VSG damping adaptive adjustment based on BP neural network

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Abstract. The moment of inertia and damping of virtual synchronous generator (VSG) can be adjusted flexibly, which also has a significant impact on the transient performance of VSG. Constant damping or moment of inertia cannot reduce frequency overshoot and fast response performance, so it is necessary to introduce adaptive damping control. Based on universal approximation theorem, BP neural network can fit continuous nonlinear function well. At the same time, it has the advantages of simple algorithm, powerful learning ability and fast learning speed. Based on the characteristics of the control object, the BP neural network is improved and a new adaptive control strategy is designed. The strategy uses improved BP neural network to adjust VSG virtual damping $D$ online. Python-MATLAB-Simulink was used for co-simulation, BP neural network algorithm was integrated into the control object to establish an adaptive simulation model, and the proposed control strategy was simulated and verified. Simulation results show that the adaptive control strategy can eliminate overshoot and respond quickly when the frequency and active power of virtual synchronous generator change.

1. Introduction
Constant damping has major drawbacks. Too large damping can ensure the transient process without oscillation, but will make the output power of primary FM error. Low damping can reduce such errors, but again there are oscillations. In view of this contradiction, many scholars have proposed the methods of transient damping and inertia in recent years. Literature [1] proposed a solution of introducing a transient damping link that reflects the characteristics of the damping windings of synchronous generators, realizing VSG simulation of transient and steady-state characteristics of synchronous generators at the same time, and establishing a small signal dynamic model of VSG control with transient damping characteristics. Li Zhijun et al. Literature [2] whose author is from Hebei University of Technology proposed a VSG control strategy to improve the damping characteristics of inertia. By adding a differential correction link to the inertia damping control, VSG's inertia damping characteristics in different frequency bands are changed to achieve the purpose of considering the dynamic and static characteristics of the system.

These results solve the contradiction of transient damping and inertia to some extent. However, it relies too much on VSG's small signal model. Due to the linear relationship between the generator power Angle and the output power $P_e$ in a very small range, the accuracy can be guaranteed when the system frequency changes and the power instruction is changed in a small range. However, in the case of wind farm custom change or photovoltaic panel illumination mutation, the output power fluctuates greatly, and the small-signal model loses its accuracy.
2. Virtual Synchronous Generator and BP Neural Network

2.1. Virtual synchronous generator

VSG method is only an improvement on the interface inverter control algorithm, does not need to adjust the grid structure on a large scale, has a strong practical utility in engineering. The structure of the VSG can be roughly divided into two layers, the first layer calculates the active power and reactive power instructions, and the second layer controls the inverter output of the corresponding current or voltage, so that the power output of the inverter meets the requirements of the power command[2]. In this paper, VSG is a current-type virtual synchronous generator, that is, the inverter output current is selected as the control amount, and the control mode is hysteresis control[3].

![Figure 1. The topology of VSG control circuit](image)

VSG's simulation of a real synchronous generator is reflected in the calculation of power instructions. Active power instruction $P_{ref}$ equivalent to the real synchronous generator's primer input power, the inverter output power is equivalent to the real synchronous generator's output power to the external circuit.

The essence of VSG is still the control of inverter, but the control logic is the algorithm of virtual synchronous generator. Part of the algorithm is the rotor motion equation of the synchronous machine and the electromagnetic relation of the fixed rotor. The other part is frequency and voltage droop control. Combined with the distributed power supply, the rotor inertia and damping characteristics of traditional synchronous machine can be simulated while controlling voltage and frequency.

The rotor mechanical equation of a real synchronous generator is shown in equation 1:

$$\begin{align*}
J \frac{d\omega}{dt} &= \frac{P_m}{\omega} - \frac{P_e}{\omega} - D(\omega - \omega_0) \\
\frac{d\delta}{dt} &= \omega - \omega_0 \\
\dot{\delta} &= \int (\omega - \omega_0) dt = \varphi - \int \omega_0 dt \\
\varphi &= \int \omega dt
\end{align*}$$

In this equation, $\omega$ is system angle frequency, and $\omega_0$ is rated angle frequency; $J$ is the moment of inertia; $D$ is the damping coefficient; $P_m$, $P_e$, and $D(\omega - \omega_0)$ respectively represent the corresponding
power of mechanical power, electromagnetic power and damping torque. $\delta$ is the internal power angle of the synchronous generator, where $\phi$ is the phase of the port line voltage of the synchronous machine when the phase current is the reference phasor.

There is another important relation in actual synchronous generator, that is, the relationship between excitation electromotive force and generator terminal voltage. Synchronous generator armature resistance and synchronous reactance will produce voltage drop, so the excitation electromotive force, generator terminal voltage and stator current meet:

$$\dot{E} = \dot{U} + IR_f + j\dot{X}_f$$  \hspace{1cm} (2)

In (2), $\dot{E}$ is congestion electric potential, $\dot{U}$ is generator port voltage, $R_f$ and $X_f$ are a generator armature resistors and synchronous resistors, $\dot{I}$ is the stator current.

2.2. BP Neural Network

BP neural network algorithm was proposed in 1986 by Rumelhart et al. who come from Stanford University. The algorithm effectively solved the connection weight problem of hidden layers in the multi-layer network model, and effectively improved the self-learning and organization ability of neural network.

The topological structure of BP neural network is shown in Figure 2. The input layer of BP neural network acts on the output layer by the hidden layer and outputs. The quantity is obtained by nonlinear transformation. Each sample of neural network training contains input and expected output. By adjusting network weights and thresholds, the error between network output and expected output decreases along the gradient direction until the actual output and expected output are within a predetermined range.

$$\omega_y(n+1) = \omega_y(n) - \eta \frac{\partial L}{\partial Y} \frac{\partial Y}{\partial \omega_y(n)}$$  \hspace{1cm} (3)
In this equation, \( \omega_y(n+1) \) and \( \omega_y(n) \) are the weights before and after the update respectively. \( \eta \) is the learning rate, and \( L \) is the loss function of neural network. \( Y \) is the output of neural network.

3. BP neural network with VSG adaptive model

3.1. Overall framework of adaptive model

Consider the damping as a time-varying function, and the constant damping is a line parallel to the t-axis. A batch of simulation results and corresponding damping are used as the training set. The input of neural network is active power vector and the output is damping vector. After a lot of training, the neural network is fitted into the model of virtual synchronous generator, namely:

\[
F(P, Q) = D
\]  

In this equation, \( P, Q \) is respectively the input active and reactive power vector, and its specific content is shown in Table 1. When the input \( X \) is the ideal waveform, a damping vector can be obtained that causes the virtual synchronous machine to exhibit such a power response curve.

The process of this paper can be summarized as follows: acquire a large number of input data and corresponding output waveform from the perfect and detailed VSG model, and train the neural network to perform relational fitting of its input and output to complete modelling. When the neural network training is completed, the ideal active power transient curve is taken as the input, and the damping time series corresponding to the ideal active power transient curve is finally obtained. The block diagram is shown in Figure 3.

Any successful training of neural network is inseparable from a comprehensive and rich training set. The training set used in this paper includes power command step, frequency mutation active power change, network voltage drop and reactive power supplement, so as to describe the virtual synchronous generator comprehensively.

3.2. The modeling processes

Based on the simulation data based on VSG mechanism model, the steps of VSG modelling are as follows by using data-driven modelling method:

Step 1): Data acquisition and preparation. The operating data of VSG under different operating conditions were collected, and the input and output variables of neural network were obtained through data integration and preliminary calculation, forming the data of training set and test set.

Step 2): In order to prevent the adverse effects caused by the large difference in the order of magnitude of different physical quantities, all data are normalized.

Step 3): Determine the scale of the neural network, including determining the network structure and training algorithm. This paper adopts a single hidden layer network structure, with 40,000 nodes in the input layer. It is composed of \( P \) and \( Q \) vectors with length of 20,000. After many trials, when the number of hidden layer neural units is 10, the network modelling effect is better.
Step 4: Neural network training and error calculation. Input data of training set into neural network to get corresponding predictive value. According to the predicted value and the real value of the output data of the training set, the error is calculated. According to the error back propagation algorithm, the parameters of the neural network are adjusted until the error meets the accuracy or reaches the maximum number of iterations.

Step 5: The input data of the test set is input into the trained neural network to obtain the corresponding predicted value, which is compared with the real value of the output data of the test set. The root mean square error is calculated according to Formula (4) to evaluate the modelling effect.

\[ E_{\text{RMS}} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - y_r)^2} \]  

(5)

In this equation, \( y_i \) is the predicted value of the model; \( y_r \) is the true value.

4. The simulation verification

In order to verify the accuracy of the modelling method in this paper, a single VSG grid-connected system as shown in Figure 1 is built on the MATLAB/Simulink simulation platform to obtain the operating data of VSG under different working conditions. The simulation parameters of VSG are shown in Table 1.

The simulation is divided into two conditions. Under the first operating condition, the system frequency drops by 0.5 Hz, and VSG senses the system frequency drop and emits 75 kW more power. Under the second working condition, the system frequency increases by 0.5 Hz, and VSG emits 75 kW less power. The initial active power of VSG is 100 kW and 200 kW respectively, and the system frequency changes when \( t=0 \).1s. Firstly, the transient process of primary frequency modulation is observed under constant damping condition. When the damping is 50, 75, 100 and 125 respectively, the transient processes have oscillations and steady-state errors.

| Parameter                                      | Value     |
|------------------------------------------------|-----------|
| Rated active power \( P_n \)                   | 100KW     |
| Rated reactive power \( Q_n \)                  | 50Kvar    |
| Rated frequency \( f_n \)                       | 50Hz      |
| Rated line voltage \( U_n \)                    | 380V      |
| Filter capacitor reactive \( Q_c \)             | 10Kvar    |
| Line inductance \( L_f \)                       | 0.001H    |
| Parasitic resistance \( R_f \)                  | 0.004Ω    |
| Virtual Inertia \( J \)                         | 0.1s      |
| Damping coefficient \( D \)                     | 75        |
| Primary frequency modulation coefficient \( K_f \) | 150KW/Hz  |
| Reactive power regulation factor \( k_q \)       | 0.00001   |
| DC side rated voltage \( U_{dc} \)              | 700V      |

If the adaptive damping calculated by BP neural network is used for control, the system frequency change is equal to the rated value without deviation, and the whole transient process has no oscillation and no overshoot. Figure 4 shows the corresponding waveform when the system frequency drops, and Figure 5 shows the corresponding waveform when the system frequency rises.
5. Conclusion

The virtual synchronous generator with constant damping has many disadvantages. When primary frequency modulation is required, too small damping will not only bring oscillation, but also cause insufficient change of output power. Excessive damping can effectively reduce the oscillation, but correspondingly will make the change in the output power of primary FM deviate from the rated value. After adopting adaptive damping, the output power not only has no overshoot and oscillation in the transient process of primary frequency modulation, but also can accurately reach the rated value. The adaptive damping real-time control strategy based on BP neural network saves complicated calculation and trial, and does not rely on accurate model, showing great advantages.

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