Simulation of multi-power composite electric tractor based on power fluctuation ratio

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Abstract. All Combined with the characteristics of frequent abrupt load in the field operation of tractors, and aiming at the problems of single motor energy input and large fluctuation of battery state in the energy system of pure electric tractors, a power supply structure with multiple battery packs was proposed. A dynamic model considering real-time power and load fluctuation and a multi-power cooperative input model based on fuzzy control threshold logic rule based on power fluctuation ratio are established. Matlab and Simulink are used to simulate the model and compare it with the traditional single power model. The results show that when the speed is constant ploughing, the output power of the lithium battery of the multi-power cooperative input model is effectively compensated compared with that of the single-power model under sudden load. The average fluctuation ratio of rising power decreases from 5.8% / s to 2.7% / s, which realizes "peak clipping" and "slow peak" when the current fluctuates greatly, and then made the estimation of battery state of charge (SOC) more accurate, and prolonged the battery life.

1. Introduction
Modern agricultural machinery and equipment is an important support for modern agriculture. Modern agriculture has put forward higher and higher requirements for ecology, energy saving and environmental protection, and special agricultural production environments such as facilities, ecology and courtyard agriculture have an increasingly urgent demand for green power agricultural machinery and tools [1]. With the rapid development of power supply technology and motor technology, electric tractors provide a new way to achieve green agricultural machinery technology [2]. As a new energy agricultural machinery, it has the advantages of green and clean, low noise, high energy utilization rate and strong controllability. With the promotion of electric vehicles, electric tractors have been widely used in agricultural production. At present, there are some problems in the technology of electric tractors. Compared with electric vehicles on the road, the working characteristics of electric tractors have great changes. There is little change in speed and no need for acceleration during operation, but sudden load occurs frequently in field operations such as rotary tillage and ploughing, resulting in large fluctuation in power demand of the whole machine and frequent surge in current demand [3]. Paper [4] studies the energy management of electric tractors based on the random load power spectrum. The traditional electric tractor uses a single energy source, and its battery pack has poor performance under random load impact, and its battery life is reduced. Paper [5] studies the composite power supply system and verifies the feasibility and advantages of the composite power supply. Paper [6] and [7] have verified that small current fluctuation can effectively improve the estimation accuracy of lithium iron phosphate battery state (SOC). Research on the energy system of electric tractor is
helpful to improve the service life of battery pack, extend driving range and improve ride comfort in use [8-10]. In this paper, an electric tractor is taken as an example. Based on the lithium iron phosphate battery, a supercapacitor and a supercapacitor power supply battery pack are introduced to form a three-battery composite power supply system with the original battery pack. Multi-power supply operation is enabled in the operation of electric tractor, and the power distribution control strategy of multi-power supply cooperative operation with fuzzy control is designed. Lithium battery with high energy ratio and supercapacitor and high speed ratio are used for cooperative operation.

2. Energy demand analysis of the electric tractor

The tractor ploughing industry is very different from the driving operation. When the electric tractor is in the ploughing industry mode, it has the characteristics of large load, large fluctuation, constant speed and low speed. Therefore, this paper ignores the air, acceleration and grade resistance and increase the plough drag caused by its plough, the brief diagram of force analysis is shown in Figure 1:

The kinematic model is as follows:

\[ F_q = F_f + F_X \] \hspace{1cm} (1)

\[ F_f = f m g \] \hspace{1cm} (2)

\[ F_X = \lambda m g + K_i H B + \gamma H B V^3 \] \hspace{1cm} (3)

\[ T = \frac{F_q r}{i_s \eta_t} \] \hspace{1cm} (4)

Fig 1. Plow force analysis diagram

Here: \( F_q \) is the driving force, N; \( f \) is the rolling resistance coefficient, N; \( F_X \) is tractor traction resistance, N; \( m \) is the weight of the whole tractor, kg; \( \lambda \) is ploughing resistance coefficient, N; \( m_2 \) is the weight of the plow carrier, kg; \( K_i \) is soil deformation coefficient, kg; \( H \) is the ploughing depth, cm; \( B \) is the ploughing width, cm; \( \gamma \) is ploughing soil throwing coefficient; \( V \) is the operating speed of tractor, m/s; \( T \) is the required torque of the motor, N•m; \( r \) is the driving radius of the driving wheel, m; \( i_s \) is the current driveline transmission ratio; \( \eta_t \) is the transmission efficiency of the drivetrain.

Due to the large and frequent mutation loads in tractor operation, and the large changes in \( \lambda, K_i \) and \( H \) etc., random soil resistance \( F_{ran} \) is introduced. \( \lambda, K_i \) and \( H \) is equated to a constant. Thus, the new traction equation is obtained as follows:

\[ F_{X_{run}} = \lambda m g + K_i H B + \gamma H B V^3 \] \hspace{1cm} (5)

\[ F_{X_{req}} = \lambda m g + K_i H B + \gamma H B V^3 + F_{ran} \] \hspace{1cm} (6)

Here: \( F_{X_{run}} \) is the actual traction force, N; \( F_{X_{req}} \) is the demand traction force, N; \( F_{ran} \) is soil random resistance, N.

The output torque and power of the motor required during ploughing are calculated as follows:

\[ P_{req} = P_{run} + P_{\delta} \] \hspace{1cm} (7)

\[ P_{run} = P_{tur} + P_{\delta} \] \hspace{1cm} (8)

Here: \( P_{req} \) is the required power of the motor (the required power of the battery), kW; \( P_{run} \) is the required power of motor torque, kW; \( P_{run} \) is the actual power of the motor (the actual power of the
battery), kW; $P_{\text{tur}}$ is the actual torque power of the motor, kW; $P_{\delta}$ is the power loss of skid, kW.

The demand speed of the motor during ploughing is calculated as follows:

$$n_r = \frac{v_i}{0.377r}$$  \hspace{1cm} (9)

Here: $n_r$ is the required speed of motor, r/min.

Fig 2. Kinematics simulation model of electric tractor

3. Multi-power supply structure layout scheme

Fig.3 is a schematic diagram of the power transmission system of a multi-power electric tractor. The three-power source hybrid power supply structure supplies the motor using a lithium battery with high energy ratio and high power ratio to realize energy transmission. The energy system of the multi-power electric tractor mainly supplies the first battery pack (lithium battery), and the module of the second battery pack (lithium battery) in series with the super capacitor and DC/DC as the collaborative auxiliary energy, which jointly forms the multi-power energy storage system in parallel with the former. The collaborative auxiliary energy uses the DC/DC converter to adjust the voltage relationship between supercapacitance and the first and second battery packs. This structure can not only well use the output voltage and current of supercapacitance, but also supplement the energy storage of supercapacitance, and solves the disadvantage of weak supercapacitance storage capacity.

Fig 3. Power transmission system of multi-power electric tractor

4. Battery energy management strategy

The overall goal of energy management is to reduce the impact of lithium battery output power caused by the operation of electric tractors, and achieve the purpose of "cutting" and "slow peak" of lithium battery output power. Combined with the output characteristics of lithium batteries and super capacitance, the corresponding energy management method is formulated.

4.1. Battery power supply mode

When the load of the tractor in the field is been changing, so the power required by the motor fluctuates, and the power and current output of the battery also fluctuates. When the soil hardness changes greatly, the current output of the battery surges and decreases, thus affecting the service life of the battery and the estimation of SOC. Using the Battery Management System (BMS), the energy power required during the tractor operation is reasonably allocated to the multiple power system to make the output current of the first battery pack (the main energy supply) smooth, reduce its current fluctuation ratio, and realize the "peak reduction" of the current.
The multiple power supply system adjusts the different modes of the energy management system according to the motor and battery power required in different operating environments. Combining the energy management content and the tractor operation characteristics, the energy system is divided into single battery power supply mode (M1), multi-power cooperative operation mode (M2) and peak discharge mode (M3). The diagram of energy transfer of multi-power system is shown in Fig. 4 and Fig. 5.

Fig. 4. Single power supply mode (M1)  
Fig. 5. Multi-power supply cooperative mode (M2)

Fig. 4 shows the single power supply mode of the electric tractor. When the real-time power of the tractor operation is small or the working condition is stable and no mutation load, the power fluctuation of the motor and battery demand is less and the current output is stable. At this time, only the main energy supply for electric energy supply.

Fig. 5 shows the multi-power cooperative power supply mode of the electric tractor. When the tractor operation condition fluctuates greatly, the motor and battery demand power fluctuates greatly, and the real-time power exceeds the set threshold. At this time, while limiting the power fluctuations of the main supply energy, we should intervene with the auxiliary energy, and make power compensation with the characteristics of the super capacitance high power ratio.

4.2. Energy distribution model

This paper uses the energy distribution model based on logic threshold control. Limit the lithium battery power output in the case of the power mutation.

Set the following threshold control parameters: Current battery power \( P_{\text{tur}} \), battery required power \( P_{\text{req}} \), power threshold of the multi-energy system \( P_{\text{lim}} \), maximum power \( P_{\text{max}} \) provided by the multi-energy system, power fluctuation ratio \( \lambda_{\text{tur}} \), and upper limit of power fluctuation ratio \( \lambda_{\text{lim}} \).

\[
\lambda_{\text{tur}} = \frac{P_{\text{req}} - P_{\text{tur}}}{P_{\text{tur}}} \quad (10)
\]

Here: \( \lambda_{\text{tur}} \) is the power fluctuation ratio.

Judgment condition setting: \( P_{\text{tur}} > P_{\text{lim}} \) when the energy distribution model is on, " \( P_{\text{req}} \leq P_{\text{max}} \) " is N1; " \( P_{\text{req}} > P_{\text{max}} \) " is N2; " \( \lambda_{\text{tur1}} \leq \lambda_{\text{lim1}} \) " is N3; " \( \lambda_{\text{tur1}} > \lambda_{\text{lim1}} \) " is N4; " \( \lambda_{\text{tur2}} \leq \lambda_{\text{lim2}} \) " is N5; " \( \lambda_{\text{tur2}} > \lambda_{\text{lim2}} \) " is N6. Then the logical rule of energy management of electric tractors is

\[
R = \begin{cases} 
T (N1 \land N3 \land N5) \rightarrow M1 \\
T (N1 \land N4 \land N5) \rightarrow M2 \\
T (N2 \lor N6) \rightarrow M3
\end{cases}
\]

Here, \( R \) is the judgment rule. The logical threshold rule diagram is shown in Figure 6.
FIG. 6 is a logic threshold rule for multi-power tractors considering the power fluctuation ratio. It can be seen that when the power surge occurs, if the demand power fluctuation ratio is within the allowable threshold, the main supply energy performs all the power output; when the demand power fluctuation ratio exceeds the allowable threshold, the main supply energy only performs the power output within the fluctuation ratio threshold, and the part beyond the threshold is provided by the collaborative auxiliary energy.

4.3. Fuzzy control

Fuzzy control is a widely applied intelligent control method[5], it’s the core part of the control strategy. The calibration of different influencing factors (power demand, SOC, motor efficiency, etc.) can be easily realized, with good robustness[6].

Fig. 7 shows a membership function for each input and output. The actual power $P_{tur}$ theory area of the electric tractor is $[0,1]$. The corresponding fuzzy set is [ZE,PS,PM,PB]. Represents {zero, Small and small, Central, Big}; The ratio domain of power fluctuation of the main energy supply source $\lambda_{tur1}$ is $[0,1]$. The corresponding fuzzy set is [ZO,LE,PS,PM,PB]. Represents {zero, Smaller, Central, Larger, Very big}; The domain of power fluctuation $\lambda_{tur2}$ is $[0,1]$. The corresponding fuzzy set is [ZO, LE,PS,PM,PB]. Represents {zero, Smaller, Central, Larger, Large} as the input variable of the fuzzy controller, The main analysis of the output variable of the fuzzy controller, the output power $P_1$ theory is $[0,1]$. The corresponding fuzzy set is [ZE,PS,PM,PB]. Represents {zero, Small and small, Central, Big}; The output power $P_2$ theory is $[0,1]$. The corresponding fuzzy set is [ZE,PS,PM,PB]. Represents {zero, Small and small, Central, Big}, Fuzzy control over the input amount of the energy management model, The purpose of multi-power assistance and coordination can be achieved.
The fuzzy rule table established according to the above control rules is shown in Table 1, and the resulting input-output relationship change is shown in Fig. 8.

Table 1. Control law of energy output power $P_i$

| $\lambda_{tur1}$ | $\lambda_{tur2}$ | $P_{tur}$ |
|-----------------|-----------------|-----------|
| ZO              | ZO              | ZE        |
| LE              | LE              | PS        |
| PS              | PS              | PS        |
| PM              | PM              | PM        |
| PB              | PB              | PB        |

5. Simulation result analysis

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With a certain type of agricultural electric tractor as the research object, after calculation, and reference to the products sold in the market, the main parameters of the whole machine, as shown in Table 2. In order to verify the effectiveness and applicability of energy management, take the uniform ploughing condition of 5.5km/h, ignore the energy loss at the DC—DC converter, and think that the power used by the battery is equal to the total power of the motor. The single power model and the power fluctuation ratio of the multiple power model considering real-time power and load fluctuation were studied, and analyzed the above model by MATLAB/Simulink. Power supply power output pairs shown in FIG. 9 and power fluctuation ratio shown in Fig. 10 and Fig. 11.

Table 2. Machine parameters of multi-power system electric tractor

| No. | Parameter                          | Value | Unit |
|-----|------------------------------------|-------|------|
| 1   | Curb weight                        | 1870  | kg   |
| 2   | Drive wheel drive radius           | 0.42  | m    |
| 3   | Total drive ratio of plough drive system | 39.8 |      |
| 4   | Plough transmission efficiency     | 92    | %    |
| 5   | Motor rating                       | 20    | kW   |
| 6   | Peak motor power                   | 30    | kW   |
| 7   | Motor rated rotating speed         | 2100  | r/min|
| 8   | Soil deformation coefficient       | 5     | Ncm  |
| 9   | Ploughing resistance coefficient   | 0.3   |      |
| 10  | Weight of plow carrier             | 250   | kg   |
| 11  | The ploughing depth                | 15    | cm   |
| 12  | The ploughing width                | 250   | cm   |
| 13  | Ploughing soil throwing coefficient| 6     |      |

Figure 9 shows the power consumption in the constant speed ploughing process of electric tractors. The simulation results analyze that in the plough tillage industry with mutation load, the maximum electric power is 16.1kW and the minimum electric power is 7.8kW. Among them, the lithium battery output power of a single power model is the total power demand. Based on the power fluctuation than threshold of multi-power cooperative input model compared with a single power model, lithium battery power fluctuation becomes gentle, its lithium battery maximum output power is 14.1kW, the minimum power of 7.8kW, is provided by collaborative auxiliary energy, it avoids the lithium battery by mutation power output mutation current and impact, realize the lithium battery output power "peak", "slow peak", can extend the service life of lithium battery and more accurate prediction of battery SOC value.
Fig. 10 and Fig. 11 are comparing the fluctuation ratio of the multi-power cooperative input model based on the power fluctuation ratio threshold with the time interval of 0.1s and 1s of the lithium battery output power of a single power supply model. Analyze is shows that the average fluctuation ratio of rising power per s decreased from 5.6% to 2.7%, and the highest rising power fluctuation ratio per s decreased from 20.8% to 3.6%; The average fluctuation ratio of rising power per 0.1s decreased from 0.58% to 0.3% and the highest rising power fluctuation ratio per 0.1s decreased from 4% to 0.3%.

The comprehensive results show that the total power collaborative input model based on the fuzzy control threshold logic rule of power fluctuation ratio has rapid response to the load mutation and the output power can meet the demand power. It is obvious that the power growth within the fluctuation ratio threshold is provided by the main power energy, while the power surge beyond the threshold is supplied by the collaborative auxiliary power supply.

6. Conclusion

(1) By analyzing the characteristics of power output of electric tractor during random load and the output characteristics of lithium battery and super capacitance, the energy system scheme of multi-power hybrid electric tractor based on lithium battery and super capacitance is designed.

(2) A dynamic model considering real-time power and load fluctuation and a multi-power cooperative input model based on fuzzy control threshold logic rule of power fluctuation ratio are designed.

(3) Through simulation analysis, compared with the single power model without considering the power fluctuation, the average rising power output fluctuation ratio of lithium battery output power decreased from 5.6% to 2.7%, and the highest rising power fluctuation ratio per second decreased from 20.8% to 3.6% per second. The energy management model and control strategy of this paper can realize the "cutting" and "slow" of lithium battery power output on the basis of meeting the vehicle power, so that the lithium battery can output electric power in a relatively gentle and stable operating state.

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