Research on Energy Management Strategy of Diesel Hybrid Electric Vehicle Based on Decision Tree CART Algorithm

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Abstract. Aiming at the emission of nitrogen oxides from hybrid electric vehicles (HEV), a strategy of diesel hybrid energy management based on decision tree CART algorithm was proposed.Firstly, a classification algorithm combining decision tree and regression tree is proposed to predict the trend change relationship of a case from one or more predictive variables according to the category and variable characteristics.Secondly, by controlling the torque distribution between the engine and the motor, an additional degree of freedom is introduced to adjust the trade-off between pure fuel economy and pure restriction.Finally, the simulation method is used to understand the system performance and adjust the proposed energy management strategy.The results show that in the proposed energy management strategy for diesel hybrid power, the reduction of $NO_x$ has an impact on fuel consumption, and the potential of $NO_x$ emission can be limited by choosing the best operating point and limiting engine power.

1. Introduction

Hybrid electric vehicles (HEVs) are considered to be an effective way to reduce fuel consumption and emissions[1].The main goal of diesel hybrid electric vehicles is to use engines under the circumstance of improving energy efficiency and minimizing emissions[2].It can be seen that the study of hybrid energy management strategy has a very good practical significance and practical value.

Many experts and scholars at home and abroad have carried out in-depth research on the energy management strategy of diesel hybrid power.Literature [3] proposes a heuristic energy management strategy for diesel hybrid electric vehicles, but only studies the energy management in the driving cycle.The energy management strategy proposed in document [4] considers four major pollutants ($NO_x$,PM, HC, CO) weighted fuel consumption, but does not consider the instantaneous part of total emissions.In reference [5], a dynamic programming technology for automotive energy management is proposed, but the performance perception of the system is not enough to adjust the energy management strategy according to the configuration of power system.Literature [6] presents an energy management controller based on game theory, but the trade-off between fuel consumption and $NO_x$ emissions is not good.In conclusion, the above research considers more about driving cycle and less about the instantaneous emission of total $NO_x$. 
In this paper, a energy management strategy based on decision tree CART algorithm for diesel hybrid power system is proposed, which can significantly reduce $NO_x$ and decrease fuel consumption slightly [7-9]. Its main characteristics are:

1. In most of the existing methods, the trend change relationship of individual cases is not clear enough. This strategy combines regression tree and decision tree classification algorithm (CART) to predict the trend change relationship of individual cases from one or more predictive variables according to category and variable characteristics.

2. In most of the existing methods, the trade-offs between pure fuel economy and pure $NO_x$ limitation are insufficient. By controlling the torque distribution between engine and motor, the method introduces additional degrees of freedom to adjust the trade-offs from pure fuel economy to pure $NO_x$ limitation.

3. In most of the existing methods, the performance perception of the system is not enough. The method uses software-in-loop (SiL) and hardware-in-loop (HiL) simulation methods to master the system performance and adjust the energy management strategy according to the power system configuration.

The simulation and experimental results show that it is feasible to incorporate emission constraints into heuristic or model-based monitoring strategies in the energy management method for diesel HEV. The basic flow chart of energy management strategy is shown in Figure 1.

![Figure 1. Basic flow chart of energy management strategy](image1)

![Figure 2. Architecture diagram of CART algorithm system](image2)

2. Decision Tree CART Algorithms

The CART algorithm has a multi-tree structure, which can predict the changing trend of individual cases. Through the analysis of sample attributes, the amount of information in the sample subset and the class value of the sub-node samples can be determined. The algorithm starts from the root node and tests each non-child node according to the sample attributes. The new sub-node is also completed by cyclic operation until reached the termination condition, the cycle is over. In the cycle process, how to select test attributes and divide sample sets is the key link of decision tree construction. Different decision tree have different algorithms in this link. In this paper, CART algorithm is used, and its system architecture is shown in Figure 2.

When the predictive vector X is given, the conditional distribution of variable Y can be described by this algorithm. The prediction space is divided into several subsets by using the binary tree model, and the variable Y is distributed continuously on the subset. The CART also has a supervised learning function, that is, the CART algorithm must provide a corresponding learning sample set to evaluate and rebuild the CART before predicting the user’s needs.
The process of constructing tree $T_{\text{max}}$ is to match the sample set to the maximum binary tree. In the process of construction, the maximum complexity reduction algorithm is used to find the best branching rules, which mainly includes two steps: reducing the cardinality of attribute vectors and constructing standard problem sets.

3. Energy Management Scheme of Diesel HEV

Taking a diesel engine vehicle as the research object, its architecture is a parallel hybrid architecture, see figure 3. The front side of the transmission is used for a separate start generator (SSG) and the back side for a rear drive motor (EM), it can be provided for auxiliary powered, fully electric driven, regenerative braking and battery charging. It is equipped with an in-line four-cylinder 1.6-liter direct injection engine with a maximum output power of 50 kW and a peak torque of 150 N.m. The engine NO$_x$ emission is close to Euro 6 emission standard without special after-treatment. The engine has a low-pressure exhaust gas recirculation (LP EGR) circuit, and the system has a slower combustion gas stabilization time than the HP EGR mode. The engine transient is more severe due to the EGR time delay, so it is necessary to develop and validate the transient NO$_x$ limitation strategy using the power assistant system of the motor[10].

Vehicle speed curve and wheel torque are the main input of the model.

Battery is the second power source, and SOC is an important internal factor to be considered in the design of energy management strategy of hybrid power system. The basic rules are used to adjust the size of the battery to keep the ratio of battery energy to motor power constant and close to 35Wh/kW. This value is selected according to vehicle quality, hybrid power system and other parameters. The rated power of motor is 42 kW, and the energy of battery is 1.5 kWh. The change of battery SOC is calculated by battery current and power.

\[
SOC(t) = \begin{cases} 
\frac{I_{\text{bat}}}{Q_0}, & \text{if } P_{\text{elec}} > 0 \\
-\eta_{\text{bat}}(SOC) \frac{I_{\text{bat}}}{Q_0}, & \text{else} 
\end{cases}
\] (1)

$Q_0$ is the capacity of the battery and $\eta_{\text{bat}}$ represents its Faraday efficiency. Battery SOC is system state $(x(t) = SOC(t))$. The electrochemical power of the battery is:

\[
P_{\text{elec}} = -Q_0 U_{\text{bat}}(SOC) SOC(t)
\] (2)

The peak value of NO$_x$ occurs during engine transient period, which accounts for an important part of total NO$_x$ emission. For fast torque transient, the NO$_x$ peak amplitude is higher, and these peaks will
decrease as long as the torque gradient decreases[11]. In addition, peak $NO_x$ is closely related to BGR error ($\varepsilon F_t = F_t^{eng} - F_t^{mot}$). This shows that $NO_x$ emission is closely related to the torque demand, and the peak amplitude increases with the torque gradient. Therefore, a heuristic method is proposed, which includes the limitation of engine torque setting point dynamics. Based on this principle, a system model is introduced to calculate the limited engine torque requirements. The principle of this strategy is shown in Figure 4.

![Figure 4. Principle of Control Strategy for Limiting $NO_x$ Peak Amplitude during Torque Step](image)

Transient includes the step of increasing engine torque from point A to point B. In this case, EMS proposes a torque step marked $T_{eng,sp}^{up}$. The principle of this strategy is to maintain the same set point B of torque required by EMS, but to adjust the trajectory to reach point B[12]. Torque set-point control includes defining a new torque trajectory $T_{eng,sp}^{up}$ from point A to point B to avoid or reduce transient $NO_x$ peaks. Wheel torque requirements $T_{pwt,sp}^{up}$ depend on driving conditions (speed and acceleration) and can be assessed according to driver's requirements (throttle and brake pedal position). Torque settings can be positive or negative depending on vehicle operating conditions (traction or braking). $T_{mot,sp}^{up}$ is the torque set by the motor. $T_{eng,sp}^{up}$ is the set torque of the engine. In steady state, the torque distribution ratio is maintained. In the transient state, the steady-state engine and motor torque become two trajectories:

$$T_{pwt,sp}^{up}(t) = R_i T_{mot,sp}^{up} + R_{gb} T_{eng,sp}^{up}(t)$$

(3)

Among them, $R_{gb}$ is the gear ratio and $R_i$ is the front axle ratio. In either case, the wheel torque request will not be modified. Instruction $u(t)$ is defined as motor torque correction $u(t) = \Delta T_{mot}$. Then the dynamic motor torque request corresponding to the corrected motor torque setting value is as follows:

$$T_{mot,sp}^{up}(t) = T_{mot,sp}^{up}(t) + u(t)$$

(4)

Instruction $u(t)$ is a part of motor torque, which is used to compensate engine torque during transient period. Instruction $u$ is derived from formulas (3) and (4), which can be expressed as:

$$u(t) = \frac{T_{pwt,sp}^{up}(t) - R_{gb} T_{eng,sp}^{up}(t)}{R_i} - T_{mot,sp}^{up}$$

(5)

Instruction $u(t)$ is directly related to static motor and power system torque setting point and dynamic torque setting value $T_{eng,sp}^{up}$. The latter is the key variable, and calculating it limits the peak value produced during the transient period[13]. The strategy can determine the optimal operating point of some time scales and determine the engine and motor trajectory emission minimizing $NO_x$. The $NO_x$
target definition is purely heuristic and depends on the adjustable reduction factor of the maximum $NO_x$ peak amplitude. The achievable $NO_x$ target $NO_x^{sp}$ (Fig. 4) should be included between the actual (or estimated) value and the steady-state value:

$$NO_x^{est} \geq NO_x^{sp} \geq NO_x^{ss}$$  \hspace{1cm} (6)$$

The target $NO_x$ is empirically modified by an attenuation factor:

$$NO_x^{sp} = NO_x^{ss} + \Delta NO_x \left(1 - \frac{\xi}{100}\right)$$  \hspace{1cm} (7)$$

Among them, $\Delta NO_x$ is the magnitude of $NO_x$ peak value, which is called steady-state $NO_x$ value, as shown in Fig. 4.

$$\Delta NO_x = NO_x^{ss} - NO_x^{st}$$  \hspace{1cm} (8)$$

The method is simple and allows flexible adjustment of reduction level. Because the saturation of the system is not considered, the ability of the system to achieve this goal cannot be guaranteed. The value of the reduction factor $\xi$ is constant for each transient state[14]. Including system saturation to define achievable $NO_x$ objectives is a necessary improvement to make the transient torque controller more versatile and easy to adjust. Torque control strategy must consider actuator limitation, which depends on the maximum motor torque $T_{mot}^{max}$ and the static motor torque defined by the following formula:

$$T_{mot,sp}^{op}(t) = \frac{T_{mot,sp}^{op}(t) - R_{gb}T_{eng,sp}^{op}(t)}{R_i}$$  \hspace{1cm} (9)$$

Instruction $u(t)$ is limited to:

$$u(t) \in \left[0, \left(T_{mot}^{max} - T_{mot,sp}^{op}(t)\right)\right]$$  \hspace{1cm} (10)$$

The maximum and minimum engine torque can be expressed as:

$$T_{eng,sp}^{op} = \frac{T_{eng,sp}^{op} - R_{gb}T_{eng,sp}^{op}(t)}{R_i}$$

$$T_{eng,min}^{op} = T_{eng,min}$$  \hspace{1cm} (11)$$

Transient engine torque settings are obtained by saturating the engine torque trajectory:

$$T_{eng,sp}^{op} = sat \left(\min \left(T_{eng}^{i}, T_{eng}^{f}, T_{eng,min}^{op}, T_{eng,min}^{op}\right)\right)$$  \hspace{1cm} (12)$$

$$sat(u, u_n, u_g) = \begin{cases} u_n & \text{if } u(t) \leq u_n \\ u & \text{if } u_n \leq u(t) \leq u_d \\ u_d & \text{if } u(t) \geq u_d \end{cases}$$  \hspace{1cm} (13)$$
T_{eng}^{f}$ is a feasible torque trajectory, which defines a realizable transient $NO_x$ emission. The latter is the current minimum of $NO_x$ emissions that can be executed during the transient condition of the oxygen content (BGR) in the cylinder. Transient engine torque settings can be expressed as:

$$T_{eng,t}^{sp} = \text{sat}\left(T_{eng,t}^{f}, T_{eng,t}^{sp,min}, T_{eng,t}^{sp,max}\right)$$ (14)

4. Analysis of simulation and experiment results

The simulation result of transient torque control strategy is to determine whether the transient part (TP) of total $NO_x$ emission can be limited. A simulation platform is used to simulate the driving cycle of the whole hybrid electric vehicle. The idea is to simulate several values of the reductive factor of the system, ranging from 0% (baseline) to 100%. In order to satisfy the limitation of the final battery charging state, the equivalent factor was found by dichotomy:

$$SOC(t_0) = SOC(t_f) = 50\%$$ (15)

$t_0$ and $t_f$ are the initial and final driving cycles considered. Three hybrid levels defined by the power of the motor are simulated:

$$P_{mot} = \{10 kW, 15 kW, 20 kW\}$$ (16)

In fact, battery capacity and vehicle quality are adapted to motor power. Pure electric drive is only available at 20 kW. EMS finds the best steady-state torque redistribution, which minimizes the trade off between quasi-static and fuel consumption. The strategy acts on the transient phase involving the addition of BGR settings[15]. $\xi = 0\%$ corresponds to the reference case and there is no transient strategy. Two other cases (50% and 90%) illustrate the effect of adjustable transient $NO_x$ reduction parameters. For the second torque transient ($t = 203s$), the peak value of $NO_x$ can be avoided completely, and the peak amplitude can be reduced flexibly by adjusting the parameters.

In the first torque transients, reduced saturation was observed at 50% and 90%. At $\xi = 50\%$, the set value of motor torque has reached its maximum ($T_{mot}^{max}$). When the strategy is enabled, SOC decreases gradually, because peak value is reduced by consuming power during each transient phase.

Figure 5 shows the effect of this strategy on cumulative $NO_x$ emissions and fuel consumption. As the instantaneous peak value decreases, the total $NO_x$ emission decreases significantly at the cost of a slight increase in fuel consumption. At $\xi = 50\%$, the global $NO_x$ decreases by 17% and fuel consumption increases by only 2%. This proves the validity of the strategy of partial reduction rather than complete elimination.

Figure 6 shows the trade-off between $NO_x$ emission and fuel consumption in three vehicle models with transient strategy parameter $\xi$. TP of $NO_x$ emission is defined as the difference between total emission and steady emission. Because of the slight change of static operating point, even if the static part of accumulated $NO_x$ emission increases slightly with the increase of $\xi$, the total $NO_x$ emission decreases. The strategy allows the transient portion to be reduced to half (from 49% to 24%) and the cumulative $NO_x$ emissions to be reduced by 26%. For lower mixing levels (15 kW and 10 kW), the motor torque used for instantaneous $NO_x$ reduction is lower, and the emission cannot be reduced as in the case of complete mixing. At 8 kW, the motor quickly saturates and the transient is limited (Fig. 6). As long as the maximum motor torque is not reached, the transient strategy allows the control of transient emissions. With a 20 kW motor, significant emission reductions can be achieved by reasonably
increasing fuel consumption. The value of damping coefficient \( \xi \) adjusts the trade-off between TP and FC of \( NO_x \).

**Figure 5.** Effect of Transient Parameter \( \xi \) on the Trade-off between \( NO_x \) Emission and Fuel Consumption-FTP Fully Mixed 20kW

(a)FTP Fully Mixed 20kW (b)FTP Fully Mixed 15kW (c)FTP Fully Mixed 10kW

**Figure 6.** Effect of Transient Strategy Parameter \( \xi \) on Transient Part of \( NO_x \)

5. Conclusion
An energy management strategy for diesel hybrid electric vehicle based on decision tree CART algorithm is proposed. The simulation results show that the proposed scheme can reduce the transient part of \( NO_x \) emission, and the strategy allows the transient part to be limited without modifying the steady part.

The future research direction is to monitor steady-state and transient \( NO_x \) emissions, and to adjust the trade-off between \( NO_x \) emission reduction and fuel consumption through reduction factors, which is conducive to dealing with more transient driving energy management.

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