

A novel decoupling control method based on neural network for EV's Driving PMSM

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Abstract. Permanent Magnet Synchronous Motor (PMSM) is often used in Electrified Vehicle (EV), while its I_d (direct-axis current) and I_q (quadrature-axis current) are coupled. Traditional FOC (Field Oriented Control) method can't get an accurate decoupling control of them when the motor speed changed with the vehicle's driving condition, especially at high speed. This coupling issue leads an unstable torque output. And further, it deteriorates the NVH (noise vibration and harshness) performance of EV. This paper focuses on the decoupling solution and puts forward a new control strategy which combines the neural network control idea with FOC method. The novel method gives a neural network controller based on four single neuron PID controllers, which its function is to realize the d-q axis interacted adjustment and decoupling. Four single neurons PID controllers achieve the negative feedback control of I_d to U_d (direct-axis voltage), I_q to U_d , I_q to U_q (quadrature-axis voltage), and I_d to U_q respectively. Creatively, it takes PMSM speed as one of the neuron inputs to adjust the feedback weight of I_d and I_q dynamically. A comparing simulation which is set up in the Simulink platform is given in this paper. Simulation results show that this method gives a good self-adaptiveness and decouples the influence of I_d and I_q , as well as improve the motor control quality at high speed.

1. I_d/I_q coupling in PMSM

Nomenclature

I_d	direct-axis current (A)
U_d	direct-axis voltage (V)
I_q	quadrature-axis current (A)
U_q	quadrature-axis voltage (V)
T_e	electromagnetic torque (Nm)
I_s	the current of stator (A)
R_s	stator resistance (Ω)
L_d	direct-axis equivalent excitation inductance (H)
L_q	quadrature-axis equivalent excitation inductance (H)
ψ_f	the rotor flux (Wb)
β	the angle between rotor flux and the current of stator (rad)
p_0	the number of poles

The torque equation for PMSM is followed.



$$T_e = p_0 \Psi_f I_s \sin \beta = p_0 \Psi_f \times I_s \quad (1)$$

FOC control method decomposes the stator current into the rotational coordinates which is orthogonal to the rotor permanent magnet flux linkage.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta_r & \cos \left(\theta_r - \frac{2\pi}{3} \right) & \cos \left(\theta_r - \frac{4\pi}{3} \right) \\ -\sin \theta_r & -\sin \left(\theta_r - \frac{2\pi}{3} \right) & -\sin \left(\theta_r - \frac{4\pi}{3} \right) \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad (2)$$

After decoupling, the value of I_d and I_q can be adjusted by changing U_d and U_q respectively. Here I_d is excitation current, while I_q produces electromagnetic torque. To control I_d and I_q will realize the weak magnetic and torque control respectively.

In the FOC control method, the PMSM's voltage and current has the following relationship [1].

$$\begin{aligned} U_d &= L_d \frac{dI_d}{dt} + R_s I_d - \omega_r L_q I_q \\ U_q &= L_q \frac{dI_q}{dt} + R_s I_q + \omega_r L_d I_d + \omega_r \Psi_f \end{aligned} \quad (3)$$

According to formula (3), it can be seen that I_d and I_q are mutual coupled when we set the U_d as a constant. It is the same for the U_q . The coupled items are $\omega_r L_q I_q$ and $\omega_r L_d I_d$, which are related to the speed. When motor at low speed, $\omega_r L_q I_q$ and $\omega_r L_d I_d$ can be ignored. I_d and I_q are mainly decided by U_d and U_q respectively. But while motor at high speed, ω_r increased significantly, the value of $\omega_r L_q I_q$ is much bigger than $R_s I_d$, and the value of $\omega_r L_d I_d$ is much bigger than $R_s I_q$. When the motor rotated at a certain high speed, I_d is directly correlated with the voltage U_q , I_q is mainly influenced by U_d . In the middle speed, the U_d and U_q have a complex relationship with I_d and I_q .

The complicated working condition of EV motor make this problem even worse. Researchers put forward many methods to solve the influence of the cross coupling of I_d and I_q in the torque control. The commonly used techniques include feedforward compensation and diagonal compensation. One method is to compensate the cross coupling by feedforward, which takes a compensation factor which is equal to two currents cross coupling item into the transfer function[2]. Another method is to give a diagonal matrix into the current loop controller to cross compensate the voltage[3]. Other researches also gives another single PID controller to make the PID parameters of U_d and U_q controller self-adaptive[4-5].

2. Novel neural network control method

A single neuron PID controller can be obtained by combining the artificial neuron with the PID controller. PID transfer function can be written as follow.

$$\Delta V(k) = A_1 \Delta e(k) + A_2 e(k) + A_3 (e(k) - 2e(k-1) + e(k-2)) \quad (4)$$

In the formula (4), three inputs error of PID (including $\Delta e(k)$, $e(k)$ and $(e(k) - 2e(k-1) + e(k-2))$) are set to be the inputs.

$$\begin{aligned} \Delta e(k) &= U_1 \\ e(k) &= U_2 \\ e(k) - 2e(k-1) + e(k-2) &= U_3 \end{aligned} \quad (5)$$

The structure single neuron PID controller is shown in figure 1. Here, A_1 , A_2 , A_3 are the weights of the inputs.

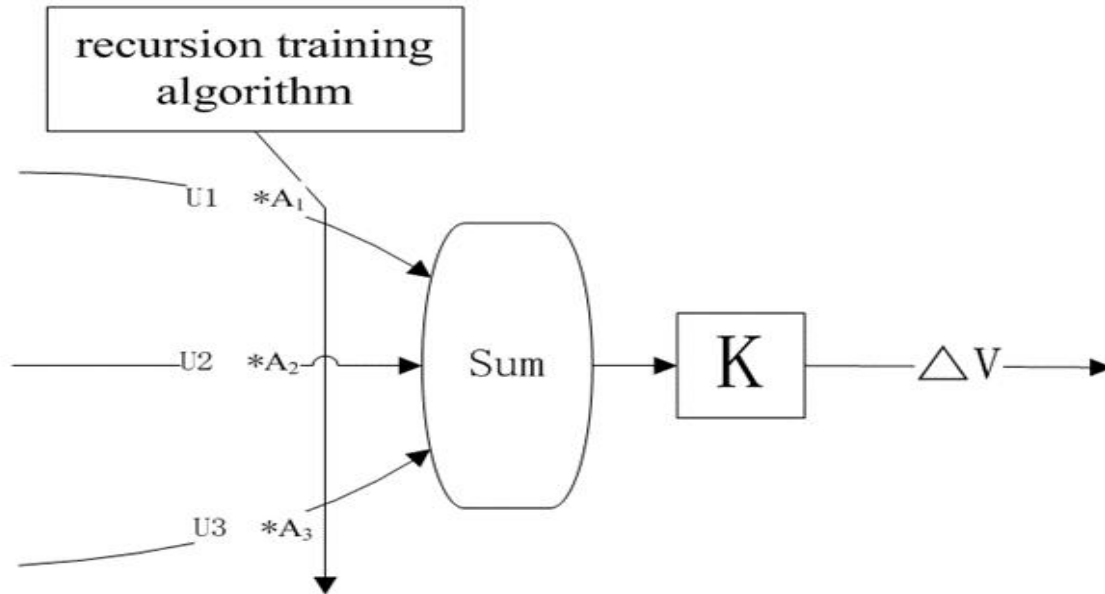


Figure 1. Single Neuron PID controller.

In figure 1, the Single Neuron controller's Recursion Training Algorithm (RTA) is used to adjust the PID parameters dynamically in order to realize a self-adaptive control. The principle of RTA method is showed in formula (6). Here, $v(k)$ is the output. A_1 , A_2 , A_3 are the weights of inputs. p_1 , p_2 , p_3 are the learning rates of the weights.

$$\begin{aligned}
 A_1(k+1) &= A_1(k) + p_1 e(k) v(k) U_1(k) \\
 A_2(k+1) &= A_2(k) + p_2 e(k) v(k) U_2(k) \\
 A_3(k+1) &= A_3(k) + p_3 e(k) v(k) U_3(k) \\
 A'_i(k) &= A_i(k) / \sum_{i=1}^3 |A_i(k)| \\
 \Delta v(k) &= v(k) - v(k-1) = K \sum_{i=1}^3 A'_i(k) U_i(k)
 \end{aligned} \tag{6}$$

Based on the single neuron PID controller method mentioned above, and also on the existing neural network control methods for PMSM[6-8], this paper puts forward a novel neural network interaction adjustment control strategy (the NNPID method). The control structure diagram is shown in figure 2. The strategy bases on four single neuron controllers, and use the motor rotated speed as one of the inputs to adjust the coupling ratio (W_d and W_q) of each neuron in the output U_d or U_q . The function of this neural network controller is to realize the d-q axis current decoupling. The four neurons achieve the negative feedback control of I_d to U_d (dd neuron), I_q to U_d (qd neuron), I_q to U_q (qq neuron), and I_d to U_q (dq neuron) respectively. Then the PMSM controller's control signal can be obtained according to the neural network's output (U_d and U_q) using SVPWM modulation method. By the proposed method, the desired I_d and I_q of PMSM can be controlled stably.

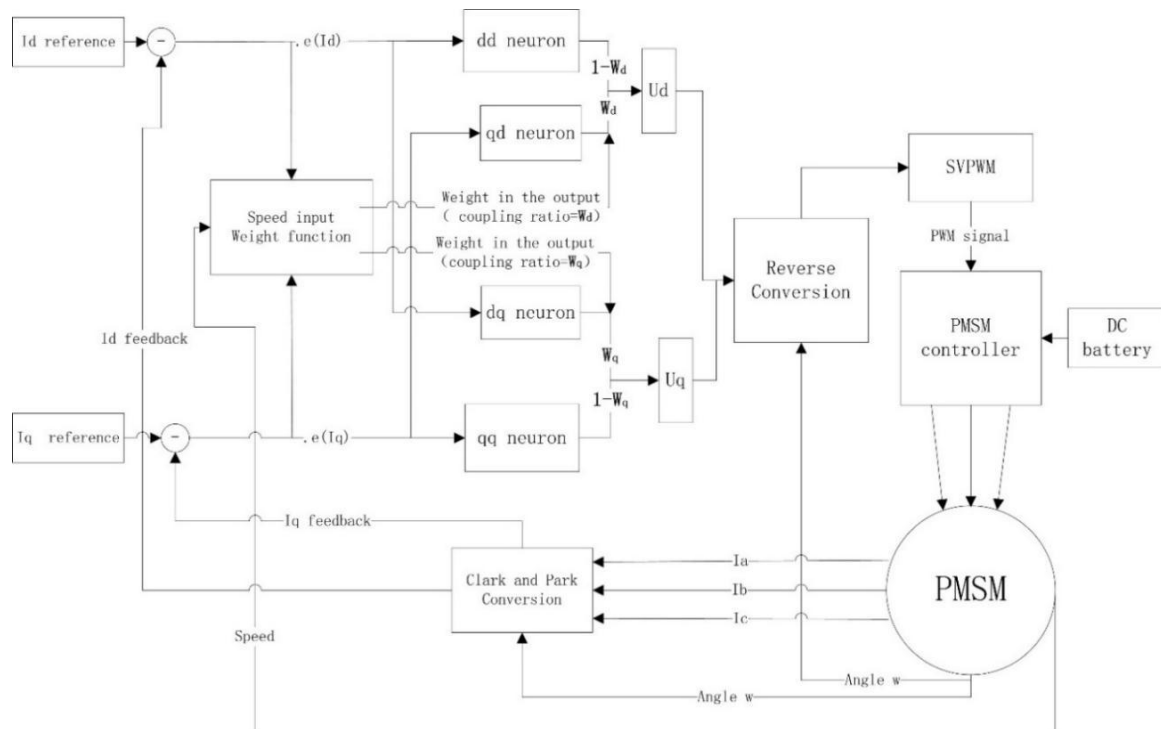


Figure 2. Interactive NNPID method for EV's driving PMSM.

3. Simulation and analysis

The simulation model is created in the Simulink software. The chosen PMSM has the following parameters, R_s is 9.8 m Ω ; L_d and L_q are 0.081mH and 0.27mH; ψ_f is 0.0396Wb; 4 pairs of pole. The Simulink sample time of this simulation is set as 1.2×10^{-6} s. In the simulation, the motor's rotated speed linear increases from 0 to 6000 rpm in 0.2 second. Shaft torque is set as 110Nm from 0rpm to 3000rpm. Then, the torque drops to 50Nm at the time of 0.1s, and keeps at 50Nm from 3000rpm to 6000rpm. According to the torque setting, we get that I_q reference is 580A before 0.1s, and 250A after 0.1s. During the simulation, I_d reference is always set as 5A without loss of generality.

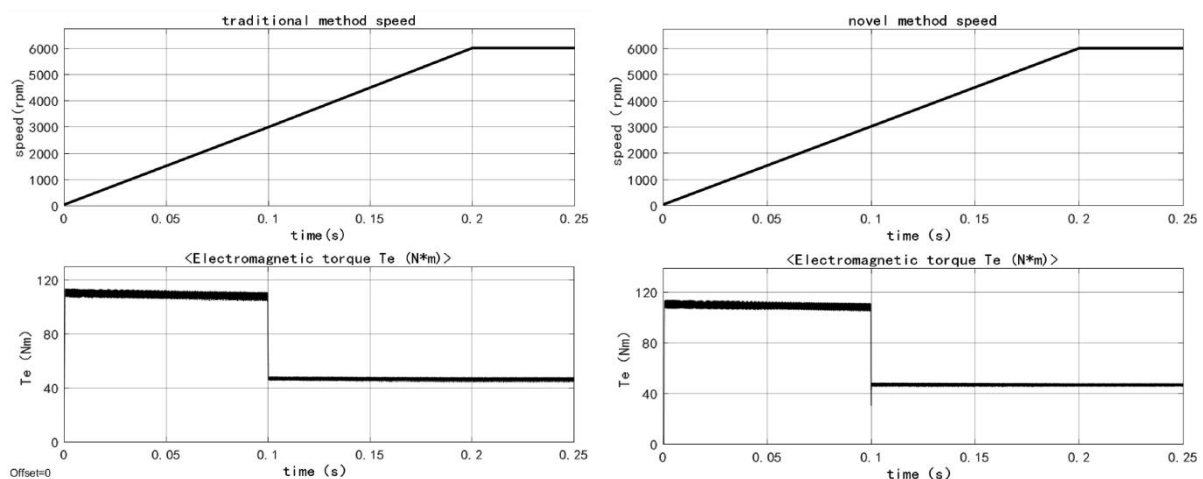


Figure 3. speed/torque for traditional PID method (left); speed/torque the novel NNPID method (right).

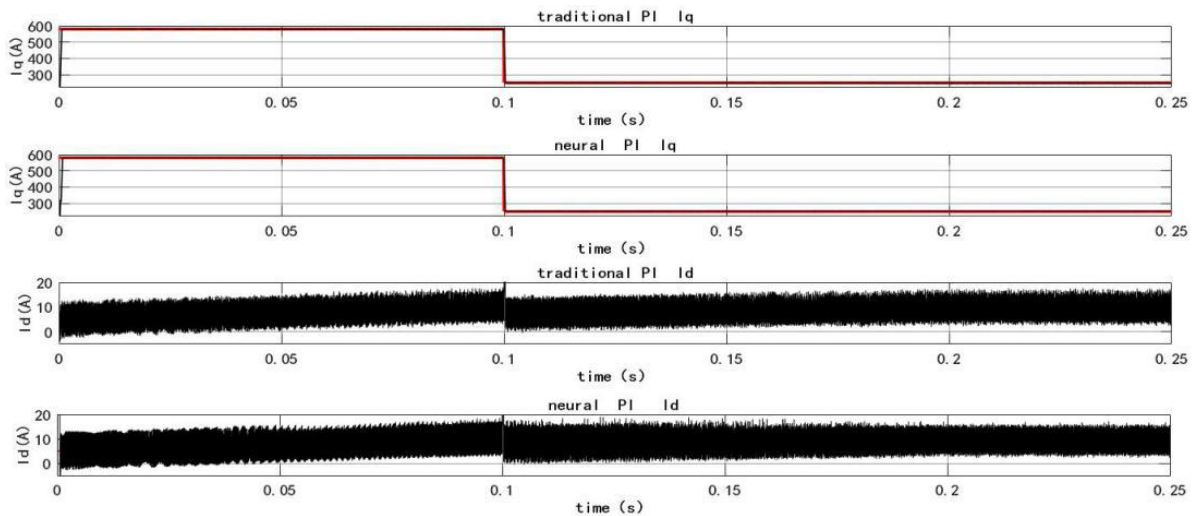


Figure 4. I_d and I_q simulation result (comparison diagram).

Figure 3 gives an illustration on the simulation results of torque output between traditional PID method and proposed NNPID method. The fluctuation of motor shaft output torque is reduced from 105-111 Nm (traditional PID method) to 107-111 Nm under novel NNPID method when motor working in low speed, and from 44.5-48 Nm (traditional PID method) reduced to 46 - 47.5 Nm under novel NNPID method when at high motor speed and low torque reference. The proposed interactive feedback control method in this paper improves the torque control stability about 1%. At the same time, the steady wave error is decreased by 57%. In figure 4, the simulation results show that this proposed control algorithm can track the target currents effectively, and achieve a brilliant current control performance during the whole process, even when the motor speed changes dramatically.

We can draw the following conclusions from the figure 3 and figure 4. At steady state, the NNPID controller's control precision is higher than traditional PID controller, the fluctuation of torque is smaller and the steady state current is more stable. Under the proposed method, the motor's response time of the current and torque are similar to the mature traditional PID control. But, here are big overshoot for torque output during torque drop-off. PID control parameters can be adjusted online, and the coupling ratio of I_q and I_d to U_q can be changed automatically to approach the coupling in the formula (3) (see figure 5).

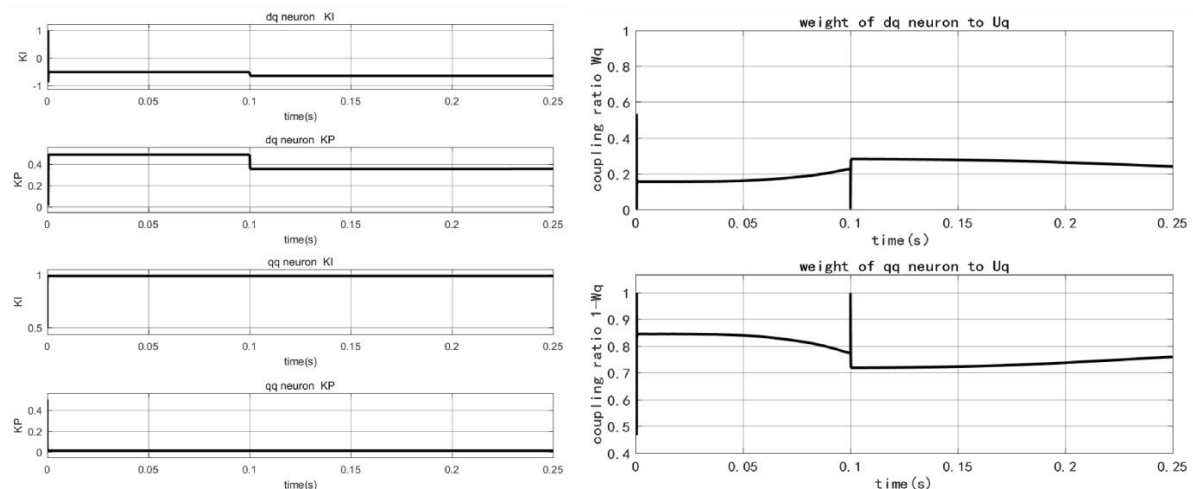


Figure 5. the adjustment of the each one's PI parameters(left) and weight for neuron qq and dq (right) .

4. Conclusion

This paper puts forward a novel NNPID method to solve the coupling of I_d and I_q in EV's PMSM driving motor. The novel NNPID method and the traditional PID method are compared by simulation. Results show that the novel method can decouple the d-q current, and give a better performance during the speed changed. But the shortage of this NNPID method is that the neuron weight adjustment algorithm needs more calculation time. The learning rate can only decide by testing, too fast learning rate will lead to non-convergent and out of control.

Acknowledgements

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