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A Battery-less Grid Connected Photovoltaic Power generation using Five-Level Common-Emitter Current-Source Inverter

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ABSTRACT

Renewable power generation using photovoltaic is very interesting to be developed to deal with the problems of conventional energy sources and environmental issues. The photovoltaic power generation can operate both in stand-alone and grid-connected operations. This paper presents an application of the single-phase five-level common-emitter current-source inverter (CE-CSI) for grid connected photovoltaic system without batteries as energy storage system. In the proposed system, the five-level CE-CSI works generating a sinusoidal output current from photovoltaic system to be injected directly into the power grid. The transformer is used in the system to step-down the grid voltage to meet the voltage level of the photovoltaic system, and also works as a galvanic insulation between the power grid and the inverter system. Two conditions of the power grid voltage, i.e. a pure sinusoidal and a distorted power grid, are tested through computer simulation using PSIM software. Furthermore, experimental test result of the five-level inverter is also presented. The test results show that the five-level CE-CSI works well injecting a sinusoidal current into the power grid with low harmonic contents, and with unity power factor operation. The results also show that the distorted grid voltage affects the harmonic contents of the current injected by the inverter.

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1. INTRODUCTION

Multilevel inverter is an inverter technology generating an alternating voltage and current waveforms from its DC power sources, with lower gradient voltage or current, and less distortion of its output waveform compared to the conventional two-level inverter configuration [1]. Based on its DC power sources, the multilevel inverters can be classified into two types, i.e. multilevel voltage source inverters (MVSI) and multilevel current source inverters (MCSI) [2]-[4]. The power sources of the MVSI is a single or multi DC voltage power sources, depends on its circuit configuration, while the power sources of the MCSI is a single or multi DC current sources [2]-[8]. Some configurations of the MCSI have been developed by researchers. The author has also proposed another circuit configuration of MCSI called as the multi-level common-emitter CSI presented in [3]. The performance of the five-level common-emitter CSI circuit constructed using reverse blocking IGBTs was described in [4].

In the renewable energy based electric power generation, there are two kind operations, i.e. stand alone operation and grid connected operation. Because most of the power loads require AC power, the DC power generated by the renewable energy sources such as photovoltaics, is converted into AC power using inverter. In case of stand-alone operation, this AC power is delivered directly to the load via the power inverter. While, in case of grid connected operation, the power generated by the renewable energy sources is injected into the utility power grid in the form of AC power [8]-[13]. In the grid connected operation, there are standards, such as IEC61727, IEEE1547, NEC690 and EN61000-3-2 imposing the limit of harmonic contents for the AC current generated by the grid connected inverter to be injected into the power grid [8], [10]-[12]. MCSI is a proven inverter technology to solve the problems related to the harmonic contents of the grid connected inverter. The immunity of the grid connected MCSI from the power grid voltage fluctuation is higher than the grid connected MVSI [12], [13]. The grid connected MCSI also does not need AC current sensors, which are mandatory for the grid connected MVSI. Furthermore, the MCSI has inherent short-circuit protection because of its high impedance DC power source [4], [12].

In this paper, a new grid connected photovoltaic system without batteries is proposed. The five-level common-emitter current-source inverter (CE-CSI) is used as the grid connected inverter. The operation of the proposed grid connected photovoltaic system is tested through computer simulation using PSIM Software and experimentally in laboratory.

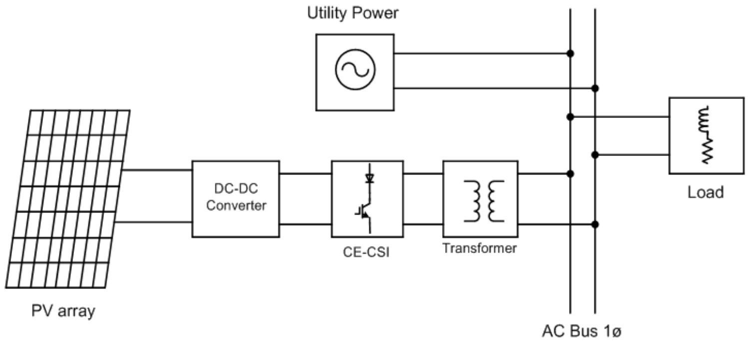

Figure 1. Proposed battery-less grid-connected photovoltaic system

2. PROPOSED SYSTEM

2.1. Operation Principle

Figure 1 shows the proposed configuration of the grid connected photovoltaic system. The PV array can be composed by series and parallel connection of some PV modules to obtain higher output power. The DC-DC converter in this system is used to generate DC current-sources for the inverter circuits. The inverter works generating a sinusoidal output current to be injected into the single phase AC bus or AC power grid. The transformer isolates the inverter system and the power grid [12]. The transformer also works to step-down the power grid utility voltage to meet the voltage level of the PV system.

Figure 2 shows the configuration of the DC-DC converter, and the five-level CE-CSI applied in this system. The five-level CE-CSI is connected to the power grid through the power transformer. The PV array is represented by a DC voltage source V_{PV}. The five-level CE-CSI works generating a five-level pulse width modulation (PWM) current waveform that will be filtered by the capacitor (C_f) to become a sinusoidal output current to be injected into the AC power grid.

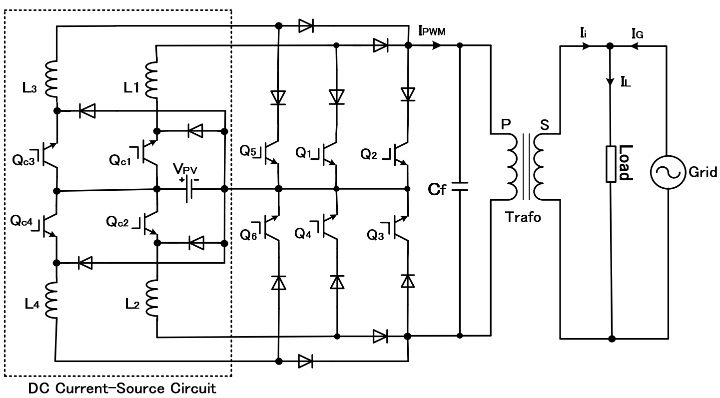

Figure 2. The five-level CE-CSI with power grid connection [3], [4]

The DC-DC converter is composed by four controlled power switches (Q_{C1}, Q_{C2}, Q_{C3},Q_{C4}), four diodes and four inductors. The switches regulate the currents flowing through the inductors to generate DC currents for the inverter circuits. The five-level CE-CSI is constructed by six unidirectional controlled power switches, i.e. IGBTs or MOSFETs connected in series with diodes. All of the inverter's power switches are connected at a common-emitter line [3], [4]. The inverter generates a PWM five-level current waveform before filtering. The filter capacitor C_f is used to filter the high frequency components of the five-level PWM current waveform to obtain a sinusoidal output current. For analysis purpose, Figure 3 shows the five-level CE-CSI with four ideal DC current-sources, I/2. Table 1 lists the switching combination of the five-level CE-CSI for the five-level output current waveform generation.

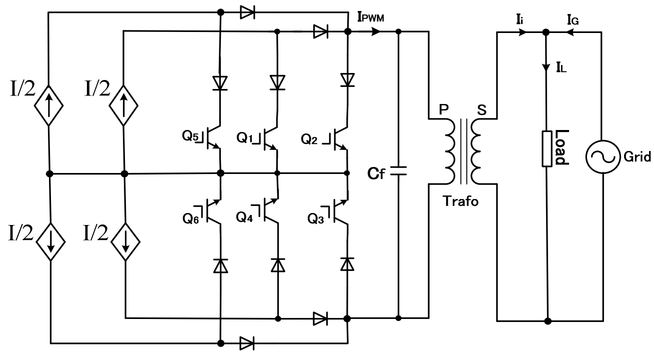

Figure 3. The grid connected five-level CE-CSI with ideal DC current sources [3], [4]

Table 1. Switching combination of five-level CE-CSI [3], [4]

Q1	Q2	Q3	Q4	Q5	Q6	Output current level
OFF	OFF	ON	ON	OFF	ON	+I A
OFF	OFF	ON	ON	ON	ON	+I/2 A
ON	OFF	OFF	ON	ON	ON	0 A
ON	ON	OFF	OFF	ON	ON	-I/2 A
ON	ON	OFF	OFF	ON	OFF	-I A

2.2. Current Controller and PWM Modulation Strategy

In the proposed grid connected photovoltaic system using the five-level CE-CSI, the controller used to regulate the current that will be injected into the power grid is the proportional integral (PI) controllers. These controllers will also determine the DC currents flowing through the DC smoothing inductors of the five-level CE-CSI, i.e. L_1, L_2, L_3, and L_4 [3]-[4], [12]. The amplitudes of the DC currents flowing through the smoothing inductors are set at 50% of the peak value of the five-level PWM output current. The error signals between the measured current and the reference current of the PI current controller are processed for the gating signals generation of the DC-DC converter as shown in Figure 4.

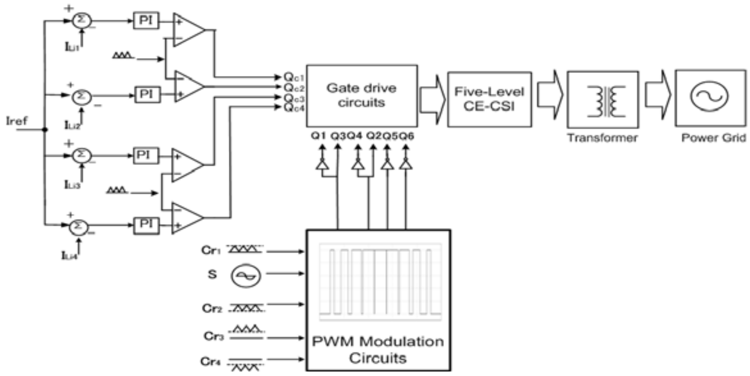

Figure 4. Control diagram and PWM modulation strategy of the grid connected five-level CE-CSI

Generating a low distortion of sinusoidal output current to be injected into the power grid is the most important feature of a grid connected inverter circuits [10]. In order to achieve a sinusodal output current waveform with low distortion, a carrier based sinusoidal pulse width modulation (PWM) technique is used to evoke the gating signals of the five-level CE-CSI. Four triangular carrier waveforms with different DC offset levels (C_{r1}, C_{r2}, C_{r3}, C_{r4}), at the same frequency and phase are used in this modulation strategy. Some literatures called this method as level-shifted multi-carrier based sinusoidal PWM. The frequency of the modulated signal (the sinusoidal waveform, S) will assign the fundamental frequency of the inverter's output current. The switching frequency of the five-level CE-CSI is specified by the frequency of the triangular carrier waveforms used in the modulation circuits [3]-[4], [12]-[13]. Figure 4 shows the control diagram and modulation strategy of the grid-connected five-level CE-CSI.

3. TEST RESULTS AND ANALYSIS

The proposed grid connected photovoltaic system using the five-level CE-CSI is tested and examined through computer simulations with a PSIM software. The parameters of the tested system are listed in Table 2. Two conditions of the power grid voltage are evaluated in this system, i.e. pure sinusoidal grid voltage and distorted power grid. Figure 5 presents the computer simulation test results of the proposed system when the power grid is a pure sinusoidal grid voltage. The five-level PWM current (I_{PWM}), the inverter's current in the primary side of transformer (I_{inv}), the current injected into the power-grid (I_i), and the power grid voltage (V_{Grid}) are shown in this figure. The five-level CE-CSI works properly injecting a sinusoidal current into the power grid. The phase different between the injected current and the grid voltage is almost zero. In another word the proposed system works with high power factor (unity power fator). Figure 6 shows the harmonic spectra of the current injected by the inverter (I_i). All of low harmonic components are less than 1%, proving high quality power injecting by the inverter. Figure 7 shows the harmonic spectra the power grid voltage which is only the fundamental component of 50 Hz (a pure sinusoidal voltage).

Table 2. Parameters of the system

Power grid voltage (rms)	220 V
DC input voltage of inverter	48 V
Smoothing inductors of inverter	2.2 mH
Switching frequency of inverter	22 kHz
Filter capacitor of inverter	10 F
Filter inductor of inverter	1 mH
Local Load	R = 6.5 Ω, L =10 mH
Output current frequency of inverter	50 Hz
Power transformer ratio	1:10

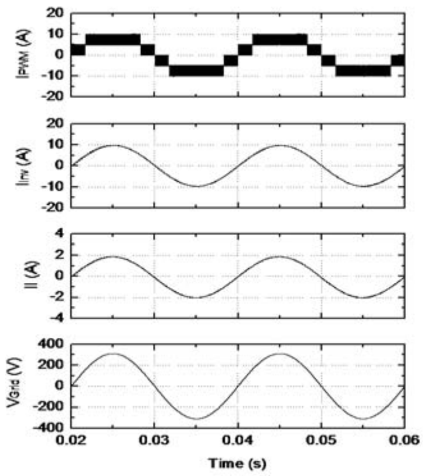

Figure 5. Simulation results when the inverter is connected with a pure sinusoidal power grid voltage

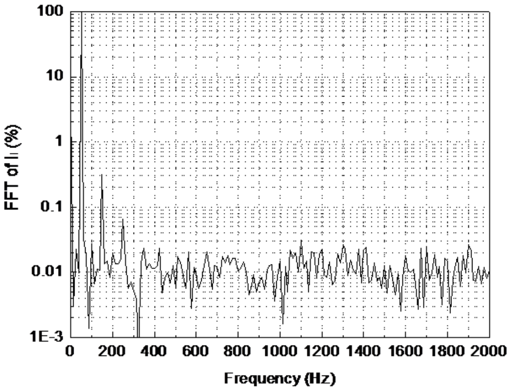

Figure 6. Harmonic spectra of the inverter's output current

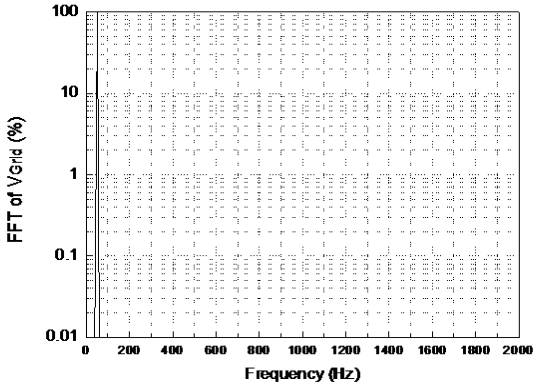

Figure 7. Harmonic spectra of power grid voltage

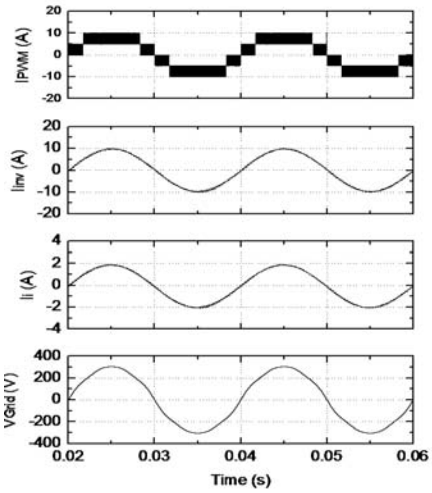

Figure 8. Simulation results when the inverter is connected with a distorted power grid voltage

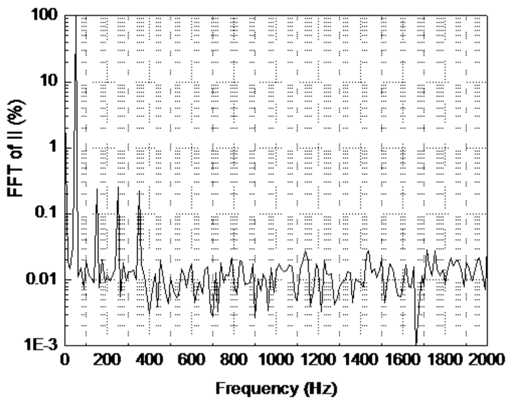

Figure 9. Harmonic spectra of the inverter's output current

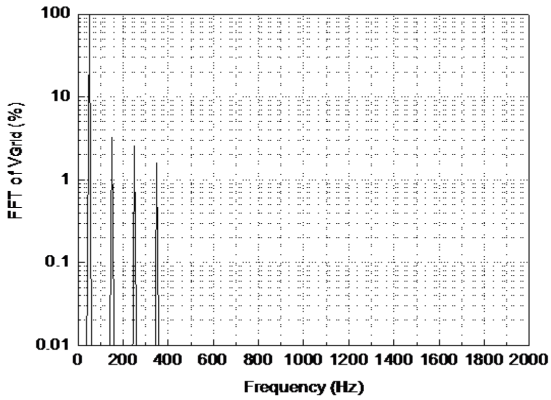

Figure 10. Harmonic spectra of the power grid voltage

Furthermore, Figure 8 shows the test results when the power grid voltage is a distorted power grid (contain low harmonics components). Figure 9 and Figure 10 show the harmonic spectra of the current injected by the inverter into the power grid (I_i), and the distorted power grid voltage (V_{Grid}), respectively. The 3^{rd}, 5^{th} and 7^{th} harmonics orders are the major harmonic components of the grid voltage. Compared to the first condition of the grid voltage, the 5^{th} and the 7^{th} harmonic orders of the current increased in this condition. It is caused by the harmonics components of the power grid voltage. Figure 11 shows the transient test result of the proposed system. In this figure, the amplitude of the inverter's output current was changed from 5 A to 8 A. I_{L1} and I_{L2} are the DC currents flowing through the smoothing inductors L_1 and L_2 of the inverter circuits. It can be seen that the controller works well keeping stable DC currents flowing through the smoothing inductor during this step response. Fig 12 presents an experimental test result showing the output current waveform of the inverter. Sinusoidal and five-level PWM current waveforms are properly generated by the five-level CE-CSI.

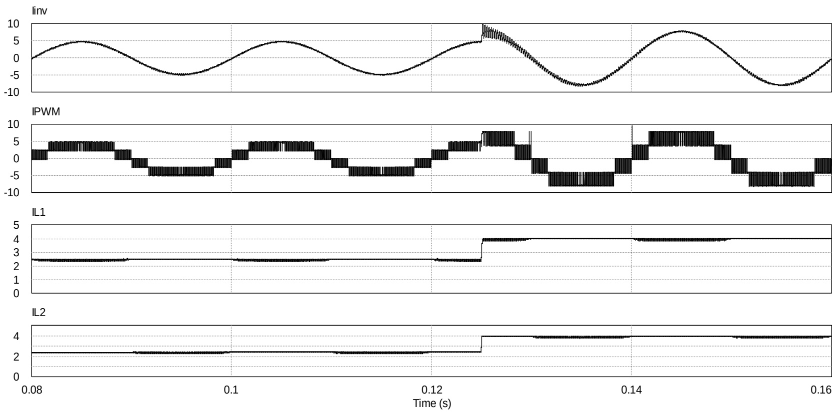

Figure 11. Transient test result waveforms

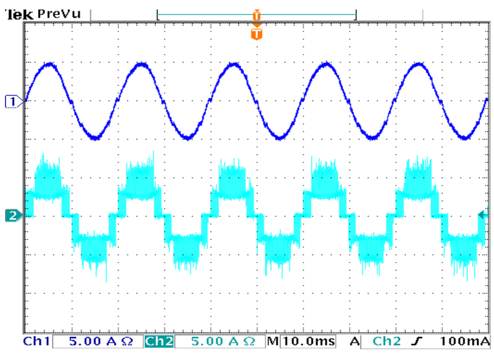

Figure 12. Output current waveforms of the five-level CE-CSI

4. CONCLUSION

A new grid connected photovoltaic system using the five-level CE-CSI is proposed and examined. The proposed system does not used battery system that make the system need less maintenance and cheaper. The test results show the proper operation of the five-level CE-CSI as a grid connected inverter injecting a sinusoidal output current into the power grid with a unity power factor operation. All of the harmonic components of the injected current are less than 1 %, even the system is connected with a distorted grid voltage. A good transient test result is also achieved, showing a good performance of the proposed system.

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Suroso received the B. Eng. degree in electrical engineering, from Gadjah Mada University, Indonesia in 2001, and the M. Eng. degree in electrical and electronics engineering from Nagaoka University of Technology, Japan in 2008. He was a research student at electrical engineering department, Tokyo University, Japan from 2005 to 2006. He earned the Ph.D degree in energy and environment engineering department, Nagaoka University of Technology, Japan in 2011. He was a visiting researcher at electrical and electronics engineering department, Shizuoka University, Japan from 2009 to 2011. Currently, He is an assistant professor at department of electrical engineering, Jenderal Soedirman University, Purwokerto, Jawa Tengah, Indonesia. His research interest includes static power converters, and its application in renewable energy conversion and distributed power generation.

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