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Hardware-in-the-loop Simulation Platform of Photovoltaic Grid-Connected System

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Abstract

The modeling and simulation of photovoltaic power generation system has become an important issue in the field of power generation. Research on the characteristics of photovoltaic (PV) grid-connected system by hardware-in-the-loop simulation could provide convenient experiment condition and accurate result. This article designs a photovoltaic grid-connected simulation platform for digital/physical hybrid real-time simulation, in which RTDS uses a digital-to-analog interface to communicate with external DSP devices. Maximum power point tracking (MPPT) and grid-connected control of a 520kWp PV system are performed on the platform. And the feasibility and effectiveness of hybrid PV system are validated by the analysis of hardware-in-the-loop result in RTDS.

Keywords: *solar energy, PV grid-connected system, hardware-in-the-loop simulation, RTDS*

1. Introduction

In a number of renewable energy, solar energy has been unanimously favored because of its unique advantages. Photovoltaic power generation has become a developing renewable energy development strategy in China [1]. However, its power generation characteristics are different from the conventional ones in large output power fluctuations. Thus the modeling and simulation of photovoltaic power generation system has become an important issue in the field of power generation [2-4].

Electromechanical transient or electromagnetic transient digital simulation can only conduct the simulation analysis for a specific scope and phenomenon. Faced with the rapid development of modern power system, it’s often difficult to describe and analyze a number of new phenomena and problems; Additional physical experiments can accurately simulate the actual situation, but there are some inadequate factors such as huge investment in the construction, difficulty in parameter changing and size limitation of simulation. To a certain extent, digital and physical hybrid simulation technology can make up for the lack of these two methods, which broadens the scope of the digital simulation technology of power system, and becomes one of the hot and cutting-edge issues in the field [5].

Currently, digital and physical mixed real-time simulation technology is mainly concentrated on the high-voltage transmission, characteristics of power electronic device, and renewable energy generation issues. On the aspect of AC and DC high-voltage transmission, Literature [6] based on the power connection technology has built an analog-digital mixed simulation platform, which is suitable for AC and DC large grid simulation. It has achieved a digital and physical hybrid simulation between HVDC equipment and digital large grid; Literature [7] uses Hypersim, an all-digital real-time simulation software, to implement the interconnection of all-digital simulation program with DC physical simulation device and control protection device via the signal interface and power interface, which is based on SGI supercomputer to achieve large-scale AC and DC power grid real-time hybrid simulation. On the aspects of power electronic device characteristics, Literature [8] carries out a detailed analysis of the characteristics of the feedback current filter in power electronic systems through hardware-in-the-loop simulation. Considering renewable energy generation, Literature [9] designs a doubly-fed wind turbine simulation system based on RTDS and presents the development details of digital/physical simulation system and the converter control system. Literature [10] and [11]

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build a simulation model of photovoltaic simulator, and carry out modeling and experimenting of hardware-in-the-loop model and speed control model using RT-LAB real-time simulation platform; Literature [12] builds hybrid experimental platform for the feature test of PV panels, and calibrates the results with combination of RT-LAB and MATLAB/Simulink; Literature [13] studies the low voltage ride through of PV system based on RTDS platform, but does not apply the hardware-in-the-loop hybrid simulation methods.

This article designs a photovoltaic grid-connected simulation platform for digital/physical hybrid real-time simulation, in which RTDS uses a digital-to-analog interface to communicate with external DSP devices. Maximum power point tracking and grid-connected control of a 520kWp PV system are performed on the platform. And the feasibility and effectiveness of hybrid PV system are validated by the analysis of hardware-in-the-loop result in RTDS.

2. PV Grid-Connected System Modeling

The structure of grid-connected PV system is shown in Figure 1. The PV array converts light energy into electrical energy and the photovoltaic inverter converts DC into AC for line connection. The technical difficulty of the entire system lies in the high demand of output power quality. The frequency, harmonics, stability parameters all need to meet the standards of grid-connected distributed power generation [14].

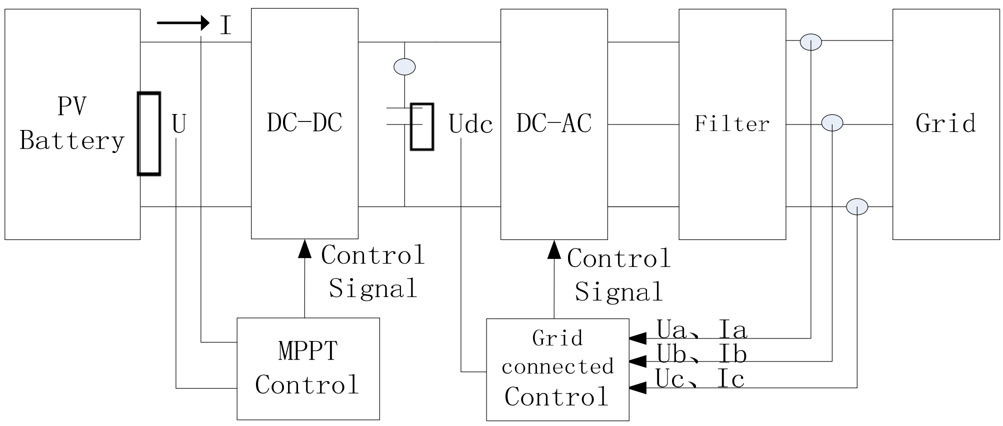

Figure 1. PV Grid-connected Power Generation System

2.1. PV Cell Modeling

The equivalent circuit of photovoltaic cell is shown in Figure 2, which consists of controllable current source, diode, parallel resistor and series resistor [15].

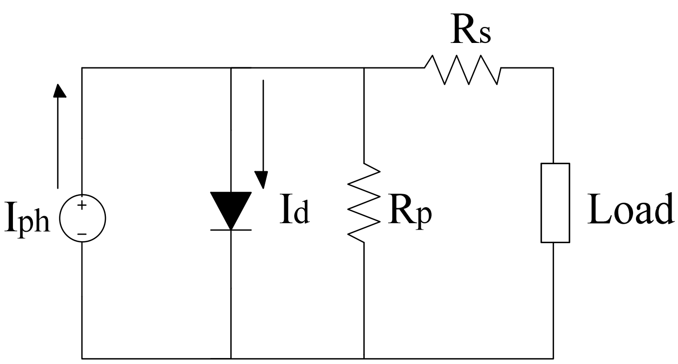

Figure 2. Equivalent Circuit of PV Battery

The output current of the photovoltaic cell can be described as a function of the output voltage:

$$I = I_{ph} - I_d\{\exp[\frac{q(V + R_s I)}{AkT}] - 1\} - \frac{V + R_s I}{R_p} \quad (1)$$

Where, V and I are the solar battery output voltage and current, I_{ph} is the short circuit current determined by light intensity, I_d is the current flowing through the diode, R_s and R_p are actual series and shunt impedance, q is the electron charge, k is Boltzmann constant, T is temperature, A is the diode ideality factor.

In practical applications, PV array is composed of series and parallel PV modules, while PV module is composed of series and parallel PV cells. The output characteristics of a PV array, which consists of N_{sM}*N_{pM} (where N_{sM}, N_{pM}, are respectively PV modules number in series and parallel) PV modules are:

$$I = N_{pM} I_{scM} - \frac{N_{pM} I_{scM}}{\exp\left(\frac{qV_{ocM}}{N_s kT}\right)[\exp\left(\frac{q\left(V_A + R_{sA} I_A\right)}{AkTN_s N_{sM}}\right) - 1]} \quad (2)$$

Where, I_{scM} and V_{ocM} are respectively open-circuit voltage and short-circuit current of PV array, R_{SA} is the equivalent impedance of the PV array.

2.2. DC-DC Modeling

In order to improve the efficiency of PV system, PV cells often require for maximum power point tracking control. DC-DC converter adjusts and controls the PV cells to work at the maximum power point by changing the duty cycle of the power switch. The essence of MPPT is a dynamic self-optimization process, which calculates the present output power via detection of the PV array output voltage and current. Then compares the output power with previous one and keeps PV arrays dynamically operating at maximum power point [16, 17].

The method of MPPT used in this hybrid simulation system is incremental conductance method. The calculation process is shown in Figure 3.

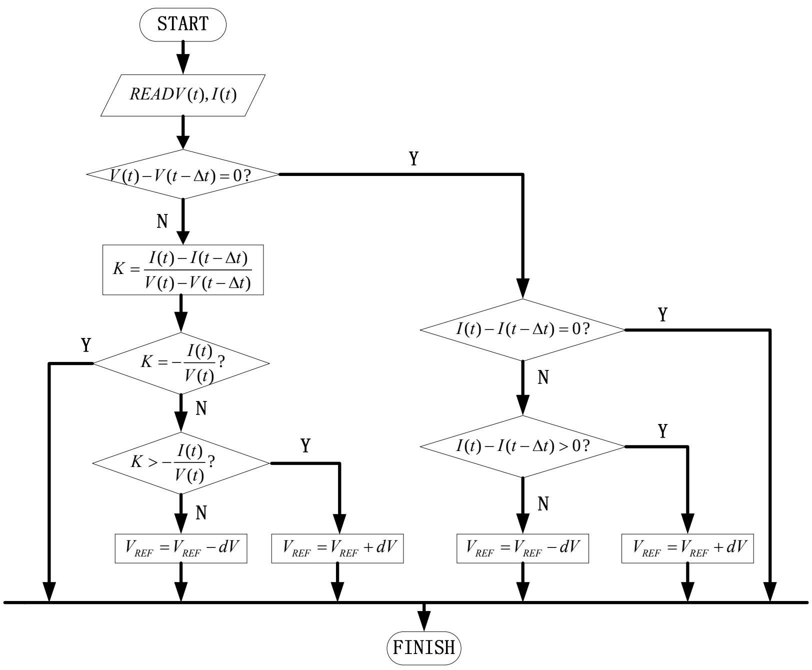

Figure 3. Flow Chart of the Incremental Conductance Algorithm

2.3. DC-AC Modeling

Literature [18] proposes a method of connecting photovoltaic system with the grid using PQ control method. After the inverter is connected to the grid, the output voltage of inverter is equal to the grid voltage, thus decoupling control of the active and reactive power can be achieved by the inverter output current.

The circuit structure of the three phase inverter is shown in Figure 4.

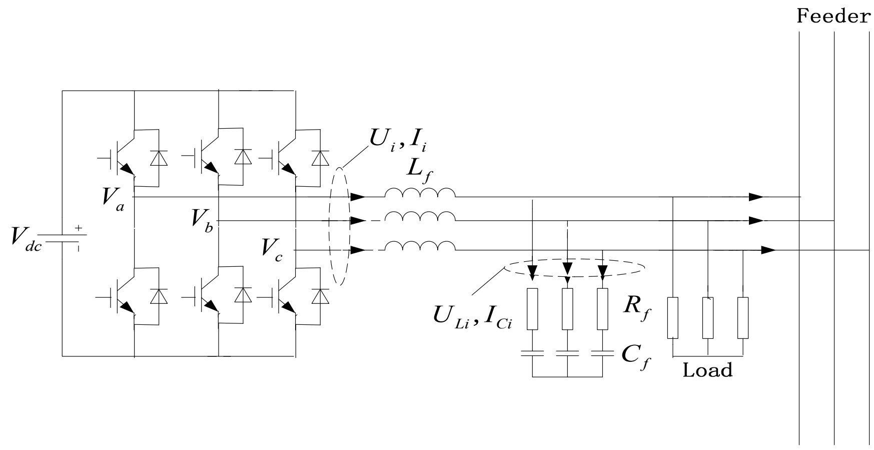

Figure 4. Circuit Structure of Three-phase Inverter

Current state equations can be listed as follows while the inductor currents are taken as state variables:

$$L_f \frac{di_i}{dt} = u_i - u_{Li} \tag{3}$$

Convert the Equation (3) with park transformation, and we can get the current state equations in *dq* rotating coordinate system:

$$\begin{cases} L_f \dfrac{dI_d}{dt} = U_d - U_{Ld} + \omega L_f I_q \\ L_f \dfrac{dI_q}{dt} = U_q - U_{Lq} - \omega L_f I_d \end{cases} \tag{4}$$

Meanwhile, in the *dq* rotating coordinate system, active and reactive power are respectively as follows:

$$\begin{cases} P = \dfrac{3}{2} U_d I_d + \dfrac{3}{2} U_q I_q \\ Q = -\dfrac{3}{2} U_d I_q + \dfrac{3}{2} U_q I_d \end{cases} \tag{5}$$

As in the synchronous rotating coordinate system U_q = 0, the formula of power calculation simplifies to:

$$\begin{cases} P = \dfrac{3}{2} U_d I_d \\ Q = -\dfrac{3}{2} U_d I_q \end{cases} \tag{6}$$

If the grid voltage U_d is kept constant, the active power of grid side inverter is proportional to the *d*-axis current, and the reactive power is proportional to the *q*-axis current, which means, active and reactive power can be separately controlled by adjusting the *d*- and *q*-axis current [19].

This paper uses double closed loop control strategy. The outer loop controls the DC bus voltage, and the inner loop controls integration current. The schematic diagram is shown in Figure 5.

3. Overall Design of Digital/Physical Hybrid Simulation for Photovoltaic Grid-Connected System based on RTDS

The architecture of digital and physical hybrid simulation system established on RTDS platform is shown in Figure 6. The parameters of PV grid-connected system are set based on the actual PV inverter system.

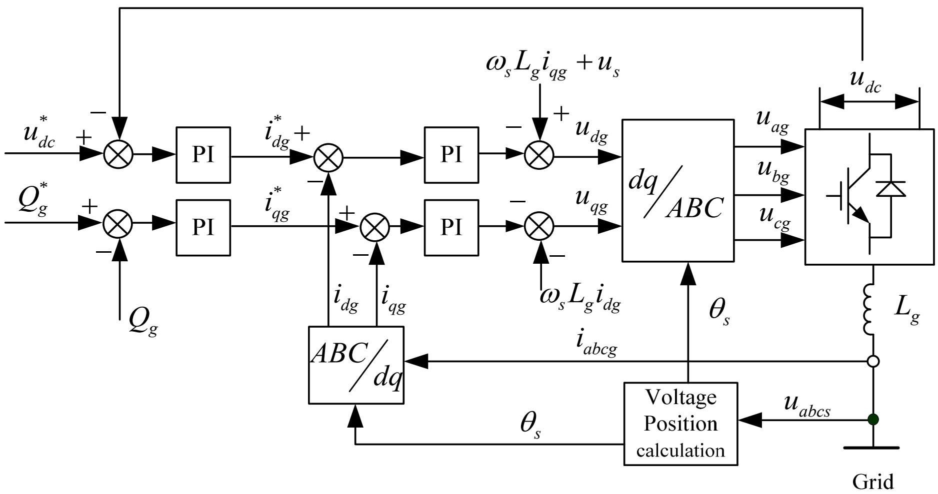

Figure 5. Schematic Diagram of a Three-phase Inverter

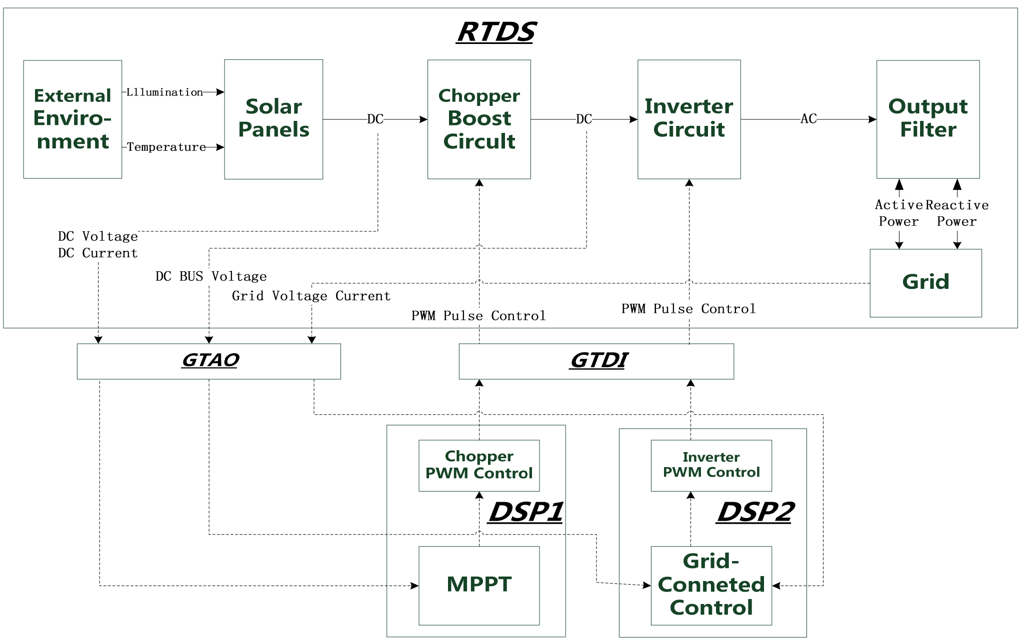

Figure 6. Framework of Hardware-in-loop Simulation System

MPPT part adopts incremental conductance method, and grid-connected strategy adopts double closed loop direct current control method. System control strategies are realized by DSP control panel which is the physical system. The physical system requires two DSP chips: DSP1, part of the boost chopper, achieves MPPT algorithm, DSP2 achieves double closed loop control algorithm of grid-connection. The communication between RTDS and two DSPs, namely, the signal transmission between the digital and physical system, is then built. The current and voltage of PV array, the DC bus voltage, the grid-connected voltage and current, and the frequency and phase of grid in RTDS digital system are transmitted to DSP panels for the correlation calculation. Afterwards, DSP1, which charges the MPPT algorithm, sends the control signal to boost chopper circuit in the digital system to drive the power switch. DSP2, which is responsible for the grid-connected double closed loop algorithm, sends control signals to the inverter circuit to drive the power switches. Finally, RTDS and the two DSP panels are linked together and the digital/physical hybrid real-time simulation platform for photovoltaic system is constructed.

4. Resource Allocation of Photovoltaic Grid-connected Hybrid System

The hybrid simulation of the built PV grid-connected system needs RTDS and two DSP chips running together. PV system simulated on RTDS platform requires three GPC cards to accomplish real time simulation. The resource allocation is shown in Figure 7. GPC1 conducts network computing of the small step voltage source device. GPC2A conducts the calculation of the control section. GPC2B calculates the overall network power flow. GPC3 conducts the calculation of PV panels and power supply.

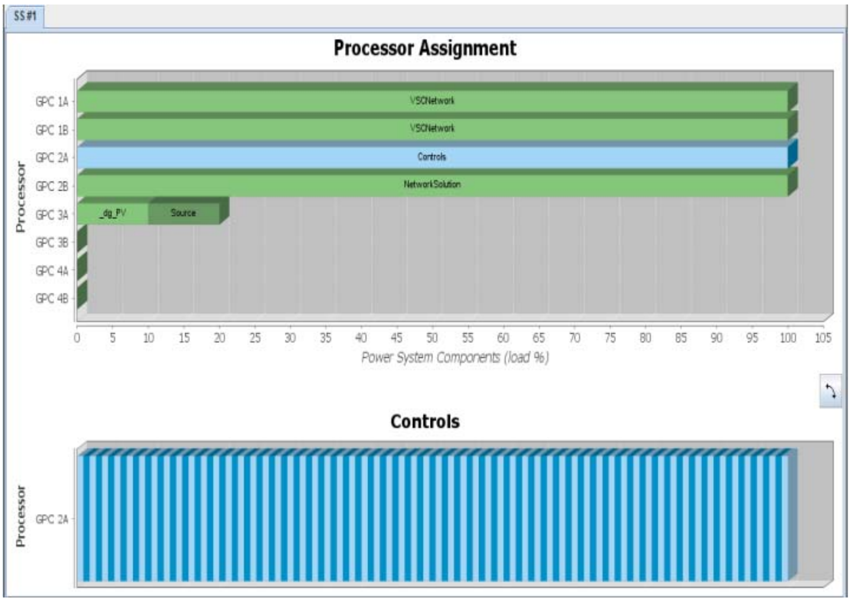

Figure 7. Processor Assignment Map of Hybrid PV System

In the hybrid simulation system, communication between RTDS digital system and the physical system, consisting of two DSPs, is a very important part, which uses digital input card (GTDI) and analog output card (GTAO) in RTDS real-time emulator.

GTDI card is digital input card in RTDS, which requires 24V power supply and provides 64 isolated digital input channels. It's able to recognize PWM signal with maximum switching frequency of 15 kHz. Two DSP boards in the hybrid system uses GTDI card to send back 7 channels of PWM signals, including a drive signal for IGBT in boost circuit and six drive signals for grid-connected inverter circuit.

GTAO card is analog output card in RTDS, which requires 24V power supply, provides 16-bit accuracy D/A converter and is capable of output 12 channels of +/-10V analog signals.

Output channels use an oversampling method with the period of 1μs to ensure the synchronization. The GTAO cards send analog output to the AD sampling port of the DSP card, and then the AD module converts the analog to digital for subsequent calculations of DSP. GTAO cards' analog output range is 0-10V, while the DSP control board's AD sampling range is 0-3V. So, the GTAO cards' output range needs to be adjusted, which should use AD sampling as much as possible without exceeding the scope. GTAO card's setting parts in RSCAD are shown in Figure 8. The signals processed by the GTAO card comprise the grid side and solar side, wherein the grid side needs output signals of three phase voltages, currents and DC bus voltage with a total number of seven channels in GTAO card. Solar panel side needs output of DC voltage and current with a total number of two channels occupancy in GTAO card. In total, the physical system requires nine GTAO channels and seven GTDI channels.

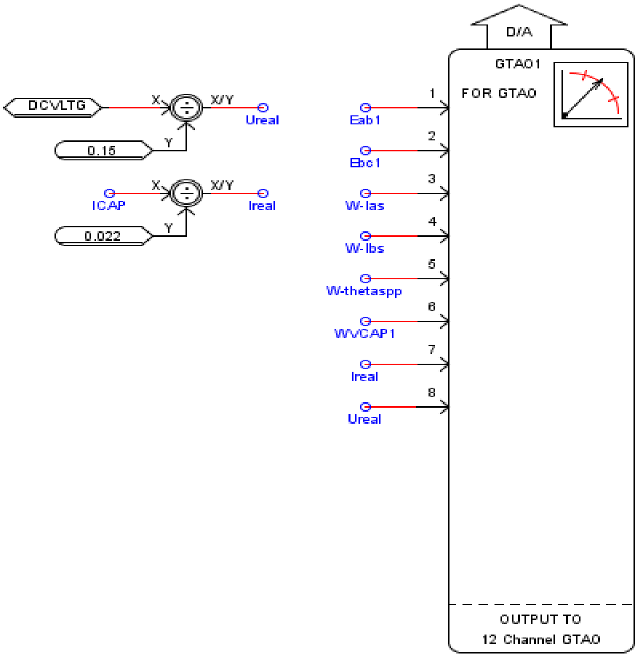

Figure 8. Setup of GTAO Card in RTDS

Provide a statement that what is expected, as stated in the "Introduction" chapter can ultimately result in "Results and Discussion" chapter, so there is compatibility. Moreover, it can also be added the prospect of the development of research results and application prospects of further studies into the next (based on result and discussion).

5. Simulation Results

Eventually, a digital/physical hardware-in-the-loop simulation platform for photovoltaic grid-connected system is built to verify the control strategy and real-time simulation. The capacity of model is 520kWp and the switching frequency is 2.5kHz. The specific parameters and the main results are shown in Table 1.

Tracking effect of MPPT can be seen from Figure 9. When simulation starts, the system works at the preset duty cycle situation, which outputs voltage of 240V. MPPT starts working around 3.38s, and after about 0.30s, the operating voltage of PV panel goes steady. At 3.68 s, the PV panel operating voltage stabilizes at maximum power point voltage of 750V. The fluctuation of output voltage is 5V, which is 0.67% of the MPP voltage.

Figure 10 and Figure 11 show the grid-connected voltage and current. PV systems eventually merge into 690V three-phase AC power grid. The current waveform in Figure 11 is close to sinusoidal waveform and the THD value is 2.07%.

Figure 12 shows the curve of the active and reactive power, and the ordinate units are 2MW and 2MVar. The average real power is stabilized at about 0.25 * 2MW = 0.5MW, while the average reactive power is stablized at about 0.045 * 2MVar = 0.09MVar. The whole system efficiency is 500kW/520kWp = 96.15%.

Table 1. Simulation Results of Hybrid PV System

PV Panels Section	
Solar Panel Capacity	520kWp
MPPT Voltage	750V
DC/DC Boost Section	
Switch Frequency	2.5kHz
Inductance parameter	10mH
MPPT Tracking Time	0.30s
MPPT Tracking Results	At the MPP the voltage fluctuation is around 5V, which is 0.67% of the MPPT voltage
DC/AC Converter Grid-Connected Section	
DC Bus Capacitor	22000uF
DC Bus Voltage	1200V
Switching Frequency	3kHz
Grid-Connected Control Strategy	Two-level PQ decoupled control with double loop, SVPWM Modulation
Grid Connected Parameter	Grid connection current is close to sinusoidal waveform. THD value is 2.0%.
Overall Efficiency	Grid transmission power is 500kW; PV panels capacity is 520kWp; PV system overall efficiency is 96.15%.

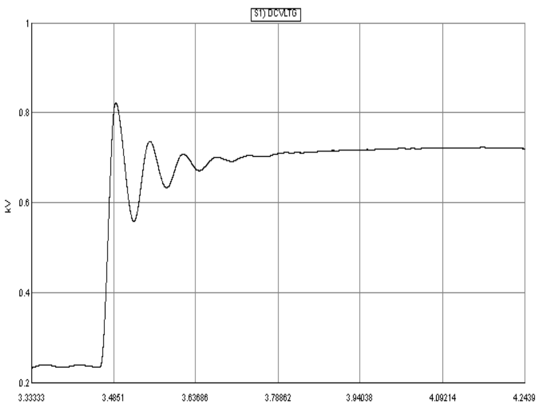

Figure 9. Voltage of PV Array when MPPT Starts

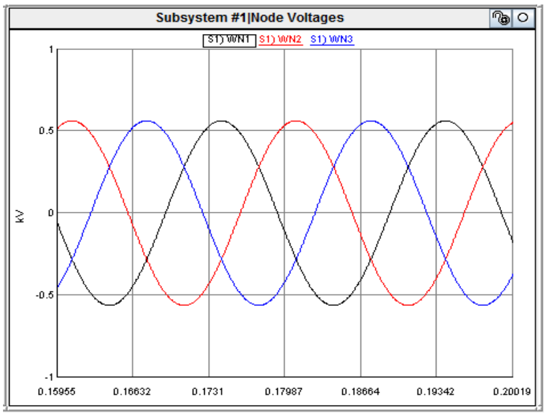

Figure 10. Grid-connect Voltage of Hybrid PV System

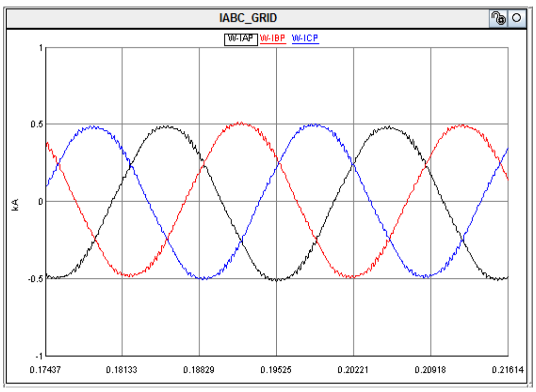

Figure 11. Grid-connect Current of Hybrid PV System

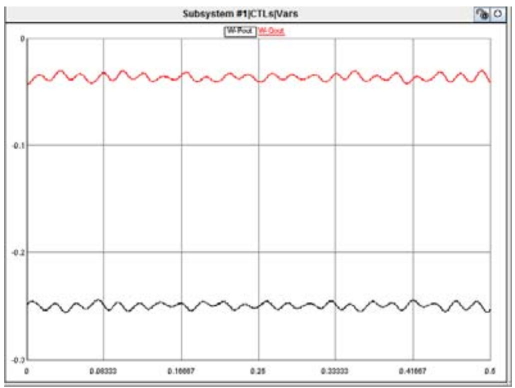

Figure 12. Active Power and Reactive Power of Hybrid System

6. Conclusion

A digital/physical hybrid simulation platform is designed in this paper, which is capable of performing the hardware-in-the-loop simulation for PV grid-connected system with maximum power tracking and grid integration control. The hybrid simulation platform integrates digital and physical advantages, which can provide accurate simulation results for the study of PV grid-connected system. Also, it provides a new and effective test and analysis method for issues in PV grid-connected system as multi-station aggregation, performance under partial shaded conditions and low voltage ride through, etc.

Acknowledgements

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