Drive system failure control for distributed drive electric vehicles

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Abstract. Aiming at the failure problem of distributed electric drive vehicle, the conventional control strategy of drive system failure is designed according to the characteristics of each wheel torque independent control and the redundant configuration of the power unit. On this basis, combined with the traditional body stability control technology, the direct yaw moment control method is used. The simulation results show that the conventional control method designed of the drive system failure can effectively improve the driving condition of the vehicle. The driving stability of the vehicle is further improved after the direct yaw torque control is applied.

1. Introduction
Distributed drive electric vehicles will be installed in the motor drive wheel or in the vicinity of the wheel, with high transmission efficiency, fast response, conducive to the overall layout of the vehicle, the wheel torque is independently controlled, easy to coordinate control, etc., is the electric car Areas of development important direction\textsuperscript{[1-3]}. Aiming at the failure control problem of distributed driving electric vehicle, some scholars put forward the idea of zeroing the output torque of the driving wheel\textsuperscript{[4, 5]}. However, this method does not make full use of the redundant configuration of the power unit and weaken the drive ability\textsuperscript{[6-8]}.

In this paper, to maintain stability and power as the goal, the failure control method of driving system is designed. Based on the traditional body stability control technology\textsuperscript{[9-11]}, the direct yaw moment failure control system is designed, and the CarSim-Simulink joint simulation platform is designed to simulate the failure control algorithm of the drive system.

2. Conventional Control for Drive System Failure
In the rotor flux based method, rotor flux observer of voltage model is used as the reference model, because the observer doesn’t contain the quantity of rotor resistance and the output of the observer is free from rotor resistance. Rotor flux observer of voltage model under stationary reference frame is written as follows: Before the motor fails, the sum of the four-wheel longitudinal drive torque ($T_\beta$, $T_\delta$, $T_R$, $T_N$) is equal to the longitudinal torque expected by the driver ($T_x$).

$$T_x = T_\beta + T_\delta + T_R + T_N \quad (1)$$

After the drive motor fails, the driver's direct yaw moment requirements aren't considered, so the yaw moment of the vehicle is zero\textsuperscript{[12]}.
\[
\frac{d_f T_f}{2R} - \frac{d_r T_r}{2R} + \frac{d_f T_f}{2R} - \frac{d_r T_r}{2R} = 0
\]  
(2)

Where \( d_f \) and \( d_r \) is the front and rear axle wheelbase and \( R \) is the tire radius. It is generally believed that the front and rear axles are the same.

\[
T_{\beta} - T_{\beta'} + T_{\phi} - T_{\phi'} = 0
\]  
(3)

The output torque can't exceed the maximum torque of the motor.

\[
T_i \leq T_{\text{max}}
\]  
(4)

Under the constraints of inequality (4), it is difficult to guarantee that equations (1) and (3) have solutions, so we need softening constraints and set the main control objectives. The core idea of drive system failure control is to ensure vehicle safety, so it should give priority to meet the equation (3), to stability-based.

2.1. **Single drive motor failure control**

Single drive motor failure control, left front wheel failure as an example, this time the left front wheel motor output torque is zero, the system will transfer left front wheel motor torque loss to the left rear wheel motor.

\[
T_{\beta'} = 0, T_{\phi'} = T_{\beta'} + T_{\phi}, T_{\phi} = T_{\phi'} = T_{\phi'}
\]  
(5)

Taking into account the motor output torque can't exceed its maximum torque, when \( T_{\beta'} + T_{\phi'} \geq T_{\text{max}} \):

\[
T_{\phi'} = 0, T_{\phi} = T_{\text{max}}, T_{\phi'} = T_{\text{max}} - T_{\phi'}
\]  
(6)

2.2. **Two-side two motors failure control**

Take the left front wheel and the right rear wheel failure as an example. At this time, the left front wheel and right rear wheel torque is zero, and the system will transfer the loss torque to the left rear wheel and right front wheel motor.

\[
T_{\beta'} = 0, T_{\phi'} = 0, T_{\phi} = T_{\beta'} + T_{\phi}, T_{\phi'} = T_{\phi} + T_{\phi'}
\]  
(7)

Similarly, when \( T_{\beta'} + T_{\phi} \geq T_{\text{max}} \) or \( T_{\phi} + T_{\phi'} \geq T_{\text{max}} \):

\[
T_{\phi} = T_{\phi'} = T_{\text{max}}
\]  
(8)

2.3. **One-side two motors failure or multiple motors failure control**

When one-side two motors fail or multiple motors fail, the body force imbalance\(^{[13]}\), for dangerous conditions, all drive motors should be set to zero and immediately stop the vehicle.

3. **Direct Yaw Moment Control for Drive System Failure**

3.1. **Yaw Moment Calculation**

According to the two-degree-of-freedom vehicle reference model, considering the vehicle's yaw moment input, list the vehicle's motion equation.

\[
\begin{align*}
\frac{mV}{dt} + d\frac{\beta}{dt} + 2(k_i + k_i)\beta + [mV + \frac{2}{V}(l_i k_i - l_i k_i)]r = 2k_i \delta \\
2(l_i k_i - l_i k_i) + I \frac{dr}{dt} + \frac{2(l_i^2 k_i + l_i^2 k_i)}{V} = 2l_i k_i \delta + M
\end{align*}
\]  
(9)

The Laplace transform of the equation (9) yields the response of the yaw rate to the steering angle and the yaw moment.
\[
r(s) = \frac{G_0^e(0)(1+T_s)s\delta(s) + G_M(0)(1+T_Ms)M(s)}{1 + \frac{2\zeta}{\omega_n}s + \frac{1}{\omega_n^2}s^2} = \frac{\omega_n^2 H_M(s)}{s^2 + 2\zeta\omega_n + \omega_n^2}
\]

Here,
\[
H_M(s) = G_0^e(0)(1+T_s)s\delta(s) + G_M'(0)(1+T_Ms)M(s)
\]
\[
G_M'(0) = \frac{(k_i + k_f)V}{2l^2k_fk_i(1+AV^2)}
\]
\[
G_0^e(0) = \frac{1}{1+AV^2} \frac{V}{l}
\]
\[
T_M = \frac{mv}{2(k_i + k_f)}
\]
\[
T_s = \frac{mAV}{2k_i}
\]
\[
A = -\frac{m}{2l} \frac{l_1k_i - l_2k_f}{k_i}
\]
\[
\omega_n = \frac{2l(k_i + k_f)^{1/2}}{V}\left(1+AV^2\right)^{1/2}
\]
\[
\zeta = \frac{m(l_1^2k_i + l_2^2k_f) + l_1k_f}{2l}\left[mk_i(1+AV^2)\right]^{1/2}
\]

For the yaw rate velocity feedforward model, the desired yaw rate model is as follows:
\[
r_0^e(s) = \frac{G_e}{1+T_e} \delta(s)
\]
Where \(G_e\) is the desired yaw rate response gain and \(T_e\) is the yaw angular velocity response to the first order delay.

Make the first-order delay response error zero.
\[
(s + \frac{1}{T_g})(s + \frac{1}{T_e})[r(s) - r_0^e(s)] = 0
\]

Arrange the above formulas to obtain the yaw moment required to follow the yaw angular velocity response as equation (21).
\[
M(s) = \left[-\frac{G_0^e(0)}{G_M(0)} \frac{1+T_s}{1+T_Ms} + \frac{G_e}{\omega_n^2 T_g T_s G_M'(0)} \frac{1+T_s}{1+T_Ms}\right] \delta(s) - \frac{c_0}{\omega_n^2 G_M'(0)} \frac{1+c_0^2}{1+T_Ms} s r(s)
\]

Here,
\[
c_1 = \frac{1}{T_g} + \frac{1}{T_e} - 2\zeta\omega_n
\]
\[
c_0 = \frac{1}{T_g} - \omega_n^2
\]

3.2. Torque Distribution
The yaw moment of the vehicle should meet the requirements.
\[
M_s = \frac{d}{2} [(F_{sa} - F_{sv}) + (F_{sa} - F_{sv})]
\]
In addition, should try to meet the vehicle longitudinal force requirements.
\[
\min D = \left| F_x - (F_{x1} + F_{x2} + F_{x3} + F_{x4}) \right|
\] (25)

In addition, the vehicle longitudinal driving force is limited by the condition of the road attachment and the capacity of the single motor output

\[-\mu F_{zi} \leq F_{zi} \leq \min(\mu F_{zi}, F_{max})\] (26)

When the only solution can't be obtained according to the constraints, the equation (27) is introduced by the front and rear axle average distribution, and the torque distribution strategy is shown in Table 1.

\[F_{x2} - F_{x1} = F_{x4} - F_{x3}\] (27)

| Failure type                  | Constraints                                      | Distribution strategy                        |
|------------------------------|--------------------------------------------------|----------------------------------------------|
| Single motor failure         | \[M_z = \frac{d}{2} [(F_{x2} - F_{x1}) + (F_{x4} - F_{x3})] \] | The objective function: equation (25)       |
|                              | \[-\mu F_{zi} \leq F_{zi} \leq \min(\mu F_{zi}, F_{max})\] |                                              |
| Two-side two motors failure  | \[M_z = \frac{d}{2} [(F_{x2} - F_{x1}) + (F_{x4} - F_{x3})] \] | The objective function: equation (25)       |
|                              | \[-\mu F_{zi} \leq F_{zi} \leq \min(\mu F_{zi}, F_{max})\] |                                              |

4. Simulation Analysis and Results Discussion

Set up the CarSim-Simulink simulation test platform, the vehicle model is established in CarSim, and the drive system failure control algorithm is built in Simulink\cite{4,15}. The vehicle speed is 60km/h, the steering angle is constant at 0, the left front wheel motor is faulty at 2s, the right rear wheel motor is faulty at 7s, and the right front wheel motor is faulty at 12s. The simulation results are shown in Figure 1-4.

**Figure 1.** Yaw rate comparison  
**Figure 2.** Sideslip angle comparison
It can be seen from Figure 1 that the conventional failure control method can effectively reduce the undesirable yaw rate, and after the yaw moment control is applied, the yaw rate follows the expected value and the running stability of the vehicle is higher. In Figure 2-4, it can be seen that the vehicle sideslip angle, lateral acceleration and lateral migration after direct yaw moment control are reduced and the vehicle is more stable. In summary, the use of conventional drive system failure control method can effectively improve the vehicle running state, the application of direct yaw moment control, to further improve the vehicle's driving safety.

5. Conclusion

This paper studied the problem of failure control of distributed driving electric vehicle drive system. According to the characteristics of power unit redundant configuration, the control method of drive system failure was designed to keep stability and power. This paper completed the work:

(1) Analyzed the drive system failure situation for distributed drive electric vehicles and developed the conventional control method for the drive system failure.

(2) Combined with the traditional body stability control technology, designed the direct yaw moment failure control system.

(3) The CarSim-Simulink simulation platform was built, and the correctness and effectiveness of the drive system failure control algorithm were verified by comparing the analysis results.

References

[1] Qian Danjian. Study on yaw moment control and torque distribution for distributed drive electric vehicles[D]. Jilin University, 2015.
[2] M. Satyendra Kumar, Shripad. T. Revankar. Development Scheme and Key Technology of an Electric Vehicle: An Overview[J]. Renewable and Sustainable Energy Reviews, 2016.
[3] Xiong Lu, Fu Wen. Summarization of distributed drive electric vehicle configuration[J]. China New Technologies and Products, 2014,(22):84-85.
[4] Mutoh N, Takahashi Y, Tomita Y. Failsafe drive performance of electric vehicles with the structure driven by the front and rear wheels independently[C/CD]//The 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON). Taipei, China, 2007.
[5] Mutoh N, Takahashi Y. Front-and-rear wheel independent drive type electric vehicle (FRID EV) with the outstanding driving performance suitable for next-generation advanced EVs[C/CD]//Vehicle Power and Propulsion Conference, Michigan, 2009.
[6] Kawakami K, Matsugaura S, Onishi M, et al. Development of fail-safe technologies of ultra high performance EV “KAZ”[C/CD]//The 18st International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exposition. Berlin, 2001.
[7] Wang Bo, Luo Yugong, Fan Jingjing, et al. A study on driving force distribution of four wheel independent drive electric vehicle based on control allocation[J]. Automotive
Engineering, 2010, 32(2): 128-132

[8] Yu Jiancheng, Zhang Aiqun, Wang Xiaohui. Research on thruster fault tolerant control allocation of a 7000m manned submarine[J]. Robot, 2006, 28(5): 519-524.

[9] Lin Cheng, Xu Zhifeng, Zhou Fengjun, et al. Stability hierarchical control strategy for distributed-driving electric vehicle[J]. Transactions of Beijing Institute of Technology, 2015, 35(5): 490-493

[10] Leonardo De Novellis, Aldo Sorniotti, Patrick Gruber. Wheel torque distribution criteria for electric vehicles with torque-vectoring differentials[J]. IEEE Transactions on Vehicular Technology, 2014, 63(4): 1593-1602

[11] Nan Ming Yan, Yu Nan Zhang, Nian Yu Li. Research on Control System for Multi-Wheel Independent Electric Drive[J]. Advanced Materials Research, 2013, 2526(753).

[12] Chu Wenbo, Luo Yugong, Han Yunwu, et al. Rule-based traction system failure control of distributed electric drive vehicle[J]. Journal of Mechanical Engineering, 2012, 48(10): 90-95.

[13] Zheng Hangeng. Research on electric drive system failure control of four in-wheel drive electric vehicle[D]. University of Electronic Science and Technology, 2013.

[14] Xiong Lu, Chen Chen, Feng Yuan, et al. Modeling of distributed drive electric vehicle based on co-simulation of Carsim/Simulink[J]. Journal of System Simulation, 2014, 26(5): 1143-1148.

[15] Chen Guoying. Research on Experiment Platform of By-wire Electric Vehicle with four wheels independent control and its integrated chassis control strategy[D]. Jilin University, 2012.