The Rapid Development of Three-phase Grid-forming Micro-source Inverter Based on SMC and PI Control

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Abstract—The rapid development process of a proposed three-phase grid-forming micro-source inverter is presented in the paper. Sliding mode control (SMC) and PI control strategies are adopted synthetically to implement the dual closed-loop controller. In order to avoid the repeated selection of control parameters, the particle swarm optimization (PSO) algorithm is applied for parameters’ optimization. Simulation results certificate the correctness of the proposed controller. And then, the automatic generation of control codes is realized based on the model design method. The actual hardware experiments corresponding to the simulation ones are presented in the paper. The results demonstrate that the inverter based on the rapid development is effective and the proposed controller performs better robustness property over conventional PI-based control strategy.

Keywords—grid-forming micro-source inverter, sliding mode control, PI control, particle swarm optimization, model design method

I. INTRODUCTION

A three-phase micro-source inverter named as grid-forming inverter (GFI) is widely utilized to establish voltage and frequency in AC microgrid system. It plays a significant role for microgrid, especially in an islanded mode. The rapid development of GFI with strong stability and robustness is necessary and practical.

The voltage and current dual closed-loop control structure has been greatly employed and concerned [1-2]. As the most widely used control strategy in the industrial applications, PI control has the advantages of simple structure and high reliability. However, PI controller performs weak dynamic and static characteristics in the case of load disturbance or system parameter perturbation [3]. A dual-loop control structure with a neural network inner current loop and a hybrid fuzzy-PI outer voltage loop is presented in [4]. But the neural-network based controller needs to undergo a complex training process. Wu proposes to combine repetitive control with PI control together to design the controller [5]. Whereas, the repetitive control has the disadvantage of slow dynamic response. Sliding mode control (SMC) strategy for full bridge inverter is proposed in [6-7]. SMC is with high robustness to parameter variation and perturbation insensitivity, as well as advantages of fast response and simple physical implementation [8-9]. Considering the advantages and disadvantages of each controller, PI and SMC control strategies are adopted in this paper.

This paper takes the rapid development of a three-phase GFI as the research purpose. Firstly, the proposed SMC+ PI dual closed-loop controller is designed in Section II. The sliding mode control is applied to keep the switching frequency constant and achieve fast response to the system change, which can effectively enhance the robust performance of the inverter. The classic PI control is applied in the outer voltage loop to deal with the fast voltage tracking property. In order to avoid repeated selection of control parameters in the process of controller design, the particle swarm optimization (PSO) algorithm is applied for parameters’ optimization. The principle and implementation steps are presented in Section III. Section IV gives simulation evaluation. And then, the DSP executable codes are generated automatically from the Simulink controller model based on the model design method, which makes it possible to realize the rapid development of GFI. Section V shows the hardware experiments based on the developed GFI. At last, the paper gets the conclusion.

II. DESIGN OF DUAL CLOSED-LOOP CONTROLLER FOR GFI

A. Dual Closed-loop Control Structure of GFI

The GFI is with three-phase full-bridge structure and LC filter. Fig. 1 shows the dual closed-loop control structure diagram of GFI. The dual closed-loop control structure includes an outer voltage loop and an inner current loop. The outer voltage loop adopts PI control strategy to ensure the amplitude and frequency of the output voltage stable. SMC strategy is employed in the inner current loop, which can accelerate the dynamic process of resisting interference.
In order to eliminate the coupling, the controller is designed in the d-q synchronous rotating reference frame. The system loop equations are shown as (1).

\[
\begin{align*}
L_d \frac{di_d}{dt} &= u_d - u_{id} - R_f \cdot i_d + \omega \cdot L_f \cdot i_q \\
L_q \frac{di_q}{dt} &= u_q - i_{dq} - R_f \cdot i_q - \omega \cdot L_f \cdot i_d
\end{align*}
\]

(1)

**B. Design of the Outer Voltage Loop**

The outer voltage loop adopts PI control strategy to adjust the system output voltage. Moreover, the inner current loop reference is generated by the outer voltage loop control, as shown in (2).

\[
\begin{align*}
i_{d\text{ref}} &= (u_{d\text{ref}} - u_{id}) (k_{pu} + \frac{k_u}{s}) + u_{id} \omega i_f \\
i_{q\text{ref}} &= (u_{q\text{ref}} - u_{iq}) (k_{qu} + \frac{k_u}{s}) + u_{iq} \omega i_f
\end{align*}
\]

(2)

where \(k_{pu}\) and \(k_{qu}\) are PI coefficients; \(u_{d\text{ref}}\) and \(u_{q\text{ref}}\) represent voltage references for Space Vector Pulse Width Modulation (SVPWM) module. The output current \(i_{d\text{ref}}\) and \(i_{q\text{ref}}\) are forward feedback, to suppress the impact of load fluctuation on the output voltage.

**C. Design of the Inner Current Loop**

The inner current loop controller needs to achieve excellent current tracking. SMC controller is designed. Set the sliding surface functions \(S_d\) and \(S_q\) according to (3).

\[
S_d = e_d + \lambda \int e_d dt, \quad S_q = e_q + \lambda \int e_q dt
\]

(3)

\(i_{d\text{ref}}\) and \(i_{q\text{ref}}\) represent current reference; \(e_{d\text{ref}}\) and \(e_{q\text{ref}}\) are control errors of inner current, expressed as \(e_{d\text{ref}} = i_{d\text{ref}} - i_d\) and \(e_{q\text{ref}} = i_{q\text{ref}} - i_q\). \(\lambda\) is the weighting factor for the error integral, which is a positive real number and used to eliminate the steady-state control deviation [10].

Considering the components in the d-axis and q-axis are similar, only the d-axis components are designed for analysis. According to (1) and (3), the time derivative of \(S_d\) is calculated as

\[
\begin{align*}
\dot{S}_d &= \frac{d}{dt} (e_d + \lambda \int e_d dt) = \frac{di_{d\text{ref}}}{dt} - \frac{di_d}{dt} + \lambda \frac{de_d}{dt} \\
&= \frac{di_{d\text{ref}}}{dt} - \frac{1}{L_f} \left[ u_d - R_f i_d + \omega \cdot L_f \cdot i_q \right] + \lambda \frac{de_d}{dt}
\end{align*}
\]

(4)

The d-axis voltage control component \(u_d\) can be described as (5).

\[
\begin{align*}
u_d &= -L_f \dot{S}_d + L_f \frac{di_{d\text{ref}}}{dt} + u_{id} + R_f i_d - L_f \omega i_q + L_f \lambda \frac{de_d}{dt}
\end{align*}
\]

(5)

Due to inaccurate measurement or aging degradation, the filter of GFI may face the problem of parameter perturbation. Assuming that the inductance and resistance values of the filter are made an inaccurate measurement, there will be significant deviations between the actual value \((L_f\) and \(R_f\)) and the nominal value \((L_{f\text{nom}}\) and \(R_{f\text{nom}}\)).

The exponential reaching law is selected to reach the sliding mode surface quickly [11], as shown in (7).

\[
\begin{align*}
\dot{S}_d &= -\epsilon \text{sgn}(S_d) - kS_d \\
\dot{S}_q &= -\epsilon \text{sgn}(S_q) - kS_q
\end{align*}
\]

(7)

where \(\epsilon\) and \(k\) are positive real constants. Their values may determine the effect of resisting parameters’ disturbance. According to (6) and (7), \(u_{d\text{smc}}\) and \(u_{q\text{smc}}\) are defined as (8).

\[
\begin{align*}
u_{d\text{smc}} &= L_f (\epsilon \text{sgn}(S_d) + kS_d + \lambda e_d) \\
u_{q\text{smc}} &= L_f (\epsilon \text{sgn}(S_q) + kS_q + \lambda e_q)
\end{align*}
\]

(8)

**III. OPTIMAL DESIGN OF CONTROL PARAMETERS BASED ON PARTICLE SWARM OPTIMIZATION ALGORITHM**

The selection of inverter control parameters is the key to determine the response speed and tracking accuracy of the system. However, in the development and application of the project, it is facing repeated trial problems, resulting in a waste of time. Particle Swarm Optimization (PSO) has a strong adaptability to nonlinear systems and is easy to implement [12]. Therefore, the particle swarm optimization algorithm is adopted to optimize the control parameters of the inverter controller and speed up the process of parameter debugging. The optimized parameters include proportional and integral coefficients of the voltage loop \((k_p\) and \(k_i\)), together with the adjustment coefficients of current loop \((\epsilon, k\) and \(\lambda\)).
A. PSO Principle

The basic principle of PSO is as follows. The initial population is randomly generated in the feasible solution space, and an adaptive value is determined by the objective function. The velocity determines the direction and distance of the particles’ motion in the solution space. Particles search the current optimal particle, and through the iterate search to update the random particles and seek the optimal solution. In each generation, the particle needs to track two extremes: the current optimal solution of the particle (pbest) and the current optimal solution of the population (gbest).

Suppose that there is a population of particles \( X = \{x_1, x_2, ..., x_n\} \) in a N-dimensional space, where \( x_i = \{x_{i1}, x_{i2}, ..., x_{in}\}^T \) represents the position of the \( i \)-th particle; \( v_i = \{v_{i1}, v_{i2}, ..., v_{in}\}^T \) represents the flight speed of the \( i \)-th particle; \( p_i = \{p_{i1}, p_{i2}, ..., p_{in}\}^T \) represents the extreme value of each individual, \( p_g = \{p_{g1}, p_{g2}, ..., p_{gn}\}^T \) represents the global extreme value of the population. The particle \( x_i \) will follow the principle of the current optimal particle to update speed and position as follows [12]:

\[
\begin{align*}
v_{id}^{k+1} &= v_{id}^k + c_1 r_1(p_{id}^k - x_{id}^k) + c_2 r_2(p_g^k - x_{id}^k) \\
x_{id}^{k+1} &= x_{id}^k + v_{id}^{k+1}
\end{align*}
\tag{9}
\]

where \( d \) represents the current sampled time; \( i = 1, 2, ..., n \); \( m \) is the population size; \( h \) represents the current number of iterations; Nonnegative \( c_1 \) and \( c_2 \) are learning factors; \( r_1 \) and \( r_2 \) are random numbers between \([0,1]\).

The optimal position vector of the particle contains the optimal control parameters of PI controller \((k_{pu} \text{ and } k_{iu})\) and SMC controller \((\dot{e}, \dot{\alpha}, \text{ and } \lambda)\).

The integrated time-weighted squared error (ITAE) is taken as the PSO’s objective function, designed as (10):

\[
J = \sum_{t=0}^{N-1} \int_t^{t+1} W \cdot |E(t)| dt
\tag{10}
\]

where \( t \) represents the current sampled time; Simulation time starts from \( t_0 \) to \( t_f \); \( W \) is a weighting matrix; \( |E(t)| \) is the absolute error matrix defined as (11).

\[
E(t) = [u_{adef} - u_{ad}, u_{qref} - u_{aq}, i_{dref} - i_d, i_{qref} - i_q]^T
\tag{11}
\]

B. PSO Algorithm Implementation Steps

The PSO algorithm is implemented as follows [13]:

1) Initialize the system parameters, including particle velocity, maximum iteration number of particle position, position limits and so on, which are generated randomly.

2) Calculate the fitness function value of each particle according to equation (11).

3) Compare the particle fitness values, and update pbest and gbest.

4) Update particle velocity and position according to equation (9), resulting in a new population.

5) If satisfy the termination criteria (reach a given precision or reach the number of iterations) go to 6), or go to 2).

6) End the PSO calculation and output the optimized parameters.

\[
\begin{array}{|c|c|c|}
\hline
\text{Symbol} & \text{Description} & \text{Value} \\
\hline
m & \text{Population Size} & 15 \\
\hline
n & \text{Number of Iterations} & 30 \\
\hline
k & \text{Learning Factors} & c_1=c_2=2 \\
\hline
W & \text{Weighting Matrix} & \begin{bmatrix} 1 & 0.1 & 0.1 & 0.1 & 0.1 \end{bmatrix} \\
\hline
\end{array}
\]

C. PSO Optimization Process and Results

According to the parameters in Table I, PSO algorithm is written by m language. In the m file, the Simulink model of GFI is called by the function “SimOut = SIM('MODEL', 'PARAMETERS')”. In each call, the particle swarm fitness value is obtained according to (11). Then compare the particle fitness values, and update pbest and gbest. Repeat the calculation until the termination criteria, and the particle swarm optimization parameters are obtained.

Based on PSO, the optimization parameters of the controller are obtained within 1 hour, which is far more quickly than the artificial trial method. The fitness convergence curve achieves the best in the 12th generation, with a fitness value of 28.6. The optimized parameters of PI controller are \( k_{pu}=4.86, k_{iu}=0.24 \); The optimized parameters of current loop controller are \( e = 306, k = 15600 \) and \( \lambda = 247 \). Using PSO algorithm to get optimized controller parameters could speed up the controller design.

IV. DEVELOPMENT OF CONTROLLER BASED ON THE MODEL DESIGN METHOD

Model design method is adopted in the controller development process. The method could directly generate executable DSP codes from MATLAB/Simulink model, effectively simplifying the development cycle of GFI.

A. Hardware and Software Platform

TMS320F28335 DSP is selected as the controller chip for the GFI control system. The advantage of floating point operation of DSP28335 is taken to improve data conversion accuracy from MATLAB to DSP. Software development environments include CCS5.5 and MATLAB2012b (or higher versions).

B. Simulation in MATLAB/Simulink

The three-phase GFI model is built up in MATLAB/Simulink. The values of model devices are set the same as the hardware parameters in the actual experimental platform, so that the codes can be generated from the model directly. The model simulation parameters are shown in Table II.
In order to verify the dynamic performance of the controller, the load is switched from a purely resistive load of 150 ohms to a non-linear load at 0.1 s. The non-linear load is composed of a three-phase uncontrolled rectifier bridge, and the DC side of the rectifier bridge connects a 350 ohms pure resistive load. At the time of 0.16s, switch the load back to the original one. In order to verify the performance of designed SMC+PI controller, another dual PI (PIPI) controller is adopted as a comparison object. The parameters of PIPI controller are as follows: \( k_{pu} = 4.86 \), \( k_{iu} = 0.24 \) (the same as the PI parameters of SMC+PI controller), \( k_{pi} = 2.71 \), \( k_{ii} = 5.00 \).

Fig. 2 and Fig. 3 respectively show the simulation results of output voltage and current based on the dual PI closed-loop algorithm and SMC+PI dual closed-loop algorithm. Moreover, the values of voltage THD are respectively 1.02% and 0.94%. It can be seen from the figures that the two types of control strategies can guarantee stable amplitude and frequency of the three-phase output voltage. No matter the load is suddenly increased or decreased, even with the load property changing, the dynamic performance of the two strategies perform well.

Fig. 4 shows the simulation results of SMC+PI controller with the conventional manual setting parameters. The voltage THD is 1.39%, higher than that using PSO optimized parameters. Simulation results show that the GFI with the optimized controller parameters outputs better waveforms.

So as to compare the sensitivity of parameter perturbation based on both algorithms, the inductance value of output filter is changed to 0.7 times of the original one and the controller parameters are kept unchanged. Resistive load is adopted.

Fig. 5 and Fig. 6 show the outputs of the inverter with 0.7 times \( L \). The values of voltage THD are calculated as 7.98% and 1.21% respectively. In Fig. 5, with the PIPI control algorithm, the harmonics of inverter output voltage increase significantly, due to the attenuation of the inductor. The voltage THD increases from 1.02% to 7.98%.

### Table II. The Parameter Table for Simulation Model

| Symbol | Description | Value |
|--------|-------------|-------|
| \( V_{dc} \) | DC Voltage | 400 V |
| \( V_{acref} \) | AC Output Reference | 110V |
| \( f \) | Fundamental Frequency | 50Hz |
| \( f_s \) | Switch Frequency | 10 kHz |
| \( L_f \) | Inductance of the Output Filter | 6.6mH |
| \( C_f \) | Capacitance of the Output Filter | 4.8uF |
| \( t_m \) | The Period of Changing Load | 01s-0.16s |
| Load1 | Initial Load | \( R=150\Omega \) |
| Load2 | Mutation load | Three phase non-controlled rectifier bridge |

![Fig.2 The output voltage and current waveforms of GFI based on the PIPI strategy](image)

![Fig.3 The output voltage and current waveforms of GFI based on the SMC+PI strategy.](image)

![Fig.4 The output voltage and current waveforms of GFI based on the SMC+PI strategy with the manual setting controller.](image)

![Fig.5 The output voltage and current waveforms of GFI with 0.7 times \( L \) based on the PIPI strategy.](image)
However, in the same situation, the inverter based on the SMC+PI strategy shows good output waveforms with stable voltage and frequency in Fig. 6. The voltage THD just increased from 0.94% to 1.21%.

Simulation results prove that the GFI model is valid and the control strategies are correct. Then, they will be translated to control codes automatically by MATLAB.

C. Controller Codes Automatic Generation

Controller modules that need to be converted to codes include abc-dq transformation subsystem, voltage and current dual closed-loop control subsystem, SVPWM modulation subsystem. The process of codes automatic generation can be described as following steps [14].

1) Verify that the C codes generated by the controller model is equivalent to the original Simulink controller model through the “Software in the Loop” test.

2) Add the DSP module in the controller model, and configure DSP hardware module parameters according to the actual application.

3) Execute the codes automatic generation operation, and DSP project files, such as main program, DSP register configuration files, algorithm subroutines, are generated.

4) Download the generated codes to DSP, and then, carry out hardware and software joint debugging on the test platform.

V. INVERTER DEVELOPMENT AND EXPERIMENTAL RESULTS

The hardware parameters are identical as the simulation settings, shown as Table I. In addition, due to the application of the model design method, the parameters of controller are exactly the same as the simulation ones. Mitsubishi intelligent power module IPM-PS21564 is selected as the power switch, and the switch frequency is set to 10kHz. Inverter output currents and voltages are sampled by hall voltage and current sensors. The developed GFI experiment platform is shown as Fig. 7.

Figs. 8-9 compare the output voltage and current waveforms of inverter based on the PIPI and SMC+PI control strategies in response to a load change from Load1 to Load2 (Experiment 1).

Figs. 10-11 show the experimental results of Experiment 2 (with Loads but 0.7 times parameter uncertainties in L— by using two control strategies. The voltage THD with the proposed SMC+PI approach is just 2.87%, whereas the one with PIPI approach is 8.22%. As shown in Table III, the proposed SMC+PI approach has lower voltage THD than the PIPI approach, which are in accordance with the comparison results in the simulation. Considering that there are still some detail differences between the Simulink modules and the actual hardware devices, such as the internal parameters of power switch and the sample accuracy of sensors, so the experimental THD results are not 100% identical with the simulation ones.

Figs. 8-9 Experimental1 results: The output voltage and current waveforms in response to a load change from Load1 (linear load) to Load2 (non-linear load) based on the PIPI strategy.

Figs. 10-11 Experimental1 results: The output voltage and current waveforms in response to a load change from Load1 (linear load) to Load2 (non-linear load) based on the SMC+PI strategy.
TABLE III  COMPARISON OF THD FOR OUTPUT VOLTAGE

| Scenario     | PIPI Control | SMC+PI Control |
|--------------|--------------|----------------|
| Experiment 1 | Load1 3.11% | Load1 3.35%    |
|              | Load2 3.35% | Load2 3.62%    |
| Experiment 2 | Load1 2.86% | Load1 2.90%    |
|              | Load2 2.68% | Load2 2.87%    |

The experimental results show that the SMC+PI strategy has better output voltage quality and lower THD than those based on the dual PI strategy, under both load conditions and parameter uncertainty scenario.

VI. CONCLUSION

This paper accomplished the rapid development of a three-phase microgrid GFI based on SMC and PI control. Using PSO algorithm to get optimized controller parameters, not only speeded up the controller design, but also got better control effect of system. With model design method, the development process was simplified and the development cycle from simulation to programming was shortened obviously. The experiments certified that the rapid development of a GFI was effective and simple. Moreover, compared with the conventional PIPI controller, the developed GFI with the proposed SMC+PI control strategy performed better robustness in the case of different load conditions and parameter perturbation scenario.

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