Research on mutual test method and strategy of bi-directional power grid connected inverter

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Abstract. In order to improve the utilization rate of grid connected inverter and expand its auxiliary service capacity for power grid, the demand of grid connected inverter supporting V2G, V2B, V2H and other technology applications is increasingly obvious. However, due to its detection technology has not yet carried out systematic research, if the existing detection technology is applied, it will not only follow the shortcomings of the current technology, but also abandon the advantages of bi-directional power control topology. In order to solve this problem, this paper proposes a test method and control strategy for multiple bi-directional power grid connected inverters: Taking two bi-directional power grid connected inverters as examples, the circuit topology of back-to-back mutual test is proposed, and its working mode is analyzed; PID control with coupling inner membrane control is introduced to improve the dynamic response ability; The MATLAB simulation model is built and verified. The results show that the proposed test method and control strategy can effectively realize the test of bi-directional charging facilities, and provide a certain reference for the corresponding industry.

1. Introduction
Under the dual pressure of energy security and environmental pollution problems, new energy generation systems based on hybrid energy storage have been vigorously developed [1]. As a necessary infrastructure for new energy sources to participate in grid operation, the reliability and safety of the throughput energy is crucial, and non-compliant operation can have a bad impact on the life of the system and even lead to safety accidents [2-3]. Therefore, grid connected inverters in operation should be subjected to regular on-site inspections for their reliability [4].

Considering the huge order of magnitude and distribution of grid connected inverters, if traditional test instruments are used, it is necessary to complete the installation and commissioning of the equipment in the place where the inverter is located [5], which will undoubtedly bring additional losses to the equipment operators; At the same time, considering the application of grid connected inverter in the field of V2G and V2B, corresponding simulated loads, such as resistance matrix load and real battery load, should be configured for the test. The anti-potential characteristics of the battery can not be reflected by using the resistance as the load, and the real charging process of the battery can not be simulated; However, using the real battery test method, the battery voltage can not be adjusted continuously, so the current voltage of 200V DC ~ 750V DC full voltage range test can not be realized, and a lot of power is wasted, and the system efficiency is low.
The development of current remote testing techniques has also been extensively reported [6]. The main drawbacks are that the test items and parameters are subject to many constraints, the application algorithms are complex and it is difficult to achieve full coverage.

The inverter test platform proposed in the literature [7] covers a wide enough voltage range to enable routine testing of general inverters, but it employs a large number of test instruments inside, resulting in the test platform itself being too heavy. The literature [8] proposes an inverter testing device with strong mobility and high intelligence, which can respond to the testing requirements such as portability and intelligence proposed above, but still cannot provide testing services for bi-directional grid connected inverters.

Therefore, it has significant technical and economic value and market prospects to study the new detection technology of grid connected inverter suitable for bi-directional power control.

To solve this problem, this paper proposes a test method and control strategy for multiple bi-directional grid connected inverters. Taking two bi-directional power grid connected inverters as an example, the circuit topology of back-to-back mutual test of two facilities is proposed. According to the message information, the tested inverter and the analog energy storage inverter control the front-end converter and lock the back-end bridge arm IGBT to complete the mutual test and realize the energy inflow and equal outflow. The application of the mutual test method is compared and analyzed. In addition, in order to improve the dynamic response ability of the system and deal with the problem of parameter mismatch, the front-end of the inverter adopts the PID control of coupling inner membrane control(IMC-PID); Finally, a simulation model is built in Matlab / Simulink environment to verify the test method and the control strategy of the topology.

2. Principle of mutual test technology for bi-directional grid connected inverter

At present, the back-end topologies of mainstream bi-directional grid connected inverters are isolated bi-directional full bridge DC / DC converter and Buck-Boost DC / DC converter. The former can realize soft switching control, with small device stress and high working frequency, but with more devices, complex control and high cost [9]; The latter has the advantages of simple control, less devices and low cost, but high device stress and limited working frequency [10-11]. Considering the cost, reliability, system adaptability and other indicators, this paper describes the working principle of mutual test method for Buck-Boost DC / DC bi-directional grid connected inverter, and the proposed mutual test method for grid connected inverter is shown in Figure 1.

As shown in Figure 1, the DC output sides of two grid connected inverters are interconnected, one is the device under test, and the other is the analog energy storage device. The device under test operates according to the charging control strategy for the energy storage device; The simulation energy storage device operates according to the voltage variation characteristics of the energy storage terminal and the control strategy of inverting the absorbed active power to the power grid. The two-way flow of energy is realized through grid connected inverter to achieve the goal of fast and accurate testing.

![Figure 1. Topology of back-to-back mutual measurement principle of grid connected inverter.](image-url)

The front-end PWM rectifier of the grid connected inverter under test controls the DC output voltage of the rectifier based on the given voltage, the back-end Buck-Boost chopper works in the buck chopper mode, the boost IGBT of the lower bridge arm is locked, and the current is controlled
according to the information uploaded by the analog energy storage inverter message system; The IGBTs of the upper and lower bridge arms of the Buck-Boost chopper at the back end of the analog energy storage device are all locked. The front-end PWM rectifier controls the DC output voltage of the rectifier based on the voltage of the analog energy storage device, and feeds back the active power absorbed by the inverter to the grid.

After the completion of the test, the inverter under test is changed to analog energy storage inverter, and the one originally set as analog energy storage is changed to the inverter under test, so that the mutual test of grid connected inverters can be completed quickly.

The test method proposed in this paper has the following characteristics:
1) Automatic test of grid connected inverter in idle standby state does not affect the interaction between new energy and power grid, does not need human intervention, and has high test efficiency;
2) The test data is associated with multiple information (season, temperature, etc.) to facilitate long-term orderly accumulation and form big data for grid connected inverter operation and maintenance;
3) The test system can monitor remotely, give early warning in case of problems, generate maintenance plan, and improve equipment availability;
4) Remote operability, mutual test method can support remote automatic detection; existing test methods only support field operation;
5) The test power feedback to the grid, and the test energy efficiency is high.

3. Control strategy of mutual test technology for bi-directional grid connected inverter
The whole test system is divided into two parts: the inverter under test and the simulated energy storage inverter, which adopt different control strategies.

3.1. Control strategy of inverter under test
According to Figure 1, the control strategy of the tested inverter consists of two parts: PWM rectifier and Buck-Boost bi-directional DC / DC converter. The control strategies are analyzed respectively in the following.

3.1.1. PWM rectifier. The front-end PWM rectifier controls the rectifier DC output voltage based on the given voltage. The control block diagram is shown in Figure 2.

In Figure 2, the rectifier uses active and reactive current decoupling control. Current decoupling control can more intuitively control the active and reactive power during operation [12]. The deviation $\Delta i_d$, $\Delta i_q$ between the given current value and the actual value passes through a PID controller coupled with inner membrane control(IMC-PID), after the coordinate transformation from the dq0 axis to the abc axis, the three-phase control signals $S_a$, $S_b$, $S_c$ are obtained, compared with the triangular carrier, the SPWM wave with a phase difference of 120 degrees is generated to control the operation of the inverter circuit.

In order to improve the robustness of the system and deal with problems such as parameter mismatch, this paper combines the traditional PID control with the inner membrane control, and proposes the PID control of the coupled inner membrane control. The structure is shown in Figure 3.
In the figure above, \( G_{IMC}(s) \) is the inner membrane controller, \( G_p(s) \) is the controlled object, \( G_M(s) \) is the inner membrane of the controlled object, and \( D(s) \) is the interference term. The equivalent feedback control structure is shown in Figure 4.

**Figure 3.** Intimal Control Structure.

**Figure 4.** Equivalent Feedback Control Structure of Inner Membrane Control.

According to the equivalent feedback structure of the inner membrane control in Figure 4, the closed-loop response of the system and the inner-loop feedback controller are shown in the following equations respectively

\[
Y(s) = \frac{G_{IMC}(s)G_p(s)R(s) + [1-G_{IMC}(s)G_M(s)]D(s)}{1+G_{IMC}(s)[G_p(s)-G_M(s)]}
\]

(1)

\[
G_c(s) = \frac{G_{IMC}(s)}{1-G_{IMC}(s)G_M(s)}
\]

(2)

It can be seen from formula (1) that when the mathematical model of the controlled process is accurate, that is, \( G_M(s) = G_p(s) \) and \( G_{IMC}(s) = G_M(s)^{-1} \), then \( Y(s) = R(s) \), the model exactly matches the object. Due to the introduction of an internal model, the amount of feedback changes from the output full feedback to an estimate of disturbance. The feedback signal reflects the uncertainty of the process model and the influence of disturbances, thereby facilitating the design of system anti-interference and enhancing system robustness.

The design analysis of the inner membrane controller is as follows:

For the first-order inertia plus pure lag process, take

\[
G_p(s) = \frac{K}{1+Ts} e^{-rs}
\]

(3)

Decompose the process model \( G_M(s) \) into \( G_M(s) \) and \( G_{M-}(s) \), namely

\[
G_M(s) = G_{M+}(s)G_{M-}(s) = \frac{K}{Ts+1} e^{-rs}
\]

(4)

In the formula, \( G_{M+}(s) \) is the transfer function of the all-pass filter. For all frequencies \( \omega \) satisfies \( |G_M(j\omega)| = 0 \), all time delays and right half-plane zeros are included in \( G_{M+}(s) \). \( G_{M-}(s) \) is the transfer function with the smallest phase characteristic, stable and does not include the prediction term.

At the same time, in order to suppress the influence of model errors on the system and enhance the robustness of the system, a low-pass filter is added to the controller

\[
F(s) = \frac{1}{\frac{1}{\lambda s}}
\]

(5)

Among them, \( \lambda \) is the time constant, and \( G_M(s) \) is combined with it to achieve undisturbed control, which can be obtained

\[
G_{IMC}(s) = G_M(s)^{-1} F(s)
\]

(6)
By adjusting the structure and parameters of the filter, the desired dynamic quality and robustness can be obtained. Substituting formula (5) into formula (2), we can get

$$G_c(s) = \frac{G_{M1}(s)}{\lambda s + 1 - e^{\tau s}}$$

(7)

Take the first-order Padé approximation to the time delay term, namely

$$e^{-\tau s} = \frac{1 - 0.5 s}{1 + 0.5 s}$$

(8)

Substitute equation (8) into equation (7) to get

$$G_c(s) = \frac{T + 0.5 \tau}{K(\lambda + \tau)} \left[ 1 + \frac{1}{(T + 0.5 \tau)s} + \frac{0.5 \lambda \tau}{(T + 0.5 \tau)s} \right] \frac{0.5 \lambda \tau}{(\lambda + \tau) + 1}s$$

(9)

The above formula is the IMC-PID controller with low-pass filter, corresponding to PID parameters, the parameter setting formula is as follows

$$K_p = \frac{T + 0.5 \tau}{K(\lambda + \tau)}; K_i = T + 0.5 \tau; K_D = \frac{0.5 \lambda \tau}{(T + 0.5 \tau)}; T_f = \frac{0.5 \lambda \tau}{\lambda + \tau}$$

(10)

Among them, $K_p$ is the proportional coefficient, $K_i$ is the integral time coefficient, $K_D$ is the differential time coefficient, and $T_f$ is the low-pass filter coefficient. Compared with the traditional PID adjustment that needs to adjust three parameters, IMC-PID only needs to adjust the coefficient $\lambda$ of the filter, which improves the robustness of the system.

### 3.1.2. Buck-Boost chopper

The Buck-Boost chopper at the back end of the tested inverter works in the buck chopper mode. The boost IGBT of the lower bridge arm is locked. According to the information uploaded by the simulated battery management system message system, it is controlled according to the constant current. The control is shown in Figure 5. It can be seen that the deviation between the given current and the actual current passes through the PID regulator, and its value is compared with the triangular wave, so as to generate a PWM wave to control the on and off of the chopper.

![Figure 5. Buck Chopper Control of Inverter under Test.](image)

### 3.2. Control strategy of analog energy storage inverter

The IGBT of the upper and lower bridge arms of the Buck-Boost chopper at the back end of the analog energy storage inverter are all locked. The front-end PWM inverter controls the DC bus voltage of the inverter based on the analog energy storage voltage, and feeds back the absorbed active power to the AC power grid. In the steady state, the current setting value $i_d^* < 0$, $i_q^* = 0$, and its control strategy is consistent with that of the inverter under test, as shown in Figure 2.

### 4. Simulation research

#### 4.1. Selection of simulation parameters

In the MATLAB simulation environment, the simulation parameters are set as follows: three-phase power supply voltage frequency($\omega$) is 50 Hz, line voltage RMS is 380 V, inverter output power is 9 kW. The DC side filter inductance of the front-end converter considers the maximum utilization of PWM phase voltage, and the DC side regulator capacitor considers the switch active power loss, which can be calculated by the following formula respectively:
\[ L \approx \left( E_m \sin \delta + \sqrt{E_m^2 \sin^2 \delta + \frac{1}{4}U_{dc}^2 - E_m^2} \right) / \omega I_m \times 10^6 \]  

(11)

In the formula, \( L \) is the DC side filter inductance, \( E_m \) is the peak value of the grid phase voltage, \( I_m \) is the peak value of the fundamental phase current on the AC side, \( \delta \) is the power factor of the AC side of the converter, and \( U_{dc} \) is the voltage on the DC side.

The back-end Buck-Boost chopper can be obtained by the ripple design of output voltage and inductance current:

\[ L_b = \frac{U_{in} D \Delta i}{f} \quad C_b = \frac{I_o D_y}{\Delta U_o} \]  

(12)

In the formula, \( L_b \) and \( C_b \) are the inductance and capacitance of the chopper, \( U_{in} \) is the input voltage, \( \Delta i \) is the inductor current ripple, \( f \) is the switching frequency, \( I_o \) is the output voltage, \( \Delta U_o \) is the output voltage ripple, and \( D_y \) is the duty cycle.

At the same time, according to the above formula, the AC side inductance of the rectifier circuit is 3.6mH, the DC output side flat wave inductance is 3.6mH, the DC bus capacitance is 5mF, and the DC output side constant voltage capacitance is 10mF.

4.2. Inverter simulated energy storage terminal voltage 500V DC

The simulated energy storage inverter simulates the energy storage with 500V voltage, that is, the given value of DC side voltage \( U_{dc} = 500V \), and controls the output current of the inverter to be tested to maintain 18A. The simulation results are shown in Figures 6 and 7.

![Figure 6. Buck Chopper Control of Inverter under Test.](image)

The waveforms in Figure 6 are AC grid voltage \( U_a \), current \( I_a \), and input current \( I_{i0} \) of analog energy storage inverter. From the simulation results, it can be seen that the current \( I_a \) and \( I_{i0} \) are close to sine wave, \( I_a \) and \( U_a \) are in the same phase, and the inverter to be tested operates at unity power factor, and the phase difference between \( I_{i0} \) and \( U_a \) is 180 degrees. The analog energy storage inverter operates at unity power factor inverter state, and feeds back electric energy to the grid.

As shown in Figure 7, the output voltage \( U_{dc} \) of the inverter to be tested is maintained at 500V, the current \( I_0 \) is maintained at 18A, the output power \( P_0 \) is 9 kW, the output power \( P_g \) of the analog energy storage inverter is -9 kW, and the reactive power is 0, which means that all the output power of the inverter to be tested is fed back to the grid.

![Figure 7. Simulation Diagram of Analog Energy Storage with 500V DC Terminal Voltage.](image)
5. Conclusion
Research on the new detection technology of bi-directional power control grid connected inverter has significant technical and economic value and market prospects. In this paper, a test method and control strategy are proposed for multiple bi-directional power grid connected inverters:

(1) The front-end PWM rectifier of the tested inverter controls the DC output voltage of the rectifier based on the given voltage, the back-end Buck-Boost chopper works in the buck chopper mode, the boost IGBT of the lower bridge arm is locked, and the current is controlled according to the information uploaded by the simulated BMS message system.

(2) The IGBTs of Buck-Boost chopper at the back end of the analog energy storage inverter are all locked, and the front-end PWM rectifier controls the DC output voltage of the rectifier based on the analog energy storage voltage, and feeds back the absorbed active power to the AC power grid.

(3) The test method and control strategy can effectively support remote automatic detection, and maximize the availability of grid connected inverter flexible transmission and grid support.

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