Adaptive speed control of PMSM for energy storage process of MEES

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Abstract. Mechanical elastic energy storage (MEES) system completes the energy storage process through permanent magnet synchronous motor (PMSM) rotates and tightens the energy storage boxes which contains large spiral torsion springs (STSs) to convert electrical energy into elastic potential energy. The torque of the storage box is gradually increased while the moment of inertia is gradually reduced in the process of energy storage. Thus, this paper proposed an backstepping control scheme with torque and inertia adaptive law and the stability was proved in the sense of Lyapunov theory. The effectiveness of the proposed scheme was verified through hardware experiments. The results indicated that the proposed scheme ensures the speed to track the given value rapidly and the energy storage process can be carried out smoothly.

1. Introduction
With the depletion of traditional fossil energy and the rapid development of new energy technology, energy storage has become one of the core technologies. It is necessary to develop a variety of complementary energy storage technologies with different forms and characteristic. Mechanical elastic energy storage (MEES) is a new energy storage technology which storage components is spiral torsion spring (STS). In the energy storage stage of the MEES\textsuperscript{1}, a reliable actuator is required to tighten the STSs fixed in storage box. Permanent magnet synchronous motor (PMSM)\textsuperscript{2, 3} is selected as the actuator of the MEES device because of its many advantages. The torque and inertia of energy storage box which is the load of the MEES are changing continuously in the process of energy storage, and a novel control algorithm is needed. An adaptive control scheme considering the variations of load inertia for PMSM speed-regulation system is proposed in [4], however, the continuous variation of load torque is not considered. A low speed control algorithm considering simultaneous changing load torque and inertia is designed for MEES device in [5], but the identification algorithm of the load variables and the speed control algorithm are independent, so the derivation process is very complex. In this letter, an adaptive speed control method is designed for the energy storage process for MEES device, which can satisfy the control requirements absolutely, meanwhile, the derivation process is relatively simpler and easier.
2. System Description
Figure 1 displays that with the increase of elastic potential energy stored in STS, STS will be gradually wound up from external housing to central spindle, which reduces the inertia and enlarges the torque of STS.

The external torque $T_L$ and inertia $J$ of STS can be written as

$$
\begin{align*}
T_L &= T_0 + k_T \int \omega dt \\
J &= J_0 \left(1 - \frac{\omega t}{2n_s}\right)
\end{align*}
$$

(1)

Where $T_0$ is the initial torque, $\omega$ is the rotating velocity of spindle, $n_s$ represents the maximum energy storage circle number. $k_T$ is storage coefficient, and $t$ is the time.

Due to its various advantages, PMSM is utilised an actuator for MEES device. The motor dynamic equation is stated as (2)

$$
\begin{align*}
J \frac{d\omega}{dt} &= T_e - B_m \omega - T_L \\
\frac{di_d}{dt} &= -\frac{R}{L}i_d + n_p\omega i_q + \frac{1}{L}u_q \\
\frac{di_q}{dt} &= -\frac{R}{L}i_q - n_p\omega i_d - \frac{n_p\psi_f}{L} + \frac{1}{L}u_d
\end{align*}
$$

(2)

Where $T_e$ is the electromagnetic torque, $B_m$ is the viscous friction coefficient, $n_p$ is the number of rotor pole pairs, $\psi_f$ is the flux linkage, $R$ is the phase resistance of the stator windings, $L$ is the phase inductance of stator windings, $i_d$ and $i_q$ are the d-q axis currents, $u_d$ and $u_q$ are the d-q axis voltages.

3. Adaptive Speed Control Strategy Design
For the MEES system, $\omega^*$ is the speed reference signal, $i_d^*$ and $i_q^*$ are the d-q axis current reference signals, it is assumed that the tracking error $e_\omega$, $e_d$ and $e_q$ are

$$
\begin{align*}
e_\omega &= \omega^* - \omega \\
e_d &= i_d^* - i_d \\
e_q &= i_q^* - i_q
\end{align*}
$$

(3)

The estimated value of the load torque is $\hat{T}_L$, the estimated value of the inertia is $\hat{J}$, then the estimations error $\Delta T_L$ and $\Delta J$ can be expressed as follows

$$
\begin{align*}
T_L &= \hat{T}_L - \Delta T_L \\
J &= \hat{J} - \Delta J
\end{align*}
$$

(4)

Lyapunov function $V$ is chosen as follows
\[ V = \frac{J}{2} e_\omega^2 + \frac{J}{2} e_i^2 + \frac{1}{2} e_q^2 + \frac{\Delta J^2}{2 r_1} + \frac{\Delta T_L^2}{2 r_2} \]  

(5)

Where \( r_1 \) and \( r_2 \) represents positive adaptive gains, The derivative of (5) can be written as

\[
\dot{V} = e_\omega \left( T_L - \frac{3 n_p \psi_L}{2} i_q \right) + e_i \left[ -k_i i_q + \frac{2 k_i \dot{T}_L}{3 n_p \psi_L} + 2 \frac{\Delta T_L}{3 n_p \psi_L} + j \left( R i_q + n_p \omega i_d + \frac{n_p \psi_L}{L} \omega - \frac{1}{L} u_q \right) \right]
\]

\[-e_q \left[ \frac{2 k_i}{3 n_p \psi_L} \Delta T_L + \frac{2 \Delta J}{3 n_p \psi_L} \Delta \dot{T}_L + \Delta J \left( \frac{R}{L} i_q + n_p \omega i_d + \frac{n_p \psi_L}{L} \omega - \frac{1}{L} u_q \right) \right] \]

\[-e_q \left( \frac{R}{L} i_d - n_p \omega i_q - \frac{1}{L} u_d \right) + \Delta \dot{T}_L \]  

\[ \dot{T}_L + \frac{\Delta J}{r_1} + \frac{\Delta T_L}{r_2} \]  

The \( d-q \) axis voltage of PMSM \( u_d^* \) and \( u_q^* \) can be chosen as

\[
\begin{align*}
    u_d^* &= R i_d + L n_p \omega i_q - k_1 L e_d \\
    u_q^* &= R i_q + L n_p \omega i_d + n_p \psi_L + \frac{L}{J} \left( -k_2 i_d + \frac{2 k_2 \dot{T}_L}{3 n_p \psi_L} + k_3 e_q + \frac{2 \Delta \dot{T}_L}{3 n_p \psi_L} \right)
\end{align*}
\]  

(7)

Where \( k_1, k_2, k_3 \) represents positive control gains. The adaptive law orque and intertia can be chosen as

\[
\begin{align*}
    \Delta \dot{T}_L &= r_1 \left( e_\omega + \frac{2 k_i e_d}{3 n_p \psi_L} \right) \\
    \Delta J &= r_1 \left( e_q - \frac{2 e_q}{3 n_p \psi_L} \Delta T_L \right)
\end{align*}
\]  

(8)

Substituting (7) and (8) into (6), we can obtain

\[ \dot{V} = -k_1 e_\omega^2 - k_2 e_i^2 - k_3 e_q^2 \leq 0 \]  

(9)

Hence, according to the Barbalat’s lemma, we can acquire

\[
\lim_{t \to \infty} e_\omega = \lim_{t \to \infty} e_i = \lim_{t \to \infty} e_q = 0
\]  

(10)

Therefore, all the variables are bounded.

4. Experimental results

In order to verify the effectiveness of the new algorithm, the performance is tested through a hardware platform shown in Figure 2 and 3. STSs as the load are packed in energy storage boxes. PMSM is connected with the spindle which STSs are wound on across a speed sensor. A electromagnetic brake is used to lock the spindle when the device stops running. The parameters of PMSM and STS are shown in Table 1. A TMS320F28335 DSP chip is served as the controller.
### Table 1. Parameters of PMSM and STS

| Parameter | Value       | Parameter | Value       | Parameter | Value       |
|-----------|-------------|-----------|-------------|-----------|-------------|
| $R$       | 2.875Ω      | $k_T$     | 3.95 N·m/r  | $\psi_f$  | 0.38 Wb     |
| $L$       | 3.3 mH      | $T_0$     | 5 N·m       | $n_p$     | 10          |
| $J_e$     | 0.03 kg·m²  | $n_s$     | 15 r        |           |             |

The controller parameters of the method in this letter are $k_1 = 0.01$, $k_2 = 230$, $k_3 = 2000$, the adaptive identification parameters $t_1 = 4.52$, $t_2 = 4.78$. The experiment results are given in Figure 4 to 7.

It can be seen from Figure 4 that the system speed can track the reference value quickly, the adjustment time is short and no overshoot. Figure 5 shows that the control algorithm achieves $i_d = 0$, and there is a tiny spike only when the speed changes, but it converges quickly. Figure 6 is $q$ axis current, as the energy storage process of the device is carried out, the torque of the storage box is gradually increasing, so the $q$ axis current value of the PMSM is gradually increasing. Figure 7 shows the stator phase current, the amplitude increases with the increase of the energy storage process, and the wave of stator phase current is perfect.

### 5. Conclusion

In this paper, a backstepping control with torque and inertia adaptive law for PMSM which is utilised as an actuator for MEES device is proposed. By establishing a novel function, the control algorithm is finished and its convergence is proved. The experimental results show that the algorithm can effectively suppress the parameters disturbance of the energy storage box, and the energy storage process of the storage can be carried out smoothly.

### References

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