Frequency Regulation Control and Parameter Optimization of Doubly-Fed Induction Machine Pumped Storage Hydro Unit

LINJUN SHI¹, (Member, IEEE), WENJIE LAO¹, FENG WU¹, (Member, IEEE), TAO ZHENG², AND KWANG Y. LEE³, (Life Fellow, IEEE)
¹College of Energy and Electrical Engineering, Hohai University, Nanjing, Jiangsu 210098, China
²NARI Group Corporation, Nanjing, Jiangsu 211100, China
³Department of Electrical and Computer Engineering, Baylor University, Waco, TX 76798, USA

Corresponding authors: Linjun Shi (eec@hhu.edu.cn), Wenjie Lao (lwj00310@163.com), and Kwang Y. Lee (kwang_y_lee@baylor.edu)

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ABSTRACT Since doubly-fed induction machine pumped storage hydro (DFIM-PSH) unit can adjust active power flexibly through adjustable-speed operation, it has frequency regulation capability in both generating and pumping modes. In order to explore the frequency regulation capability of DFIM-PSH unit under different working conditions, this paper develops a frequency control module for DFIM-PSH unit in pumping mode, which is quite different from that in generating mode, and then optimizes the frequency control parameters aimed at minimizing the frequency deviation in multiple operating conditions. Based on the dynamic model of the DFIM-PSH unit, the system frequency response model is built to analyze the influence of parameters on frequency dynamic characteristics. An optimization method of frequency control parameters is developed based on improved particle swarm optimization algorithm to maximize its frequency regulation capability under different operating conditions while ensuring safe and stable operation. Finally, a four-machine two-zone power system model with a DFIM-PSH unit is simulated, and the simulation results show that the proposed strategy can make the DFIM-PSH unit have great frequency regulation performance in a wide range of operating conditions.

INDEX TERMS Doubly-fed induction machine, pumped storage hydro unit, different working conditions, frequency regulation, system frequency response model, frequency control parameter optimization.

I. INTRODUCTION

With the increase of penetration for grid-connected renewable energy sources (RESs) such as wind power and photovoltaic power, the frequency characteristics of power grid are experiencing further deterioration. Pumped storage hydro (PSH) unit is one of the most important tools to solve the frequency problem of the grid, but traditional PSH units generally will not participate in the frequency regulation due to its inability to adjust active power continuously in the pumping mode [1], [2], [3].

New PSH power station based on doubly-fed induction machine (DFIM) (DFIM-PSH) can not only overcome the disadvantages of traditional PSH unit including low efficiency and inability to adjust power in the pumping mode, but also has more flexible power regulation capability since it can realize variable-speed operation [4], [5], [6]. Therefore, it can be seen that DFIM-PSH unit is equipped with additional frequency regulation capacity and frequency regulation potential through variable-speed operation, which provides a feasible scheme for relieving the increasing frequency regulation pressure of the grid. However, since control strategies adopted by DFIM-PSH unit will lead to the decoupling of unit’s speed and the grid’s frequency, the unit cannot automatically participate in frequency adjustment, which needs
to be realized by constructing additional frequency control modules [7], [8], [9]. Therefore, it is of great significance and value to explore the frequency regulation potential of DFIM-PSH unit and study its frequency control strategies under both generating and pumping modes, which are beneficial to improve the frequency characteristics of the grid and enhance its stability and safety.

In recent years, works on DFIM-PSH unit mainly focus on its modeling and power decoupling control. In [4] and [10], the electrical and hydraulic mechanical parts of DFIM-PSH are modeled, and its steady-state and transient characteristics are further discussed. According to these, fast power response control strategies are discussed based on the analysis of unit’s operating characteristics [9], [11]. Since the control characteristics of DFIM-PSH in generating mode are similar to those of DFIM-based wind generator, recent studies on DFIM-PSH unit’s participation in frequency regulation are mainly developed based on the frequency control strategies of DFIM-based wind generator, using droop control and virtual inertia control to convert frequency deviation into auxiliary power instructions. In [12], an improved inertia control strategy using $\frac{d\Delta f}{dt}$ control link instead of $\frac{df}{dt}$ was proposed, which avoided negative damping effect in the later stage of frequency regulation compared with traditional virtual inertia control. Li et al. [13] analyzed the effects of frequency deviation and its rate of change on frequency response, and then proposed a frequency control strategy with droop coefficient adjusted in real time.

Although the above studies have verified their effectiveness of proposed strategies on enabling DFIM-PSH to automatically participate in frequency regulation in both generating and pumping modes, they were all based on power priority control strategy and did not take the characteristics of reversible pump/turbine into consideration. In [7], the electromechanical transient model of DFIM-PSH considering reversible pump/turbine was developed under pumping condition, and the mechanism of its function for improving the frequency characteristics of power grid was clarified. Accordingly, the recommended range of controller parameters under specified operating condition was given, but the specific selection criteria of parameters was not presented.

At the same time, since the operating state of DFIM-PSH changes greatly, the frequency control parameters optimized or calculated under one specific operating condition may not ensure the safety and stability of the unit in other states. In the field of DFIM-based wind generator, Zhao et al. [14] and Peng et al. [15] discussed how to improve the robustness of frequency control strategy under different wind speeds and disturbances and formed appropriate methods of determining the parameters. However, such studies are rarely involved in the field of DFIM-PSH.

This paper carries out relevant research work to alleviate the problems existing in current frequency control strategy for DFIM-PSH. Firstly, on the basis of dynamic mathematical model of DFIM-PSH, an additional frequency control module is constructed for the unit in pumping mode, where frequency deviation is converted into additional speed and active power instructions and then the flexible power regulation ability of DFIM-PSH can be played through the coordination between converter and reversible pump/turbine, and the module’s mechanism and characteristics of frequency regulation can be analyzed in detail. Secondly, by constructing the system frequency response model with DFIM-PSH, the root-locus method is used to analyze the influence of frequency control parameters on frequency dynamic characteristics, and the recommended range of each frequency control parameter is given. Accordingly, aiming at minimizing the frequency deviation with DFIM-PSH under multiple operating conditions, an optimization method for frequency control parameters is developed based on improved particle swarm optimization algorithm to maximize its frequency regulation capability under different operating conditions while ensuring safe and stable operation. Finally, a four-machine two-zone power system model with DFIM-PSH is simulated, and the system’s dynamic frequency responses under traditional frequency control and the proposed control are compared, verifying the effectiveness and robustness of the proposed frequency control strategy when the unit is under different operating conditions and different disturbances.

II. MATHEMATICAL MODEL AND CONTROL STRATEGIES OF DFIM-PSH

DFIM-PSH is mainly composed of reversible pump/turbine and its regulating system, DFIM, back to back converter and corresponding control modules. Through the coordination of hydraulic mechanical part and electrical part under different working conditions, speed regulation and decoupling control of active and reactive power can be realized.

A. MATHEMATICAL MODEL OF REVERSIBLE PUMP/ TURBINE

As the prime mover/load of DFIM-PSH, reversible pump/turbine can realize the switch between turbine and pump modes by changing the direction of rotation. Based on the IEEE nonlinear model, its mathematical model can be established as [16]:

$$\begin{cases}
\frac{dq}{dt} = \frac{h_0 - h - h_1}{T_0} \\
q = z\sqrt{h} \\
h_1 = f_0q^2 \\
p_{mech} = A_r h(q - q_N) - D_2(\omega_r - \omega_0)
\end{cases}$$

(1)

To simplify the analysis, the ideal model is often used to describe it:

$$G(s) = \frac{\Delta p_{mech}}{\Delta z} = \frac{1 - T_0s}{1 + 0.5T_0s}$$

(2)

Here, prefix $\Delta$ is used to represent change, $q$ is the relative value of flow, $H$ is the relative value of head, $z$ is the relative value of guide vane opening, $p_{mech}$ is the relative value of mechanical power, $\omega_r$ is the relative value of speed, $h_0$ is the relative value of initial head, $h_1$ is the relative value of
head loss, $q_{NL}$ is the relative value of no-load flow, $f_p$ is the head loss coefficient, $A_t$ is the proportional coefficient, $D$ is the velocity deviation damping coefficient, $\omega_0$ is the relative value of initial speed, and $T_{eo}$ is the inertia time constant of water flow.

**B. MATHEMATICAL MODEL OF DOUBLY-FED INDUCTION MACHINE**

Different from traditional pumped storage unit, DFIM-PSH adopts DFIM, which can help to realize the flexible and rapid adjustment of various physical quantities by adopting appropriate control strategy. When motor conventions are used on both stationary and rotor sides, the expressions of electromagnetic torque $T_e$ and active power $P_s$ and reactive power $Q_s$ can be derived based on the mathematical model of DFIM in the synchronous rotation coordinate system [17]:

$$T_e = \frac{3}{2} n_p (\psi_{sd} i_{sd} - \psi_{sq} i_{sq})$$

$$P_s = \frac{3}{2} (u_{sd} i_{sd} + u_{sq} i_{sq})$$

$$Q_s = \frac{3}{2} (u_{sd} i_{sd} - u_{sq} i_{sq})$$

Here, subscripts $s$ and $r$ indicate that the physical quantity belongs to stator side or rotor side, respectively. Subscripts $d$ and $q$ indicate that the physical quantity is the d-axis or q-axis component in the synchronous rotation coordinate system, $u$ is the voltage, $i$ is the current, $\psi$ is the flux linkage, and $n_p$ is the number of poles.

**III. MODEL OF CONVERTER**

Rotor side converter is the key component for DFIM-PSH to realize variable-speed operation. It controls its power flexibly and rapidly by adjusting the phase, amplitude and frequency of the exciting current. When vector directional control strategy is applied, the converter usually adopts a typical double-loop control structure. The response time scale of current inner loop is in millisecond level, and its action is instantaneous in the electromechanical transient process, so the converter model can be simplified as a first-order inertia link [7]:

$$G_c(s) = \frac{i_r}{i^*_r} = \frac{1}{\tau_c s + 1}$$

Here, $i_r$ is the actual value of rotor current, $i^*_r$ is the reference value of rotor current, and $\tau_c$ is the response time constant of converter.

**A. POWER DECOUPLING CONTROL STRATEGY**

Based on vector directional control strategy, decoupling control of unit’s real and reactive power is realized in this paper, as shown in the dotted box in Fig. 1(a), where subscript $\text{ref}$ represents the reference value. Additionally, the optimal running point selection module of pump/turbine is established based on the efficiency optimization control proposed in [13], so that the unit can adjust speed in real time according to active power instructions under different operating conditions, ensuring the efficient operation of pump/turbine.

Currently, the power priority control strategy is mostly adopted to realize the regulation of DFIM-PSH’s speed and power [11], [18], as shown in Fig. 1(a). The active and reactive power are set as the control target of the converter, which can be adjusted rapidly by altering rotor current. At the same time, the optimal speed calculated according to active power instructions is set to be adjusted by changing the guide vane opening of turbine. Under such control structure, the rapid and flexible adjustment of active power can be guaranteed in priority, so power priority control strategy is adopted when the unit is in generating mode.

Although the power priority control strategy can accelerate the response of active power, it cannot facilitate the accurate and rapid tracking of rotor speed. In pumping mode, since it is usually required that the unit can directly control the speed to the optimal [19], [20], speed priority control strategy is selected here. The optimal speed is calculated according to the real-time active power at first, and then given to the converter as the priority control object for rapid adjustment. Meanwhile, the active power is precisely adjusted through the controller in pump, as shown in Fig. 1(b).

**IV. FREQUENCY CONTROL STRATEGY**

**A. ADDITIONAL FREQUENCY CONTROL MODULE**

When DFIM-PSH is in generating mode, as shown in Fig. 2(a), the traditional frequency control strategy combining...
droop control and virtual inertia control is adopted to convert frequency deviation into additional active power instructions, which can be quickly controlled by the converter. In the figure, $K_p$, $K_d$ are the proportion and differential coefficients respectively, $\Delta f$ is the frequency deviation, $P_{0\text{-}ref}$ is the initial active power reference, and $s$ is the differential operator.

In pumping mode, since the unit’s active power is controlled through the pump/turbine, if the traditional frequency control strategy is still adopted, the regulating speed will be significantly slower than that in generating mode, so the rapid response of frequency control cannot be guaranteed. Therefore, this paper proposes a frequency control strategy based on the coordination of converter and pump/turbine for DFIM-PSH in pumping mode. According to the characteristics of pumps that the active power can also be adjusted by changing the pump’s speed, an additional frequency control module is constructed in the speed controller of the converter, where the frequency deviation is turned into auxiliary speed instructions. This module cooperates with the frequency control module built in active power controller of the pump, so that the function of frequency regulation can be better realized. The PD controllers are adopted here to ensure that the unit can participate in frequency regulation by rapidly adjusting speed in the early stage of frequency regulation, while the regulating effect will be weakened in the later stage to avoid continuous offset of the unit’s operating state. The specific control block diagram is shown in Fig. 2(b), where $K_{pp}$, $K_{pd}$, $K_{isp}$, $K_{isp}$ are the proportion and differential coefficients of frequency control modules at active power controller and speed controller, and $\omega_{0\text{-}ref}$ is the initial speed reference.

### B. FREQUENCY REGULATION CHARACTERISTICS OF DFIM-PSH

After adopting the above frequency control modules, DFIM-PSH can not only provide support for frequency regulation by changing the output power in generating mode, but also participate in frequency regulation as a variable load in pumping mode. The frequency regulation characteristics of DFIM-PSH can be reflected by the relationship between the change of frequency $\Delta f$ and the change of unit’s active power.

In generating mode, the additional active power instruction generated by DFIM-PSH due to frequency control can be expressed as:

$$\Delta P_{DFIM-PSH\text{-}gen} = (K_p + K_d s) \Delta f$$  \hspace{1cm} (6)

At this point, DFIM-PSH controls the output active power through the converter, and then further realizes the energy exchange with the grid. Combined with the response model of converter, the transfer function between the unit’s active power and frequency can be deduced:

$$G_{gen}(s) = \frac{\Delta P}{\Delta f} = \frac{K_p + K_d s}{\tau_r s + 1}$$  \hspace{1cm} (7)

In pumping mode, since the active power and speed control channels are both equipped with additional frequency control modules, DFIM-PSH can not only directly adjust active power through the frequency control module in pump/turbine, but also can indirectly change it by altering speed through the module in converter at the same time. The additional active power and speed instructions of DFIM-PSH generated by frequency control can respectively be expressed as follows:

$$\Delta P_{DFIM-PSH\text{-}mot} = (K_{pp} + K_{pd} s) \Delta f$$  \hspace{1cm} (8)

$$\Delta \omega_r = (K_{isp} + K_{ispp} s) \Delta f$$  \hspace{1cm} (9)

According to (1), the active power output of the pump can be described as a polynomial related to the rotational speed. For simplification, the active power change caused by the speed deviation $\Delta \omega_r$ can be described as $\Delta P_{mech} = k \Delta \omega_r$ by linearization, where $k$ is the slope of the polynomial curve at the optimal running point of pump. For convenience, the transfer function between active power and frequency is derived based on the ideal model of pump/turbine:

$$G_{mot}(s) = \frac{\Delta P_{mech}}{\Delta f} = k \frac{K_{isp} + K_{ispp} s}{\tau_r s + 1} + (K_{pp} + K_{pd} s) \frac{1 - T_{\omega} s}{1 + 0.5 T_{\omega} s}$$  \hspace{1cm} (10)

### C. FREQUENCY REGULATION CHARACTERISTICS OF POWER SYSTEM WITH DFIM-PSH

In order to study the influence of DFIM-PSH on the frequency dynamic response of the system, this paper establishes the system frequency response model including DFIM-PSH.
and the frequency deviation can be expressed as:

\[
\frac{\Delta f}{-\Delta P_L} = \frac{1}{2\sum_{i=1}^{m} \left( \frac{S_{TNi}}{S_N} \right) H_{NI}(s) + D + \sum_{i=1}^{n} \left( \frac{S_{HNi}}{S_N} \right) G_{HI}(s) - G_{mot}(s)}
\]

(11)

In pumping mode, DFIM-PSH works as load, and the frequency deviation can be expressed as:

\[
\frac{\Delta f}{-\Delta P_L} = \frac{1}{\sum_{i=1}^{m} \left( \frac{S_{TNi}}{S_N} \right) H_{NI}(s) + D + \sum_{i=1}^{n} \left( \frac{S_{HNi}}{S_N} \right) G_{HI}(s) - G_{mot}(s)}
\]

(12)

Here, \(S_N\) is the rated apparent power of the whole system, \(S_{TN}\) and \(S_{HN}\) are respectively the rated apparent power of thermal power and hydropower units, \(S_{DN}\) is the rated apparent power of DFIM-PSH, \(H_T\) and \(H_H\) are respectively the equivalent inertia time constant of thermal power and hydropower units, and \(m\) and \(n\) are the number of thermal power and hydropower units, respectively.

By substituting (7) and (10) into (11) and (12), the specific expression of frequency deviation when DFIM-PSH is in generating and pumping modes can be obtained. Furthermore, the frequency dynamic response indices including the maximum frequency deviation rate \(d\Delta f/dt|_{\text{max}}\), the steady-state frequency deviation \(\Delta f_{\text{st}}\), and the maximum frequency deviation \(\Delta f_{\text{max}}\) can be derived based on inverse Laplace transform mentioned in [22]. In general, the addition of proportional control in frequency controller increases the system’s damping, which is conducive to reducing \(\Delta f_{\text{max}}\) and \(\Delta f_{\text{st}}\). On the other hand, the differential part increases the inertia of the system to improve the frequency stability of the system by decreasing \(d\Delta f/dt|_{\text{max}}\).

V. OPTIMIZATION OF FREQUENCY CONTROL PARAMETERS

A. DETERMINATION OF FREQUENCY CONTROL PARAMETERS’ RANGES

According to the analysis above, larger frequency control parameters can help to improve the frequency regulation ability of DFIM-PSH. However, since the speed and active power of the unit will be affected by frequency control parameters, too large parameters will result in excessive response and further make speed difficult to restore. Therefore, the selection of frequency control parameters should be on the basis of ensuring the safe and stable operation of DFIM-PSH and thus take the goal of realizing the optimal capability of frequency regulation into consideration.

Therefore, based on (11) and (12), the zero-pole trajectories of the transfer function of frequency deviation when each frequency control parameter changes from 0 to ∞ are plotted using the generalized root-locus method, and the influence of each parameter on the stability of frequency response and its dynamic performance is observed. Figs. 4 and 5 show the root...
locus curves when fixed parameters are selected based on the traditional PID parameter tuning method.

In generating mode, the frequency control parameters to be determined include $K_p$ and $K_d$. As can be seen from Fig. 4(a), when $K_d$ changes from 0 to $\infty$, the zeros and poles are always located in the left half of the S plane, so the system can remain stable. When $0.791 < K_d < 18$, the system is underdamped and the absolute value of pole’s real part is large while the imaginary part is small, contributing to better dynamic response performance towards step disturbance. According to Fig. 4(b), when $K_p$ changes between 0 and 557, the system can be stable and underdamped. To guarantee the rapid response of frequency regulation, the range of $K_p$ is further narrowed to $(0, 35.6)$, where the corresponding damping ratio and overshoot are both relatively small.

In pumping mode, there are two frequency control channels, speed channel and active power channel. The speed channel works mainly in the initial stage of frequency regulation, namely the inertial response stage, by adjusting the rotational speed of DFIM-PSH to quickly participate in frequency regulation, while the active power channel mainly plays a role in the later stage, namely the primary frequency response stage due to the slow response of the pump. These two channels can work separately or together for better frequency adjustment, and frequency control parameters to be determined include the coefficients of active power channel $K_p$ and $K_d$, and those of speed channel $K_{\omega_p}$ and $K_{\omega_d}$. Here, the zero-pole trajectories of frequency deviation closed-loop transfer function with single channel are firstly analyzed to preliminarily determine the ranges of parameters on the premise of ensuring system’s stability. Accordingly, the zero-pole trajectories with dual channels are drawn as shown in Fig. 5.
Similarly, taking the system’s stability as the basic goal and considering the dynamic performance requirements of inertia response and primary frequency regulation response, the preliminary selection of each frequency control parameter is made. As can be seen from Fig. 5(a), when $9.51 < K_{od} < 24$, the system is underdamped with damping ratio over 0.707 and overshoot below 5%, so that the maximum frequency deviation and the stability time will be reduced in the corresponding frequency regulation process. According to the same principle, the basic ranges of other frequency control parameters can be determined, where $0 < K_{op} < 25.5$, $0 < K_{pd} < 5.77$, $0 < K_{pp} < 36.3$, as shown in Figs. 5(b) – 5(d), respectively.

**B. OPTIMIZATION OF FREQUENCY CONTROL PARAMETERS**

Since the speed and active power of DFIM-PSH are affected by many other factors such as the initial working conditions and disturbances, parameters optimized in a specific operating state may not be robust, so that the variation of speed or active power may exceed the allowable range when the unit is in other states. Therefore, based on the improved particle swarm optimization algorithm (PSO), this paper proposes an optimization method for frequency control parameters considering various operating conditions of DFIM-PSH, which is aimed at finding out the parameters with robustness and overall optimal frequency regulation effect when the unit is in different working conditions.

Unlike regular optimization method of parameters which is carried out when the unit is in a specific operating state, the method proposed in this paper takes unit’s multiple working conditions into consideration and then forms the objective function shown below based on the integral of time multiplied by squared error criterion, which can help to ensure that the overall frequency tuning effect is optimal with DFIM-PSH under different working conditions and the variation of rotational speed and active power can always be maintained within allowable ranges during the process of frequency regulation.

$$F = \min \sum_{i=0}^{M} \int_{0}^{T} (\Delta f)^2 dt$$

$$\omega_r \min \leq \omega_r \leq \omega_r \max$$

$$P \min \leq P \leq P \max$$

(13)

Here, $\omega_r \min$ and $\omega_r \max$ are respectively the minimum and maximum speed allowed by the unit, $P \max$ and $P \min$ are respectively the minimum and maximum input/output active power, $M$ is the number of typical operating states selected in the simulation, and $T$ is the simulation time.

To further improve the efficiency of optimization, this paper improves the original PSO algorithm. Firstly, the initial ranges of these particles are determined according to the ranges of frequency control parameters deduced before, which can keep the system stable and contribute to good dynamic performance. Secondly, according to the calculation formula of frequency dynamic response indices given in [22], deleting the particles with high values of $\Delta f_{max}$ and $d\Delta f/dt_{max}$ before the simulation model is invoked can help to improve the quality of initial particles, so as to accelerate the convergence of the algorithm. Fig. 6 shows the convergence of the algorithm before and after improvement. The parameters optimized in generating mode can be listed as follow: $K_p = 21.47$, $K_d = 11.15$, and those in pumping mode are $K_{pp} = 21.78$, $K_{pd} = 3.85$, $K_{op} = 15.3$, $K_{od} = 11.98$.

**VI. CASE STUDIES**

A simulation model of a DFIM-PSH connected to an improved four-machine two-area power system, as shown in Fig. 7, is built on PSCAD/EMTDC, and the dynamic frequency response is observed by setting load disturbance. The specific simulation parameters are shown in Table 2. For simplicity, the optimal running point tracking is not considered in the process of frequency regulation.

**A. VERIFICATION OF FREQUENCY REGULATION EFFECTS IN PUMPING MODE**

To verify the effectiveness of additional frequency control module in pumping mode, this section compares the frequency regulation effects of DFIM-PSH using speed channel only, active power channel only and dual channels, i.e., both speed and active power channels. At the same time, influences of each parameter on frequency dynamic response are analyzed by simulations with different parameters. The initial
active power instruction of DFIM-PSH is set as $-0.8$ p.u., and the corresponding optimal speed instruction is $1.02$ p.u. After operating for 20 s, 10% load increase is set.

The responses of system frequency, unit’s speed and active power when DFIM-PSH adopts different frequency control strategies in pumping mode are shown in Fig. 8. The speed channel can make the unit change its active power input rapidly by greatly adjusting speed, to suppress the change of frequency quickly at the early stage of frequency regulation,
and then help to reduce $d \Delta f/dt$ and $\Delta f_{\text{max}}$. However, the speed channel will not function for a long time, so there is little help for decreasing $\Delta f_{st}$ in the later stage. Although the speed channel control can speed up the response of frequency regulation, the change of speed caused by it will lead to instability of DFIM-PSH, which may even cause reverse adjustment of active power and then hinder the recovery of frequency. That is the reason why the overall frequency fluctuation will be relatively large with only speed channel adopted. On the contrary, due to the slow response of pump, frequency regulation with only active power channel cannot act quickly when frequency deviates, so that $d \Delta f/dt$ in the initial stage cannot be decreased effectively. Nevertheless, the effect of active power channel can last for a long time, and then help to reduce $\Delta f_{st}$ and shorten the frequency stability time $t_{st}$. Based on above analysis, it is not difficult to find that dual channel control can effectively combine the advantages of these two channels to achieve better effects.

In Fig. 9, the frequency responses of DFIM-PSH with different frequency control parameters when only the speed channel or the active power channel functions are compared. The corresponding dynamic response indices of frequency are compared as shown in Table 3 to analyze the effect of each parameter. It can be found that larger $K_{\omega p}$ of speed channel can contribute to smaller $d \Delta f/dt$ and $\Delta f_{\text{max}}$, but the increment of $K_{\omega d}$ will not promote the reduction of $\Delta f_{\text{max}}$ obviously. As for the active power channel, larger $K_{pd}$ can also help to reduce $d \Delta f/dt$ and $\Delta f_{\text{max}}$, while since differential control has weak effect in late regulation stage when the deviation rate of frequency becomes small, it cannot further promote the reduction of $\Delta f_{st}$. As the effect of active power channel can last for a relatively long time, the reduction of $\Delta f_{st}$ can be realized by selecting larger $K_{pp}$. 

FIGURE 10. System dynamic responses when DFIM-PSH is in sub-synchronous generating mode. (a) Frequency response. (b) Active power response. (c) Speed response.

FIGURE 11. System dynamic responses when DFIM-PSH is in super-synchronous generating mode. (a) Frequency response. (b) Active power response. (c) Speed response.
B. VERIFICATION OF THE ROBUSTNESS OF FREQUENCY CONTROL STRATEGY

To verify the frequency control parameters optimized can improve DFIM-PSH’s frequency regulation ability under different working conditions on the basis of safe and stable operation, two simulation experiments are carried out in this section, where DFIM-PSH is in different working conditions and a different load disturbance is set. The simulation results are further compared with those under the control of two different groups of parameters. Parameter I refers to the group of traditional frequency control parameters proposed in [23], which are relatively small, and Parameter II is that with relatively larger values selected from the initial ranges deduced above.

1) DIFFERENT WORKING CONDITIONS

The DFIM-PSH with 0.6 p.u. and 0.9 p.u. active power instructions in generating and pumping modes, respectively, are simulated. At 20 s, 10% load increase is provided, and the responses of each physical quantity with DFIM-PSH adopting different frequency control parameters are shown in Figs. 10-13. It can be seen that compared with the traditional frequency control parameters (Parameter I), the optimized parameters can help to reduce \( \Delta f_{\text{max}} \), \( \Delta f_{\text{st}} \), and \( d\Delta f/dt \) more significantly. At the same time, DFIM-PSH can maintain safe and stable operation under different working conditions and maintain the speed and power within allowable ranges in the whole regulation process. In other words, the optimized frequency control parameters in this paper have a good robustness.

In generating mode, the unit’s speed can be rapidly adjusted under the action of frequency control modules, which provides great active power instantaneously in the initial stage of frequency regulation, thus making \( \Delta f_{\text{max}} \) and \( d\Delta f/dt \) reduced significantly. At the same time, the constant increase of output active power also leads to obvi-
ous decrease of $\Delta f_{st}$. By comparing the dynamic frequency response indices under the optimized parameters with those under Parameter I, it can be found that when adopting the optimized parameters $\Delta f_{\text{max}}$ decreases from 0.2285 Hz to 0.1695 Hz in sub-synchronization state, about 25.82% lower than before, and 0.065 Hz (about 28.75% lower) in super-synchronization state. At the same time, $\Delta f_{st}$ decreases by more than 17% in both generating and pumping modes. On the other hand, when larger parameters (Parameter II) are adopted, although the frequency regulation capability of DFIM-PSH can be slightly improved, its active power output and speed will have drastic fluctuations during the process of regulation, which will affect the safe and stable operation of the unit.

In pumping mode, DFIM-PSH can adjust speed rapidly to change the active power input when frequency deviation occurs, making $\Delta f_{\text{max}}$ decrease obviously. At the same time, the decrease of steady-state active power and rotational speed of the unit also makes $\Delta f_{st}$ decrease greatly. Specifically, compared with Parameter I, $\Delta f_{\text{max}}$ drops from 0.2665 Hz to 0.1821 Hz in sub-synchronization state, about 31.67% lower than before, and decreases from 0.2584 Hz to 0.1816 Hz, about 29.7% lower. The decrease of $\Delta f_{st}$ in two states, though not very significant, also reaches more than 8%. At this time, adopting larger frequency control parameters (Parameter III) also cannot help to reduce $\Delta f_{\text{max}}$ and $\Delta f_{st}$ and then improve the frequency regulation capability of DFIM-PSH greatly, but causes a large shift in the speed, as shown in Fig. 12 (c), which is beyond the normal operating range.

2) DIFFERENT LOAD DISTURBANCE

The DFIM-PSH with 0.8 p.u. active power instructions in generating and pumping modes are simulated, and then 5% and 10% load increase and decrease are set after 20 s. The curves of system dynamic responses are shown as Figs.14 and 15, from which it can be seen that whatever disturbance, the optimized parameters can contribute to the decrease of $d\Delta f/dt$, $\Delta f_{\text{max}}$, and $\Delta f_{st}$ on the basis of safe and stable operation.
response model with DFIM-PSH is built, and the influence of frequency control parameters on frequency dynamic response characteristics is analyzed using root-locus method. To give full play to the frequency regulation ability of DFIM-PSH under different working conditions on the basis of stable operation, this paper further presents optimization method of frequency control parameters based on improved particle swarm optimization algorithm, which is aimed at minimizing the frequency deviation with DFIM-PSH under multiple working conditions. The main conclusions can be drawn as follows:

1. The frequency control module of DFIM-PSH in pumping mode established in this paper, where the frequency deviation is turned into auxiliary speed and active power instructions and then adjusted by the coordination of converter and pump/turbine, can help to significantly reduce \( d\Delta f/dt \) and \( \Delta f_{\text{max}} \) by rapidly adjusting speed at the initial stage of frequency regulation, and reduce \( \Delta f_{\text{r}} \) by continuously changing active power at the frequency recovery stage.

2. The optimization method of frequency control parameters based on improved PSO, which is aimed at minimizing the overall effects of frequency regulation when the unit is under multiple working conditions and takes the change of speed and active power within allowable ranges as constraints, has great robustness when DFIM-PSH is under different working conditions or suffers from different load disturbances. The overall frequency control strategy can improve the frequency regulation ability of DFIM-PSH by reducing \( d\Delta f/dt \), \( \Delta f_{\text{max}} \), and \( \Delta f_{\text{r}} \), so as to improve the frequency characteristics of power grid.

**REFERENCES**

[1] P. J. Donalek, “Pumped storage hydropower: Then and now,” *IEEE Power Energy Mag.*, vol. 18, no. 5, pp. 49–57, Sep. 2020.

[2] M. Valavi and A. Nysveen, “Variable-speed operation of hydropower plants: A look at the past, present, and future,” *IEEE Ind. Appl. Mag.*, vol. 24, no. 5, pp. 18–27, Sep./Oct. 2018.

[3] S. Nag and K. Y. Lee, “Neural network-based control for hybrid PV and ternary pumped-storage hydro plants,” *Energies*, vol. 14, no. 15, p. 4397, Jul. 2021.

[4] J. K. Lung, Y. Lu, W. L. Hung, and W. S. Kao, “Modeling and dynamic simulations of doubly fed adjustable-speed pumped storage units,” *IEEE Trans. Energy Convers.*, vol. 22, no. 2, pp. 250–258, Jun. 2007.

[5] S. Nag and K. Y. Lee, “Network and reserve constrained economic analysis of conventional, adjustable-speed and ternary pumped-storage hydropower,” *Energies*, vol. 13, no. 16, p. 4140, Aug. 2020.

[6] S. Nag, K. Y. Lee, and D. Suchitra, “A comparison of the dynamic performance of conventional and ternary pumped storage hydropower,” *Energies*, vol. 12, no. 18, p. 3513, Sep. 2019.

[7] Y. Chen, C. Deng, Y. Liu, Z. Xu, D. Li, M. Chen, and P. Peng, “Electromechanical transient modelling and active power-frequency coupling characteristics of doubly-fed variable speed pumped storage under pumping mode,” *Proc. CSEE*, vol. 42, no. 3, pp. 942–957, Feb. 2021.

[8] T. Mercier, J. Jomaux, E. De Jaeger, and M. Olivier, “Provision of primary frequency control with variable-speed pumped-storage hydropower,” in *Proc. IEEE Manchester PowerTech*, Jun. 2017, pp. 1–6.

[9] W. Hu, P. Zhang, Z. Chen, J. Li, S. Chen, and W. Ruan, “Model-based control for doubly fed adjustable-speed pumped storage units with fast power support,” in *Proc. 13th IEEE Conf. Ind. Electron. Appl. (ICIEA)*, Wuhan, China, May 2018, pp. 2227–2232.

[10] Z. Zhu, W. Fan, T. Liu, Y. Li, and M. Liu, “Dynamic modeling and eigen analysis of adjustable-speed pumped storage unit in pumping mode under power regulation,” *IEEE Access*, vol. 9, pp. 155035–155047, 2021.
M. A. Bidgoli, H. A. Mohammadpour, and S. M. T. Bathae, “Advanced vector control design for DFIM-based hydropower storage for fault ride-through enhancement,” *IEEE Trans. Energy Convers.*, vol. 30, no. 4, pp. 1449–1459, Dec. 2015.

H. Li, H. Liu, E. Song, H. Xiao, L. Lao, and Z. Huang, “Improved virtual inertia control strategy of doubly-fed pumped storage unit for power network frequency modulation,” *Autom. Electr. Power Syst.*, vol. 41, no. 10, pp. 58–65, May 2017.

H. Li, K. Wang, H. Liu, E. Song, X. Xie, and M. Zhen, “Variable droop coefficient frequency control strategy of AC excited pumped storage unit,” *Electr. Power Autom. Equip.*, vol. 38, no. 7, pp. 68–73, Jul. 2018.

J. Zhao, X. Lyu, Y. Fu, X. Hu, and F. Li, “Coordinated microgrid frequency regulation based on DFIG variable coefficient using virtual inertia and primary frequency control,” *IEEE Trans. Energy Convers.*, vol. 31, no. 3, pp. 833–845, Sep. 2016.

X. Peng, W. Yao, C. Yan, J. Wen, and S. Cheng, “Two-stage variable proportion coefficient based frequency support of grid-connected DFIG-WTs,” *IEEE Trans. Power Syst.*, vol. 35, no. 2, pp. 962–974, Mar. 2020.

L. Quan, “Research on power regulation of adjustable-speed pumped-storage system based on virtual head technology,” M.S. thesis, Dept. Elect. Eng., North China Electr. Power Univ., Beijing, China, 2019.

W. Pan, Z. Zhu, T. Liu, M. Liu, and W. Tian, “Optimal control for speed governing system of on-grid adjustable-speed pumped storage unit aimed at transient performance improvement,” *IEEE Access*, vol. 9, pp. 40445–40457, 2021.

J. Schmidt, W. Kemmetmüller, and A. Kugi, “Modeling and static optimization of a variable speed pumped storage power plant,” *Renew. Energy*, vol. 111, pp. 38–51, Oct. 2017.

D. Li, G. Gong, J. Lv, X. Jiang, and R. He, “An overall control of doubly-fed variable speed pumped storage unit in pumping mode,” in *Proc. IEEE 4th Conf. Energy Internet Energy Syst. Integ. (EI2)*, Oct. 2020, pp. 3709–3714.

A. Joseph, K. Desingu, R. R. Semwal, T. R. Chelliah, and D. Khare, “Dynamic performance of pumping mode of 250 MW variable speed hydro-generating unit subjected to power and control circuit faults,” *IEEE Trans. Energy Convers.*, vol. 33, no. 1, pp. 430–441, Mar. 2018.

Y. Chen, W. Xu, Y. Liu, E. M. Rashad, Z. Bao, J. Jiang, and Z. Mao, “Reduced-order system frequency response modeling for the power grid integrated with the type-II doubly-fed variable speed pumped storage units,” *IEEE Trans. Power Electron.*, vol. 37, no. 9, pp. 10994–11006, Sep. 2022.

T. Wang and X. Cheng, “Variable droop coefficient control strategy of a DFIM considering rotor speed limit,” *Power Syst. Protection Control*, vol. 49, no. 9, pp. 10994–11006, May 2021.

H. Liu, “Research on control strategies of AC excited pumped storage units to participate in power system frequency regulation,” M.S. thesis, Dept. Elect. Eng., Chongqing Univ., Chongqing, China, 2017.

**LINJUN SHI** (Member, IEEE) received the B.S. and M.S. degrees in electrical engineering from Hohai University, Nanjing, China, in 1999 and 2003, respectively, and the Ph.D. degree in electrical engineering from Southeast University, Nanjing, in 2010.

He was a Visiting Scholar with the Department of Electrical and Computer Engineering, Baylor University, Waco, TX, USA, in 2014. He is currently an Associate Professor with the College of Energy and Electrical Engineering, Hohai University. His research interests include power system analysis and control, new energy, and energy storages applications to power systems.

**WEIJIE LAO** received the B.S. degree in electrical engineering from Hohai University, Nanjing, China, in 2021, where she is currently pursuing the M.S. degree. Her research interests include pumped storage technology and energy storage technology and their application in power systems.

**FENG WU** (Member, IEEE) received the B.S. and M.S. degrees in electrical engineering from Hohai University, Nanjing, China, in 1998 and 2002, respectively, and the Ph.D. degree from the University of Birmingham, U.K., in 2009.

He is currently a Professor in electrical engineering with the College of Energy and Electrical Engineering, Hohai University. His research interests include modeling and control of renewable power generation systems. He is the Winner of the National Outstanding Young Science Foundation of China.

**TAO ZHENG** received the B.S. and M.S. degrees in power system and automation from the Huazhong University of Science and Technology, Wuhan, China, in 2000 and 2003, respectively. He is currently a Senior Engineer with NARI Technology Development Company Ltd. His research interests include integrated energy system operation, optimization, and control.

**KWANG Y. LEE** (Life Fellow, IEEE) received the B.S. degree in electrical engineering from Seoul National University, Seoul, South Korea, the M.S. degree in electrical engineering from North Dakota State University, Fargo, ND, USA, and the Ph.D. degree in system science from Michigan State University, East Lansing, MI, USA.

He has been on the faculties of Michigan State University, Oregon State University, Houston University, The Pennsylvania State University, and Baylor University, where he is currently a Professor and the Chair of the Electrical and Computer Engineering and the Director of the Power and Energy Systems Laboratory. His research interests include power systems control, operation and planning, and intelligent systems applications to power plant and power systems control. He was elected as a fellow of IEEE, in January 2001, for his contributions to the development and implementation of intelligent system techniques for power plants and power systems control.