

A Method for Identifying Key Parameters of Frequency Modulation in GFM Converters Based on LS-GA

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ABSTRACT With the high proportion of renewable energy connected to the grid through power electronic interfaces, the frequency support of the system gradually shifts from being dominated by traditional synchronous machine inertia to being dominated by control strategies. Its dynamic inertia exhibits obvious scene dependence and time-varying characteristics, which brings higher difficulty to the identification of key frequency regulation parameters. Especially when the grid-forming (GFM) converter participates in frequency regulation, the superposition of different control links will result in strong coupling and segmented changes in power frequency response. Traditional equivalent inertia evaluation methods based on fixed model parameters are difficult to directly apply. To address this issue, this paper develops a parameter identification method that combines least squares (LS) fitting with a genetic algorithm (GA). Firstly, the influence of key frequency-regulating parameters on various frequency dynamic response indicators is analyzed. Then, a collaborative estimation method is proposed, utilizing the LS method and GA for sliding-window fitting to estimate the inertia and damping of GFM converters. Simultaneously, considering the challenge of verifying the validity of estimation results, a dual-model comparative verification method based on the P - ω admittance method is presented. The proposed parameter identification method is applicable to various GFM converter carriers. Finally, based on the proposed method, key frequency-regulating parameters of a receiving-end GFM converter in an example system connecting photovoltaics via VSC-HVDC are estimated and verified under different operating conditions. This enables intuitive verification of estimation result accuracy, providing an essential foundation for overall system estimation and security and stability analysis.

INDEX TERMS equivalent inertia time constant, damping coefficient, GFM converter, inertia, parameter estimation, flexible DC transmission.

I. INTRODUCTION

As indicated in the latest report released by the International Energy Agency (IEA), wind and solar power—two typical renewable energy sources—will contribute to 95% of the global growth in electricity generation by 2030 [1]. The energy transition is driving changes in the power source structure of the power system, and the dominant position of renewable energy sources will become increasingly prominent in the future. This change is accelerating the transformation of the power system from synchronous machine-dominated physical inertia to renewable energy-dominated virtual inertia. However, renewable energy units such as wind power and photovoltaics are connected to the grid through converter interfaces, and their conventional control strategies lead to decoupling of output power from system frequency [2], weakening the damping effect of traditional rotational inertia. At the same time, the introduction of multiple control strategies (such as grid-following, GFL

and GFM, GFM) to improve frequency regulation capability has significantly increased the complexity of evaluating system equivalent inertia and damping parameters due to the strong nonlinearity of dynamic responses and time-varying parameters.

At present, the issue of inertia assessment has become an important research direction in current safety and stability analysis [2]–[4], and the core link of inertia level assessment research is the estimation of inertia parameters. From the perspective of research objects, existing studies on inertia level assessment mainly focus on three levels: node, regional, and system. Reference [5] focuses on analyzing the temporal and spatial distribution characteristics of the inertia of the entire system based on the output error model and multi-innovation identification method. However, this method has high requirements on the number of measuring points, is difficult to implement in practical engineering, and the identification accuracy needs to be improved. References

[6], [7] divide the power grid into multiple frequency response coherent regions based on the principle of coherent frequency response of units in the same region, and estimate the inertia response parameters of each region respectively. However, this method needs to determine the region division before estimation and consider the setting of observation points for measurement data, is sensitive to system topology changes, and is not suitable for engineering practice. In contrast, the system-level inertia estimation method directly evaluates the inertia time constant of the entire system through the power-frequency response model, but usually faces problems such as complex modeling process and model order reduction [3].

The high temporal resolution measurement provided by phasor measurement units (PMU) creates conditions for short-term dynamic identification after disturbance. References [8]–[10] complete inertia parameter assessment based on mechanism modeling methods, which require constructing mathematical models based on known internal system operation control methods and parameters, and deriving system inertia parameters through model derivation. Due to the large amount of data required in the estimation process and strong dependence on the model, this method faces difficulties in promotion in practical applications. References [11]–[13] complete system inertia parameter estimation based on port characteristic modeling methods. Among them, Reference [11] completes inertia estimation of the microgrid system based on the full sequence data of frequency measurement; Reference [13] uses the cubature Kalman filter method in the inertia parameter estimation process, but this method faces difficulties in estimating current source-type virtual inertia. Reference [7] proposes an inertia parameter estimation method based on measurement data with high accuracy, but this method is based on the identical control strategies and parameters adopted by renewable energy units, without considering the differences in the setting of power frequency modulation control parameters in practice. In engineering practice, regions such as Australia and the European Union have proposed to identify the risk of insufficient system inertia by monitoring the rate-of-change-of-frequency (RoCoF). For example, some regions monitor RoCoF with a 500ms time window to detect the problem of insufficient system inertia [14], [15], but in complex systems, the sliding window calculation method brings large lag calculation errors.

Compared with inertia parameter estimation, there are few cutting-edge studies on damping parameter estimation technology at present. Existing studies on damping parameter estimation are mostly limited to traditional power system operation scenarios, focusing on the estimation of damping parameters of synchronous generators. Reference [16] proposes an evaluation model of inertia damping parameters under a simplified generator model derived from the sixth-order detailed practical model of synchronous generators, and uses the Prony analysis method to achieve parameter estimation. However, this method can only be performed

before the generator is put into operation or after overhaul, with disadvantages such as long time consumption and low accuracy. Reference [17] processes the data measured by PMU with a low-pass filter to obtain transient and sub-transient slow-changing data, reconstructs the generator rotor motion equation, and proposes an independent identification method for generator inertia and damping parameters. Reference [18] combines the polynomial approximation method and the time-step finite element method to calculate the generator damping coefficient using disturbance data. Reference [19] proposes a dynamic mode decomposition method to reconstruct the rotor motion equation in the frequency domain, turning the estimation of inertia and damping parameters of synchronous generators into a linear estimation problem. However, the accuracy of this method needs to be improved when used to estimate the inertia damping parameters of virtual synchronous machines.

With the development of power systems, damping support control of grid-connected power source interface converters is one of the key solutions to solve the problem of low-frequency oscillations in power systems, and the estimation of its damping parameters needs to be emphasized. Reference [20] proposes to use the nonlinear LS method to identify the inertia and damping control parameters of virtual synchronous machines based on synchronous machine load rejection experiments, but this method is only applicable to parameter estimation of a single unit. In addition, the $P-\omega$ admittance method, with its advantages of clear modeling and definite physical meaning, has been gradually applied to frequency dynamic analysis of renewable energy systems and shows good application potential in frequency modulation control parameter identification [21], [22].

This paper innovatively proposes a method for identifying key frequency-regulating parameters of GFM converters based on the LS method and GA. Firstly, the parameters affecting frequency dynamic response indicators are analyzed. Then, a scheme is designed to perform sliding-window fitting for estimating the inertia and damping of GFM converters using the LS Method and GA. To address the challenge of verifying the effectiveness of the estimation results, this paper designs a dual-model comparative verification method based on the $P-\omega$ admittance method. The proposed parameter identification method is applicable to various GFM converter carriers such as centralized GFM energy storage systems, GFM Static Var Compensators, and GFM VSC-HVDC systems. Finally, based on the proposed method, the key frequency-regulating parameters of the receiving-end GFM converter in an example system where photovoltaics are integrated via VSC-HVDC are estimated under different operating conditions. The effectiveness of the method was verified, while simultaneously providing a foundation for estimating key frequency-regulating parameters of the overall system and performing security and stability analysis.

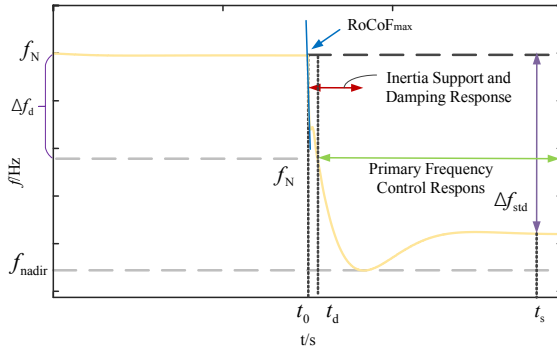


FIGURE 1. Consider the frequency response process after disturbance in damping control

II. THE FREQUENCY RESPONSE ANALYSIS OF GFM CONVERTERS

A. POST-DISTURBANCE FREQUENCY RESPONSE PROCESS

Under statically stable conditions, the power-frequency dynamic response process of the photovoltaic grid-connected system via flexible DC after being subjected to a disturbance can be divided into the following three stages, as shown in Fig. 1.

As shown in Fig. 1, after the static stable photovoltaic through flexible DC grid connection system is subjected to disturbance, its dynamic response process of power-frequency at the receiving end of the grid can be decomposed into three stages.

The first stage is the disturbance power distribution stage (at time t_0). At the moment the disturbance occurs, there is an imbalance of active power in the system, and the GFM converters automatically distribute the unbalanced power according to their own synchronizing power coefficients.

The second stage is the inertia support and damping response stage of each GFM converter (t_0 to t_d). Through inertia response control, the GFM converters deliver energy or absorb excess energy from the system to reduce the unbalanced power. The damping control loop suppresses the oscillation of power and frequency, reduces the overshoot, and shortens the system recovery time.

The third stage is the primary frequency modulation response stage (after t_d). In this stage, the frequency exceeds the dead band range of the power supply's primary frequency modulation, and the primary frequency modulation responds to frequency changes according to the frequency deviation value. During this stage, the inertia, damping, and primary frequency modulation links work together to prevent frequency changes.

Frequency modulation resources in the new-type power system include synchronous machines, renewable energy generation, energy storage, and DC systems. Common control methods include conventional control (MPPT control), virtual synchronous control, and virtual inertia control. The influence of each frequency modulation resource on the system's rotor motion equation is shown in Figure 2. This

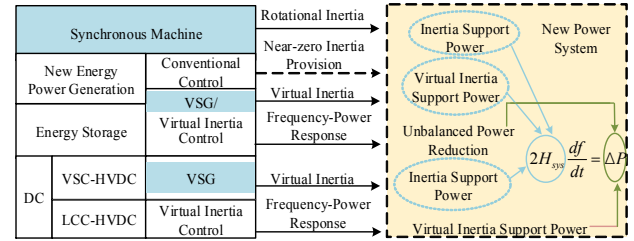


FIGURE 2. Effect of frequency modulation resource on rotor motion equation

article focuses on the research direction of frequency modulation key parameter estimation method for the receiving end networked converter in the system.

B. ANALYSIS OF FREQUENCY RESPONSE OF GFM CONVERTER AFFECTED BY INERTIA

The rotating mechanical structure of a synchronous machine changes its own speed, releasing or absorbing energy to offset unbalanced power. This is a spontaneous energy transfer process generated by the inertia of the rotating mechanical structure itself. Therefore, the rotational kinetic energy possessed by the rotating mechanical structure during rotation is called inertia, which is essentially a type of kinetic energy, denoted as E_J , and its expression is:

$$E_J = \frac{1}{2} J \omega^2 \quad (1)$$

Where J is the rotational inertia coefficient, which, like the mass of an object, has characteristics only related to the properties of the rotating mechanical structure itself and is independent of rotational speed. Its unit is $\text{kg} \cdot \text{m}^2$.

$$H = \frac{E_J}{S_N} = \frac{J \omega_N^2}{2 S_N} \quad (2)$$

The physical meaning of H is the acceleration time required for the rotor to go from rest to the rated angular velocity when the rated power S_N is applied to the generator rotor, with the unit being seconds.

In response to the low inertia problem in the new power system, numerous studies have proposed converter-based renewable energy inertia active support strategies. According to the control paradigm of voltage-source converters (VSC), these strategies are divided into two categories [22]: GFL and GFM control. The essence of the inertia response control strategy for GFL converters is similar to droop control, and thus they cannot actively participate in frequency support. GFM converters embed the rotor motion equation and electromagnetic relationship of synchronous generators into the control loop, thereby exhibiting voltage source external characteristics similar to synchronous generators, which equivalently increases the system's inertial response capability and static stability coefficient [24]. Table I summarizes the typical setting ranges of equivalent inertia time constants for various frequency modulation resources in current cutting-edge frequency modulation control research.

TABLE I. THE TYPICAL EQUIVALENT TIME CONSTANT OF A REPRESENTATIVE FREQUENCY MODULATION RESOURCE

Power Source Type	Inertia Source	Typical Equivalent Inertia Time Constant /s
Synchronous Machine	rotational kinetic energy	2–10 [25]
Wind Turbine	rotational kinetic energy	2–6 [26], [27]
	wind-storage coordinated frequency regulation	0.1–0.32 [28], [29]
Photovoltaic	Photovoltaic energy storage system	0.2 [30]
	DC capacitor	2 [31]

The frequency assistance service was not activated at the initial moment of power disturbance. At this time, the GFM converter outputs the maximum RoCoF, which can be expressed as:

$$H = \frac{E_J}{S_N} = \frac{J\omega_N^2}{2S_N} \quad (3)$$

Where ΔP_{e0}^* represents the nominal value of the power perturbation quantity.

Based on the segmented linearization approach, the expression for the maximum frequency deviation of the GFM converter output after the grid is disturbed is determined. Assume the fault occurs at the initial moment, the output frequency of the GFM converter reaches its extremum at t_{nadir} , and integrate from 0 to t_{nadir} without considering the damping coefficient:

$$\begin{aligned} \int_0^{t_{\text{nadir}}} \frac{df}{dt} dt + \frac{1}{2H\sigma} \int_0^{t_{\text{nadir}}} (f_N - f) dt \\ = \frac{1}{2H} \int_0^{t_{\text{nadir}}} (P_m - P_e) dt \end{aligned} \quad (4)$$

Using piecewise linearization technique to simulate the active power-frequency regulation process of the GFM converter after a fault disturbance, Equation (4) can be approximately expressed as:

$$\begin{aligned} f_{\text{nadir}} - f_N + \frac{\sigma^{-1}(f_{\text{nadir}} - f_N) t_{\text{nadir}}}{2H} \\ = \frac{f_N}{2H} \left(\Delta P \cdot t_{\text{db}} - \frac{\Delta P^2}{2R^{\text{SYS}}} \right) \end{aligned} \quad (5)$$

Where t_{nadir} and t_{db} are respectively the time when the GFM converter's output frequency reaches the extreme point under disturbance and the deadband time of the system's primary frequency modulation, and their expressions are as follows:

$$\begin{cases} t_{\text{nadir}} = t_{\text{db}} + \frac{\Delta P}{R^{\text{SYS}}}, \\ t_{\text{db}} = \frac{4H f_{\text{db}}}{2\Delta P - \sigma^{-1} f_{\text{db}}}. \end{cases} \quad (6)$$

Where f_{db}^* is the set value for the deadband action of primary frequency modulation. Substituting Equation (6) into Equation (5), the extreme value of the GFM converter's output frequency, f_{nadir} , can be obtained:

$$\begin{aligned} f_{\text{nadir}} = f_N - f_{\text{db}} \\ - \frac{(2\Delta P - \sigma^{-1} f_{\text{db}})(\Delta P - \sigma^{-1} f_{\text{db}})}{8HR^{\text{SYS}} + \sigma^{-1}(2\Delta P - \sigma^{-1} f_{\text{db}})} \end{aligned} \quad (7)$$

The GFM converter's maximum frequency deviation value is ΔP_{max} :

$$\begin{aligned} \Delta f_{\text{max}} = f_N - f_{\text{nadir}} \\ = f_{\text{db}} + \frac{(2\Delta P^* - \sigma^{-1} f_{\text{db}})(\Delta P - \sigma^{-1} f_{\text{db}})}{8HR^{\text{SYS}} + \sigma^{-1}(2\Delta P - \sigma^{-1} f_{\text{db}})} \end{aligned} \quad (8)$$

To intuitively show the curves of frequency deviation values output by the GFM converter under different inertia time constants after being disturbed, as shown in Fig. 3.

From Expression (3) for the maximum rate of change of GFM converter output and expression (8) for the maximum frequency deviation value, it can be seen that under the same disturbance, as the value of H increases, the maximum frequency deviation value and the maximum of RoCoF after the disturbance both show a decreasing trend.

C. ANALYSIS OF FREQUENCY RESPONSE OF GFM CONVERTER AFFECTED BY DAMPING

The main function of the damping link is to reduce power and frequency oscillations, improve the convergence of the transition process, thereby reducing peak deviations and shortening the time required to return to the vicinity of the steady state. The introduction of damping control effectively alleviates oscillations in active power and frequency, which in turn decreases overshoot and improves the speed of system stabilization. In the rotor motion equation, both the damping term and the active power droop term are associated with the frequency deviation through a coefficient-multiplication form. Accordingly, for a GFM converter, the damping coefficient D in the dynamic response process can be written as:

$$D = -\frac{\Delta P_D^*}{\Delta f^*} \quad (9)$$

Where ΔP_D^* represents the nominal value of the damping response power, and Δf^* represents the nominal value of the frequency difference between the actual frequency and the system's rated frequency.

To demonstrate the impact of damping parameters on the stable response performance of grid-connected converter output frequency, this study conducts a comparative analysis using a photovoltaic grid-connected system. The comparison focuses on active power and frequency oscillations under damping control in the converter's control loop. Figure 3 presents the output frequency and power output comparison between damping-equipped and non-damping grid-connected converters when the grid frequency drops by 0.1 Hz.

In the operating conditions of sudden load reduction, sudden grid frequency reduction, and a sudden 10% increase in irradiance, the maximum output frequency deviation and overshoot of the GFM converter with damping and without damping in the frequency regulation control loop are shown in Table II.

As can be seen from Table II, under the three types of disturbances set, after introducing damping control, the

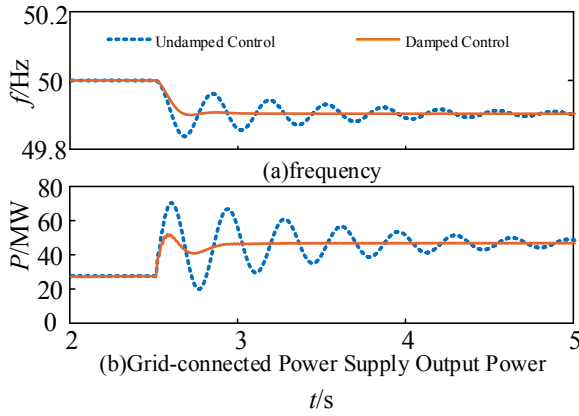


FIGURE 3. Comparison of frequency and power response of grid-connected converter after load disturbance

TABLE II. COMPARISON OF FREQUENCY RESPONSE INDEXES WITH DAMPING AND WITHOUT DAMPING UNDER DIFFERENT WORKING CONDITIONS

Frequency modulation control	working condition	Maximum frequency deviation/Hz	overshoot /%
undamping control strategy	The load suddenly decreased by 20MW	0.210	0.230
	The frequency of the power grid is reduced by 0.1Hz	0.130	0.130
	Increase irradiance by 10%	0.028	0.050
damping control strategy	The load suddenly decreased by 20MW	0.120	0.170
	The frequency of the power grid is reduced by 0.1Hz	0.033	0.061
	Increase irradiance by 10%	0.009	0.019

maximum frequency deviation and overshoot have significantly decreased, indicating that this component plays a positive role in improving the short-term dynamic quality.

III. FAST ESTIMATION OF INERTIA AND DAMPING COEFFICIENT OF GFM CONVERTER BASED ON LS AND GENETIC OPTIMIZATION

In a very short time after the disturbance occurs, the frequency adjustment has not yet taken action, and there is:

$$2H \frac{df}{dt} = P_m - P_e + D(f_N - f) \quad (10)$$

The PMU is installed at the outlet of the GFM converter to sample information such as output power and frequency. Since direct measurement of P_m cannot be achieved at this installation point, $P_e(t_0)$ is used instead of the P_m value. Considering that the LS method is a commonly used and effective method for solving multivariate parameter regression problems, and the GA can efficiently and accurately solve the optimal solution under the LS method [32], this paper realizes the fitting of inertia and damping parameters in Equation (10) based on the LS and GA. The solution process is shown in Figure 4, and the specific steps are as follows:

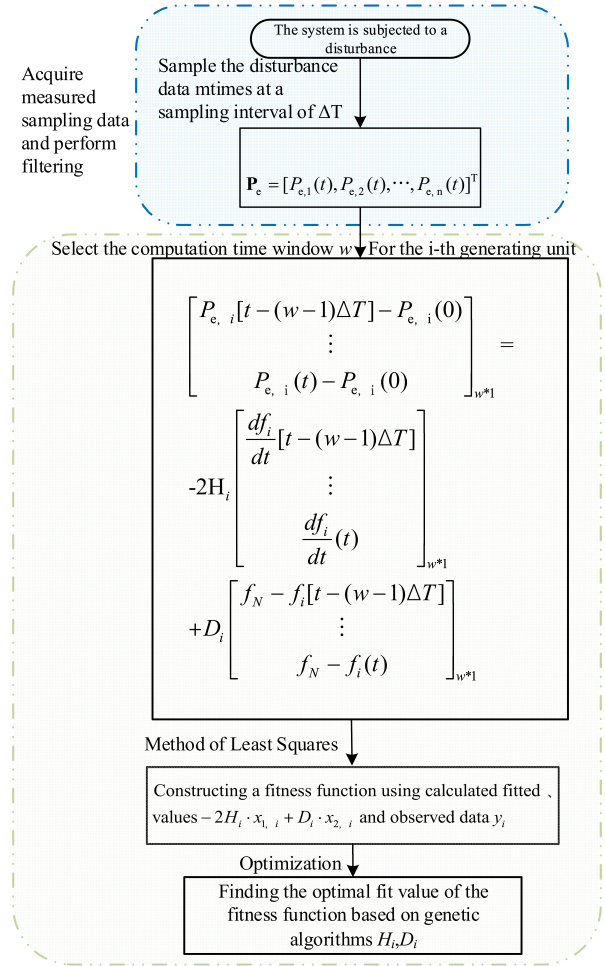


FIGURE 4. Flow chart of inertia and damping coefficient estimation for network-type converter based on LS and GA algorithms

1) If there are n GFM converters in the system, obtain the measurement data based on the installed PMU devices and filter the required measurement data:

$$P_e = [P_{e,1}(t), P_{e,2}(t), \dots, P_{e,n}(t)]^T \quad (11)$$

$$f = [f_1, f_2, \dots, f_n]^T \quad (12)$$

$$P_m = [P_{m,1}, P_{m,2}, \dots, P_{m,n}]^T \quad (13)$$

$$= [P_{e,1}(0), P_{e,2}(0), \dots, P_{e,n}(0)]^T$$

Wherein, $P_{e,i}(t)$ ($i = 1 \sim n$) is the output active power of the i -th GFM converter at time t , and matrix P_e is the output active power matrix of each GFM converter at time t ; f_i is the output frequency of the i -th GFM converter at time t , and matrix f is the output frequency matrix of each GFM converter in the system at time t ; $P_{m,i}(t)$ ($i = 1 \sim n$) is the mechanical power of the i -th GFM converter at time t , and matrix P_m is the mechanical power matrix of each GFM converter at time t .

2) Determine the disturbance occurrence time based on the detrended fluctuation analysis method.

The core of detrended fluctuation analysis is to eliminate long-term trends in the data, thereby more accurately capturing short-term fluctuation characteristics and ultimately achieving the identification of the moment when a transient occurs. The specific process is as follows: Use M as the window length for detrended fluctuation analysis, and each time select $M-1$ historical data points and the current time data as the object of a single detrended fluctuation analysis. The serial number of the measured signal is denoted by k . The original measured signal $a(k)$ is “detrended” to obtain the integrated signal $b(k)$.

$$b(k) = \sum_{i=1}^k [a(i) - \bar{a}] \quad (14)$$

In the formula, $\bar{a}$ is the average value of k original measured signals.

Next, the $b(k)$ signal within the M -length window is equally divided into data segments of length m . Each segment of data is fitted by the LS method to obtain the “local trend” $b_m(k)$ of each segment. Then, the local trend values in $b(k)$ are subtracted to obtain the detrended signal:

$$c(k) = b(k) - b_m(k) \quad (15)$$

The fluctuation degree of M data within the window is reflected by the root mean square fluctuation function F :

$$F = \sqrt{\frac{1}{M} \sum_{k=1}^M [c(k)]^2} \quad (16)$$

The larger the value of F obtained at a certain moment, the greater the variance in the signal, which indicates a more significant transient in the measured signal at the current moment.

Based on the detrended fluctuation analysis method, this paper can accurately identify the time point when large fluctuations occur in the system by directly analyzing real-time measured quantities, without the need to establish complex models to calculate the inertia and primary frequency modulation parameters at each time point in the system, thus improving the estimation speed and saving memory.

3) After determining the key time nodes, focus on the time periods of inertia response and damping response in Figure 1 to complete the estimation. The i -th GFM converter satisfies Equation (8) at any time t before the primary frequency modulation response. To improve the accuracy of dynamic fitting, the estimation adopts the sliding LS fitting method, that is, whenever a new point is sampled, this point is taken as the end, and the previous $w-1$ points are looked back for fitting. w is the calculation time window length. In this case, the fitting frequency is equal to the sampling frequency; select the calculation time window length w , and bring the observed quantities into Equation (8), that is, the frequency response process of the i -th GFM converter satisfies the following LS theoretical function:

$$\mathbf{y}_i = -2H_i\mathbf{x}_{1,i} + D_i\mathbf{x}_{2,i} \quad (17)$$

$$\mathbf{y}_i = \begin{bmatrix} P_{e,i}[t - (w-1)\Delta T] - P_{e,i}(0) \\ \vdots \\ P_{e,i}(t) - P_{e,i}(0) \end{bmatrix}_{w \times 1} \quad (18)$$

$$\mathbf{x}_{1,i} = \begin{bmatrix} \frac{df_i}{dt}[t - (w-1)\Delta T] \\ \vdots \\ \frac{df_i}{dt}(t) \end{bmatrix}_{w \times 1} \quad (19)$$

$$\mathbf{x}_{2,i} = \begin{bmatrix} f_N - f_i[t - (w-1)\Delta T] \\ \vdots \\ f_N - f_i(t) \end{bmatrix}_{w \times 1} \quad (20)$$

Where $\mathbf{y}_i$, $\mathbf{x}_{1,i}$, and $\mathbf{x}_{2,i}$ are the observed quantities in the LS fitting process. $\mathbf{y}_i$ represents the active power variation of the i -th GFM converter within the window; $\mathbf{x}_{1,i}$ is the frequency change rate of the i -th GFM converter within the window; $\mathbf{x}_{2,i}$ denotes the frequency deviation of the i -th GFM converter within the window. All vectors are of $w \times 1$ dimension, and H_i and D_i are undetermined parameters.

Where $\mathbf{y}_i$, $\mathbf{x}_{1,i}$, $\mathbf{x}_{2,i}$, $\mathbf{x}_{3,i}$ represent the LS fitting measurement values (for the i -th GFM converter within the window): $\mathbf{y}_i$ is the active power change, $\mathbf{x}_{1,i}$ is the frequency change rate, $\mathbf{x}_{2,i}$ is the frequency deviation, $\mathbf{x}_{3,i}$ is the DC voltage deviation; each vector is of the $w \times 1$ dimension, and H_i , D_i are the undetermined parameters.

4) Construct the fitness function (i.e., error function) required for fitting based on the LS error:

$$\begin{aligned} \text{Fitness}(H_i, D_i) &= \text{error}(H_i, D_i) \\ &= \|\mathbf{-2H_i x_{1,i} + D_i x_{2,i} - y_i}\|^2 \\ &= \sum_{k=1}^n (-2H_i x_{1,i} + D_i x_{2,i} - y_i)^2 \end{aligned} \quad (21)$$

5) Use the GA to solve the optimal solution of Equation (21) and obtain the optimal solutions H_i and D_i for each fitting.

To narrow the search range of H_i , set the search boundary of H_i by referring to the typical setting value range of H_i for various frequency modulation resources summarized in Table I, and set the lower search bound of the damping coefficient D_i to 0, so as to shorten the solution time of the GA and improve the solution accuracy of the algorithm.

IV. DESIGN OF VERIFICATION METHOD FOR INERTIA AND DAMPING COEFFICIENT ESTIMATION RESULTS

In existing studies [33], it has been pointed out that the VSC frequency modulation control strategy based on fixed damping parameters has certain limitations. When the grid strength changes, the frequency modulation performance of damping control may be reduced or even deteriorated. To make the damping control strategy applicable to multiple scenarios, in current common damping control strategies such as additional damping [34] and adaptive damping parameter control [35], damping control is not added to the

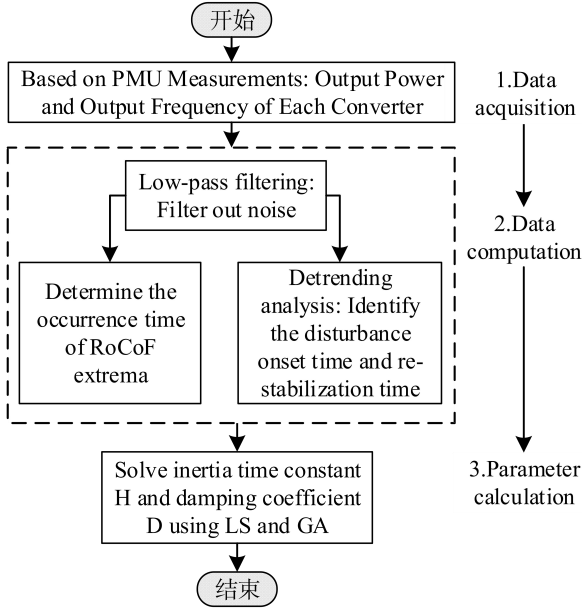


FIGURE 5. The estimation process of inertia and damping parameters of networked converter with damping control is considered

frequency modulation control link in the form of the product of fixed damping parameters and frequency difference [36]. If expressed by the classic Phillips–Heffron model [37], the damping control parameter K_D varies under different excitations. At this time, although the estimated damping parameter value can be obtained via the damping estimation method, verifying the validity of the result is challenging as the specific setting of the damping parameter under current excitation is unknown.

According to existing research results of the P - ω admittance method: Under the same excitation, the GFM converter's power/frequency responses in the P - ω admittance-based generalized model match the actual model. Considering the mapping between frequency modulation control link parameters and circuit model component parameters. The expressions of the component parameters in the circuit model can be derived based on the P - ω admittance method and frequency modulation control strategy [34], and the estimated values of key frequency modulation parameters can be converted into component parameter values in the circuit model under the estimated values. By replacing the component parameter values of the generalized circuit model in the actual system with those calculated from the parameter estimation results, the generalized circuit model of the actual system under the parameter estimation results can be constructed.

Based on the above, this paper designs a P - ω admittance-based dual-model comparison verification method:

1) Construct the generalized circuit model based on P - ω admittance in the actual system. In this process, derive the expressions of component parameters in the circuit model according to the control block diagram and P - ω admittance modeling.

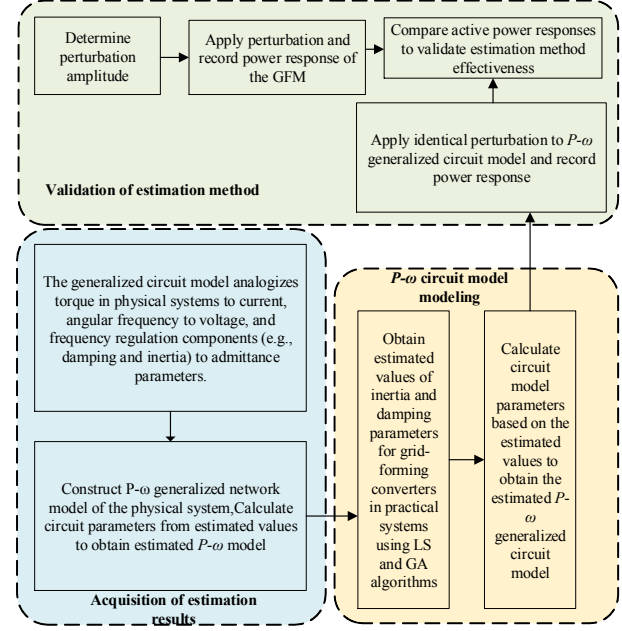


FIGURE 6. Key frequency modulation parameter estimation and verification steps

2) Record the estimated frequency modulation parameters as a column vector, reversely derive the corresponding component parameter values in the circuit model under the estimated frequency modulation parameters, and replace the original parameter values in the circuit components with them to obtain the generalized circuit model under the estimated values.

3) In the comparison process, two models are involved: one is the simulation verification model of the actual system, and the other is the generalized circuit model under the estimated values. Record and compare the GFM converter's active power responses in the two models under the same excitation. If the responses are consistent, the accuracy and validity of the estimated system inertia and damping parameters can be verified.

The specific process of estimation and result verification is shown in Figure 6.

Directly plotting and comparing the GFM converter's output power waveforms between actual and circuit models can visually check response consistency, but it cannot quantitatively analyze the effectiveness and estimation accuracy of the estimation results. To quantitatively assess inertia and damping parameter estimation accuracy, this chapter uses the root mean square error (RMSE) of active power response to determine overall accuracy. Specifically, during the phase with only inertia and damping responses, the RMSE between the output power P_{e_r} of the GFM converter in the simulation and the active power response P_{e_t} of the circuit model under disturbance conditions is calculated. The formula is as follows:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n [P_{e_r}(i) - P_{e_t}(i)]^2}{n}} \quad (22)$$

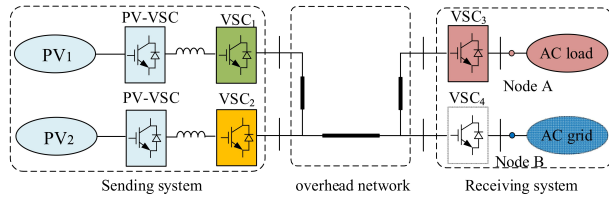


FIGURE 7. Flexible calculation example system

Where n denotes the number of measurement points from the phase characterized by only inertia and damping responses.

V. SIMULATION VERIFICATION

A. SIMULATION CASE INTRODUCTION AND OPERATING CONDITION SETUP

This chapter estimates the key frequency modulation parameters of the GFM converter at the receiving end in the photovoltaic (PV) grid-connected system via active support-type flexible DC, to verify the effectiveness and accuracy of the proposed estimation technique. As shown in Figure 7 [34], The simulation case includes two parallel PV systems, a power grid, and AC loads. The system mainly consists of a flexible DC sending-end system (photovoltaic power generation), transformers, sending-end converters (VSC1 and VSC2), receiving-end converters (VSC3 and VSC4), and a receiving-end system (AC grid and AC loads). Control strategies adopted by each VSC: VSC1 and VSC2 on the PV system side use U_{DC} - f droop control; VSC3 on the AC load side employs virtual synchronous machine control; VSC4 on the AC grid side adopts inertial synchronization control with additional virtual DC power damping, which forms virtual power damping by introducing DC-side current, rated voltage, and a band-pass filter.

In addition, the reference values selected during the estimation process are: the capacity reference value S_B is 100 MW, and the frequency reference value f_B is 50 Hz. Furthermore, the computer configuration used for simulation verification includes an Intel Core i9 CPU, 1 TB of memory, and a PMU sampling frequency of 100 Hz. The proposed estimation algorithm was validated by installing PMUs at nodes A and B to measure the equivalent inertia time constant and damping coefficient of the grid-connected converter in the flexible DC system, with results compared against preset frequency regulation parameters. During simulation verification, two disturbances were applied: Condition 1: 20MW decrease in AC load; Condition 2: 0.1Hz frequency drop on the grid side.

B. ESTIMATION OF FREQUENCY MODULATION PARAMETERS

VSC4 adopts inertial synchronization control with additional virtual DC power damping. Firstly, the disturbance occurrence time is determined based on detrended fluctuation analysis, and the required observed variables are

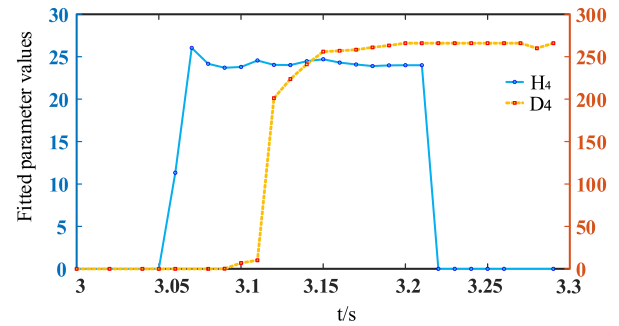


FIGURE 8. Improved control strategy for receiving end converter based on virtual DC power damping

TABLE III. THE ESTIMATED FREQUENCY MODULATION PARAMETERS OF VSC3 AND VSC4 IN THE EXPERIMENT

Experiment number	VSC3		VSC4		
	H_3 estimated value/s	H_3 relative error/%	H_4 estimated value/s	H_4 relative error/%	D_4 estimate results/rad $^{-1}$
Condition 1	6.61	-0.87	11.9	-2.93	253.4
Condition 2	6.96	4.38	11.7	-4.22	243.1

obtained. The sliding fitting of H_4 and D_4 is completed using LS (LS) and GA (GA), with the estimation results shown in Figure 8. Since VSC3 is known to have no damping control loop, D_i in the error function can be assigned a value of 0, and estimation is performed according to the aforementioned method. Damping parameters vary under different excitations, and the specific set value of the damping parameter under the current excitation cannot be determined; therefore, no set value is available for the damping parameter. Finally, the estimation results and estimation errors of frequency modulation parameters in Operating Condition 1 and Operating Condition 2 are summarized in Table III.

Analysis of Table III shows that when estimating the frequency modulation parameters of a single power source using this method, the estimation error of the equivalent inertia time constant does not exceed 5%, indicating the effectiveness and accuracy of the proposed method.

C. VERIFICATION OF ESTIMATION RESULTS CONSIDERING DAMPING CONTROL

For validation under damping control, the estimated values are mapped to the relevant component parameters in the generalized circuit model of the case system, and the corresponding original circuit parameters are replaced. Under the same disturbance condition adopted in the estimation process, the active power response of the simulation model with preset parameters is compared with that of the receiving-end GFM converter in the generalized circuit model with estimated parameters, so as to verify the effectiveness of the estimation results.

1) Construction of the generalized circuit model for the case system

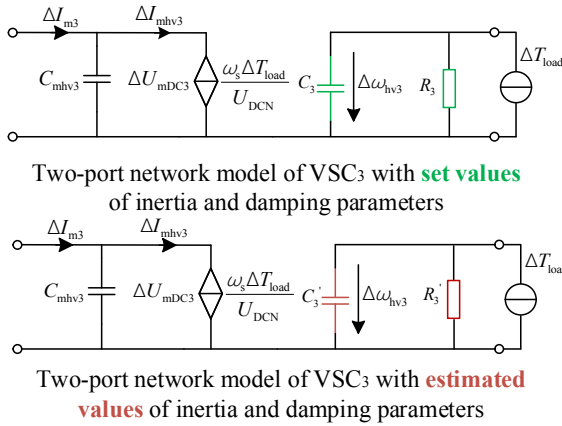


FIGURE 9. The inertia damping parameters are the VSC3 two-port network model with set value and estimated value respectively

Reference [34] has constructed a generalized circuit model for the photovoltaic grid-connected case via flexible DC (Figure 7).

2) Replacement of circuit component parameters related to key frequency modulation parameters

Reference [34] has derived expressions for all circuit components constituting the generalized circuit model, which are not elaborated here. The focus is on the expressions of circuit component parameters related to the key frequency modulation parameters of VSC3 and VSC4.

① For VSC3

The two-port circuit model of VSC3 [34] is:

C_3 is related to the inertia link of VSC3, and R_3 is related to the primary frequency modulation link of VSC3. The conversion relationship between C_3 , R_3 and the frequency modulation parameters of the case system is shown in the following equation:

$$\begin{cases} C_3 = \alpha \frac{2S_N H_3}{\omega_N^2}, \\ R_3 = \frac{\sigma_3 \omega_N}{S_N}. \end{cases} \quad (23)$$

The estimated values of frequency modulation parameters H_3 and σ_3 of VSC3 are substituted into the circuit parameter formula (23) to obtain the circuit parameters C'_3 and R'_3 . After replacing C_3 and R_3 in the VSC3 two-port network model under the set values with C'_3 and R'_3 , the VSC3 two-port network model under the estimated inertia damping parameters can be obtained. This process is shown in Figure 9.

② For VSC4

In this case model, the virtual DC damping link of VSC4 is converted into a parallel form of G_{mhv} , R_{mhv} , and L_{mf} , and the inertia control link is converted into C_{mhv4} , as shown in Figure 10 [34].

The conversion relationship is:

$$C_{mhv4} = \frac{\alpha S_N H_4}{\omega_N^2} \quad (24)$$

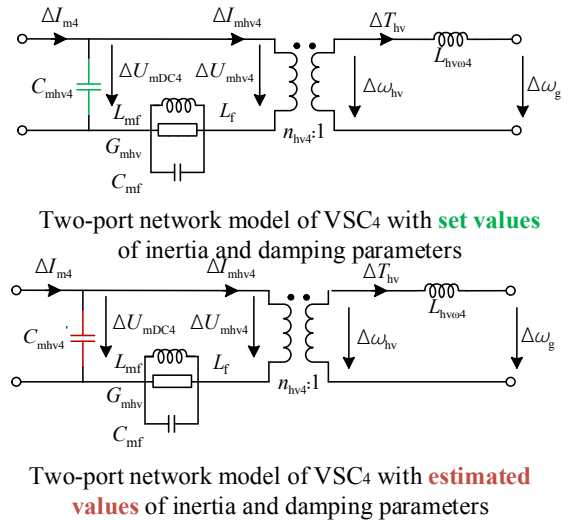


FIGURE 10. The inertia damping parameters are the VSC4 two-port network model with set value and estimated value respectively

$$\begin{cases} G_{mhv} = \frac{\alpha S_N}{U_{DCN} D_4 \omega_N}, \\ L_{mf} = \frac{\alpha S_N}{L_f \omega_N}, \\ C_{mf} = \frac{\alpha S_N}{C_f \omega_N}. \end{cases} \quad (25)$$

During the verification process, substituting the estimated H_4 and D_4 into equations (24) and (25) yields a new set of C_{mhv4} and G_{mhv} . The replacement process is identical to that for VSC1, as illustrated in Figure 10. Parameters C_{mf} and L_m related to the band-pass filter remain unchanged.

To verify the parameter estimation accuracy, the circuit component parameters in the generalized circuit model corresponding to the case system shown in Figure 7 are modified. Circuit parameters C_{mhv4} , G_{mhv} , C_3 , and R_3 —relevant to the key frequency modulation parameters of VSC3 and VSC4—are replaced with C'_{mhv4} , G'_{mhv} , C'_3 , and R'_3 derived from the estimation results under corresponding operating conditions (1 and 2). This yields the generalized circuit model under the parameter estimation results. For comparative analysis of active power response curves, the same disturbance excitation as in the original case simulation is applied to the generalized circuit model, and the following two types of outputs are recorded and compared. Figures 11 and 13 present the comparison results with $\pm 5\%$ relative error bands. It can be intuitively observed that the active power response of the actual case system all the time lies within this error range, with the relative error between the two response curves consistently maintained within 5%.

The RMSEs of the output power curve of the simulation model in Figure 7 and the output power curve of the generalized circuit model under the estimation results are calculated respectively by Equation (22) to complete the quantitative analysis of the joint estimation accuracy of inertia and damping. It is concluded that during the simul-

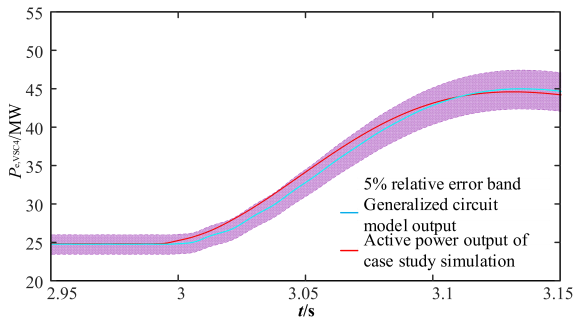


FIGURE 11. Comparison Chart of Active Power Response between Simulation Model and Estimated Parameters-based Circuit Model under Operating Condition 1

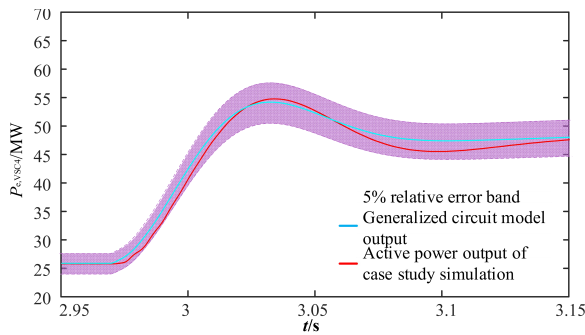


FIGURE 12. Comparison Chart of Active Power Response between Simulation Model and Estimated Parameters-based Circuit Model under Operating Condition 2

taneous response phase of inertia and damping, the RMSE of operating condition 1 is 1.23MW, and that of operating condition 2 is 1.37MW, which effectively quantifies the parameter estimation accuracy. The comparison results in Figures 11 and 12, along with the RMSE values, verify the accuracy and effectiveness of the LS-GA-based estimation method for system inertia and damping parameters. The estimation errors of system inertia and damping parameters are strictly controlled within the 5% threshold, verifying the accuracy of the proposed inertia and damping estimation method.

VI. CONCLUSION

This paper addresses the estimation of inertia and damping parameters in GFM converters, proposes a method for identifying key frequency-regulation parameters, and demonstrates the effectiveness of the proposed method. The main conclusions are summarized as follows:

- 1) Exploiting the temporal characteristics of post-disturbance frequency-regulation dynamics, this paper develops an LS-GA-based method for estimating inertia and damping parameters and establishes a fast estimation framework for GFM converters.
- 2) Based on the P - ω admittance method, a dual-model comparative validation framework is established. The estimated parameters are incorporated into the generalized circuit model, and the validity of the estimation results

is examined through the consistency of the active power responses of the actual system and the GFM converter in the circuit model under the same disturbance condition. The estimation accuracy is quantitatively evaluated by the RMSE of the two response curves.

3) Validation on a photovoltaic grid-connected system based on VSC-HVDC indicates that the proposed method is capable of rapidly estimating the key parameters of the receiving-end GFM converter within 0.2s following a disturbance, with the estimation error maintained below the 5% threshold.

This method realizes the fast estimation of inertia and damping parameters of GFM converters in photovoltaic grid-connected systems via VSC-HVDC. However, how to propose a system stability margin index based on frequency modulation parameters according to the estimation results of frequency modulation parameters, frequency deviation, and safety thresholds of RoCoF, so as to realize the quantitative evaluation of the system frequency stability level, remains to be further studied.

The proposed method provides a fast means of estimating the inertia and damping parameters of GFM converters in PV grid-connected systems via VSC-HVDC. Nevertheless, further study is required to establish a system stability margin index based on frequency-regulation parameters by integrating the estimated parameter values, frequency deviation, and RoCoF security thresholds, thereby enabling quantitative assessment of system frequency stability.

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