Hardware-in-the-loop simulation of inverter power supply controller based on StarSim and DSP

Han Zhou1a, Yongxin Zhao2c, Guochu Chen1b*

1 School of Electrical Engineering, Shanghai Dianji University, Shanghai 201306, China
2 Shanghai Zhenhua Heavy Industries Co., LTD, Shanghai 200125, China
a 316085378@qq.com, b*chengc@sdju.edu.cn, c zhaoyongxin@zpmc.com

Abstract—Aiming at the contradiction between the requirements for rapid development and verification of inverter power supply controller products and the actual construction of real inverter power supply circuit topology, this paper proposes to build a semi-physical simulation platform based on StarSim and DSP. This paper takes the single-phase full-bridge inverter power supply as an example, use Shanghai ModelingTech company’s StarSim real-time simulator as the hardware platform, establish the circuit model in Matlab/Simulink and select NI PXIe-7846R board to run circuit extensions, and use TMS320F28335 as controller of the phase inverter power supply, based on StarSim HIL host computer program to load the model, configure the IO, and test and verify. The experimental results show that the semi-physical test platform has high accuracy and feasibility, shortens the development cycle of the controller, and greatly reduces the development cost of the controller.

1. Introduction

Single-phase full-bridge voltage inverter power supplies are widely used in power electronic devices such as frequency converters for AC motor speed regulation, uninterruptible power supplies, induction heating power supplies. Among them, the controller test is one of the important methods to verify the feasibility and stability of the entire inverter power supply. However, in the entire product cycle development process of the controller, the traditional full-physical test method requires a large number of power electronic devices, so it has the disadvantages of high test cost, complex test process, and long test cycle. Semi-physical real-time simulation, also known as hardware in the loop simulation (HIL), can use model-level verification for the controller in the early stage, and combine the real-time simulation system and the controlled object model in the later stage to control most of the controller's functions Perform verification to reduce the workload of controller testing and shorten the development cycle[1].

At present, HIL testing for the automotive industry is more and more widely used in academia and industry. However, in the development of controllers for photovoltaic inverters and wind power converters, there are not many companies that apply HIL to the development process. It is more common, mainly due to the high cost of the HIL system, especially the high threshold for researchers. Literature [2] Based on the real-time simulation model of the multi-level inverter of CPU and FPGA, a corresponding HIL simulation experiment platform was built. Literature [3] Based on the model parameter test platform of the controller hardware-in-the-loop simulation, the model parameter test of the static var generator controller is carried out. The literature [4] is based on the RT-LAB simulation
platform, and builds the CPU simulation model and the CPU+FPGA simulation model of the permanent magnet direct-drive wind turbine. However, the above research mainly focuses on the modeling of the controller system model, and there is little involved in the related configuration and testing of the controller in HIL applications.

In addition to the development of controller models by related scholars, more and more domestic and foreign commercial simulation software and tools have supported HIL test applications in recent years. Among them, foreign real-time simulation controllers such as NI, dSPACE, RT-Lab, etc., domestic real-time simulation controllers include Shanghai ModelingTech company’s StarSim and Nanjing Yanxu company’s YXSPACE, and simulator platform software includes Carsim, dSPACE ASM, RT-lab, and StarSim HIL etc[1]. Based on these commercial simulation software and real-time tool platforms, controller modeling and control strategy development can be carried out quickly. However, due to the variety of controller types and structural forms, for the development of control strategies for different controllers, corresponding circuit topology models must be established. This article will establish a single-phase full-bridge inverter circuit model based on Matlab/Simulink, and use StarSim HIL software to import StarSim simulator; select DSP28835 as the controller, use CCS6.0 development software to program the controller, and download it to the controller after debugging; configure the relevant IO in the StarSim HIL software, and use the signal transfer board to correspond the analog signal of the simulation circuit to the control signal one-to-one; finally, based on the StarSim and DSP28335 controllers of Shanghai ModelingTech company, establish a hardware-in-the-loop The test platform is used to test the single-phase full-bridge inverter power supply controlled by SPWM.

2. Single-phase full-bridge inverter power supply

2.1. Principle of single-phase full-bridge inverter circuit
Single-phase full-bridge voltage inverter power supply is the most widely used single-phase inverter circuit, and it is the most basic inverter circuit in power electronics technology. As shown in Fig.1, there are four bridge arms, and each bridge arm has an IGBT, and the load is an inductive load. IGBT1 and IGBT4 are a pair, IGBT2 and IGBT3 are a pair, the paired IGBT devices are turned on at the same time, and the two pairs are turned on for 180° alternately.

![Fig.1 Diagram of single-phase full-bridge inverter circuit](image)

2.2. SPWM control of ePWM module
According to the impulse theorem, the PWM waveform that is equivalent to the sine wave with the pulse width changing according to the sine law, that is, the SPWM waveform, controls the on and off of the switching devices in the inverter circuit, so that the area of the output pulse voltage is in line with the desired output sine wave[5]. The area in the corresponding interval is equal, and the frequency and amplitude of the output voltage of the inverter circuit can be adjusted by changing the frequency.
and amplitude of the modulating wave. Many documents on this part have been introduced in detail, so this article will not repeat them.

The ePWM module of F28335 is an enhanced module. Each ePWM consists of two ePWM outputs, ePWMxA and ePWMxB. This pair of PWM outputs can be configured as two independent single-edge PWM outputs, or two independent but symmetrical dual-edge PWM outputs, or a pair of dual-edge asymmetrical PWM outputs. There are 6 pairs of such ePWM modules, plus With the above 6 APWM modules, F28335 can have up to 18 PWM outputs. Each set of ePWM modules includes the following 7 modules: time base module TB, counting comparison module CC, action comparison module CC, action module AQ, dead zone generation module DB, PWM chopper module PC, error protection module TZ, event trigger Module ET, as shown in Fig2.

```
void InitEPwmExample()
{
    EALLOW;
    SysCtrlRegs.PCLKCR0.bit.TBCLKSYNC = 0;
    EDIS;
    EpwmRegs.TBCTL.bit.SYNCOSEL = 0x01;
    EpwmRegs.TBPRD = sanjaobo;
    EpwmRegs.TBPHS.half.TBPHS = 0;
    EpwmRegs.TBCTR = 0;
    EpwmRegs.TBCTL.bit.CTRMODE = TB_COUNT_UPDORN;
    EpwmRegs.TBTCR = 1;
    EpwmRegs.TBTCR.bit.PHSEN = 0;
    EpwmRegs.TBTCR.bit.HSPCLKDIV = Hfp;
    EpwmRegs.TBTCR.bit.CLKDY = Cfp;
    EpwmRegs.CMPCTL.bit.SHDA MODE = CC_IMMEDIATE;
    EpwmRegs.CMPCTL.bit.SHDBMODE = CC_IMMEDIATE;
    EpwmRegs.ACTLA.bit.CAU = AQ.CLEAR;
    EpwmRegs.AQCTLA.bit.CAU = AQ.SET;
    EpwmRegs.DBCCTL.bit.OUT_MODE = DB.FULL_ENABLE;
    EpwmRegs.DBCCTL.bit.POLSEL = DB.ACTFY_HIC;
    EpwmRegs.DBCCTL.bit.IV_MODE = 0;
    EpwmRegs.DBRED = Epwm.MIN_DB;
    EpwmRegs.BBBED = Epwm.MIN_DB;
    EpwmRegs.ESET.bit.INTSEL = ET.CTR.ZERO;
    EpwmRegs.EFET.bit.INTSEL = ET.IPRD;
    EpwmRegs.EIFPS.bit.INTPRD = ET.1ST;
}
```

Fig. 2 Part of the code of the SPWM

The frequency of SPWM is determined by the time base module TB, which is determined by setting the time base period register value (TBPRD) and the counting mode of the time base counter (TBCTRL). Configure the register CMPA and register CMPB in the counting comparison module CC to control the duty cycle of PWM. The action module plays a key role in the formation of the PWM waveform. It determines what level should be output when the corresponding event occurs. Write the SWPM waveform running code in CCS6.0. The picture shows the initialization and generation of SPWM1 waveform, and the same applies to SPWM2~SPWM4.

3. HIL modeling and configuration of single-phase full-bridge inverter circuit

3.1. Single-phase full-bridge inverter circuit model

In view of the introduction of the above-mentioned inverter circuit principle and SPWM control, the circuit topology modeling is carried out based on the StarSim real-time simulation platform StarSim HIL. StarSim HIL is a host computer program of a real-time simulation system launched by ModelingTech. It can import Matlab/Simulink simulation files and can be used to build hardware-in-the-loop based on FPGA or DSP with software such as StarSim FPGA Solver which is a configurable software [6]. You only need to download the model, map the input and output of the model to the actual hardware IO, and then perform real-time simulation.

Use the relevant modules in Matlab/Simulink to build a single-phase full-bridge inverter circuit, as shown in the fig.3.
3.2. HIL model interface configuration

In order to realize the HIL hardware-in-the-loop test of the inverter power supply controller and the inverter power supply circuit model, it is necessary to configure the interfaces of the models respectively[7]. The inverter power supply circuit model simulates the controlled object of the circuit, so it should be equipped with corresponding output voltage signal and current signal. These two signals are analog circuit signals and should be connected to the analog signal end of the signal transfer board, and DSP28335 sends out a digital signal, which needs to be connected to the digital signal section of the signal transfer board.

4. HIL hardware-in-the-loop test of inverter power supply controller based on StarSim

4.1. Hardware-in-the-loop platform based on StarSim

As shown in Fig.4, based on the StarSim real-time simulation simulator of Shanghai ModelingTech company, the DSP28335 of TI Company is used as the controller to establish a hardware-in-the-loop test platform. The inverter power supply circuit model established in Matlab/Simulink is downloaded to the PXie-7846R board of StarSim through the StarSim HIL host computer software to run, and the controlled object is simulated, and the SPWM control strategy in DSP28335 is tested by hardware in the loop.
The Framework diagram of hardware-in-the-loop test platform is shown in the fig.5. The PXIe-7846R board is the core board component of the StarSim real-time simulation system. The single-phase full-bridge inverter circuit model runs in the system.

4.2. Inverter power HIL model hardware-in-the-loop results
It can be seen from Fig.6 and Fig.7 that the output current is close to a sine wave as a whole, and the output voltage is a rectangular wave. The DC-AC full-bridge inverter circuit controlled by SPWM has been implemented in the hardware on the StarSim platform.

5. Conclusion
Based on the results and discussions presented above, the conclusions are obtained as below:
In this paper, for the HIL test of the inverter power supply controller, an open-loop test of the SPWM control strategy of the single-phase full-bridge inverter circuit is carried out. The results show that the inverter power supply HIL model established in this paper can realize real-time simulation based on the StarSim simulation platform. It is used to test the inverter power system in the loop test platform.
(1) The hardware-in-the-loop test platform is established by the PXIe-7846 board in StarSim and DSP28335.

(2) It is shown that the output current is close to sine wave as a whole, and the output voltage is rectangular wave.

(3) It is concluded that the HIL model of the inverter power supply established in this paper can realize real-time simulation based on the StarSim simulation platform, which is used to test the inverter power system in the loop test platform. Based on the results of the model established in this paper, the control strategy development and testing of other inverter power sources can be carried out in the future.

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