Research on the Motor Drive Based Operating Mechanism for High Voltage Circuit Breaker

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\textbf{Abstract.} This paper describes an operating mechanism driven by a three-phase permanent magnet synchronous motor (PMSM) for high voltage circuit breakers (HVCB). It analyzes the relationship between the optimal moving contact travel of HVCB and the PMSM torque, and proposes the main parameters and requirements of PMSM to be suitable for the optimal contact travel. The simulation model of the operating mechanism driven by PMSM was built using Matlab. It simulates and calculates the mechanism’s opening and closing operations characteristics. The voltage waveforms of stator currents analyzing, offers a helpful reference to compile the Digital Signal processing (DSP) programs. The performances of the opening and closing operations could be improved by debugging the DSP programs in the control unit.

\textbf{Introduction}

High Voltage Circuit Breakers (HVCB) is the most important switches apparatus in the electric power system. They are responsible for control and protect of the power system. The operating mechanism is the basic device which controls the opening and closing operations of HVCB. At present, there are several conventional types of operating mechanisms which have been widely used, such as spring, hydraulic or pneumatic. Such mechanisms have many prominent merits, but also have some insurmountable limitations. These conventional mechanisms constructed by complex frames, need periodic check-ups, highly cost operating and maintenance, and they are quite difficult to be debugged. Additionally, they are especially uncontrollable and non-detectable during the opening and closing operations.

To overcome such inherent limitations, and to improve the performance of conventional mechanisms, the operating mechanism driven by PMSMs is introduced to meet the requirements. The proposed operating mechanism is based on power electronic and motor digital control technologies. This mechanism has quite a lot of good advantages: simple frames, manipulative opening and closing operations, wide range of uses and so on.

\textbf{Design of the operating mechanism}

The suggested operating mechanism consists of AC (or DC) power supply, energy buffer, converter unit, control unit, and the motor. Fig.1 (a) shows the System diagram of motor driven mechanism. The motor is controlled by an IGBT Converter, rotate speed and positions of the motor are measured using a fixed sensor on the rotating shaft. The travel of the moving contactor is measured by the position sensor. The control unit adopts DSP as the processing core, and according to the vector control of the motor, the control unit generates PWM signals to activate the IGBT Converter, and then drives the motor to implement the opening and closing operations of HVCB.
Simulation of the motor drive

Fig.1 (b) shows the circuit breaker operating device. In the opening operation driven by the motor drive mechanism, the crank (8) rotates counterclockwise; pulling the insulating rod (7) down. This will quickly drive the moving arc contact (3) downwards. At the end of the opening operation, the motor applies a clockwise torque, as a buffering force, on the driving shaft (9) to decelerate the crank (8) rotation. The moving arc contact (3) speed will smoothly decrease and the mechanical impact will be limited. On the other hand, in the closing operation: the crank (8) rotates clockwise, pushing the insulation rod (7) upwards. The moving contact (3) accelerates up toward the fixed contact. Using a pre-set calculations and control for speed and position, the motor then applies a reverse counterclockwise torque to decelerate the moving contact, thus to reduce the mechanical impact between the breaker’s contacts.

In the initial period, SF6 circuit breakers demand a great operating physical force to accelerate the moving parts and to compress SF6. This operating force makes the main moving contact reaches the demanded velocity required in the opening operation. Fig.3 (c) shows the curves of both the travel of the main moving contact and the operating physical force of HVCB.

The processes of the opening and closing operations are link motions made up of the moving parts. The velocity of the main moving contact can be calculated according to the travel as in Fig. 1 (b). Assumed that, the mass center of the main moving contact is at its center, and the mass centers of the connecting rod and the regulating lever are also at their centers. Then the whole equivalent rotary (rotational) inertia $J$ of the moving parts about the revolution (rotating) axis in part 9 shown in Fig.1 (b) are given as follows:

$$J = J_6 + J_7 + J_8$$  \hspace{1cm} (1)

Of which,

$$J_6 = \frac{1}{3} m_6 l_6^2 + m_6 (l_6^2 + l_7^2 + 2l_6 l_7 \cos(\theta_2 - \theta_3))$$  \hspace{1cm} (2)

$$J_7 = \frac{1}{3} m_7 l_7^2 + m_7 (l_7^2 + l_8^2 + l_7 l_8 \cos(\theta_7 - \theta_8))$$  \hspace{1cm} (3)

$$J_8 = \frac{1}{3} m_8 l_8^2$$  \hspace{1cm} (4)

Where $m_6$, $m_7$ and $m_8$ are the mass quantities of the moving parts, $l_6$, $l_7$ and $l_8$ are the lengths, $J_6$, $J_7$ and $J_8$ are the rotary rotational inertias about the revolution rotating axis.

In general, the whole equivalent rotary inertia will reach the maximum value at the initial position during the opening operation.

$$J_{\text{max}} = (J_6 + J_7 + J_8) \left|_{\theta_3=0}^{\theta_3=\pi} \right.$$  \hspace{1cm} (5)

In the process of opening operations, the kinetic energies of the moving parts are variable. Their equations are:

$$E_6 = \frac{1}{2} m_6 V_6^2 = \frac{1}{2} m_6 (\dot{\theta}_2 \sin \theta_2 + l_7 \dot{\theta}_3 \cos \theta_3)^2$$  \hspace{1cm} (6)

$$E_7 = \frac{1}{2} m_7 V_7^2 = \frac{1}{2} m_7 (V_{7x}^2 + V_{7y}^2)$$  \hspace{1cm} (7)
\[
\begin{align*}
&= \frac{1}{2} m_2 l_3 (l_3 \sin \theta_3 + l_2 \sin \theta_2, l_3 \cos \theta_3 + l_2 \cos \theta_2) + \frac{1}{2} \left[ (l_3 \sin \theta_3 + l_2 \sin \theta_2, l_3 \cos \theta_3 + l_2 \cos \theta_2) \right] \sin \theta_2 + \frac{1}{2} \left[ (l_3 \cos \theta_3 + l_2 \cos \theta_2) \right] \cos \theta_2 \\
&= \frac{1}{2} m_3 \left[ (l_2 \theta_2)^2 + \frac{1}{4} (l_2 \theta_2)^2 + l_2 \theta_2 \theta_3 \cos (\theta_3 - \theta_2) \right] \\
E_a &= \frac{1}{2} m_a V_s^2 = \frac{1}{2} m_a \left( \frac{1}{2} l_a \theta_2 \right)^2 = \frac{1}{8} m_a \left( l_a \theta_2 \right)^2 \tag{8}
\end{align*}
\]

Where \( E_6 \) is the kinetic energy of the main moving contact, \( E_7 \) and \( E_8 \) are the kinetic energies of the connecting rod and the regulating lever.

Considering the effects of the weight and the requirements of the operating physical force (considering the weight and the operating force requirements effects), the output power of the motor for driving the operating mechanism can be calculated (the operating mechanism driving motor output power can be calculated). The equation of the motor power is:

\[
P = \frac{\Delta(E_6 + E_7 + E_8) - (m_g \Delta h_6 + m_g \Delta h_7 + m_g \Delta h_8) + \text{OPF} \cdot \Delta}{\Delta}
\tag{9}
\]

Where \( h_6, h_7 \) and \( h_8 \) are the fallen distances of \( m_6, m_7 \) and \( m_8 \), and \( \text{OPF} \) is the operating physical force.

For the analysis and calculations above, the torque affected (applied on) the regulating lever and the motor’s power in the process of opening operation can be obtained. The curves of torque and the power of the drive motor can be seen in Fig.2 (a). (The obtained/estimated drive motor torque and power are shown in Fig.2 (a)).

![Fig.2. the Simulation of actuating device](image)

(a) the Torque and Power (b) the Simulation Model (c) the Voltage Waves of PMSM

As could be noticed in Fig.2, the maximum instantaneous power is 1500W, and the maximum instantaneous torque is 85 N∙m. As the time of the opening operation is about 40 to 60ms, the motor (rotates/operates) in the start-up phase. Therefore, the motor works in the transient state during the process of the opening operation. According as the maximum instantaneous torque can be 2 to 5 times than the nominal torque, and the maximum instantaneous power can be 2 to 4 times than the rated power, it is suitable to choose the motor that its nominal torque is 17 to 42.5 N∙m and its rated power between 375 and 750 W.

In addition, the chosen motor should have quite small moment of inertia, to carry out the opening and closing operations well. Since the whole equivalent rotary inertia of the moving parts is a relatively large (in the simulation model, \( J_{\text{max}} = 0.18 \text{ kg} \cdot \text{m}^2 \), \( J_{\text{min}} = 0.13 \text{ kg} \cdot \text{m}^2 \). Based on the previous and by comparing with other types of motors, PMSM (Permanent Magnet Synchronous Motor) is chosen to be the drive motor of the (proposed HVCB operating) mechanism.

**Simulation Results**

The simulation model of the operating mechanism driven by the motor was built using Matlab, shown in Fig.2 (a). The drive motor PMSM was manipulated by the vector control of \( id = 0 \). The calculated torque was taken as the input load of the PMSM. The deviation that is the error between the given torque and the feedback torque, passed through a PI adjuster, and was put out as the reference \( i_{\text{sref}} \) current to control the PMSM torque. The \( i_{\text{sref}} \) and \( i_{\text{dref}} \) (equal to 0) currents
passing the Park and Clark transforms, turn into the current $i_{\text{abref}}$. Both $i_{\text{abref}}$ and $i_{\text{abc}}$ (the three-phase stator currents of the PMSM) as the comparative signals were put into the PWM inverter, and then PWM signals were regenerated to control the PMSM. The parameters of PMSM in this simulation model were: $R = 2.875 \, \text{ohm}$, $L_d = L_q = 8.5 \times 10^{-3} \, \text{H}$, $\varphi = 0.25 \, \text{Wb}$, $P = 4$, and $J = 0.8 \times 10^{-3} \, \text{kg} \cdot \text{m}^2$.

According to this simulation model, both the power output and the torque output of PMSM can be obtained. The curves of the power and the torque were shown in Fig.2. (b), it is obvious that the power and torque outputs are suitable with the requirements of the operating mechanism driven by the motor.

Additionally, $U_{\text{ab}}, U_{\text{bc}}, U_{\text{ca}}$; the line voltages of PMSM can be obtained; their waves were shown in Fig.2. (c), based on the line voltage waves, the IGBT switches sequences in the convert unit can be comprehended. The sequences offer a quite significant reference to compile the DSP program to control the PMSM rotation. The performances of the opening and closing operations could be improved by debugging the DSP programs in the control unit.

Conclusion

This paper analyzes the relationships of the power and torque to operate the operating mechanism, and finally chooses PMSM to be the drive motor. By establishing the simulation model, the simulation results are accorded with the calculated. This means it is feasible to drive the operating mechanism of HVCB by PMSM in theory.

The operating mechanism power – torque characteristics were analyzed. Based on this characteristics, the PMSM was chosen to be the drive motor for the HVCB operating mechanism. The established simulation model results are in good agreement with the calculations. Such close agreement means to drive the HVCB operating mechanism by PMSM is feasible in theory.

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