-phase three-level T-type photovoltaic inverter system which is operated with conjunction with grid. Different from the two-level topology mainly used previous, switch elements are increased by 6 pieces, it has the advantages such as the efficiency of the inverter, less stress in the switching elements, and less harmonic component in the output current. This paper will suggest the boost convert always supplying constant DC voltage for a three-phase three-level T-type photovoltaic inverter, and also presents the stability and excellence of the 3 level boost converter through experiments. Also, it offers the stable and high-efficient MPPT algorism and through solar irradiation change experiment and MPPT efficiency assessment, the excellence and efficacy of three-level T-type inverter was verified from experiments.

Keywords: *Three-Phase Grid-connected PV Inverter, Photovoltaic, MPPT, PLL, Three-Level Boost Converter, T-type photovoltaic inverter*

1. Introduction

Recently, due to the environmental pollution and depletion of fossil fuels, alternative energy studies have been on the progress, and in particular, the photovoltaic research is constantly being conducted. As electricity generated from solar power system is operating the energy more efficiently in connection with electricity grid, and from the user's standpoint, it is more stable, the electricity grid-connected technology produced from the solar power system is becoming a lot of interest [1].

Electricity generated from photovoltaic system is changeable in its operating characteristic and maximum output depending upon the amount of solar radiation, operating voltage and operating temperature etc. Accordingly, it is necessary to draw a lot of energy from the solar cell and increase the efficacy. MPPT (Maximum Power Point Tracking) controlling technique (which controls the operating point of solar cell in order to always operate at the maximum output in the consideration of the environmental sectors such as temperature or amount of solar radiations as well as the photovoltaic output changeable depending upon the operating status) and DC to DC converter controlling technique which is to provide the stable DC power from inverter are essential [2].

For PCS of photovoltaic system, many topologies and new techniques are now proposed in various ways. The existing three-phase two-level photovoltaic inverter can be implemented easily by using the simple composition and already proved controlling and PWM techniques. However, 2-level inverter has disadvantages such as high harmonic content in the output voltage, efficient limitation, and a lot of stress on the switching element (IGBT). Meanwhile, the 3-level T-Type topology has the advantages such as the inverter's efficacy of the existing 2-level inverter, the high harmonic content, less stress of the switching element, however, the disadvantage that its circuit is more complex than that of the existing 2 level inverter [3].

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This paper intends to design the boost converter always supplying constant DC voltage to inverter for a 3-phase 3-levels T-Type photovoltaic inverter and, through experiments, presents the stability of a 3 levels boost converter. And it also intend to verify, through solar irradiation change experiment and MPPT efficacy assessment on MPPT, the excellence of three level T-type inverter and the proposed algorism.

2. Grid Connected Three-Phase Three-level T-Type Photovoltaic Inverter

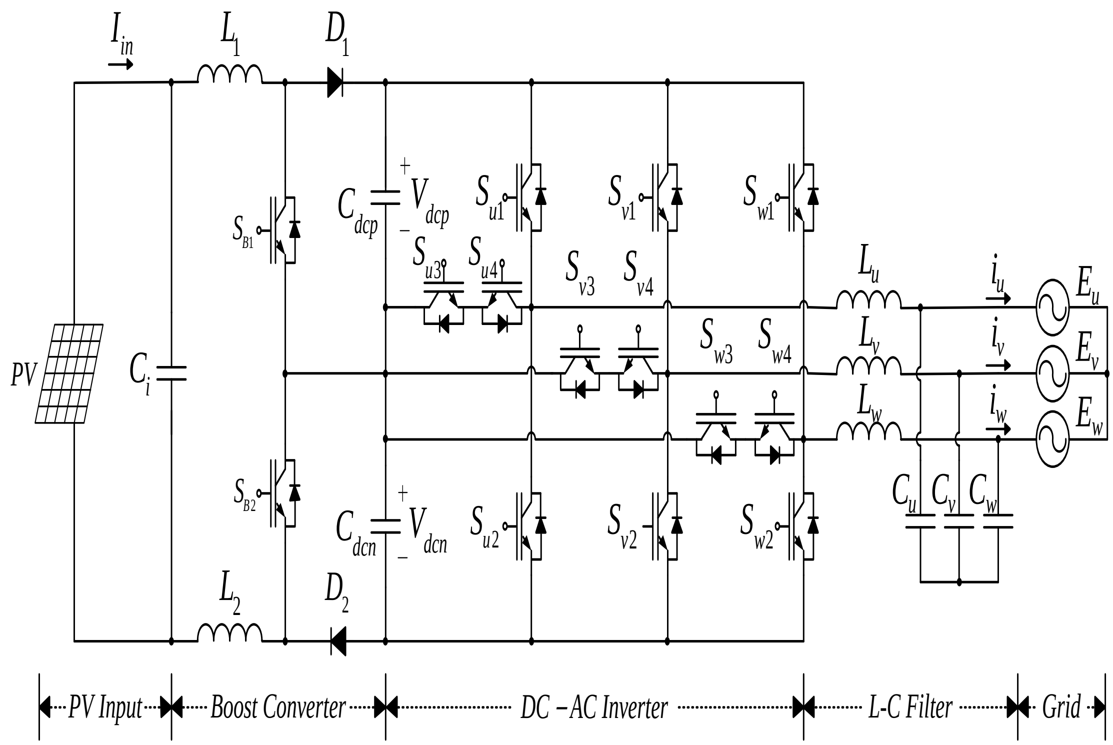


Figure 1. Circuit Diagram of Three-phase Three-level T-Type PV Inverter

For PCS of photovoltaic system, many topologies and new techniques are now proposed in various ways. Low-frequency transformer method, high-frequency link system, non-transformer method are mainly used, and each topology has advantages and disadvantages. However, this paper implements the system using the topology of non-transformer method which as the advantageous characteristics of high efficacy, small size, and light weight, not using the low frequency transformer method [4, 5].

Grid connected photovoltaic generation system is composed of the boost converter which maintains a constant voltage regardless of the solar cell module and input voltage supplying DC power source to photovoltaic inverter, and the inverter which converts to the grid AC .

Figure 1 shows the three-level T-Type topology of three-phase grid-connected photovoltaic inverter which is proposed in this paper. By using 12 pieces of IGBT, it implements a DC-AC inverter, and by using a reactor L and a C filter disconnected with Y at the inverter output part, reduces the ripple of output and harmonic components.

The control techniques for the grid-connected photovoltaic inverter requires PPL control technique to supply power to the grid, and MPPT control technique to maximize the power generation of solar cell modules, and the output current control technique to output the outputting current to the grid.

2.1. Three-Level Boost Converter

Photovoltaic should constantly maintain the dc link voltage in order to convert the DC power of solar cells to the AC power of the inverter. However, a power-voltage curves, a current-voltage curves of the solar cells tends to be nonlinearly changed according to the external environment such as amount of solar radiation, temperature etc. So, to supply the constant power to the inverter in accordance with these nonlinear characteristics, the boost converter is inevitable [6].

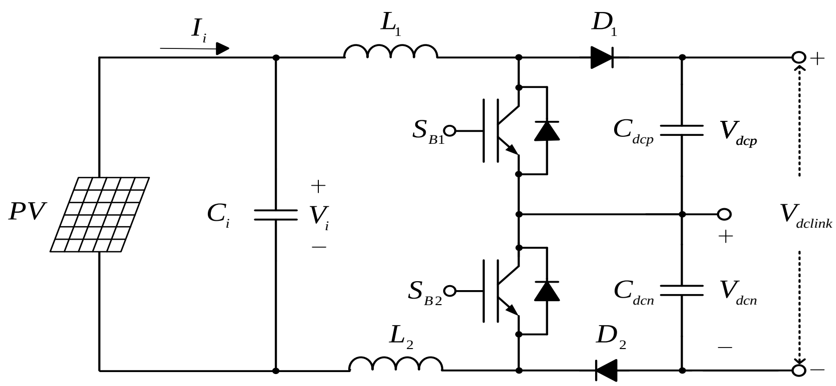


Figure 2. Circuit Diagram of Three Level Boost Converter

Figure 2 shows the three-level boost converter circuit implemented in this paper. In comparison with the conventional two level boost converter, three level boost converter has the superiority in terms of that voltage gain is doubled but the voltage across the switching element and diode halves. Also, through the control of midpoint, it also has the advantage to maintain the voltages of V_{dcp} and V_{dcn} equivalently so as to implement the multi-level inverter.

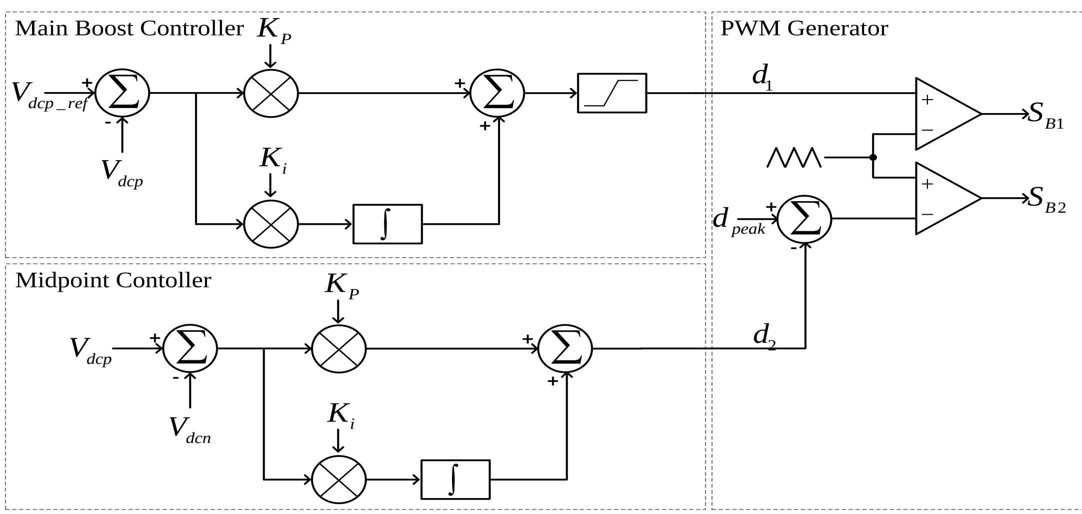
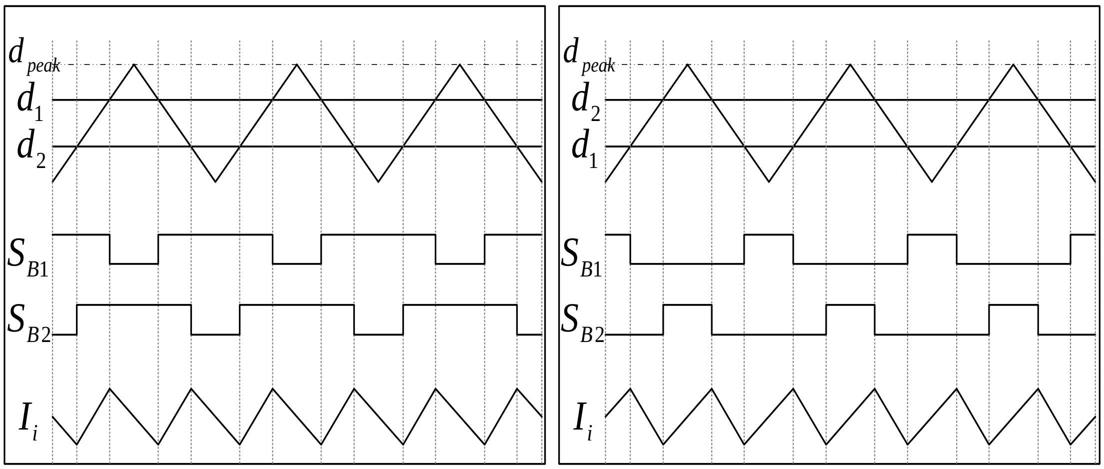


Figure 3. Block Diagram of Three Level Boost Converter

Figure 3 is the structure of boost converter to implement the optimal MPPT algorithm. Boost converter has two controllers and one PWM Generator. The controller controls the output power by using a PI controller which is widely used in automation systems. Usually the voltage unbalances between V_{dcp} and V_{dcn} can occur. To reduce this voltage unbalance, the difference between two voltages is to be controlled to 0 through PI controller. Finally, the PWM Generator generates PWM by using d_1 and d_2 which come out of the controller [7].



(a) $0.5 \le d_1 \le 1$ or $V_i \ge \frac{V_{dclink}}{2}$ (b) $0 \le d_1 < 0.5$ or $V_i < \frac{V_{dclink}}{2}$

Figure 4. Key Wave Form of Three Level Boost Converter

Figure 4 shows the important waveforms concerning the proposed three level boost converter waveforms. In Figure 4, the waveform of (a) is the waveform showing that d_1 is located over 50% when V_i is greater or equal than $V_{dclink}/2$, and (b) is the waveform showing that d_1 is located less than 50%, when V_i is smaller than $V_{dclink}/2$.

2.2. MPPT(Maximum Power Point Tracking)

Grid connected photovoltaic inverter should always generate the maximum power from the solar cells with the non-linear current characteristics and requires the stable control. If it doesn't follow the maximum power or unstable, the output power from the inverter is controlled unstably and the power quality becomes degraded. The MPPT algorithm proposed in this paper stably follows the maximum power point and, in case of the rapid fluctuations of solar radiation, it also follows the maximum power point [8].

MPPT method is differentiated into two methods. One is the method to change Duty Cycle of the Boost Converter and the other is the method to change the current of inverter maintaining DC link reference voltage by the Boost converter with PI controller. The MPPT algorithm to be proposed by this paper is designed in the method to change the pulse width of the Boost converter, and the flow chart of the algorithm is shown in Figure 5.

Figure 5 shows the flow chart of MPPT algorithm proposed in this paper. It is the method to follow the maximum power point of the solar cell arrays by comparing the present power and the past power as well as increasing or decreasing the output voltage of the solar cell array. When solar cell voltage (V_{solar}) is smaller than the minimum DC link voltage (V_{Boost_min}), the DC link reference voltage (V_{Boost_ref}) is to fix as the DC link minimum voltage and either increasing or decreasing the pulse width of booster-type converter, follow the maximum power point. When the solar cell voltage is greater than the DC link minimum voltage, DC link reference voltage V_{Boost_ref} is to set as the DC link voltage V_{DCLINK}, and either increasing or decreasing the DC link reference voltage, follow the maximum power point. Accordingly, it is possible to follow without the intervention of open-circuit voltage of the solar cell.

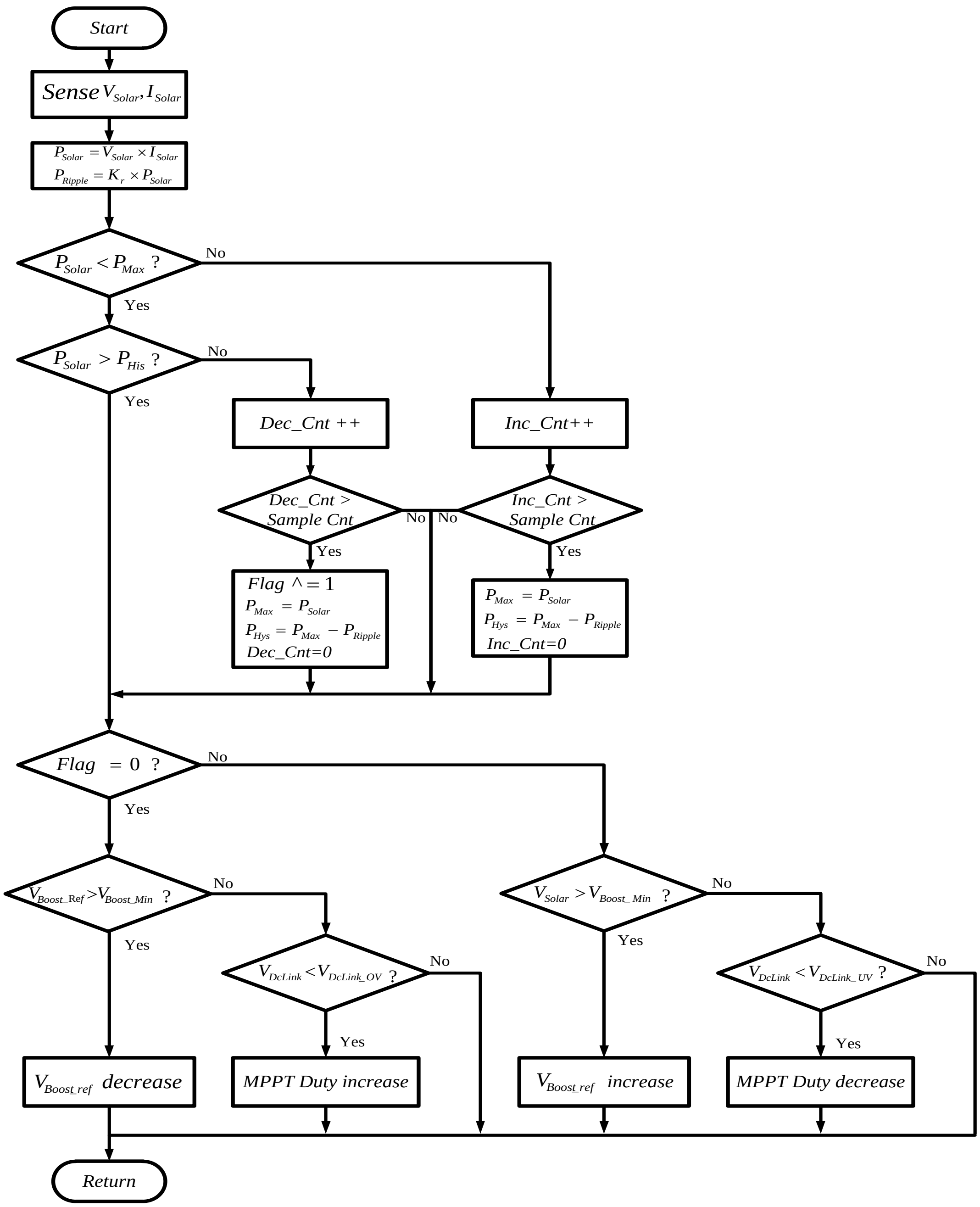


Figure 5. Flowchart of Proposed MPPT Algorithm

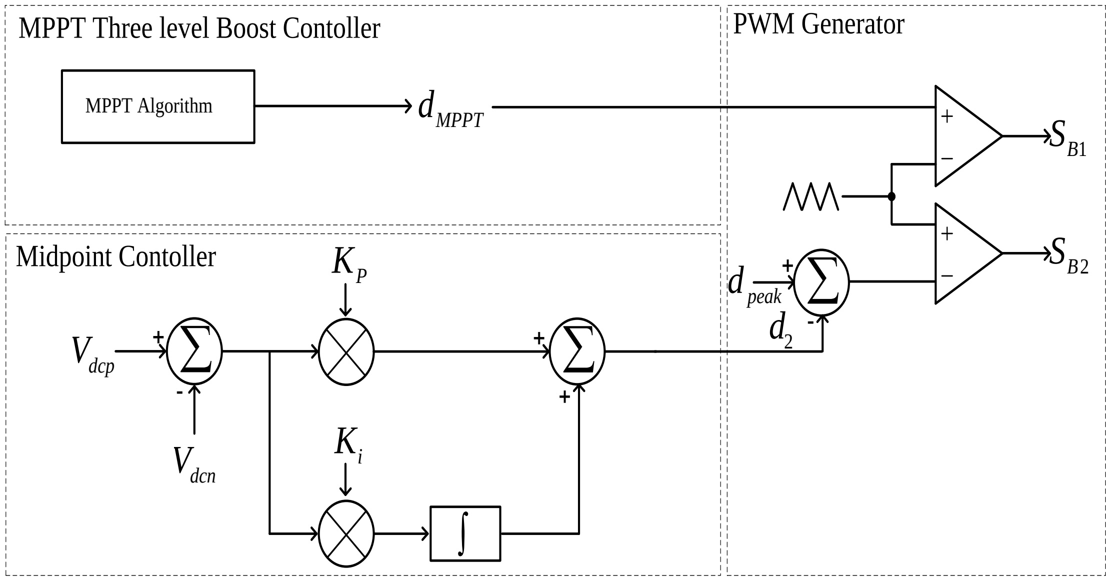


Figure 6. DC Link Voltage Balancing Controller for MPPT

Figure 6 shows a boost MPPT Controller proposed in this paper. When the DC link voltage is constantly maintained by the three level boost controller of Figure 3 and MPPT algorithm starts, it changes to MPPT three levels Boost controller of Figure 7. The d_1 outputted from the conventional controller is inputted as the default value of d_{MPPT} of the converted controller. Through MPPT algorithm, d_{MPPT} is changed and the conventional midpoint controller is to be maintained as it is.

2.3. Three-Phase T-Type PV Inverter

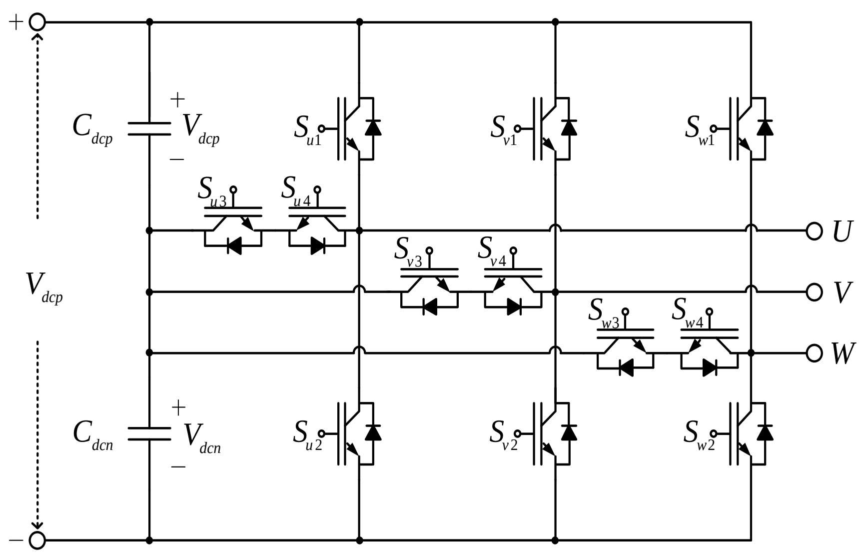


Figure 7. Circuit Diagram of a Three-phase T-Type PV Inverter

T-Type inverter has the structure as Figure 7. Compared to the conventional two-level inverter, the power switch is to be increased by 6 pieces, but compared to the generally used diode clamp inverter; it is the structure to reduce 6 diodes [9].

Table 1 Switching States

State	V_{Out}	S_{m1}	S_{m2}	S_{m3}	S_{m4}
P	$+V_{dcp}$	On	Off	On	Off
0	0	Off	Off	On	On
N	$-V_{dcn}$	Off	On	Off	On

Table 1 shows the output of each phase in accordance with a switching state The U, V, W phase of each output. S_{pn} is each output of U, V, W phases. Here, p is each phase, and n is the number of the switch elements. When S_{m1} turns on, V_{dcp} is outputted. When the bidirectional switch S_{m3} and S_{m4} turns on, 0 is outputted. When S_{m2} turns on, $-V_{dcn}$ is outputted. When the midpoint voltage is outputted from this system, the conduction is made through the bidirectional switch S_{m4} and S_{m4}, but when using the upper and lower switches, only the switch S_{m1} and S_{m2} are conducted. So, it has the advantage to reduce the numbers of elements. It means, in all of the switching state, the conduction element has can reduce the conduction loss than diode clamped inverter with two conduction elements, and considering a three-level inverter switching losses are the same, the high efficiency can be structurally obtained [10].

2.4. PLL (Phase Locked Loop)

It is important that Grid-interactive photovoltaic inverters should be controlled and outputted by the phase and conduction of the grid voltage. To do this, the grid-connected photovoltaic inverter essentially requires PLL (Phase Locked Loop). When the phase difference between the grid and the inverter occurs, the system becomes unstable and the power quality degrades and then the reliability is hard to obtain.

2.4.1. PLL Method of the Synchronization Coordinate System

When power element three-phase voltage is in equilibrium and has each frequency ω , and then, based on the phase voltage, the following equations can be obtained [11].

$$\begin{aligned} e_a &= E \sin \omega t \\ e_b &= E \sin\left(\omega t - \frac{2\pi}{3}\right) \\ e_c &= E \sin\left(\omega t + \frac{2\pi}{3}\right) \end{aligned} \quad (1)$$

Also, the equation (1) is expressed in the d-q stationary coordinate system as the following equation.

$$\begin{aligned} e_d^s &= E \cos \omega t \\ e_q^s &= -E \sin \omega t \end{aligned} \quad (2)$$

Furthermore, the equation (2) is expressed in the d-q synchronous coordinate system as the following equation.

$$e_q^e = E \qquad e_d^e = 0 \tag{3}$$

From equation (2), the phase angle of the controller can be calculated by the following equation.

$$\theta = \tan^{-1}\left(\frac{-e_q^s}{e_d^s}\right) \tag{4}$$

The synchronization coordinate q-axis power voltage calculated by the controller will be '0', when the control phase angle(θ) is matching with the actual phase angle (θ^*), and in case that the control phase angle(θ) is ahead of the actual phase angle (θ^*), it will have – value, and in case that the control phase angle(θ) is behind the actual phase angle (θ^*), it will have + value. Controlling by using PI controller to make the d-axis power supply voltage '0' in the synchronous coordinate system shown in Figure 4, it is possible to match the actual phase angle and the control phase angle.

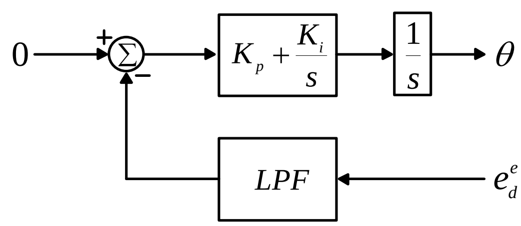


Figure 8 Structure of Phase Angle Controller

2.4.2. PPL Method by Using the Extraction of the Normal Sequence

PLL method using the conventional synchronous coordinate system is simple in principle and its implementation. However, if harmonic is mixed in power supply voltage, each extracted information shows the harmonic ripple. In order to remove the impact of power supply voltage un-equilibrium from the controller for the phase angle extraction, by obtaining the normal sequence voltage – that is, three phase equilibrium voltage – and use it as the input of the phase angle control extraction. Converting this obtained normal sequence voltage into the synchronous coordinate system, the inverse sequence voltage -which induces the ripple voltage corresponding to 2 times of the power supply frequencies if the existing unbalanced power voltage converts into the synchronous coordinate system disappears at the existing unbalanced power [11].

$$\begin{bmatrix} E_{pa} \\ E_{pb} \\ E_{pc} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ a^2 & 1 & a \\ a & a^2 & 1 \end{bmatrix}\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = \begin{bmatrix} \frac{1}{2}E_a - \frac{1}{2\sqrt{3}j}\left(E_b - E_c\right) \\ -\left(E_{ap} + E_{bp}\right) \\ \frac{1}{2}E_c - \frac{1}{2\sqrt{3}j}\left(E_a - E_b\right) \end{bmatrix} \tag{5}$$

Where, $a = \exp\left(j\frac{2\pi}{3}\right)$

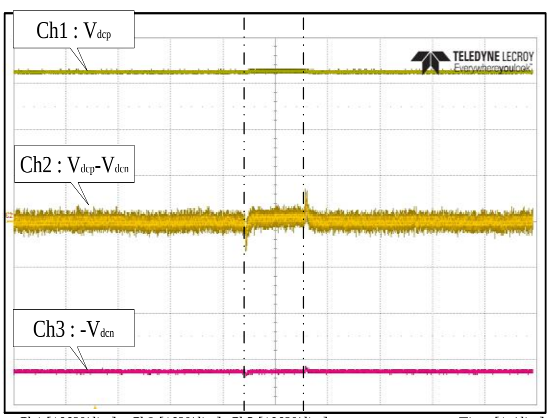
3. Experimental Results and Discussion

In this paper, a 10KW class three phase grid connected photovoltaic inverter was designed and used. In order to control Boost Converter, DC to AC Inverter, MPPT (Maximum Power Point Tracking), PLL (Phase Locked Loop) and all the photovoltaic generation systems, the digital main controller is based on digital signal processor (K60FX512VLQ15) which is running at 150 MHz. The output voltage of the photovoltaic inverter is 380v_{ac} / 60Hz and the rated current of the photovoltaic inverter was set as 15Aac. For inputting of photovoltaic inverter, instead of solar cell, REGARTRON CO's TopCon, and Quadro, and the simulation program, SAS Control were used. In addition, this paper showed the excellence of operating in conjunction with the actual grid. Table 2 shows the specifications of the controller.

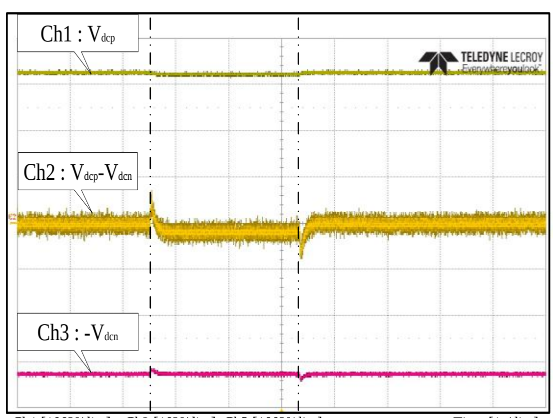
Table 2. Controller Specifications

specification		value
Processor	DSP	K60FX512VLQ15
	System Clock	150MHz
A/D Converter	Resolution	16bit
	Sample Frequency	15kHz
PWM	Frequency	15kHz
	Dead Time	2us

3.1. Three Level Boost Converter



(a) Vdcp resistance variation: 250Ω -> 166Ω -> 250Ω



(b) Vdcp resistance variation: 250Ω -> 166Ω -> 250Ω

Figure 9. Waveform of Resistance Load Variation

In Figure 9, by using the Boost Converter proposed in this paper, 320V was boosted to 650V. The waveform of (a) is the waveform that fluctuated a resistance load from 250Ω to 166Ω at v_{dcp} and after 1.5 seconds fluctuated it to 250Ω again and watched the result.

And the waveform of (B) is the waveform that fluctuated a resistance load from 250Ω to 166Ω at v_{dcn} and after around 3 seconds fluctuated it to 250Ω again and watched the output voltage. All of these two waveforms showed that midpoints were shown swaying at the initial stages of fluctuations.

However, within about 100ms, it was observed that they returned to the original voltages. At this time, the swaying voltage width has been stabilized within about 5 V.

3.2. MPPT (Maximum Power Point Tracking)

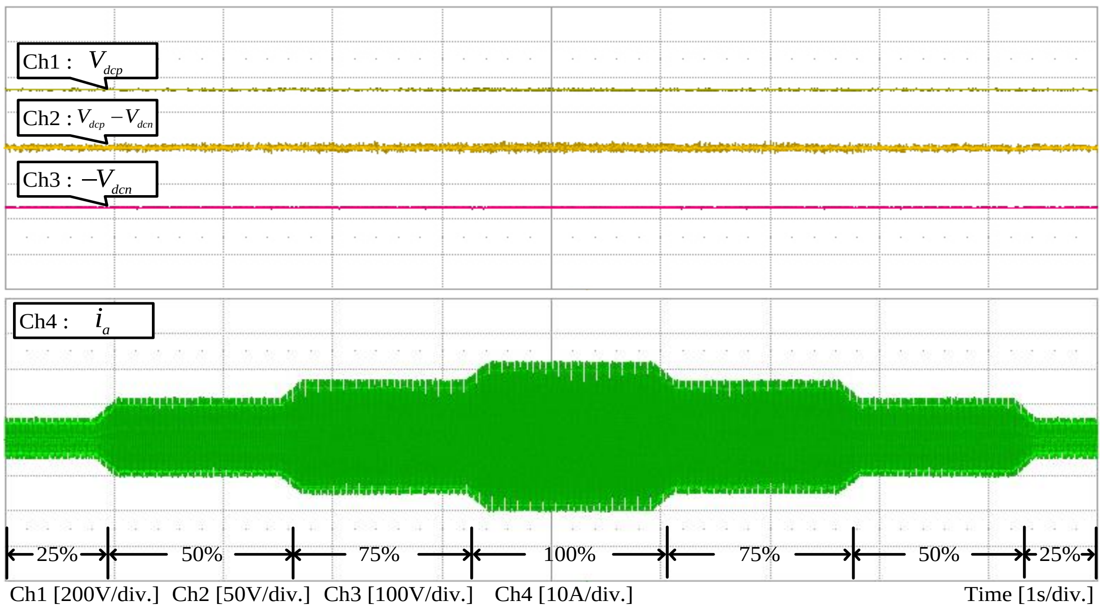


Figure 10. Waveform of Solar Irradiance Fluctuation

Figure 10 shows the DC link voltage and the output current of the photovoltaic inverter corresponding to the fluctuations of solar irradiance in order to show the excellence of MPPT (Maximum Power Point Tracking) proposed in this paper. It fluctuates for 0.5 second at 2.5KW and maintained for 1.5 seconds. It was observed that the un-equilibrium of DC link voltage was not created but maintained despite of the fluctuation of 25% solar irradiance, and also was confirmed that the output current of the inverter followed the maximum power stably.

Table 3. Efficiency of Maximum Power Point Tracking

Solar Irradiance	MPPT Efficiency
100%	99.95%
75%	99.94%
50%	99.94%
25%	99.93%

Table 3 presents the efficacy of MPPT(Maximum Power Point Tracking) corresponding to the fluctuation of solar irradiance. It was confirmed that more than 99.99% efficacy was generated and the proposed MPPT algorithm was great.

3.3. Three-Phase Three-Level T-Type Inverter

Figure 11 describes the voltage output of a 3-phase 3-level T-Type inverter. The output voltage of the inverter was 380 V_{RMS} / 60Hz, and DC link voltage was set as 650 V_{DC} for the experiment.

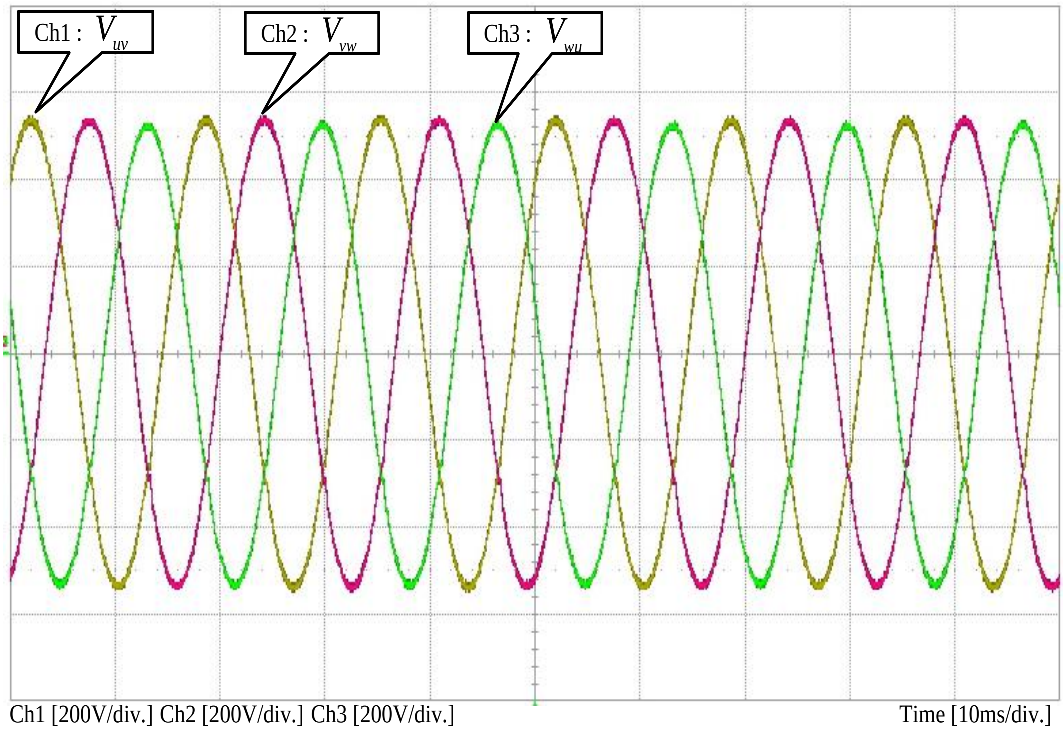


Figure 11. Waveform of Three-Phase T-Type PV Inverter

As seen in Figure 11, it was confirmed that the clean AC voltage was outputted.

Table 4. Efficiency of 3-phase 3-level T-Type Inverter

Solar Irradiance	Input Power(kW)	Output Power	Efficiency (%)
100%	9.9989 kW	9.6792 kW	96.8
75%	7.4989 kW	7.2515 kW	96.7
50%	4.9878 kW	4.8088 kW	96.4
25%	2.4997 kW	2.4025 kW	96.1

Table 4 shows the efficacy of a 3-level 3-phase T-type inverter. If more than 25% of solar radiation, the superior efficacy of more than 96% was confirmed.

4. Conclusion

Compared to the conventional 2-level inverter, 3-level inverter has the disadvantages that require the control techniques on midpoint and the increase of number of power switches. However, it has the advantages such as the high efficacy of the inverter, low harmonic content, less stress on the power switch. This paper proposed the 3-level 3-phase T-type structure of the high efficient grid connected three phase photovoltaic inverter. Also, the 3-level 3-phase T-type structure of the inverter control algorithm which controls the midpoint voltage was offered and its superiority was proved by experiment.

For the 3-level inverter, as the midpoint voltage may affect the output current of the inverter and also adversely impact the loads connected to the power grid, the difference between (V_{dcp}) and (V_{dcn}) should be maintained as 0V. To achieve this, it was verified the boost controller proposed in this paper maintained the difference of (V_{dcp}) and (V_{dcn}) as 0V.

The grid connected photovoltaic inverter needs to always generate the maximum power from the solar cell of the non-linear current characteristics. This paper verified that the efficacy of MPPT could be maintained more than 99.99% by the proposed MPPT algorithm which controlled the duty cycle of the boost converter, and confirmed the excellent MMPT performance was maintained despite of the fluctuation of solar irradiances by experiment.

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