Characteristics analyses of energy consumption for bridge crane based on the energy flow

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Abstract. Aiming at the problems of energy consumption disorder and energy waste of bridge crane, based on the characteristics analysis of working condition and energy consumption, the power balance equation is established combining with the energy transmission process of bridge crane, which provides an important theoretical basis for the evaluation of crane energy consumption.

1. Introduction

Bridge cranes are indispensable special equipments for national economic construction and are widely used in industrial and mining enterprises, port terminals, logistics turnover and other fields. In the face of increasingly harsh environmental problems and the inevitable trend of energy conservation and emission reduction, exploring the energy-saving measures and detection and evaluation technologies of bridge cranes has become a hot research topic [1-3].

In recent years, some scholars have conducted some research on the energy consumption characteristics of cranes. Li used the bridge crane as the evaluation object. Based on the principle of energy conservation during the use of the bridge crane, the energy consumption characteristics of the hoisting mechanism, the trolley running mechanism and the running mechanism of the cart were studied respectively [4]. Fu taken the variable frequency gantry crane as the research object. From the perspective of energy flow, the energy consumption characteristics of the main working links of the running mechanism and the hoisting mechanism are studied respectively, and the frequency conversion gantry crane mechanism system is established [5]. The start and brake of the bridge crane is the most important component of energy consumption. Ge focused on the energy consumption of these two processes [6].

In this paper, the bridge crane is taken as the research object, and the working characteristics and energy consumption components of the bridge crane are analysed. On the basis of this, combined with the characteristics of energy transmission of the bridge crane, the power balance equation of the bridge crane is established and the characteristics analysis of energy consumption is completed.

2. Overview of bridge crane

2.1. Composition of bridge crane
Bridge crane is a kind of mechanical equipment that moves materials in three-dimensional space by vertical lifting and horizontal movement of the lifting device such as hooks. It consists of working

mechanism, metal mechanism, power and electrical control system, and safety protection system [7]. The working mechanism is composed of a lifting and running mechanism, and the lifting mechanism is used to realize the vertical lifting movement of the material; the running mechanism refers to an actuator that realizes the horizontal movement of the material (or the whole machine) by the movement of the crane trolley (or the large vehicle). The metal structure serves as a support platform and skeleton for forming a working space of the whole machine, and is used to support the working mechanism and bear the load. The power and electrical control systems include power sources and drives, as well as lighting, steering, and control tasks. The safety protection system usually consists of safety devices, guards and safety indicating devices. It is mainly used for the comprehensive safety system of the other three parts.

2.2. Working characteristics of bridge crane
The operation of the overhead crane refers to the cycle of taking, transporting, unloading and resetting. From the perspective of mechanical movement characteristics: in a working cycle of the bridge crane, the working mechanism is in the forward and reverse alternate operation, such as the vertical lifting movement of the lifting mechanism, the horizontal reciprocating motion of the operating mechanism. From the running time characteristics: a work cycle is relatively short, usually tens of seconds, a few minutes, and each organization has a short pause at different times, and there is a sharp difference from the mechanical equipment that works continuously. From the perspective of load and usage: crane working load is not always full load, but also light load and half load; the working environment also changes with the change of work requirements and location; frequent forward and reverse operation makes power system and working structure bear certain impact and vibration; the overall performance is intermittent, random, and dynamic shock.

Therefore, the operation requirements and working process of the bridge crane determine its unique working characteristics: intermittent work, variable load, frequent positive and negative, short-duration, cycle.

2.3. Energy composition of bridge crane
From the whole life cycle of bridge crane, its energy consumption mainly consists of energy consumption in design stage, manufacturing stage, use stage and maintenance stage. This paper focuses on the analysis of the largest proportion of energy consumption in the use stage, which can be divided into standby energy consumption and work energy consumption according to their different working conditions. Among them, standby energy consumption components include electrical control system, lighting and safety protection system monitoring system; work energy consumption can be divided into lifting energy consumption, reducing energy consumption and running energy consumption according to the working characteristics of the working mechanism.

3. Energy consumption analysis of working mechanism
The working mechanism of bridge crane mainly includes two parts: motor and transmission system, which are important energy consumption units. The internal consumption of working mechanism mainly includes the loss of motor and transmission system.

3.1. Energy consumption of motor
During the operation of the overhead crane, the electric motor converts electrical energy into mechanical energy. The basic working principle is that a current generates a rotating magnetic field in the air gap through the stator winding, and there is relative motion between the magnetic field and the rotor. The rotor winding cuts the magnetic field to generate an electromotive force, and generates a current in the rotor winding, and the rotor charged conductor will be in a changing magnetic field. The electromagnetic force generates electromagnetic torque, which drives the rotor to rotate. The structure and working principle of the three-phase asynchronous motor determine that the speed control method of the bridge crane can be divided into three basic types, namely, variable pole speed regulation, variable slip speed regulation and frequency conversion speed regulation [8]. The variable pole speed regulation is generally only used on the electric hoist motor with a small capacity. The variable speed

regulation is widely used on bridges and gantry cranes because of its simplicity and reliability. The common form is the control method of the rotor string resistance. The frequency conversion speed regulation is characterized by changing the frequency of the motor power supply and making it have a large speed regulation range, hard mechanical characteristics and smooth speed regulation. The use of frequency conversion technology is beneficial to save energy and the service life of the whole machine. At present, crane manufacturers are also actively promoting the frequency conversion transformation of cranes. The equivalent schematic diagram and energy flow diagram of the three-phase asynchronous motor are shown in figure 1.
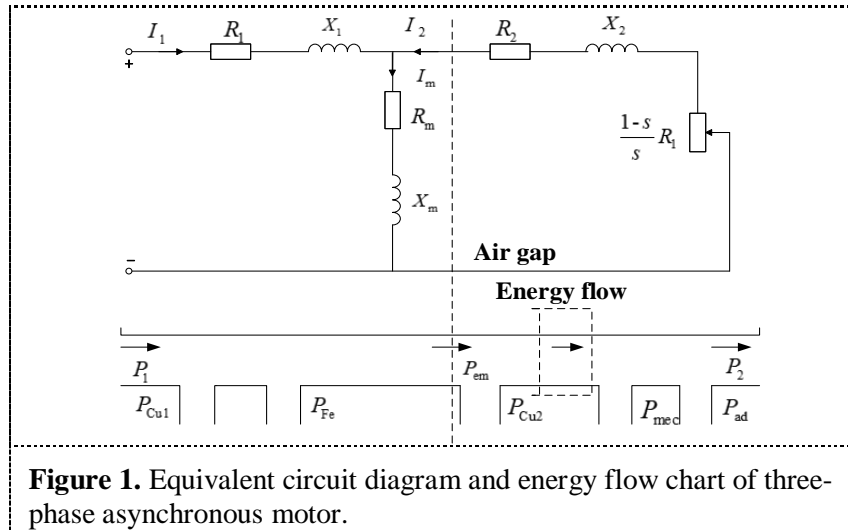

Figure 1. Equivalent circuit diagram and energy flow chart of three-phase asynchronous motor.

When the motor is working, the current passes through the stator winding, which will cause the winding to generate heat and lose some power. This is called the stator copper consumption P_{Cu1}. At the same time, due to the existence of eddy current phenomena and hysteresis, a certain eddy current loss and hysteresis loss will be collectively referred to as core loss P_{Fe}. The copper loss, core loss, and energy stored in the electromagnetic field stored in the stator winding E_m are removed, and the rest will be transferred to the rotor portion through the air gap. In normal operation, since the difference between the rotor speed and the magnetic field speed is small, the rotor iron loss is small and negligible. Therefore, the power transmitted to the rotor is converted into mechanical energy by the motor, except that part of the power (copper consumption P_{Cu2}) is consumed by the rotor winding heat, which is called the total mechanical power P_M of the motor. The total mechanical power mainly includes the mechanical power P_2 transmitted to the transmission system, and the mechanical loss

P_{mec} and the additional loss (stray loss) P_{ad} caused by the friction torques such as bearings and wind resistance. Based on the above analysis, the energy loss of the three-phase asynchronous motor can be divided into two parts: the power loss P_{Ld} and the mechanical energy loss P_M, namely:

$$P_1 = P_{Ld} + P_M \tag{1}$$

In which, power loss includes stator winding loss, rotor winding loss, stator core loss and electromagnetic field energy storage change are expressed by P_{Ld}:

$$P_{\mathrm{Ld}} = \frac{dE_{\mathrm{m}}}{dt} + P_{\mathrm{Cu1}} + P_{\mathrm{Fe}} + P_{\mathrm{Cu2}} \qquad (2)$$

The mechanical energy loss includes the mechanical loss of the rotor, the stray loss of the mechanical system of the motor, the change of the kinetic energy of the mechanical system and the power transmitted to the transmission system. Therefore, the mechanical energy loss P_{M} is as follows:

$$P_{\mathrm{M}} = P_{\mathrm{mec}} + P_{\mathrm{ad}} + \frac{dE_{\mathrm{km}}}{dt} + P_2 \qquad (3)$$

3.2. Energy consumption of driving system

The transmission mechanism of the working mechanism is the most important part of the energy transmission of the mechanism. In the energy transmission process of the transmission system, there are various kinds of energy loss, which can be mainly divided into two parts, one part is the Coulomb friction power loss P_{k} which is approximately proportional to the angular velocity, and part of which is proportional to the square of the angular velocity. Viscous friction power loss P_{c}. The Coulomb friction power loss can be divided into the load power loss P_{a} related to the transmission system output power (load power) and the load-independent non-load Coulomb friction power loss P_{ua}. The sum of the non-load Coulomb friction power loss and the viscous friction is called the non-load power loss. According to the above analysis, the power composition of the transmission system energy flow process is shown in figure 2.
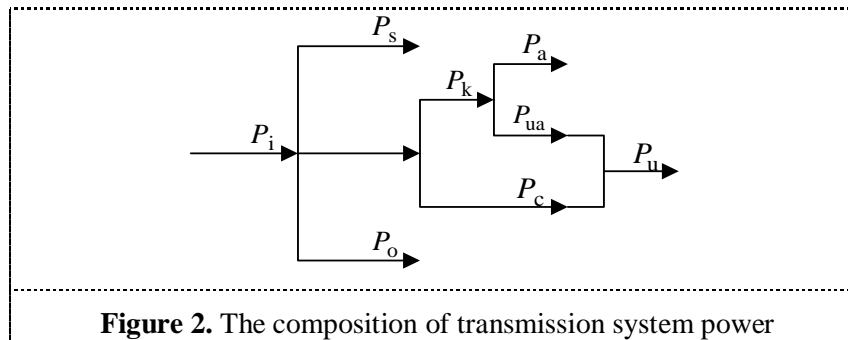

Figure 2. The composition of transmission system power

Further, the energy flow of the transmission mechanism of the bridge crane working mechanism is shown in Gigure 3. In the figure, P_{ii} is the input power of the *i*-th transmission link, P_{mi} is the mechanical loss of the *i*-th transmission link, and P_{si} is stored for each component of the *i*-th transmission link.
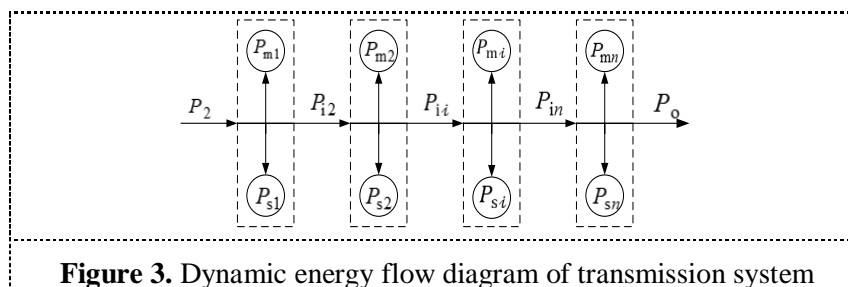

Figure 3. Dynamic energy flow diagram of transmission system

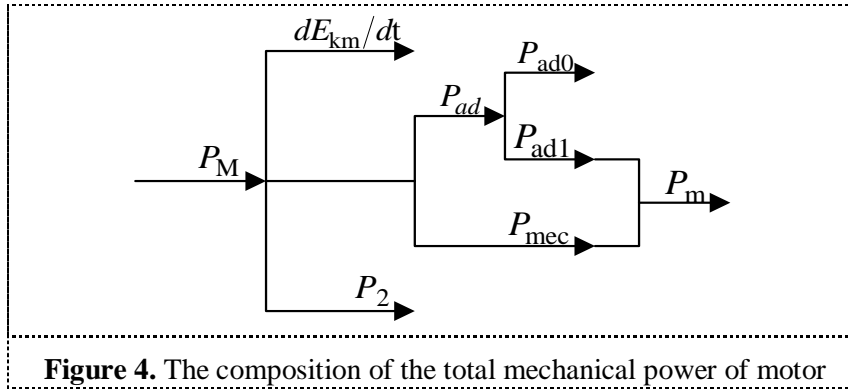*3.3. Power balance equation of working mechanism*

The above not only analyses the internal loss of the working mechanism, but also establishes the power equation of the electric motor and the transmission system. The power balance equation for the entire working mechanism is established below. Based on the above analysis, the energy loss of the working mechanism is divided into two parts according to the transmission form. One is that the power loss part includes the iron loss and copper loss of the motor, and the other is the mechanical energy loss part, including the mechanical and stray losses of the motor and the energy loss of the transmission system.

Considering the stray loss of the motor P_{ad} will generate a braking torque of the braking property. Therefore, it is studied to divide the stray loss of the motor into the energy loss P_{ad0} related to the motor output power P_2 and the energy loss P_{ad1} independent of P2. Among them, P_{ad1} is incorporated into the mechanical power loss P_{mec} of the rotor, which is counted as P_{m0}, and is processed according to the method of analysing the mechanical loss of the transmission system, and there are equations (4) and (5). The power distribution of the mechanical drive of the asynchronous motor is shown in figure 4.

$$P_{M} = P_{2}(1+b_{m}) + M_{m}\omega + B_{m}\omega_{m}^{2} + J_{m}\omega_{m}\frac{d\omega_{m}}{dt} \tag{4}$$

$$b_{m} = \frac{P_{ad0}}{P_{2}} \tag{5}$$

In which, b_{m} is the motor load factor; M_{m} is the motor non-load Coulomb friction torque; B_{m} is the motor damping coefficient; J_{m} is the moment of inertia on the motor shaft.

Figure 4. The composition of the total mechanical power of motor

Substituting equation (4) into equation (1), the power balance equation of the working mechanism is obtained:

$$P_{1} = P_{Ld} + \alpha_{t}P_{o} + \beta_{t}\omega_{m} + \gamma_{t}\omega_{m}^{2} + \lambda_{t}\omega_{m}\frac{d\omega_{m}}{dt} \tag{6}$$

$$\alpha_{t} = (1+b_{m})\alpha_{m} \tag{7}$$

$$\beta_{t} = M_{m} + (1+b_{m})\beta_{m} \tag{8}$$

$$\gamma_{t} = B_{m} + (1+b_{m})\gamma_{m} \tag{9}$$

$$\lambda_{t} = J_{m} + (1+b_{m})\lambda_{m} \tag{10}$$

4. Conclusion

In this paper, the energy consumption of bridge crane in the whole life cycle is discussed, and the energy consumption in the use stage is mainly analysed. According to the operation status of bridge crane, the energy consumption is divided into standby energy consumption and working energy consumption. And, based on the working characteristics of the working mechanism, the working energy consumption is divided into lifting energy consumption, reducing energy consumption and running energy consumption, and the causes of energy consumption are analysed. At the same time, starting from the energy consumption analysis of motor and transmission system, the internal losses of the working mechanism are mainly discussed, and the power balance equation of the working mechanism is established.

According to the power balance equation of the working mechanism, the higher the mechanism transmission efficiency, the lower the energy consumption. Moreover, the power balance equation of the working mechanism consists of a plurality of transmission links, so under the same transmission efficiency, the less the transmission link, the lower the overall energy consumption. In summary, the efficiency of transmission link and the design scheme of transmission system are important factors of crane energy consumption, as well as an important basis for analysing energy consumption factors, establishing energy consumption index system and realizing energy consumption evaluation of bridge crane.

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