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Design and Implementation of a Four-Quadrant Grid Simulator

[1]Minhua Qian, [2]Ruixiang Fan, [1]Yandan Lin and [1]Yaojie Sun
[1]Department of Illuminating Engineering and Light Sources, School of Information Science and Engineering, Fudan University, Shanghai 200433, China
[2]Jiangxi Electric Power Research Institute, Nanchang 330096, China

Abstract: This study presents the development of a grid simulator which is capable of generating sinusoidal waveforms with variable amplitude and frequency over a wide range. Moreover, it can achieve four-quadrant operation and allows bi-directional power flow due to the back-to-back topology. The transient grid conditions generated by this grid simulator can comply with the requirements of the international standards, such as VDE-AR-N 4105. So, it is well suited for testing grid-connected photovoltaic inverters. Both simulation and experiment results showed that the grid simulator designed in this study can provide transient grid conditions and achieve four-quadrant operation.

Keywords: Four-qudrant operation; Grid simulator; back-to-back converter

INTRODUCTION

Nowadays, PV power generation has been widely used in many areas. Solar energy is becoming more and more important in our energy supply system (Yuvarajan *et al*., 2004). And, as the crucial part of the PV power generation system, the grid-connected photovoltaic inverters' efficiency, reliability and protective functions will directly affect the entire PV power generation system. So we need an equipment to simulate the real utility. This equipment is called the grid simulator which can change its output voltage and frequency to simulate the transient grid conditions (Muyeen *et al*., 2007).

There are several studies that have done some research in designing the grid simulator. Zhang *et al*. (2002) proposed a new control method which can provide an infinite control gain. Using this method the grid simulator can achieve superior steady state and dynamic performance (Zhang *et al*., 2002). Kay Soon Low designed a digital controller based on the generalized predictive control approach which can reduce both the tracking error and the control signal (Kay, 1999). Tzou *et al*. (1997) proposed a new control scheme which consists of a tracking controller and a repetitive controller. This control scheme can improve both the transient and steady-state responses (Tzou *et al*., 1997). The above research is all focused on improving the grid simulator's static characteristic and dynamic response by using complicated control method. However, during the testing process we need extra loads to consume the output energy of the inverter which is under test. This is a way of wasting energy, especially when the inverter is operating at rated power for hours even days to test its reliability. This kind of energy loss is considerable. So, it is needed to design a grid simulator which can deliver the generated power from the inverter back to the utility grid, not consumed using extra loads.

In this study , a practical grid simulator is designed which can simulate the transient grid conditions. And moreover, it allows a four-quadrant operation, meaning that the power generated from the inverter can be delivered back to the utility grid (Namwon *et al*., 2010). The grid simulator is designed by simulation with Matlab/Simulink to verify its control algorithm and manufactured for the experiment of generating transient grid conditions and four-quadrant operation. The simulation and experiment results both show the grid simulator designed in this study is well suited for transient analysis of grid-connected photovoltaic inverters and it can achieve a four-quadrant operation.

DESIGN OF THE GRID SIMULATOR

Design requirements: The designed grid simulator is used to test the grid-connected photovoltaic inverters' performance indexes under different conditions. And these testing conditions are detailed in standards such as VDE-AR-N 4105 for power generation systems connected to the low-voltage distribution network7, BDEW guideline for generating plants' connection to and parallel operation with the medium-voltage network8. In VDE-AR-N 4105 it requires that the

Corresponding Author: Minhua Qian, Department of Illuminating Engineering and Light Sources, School of Information Science and Engineering, Fudan University, Shanghai 200433, China

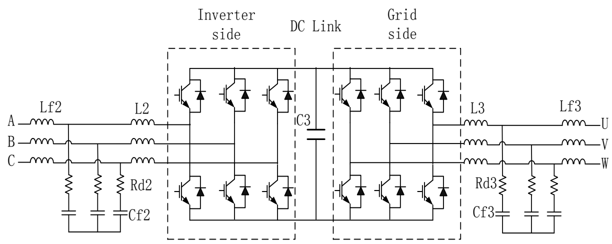


Fig. 1: Structure of the grid simulator

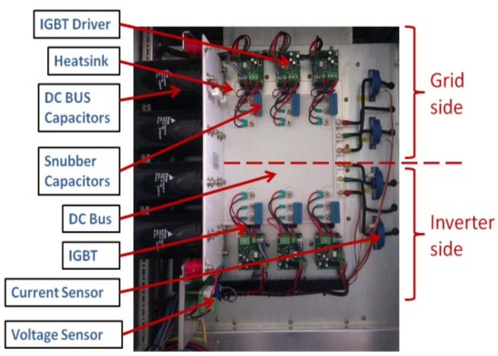
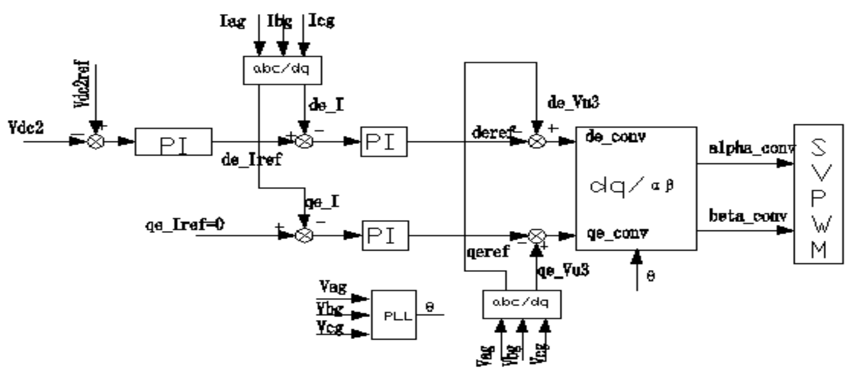


Fig. 2: Practical picture of the main power unit

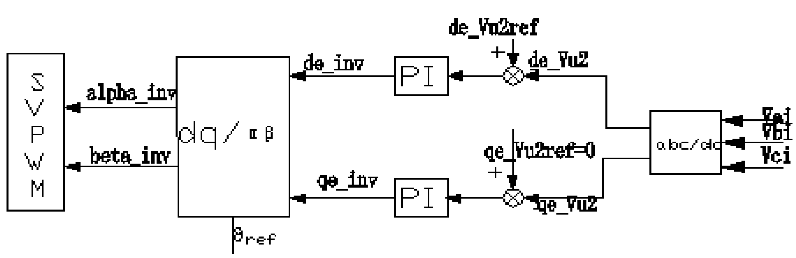
inverter's output active power can be adjusted with the change of utility grid frequency. And the step size of the frequency is less than 0.01Hz. This means the resolution of grid simulator's output frequency must at least be 0.01Hz. And in order to save energy the grid simulator must have the ability to feed power back to the utility grid.

Structure design: The designed grid simulator mainly consists of two LCL9filters and a back-to-back converter, as shown in Fig. 1. The back-to-back converter is suitable for bi-directional power flower, because of its ability of achieving four-quadrant operation10. Two LCL filters, one at the grid side and the other at the inverter side, are used to reduce the current harmonics around the switching frequency. The main power unit of the practical grid simulator is shown in Fig. 2. There are six IGBTs mounted on top of the heatsink. Three IGBTs on the upper side is used as grid side converter and the others are used as the inverter side converter. On the top of each IGBT module, there is one snubber capacitor which is used to absorb the overvoltage. Each IGBT module needs two IGBT drivers. The main component of the driver is HCPL-316J. Voltage and current sensors are used to measure the 3 phase voltage and current and send date to the controller for generating the PWM control signal. A DC bus is used to reduce distributed inductance.

Control strategy: The control diagrams of the grid side converter and inverter side converter are shown in Fig. 3a and b respectively. In grid side converter there



(a)



(b)

Fig. 3: Control block diagram of grid simulator ; (a) Grid side converter (b) Inverter side converter

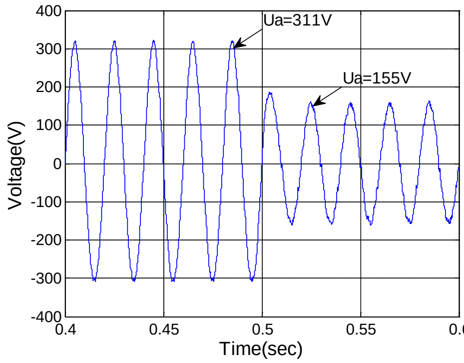


Fig. 4: Amplitude variation of output voltage

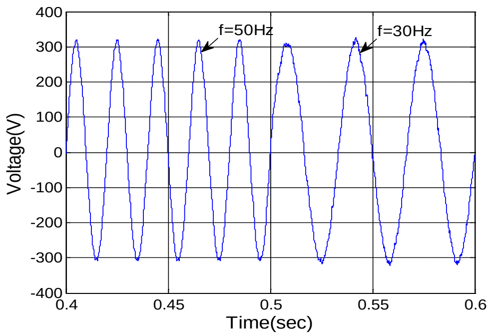


Fig. 5: Frequency variation of output voltage

tow control loops, voltage loop and current loop, based on the dqo transformation11. The outer voltage loop senses the voltage of the DC-link capacitor and compares it with the reference value. The difference is used as the reference value of the inner current loop. The d-axis current controls the amplitude of the grid side current. So the energy flows into or out of the DC-link capacitor is controlled in order to maintain the DC-link voltage constant. The q-axis current can control the reactive power exchanged between the utility grid and grid simulator. The reference value of the q-axis current is set to be zero for unity power factor operation. The angle of the dqo transformation is calculated from the grid side voltage using the PLL module. In inverter side converter, the three phase measured voltage is transformed into a dqo synchronously rotating reference frame using Clark and Park transformations12. The current is already controlled by the grid side converter and due to active power conservation; there is no need to control the current in the inverter side converter. So the inverter side converter only has two voltage loops to control the amplitude and frequency of the output three-phase voltage.

SIMULATION RESULTS

In order to verify the previously designed grid simulator, a software-based simulation was performed using MATLAB/Simulink. The grid simulator was tested to confirm its ability of generating transient grid conditions and achieving four-quadrant operation.

Figure 4 depicts the amplitude variation of the output voltage. The amplitude is changed from 311V to 155V at 0.5s. Figure 5 depicts the frequency variation of the output voltage. The frequency is changed from 50Hz to 30Hz at 0.5s.

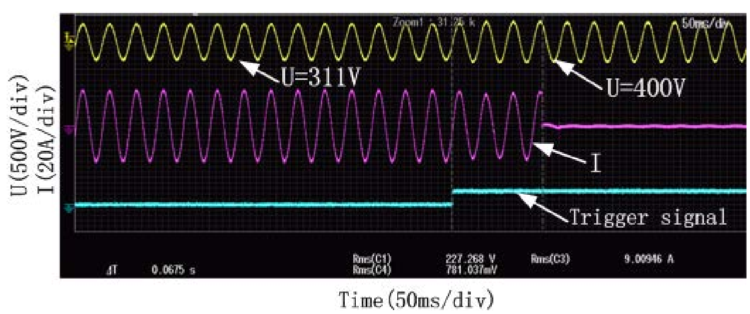


Fig. 6: Inverter tested under voltage variation condition

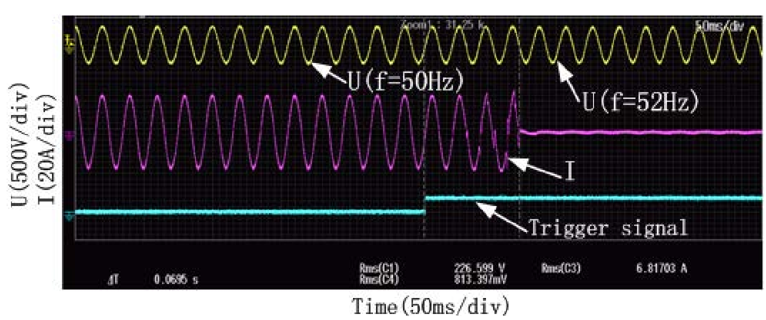


Fig. 7: Inverter tested under frequency variation condition

EXPERIMENT RESULTS

The proposed grid simulator is implemented to test the grid-connected photovoltaic inverters. It performs two major functions: generates transient grid conditions required in international standards to test the inverter's ability of disconnecting from the utility grid when an abnormal condition occurs; achieve bi-directional power flow in order to save energy. To confirm the above functions, several experiments were performed. In Fig. 6 and 7, the output voltage of the grid simulator is denoted by U and the output current of the tested inverter is denoted by I. And there is a trigger signal, the rising edge of which indicates the moment when the amplitude or frequency of the output voltage begins to change. So, using this trigger signal we can record the time between the beginning of the voltage variation and the point at which the inverter stops. Figure 6 shows the amplitude of the voltage changes from 311V to 400V and the tested inverter disconnected after about 67.5ms. Figure 7 shows the frequency of the output voltage changes from 50Hz to 52Hz. And the disconnected time is about 69.5ms. From both Fig. 6 and 7 we can see that the phase of the output voltage is opposite to the current. This means the designed grid simulator can deliver energy back to the utility grid and achieve bi-directional energy flow.

CONCLUSION

In this study, a grid simulator is designed and implemented for testing grid-connected photovoltaic inverters under different transient grid conditions. Firstly detailed structure of the grid simulator is presented. And the operating principle of the key topology, the back-to-back converter, is described. Then the control strategy is presented. Using this control strategy a simulation based on MATLAB/Simulik is performed. Finally the grid simulator is manufactured and used to test the real inverter. The test results showed that the grid simulator can fulfill the requirements of testing grid-connected photovoltaic inverters and can save energy by achieving four-quadrant operation.

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