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# Research on Tension Control Strategy of Battery Pole-piece Winding and Unwinding System Based on Fault-tolerant Control

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## Abstract

A research on fault compensation method of battery pole-piece winding and unwinding system based on fault-tolerant control. Firstly, the method is designed to detect and isolate the fault. Then, a reconfiguration mechanism module is switched on to be used in control reconfiguration and fault compensation. This approach was applied to the tension control of winding and unwinding system for the diagnosis and compensation and was demonstrated to be effective by the simulation experiment.

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*Keywords:* Fault-tolerant control; Fault diagnosis; Winding and unwinding system; Tension control

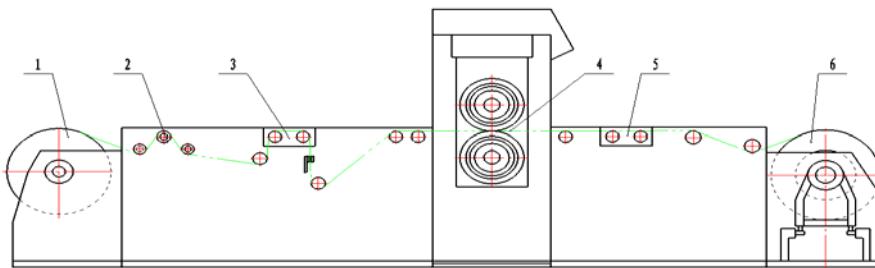
## 1. Introduction

Energy research is an important field in today's scientific research. Lithium battery is an energy storage device which is safe, clean, widely used and with high performance. It is a hotspot in battery research nowdays. Lithium battery is made of rolled pole-piece. The winding, rolling, cutting and unwinding of the

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pole-piece is always the key link in the process of lithium battery production. So the link control is the key to ensure the quality of the battery in the process. Figure 1 illustrates how the winding and unwinding system of battery working. From the illustration we know tension control is the key link in control system. The control performance, precision will directly affect the performance of lithium battery eventually. So the aim of the tension control is to ensure the stable operation of the device, especially in the speed change. To the tension control for winding device, the existing large-scale equipment always uses DCS(Distributed Control System) to reduce equipment control complexity and improve control reliability<sup>[1]</sup>. Due to the controlled objects quantity is so large, the fault in potential is growing.

The system reliability will be decreased badly. Meanwhile the costly of DCS prevent its promotion of use; The key actuator of winding system is very sensitive to system fault. Its fault state will affect winding process performance and winding shaping quality, even cause winding process discontinuous. This paper put forward a control method based on fuzzy fault diagnosis and the fault-tolerant control strategy. It works under the condition of the fault of actuators fault diagnosis and fault compensation. This method has been applied to the winding machine in tension control system in actuators fault diagnosis and compensation. The simulation experiments prove the effectiveness of this method.

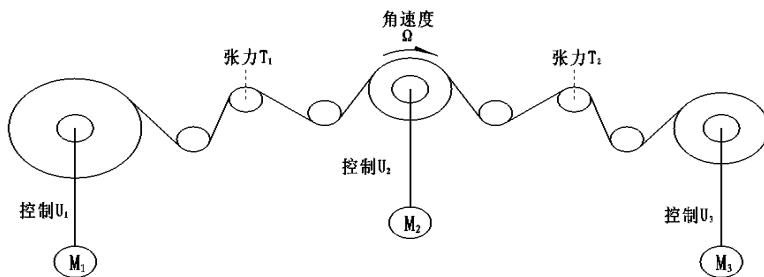


1. unwinding system 2. tension control 3. deviation rectifying set 4. rolling mill

5. tension control 6. winding system with deviation rectifying set

**Fig.1.** Diagram of the transmission on Lithium battery winding and unwinding system

## 2 Winding device modeling



**Fig.2.** Diagram of tension control on winding and unwinding system

As shown in figure 2. It is the diagram of tension control on winding and unwinding system. In the figure we know that the system is made up of 3 reels which are driven by servo motors (M1,M2,M3), gear reducer which is connect with reels and a tape of raw material (Fig.2). Motor 1 controls retreat scroll, motor 3 controls unwinding roller and motor 2 controls rolling mill. The position of M2 and the tension on material tape between scrolls are measured by a tachometer and a tensiometer. Every motor is controlled by a partial driver. Separately, we carried out torque control to M1 and M3 and speed control to

M2.

The inputs of 3 motors are U1, U2, U3: U1 and U3 correspond to I1 and I3, the set value of partial controllers. U2 is voltage input of M2. Tension T1, T2 and the speed of material tape are main controlled members in winding. Linear velocity can't be measured directly, but the radius of tractive scroll is constant so the linear velocity is controlled by angular velocity  $\Omega$ .

We set sampling interval  $T^5 = 0.1\text{ s}$ , around work points  $u_0 = [-0.15 \ 0.6 \ 0.15]$ ,  $y_0 = [0.6 \ 0.55 \ 0.4]$ . Linear model of winding equipment is provided by the expression of discrete state space as follows:

$$x_{k+1} = Ax_K + Bu_K + w_K, \quad (1)$$

$$y_K = Cx_K + v_K, \quad (2)$$

$$x_K = [T_1 \ \Omega_2 \ T_3]^\top, \ u = [u_1 \ u_2 \ u_3]^\top, \quad (2)$$

$C$  is unitary matrix  $I_3$ . The system described by matrix is fully observable and control variable.

Due to abnormal operation or material ageing, different additivity or multiplicative fault may affect the system. Additivity fault is expressed by sensors and actuators <sup>[2]</sup>. In this paper we concern on the fault of actuator.

Considering the vectorial fault of unknown input  $n_k$ , system model can be rewritten for

$$x_{k+1} = Ax_k + Bu_k + Fn_k + w_k, \quad (3)$$

$$y_k = Cx_k + v_k. \quad (4)$$

thereinto,  $x_k \in R^n$  is state vector,  $y_k \in R^m$  is output vector,  $u_k \in R^p$  is input vector. Noise  $w_k$  and  $v_k$  is zero average irrelevant random sequence

$$E\left\{\begin{bmatrix} w_K \\ v_K \end{bmatrix} \begin{bmatrix} w_j^T & v_j^T \end{bmatrix}\right\} = \begin{bmatrix} W & 0 \\ 0 & I \end{bmatrix} \delta_{kj}, \quad (5)$$

thereinto,  $W \geq 0$ .

### 3 Strategy of Fault-tolerant Control

Fault-tolerant is a concept that originally applied in computer system design. It points out even if the system suffers from internal link partial failure or become invalid, it can run normally still<sup>[3]</sup>. Although we cannot assure each link of the system is absolutely reliable, if we introduce fault-tolerant concept in control system, forming a fault-tolerant control system, making each fault factors in the system on the control of influence is significantly weakened, it also means that it has improved the control system reliability indirectly. Especially when a control system of each component reliability were unknown, before check in system design stage fault-tolerant is the main way to guarantee system reliability<sup>[4]</sup>.

The fault compensation based on fault-tolerant control by three fault-tolerant control modules to complete, there is a control module, a fault diagnosis module and a reconstruction mechanism module which link the former two modules<sup>[5]</sup>.

#### 3.1 Diagnosis and isolation of fault

Fault diagnosis means that the deviations in design in the conditions with no fault in close to zero but in fault conditions there is significant deviation. This paper used a rejector with dimensional state observer to produce output residual which can respond to every fault in general<sup>[6]</sup>.

Formula (3) and (4) show the discrete-time linear system, it's residual generator is:

$$\hat{x}_{k+1} = A\hat{x}_k + Bu_k + K(y_k - C\hat{x}_k), \quad (6)$$

$$r_k = L(y_k - C\hat{x}_k) \quad (7)$$

Thereinto  $\hat{x}_k$  is the state of filter,  $r_k$  is the output of filter,  $L \in R^{q \times m}$  and  $K \in R^{n \times m}$  are the unkown gain matrix that we design which satisfied fault detect and isolation demand.

In the case of linear, invariant system (6), (7) has fault detect index as follows:

$$\rho_i = \min_{\psi} \{v : CA^{v-1} f_i \neq 0, v=1,2,\dots\} \quad (8)$$

Define the fault detect matrix

$$D = C\psi \quad (9)$$

Thereinto,

$$\psi = A^{\rho_1-1} f_1 \cdots A^{\rho_i-1} f_i \cdots A^{\rho_q-1} f_q \quad (10)$$

So, the failure isolation filter is described by the following equation:

$$\hat{x}_{k+1} = A\hat{x}_k + Bu_k + (\omega\Pi + \bar{K}_k\Sigma)(y_k - C\hat{x}_k), \quad (11)$$

$$\bar{P}_{k+1} = (\bar{A} - \bar{K}_k\bar{C})P_k(\bar{A} - \bar{K}_k\bar{C})^T + \bar{W} + \bar{K}_k\bar{V}\bar{K}^T \quad (12)$$

thereinto  $\bar{A} = A - \omega\Pi C$ ,  $\bar{C} = \Sigma C$ ,  $\bar{V} = \Sigma\Sigma^T$ ,  $\bar{W} = W + \omega\Pi\Pi^T\omega^T$ .

from the filter equation we get  $\hat{x}_{k+1} = A\hat{x}_k + Bu_k + \omega r_k + \bar{K}_k\gamma_k$ ,  $\quad (13)$

obviously  $\gamma_k = \Sigma(y_k - C\hat{x}_k)$   $\quad (14)$

and fault decoupling then  $r_k = (\Pi + \bar{L}\Sigma)(y_k - C\hat{x}_k)$   $\quad (15)$

With the method we have put forward, the feature that can response to every fault orientation of output residual caused by fault filter can be used to detect failure and achieve isolation.

### 3.2 Fault Compensation

The theory of fault compensation what we come up with is used to make reconstruction system and nominal system to close as far as possible. Once the fault is isolated, the corresponding fault estimation and compensation module will be activated to reduce the influence of fault for system. Estimating the fault critical value and adding a new control rules to nominal rules to prevent the influence from the system failure. From equation (15) we get that  $r_k$  expresses an estimation of faults. Therefore, a trouble-free estimation of actual state vector can be expresssde by the following equation and used to control the reconstruction.

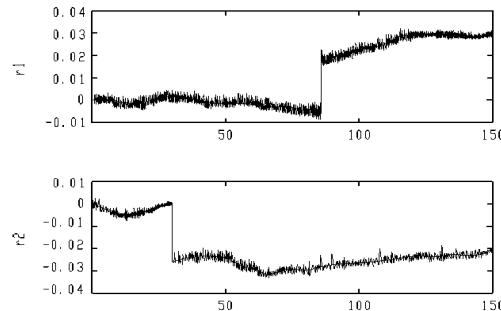
Reconstruction mechanism plays a role as following : Trouble-free state estimation is used to response to the feedback of controller, while an additivity control signal  $u_{ad}$  is used to compensate the influence of fault on the system. Therefore, the general control rules applied in the system is expressed by the following equation

$$u_k = -[K_1 \ K_2] \begin{bmatrix} x_k^{rec} \\ z_k^{rec} \end{bmatrix} + u_k^{ad} \quad (16)$$

### 4 The application on the tension control system of winder.

This paper applies the method whien based on fuzzy fault diagnosis and fault-tolerant control to the winder tension control system, and perform a simulation experiment on fault-tolerant control efficiency

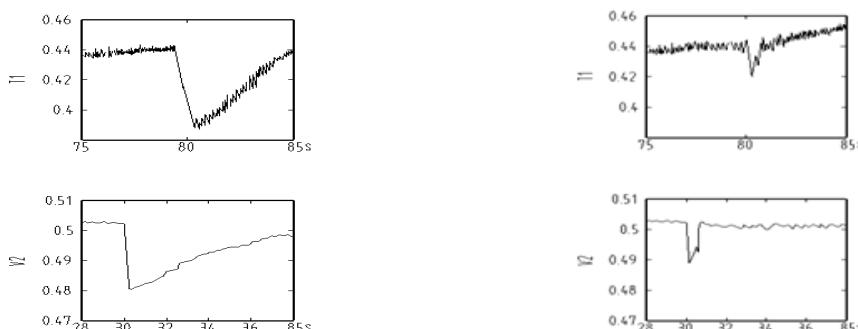
of the actuator in fault situation. In order to control effectiveness reduced but without destroying the system, we have to make sure the input of No.I  $U_i$  is equal to the control input multiply the constant coefficient  $\alpha_i$  ( $0 < \alpha_i < 1$ ) which is determined by controller.



**Fig. 3.** The residual of sysout when the control effectiveness is lower

Assuming the first kind of situation, we bring an effectiveness reducing of 5% on the second actuator  $M_2$  which is acting on the speed of material type when on the 30s, the breakdown which responses to the input of coefficient  $\alpha_2 = +0.05$  appears suddenly. Assuming the second kind of situation, we bring an effectiveness reducing of 20% on the actuator  $M_1$  which is acting on the material type when on the 80s, the breakdown which responses to the input of coefficient  $\alpha_1 = +0.20$ . The residuals of output in the both of situations show in fig.3.

From figure 3, according to the method we mentioned before, results two direct residuals: residual  $r_1$  and  $r_2$  are designed to be only sensitive to the failure but not to the others. Comparing results in two situations it clearly shows that two detection results of residual and the ability to isolate two kinds of fault. Once the fault is isolated, the corresponding fault estimation and compensation module are activated to reduce the influence of fault for system. The controller gets the feedback of trouble-free state estimation simultaneously the estimation of fault input is used to produce additive control input, and results in the compensation for failure.



(a) The response of filter under the condition without reconstruction

(b) The response of filter under the condition with reconstruction

**Fig.4.** Diagram of effect on FTC application

Figure 4 presented both the responses of filter with reconstruction and without reconstruction for failure. In some winding equipment, systems are required to compensate as soon as possible once the fault appeared. Figure 4 clearly shows the compensation ability of FTC method to actuator failures. We can see from figure 4, in the condition of no fault compensation, strip tension don't returns back to nominal value in until the fault appeared 7s later (due to a actuator fault in the system only makes once disturb a time, even without compensation, systems may also recover to the nominal state in a certain time); But under the condition of using FTC method to compensate only spends 1s to return to nominal value. Therefore, fault-tolerant control method plays an positive role in applying in actuators failure detection, isolation and compensation.

## 5 Conclusion

This paper made a research on a method of fault compensation based on the fault-tolerant control, and applied it to a typical tension control of lithium battery winding and unwinding system, it turned out that this method can achieve the detection and isolation based on fuzzy theory of fault effectively, reducing the influence of the fault on the system easily. Once the fault was detected or isolated, the reducing performance can be returned to nominal value approximate in short time, then the process control start again. The method prevent stopping the system forcibly and ensure the continuity of the system process.

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