Application of RBF Sliding Mode Control in Pump System for Electric Vehicle Heat Air Conditioning

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Abstract: Aiming at the characteristics of time-varying, time-delay and non-linearity of electric vehicle heat pump air-conditioning system, this paper presents a sliding mode control method based on RBF neural network. The RBF neural network can approximate the nonlinear function with arbitrary precision under certain conditions, and has strong self-learning and self-adaptive ability. Combining the RBF neural network with the sliding mode variable structure control not only has the anti-interference of the sliding mode control and the robustness to the parameter changes, but also effectively reduces the flutter caused by the sliding mode control. The simulation results show that the RBF neural network sliding mode control method can improve the system control accuracy, effectively weaken the chattering, and has good adaptability to the interference conditions.

1. Introduction
The air conditioning system has the functions of heating, cooling, defogging, defrosting, blowing, filtering, etc., and has become an indispensable auxiliary system for automobiles. It regulates the air inside the car to ensure the comfort and safety of the passenger compartment. For pure electric vehicles, the energy source of the whole vehicle is only the power battery. This requires the air conditioning system can not only meet the needs of the passenger cabin comfort, but also to meet the requirements of high efficiency and energy saving. The heat pump air conditioning system is the most suitable air conditioning system for pure electric vehicles because of its high energy efficiency ratio and integration of heating and cooling [1].

The heat pump air conditioning system control has the following characteristics: First, the heat pump air conditioning system itself has hysteresis and non-linearity, and many interference factors, such as ambient temperature, driving speed, personnel intensive, door opening, etc., it is difficult to establish an accurate mathematical model. Secondly, because the pure electric vehicle itself has the shortcomings of short mileage, the energy saving of the air conditioning system is also very important [2].

The PID controller is widely used in the control field because of its simple structure and easy implementation. However, in the face of the complicated and variable working conditions of the heat pump air conditioning system, it is difficult for the PID controller to make adjustments in time, and the control effect is not good. The fuzzy controller can simplify the complexity of the system and is suitable for the control of such nonlinear, time-varying, and hysteretic systems, and does not depend on the accurate mathematical model of the system. X. Wang used the fuzzy theory in the research of automotive automatic air conditioning control. The difference between temperature and set temperature and the temperature difference change rate were used as the dual input of the system. Under different vehicle speed conditions, the fan air volume and compressor were controlled by fuzzy controller to achieve
better control results. However, the fuzzy rules and membership functions of fuzzy controllers are all
designed by personal experience and lack of systematization [3]. Zheng combined traditional PID
control with Smith algorithm and fuzzy control algorithm, proposes Smith-Fuzzy-PID control method,
and applies the method in automotive air conditioning system, which reduces system overshoot
compared with traditional PID controller. And response time [4]. He proposed a Neuro-Fuzzy control
method. This method and the traditional fuzzy controller in the automotive air conditioning temperature
control comparison experiment, greatly improve the system’s adaptability and sensitivity [5]. Zhang
proposed a sliding mode control method, which controls the temperature inside the vehicle through the
compressor speed, so that the air conditioning system has good robustness to external temperature
changes and wind speed changes, and mitigates chattering by switching gain method [6].

2. Model of electric vehicle heat pump air conditioning system

2.1 heat pump air conditioning working principle
The heat pump air conditioning system is mainly composed of electric compressor, four-way reversing
valve, two-way expansion valve, in-vehicle heat exchanger and external heat exchanger. The electric
energy drives the compressor to work, so that the working fluid repeatedly undergoes the physical
process of evaporation endotherm and condensation heat release, and realizes heat exchange and transfer
inside and outside the passenger compartment [7-9]. The heat pump air conditioning system controls the
flow direction of the working medium through the four-way reversing valve to realize the switching
between the heating mode and the cooling mode, and realizes the adjustment of the cooling capacity and
the heating amount by controlling the rotation speed of the compressor.

2.2 heat pump air conditioning mathematical model
The thermal load of a car mainly comes from the heat of the air, the heat of the solar radiation, and the
heat radiated by the human body. In order to establish an applicable air conditioning model, the
temperature distribution of the member cabins of the car is evenly distributed, and the heat balance
equation of the member cabins can be written as:
\[
\rho V C_p \frac{dT_i}{dt} = \rho V C_p (T_r - T_i) + \sum_{j=1}^{4} K_j F_j (T_o - T_i) + Q
\]
(1)

where, \( \rho \) is the air density; \( C_p \) is the specific heat; \( T_i \) is the air temperature inside the vehicle; \( T_r \) is
the fresh air temperature; \( V \) is the air volume inside the vehicle; \( V_f \) is the fresh air volume; \( K \) is the heat
transfer coefficient; \( F \) is the heat transfer area; \( j \) takes 1, 2, 3, 4, respectively represent the roof, body
side, floor, window; \( Q \) is the heat released by the people inside the car.

Bringing a specific parameter of a car into Eq.1, the equation of state is written as:
\[
\dot{x} = Ax + Bu
\]
(2)

2.3 heat pump air conditioning model
According to the working principle of heat pump air conditioner, the model of electric vehicle heat pump
air conditioning system is built by AMESim/MATLAB software, and joint simulation is carried out to
explore the control effect of control method on heat pump air conditioning system and its influence on
system power consumption and energy efficiency ratio (COP).

3. controller design
In order to improve the control accuracy and anti-interference of the heat pump air conditioning system,
the RBF neural network sliding mode controller is designed here. The control objective is to track the
actual temperature of the passenger compartment to the desired temperature to ensure the comfort of the
driver.
3.1 RBF neural network sliding mode control law design

Assume the state equation of a nonlinear uncertain:

\[ x = f(x) + g(x)u \]  \hspace{1cm} (3)

Where \( x = [x_1, x_2, \ldots, x_n] \) is the system observable variable, \( u \) is the control input, \( f(x) \) and \( g(x) \) is an unknown nonlinear function.

The design goal of the sliding mode controller is to make the initial point of the system, regardless of the position of the state space, the movement of the system can tend to switch faces for a limited time [10-11]. Taking the passenger compartment temperature as the tracking object, taking the temperature feedback to obtain the state error and its derivative, the design sliding surface is:

\[ S = c_1e + c_2e^2 + \ldots + c_{n-1}e^{(n-2)} + e^{(n-1)} = 0 \]  \hspace{1cm} (4)

Where \( e \) is the tracking error, the polynomial \( P(p) = c_1 + c_2p + \ldots + c_{n-1}p^{(n-2)} + p^{(n-1)} \) is Hurwitz stable, \( p \) is the laplace operator, \( c_i \) is the normal number, \( i = 1 \ldots n-1 \), and its value determines the speed of the additional error decay.

The tracking problem of the system can be transformed into the stability problem of the sliding surface. The Lyapunov function is defined as follows:

\[ V = \frac{1}{2} \dot{s}^2 \]  \hspace{1cm} (5)

The sliding mode existence condition can be written as:

\[ \dot{s} \leq -\eta |s| \]  \hspace{1cm} (6)

Where \( \eta \) is constant. It ensures the stability of the system. Deriving the sliding mode switching function \( s \) can be obtained:

\[ \ddot{s} = c_1 \dot{e} + c_2 \dot{e} + \ldots + c_{n-1} e^{(n-2)} + e^{(n-1)} = \sum_{i=1}^{n} c_i e^{(i)} + x_1^{(n)} + y_d^{(a)} = \sum_{i=1}^{n} c_i e^{(i)} + \dot{f}(x) + g(x)u + p + y_d^{(a)} \]  \hspace{1cm} (7)

If \( f(x) \) and \( g(x) \) are known precisely, the ideal sliding mode control law is:

\[ u^i = u_{eq}^i + u_{sw}^i = \frac{1}{g(x)} \left[ -\dot{f}(x) + y_d^{(a)} - \sum_{i=1}^{n} c_i e^{(i)} - k \text{sgn}(s) \right] \]  \hspace{1cm} (8)

Where \( k \geq P + M + \eta \).

\( u_{eq}^i \) is the ideal equivalent control and \( u_{sw}^i \) is the ideal switching control. Since \( f(x) \) and \( g(x) \) are actually unknown, an ideal sliding mode controller cannot be implemented. Considering the universal approximation theorem of RBF neural network, we use the RBF neural network to adaptively approximate the \( f(x) \) and \( g(x) \), thus constructing and replacing \( f(x) \) and \( g(x) \), then the actual slip. The mode control law is:

\[ u^i = \frac{1}{g(x)} \left[ -\dot{f}(x) + y_d^{(a)} - \sum_{i=1}^{n} c_i e^{(i)} - k \text{sgn}(s) \right] \]  \hspace{1cm} (9)

3.2 Adaptive Law Design

Substituting Eq.8 into Eq.6 yields
\[
\dot{s} = \sum_{i=1}^{n} c_i e^{(i)} + f(x) + g(x)u + p - y_d^{(a)}
\]
\[
= \sum_{i=1}^{n} c_i e^{(i)} + f(x) + \hat{g}(x)u + \hat{g}(x)u - \hat{g}(x)u + p - y_d^{(a)}
\]
\[
= f(x) - \hat{f}(x) + \left[ g(x) - \hat{g}(x) \right]u - k \text{sgn}(s) + p
\]
\[
= (w_s^* - w_s^r)\phi(x) + (w_s^r - w_s^f)\phi(x)u - \delta - k \text{sgn}(s)
\]
\[
= \eta_f^r \phi(x) + \eta_s^r \phi(x)u - \delta - k \text{sgn}(s)
\]

Where \( \eta_f^r = w_s^r - w_f^r \), \( \eta_s^r = w_s^r - w_s^f \).

The task of the adaptive law is to adjust the weights \( w_f \) and \( w_s \) such that the sliding variable \( s \) and the parameter errors \( n_1 \) and \( n_2 \) approach 0, so consider the following Lyapunov function as follows:
\[
V = \frac{1}{2} s^2 + \frac{1}{2\rho_1} \eta_f^r \eta_f + \frac{1}{2\rho_2} \eta_s^r \eta_s
\]

Where \( \rho_1 \) and \( \rho_2 \) are constant. The derivative of the Eq.10 can be written as
\[
\dot{V} = s(\eta_f^r \phi(x) + \eta_s^r \phi(x)u - \delta - k \text{sgn}(s)) + \frac{1}{\rho_1} \eta_f^r \dot{\eta}_f + \frac{1}{\rho_2} \eta_s^r \dot{\eta}_s
\]
\[
= \frac{1}{\rho_1} \eta_f^r (\rho_1 s \phi(x) + \eta_f) + \frac{1}{\rho_2} \eta_s^r (\rho_2 s \phi(x)u + \eta_s) - s \delta - k|s|
\]

By setting \( \dot{\eta}_f = -\rho_1 s \phi(x) \), \( \dot{\eta}_s = -\rho_2 s \phi(x) u \).

Eq.11 is rewritten as:
\[
\dot{V} = -s \delta - k|s|
\]

According to the approximation theory of RBF neural network, as long as there is enough implicit interruption, the adaptive RBF neural network can realize the approximation error is very small, so the adaptive law is designed as:
\[
\dot{w}_f = \rho_1 s \phi(x)
\]
\[
\dot{w}_s = \rho_2 s \phi(x) u
\]

4. system simulation and analysis

In order to verify the above design and control methods, this paper analyzes and compares the control effects of RBF neural network sliding mode controller and PI controller under steady state and transient conditions in AMESim/MATLAB joint simulation environment.

Due to changes in the driving conditions of the car, factors such as light, vehicle speed and ambient temperature will affect the operation of the heat pump air conditioner. The control effect of the two control methods is verified by the vehicle speed as the interference amount. The increase of the vehicle speed will increase the heat exchange between the passenger compartment and the external environment, causing the passenger compartment temperature to fluctuate with the change of the vehicle speed. The transient conditions are set to: ambient temperature -10 °C, humidity 40%, light intensity 0, vehicle speed is NEDC working condition, heat pump air conditioning system enters inner circulation heating mode. The simulation sets the passenger cabin target temperature to 20 °C.
The passenger cabin based on the RBF sliding mode controller has higher temperature accuracy and less fluctuation. Compared to PI control, the RBF neural network-based sliding mode controller output can quickly change the corresponding vehicle speed, and has better accuracy and anti-interference for maintaining the passenger compartment temperature.

The RBF sliding mode controller based compressor has a relatively small rate of change in speed, which can effectively reduce the vibration of the compressor and prolong its service life, and the air conditioning system operates at a higher energy efficiency ratio, which is more energy efficient.

5. Conclusion
For the control of nonlinear systems that are difficult to establish accurate mathematical models, traditional control theory and control methods have great limitations. Sliding mode control has the advantages of fast response, insensitivity to system parameter changes and strong anti-interference, and is widely used in the control of nonlinear systems.

Aiming at the problems of low control accuracy and poor anti-interference of heat pump air-conditioning system, this paper designs a sliding mode controller based on RBF neural network. The simulation results show that the RBF neural network sliding mode controller not only improves the control precision and anti-interference of the heat pump air conditioning system, but also effectively reduces the chattering, and smoothly controls the compressor and prolongs the service life.

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