

Research on parameter adaptive control for MEES

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Abstract. The Mechanical elastic energy storage (MEES) is a new type of physical energy storage. The energy storage medium is large-scale planar vortex spring (LSPVS), and the energy storage form is mechanical elastic potential energy. Multiple groups of LSPVS are fixed in a single energy storage box, and multiple energy storage boxes are connected in series to form a linked energy storage box group as the energy storage unit of MEES. In the process of energy storage, the torque and inertia of LSPVS change simultaneously. The permanent magnet synchronous motor (PMSM), as the driving device, is required to realize the fast response of torque change and effectively suppress the disturbance of inertia. In this paper, firstly, the mathematical model of linked energy storage box group is established. Secondly, combining with the direct torque control (DTC) model of PMSM and the backstepping control algorithm, the adaptive parameters of torque and inertia control strategy is designed. Finally, the experimental verification shows that the control strategy proposed in this paper has faster torque response and the disturbance of inertia is suppressed simultaneously, so as the energy storage process of MEES can be carried out smoothly and efficiently.

1. Introduction

Energy storage technology is the key technology of smart grid ^[1], and the mechanical elastic energy storage (MEES) is a kind of power type energy storage technology ^[2], which is suitable for short-term and high-power application occasion. In the process of energy storage of MEES, the permanent magnet synchronous motor (PMSM) drives the linked energy storage box group to gradually tighten the large-scale planar vortex spring (LSPVS) encapsulated in its inner part. The torque and inertia of LSPVS change continuously simultaneously in this process. The output torque of PMSM is required to respond to the torque change quickly, so as to avoid the mechanical buffeting of LSPVS, thus improving the energy storage efficiency and extending the service life of MEES. At the same time, the control system should be able to effectively suppress the disturbance caused by the change of the inertia of LSPVS, so as to ensure the stability of energy storage process.

There are usually two strategies which are direct torque control (DTC) and vector control (VC) for PMSM. The DTC which has fast torque response is suitable for MEES, but its torque and flux ripple will cause LSPVS fatigue. The method to improve the torque and flux ripple of traditional DTC by using multi-stage hysteresis controller is proposed in [3]. In [4], the new type of sliding mode controller is designed, which can effectively reduce the torque and flux ripple of traditional DTC combined with space vector modulation. Based on the algorithm of backstepping control ^[5], the new DTC strategy based on space vector modulation is proposed in [6]. Compared with the traditional DTC, it has the same response speed and significantly reduces the torque and flux ripple. However, the control strategies in [3] - [6] all set the inertia of load as a fixed value, which is not suitable for the situation of MEES which the torque and inertia of load continuous change simultaneously. Based on the control strategy proposed

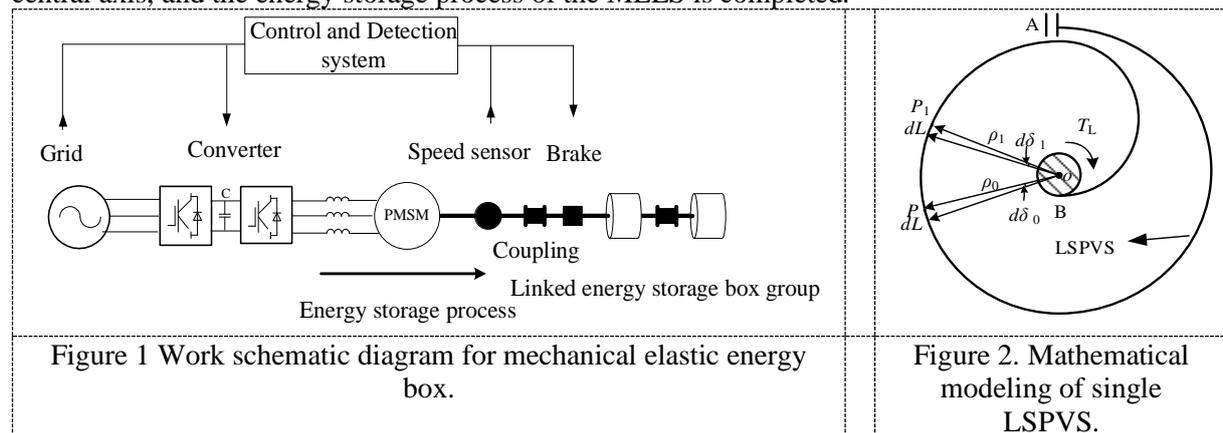


in [6], the real-time parameters of the LSPVS is identified by the forgetting factor least square identification algorithm, and then the results are returned to the control system and the identification error is suppressed by the adaptive algorithm in [7]. Although this method meets the requirements of MEES performance, the control method is extremely complex and the calculation is huge because different calculation methods are used for identification and control process.

In this paper, the mathematical model of power-capacity configuration of linked energy storage box group is established firstly. Secondly, the parameter adaptive backstepping DTC strategy is proposed. By combining the torque and inertia adaptive law with the backstepping control algorithm, the parameter identification of LSPVS and the control of PMSM can be executed at the same time. Finally, the comparative experiment with the traditional DTC and the method proposed in this paper is carried out. The experimental results show that the torque response of the proposed control strategy is rapid and can effectively suppress the inertia disturbance simultaneously, so the energy storage process of MEES can be completed smoothly and efficiently.

2. System Description

The energy storage side device of MEES is shown in Figure 1, which is composed of converter, PMSM, linked energy storage box group and control and detection system. As shown in Figure 2, With the rotation of the energy storage box, the LSPVS gradually shrinks until it is completely wrapped on the central axis, and the energy storage process of the MEES is completed.



2.1. Mathematical model of linked energy storage box group

As shown in Figure 2, one end of LSPVS is fixed on the wall A and the other end is fixed on the central axis B of the energy storage box. Under the action of the core shaft torque T_L , the micro element dL moves from point P to point P_1 , the curvature radius of point P is ρ_0 , the rotation angle of dL relative curvature center is $d\delta_0$, the curvature radius of point P_1 is ρ_1 , and the rotation angle of dL relative curvature center is $d\delta_1$. According to the theory of material mechanics, we can get

$$\begin{cases} T_L = EI \left(\frac{1}{\rho_1} - \frac{1}{\rho_0} \right) \\ I = \frac{bh^3}{12} \end{cases} \quad (1)$$

Where E is the modulus of elasticity of LSPVS, I is the moment of inertia of LSPVS cross section, l 、 b 、 h are the length, width and thickness of LSPVS respectively.

It can be seen from Figure 1 and Figure 2 that the linked energy storage box group consists of several energy storage boxes, assumed to be m , and each energy storage box is encapsulated with several LSPVS, assumed to be n . The torque of each energy storage box is equal, and the T_{mL} of energy storage box group can be written as

$$T_{mL} = nT_0 + \frac{nEb^3}{12ml} \omega t \quad (0 \leq t \leq mt_{\max}) \quad (2)$$

It can be seen from equation (2) that n determines the rated power of the MEES, m determines the operation time of the MEES under the rated power, so determines the energy storage capacity of the MEES. Similarly, the moment of J_{mm} of the linked energy storage box group can be expressed by formula (3), where J_0 is the fixed part of the inertia of LSPVS, J_e is the maximum value of the change part of the inertia of LSPVS, n_{\max} is the effective number of working cycles of the linked energy storage box group.

$$J_{mm} = nJ_0 + nJ_e \left(1 - \frac{\omega t}{2\pi mn_{\max}} \right) \quad (0 \leq t \leq mt_{\max}) \quad (3)$$

2.2. Mathematical model of PMSM

The mathematical model of PMSM in two-phase stationary α, β coordinate system can be written as

Current equation

$$\begin{cases} \frac{di_\alpha}{dt} = \frac{u_\alpha}{L} - \frac{R}{L}i_\alpha - \frac{E_\alpha}{L} \\ \frac{di_\beta}{dt} = \frac{u_\beta}{L} - \frac{R}{L}i_\beta - \frac{E_\beta}{L} \end{cases} \quad (4)$$

Where u_α and u_β are the components of stator voltage in α axis and β axis, i_α and i_β are the components of stator current in α axis and β axis, L is the equivalent inductances of stator windings, R is the phase resistance of the stator windings, t is the time.

Flux linkage equation

$$\begin{cases} \frac{d\psi_\alpha}{dt} = u_\alpha - Ri_\alpha \\ \frac{d\psi_\beta}{dt} = u_\beta - Ri_\beta \\ \psi_s = \psi_\alpha^2 + \psi_\beta^2 \end{cases} \quad (5)$$

Where ψ_α, ψ_β is the α axis and β axis flux linkage of the stator windings, ψ_s is the square of the stator flux linkage.

Rotor equation

$$J \frac{d\omega}{dt} = n_p (T_e - T_L) - B_m \omega \quad (6)$$

Where n_p is the number of rotor pole pairs, T_e is the electromagnetic torque, T_L is the load torque, J is the moment of inertia, B_m is the viscous friction coefficient, ω is mechanical angular velocity of the rotating rotor.

Electromagnetic torque equation

$$T_e = \frac{3}{2} n_p [\psi_\alpha i_\beta - \psi_\beta i_\alpha] \quad (7)$$

3. Parameter Adaptive Control Strategy Design

It can be seen from the above that the torque and the inertia of the linked energy storage box group continuous change in the process of energy storage. The control target of the system is speed, torque and flux of PMSM. According to the principle of backstepping control, the error variables e_ω, e_T, e_ψ are defined as follows

$$\begin{cases} e_\omega = \omega - \hat{\omega}_{ref} \\ e_T = T_e - T_{eref} \\ e_\psi = \psi_s - \psi_{sref} \end{cases} \quad (8)$$

For the PMSM system, ω_{ref} is the speed reference signal, T_{eref} is the electromagnetic torque reference signal, ψ_{sref} is the flux linkage reference signal, Lyapunov function V_1 is selected as follows

$$V_1 = \frac{1}{2}e_\omega^2 + \frac{1}{2}e_T^2 + \frac{1}{2}e_\psi^2 > 0 \quad (9)$$

The real time value of the torque and inertia of load is \hat{T}_L and \hat{J} , then the change value of the torque and inertia of load is ΔT_L and ΔJ , the T_L and J can be expressed as follows

$$\begin{cases} \hat{T}_L = T_L + \Delta T_L \\ \hat{J} = J + \Delta J \end{cases} \quad (10)$$

By substitution of (10) into the derivative of (9), we can obtain

$$\begin{aligned} \dot{V}_1 = & -k_1 e_\omega^2 - k_2 e_T^2 - k_3 e_\psi^2 + e_T \left[u_\alpha i_\beta - u_\beta i_\alpha - \frac{\psi_\beta}{L} u_\alpha + \frac{\psi_\alpha}{L} u_\beta + \frac{R\psi_\beta}{L} i_\alpha \right. \\ & \left. - \frac{R\psi_\alpha}{L} i_\beta + \frac{\psi_\beta E_\alpha}{L} - \frac{\psi_\alpha E_\beta}{L} - \frac{\hat{J}}{n_p} (\ddot{\omega}_{ref} + k_1 \dot{\omega}_{ref}) - k_1 (T_e - \hat{T}_L) + \hat{T}_L + k_2 e_T \right] \\ & + e_\psi \left[2\psi_\alpha u_\alpha + 2\psi_\beta u_\beta - 2R\psi_\alpha i_\alpha - 2R\psi_\beta i_\beta + k_2 e_\psi + e_T \left[\frac{(\ddot{\omega}_{ref} + k_1 \dot{\omega}_{ref})}{n_p} \Delta J - k_1 \Delta T_L \right] \right] \end{aligned} \quad (11)$$

Where k_1, k_2, k_3 represents the positive control gain, the α, β axis voltage of PMSM can be chosen as

$$\begin{aligned} u_{\alpha ref} = & \frac{L}{(\psi_\alpha - Li_\alpha)\psi_\alpha + (\psi_\beta - Li_\beta)\psi_\beta} \left[\left(\frac{\psi_\alpha}{L} - i_\alpha \right) (R\psi_\alpha i_\alpha + R\psi_\beta i_\beta + \frac{k_3}{2} e_\psi) - \frac{2\psi_\beta \hat{J}}{3n_p^2} (\ddot{\omega}_{ref} + k_1 \dot{\omega}_{ref}) \right. \\ & \left. - \frac{2\psi_\beta}{3n_p} \left(\hat{T}_L + k_1 T_e - k_1 \hat{T}_L \right) - \psi_\alpha \psi_\beta \left(\frac{R}{L} i_\beta + \frac{E_\beta}{L} \right) + \psi_\beta^2 \left(\frac{R}{L} i_\alpha + \frac{E_\alpha}{L} \right) + \frac{2k_2 \psi_\beta}{3n_p} e_T \right] \end{aligned} \quad (12)$$

$$\begin{aligned} u_{\beta ref} = & \frac{L}{(Li_\alpha - \psi_\alpha)\psi_\alpha + (Li_\beta - \psi_\beta)\psi_\beta} \left[\left(i_\beta - \frac{\psi_\beta}{L} \right) (R\psi_\alpha i_\alpha + R\psi_\beta i_\beta - \frac{k_3}{2} e_\psi) - \frac{2\psi_\alpha \hat{J}}{3n_p^2} (\ddot{\omega}_{ref} + k_1 \dot{\omega}_{ref}) \right. \\ & \left. - \frac{2\psi_\alpha}{3n_p} \left(\hat{T}_L + k_1 T_e - k_1 \hat{T}_L \right) + \psi_\alpha \psi_\beta \left(\frac{R}{L} i_\alpha + \frac{E_\alpha}{L} \right) + \psi_\alpha^2 \left(\frac{R}{L} i_\beta + \frac{E_\beta}{L} \right) + \frac{2k_2 \psi_\alpha}{3n_p} e_T \right] \end{aligned} \quad (13)$$

By substitution of (12) and (13) into (11), we can acquire

$$\dot{V}_1 = -k_1 e_\omega^2 - k_2 e_T^2 - k_3 e_\psi^2 + e_T \left[\frac{(\ddot{\omega}_{ref} + k_1 \dot{\omega}_{ref})}{n_p} \Delta J - k_1 \Delta T_L \right] \quad (14)$$

Lyapunov function V_2 is chosen as follows

$$V_2 = V_1 + \frac{\Delta J^2}{2r_1} + \frac{\Delta T_L^2}{2r_2} \quad (15)$$

Where r_1, r_2 represents positive adaptive gains, adaptive law is obtained

$$\begin{cases} \Delta \dot{T}_L = k_1 r_2 e_T \\ \Delta \dot{J} = -r_1 e_T \left(\frac{\ddot{\omega}_{ref}}{n_p} + \frac{k_1 \dot{\omega}_{ref}}{n_p} \right) \end{cases} \quad (16)$$

By substitution of (16) into the derivative of (14), we can acquire

$$\dot{V}_2 = -k_1 e_\omega^2 - k_2 e_T^2 - k_3 e_\psi^2 < 0 \quad (17)$$

In accordance with Barbalat's Lemma, the following equation can be obtained

$$\lim_{t \rightarrow \infty} e_\omega = \lim_{t \rightarrow \infty} e_T = \lim_{t \rightarrow \infty} e_\psi = 0 \quad (18)$$

4. Experimental verification

The energy storage side of MEES is shown in Figure 3, which is composed of linked energy storage box group, brake, sensor, PMSM. The parameters of PMSM are $R = 875 \Omega$, $L = 0.033 \text{ H}$, $n_p = 10$, $\psi_s = 0.38 \text{ Wb}$, and the parameters of energy storage box are $E = 2 \times 10^{11} \text{ E/N/m}^2$, $l = 14.639 \text{ m}$, $h = 0.0018 \text{ m}$, $b = 0.05 \text{ m}$, $T_0 = 5 \text{ N}\cdot\text{m}$, T_L range is $5 \sim 60 \text{ N}\cdot\text{m}$, J range is $0.3 \sim 0.5 \text{ kg}\cdot\text{m}^2$. The control parameters of the algorithm proposed in this paper are $k_1 = 0.01$, $k_2 = 300$, $k_3 = 50$, $r_1 = 0.02$, $r_2 = 0.08$. In order to discuss the advantages of this algorithm in the steady-state and transient regulation performance, a comparative experiment is carried out by using the traditional DTC.

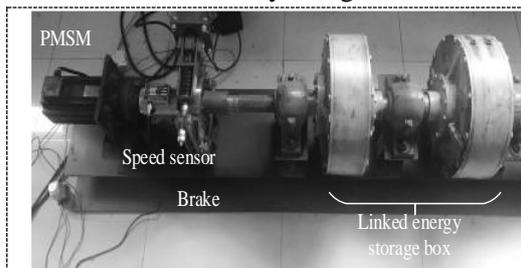


Figure 3 Energy storage device of MEES.



Figure 4 The monitoring system of MEES.

The PMSM speed reference signal is 2 r/min when the time is less than 20s. When the time is between 20s and 40s, the reference speed of PMSM suddenly changes to 4 r/min. And when the time is more than 40s, the reference speed of PMSM is restored to 2 r/min. It can be seen from Figure 5 that when the speed command of traditional DTC changes, there is long adjustment time and obvious overshoot. The speed overshoot is about 20%, and the adjustment time is about 0.2s. It can be seen from Figure 6 that the algorithm proposed in this paper has no overshoot and the adjustment time is also short. The algorithm proposed in this paper has better transient performance. From the comparison of Figure 5 and Figure 6, it can be seen that the algorithm in this paper has less pulsation than the traditional DTC. The algorithm in this paper has better steady-state performance.

When the speed command changes suddenly at 20s, the torque of the linked energy storage box group increases faster. The output torque of PMSM with two algorithms can respond quickly, however, it can be seen from Figure 7 that the torque output of the traditional DTC has long time adjustment. As shown in Figure 8, the control algorithm proposed in this paper can respond quickly and the energy storage process is relatively stable. At the same time, it can be seen from the two figures that the torque ripple of the algorithm in this paper is significantly reduced compared with the traditional DTC, which is beneficial to the MEES system.

From the above analysis, it can be concluded that the torque increases gradually and the inertia disturbance exists simultaneously of the linked energy storage box group in the energy storage process. Through comparative experiments, we can conclude that the algorithm in this paper has faster torque response speed than the traditional DTC, and can effectively suppress the adverse effect of the change of the inertia. At the same time, the control algorithm proposed in this paper can obviously reduce the speed and torque ripple, and effectively improve the control performance of the MEES system.

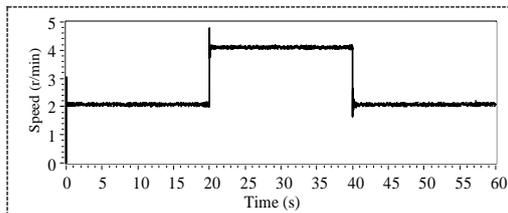


Figure 5 Speed waveform of traditional DTC.

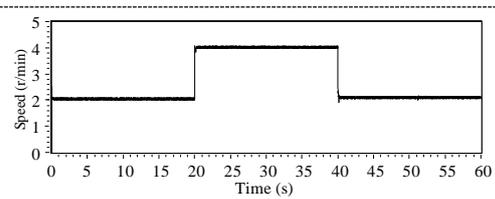


Figure 6 Speed waveform of the algorithm in this paper.

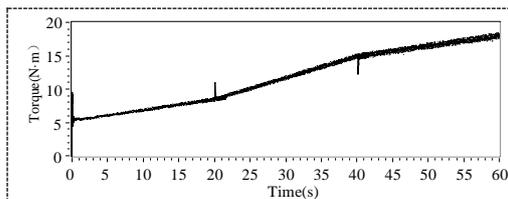


Figure 7 Torque waveform of traditional DTC.

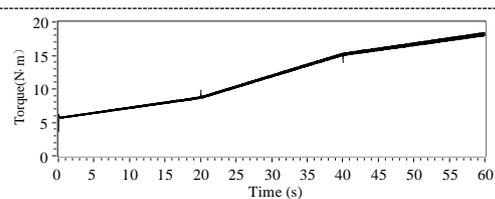


Figure 8 Torque waveform of the algorithm in this paper.

5. Conclusion

In this paper, the mathematical model mechanical elastic energy storage box group is established, which provides the basis for energy storage capacity of MEES configuration in different applications. And according to the operation characteristics of the MEES, the adaptive DTC of torque and inertia which can realize the fast response of PMSM torque and restrain the interference of inertia effectively is proposed. Compared with the traditional DTC, it has obvious improvement in both static and dynamic performance, and is suitable for the energy storage process of MEES system.

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