Journal of Theoretical and Applied Information Technology
30th September 2012. Vol. 43 No.2
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ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

ANALYSIS ON VARIABLE TRANSMISSION SYSTEM OF BATTERY ELECTRIC VEHICLE BASED ON GRAPH THEORY

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ABSTRACT

This paper first establishes the graphic model and basic circuit equation of variable transmission system of battery electric vehicle based on complex joint picture representation method and basic circuit method. Then, according to this model, the rotating relation of variable transmission system is analyzed and the calculation formula of transmission rate efficiency is deduced, moreover, the transmission efficiency of the transmission system is calculated. At last the influence degree of each gear ratio on efficiency is confirmed with the method of sensitivity analysis. The research results can provide a reference for transmission system design of battery electric vehicle.

Keywords: *Graph Theory; Battery Electric Vehicle; Transmission System; Rotating Ratio; Sensitivity*

1. INTRODUCTION

From the starting point of resolving the energy crisis and environment problems, the development of new energy resources vehicle represented by battery electric vehicle (BEV) has obtained extensive concern around the world. With the great advantages of cleanliness, low noise, simple operation and almost non-pollution during operation, BEV is the real significance of zero-emission vehicle. Motor driving system is the key technique of BEV and the operational performance of BEV depends chiefly upon type and performance of motor driving system.

Different driving conditions shall be satisfied by fixed speed ratio, which is used to decrease and increase torque. Driving motor usually has relatively broad speed range, but in order to get much higher transmission efficiency and decrease power loss， it shall try to operate in the high efficiency range while running in different conditions. For the reason that the resistance the BEV bears while running varies greatly with changes of speed, torque changes alone can’t meet the requirements of driving performance. In order to meet the performance of vehicle and simultaneously keep the driving motor running in the high efficiency ranges to ease the burden of driving motor and power batteries, a proper speed ratio in essential is designing. In most cases, a speed reducer and a transmission gear box need to be installed between the electrical motor and driving wheels. When the parameter of electrical motor is fixed, variable transmission device is often to satisfy the dynamic requirements of vehicle performance and get the ability to adjust the relation between electrical rotational speed and vehicle speed. From the analysis on the parameter sensitivity of dynamic performance and energy consumption economy of BEV, we can see that variable transmission system has considerable influence on dynamic performance and energy consumption economy [1] [2].

Graph theory is an effective mathematical tool for the composite and analysis of kinematic chain and mechanism. The graph theory method can be used to study according to the relation between components in epicyclical gear train. In recent decades, many graphical models and comprehensive methods have been put forward, which have solved the comprehensive problems of epicyclical gear train from different angles and degrees. Lam proposed the complex joint graphic representation in 1993 and defined the complex joint graphic representation of epicyclical gear train as: Components of epicyclical gear train are transformed into dots in the graph, while single joints are transformed into solid lines, gear pairs are transformed into dotted lines and rotary pairs in the

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same rotary place are transformed into complex joint polygons [3]-[6]. This paper adopts the complex joint graphical representation method to establish graphical model of variable transmission system and circuit equation of BEV, and then according to this calculates the rotational ratio and deduces the efficiency equation. Based on the efficiency equation, ways to improve the transmission efficiency can be proposed with the influence degree of each gear ratio on efficiency defined by the method of sensitivity.

2. GRAPHICAL MODEL OF VARIABLE TRANSMISSION SYSTEM

Figure 1 shows the transmission structure diagram of two speed transmission in BEV [7]. The motor power is input from sun gear 1, when sliding contact 4 moves left, planet carrier 2 and gear ring 3 separates, gear ring 3 and transmission gear case 6 contacts, at this moment the transmission system turns into 2K-H planetary gear system, all the device is output by planet carrier 2, reaches the goal of reducing transmission. When sliding contact 4 moves right, gear ring 3 and transmission gear case 6 separates, planet carrier 2 and gear ring 3 contacts, all the planetary gear sets rotate, this is called direct gear transmission. When the sliding contact is in the graphic presentation, power transmission breaks, the electrical motor drives the external gear ring 3 to rotate, power transmission breaks.

According to the definition of complex joint graphical representation, the two speed transmission device expressed in Figure 1 can be transformed into complex joint dynamic graph as expressed in Figure 2. And Figure 2 (a) shows the dynamic graph after directly driven by motor; while Figure 2 (b) shows the dynamic graph after decelerate transmission.

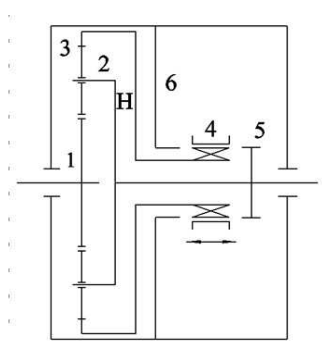
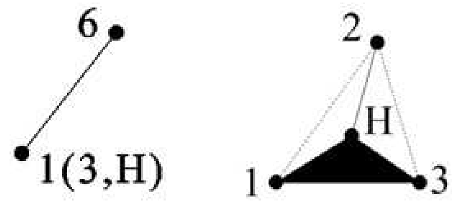


Figure 1 the transmission structure diagram of two speed transmission



(a) (b)

Figure 2 complex joint dynamic graph of the two speed transmission device

3. ANALYSIS ON REVOLUTION SPEED

In graph theory, any circuit composed of three components of a pair of meshed gears and its planet carrier is called a basic closed circuit [4]. In the basic closed circuit of dynamic graph, if the angular speed of component i, j, and k are respectively expressed as ωi ,ωj and ωk, and component i and component j are a pair of meshed gear, then the basic circuit motion equation is [3] :

$$\omega_i - r_{ij}\omega_j + \left(r_{ij} - 1\right)\omega_k = 0 \quad (1)$$

In the equation, $r_{ij} = \pm\dfrac{Z_j}{Z_i}$, Zi and Zj are respectively the gear number of gears. The positive and negative sign respectively means the gear pair is internal meshing or external meshing.

When the direct gear is on, planet carrier 2 and gear ring 3 contacts, there is no relative movement among center gear 1, planet carrier 2 and gear ring 3, and it is just like a component and planet carrier 6 forms a rotational pair, dynamic graph expresses as two vertexes and a solid line, as Picture 2(a) shows. Meanwhile, each component composes no circuit, the planetary gear mechanism is equivalent to a gear coupling and the transmission ratio is 1.

When the decelerate gear is on, from dynamic graph 2(b) we can see that there are two basic circuits (1-2-H and 3-2-H) in the transmission system. The basic circuit equations they are corresponding to are as follows:

$$\omega_2 - r_{21}\omega_1 + \left(r_{21} - 1\right)\omega_H = 0 \quad (2)$$

$$\omega_2 - r_{23}\omega_3 + \left(r_{23} - 1\right)\omega_H = 0 \quad (3)$$

When the reducing gear is on, gear ring 3 and transmission gear case 6 contact, ω3=0, then the circuit equation (3) turns into:

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ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

$$\omega_2 + (r_{23} - 1)\omega_H = 0 \quad (4)$$

Combine equation (2) and equation (4) and eliminates ω2, the system dynamic equation (5) is got.

$$\frac{\omega_H}{\omega_1} = \frac{r_{21}}{r_{21} - r_{23}} \quad (5)$$

4. ANALYSIS ON THE EFFICIENCY OF DECELERATE TRANSMISSION

Torque Analysis

Let Mi, Mj, Mk, respectively represent the torque impose on the components i, j, and k. When the mechanism is in a balance, the algebra sum of all the torques imposed on the basic circuit is zero. The conditions of equilibrium can be expressed as [3] [4]:

$$M_i + M_j + M_k = 0 \quad (6)$$

According to the energy conservation law we can know that the sum of all the power and power loss generated by the 3 components in a basic circuit is zero, namely

$$P_i + P_j + P_k + P_{Loss} = 0 \quad (7)$$

or

$$M_i\omega_i + M_j\omega_j + M_k\omega_k + P_{Loss} = 0 \quad (8)$$

This paper only considerate the meshing loss, the power loss can be expressed by the meshing loss that is generated in the transformation from basic circuit to fixed axis gear train [3].

In the basic circuit 1-2-H, the three components are 1, 2 and H, and component 1 is the driving member, the power loss is

$$P_{Loss1-2-H} = -M_1(\omega_1 - \omega_H)(1 - \eta_{12}) \quad (9)$$

In the basic circuit 3-2-H, the three components are 3, 2 and H, and component 2 is the driving member, the power loss is

$$P_{Loss3-2-H} = -M_{23-2-H}(\omega_2 - \omega_H)(1 - \eta_{23}) \quad (10)$$

Respectively insert the equation (6), (9) and (10) into equation (8) and sort out can get the basic circuit torque equations (11) and (12) of basic circuit 1-2-H and 3-2-H.

$$M_1 r_{12}\eta_{12} + M_{21-2-H} = 0 \quad (11)$$

$$M_3 r_{32}\frac{1}{\eta_{23}} + M_{23-2-H} = 0 \quad (12)$$

The torque equilibrium equations corresponding to basic circuit 1-2-H and 3-2-H are

$$M_1 + M_{21-2-1H} + M_{H1-2-H} = 0 \quad (13)$$

$$M_3 + M_{23-2-1H} + M_{H3-2-H} = 0 \quad (14)$$

The equilibrium equations of internal torque are

$$M_{H1-2-H} = M_{H3-2-H} = M_H \quad (16)$$

$$M_2 = M_{21-2-H} + M_{23-2-H} = 0 \quad (15)$$

In the reducing gear, component 1, H and 3 are respectively input, output and fixed member. Let M1, M2 and M3 respectively represent the torque imposed on the component 1, H and 3. When the mechanism is in a balance, the algebra sum of all the extra torques imposed on the basic component is zero. The conditions of balance can express as:

$$M_1 + M_3 + M_H = 0 \quad (17)$$

Combine all the equations from (11) to (17) and sorts out can get the torque relation equation of component 1 and component H. As shown in equation (18).

$$\frac{M_H}{M_1} = \frac{r_{12}\eta_{12}\eta_{13}}{r_{32}} - 1 \quad (18)$$

5. THE EFFICIENCY EQUATION OF DECELERATE TRANSMISSION

When the reducing gear works, the movement is input from component 1 and output from component H, its transmission efficiency can represented by η_{1H}. η_{1H} is the ratio of input power and output power, as equation (19) shows.

$$\eta_{1H} = \frac{P_H}{P_1} = \frac{\omega_H M_H}{\omega_1 M_1} \quad (19)$$

Insert equation (5) and equation (18) into equation (19) can get the efficiency equation of reducing gear, as equation (20) shows.

$$\eta_{1H} = \frac{P_H}{P_1} = \frac{r_{21}(r_{12}\eta_{12}\eta_{23} - r_{32})}{r_{32}(r_{21} - r_{23})} = \frac{\eta_{12}\eta_{23} - r_{21}r_{32}}{r_{21}r_{32} - 1} \quad (20)$$

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6. ANALYSIS OF INFLUENCE ON TRANSMISSION EFFICIENCY BY GEAR NUMBER RATIO

From equation (20) we can see that each gear number ratio has some influence on the transmission efficiency. Sensitivity analysis method can be used to make sure the influence degree of each gear number ratio on efficiency, and then find ways to improve transmission efficiency.

According to equation (20), $\eta_{1H} = \eta_{1H}(r_{21}, r_{32})$, then

$$S_{\eta r_{21}} = \frac{\partial \eta_{1H}}{\partial r_{21}} = -\frac{r_{32}}{(r_{21}r_{32}-1)^2}(\eta_{12}\eta_{13}-1) \quad (21)$$

$$S_{\eta r_{32}} = \frac{\partial \eta_{1H}}{\partial r_{32}} = -\frac{r_{21}}{(r_{21}r_{32}-1)^2}(\eta_{12}\eta_{13}-1) \quad (22)$$

There are two parameters in the equation (21) and (22), namely r21, r32. In order to get a comprehensive understanding of the sensitivity of each parameter, this paper respectively set the range of the two parameters as ±2%, ±4% and ±6%, which is based on the initial value. The number of each gear in Figure 1 is z1=50，z3=100，z2=25, so the initial value of each parameter is r21=-2，r32=0.25,and $\eta_{12} = 0.98$, $\eta_{23} = 0.99$. Let the abscissa represent each independent parameter, and the ordinate represent sensitivity, and then draw the curves of sensitivity function. Figure 3 to Figure 4 are respectively the sensitivity curves when independent parameters r21 and r32 change (for example, when r21 changes, the initial value of other parameters do not change). In the picture curve 1 to curve 2 are respectively representing the sensitivity function curves $S_{\eta r_{21}}$, $S_{\eta r_{32}}$.

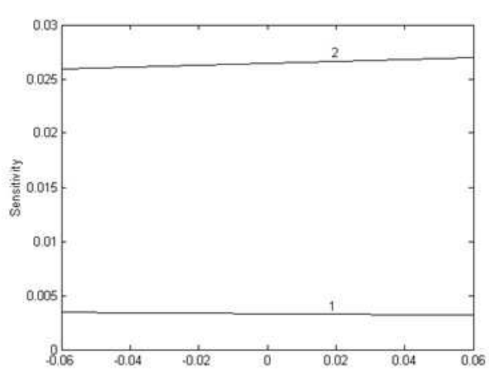

Figure 3 Sensitivity function curves under r21 changes

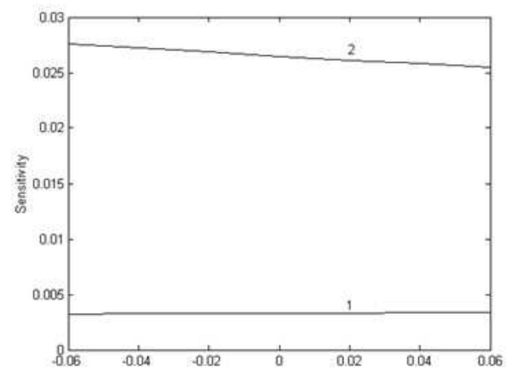

Figure.4 Sensitivity function curves under r32 changes

From Figure3 to Figure 4, we can see that no matter r21 or r32 changes, there is difference in each parameter's sensitivity. But the rule is the same: the sensitivity $S_{\eta r_{32}}$ is bigger and the sensitivity $S_{\eta r_{21}}$ is smaller. That means the planetary transmission efficiency is more sensitive to the independent parameter r32 than the independent parameter r21.

7. CONCLUSION

This paper uses graph theory as tools and adopts complex joint graph method and basic circuit to analyze on the transmission system of BEV. By using the conditions of torque equilibrium and energy conservation law, the decelerate transmission system is analyzed and the efficiency equation is deduced. By calculating and analyzing, the influence degree of each parameter (gear ratio) of transmission system on transmission is got, and the result can be used by the design of the planetary gear transmission system.

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