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Research on Compensating Electromagnetic Torque Fluctuation of Hydraulic Wind Turbine During Low Voltage Ride Through

Chao Ai*, Xuan Liu**, Han-Chao Chen **, Ya-Lun Wang **and Xiang-Dong Kong ***

Keywords： hydraulic wind turbine (HWT), low voltage ride through (LVRT), electromagnetic torque, state observer.

ABSTRACT

Since the wind farms are increasing rapidly, sets of specific requirements have been established in China. Its objective is to ensure the stability of power system. So this paper takes the hydraulic wind turbine (HWT) as research object, aiming at enhancing the ability of low voltage ride through (LVRT) of HWT. In the paper, one basic problem, how to compensate the fluctuating electromagnetic torque, is studied. To begin with, the working principle of the HWT is analyzed, and mathematical models of every part of HWT are established. Then prediction state observer based on time-delay and a method relied on adjusting the proportional throttle valve opening size to dynamic compensating electromagnetic torque fluctuation are presented. In order to avoid the damage caused by the LVRT in actual operation, the operating characteristics of HWT under low voltage condition are simulated based on MATLAB and AMESim. As verified by the experiment and simulation, the prediction results of electromagnetic torque state observer and the dynamic compensation method can promise the HWT to handle the fluctuation, the performances of HWT during LVRT with the dynamic compensation method is much better than that without. The stability of the HWT and grid power system is evaluated.

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* *Associate professor, Key Laboratory of Advanced Forging & Stamping Technology and Science (Yanshan University), Ministry of Education of China，Qinhuangdao 066004, China;*
Yanshan University Hebei Heavy Machinery Fluid Power Transmission and Control Lab, Qinhuangdao 066004, China.

** *Master , Yanshan University Hebei Heavy Machinery Fluid Power Transmission and Control Lab, Qinhuangdao 066004, China.*

*** *Professor, Key Laboratory of Advanced Forging & Stamping Technology and Science (Yanshan University), Ministry of Education of China，Qinhuangdao 066004, China;*
Yanshan University Hebei Heavy Machinery Fluid Power Transmission and Control Lab, Qinhuangdao 066004, China.

INTRODUCTION

With the proportion of wind power in supply of energy increasing gradually (Sarkhanloo S et al., 2012; Angulo et al.,2017), HWT, as a new type of wind power generation model, has aroused widespread attention (Dutta R.,2014; Saadat M. et al.,2015). Hydraulic speed control system was adopted to realize power transmission between wind turbine and generator in HWT (2016). The method of controlling hydraulic drive system to achieve real-time adjustment of generator speed and to control generator works under the condition of synchronous speed is presented, which is significant for synchronous generator connected to the grid. Compared with traditional wind turbine, the HWT has many advantages. For one thing, using the hydraulic drive system between wind turbine and generator can reduce the high failure rate of doubly fed induction generator gearboxes (2014). For another, the flexible hydraulic transmission model can solve the problem that direct drive generators, adopted in permanent magnet direct-drive wind power generation, is too large (2016). Besides, this model can decrease the overall cost of system (2014).

However, both HWT and traditional wind turbines are all facing one problem that voltage drop caused by stator current overload and negative sequence component, causes voltage asymmetry fault of HWT active power and reactive power volatility during grid fault occurs. Eventually, the high speed electromagnetic torque pulse effect the output shaft of the generator, which may cause damage to steadiness of the grid system. Therefore, some measures should be taken to reduce or even eliminate the electromagnetic torque fluctuation so as to ensure the stability of the grid in the process of LVRT.

The research of traditional wind turbines has already given a certain theoretical basis and engineering practice experience for studying voltage fault. In general, it can be divided into two categories: One is to use additional hardware protection facilities by increase the system cost. The most well-known method is using crowbar resistors connected across the rotor winding terminals and turning off the rotor side converter (2010; 2016). Besides, the performance of STATCOM is elaborated in (2016) when grid voltage drop occurs. A kind of hybrid current controlled converters is used for improving the stability of power grid by Mansour Mohseni. et al. (2011). The other is software based upon scheme that concentrates on advanced control strategy. For instance, Gilmanur et al. (2017) discussed a control strategy based on fuzzy logic control. Current control techniques for three-phase grid are carried out in (2016). Series voltage compensation and its control strategy is described by Shrikant (2014) and M. Rahimi (2010). Pedro Rodriguez et al. (2007) also investigated a flexible active power control of during grid faults.

However, HWT is short of the documents let alone the research about LVRT. At the same times, as the target of HWT to be ultra largescale grid connected wind power generation equipment, it is necessary to elevate the LVRT capability of HWT and ensure the stability of the grid to adapt to the increasingly stringent national grid code, which is the further development of the HWT and to achieve the industrialization of the problem must be solved. Therefore, it is of great practical significance to study the electromagnetic torque compensation of the HWT under the grid fault for improving the stability of the power grid.

This paper is organized as follows: Section 2 presents the technical regulation of the LVRT and handle with the instability mechanism of HWT. Section 3 constructs the mathematical model of the HWT. The electromagnetic torque compensation control law is proposed in section 4. Experiment and simulation results are discussed in section 5.

INSTABILITY MECHANISM OF HWT

Requirements for LVRT Capability

The Grid Codes is differ from countries to countries (2006, 2016). Just taking China for an instance, the technical regulation of wind turbine access to power system and the LVRT (2010,2011) requirements in China (2015) are shown in Figure 1.

The meaning of the picture below is followed:

(1) Wind turbines should be able to maintain the LVRT capability of 0.625s when the voltage drops to 20% rated voltage.

(2) The wind farm and network voltage can be recovered to 90% of the rated voltage in 2 seconds after the fall, besides the wind power unit should have the ability to run in uninterrupted power grid.

(3) The active power of wind turbine without cutting out of power grid during the fault period should increase at least 10% of rated power per second.

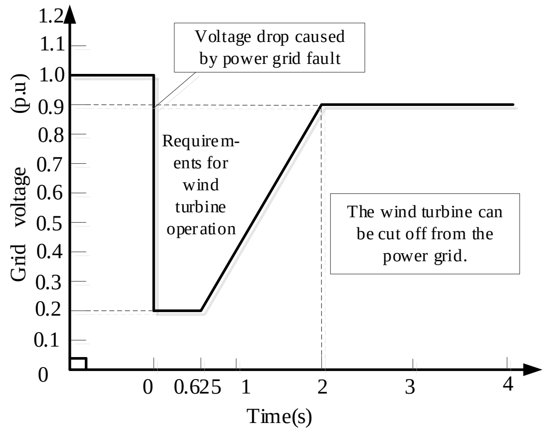


Fig. 1. LVRT specifications for wind turbine.

Electromagnetic Torque Fluctuation Mechanism

In the process of LVRT, the imbalance between the input and output power of HWT will lead to instability of the generator. Besides, electromagnetic torque fluctuation is also an important influencing factor to HWT stable operation. During the grid faults, three-phase asymmetric mutation occurs in the generator stator voltage. At the same time, transient DC component and negative sequence component appears in the stator flux. Because the generator is still in synchronous speed at this very moment, the relative speed between stator and rotor is high. So stator magnetic field will generate larger amplitude electromagnetic force in the rotor winding, then rotor magnetic field will induce stator current and rotor current in the stator and rotor winding. Eventually, the electromagnetic torque oscillates sharply, which resulted from stator current and rotor current undulation.

Besides, the electromagnetic torque fluctuation amplitude and grid voltage drop depth is positively correlated. When the large amplitude single phase grid fault occurs, the generator electromagnetic torque fluctuation will cause severe impact to the variable transmission shaft of motor, or even result in severely undulation of the output rotational speed of HWT. If the electromagnetic torque fluctuation cannot be dynamic compensated instantly, it will seriously affect the stable operation of HWT and cause set off grid or generator damage or other serious accidents. So the various motor electromagnetic torque fluctuation is an important influence factor of generator speed instability during LVRT.

The Electromagnetic Torque Fluctuation of Generator

The expression of electromagnetic torque of generator is

$$T_e = \frac{P_e}{\Omega_s} = \frac{P_{e0} + P_{e\sin 2} + P_{e\cos 2}}{\Omega_s} = T_{e0} + T_{e\sin 2} + T_{e\cos 2} , \tag{1}$$

where shows that the electromagnetic torque fluctuation value is consisted of double frequency of the sine and cosine component. What’s more, electromagnetic torque fluctuation value is changing based on power grid drop depth. Due to the high frequency fluctuation of electromagnetic torque, how to accurately predict the electromagnetic torque fluctuation and dynamic compensation of the electromagnetic torque have a very important actual value.

MATHEMATICAL MODELING

The hydraulic system schematic diagram of HWT is shown in Figure 2.

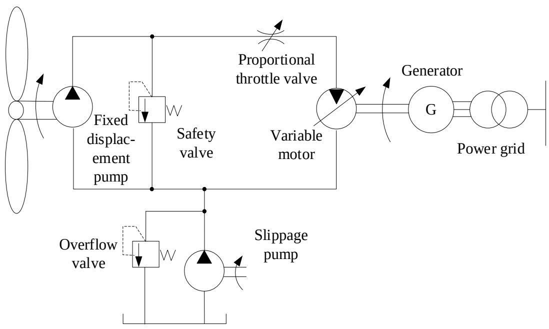


Fig. 2. The hydraulic system schematic diagram of HWT.

From which, it is seen that the entire plant with the control system can be divided into two major parts: hydraulic main drive system and electric system. When the grid fault occurs, the electromagnetic torque of the generator generates high frequency fluctuation. In order to compensate the electromagnetic torque accurately, the relevant mathematical model may be established initially as follows.

Proportional Throttle Valve Model

The valve is equipped with an electronic control unit and an inductive displacement sensor, and the equation of proportional throttle valve element is

$$X_v = KU_E , \tag{2}$$

Then, the flowing equation of proportional throttle valve is

$$Q_b = C_d W X_v \sqrt{\frac{2}{\rho}(p_{h1} - p_{h2})} = C_d W X_v \sqrt{\frac{2 p_L}{\rho}} . \tag{3}$$

Variable Motor

Flowing continuity equation of Variable motor is

$$Q_m = D_m \omega_m + C_{tm} p_{h2} , \tag{4}$$

The displacement equation of variable displacement motor is considered, which is defined as follows.

$$D_m = K_m \gamma , \tag{5}$$

Variable motor output torque equation is

$$T_m = D_m p_{h2} \eta_{mm} , \tag{6}$$

Variable motor torque balance equation is

$$T_m - T_e = J_m \frac{d\omega_m}{dt} + B_m \omega_m + G_m \theta_m , \tag{7}$$

The variable displacement motor can convert hydraulic energy into mechanical energy, and the energy balance equation of motor can be established as

$$p_{h2} Q_m = p_{h2} D_m \omega_m \eta_{mv} = T_m \omega_m \eta_{mm} \eta_{mv} , \tag{8}$$

Variable motor output stiffness is very large, based upon Eq. (5), (6) and (8) the state equation of the variable motor can be presented as

$$\dot{\omega}_m = \frac{1}{J}(K_m \gamma p_{h2} \eta_{mm} - B_m \omega_m - T_e) . \tag{9}$$

Hydraulic System Integrated Model

The output torque of the hydraulic main drive system is

$$T_h = p_{h2} K_m \gamma , \tag{10}$$

And the output power of the hydraulic main drive system is

$$P_h = K_m \omega_m p_2 \gamma \,, \tag{11}$$

From the above equations, the following state space expression can be obtained.

$$\begin{bmatrix} \dot{\omega}_p \\ \dot{P}_1 \\ \dot{\omega}_m \\ \dot{P}_2 \end{bmatrix} = \begin{bmatrix} -\dfrac{B_p}{J_p} & -\dfrac{D_p}{J_p \eta_{pm}} & 0 & 0 \\ \dfrac{Z_c(s) D_p s}{th\Gamma(s)} & -\dfrac{Z_c(s) C_{tp} s}{th\Gamma(s)} & 0 & 0 \\ 0 & 0 & -\dfrac{B_m}{J_m} & 0 \\ 0 & 0 & 0 & -\dfrac{\beta_e C_{tm}}{V_{02}} \end{bmatrix} \begin{bmatrix} \omega_p \\ P_1 \\ \omega_m \\ P_2 \end{bmatrix} + \begin{bmatrix} \dfrac{1}{J_p} & 0 & 0 & 0 \\ 0 & -\dfrac{Z_c(s) K_q s}{sh\Gamma(s)} & 0 & 0 \\ 0 & 0 & -\dfrac{1}{J_m} & \dfrac{K_m \eta_{mm}}{J_m} P_2 \\ 0 & \dfrac{K_q \beta_e}{V_{02}} & 0 & -\dfrac{\beta_e K_m \omega_m}{V_{02}} \end{bmatrix} \begin{bmatrix} T_w \\ X_v \\ T_e \\ \gamma \end{bmatrix} . \tag{12}$$

Generator Full Order Model

In order to simplify the modeling and analysis process, the following two assumptions can be used.

(1) Assuming that the power grid is still maintained when the generator is in the power grid fault.

(2) Assuming that the voltage and flux dependent quantities of the generator stator, rotor equations can be translated into stator voltage dependent or rotor current.

So the full order model of the generator can be presented as

$$\begin{cases} T_{e0} = \\ \dfrac{3L_m n_p}{2L_s \omega_s}\left(u_{sd+}^{+} i_{rd+}^{+} + u_{sq+}^{+} i_{rq+}^{+} - u_{sd-}^{-} i_{rd-}^{-} + u_{sq-}^{-} i_{rq-}^{-}\right) \\ T_{e\sin 2} = \\ \dfrac{3L_m n_p}{2L_s \omega_s}\left(-u_{sq-}^{-} i_{rd+}^{+} + u_{sd-}^{-} i_{rq+}^{+} - u_{sq+}^{+} i_{rd-}^{-} + u_{sd+}^{+} i_{rq-}^{-}\right) \\ T_{e\cos 2} = \\ \dfrac{3L_m n_p}{2L_s \omega_s}\left(-u_{sd-}^{-} i_{rd+}^{+} - u_{sq-}^{-} i_{rq+}^{+} + u_{sd+}^{+} i_{rd-}^{-} + u_{sq+}^{+} i_{rq-}^{-}\right) \end{cases} \tag{13}$$

In this model, the stator voltage u_s and rotor current i_r of the generator can be collected directly, and the stator rotating speed is considered as the synchronous speed. The observed value will eventually converge to the real value of the real time electromagnetic torque.

ELECTROMAGNETIC TORQUE COMPENSATION CONTROL METHOD

State Observer Model

When the gird fault occurs, dynamic compensating electromagnetic torque is based on accurate predictability of electromagnetic torque fluctuation rules. So a nonlinear state observer, which realizes the real-time forecast of electromagnetic torque, is presented. Because it reduces the order, so the observation error of the state observer is quiet small. After ensuring the state of genera can be observed, electromagnetic torque state observer is designed as follows.

$$\begin{cases} \begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{pmatrix} = K \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \lambda_1 & -\lambda_4 & -\lambda_3 \\ \lambda_2 & \lambda_3 & -\lambda_4 \\ -\lambda_3 & -\lambda_2 & \lambda_1 \\ \lambda_4 & \lambda_1 & \lambda_2 \end{pmatrix}^{\mathrm{T}} \begin{pmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \end{pmatrix}, \\ \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \end{cases} \tag{14}$$

where the state variables to be observed are $x = \begin{pmatrix} x_1 & x_2 & x_3 \end{pmatrix}^{\mathrm{T}} = \begin{pmatrix} T_{e0} & T_{e\sin 2} & T_{e\cos 2} \end{pmatrix}^{\mathrm{T}}$ and $K = 3L_m n_p / 2L_s \omega_s$ .State parameters of the system are $\lambda_1 = u_{sd+}^{+}$, $\lambda_2 = u_{sq+}^{+}$, $\lambda_3 = u_{sd-}^{-}$, $\lambda_4 = u_{sq-}^{-}$, $\beta_1 = i_{rd+}^{+}$, $\beta_2 = i_{rq+}^{+}$, $\beta_3 = i_{rd-}^{-}$, $\beta_4 = i_{rq-}^{-}$. Each state parameter is related to the measurable quantity, and the output variable of the system.

Prediction Method Based on Time-Delay Compensation

Having the basis that the electromagnetic torque observer is able to make prediction of generator electromagnetic torque, a prediction method of synchronous generator electromagnetic torque based upon delay compensation is presented. The system collects the voltage and current of generator in the time of k. Then it forecasts the value of electromagnetic torque in time of (k+1). Lastly, the predicted value is seen as input. Hydraulic output torque follows the predicted value to adjust in time, as shown in the Figure 3.

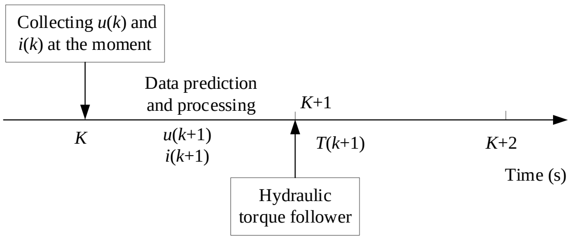


Fig. 3. The hydraulic torque following diagram based on the time delay compensation in actual system.

Compensating Method

High frequency electromagnetic torque fluctuation causes violent shaking of the hydraulic output torque. While using proportional throttle valve is an important means to realize dynamic adjustment of variable motor output torque at this time. According to the above conditions and the flowing equation of valve, a dynamic compensation electromagnetic torque fluctuation method relied on adjustment of the real-time open values of proportional throttle valve can be expressed as

$$X_{ve} = \frac{Q_b}{C_d W}\sqrt{\frac{\rho}{2p_{h1} - 2p_{h2}}}\,, \tag{15}$$

Torque fluctuation compensates value of the given model as shown in Figure 4.

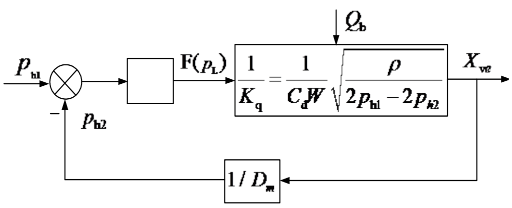


Fig. 4. Proportional throttle valve opening compensation value given model.

Grid voltage drops effect instantly makes the electromagnetic torque generated high frequency fluctuation. Adjusting the proportional throttle valve opening degree successfully realizes variable motor output torque dynamic compensation. In this way, the damage caused by electromagnetic torque fluctuation can be minimized to ensure stability of power grid.

SIMULATION

Simulation Platform

The 24kW HWT simulation platform, including wind speed and wind turbine characteristics module, main controller module, hydraulic system module, generator interconnection and fault simulation module, is built by MATLAB and AMESim. The simulation platform realizes simulation of wind turbine characteristic, hydraulic main drive system. It also can realize simulation of synchronous generator and excitation system even power grid system fault. The parameter sets source to the actual physical system, and corresponding simulation parameters setting as shown in Table 1.

Table 1. Simulation parameters.

Displacement gradient	40 ml.r^{-1}
Motor viscous damping coefficient	0.0345 N.m.(rad.s^{-1})$^{-1}$
Elastic modulus of oil volume	743×10^{6} Pa
Valve flow gain factor	1.166×10^{-4} m^{3}.rad^{-1}
Valve flow-pressure coefficient	4×10^{-12} m^{3}.s^{-1}
Pump viscous damping coefficient	0.4 N.m.(rad.s^{-1})$^{-1}$
Pump displacement	63 ml.r^{-1}
Pump leakage coefficient	1.6×10^{-11} m^{3}.(s.Pa)$^{-1}$
Variable motor leakage coefficient	1.2×10^{-11} m^{3}.(s.Pa)$^{-1}$
Equivalent total inertia of variable motor	0.462 kg. m^{-3}
Pump and total inertia of wind turbine	400 kg. m^{-3}

In the process of LVRT, synchronous generator and excitation system simulation model and parameter setting are key to simulation. Synchronous generator, excitation system parameters setting values are as shown in Table 2.

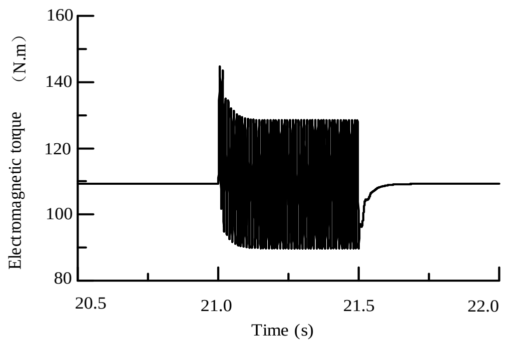
Table 2. Parameters of synchronous generator and excitation system.

Three phase rated power rate	313000 VA
Rated line voltage effective	400 V
Rated frequency	50 Hz
Generator stator resistance	0.04186 pu
Generator excitation winding	0.02306 pu
Excitation leakage reactance	0.1381 pu

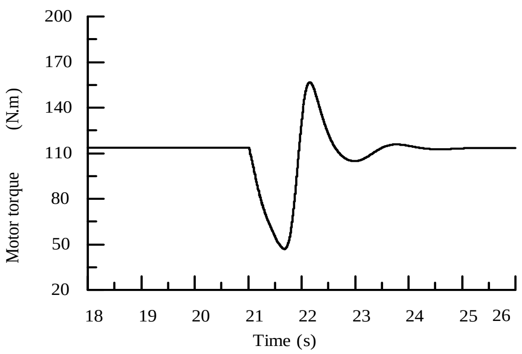
So as to enhance LVRT capability, the original grid connected power control strategy is used to analysis electromagnetic torque compensation problem in the three-phase voltage drops and single-phase voltage grounding fault.

Single Phase Voltage Drop

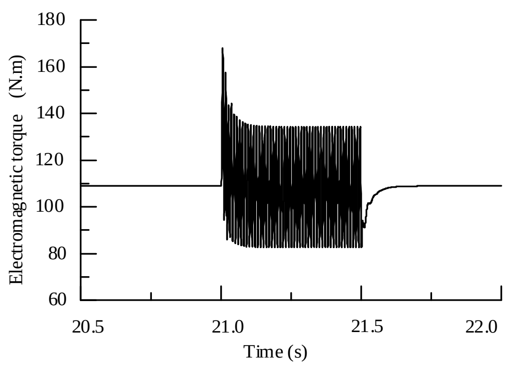
In order to simulate HWT working characteristic under single phase voltage drop, some parameters of the platform had better be set firstly as followed: grid single phase voltage from the 21s begin to drop, and drop depth is 20%, 50% and 80%, drop duration time 0.5s, and the simulation curve as shown in Figure 5.



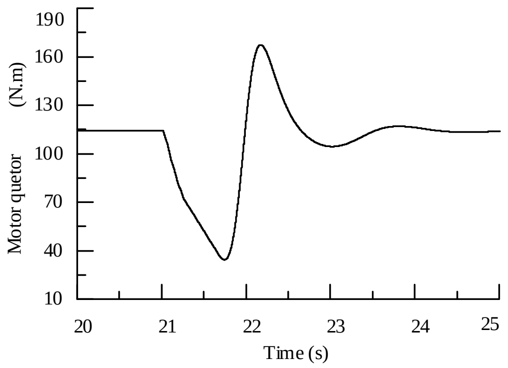
a. Electromagnetic torque of single phase drop 20%



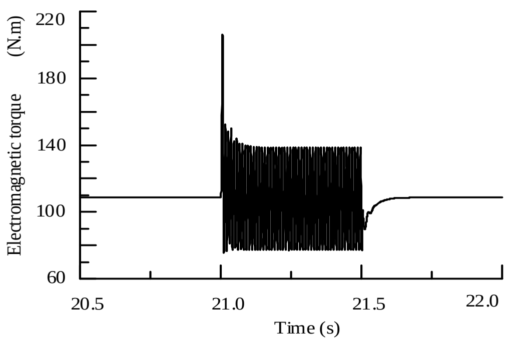
b. Various motor torque of single phase drop 20%



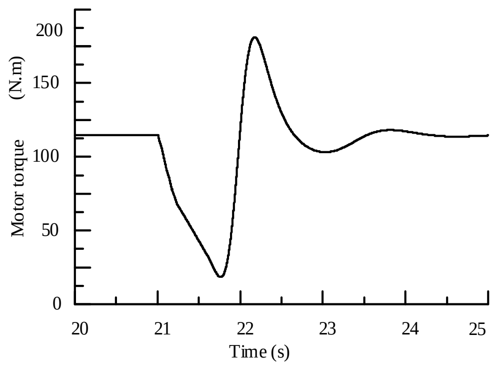
c. Electromagnetic torque of single phase drop 50%



d. Various motor torque of single phase drop 50%



e. Electromagnetic torque of single phase drop 80%



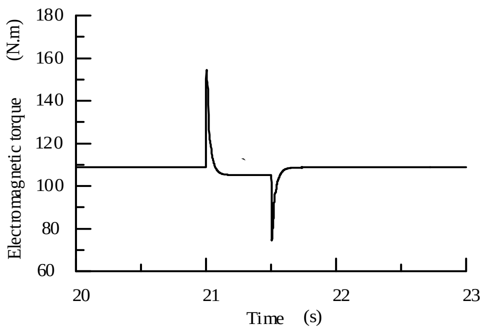
f. Various motor torque of single phase drop 80%

Fig. 5. Simulation curve of single phase voltage drop.

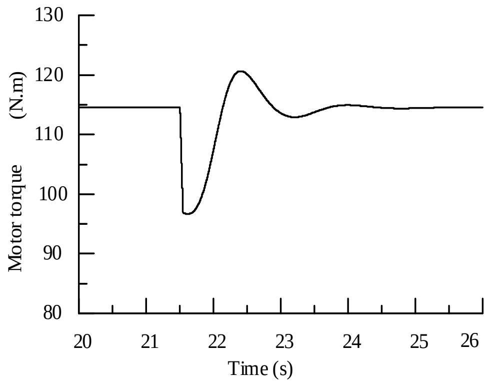
According to the simulation results, electromagnetic torque can produce high frequency (100Hz) fluctuation whose amplitude and drop depth of voltage are positively correlated. The results also verify the correctness of electromagnetic torque mathematical model as well as the results of state observer under grid fault. What's more, motor torque of hydraulic system also performs large amplitude fluctuations. There is a positive correlation between the fluctuation of the maximum amplitude and the grid voltage drop depth as well. The results of simulation provide an important reference for dynamic compensation electromagnetic torque fluctuation.

Three Phase Voltage Drop

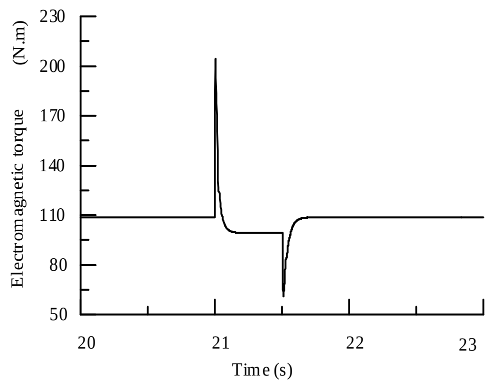
Setting the drop depth and duration as same as the single-phase voltage drop, simulation study on the three-phase voltage drop is carried out. The simulation results are shown in Figure 6.



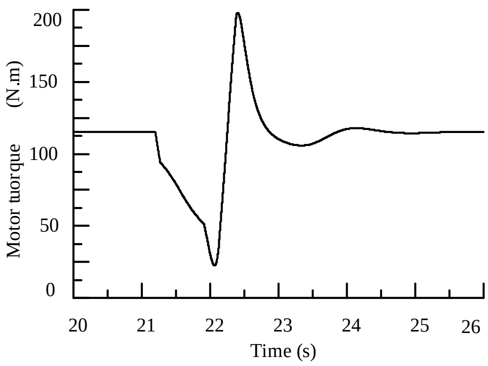
a. Electromagnetic torque of three phase drop 20%



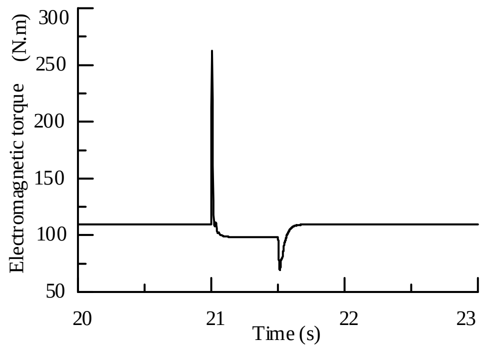
b. Various motor torque of three- phase drop 20%



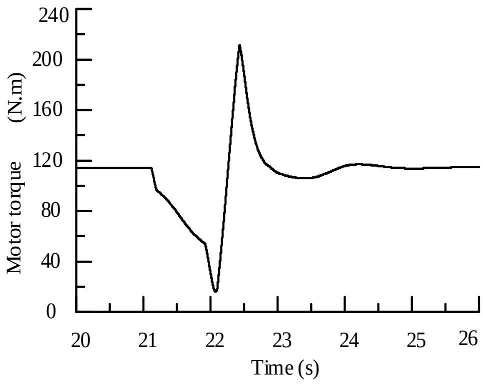
c. Electromagnetic torque of three phase drop 50%



d. Various motor torque of three phase drop 50%



e. Electromagnetic torque of three phase drop 80%



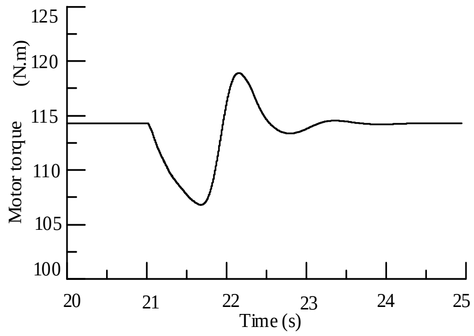
f. Various motor torque of three phase drop 80%

Fig. 6. Simulation curve of three-phase voltage drop.

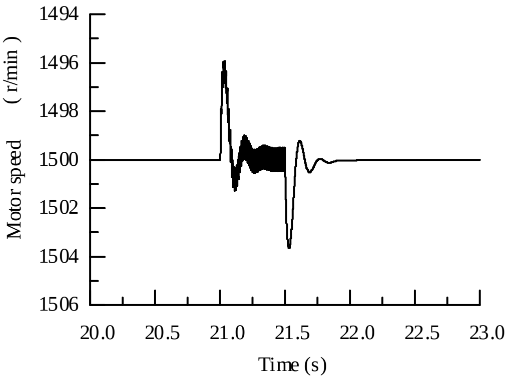
The simulation results show that fluctuation of the electromagnetic torque and the amplitude of voltage drop depths are positively correlated. At the same time, the volatility persisted for about one and a half cycle. It provides reference for studying electromagnetic torque fluctuation and stability of hydraulic system. Therefore, simulation of the dynamic compensation method is carried out to study whether the dynamic compensation method is effective or not.

Compensation of Single Phase Voltage Drop

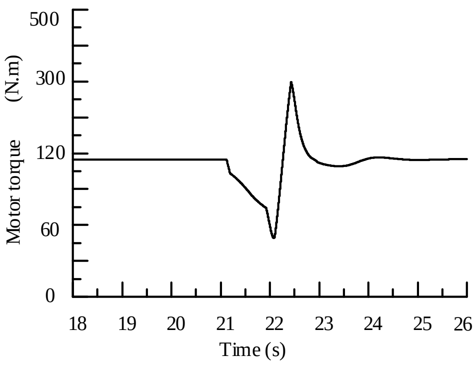
The generator electromagnetic torque appears high frequency fluctuation. Large amplitude in motor torque also occurs during single phase voltage drop, which brings great impact to variable motor speed of hydraulic system. In order to verify the effectiveness and stability of proposed applicability of electromagnetic torque fluctuation dynamic compensation control strategy, simulation of HWT work characteristics after adding the control strategy is conducted. The hydraulic system variable motor torque and speed simulation results curves are as shown in Figure 7.



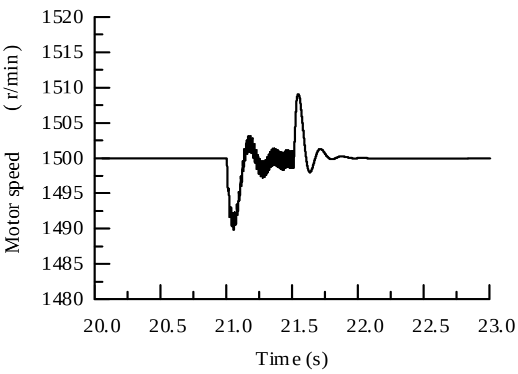
a. Various motor torque of single phase drop 20%



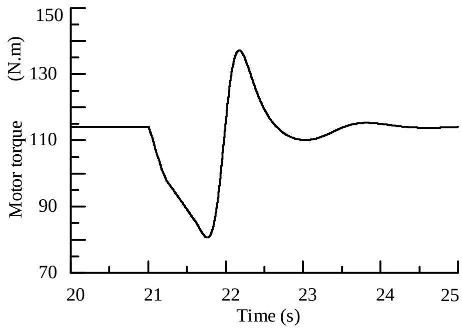
b. Various motor speed of single phase drop 20%



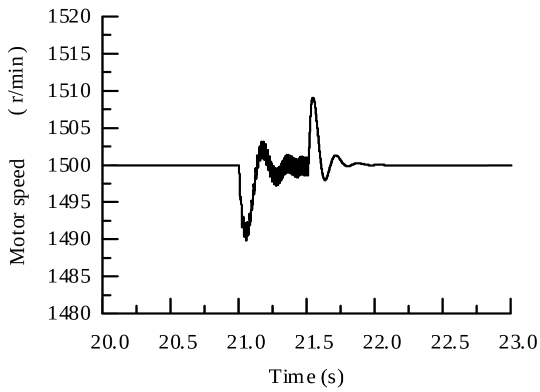
c. Various motor torque of single phase drop 50%



d. Various motor speed of single phase drop50%



e. Various motor torque of single phase drop 80%



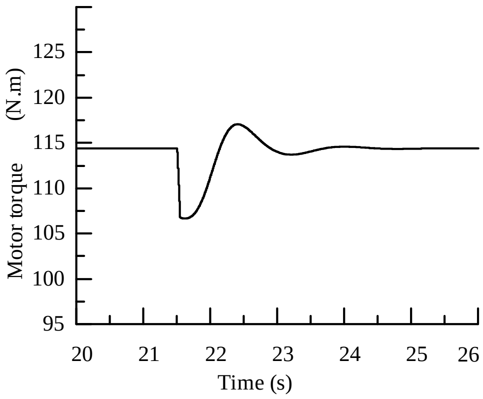
f. Various motor speed of single phase drop 80%

Fig. 7. Simulation curve of single phase voltage drop.

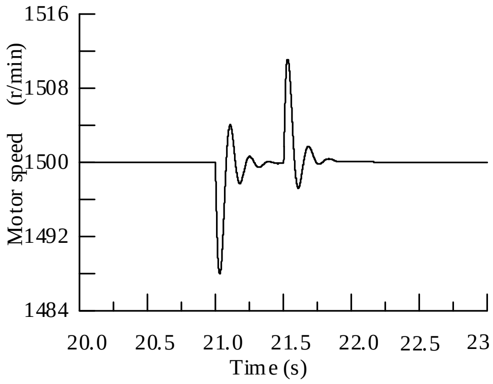
As simulation curve shows, the variable motor torque fluctuation amplitude, in different grid voltage drop depth, has decreased significantly after adding compensation control of electromagnetic torque. Variable motor speed becomes small periodic fluctuation. And fluctuation is less than equal to 10r/min, which conforms to the requirements of variable motor speed grid connected power grid. So the dynamic compensation strategy has beneficial effect is verified.

Compensation of Three Phase Voltage Drop

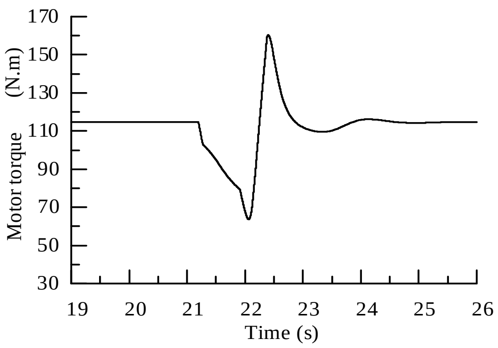
Although three-phase grid voltage drop has no high-frequency electromagnetic torque fluctuation, the output active power of the generator is changing rapidly, which causes the most serious transient impact of HWT. Aimed at verifying the effectiveness of the proposed compensation strategy, the simulation of both speed and torque of the various motor in different drop depth is carried out, the results are as shown in Figure 8.



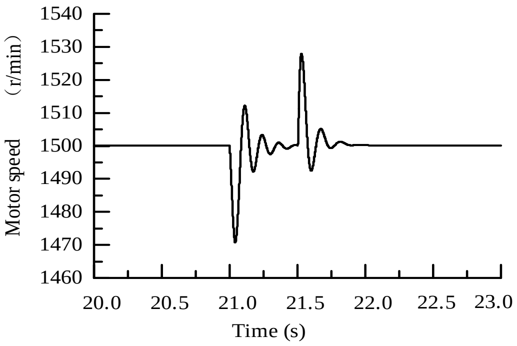
a. Various motor torque of three phase drop 20%



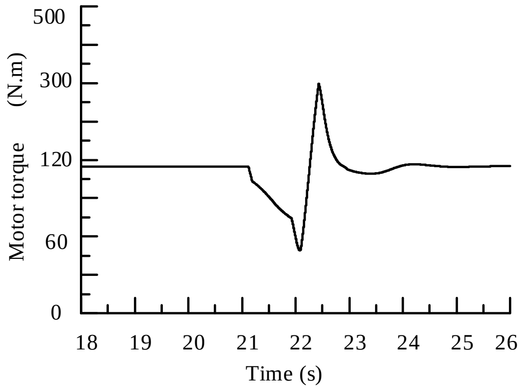
b. Various motor speed of three phase drop 20%



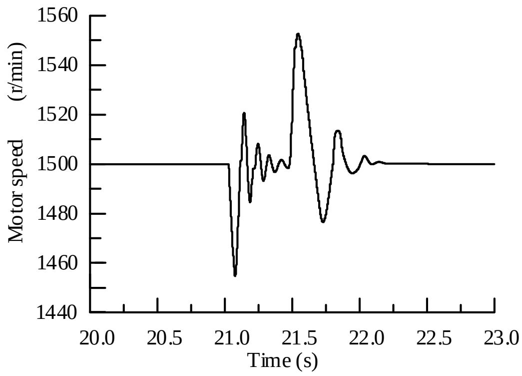
b. Various motor torque of three phase drop 50%



c. Various motor speed of three phase drop 50%



e. Various motor torque of three phase drop 80%



f. Various motor speed of three phase drop 80%

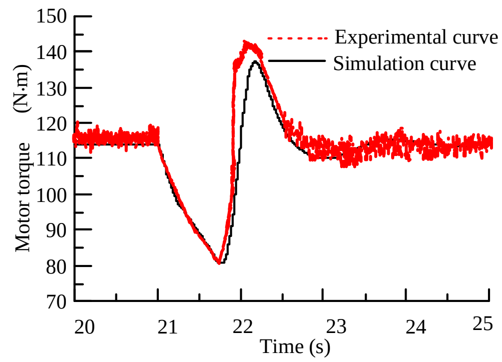
Fig. 8. Simulation curves of single phase drop in grid voltage

With the dynamic compensation control strategy, the amplitude of variable motor torque fluctuation is sharply decreased, which shows that the control strategy is effective. Meanwhile, variable motor speed jumps to periodic small fluctuations. When three-phase voltage drop depth is 20%, variable motor speed fluctuation amplitude is less than 10r/min, which meets the requirements of power grid continued operation.

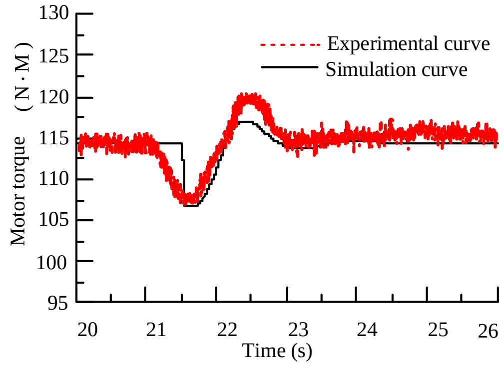
EXPERIMENTAL

As is well-known, the three-phase voltage drop is the most serious kind of power grid fault. Besides, electromagnetic torque fluctuation, resulted from single phase voltage drop, will decrease the stability of the whole system. So the research of LVRT in this two periods have significant engineering value.

During experiment, voltage drops of manually setting the grid simulator, the specific setting: three phase voltage drop occurs from 10s and drop depth of 20%. Drop duration is 0.5s. Experiment results as shown in Figure 9.



a. Various motor torque of single phase drop 80%



b. Various motor torque of three phase drop 20%

Fig. 9. Experiment curve of motor torque.

CONCLUSION

Electromagnetic torque fluctuation occurs during typical grid fault. The fluctuation do damage to output shaft of generator, and can even make HWT off the power grid.

For one thing, the instability mechanism of HWT and the reason why should compensate electromagnetic torque fluctuation are summarized. Furthermore, the state observer is designed on the basis of generator operation state equation. Then, electromagnetic torque prediction method based on the principle of time-delay compensation and the dynamic compensation method relied on adjusting the opening degree of proportional throttle valve is put forward. Finally, the performance of HWT under LVRT with and without using the dynamic compensation method is studied and compared by simulation and experiments. From the curves, it can be seen that the use of dynamic compensation method decreases amplitude of variable motor torque fluctuation. Variable motor speed change rule changes from irregular to small amplitude (less than 10r/min) periodic fluctuation. The result of the simulation and experiments shows the dynamic compensation method is effective.

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NOMENCLATURE

P_e rated electromagnetic power

P_{e0} DC component of electromagnetic power

P_{ecos2} two times of cosine component of electromagnetic power

J_m moment inertia of motor

T_{esin2} two times sine component of electromagnetic torque

B_m damping coefficient of motor

θ_m rotation angle of motor

G_m load spring stiffness of motor

X_v valve opening size

U_E voltage signal

K coefficient of proportionality

C_d discharge coefficient of orifice

W_d area gradient of orifice

ρ hydraulic oil density

p_{h1} valve inlet pressure

p_L valve pressure drop

ω_m angular velocity of motor
C_{tm} leakage coefficient of motor

K_m variable displacement gradient

γ variable motor swing angle

Ω_s synchronous angular velocity

T_{e0} DC component of electromagnetic torque

P_{esin2} two times sine component of electromagnetic power

T_{ecos2} two times of cosine component of electromagnetic torque

η_{mn} motor mechanical efficiency

η_{mv} motor volumetric efficiency

B_p coefficient of pump damp

D_p displacement of pump

C_{tp} leakage coefficient of pump

β_e elasticity modulus of oil volume

J_p rotational inertia of pump

η_{pm} mechanical efficiency of pump

T_w import torque

V_{02} control volume size

L_m inductance

n_p rotate speed of pump

L_s variable displacement gradient

ω_s angular velocity of equivalence

Q_b flux of valve

T_e electromagnetic torque to motor

液壓型風力發電機組低電壓穿越過程中電磁轉矩補償研究

艾超 劉旋 陳漢超 王亞倫 孔祥東
燕山大學河北省重型機械流體動力傳輸與控制實驗室；
先進鍛壓成型技術與科學教育部重點實驗室（燕山大學）

摘 要

隨著風電的迅速增長，中國已經制定了其並網規則，從而確保提高電力系統穩定性。本文以液壓型風力發電機組為研究對象，旨在提高機組低電壓穿越能力。本文主要研究如何補電壓跌落導致的電磁轉矩波動。首先，介紹了液壓型風電機組的工作原理，建立了機組各部分的數學模型；接著，構造了基於延時的狀態觀測器、提出了基於調節比例節流閥開口度的動態補償方法。為了避免低電壓對設備造成損害，先在 MATLAB 和 AMESim 軟件上對不同電壓跌落深度工況運行特性進行仿真分析，再進行試驗驗證。正如仿真和實驗結果證實的那樣，當系統採用本文所提出的狀態觀測器和動態補償方法后，其性能較未加補償控制之前有所提高，提高了機組的穩定性。