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Research on the winding control system in winding vacuum coater

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Abstract. A method of control of the winding speed and rewinding or unwinding tension of the rolling high-vacuum continuous coating machine is proposed. The method is based on control of the armature current of the DC motor. Its time variation is caused by a lot of factors, such as the film winding tension, motor constant friction, electrical load that can change with the speed of the friction, unload acceleration and deceleration resistance, acceleration and deceleration with a load resistance, current introduced by the rolling tension of the film and others. All these factors may influence the tension. Thus, the control of the rolling tension can be achieved through control of the armature current. In order to find the relation between this current and tension, we first established a mathematical model in accordance with the principle of the rewinding system. Based on its analysis, we designed an alternative rewinding automatic control system. Our work shows that the proposed automatic control system exhibits a quite satisfactory performance and properties. This is also confirmed by its successful application in industry.

Key words. Winding control, rewinding; unwinding, tension, armature current, speed.

1. Introduction

There are three schemes of existing winding control for selection: one is the tension closed-loop control scheme (speed mode). A feedback signal derived from the tension detecting device cooperates with the tension setting value to constitute a PID closed-loop control circuit, which adjusts motor speed to achieve the purpose of tension control. The second kind is tension open-loop control scheme (torque mode). By controlling the output torque of the motor, the objective tension can be controlled. The principle is that by setting the value of tension and volume, the torque can be calculated. This scheme does not need tension detection feedback, but for frequency converter working method and closed-loop vector control mode, a speed measuring coder and a reel diameter sensor must be equipped. In addition, the influence of rotational inertia in acceleration and deceleration process should be considered. The third kind is the tension closed-loop control scheme (torque mode).

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The tension detection feedback closed-loop control is added on the open-loop tension control scheme to realize the technique. The working principle is that PID closed-loop circuit can be obtained and output torque command can be adjusted by tension detection feedback signal and tension setting value, which would guarantee the high precision of tension control. These above control methods all should be equipped with a feedback sensor measuring the tension or radius.

Usually, the winding part is installed in the vacuum chamber, and vacuum degree is there high when working. The more components installed in vacuum chamber, the more poles elicited from the lead wires can greatly influence the vacuum degree. In addition, sensor could cause discharge when the tension or speed increases in high-vacuum environment. A control system without rewinding/unwinding tension sensor and reel diameter sensor was proposed to meet the requirements of the performance. The tension values can be obtained and controlled by two parameters: DC motor output torque and winding diameter.

2. Methods

2.1. Profile of continuous high–vacuum winding coater

Winding control plays an important part in control of continuous high–vacuum winding coating machine, whose structure diagram is shown in Fig. 1.

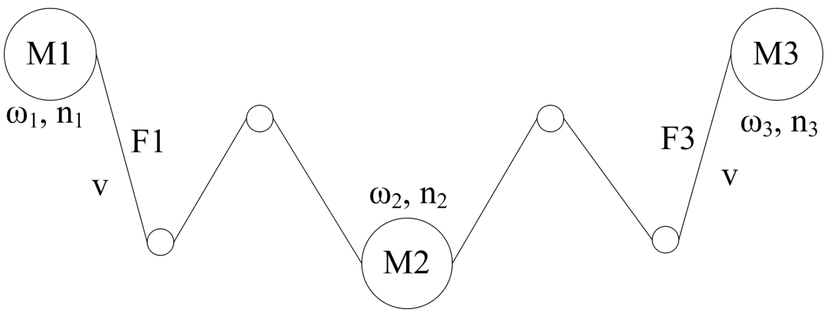

Fig. 1. Structure of winding or unwinding system

The corresponding components M1 and M3 are rewinding and unwinding motors, respectively and M2 is a water-cooled main roller motor. Symbols ω_1, ω_2 and ω_3 are the angular velocities of the three electric motors and n_1, n_2 and n_3, respectively, are their revolutions. Symbol v denotes the line speed of film winding, and symbols F_1 and F_3 stand for the rewinding and unwinding tensions, respectively.

In order to ensure a constant value of the line speed and tension in the winding process, both these quantities should be adjusted appropriately.

2.2. Analysis of winding motor

We take DC motor M1 for example. The motor is described by several equations. The equation for voltage can be written in the form

$$U_{\mathrm{a1}} = R_{\mathrm{a1}} i_{\mathrm{a1}} + L_{\mathrm{a1}} \frac{\mathrm{d}i_{\mathrm{a1}}}{\mathrm{d}t} + E_1 = R_{\mathrm{a1}} i_{\mathrm{a1}} + L_{\mathrm{a1}} \frac{\mathrm{d}i_{\mathrm{a1}}}{\mathrm{d}t} + K_{\mathrm{e1}} \varPhi_1 n_1 \,, \tag{1}$$

where U_{a1} is the armature voltage, R_{a1} denotes the armature resistance, L_{a1} stands for the armature leakage inductance, E_1 represents the armature electromotive force, $\varPhi_1$ is magnetic flux, n_1 stands for the motor speed and K_{e1} represents the torque constant.

As quantities R_{a1}, L_{a1}, K_{e1} and $\varPhi_1$ may be considered constant, we can put $K_{\mathrm{e1}}\varPhi_1 = K_1$, so that

$$U_{\mathrm{a1}} = R_{\mathrm{a1}} i_{\mathrm{a1}} + L_{\mathrm{a1}} \frac{\mathrm{d}i_{\mathrm{a1}}}{\mathrm{d}t} + K_1 n_1 \,. \tag{2}$$

The effective torque of rewinding control is described by the equation

$$T_{\mathrm{L1}} = F_1 R_1 \,. \tag{3}$$

The relationship between motor rotation angular velocity ω_1 and motor speed n_1 is

$$\omega_1 = \frac{2\pi}{60} n_1 \,. \tag{4}$$

Now, we will deal with the analysis of the load of M1. There are many parameters we should consider, for example the film winding tension, constant friction force of load, variable friction coming from the rotation of load, no-load speed resistance, loading speed resistance, etc. Symbol i_{a1} denotes the armature current, which is the sum of the currents passing through the 5 parts.

$$i_{\mathrm{a1}} = i_{\mathrm{T1}} + i_{\mathrm{FC1}} + i_{\mathrm{F}\omega 1} + i_{\mathrm{JC1}} + i_{\mathrm{J}\omega 1} \,, \tag{5}$$

where

1. Current i_{a1} varies with the change of tension and coil diameter by the formula

$$i_{\mathrm{T1}} = \frac{F_1 R_1}{K_{\mathrm{T1}} \varPhi_1} = \frac{1}{K_{\mathrm{T1}} \varPhi_1} \frac{30v}{\pi n_1} F_1 \,. \tag{6}$$

2. Current i_{FC1} can be obtained when the system is to overcome the constant friction; the current is derived when the system is under the no-load working state, and when the speed is a stable low speed. It is normally obtained when the system is working at the minimum speed (close to 0 rpm) and in a no-load working state, which is of the constant character.

3. Current $i_{\mathrm{F}\omega 1}$ is obtained when the system is to overcome variable friction force: the current and motor speed n_1 have a linear curve in a certain speed

range. There holds

$$i_{\mathrm{F}\omega 1} = K_2 n_1 \,, \tag{7}$$

where K_2 is a constant value.

4. Current i_{JC1} is an inherent acceleration and deceleration current of machine caused by load inertia, which is proportional to variation rate of the motor speed; it is given by the formula

$$i_{\mathrm{JC1}} = J_{\mathrm{c1}} \frac{1}{K_{\mathrm{T1}}\Phi_1} \frac{\mathrm{d}\omega_1}{\mathrm{d}t} = J_{\mathrm{c1}} \frac{1}{K_{\mathrm{T1}}\Phi_1} \frac{2\pi}{60} \frac{\mathrm{d}n_1}{\mathrm{d}t} \,, \tag{8}$$

where J_{c1} is the no-load inherent inertia. Its value is constant and can be obtained from the no-load test. The rated voltage is added to the no-load motor, the time t is calculated when the rewinding system accelerates from 0 rpm to the nominal speed ω_N. The current i_{Jc} can be obtained when the motor works at the rated speed according to the formula

$$i_{\mathrm{Jc}} = i - i_{\mathrm{Fc}} - i_{\mathrm{F}\omega} \,, \tag{9}$$

where i_{Fc} refers to the current when the no-load motor works at a stable minimum speed and $i_{\mathrm{F}\omega}$ is the current obtained when the motor works at the rated speed ω_N to overcome the variable friction force. The value of current $i_{\mathrm{F}\omega}$ may be obtained from the relation

$$J_{\mathrm{c1}} = i_{\mathrm{F}\omega} \frac{t}{\omega_N} K_{\mathrm{T1}}\Phi_1 \,. \tag{10}$$

5. Current $i_{\mathrm{J}\omega 1}$ is an acceleration and deceleration current caused by the change of winding inertia of the film coater in the process of winding. It is given by the formula

$$i_{\mathrm{J}\omega 1} = \frac{J_1}{K_{\mathrm{T1}}\Phi_1} \frac{\mathrm{d}\omega_1}{\mathrm{d}t} = \frac{1}{2} \frac{\sum(m_i r_i^2)}{K_{\mathrm{T1}}\Phi_1} \frac{\mathrm{d}\omega_1}{\mathrm{d}t} = $$
$$= \frac{1}{2} \frac{R_1^2 \pi R_1^2 L_1 \rho_1}{K_{\mathrm{T1}}\Phi_1} \frac{\mathrm{d}\omega_1}{\mathrm{d}t} = \frac{\pi^2}{60} \frac{\rho_1 L_1 R_1^4}{K_{\mathrm{T1}}\Phi_1} \frac{\mathrm{d}n_1}{\mathrm{d}t} \,. \tag{11}$$

Here, ρ_1 is the density of winding film, L_1 is the width of the winding film, R_1 is the radius of winding film roll. The numerical value of R_1 is continuously changeable in the winding process.

When the minimal volume diameter of the core is $R_{\min 1}$, then

$$i_{\mathrm{J}\omega 1} = \frac{\pi^2}{60} \frac{\rho_1 L_1}{K_{\mathrm{T1}}\Phi_1} \frac{\mathrm{d}n_1}{\mathrm{d}t} (R_1^4 - R_{\min 1}^4) \,, \tag{12}$$

and after substitution $R_1 = 30v/(\pi n_1)$ we finally obtain

$$i_{\mathrm{J}\omega 1} = \frac{\pi^2}{60} \frac{\rho_1 L_1}{K_{\mathrm{T1}}\Phi_1} \frac{\mathrm{d}n_1}{\mathrm{d}t} \left(\frac{30^4 v^4}{\pi^4 n_1^4} - R_{\min 1}^4 \right) . \tag{13}$$

Substitution of (6), (7), (10) and (13) into (5) provides

$$i_{a1} = \frac{1}{K_{T1}\Phi_1}\frac{30v}{\pi n_1}F_1 + i_{FC1} + K_2 n_1 + J_{c1}\frac{1}{K_{T1}\Phi_1}\frac{2\pi}{60}\frac{dn_1}{dt} +$$

$$+ \frac{\pi^2}{60}\frac{\rho_1 L_1}{K_{T1}\Phi_1}\frac{dn_1}{dt}\left(\frac{30^4 v^4}{\pi^4 n_1^4} - R_{\min 1}^4\right) = i_{FC1} + \frac{30}{K_{T1}\Phi_1 \pi}\frac{v}{n_1}F_1 + K_2 n_1 +$$

$$+ \frac{J_{c1}}{K_{T1}\Phi_1}\frac{\pi}{30}\frac{dn_1}{dt} + \frac{30^4}{60\pi^2}\frac{\rho_1 L_1}{K_{T1}\Phi_1}\frac{v^4}{n_1^4}\frac{dn_1}{dt} - \frac{\pi^2}{60}\frac{\rho_1 L_1 R_{\min 1}^4}{K_{T1}\Phi_1}\frac{dn_1}{dt}. \tag{14}$$

2.3. Analysis of winding motor and main rolling motor

A similar equation for motor M3 can be obtained as above

$$i_{a3} = i_{T3} + i_{FC3} + i_{F\omega 3} + i_{JC3} + i_{J\omega 3} = \frac{1}{K_{T3}\Phi_3}\frac{30v}{\pi n_3}F_3 + i_{FC3} + K_4 n_3 +$$

$$+ J_{c3}\frac{1}{K_{T3}\Phi_3}\frac{2\pi}{60}\frac{dn_3}{dt} + \frac{\pi^2}{60}\frac{\rho_3 L_3}{K_{T3}\Phi_3}\frac{dn_3}{dt}\left(\frac{30^4 v^4}{\pi^4 n_3^4} - R_{\min 3}^4\right) =$$

$$= i_{FC3} + \frac{30}{K_{T3}\Phi_3 \pi}\frac{v}{n_3}F_3 + K_4 n_3 + J_{c3}\frac{1}{K_{T3}\Phi_3}\frac{2\pi}{60}\frac{dn_3}{dt} +$$

$$+ \frac{30^4}{60\pi^2}\frac{\rho_3 L_3}{K_{T3}\Phi_3}\frac{v^4}{n_3^4}\frac{dn_3}{dt} - \frac{\pi^2}{60}\frac{\rho_3 L_3 R_{\min 3}^4}{K_{T3}\Phi_3}\frac{dn_3}{dt}. \tag{15}$$

Finally, the revolutions of the main rolling motor are described by the following differential equation

$$T_{m2}T_{a2}\frac{d^2 n_2}{dt^2} + T_{m2}\frac{dn_2}{dt} + n_2 = \frac{u_{a2}}{K_{e2}\Phi_2} - \frac{1}{K_{T2}K_{e2}\Phi_2^2}\left(T_{a2}\frac{dT_{L2}}{dt} + T_{L2}\right), \tag{16}$$

where T_{m2}, T_{a2} and T_{L2} represent the electric time constant of main rolling motor M2, armature circuit and winding vacuum coater with the winding film width of L, respectively. These parameters are given by the formulae

$$T_{m2} = \frac{J_{G2}R_{a2}}{K_{T2}K_{e2}\Phi_2^2}, \; T_{a2} = \frac{L_{a2}}{R_{a2}}.$$

3. Results

The main rolling motor is used to keep the film linear velocity constant. The mechanism design considered that when the tension of winding/unwinding motor is above 50 N and when winding tension F_3 is slightly higher than 5 %–10 % of unwind tension F_1 in actual use, the film coater would not slip in the main rolling motor. Thus, we can draw the conclusion that a constant line speed could be kept in film winding process as long as the rotation speed of main rolling motor is constant.

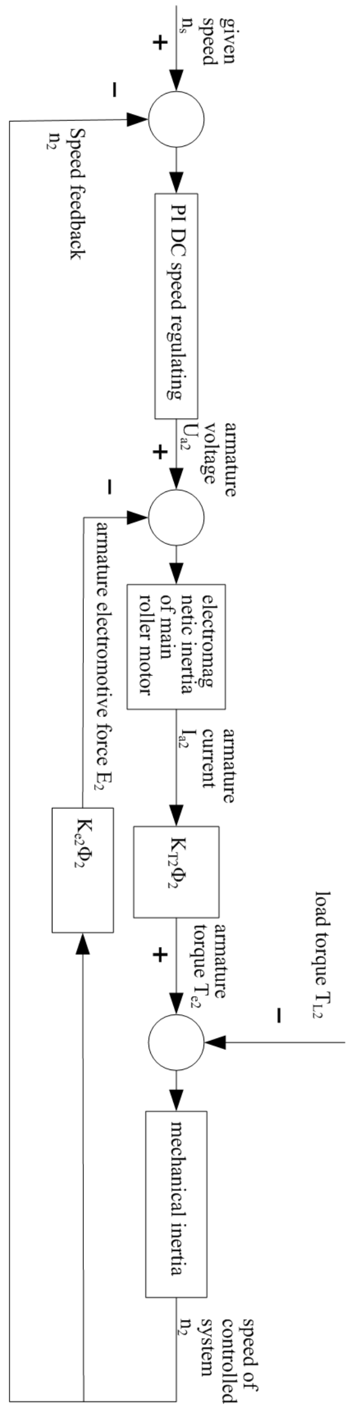

Fig. 2. Control functional block diagram of the home roll motor

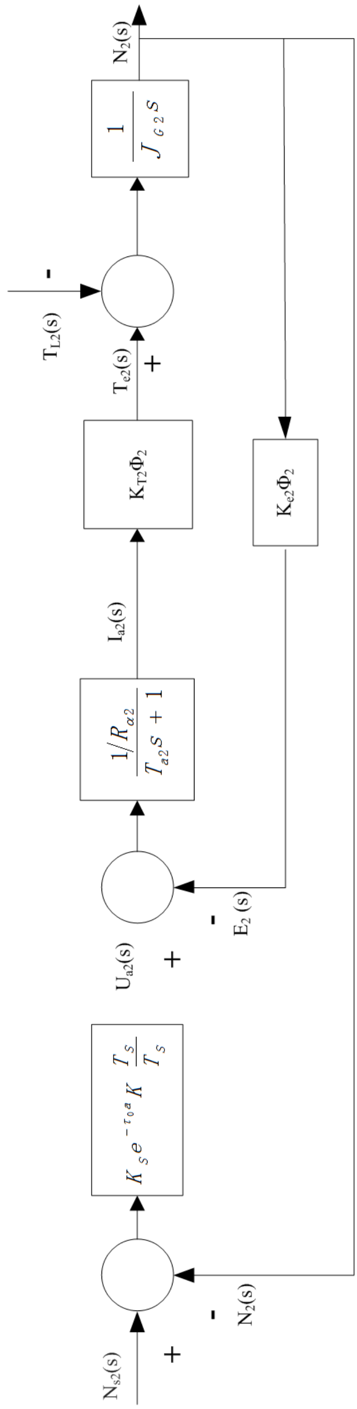

Fig. 3. Control system block diagram of the home roll motor

Line speed V, main rolling motor revolutions n_2 and angular velocity ω_2 are connected by the relation

$$V = \omega_2 R_2 = \frac{2\pi}{60} R_2 n_2 \,, \tag{17}$$

where R_2 is the radius of main rolling motor, which is a constant value.

The control scheme of the main roller motor is PI control of DC speed regulating system. The control principle block diagram is shown in Fig. 2, and the transfer function block diagram is shown in Fig. 3.

4. Discussion

According to formula (14), the working current of the motor is determined by detecting the rotate speed of the motor n_1 and linear velocity v of the film coater, when a certain value of unwinding motor tension is given. So the tension control would be turned to the working current control. The control system block is shown in Fig. 4, where, I_{a1s} is the given working current of the motor calculated from equation (14) for the given tension value F_1.

The tension control in the winding part could be transformed to the current control which is similar to the unwinding part. The motor working current I_{a3s} was calculated from equation (15) .

The parameters of control system wiring are shown in Table 1, and the flow chart is shown in Fig. 5.

Table 1. Parameters of control system wiring

HMI touch pad	S7-200 CPU226CN	EM235 4AI/1AQ	EM232 2AQ
No	Address	Function	Component model
1	I0.0–I0.2	winding rotate speed	optical encoder TRD-J-S
2	I0.3–I0.5	unwinding rotate line speed	optical encoder TRD-J-S
3	I0.6–I1.0	winding rotate line speed	optical encoder TRD-J-S
4	AIW0	main roller speed	4-20 mA
5	AIW2	winding motor real armature current	4-20 mA
6	AIW4	unwinding motor real armature current	4-20 mA
7	AIW0	unwinding motor given armature current	4-20 mA
8	AIW4	winding motor given armature current	4-20 mA

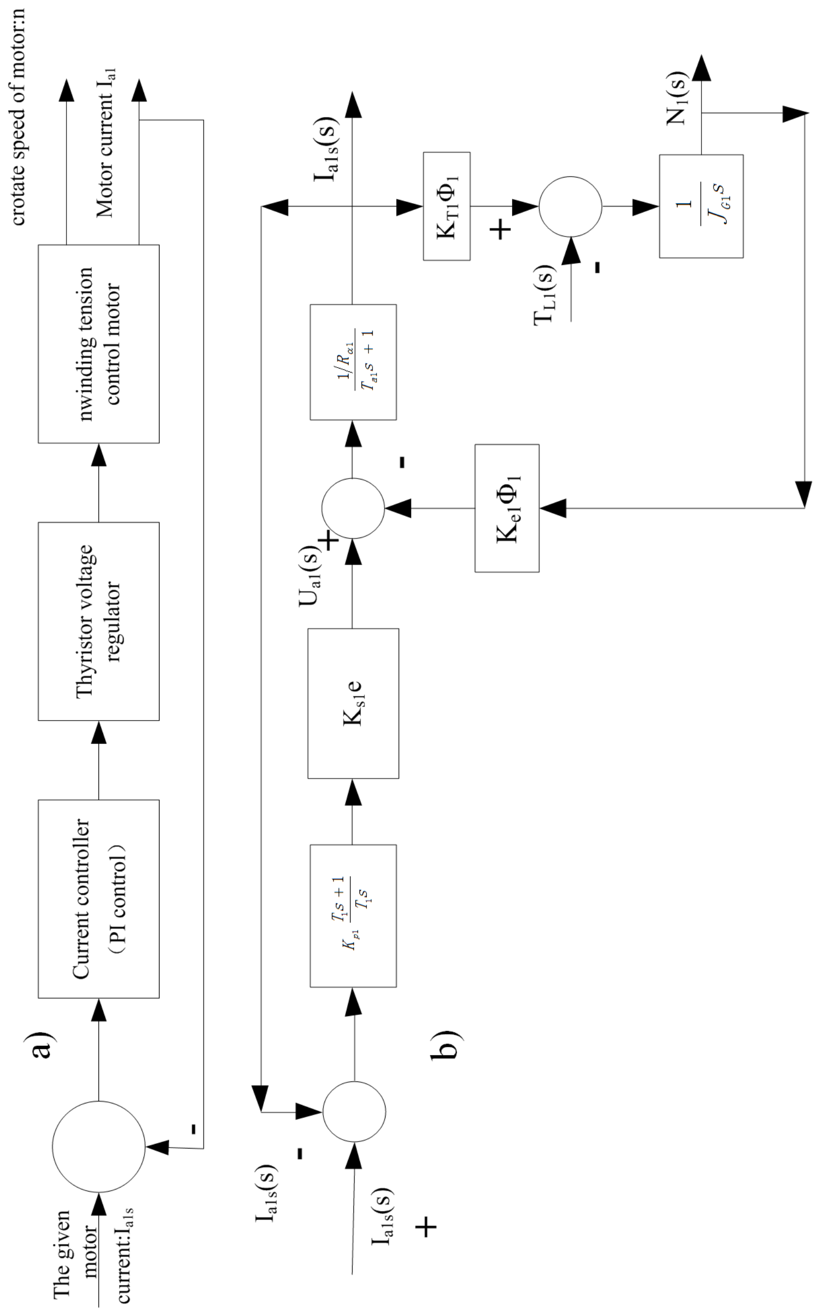

Fig. 4. Control system block diagram of the unwinding roller motor

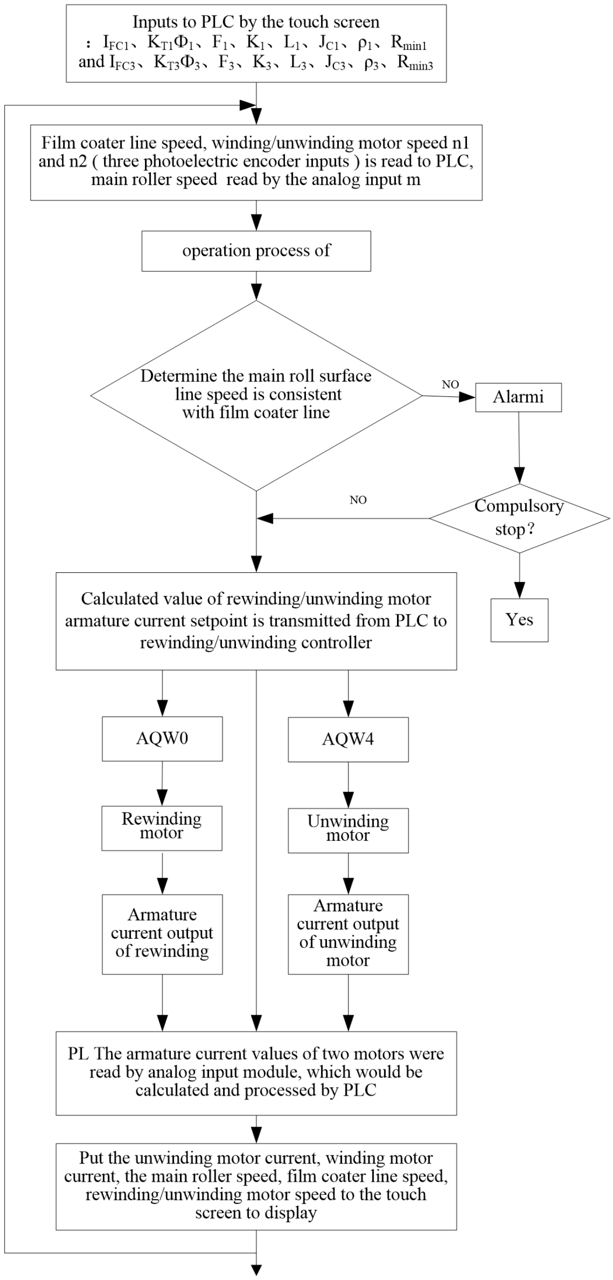

Fig. 5. Functional block diagram of the control program

5. Conclusion

The relative difficulty of system debugging was caused due to the lack of tension sensor or direct measurement to the roll diameter sensor. A high system reliability and normal working state can be obtained after more than half a year operation, In the debugging process, two control systems have been compared: one is the system with tension sensor and the other without it. The two systems both work under the standard atmospheric pressure. The result shows that tension control uniformity of the control system without tension sensor can reach the accuracy of about 3 %, which has been able to meet the actual needs of reflective film coating.

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