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A high performance simulation methodology for multilevel grid-connected inverters

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Abstract: To design a high reliability multilevel grid-connected inverter, a high performance simulation methodology based on Saber is proposed. The simulation methodology with optimized simulation speed can simulate the factors that have significant impacts on the stability and performance of the control system, such as digital delay, dead band, and the quantization error. The control algorithm in the simulation methodology is implemented using the C language, which facilitates the future porting to an actual system since most actual digital controllers are programmed in the C language. The modeling of the control system is focused mainly on diode-clamped three-level grid-connected inverters, and simulations for other topologies can be easily built based on this simulation. An example of designing a proportional-resonant (PR) controller with the aid of the simulation is introduced. The integer scaling effect in fixed-point digital signal processors (DSPs) on the control system is demonstrated and the performance of the controller is validated through experiments.

Key words: Multilevel grid-connected inverter, Simulation methodology, Proportional-resonant (PR) controller
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1 Introduction

With the rapid development of new energy sources like wind and solar energy, grid-connected inverters have been widely used. However, due to the limitation on power electronic devices, it is difficult to achieve high power ratings on traditional two-level grid-connected inverters. An effective way to achieve high power ratings is using multilevel inverters with substantial benefits, including high output voltage, reduced harmonics, and low switching device voltage stress (Alepuz *et al*., 2006; Selvaraj and Rahim, 2009). In comparison with two-level inverters, the control algorithm of multilevel inverters is very sophisticated and many new control algorithms have been proposed recently (Rabinovici *et al*., 2010; Tehrani *et al*., 2010; Haghdar *et al*., 2011). Without a full understanding of the control algorithm, the experiment will take both money and time even with safety issues. Therefore, an effective simulation methodology is needed for multilevel inverters. Among the topologies of multilevel inverters, diode-clamped three-level inverters have been widely used (Rodriguez *et al*., 2010), so we take the diode-clamped three-level inverter as an example to show the design and implementation of high performance simulation. Simulations of other topologies can be implemented based on this simulation. In this paper, the simulation methodology focuses on electrical properties.

Currently, there are two kinds of methods in power electronic circuit simulation: one is software simulation and the other is software and hardware co-simulation (Jiang *et al*., 2005; Castoldi *et al*., 2006). Software and hardware co-simulation is not widely used due to the high cost on hardware and difficulty in code porting. Software simulation waveforms have been demonstrated in many articles on multilevel grid-connected inverters (Lu *et al*., 2005; Bao and Bao, 2010; Sepahvand *et al*., 2011). Although the simulation results can verify the

proposed theory, they still have the following shortcomings. First, the simulation results are not accurate enough. The simulation is based on the assumption of an ideal environment, and does not consider such factors that have great impacts on control performance, including dead-band effect, quantization error, and digital delay. Simulation parameters are difficult to use directly in the experiment. Second, the control algorithms take much effort to be ported to an actual system. Most experimental control chips are programmed in the C language, while most simulations are built with library modules. When we port simulation algorithms to experimental control chips, extensive modification is needed and some of the algorithms may not be implemented. Third, the simulation speed is not optimized, and thus the simulation process may take much time as the topology and control systems of multilevel grid-connected inverters are very complex.

To overcome these shortcomings, a high performance simulation methodology based on Saber is proposed in this paper. The operational state of an actual system is simulated and the simulation results are more convincing. The variable types, logical processes, and algorithms are exactly the same as those in a digital signal processor (DSP). Note that the information and numerical accuracy provided by the simulation are closely related to research purposes. This paper focuses on the control algorithm of multilevel grid-connected inverters and the target is to make minimal modifications when porting the algorithm to an actual system.

Numerical simulation technology and the reliability of software simulation have been analyzed by Nichols *et al*. (1993). Saber is professional power electronic circuit simulation software produced by the Synopsys Company. It not only has the basic functions for circuit simulation but also has a user-friendly modeling language (Chwirka, 2000).

2 Simulation design

The system structure of a three-phase three-level grid-connected inverter is shown in Fig. 1. The input of the system is connected to DC voltage and the output of the system is connected to the grid. The nonlinear devices in the main circuit are 12 insulated gate bipolar transistors (IGBTs) and 6 clamping diodes. The linear devices in the main circuit are an inductor-capacitor-inductor (LCL) filter and DC link capacitors. The control system first samples inverter-side inductor currents, grid voltage, and DC capacitor voltages, and then generates 12 pulse-width modulated (PWM) output signals through a complex arithmetic operation. In this paper, the method for controlling the three-level grid-connected inverter is space vector pulse width modulation (SVPWM), which can increase DC voltage utilization and easily fulfill neutral-point potential balancing.

In stationary coordinate systems, the current control block diagram is shown in Fig. 2. Supposing that the system controller $G_c(s)$ is a PR controller, if

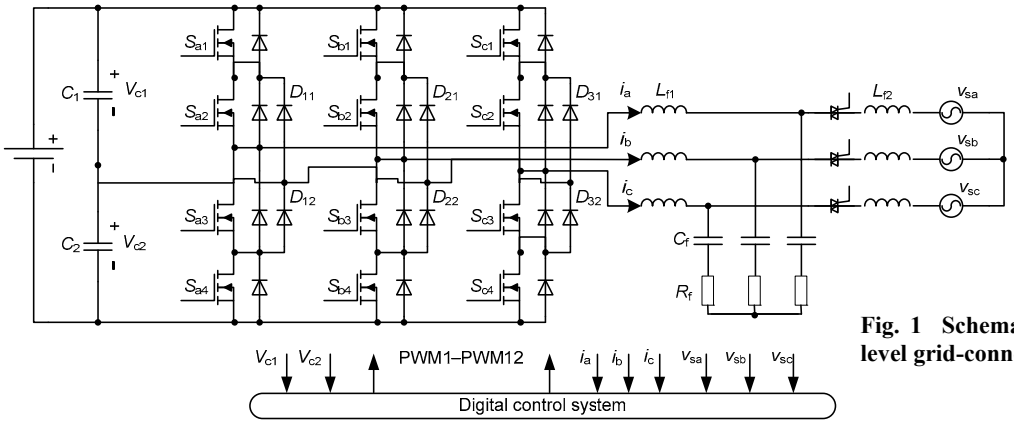

Fig. 1 Schematic of a three-level grid-connected inverter

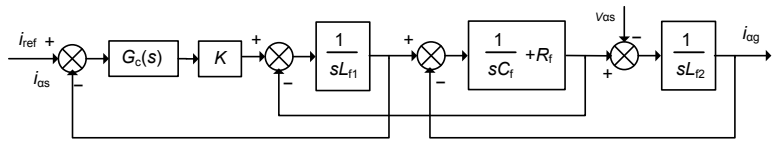

Fig. 2 Block diagram of current control in a stationary frame

we apply the control parameters calculated according to Fig. 2 to an actual system, the proposed controller is likely to fail since the system model is so inaccurate that it can be used only for theoretical analysis. For example, delay from sampling to PWM output is not considered, dead-band effect is not included, and effect of the quantization error on control performance is not taken into account. In fact, the delay from data sampling to DSP output may have a maximum of one switching cycle, and a stable system may become unstable due to this delay (Nussbaumer *et al*., 2005). In addition, feedback control cannot suppress the noise in the feedback circuit, so the feedback circuit usually contains a low-pass filter, which will limit the bandwidth of the control system. Most importantly, although the digital control method commonly used in three-level inverters improves control flexibility, it brings quantization errors, which makes it difficult to establish an accurate mathematical model. In simulation, if the data type and its memory size are the same as in an actual system, the effect of the quantization error can be simulated accurately. In short, for such a complex system as a three-level inverter, it is difficult to design control programs exactly the same as in actual systems by only theoretical analysis; however, the high performance simulation methodology proposed in this paper could solve all the above problems.

2.1 Design principles

The following principles are used in designing the simulation:

1. Considering as many factors affecting control performance as possible, the first priority in system simulation is providing accurate and necessary information to designers. For hardware designers, it is necessary to implement circuit level simulation accurately. For software designers, various control algorithms should be easily implemented and all factors having significant impacts on control performance should be considered.

2. Control algorithms can be easily ported to an actual system. Currently, the DSP in three-level grid-connected inverters is programmed mainly in the C or C++ language. Thus, it would be very simple to port if the control algorithm in simulations is implemented using the same language as in DSP.

3. Simulation speed should be optimized to improve efficiency, and various parameters and control algorithms can be tested.

2.2 Modeling main circuit devices

In the main circuit, there are IGBTs, clamping diodes, DC link capacitors, and an LCL filter. The DC link capacitors and the LCL filter are linear devices while the IGBTs and the clamping diodes are nonlinear devices. It is easy to design simulation parameters of a linear device, which can just be the same as in an actual system. However, when designing simulation parameters of a nonlinear device, the actual parameters, simulation speed, and simulation convergence should be taken into account. Simulation software finds the values of the analog circuit network through an iterative method, so if it always takes a long time for the results to converge or if the analog circuit network is very complex, the simulation speed will be very slow. IGBT is a sophisticated semiconductor device whose accurate modeling is not only complex but also unnecessary. In terms of dead-band effects, the rising time and falling time play an important role, and in terms of turning on and turning off of each IGBT, the forward voltage and on resistance have a significant impact. Therefore, we choose an ideal power switch and two power diodes supplied by the Saber library to simulate an IGBT. The ideal power switch can be seen as a variable resistor which can be used to set rising time and falling time. Using the devices supplied by the Saber library has the advantage of reducing the possibility of non-convergence because the library components have been tested and optimized by Saber. Parameters and interconnections of the ideal power switch and power diodes are shown in Fig. 3.

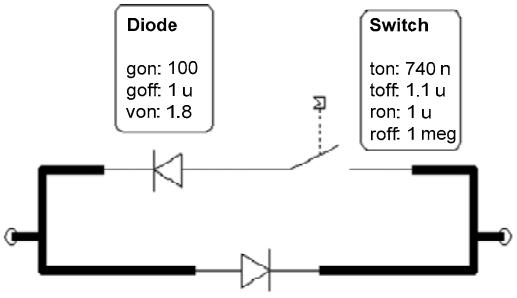

Fig. 3 Model diagram of an insulated gate bipolar transistor (IGBT)

2.3 Modeling the control system

In an actual DSP control system for a three-level grid-connected inverter, the core algorithm is implemented in interrupt routine to meet the requirements of real-time control. As shown in Fig. 4, the first step of data processing is signal sampling (the sampling data may require filtering due to the noise in the sampling circuit), then running the core algorithm, and finally setting output registers according to the results.

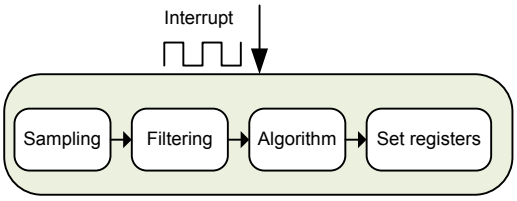

Fig. 4 Data processing diagram in an actual DSP control system

To simulate an actual DSP control system and facilitate program debugging, a digital control module (Fig. 5) is built in the Saber environment. The module has 25 pins, including 8 input pins for sampling signals, 12 output pins for PWM signals, 4 output pins for watching internal variables, and 1 input pin for interrupt signal. The interrupt signal of the model is a square wave whose frequency is half of the switching frequency. When the interrupt signal changes, the internal event_on() function will be triggered and the data processing as shown in Fig. 4 will be carried out. Since the algorithm will not be calculated until the interrupt signal changes, the calculation time is reduced. The MAST modeling language used in Saber is similar to the C language and can implement many control algorithms. However, it is not as flexible as the C language. For example, in the Saber MAST language, integer variable and shift operation which are widely used in fixed-point DSP are not supported.

In our simulation methodology, the MAST module handles only input and output signals, and the core algorithm is implemented in a foreign C subroutine which can be called by the MAST module. As shown in Fig. 6, the control system consists of four parts. During the simulation process, when the interrupt signal is triggered, the MAST module immediately reads the input signals and passes the signals to a foreign C subroutine. The foreign C subroutine first records the current simulation time and the signals passed by the MAST module, then runs the core algorithm, and finally returns calculation results to the MAST module. After receiving the results, the MAST module updates output pins after a delay of one switching period. To facilitate the study on advanced control methods, the simulation methodology also provides an offline debugging function. During offline debugging, the debugging routine running in the VC++ environment first reads the log file, and then passes the parameters to a foreign C subroutine in the same way as in the Saber simulator. Then we can use many debugging methods in the VC++ environment, such as run free, step debugging, and run to breakpoints.

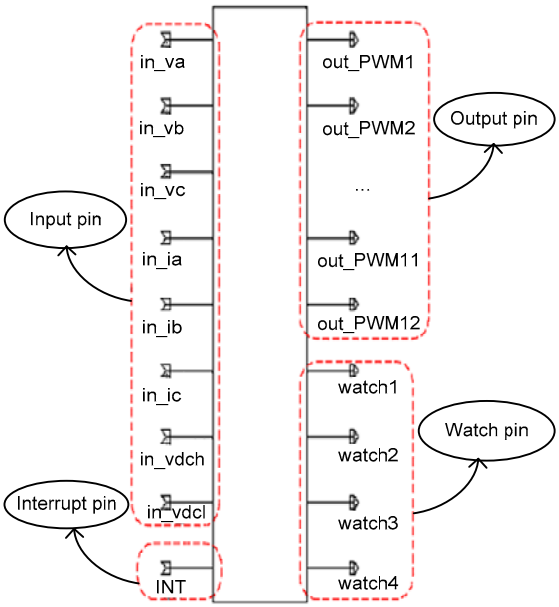

Fig. 5 Pin diagram of the controller

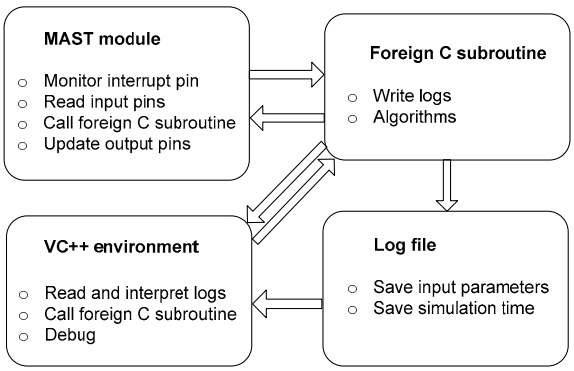

Fig. 6 Structure of the control system

2.4 PWM signal generation

Traditionally, PWM signal is generated by comparing a modulating signal produced by a control algorithm with a triangular carrier signal. To improve accuracy, the simulator will reduce simulation step time near the intersection of modulating signal and carrier signal. In fact, when the modulating signal is finalized, the duty cycle is determined and the intersection can be calculated. In the Saber simulation environment, the schedule_event function can be called directly to change the output signals in the corresponding time, which will increase the simulation speed. The dead-band is generated by the rising edge delay, and IGBT driver circuit delay is generated by the rising edge delay and falling edge delay. All delays are implemented by the schedule_event function according to the actual value.

3 Example: PR controller

The widely used method for controlling the inverter is transforming inductor currents to a synchronous frame in which the control variables are DC signals. As a consequence, zero steady-state error control can be achieved with a simple proportional-integral (PI) controller. However, the DC currents in the synchronous frame are cross-coupling and exact decoupling is difficult to realize. In the stationary frame, there is no coupling between $\alpha\beta$ axes, but the $\alpha\beta$ currents are sine waves and the steady-state error cannot be eliminated by a PI controller. Another type of controller, the PR controller, has gained large popularity in recent years due to its capability of eliminating the steady-state error in a stationary frame. Since a PR controller performs an extremely narrow band around its resonant frequency, the widely used form is the quasi-PR controller (Teodorescu *et al*., 2006). The transfer function of the quasi-PR controller is

$$G_{\mathrm{PR}}(s)=K_{\mathrm{P}}+\frac{2K_{\mathrm{R}}\omega_{\mathrm{c}}s}{s^2+2\omega_{\mathrm{c}}s+\omega_0^2}, \tag{1}$$

where K_{P}, K_{R}, and ω_{c} are control parameters, and ω_0 is the nominal angular frequency of the grid. The discretization form of Eq. (1) is given by

$$G(z)=\frac{b_0+b_1z^{-1}+b_2z^{-2}}{a_0+a_1z^{-1}+a_2z^{-2}}, \tag{2}$$

where the coefficients can be calculated as

$$\begin{aligned}
a_0&=1,\\
a_1&=\frac{2\omega_0{}^2T^2-8}{4+4\omega_{\mathrm{c}}T+\omega_0{}^2T^2},\\
a_2&=\frac{4-4\omega_{\mathrm{c}}T+\omega_0{}^2T^2}{4+4\omega_{\mathrm{c}}T+\omega_0{}^2T^2},\\
b_0&=\frac{4K_{\mathrm{P}}+\omega_0{}^2T^2K_{\mathrm{P}}+4K_{\mathrm{R}}\omega_{\mathrm{c}}T+4K_{\mathrm{P}}\omega_{\mathrm{c}}T}{4+4\omega_{\mathrm{c}}T+\omega_0{}^2T^2},\\
b_1&=\frac{2\omega_0{}^2T^2K_{\mathrm{P}}-8K_{\mathrm{P}}}{4+4\omega_{\mathrm{c}}T+\omega_0{}^2T^2},\\
b_2&=\frac{4K_{\mathrm{P}}+\omega_0{}^2T^2K_{\mathrm{P}}-4K_{\mathrm{R}}\omega_{\mathrm{c}}T-4K_{\mathrm{P}}\omega_{\mathrm{c}}T}{4+4\omega_{\mathrm{c}}T+\omega_0{}^2T^2}.
\end{aligned}$$

First, a_0, a_1, a_2, b_0, b_1, b_2 are expressed by floating type numbers. A group of control parameters that has a better control performance than others is obtained by varying-parameter sweep simulation in Saber, that is ω_{c}=5, K_{R}=150, K_{P}=1.2. Then, the $G(z)$ coefficients, which are floating type numbers, are transformed to integers in fixed-point DSP. An integer type number is yielded by left shifting n bits of a floating type number. However, when expressing floating type numbers with integers, we will encounter a lot of quantization errors during scaling and calculating. As the effects of quantization errors on control performance are difficult to model, it is difficult to choose a proper left shift number n with theoretical analysis. In our simulation methodology, we use a short integer to define a 16-bit integer variable, and a long integer to define a 32-bit integer variable. Since data type and its memory size are the same as in the actual system, the quantization error is exactly simulated. Grid currents of phase A are shown in Fig. 7 when the left shift number equals 8, 9, 10 or 11. When n<10, the phase and amplitude of output currents are out of control; when n=10, the output sine wave current is satisfactory; and when n>10, the output waveform has no significant changes in comparison with n=10.

The simulation runs on a Samsung computer of type R458, which has a 2 GHz dual core CPU and 2 GB RAM. The operating system is Windows XP

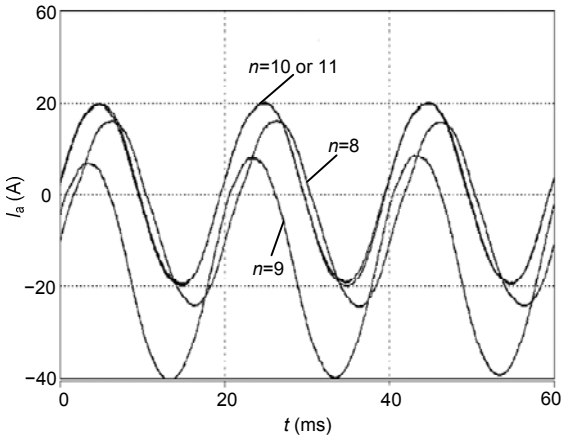

Fig. 7 Simulation waveforms of phase A current

professional SP2. We set simulation step time to 100 ns and simulation end time to 0.5 s. In our study, the three main technologies to reduce simulation time are using a simplified IGBT module, using interrupt mode to run the control algorithm, and generating PWM signals according to mathematical calculation. The simulation time is shown in Table 1. We can see that the simulation speed is significantly improved by using a simplified IGBT module and using interrupt mode to run the control algorithm, and generating PWM signals according to mathematical calculation is also helpful for improving simulation speed.

Table 1 Simulation time for four simulation methods

Method	Simulation time (s)
M1	197
M2	2938
M3	2374
M4	276

M1: the simulation method proposed in this paper; M2: the simulation method which is not using a simplified IGBT module; M3: the simulation method whose control system is not using interrupt mode; M4: the simulation method whose PWM signals are generated by comparing a modulating signal with a triangular carrier signal

The quasi-PR controller designed in the simulation is verified by an actual system (Fig. 8). The actual system is a three-level grid-connected inverter for a wind turbine. In the actual system, the IGBT driving signals are transmitted through optical fibers, the sampling signals are isolated by hall devices, and the control chip is TMS320F2812 produced by Texas Instruments Incorporation. TMS320F2812 is a fixed-point DSP which has a 32-bit accumulator. The parameters of the actual system are listed in Table 2.

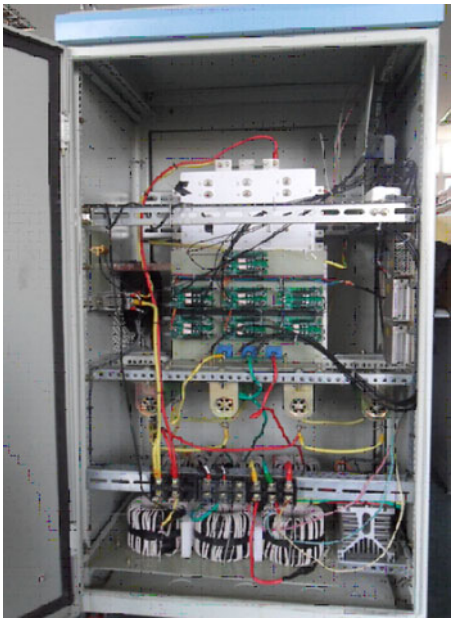

Fig. 8 Photograph of the three-level grid-connected inverter

Table 2 Values of experimental parameters

Parameter	Value
Nominal power (kW)	50
DC link voltage (V)	680
Switching frequency (kHz)	10
Sampling frequency (kHz)	10
Grid voltage (V)	380

The quasi-PR controller running in the actual system is ported from the simulation without modifications. Grid voltage waveform and grid current waveform of phase A are shown in Fig. 9 when n=10. When n>10, the waveforms have no significant changes in comparison with Fig. 9. For safety concerns, experiments are not conducted for n<10. It can be seen that the simulation results are consistent with the experimental results and the controller designed for simulation can be used in experiments without any further modification. The dynamic performance of the controller is also tested. The amplitude of the grid current reference steps from 15 to 20 A and the waveforms of the actual grid current are captured (Fig. 10). As the rotational inertia of a wind turbine is very large in most systems, this dynamic response is quick enough.

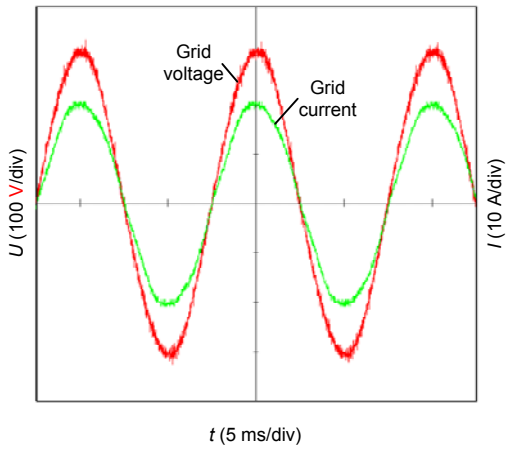

Fig. 9 Steady state of phase A current and voltage

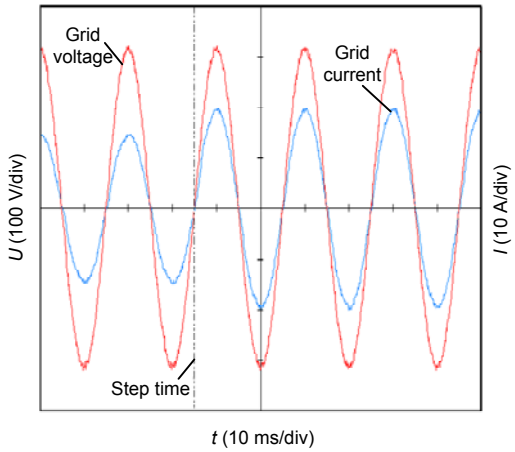

Fig. 10 Dynamic performance of phase A grid current

4 Conclusions

Considering the complex control method, high power ratings, and other issues in a multilevel grid-connected inverter, we propose a high performance simulation methodology based on Saber. The simulation methodology whose control system is modeled using the C language can simulate the factors that have great impact on control performance, such as dead band, digital delay, and the quantization error. The simulation results are more convincing and can be easily ported to an actual system. We use the diode-clamped three-level grid-connected inverter as an example to show the modeling of main circuit devices and the control system. The other multilevel grid- connected inverters can be designed based on this simulation. Experimental results show that the controller designed for simulation can be used in an actual system without modifications. The simulation methodology also provides an off-line debugging function, which will be helpful for exploring advanced control algorithms. The simulation methodology proposed in this paper can be seen as a simple and effective tool for controlling multi-level grid-connected inverters. With this simulation methodology, researchers will find it more convenient to study multi-level grid-connected inverters.

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