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# MTPA Control of IPMSM Drives Assisted by Deep Neural Network

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**Abstract.** In this paper, a novel MTPA control scheme assisted by deep neural network is proposed based on a virtual signal injection concept. The deep neural network models the complex relationship between the electromagnetic torque and the d- and q-axis currents. The mathematical model in the conventional virtual signal injection MTPA control is substituted by the deep neural network. In this way, the MTPA control errors of conventional mathematical model based MTPA control schemes and conventional virtual signal injection based MTPA control schemes due to the neglect of the derivatives of machine parameters with respect to current angle or d-axis current can be avoided. The proposed control scheme was assessed by simulations under various operating conditions. Simulation results illustrate that the proposed MTPA control scheme could control the IPMSM operating on the MTPA points accurately and the errors caused by the neglect of the derivatives of machine parameters with respect to current angle or d-axis current were avoided.

## 1. Introduction

The interior permanent magnet synchronous machines (IPMSM) have the advantages of high efficiency, high power density and wide constant power operating range. In order to achieve the efficiency optimal control of IPMSM drives, the maximum torque per ampere (MTPA) control is necessary. However, the IPMSMs are well known for their machine parameter uncertainty and non-linear characteristics due to the high level of magnetic saturation, cross-coupling effects and parameter dependency on temperature, which bring great difficulties in achieving accurate MTPA control in real applications.

The existing MTPA control schemes for IPMSM drive reported in the literature can be broadly classified into three categories, i.e., look-up table based methods [1], the mathematical model based techniques [2] and the online search-based techniques [3]. The look-up table based methods require experiments or numerical analyses to obtain the data in look-up tables. However, to obtain the data are time-consuming and require considerable resources and the accuracy of such control schemes cannot be guaranteed due to the manufacture tolerance, material property variations and temperature influence. The online-search-based MTPA control schemes [3], including the signal injection-based MTPA control schemes, adjust the current vector through perturbation until the MTPA condition is met. These MTPA control schemes are independent of machine parameters but need to inject perturbations into motor, which will cause additional losses and harmonics this greatly limits the scope of this kind of approaches for the MTPA operation. The mathematical model based MTPA control schemes calculate the optimal current angle or d-axis current online based on the mathematical model and machine parameters [2]. However,



according to the resent research [4], due to the neglect of the derivatives of machine parameters with respect to current angle or d-axis current, these MTPA control schemes lead to significant MTPA control errors at a relatively high current amplitude. In order to avoid the aforementioned issues suffered by the mathematical model based MTPA control schemes, a virtual signal injection control scheme considering machine parameter variations was proposed in [4]. Although this method could compensate the MTPA control error due to neglect of the derivatives of machine parameters with respect to current angle, it needs look-up tables of machine parameters and this greatly limits the applications of such method.

Recently, a deep neural network (DNN) based motor torque modelling technique was proposed [5]. With the assistance of DNN, motor electromagnetic torque can be modelled accurately. In this paper, the DNN based motor torque modelling technique is combined with the virtual signal injection to achieve accurate MTPA control. The proposed control scheme is verified by simulations. It is shown that the proposed control scheme can track the MTPA operation points accurately.

## 2. Principle of Existing Virtual Signal Injection

The mathematical model of a three-phase IPMSM in the d-q reference frame with sinusoidal stator current excitation is shown in (1) to (5):

$$v_q = L_q \frac{di_q}{dt} + Ri_q + p\omega_m L_d i_d + p\omega_m \Psi_m \quad (1)$$

$$v_d = L_d \frac{di_d}{dt} + Ri_d - p\omega_m L_q i_q \quad (2)$$

$$T_e = \frac{3p}{2} [\Psi_m i_q + (L_d - L_q) i_d i_q] \quad (3)$$

$$i_d = -I_a \sin(\beta) \quad (4)$$

$$i_q = I_a \cos(\beta) \quad (5)$$

Where  $v_d, v_q$  are the d- and q-axes stator voltages;  $i_d, i_q, I_a$  are the d- and q-axes stator currents and the current vector amplitude;  $R$  is the stator phase resistance;  $L_d, L_q$  are the d- and q-axes inductances;  $T_e$  is the electromagnetic torque;  $p$  is the number of pole pairs of the motor;  $\omega_m$  is the rotor angular speed in rad/s;  $\Psi_m$  is the flux linkage due to permanent magnet excitation;  $\beta$  is the current angle between the current vector and the q-axis, also known as the leading angle.

According to the principle of the virtual signal injection MTPA control [4], if a small high frequency sinusoidal virtual signal  $\Delta\beta$  with an angular frequency of  $\omega_h$  is mathematically added to the stator current angle,  $\beta$ . The corresponding d- and q-axis currents,  $i_d^h$  and  $i_q^h$ , can be expressed in (6) and (8), respectively.

$$\Delta\beta = A \sin(\omega_h t) \quad (6)$$

$$i_d^h = -I_a \sin(\beta + \Delta\beta) \quad (7)$$

$$i_q^h = I_a \cos(\beta + \Delta\beta) \quad (8)$$

Substituting (1), (2), (7) and (8) into (3), the calculated torque with the virtually injected high-frequency signal can be expressed in (9).

$$T_{e,1}^h = \frac{3p}{2} \left\{ \frac{v_q - Ri_q}{p\omega_m} - L_d (i_d - i_d^h) + \frac{v_d - Ri_d}{p\omega_m i_q} i_d^h \right\} i_q^h \quad (9)$$

If  $T_{e,1}^h$  is processed by the signal processing blocks as indicated in [4], the output of the signal processing blocks will be proportional to  $\partial T_{e,1}^h / \partial \beta$  and it will be used to adjust an integrator output until the  $\partial T_{e,1}^h / \partial \beta$  equals zero. In this way, the integrator will adjust the reference d-axis current until the MTPA operation point is reached [4].

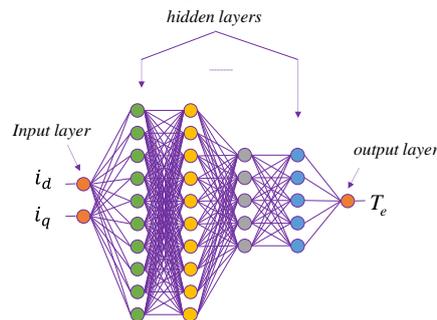
However, as indicated in [4], due to the neglect of the derivative of machine parameters with respect to the current angle, the virtual signal injection-based MTPA control consists errors. Although [4] proposed a method to compensate the errors, the method requires look-up tables of machine parameters which are

difficult to be obtained. On another hand, [5] proposed a motor torque modelling technique based on a deep neural network (DNN). The proposed DNN based modelling technique could fit the nonlinear relationship between d- and q-axis currents and motor torque accurately, without knowing machine parameters. In this paper, the DNN based motor torque modelling technique is combined with the virtual signal injection and the details of the proposed control scheme will be given below.

### 3. The Proposed MTPA Control Assisted by a Deep Neural Network

#### 3.1. Motor torque modelling technique based on a deep neural network

As indicated in [5], the complex relationship between the resultant torque and d- and q-axis currents can be modelled by a deep neural network, which is constituted by artificial neurons. The typical structure of a deep neural network is shown in figure 1.



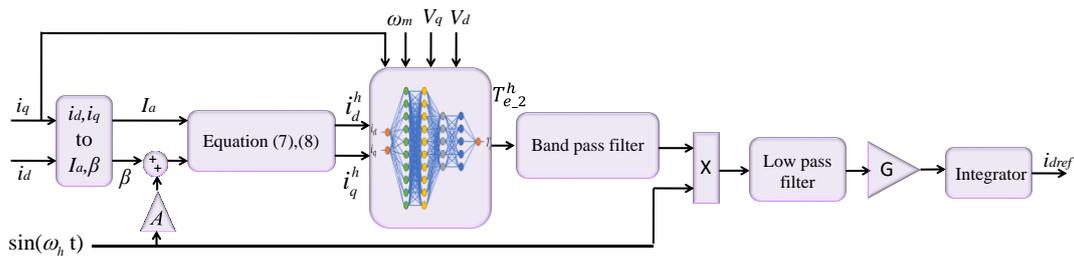
**Figure 1.** The typical structure of a DNN

As shown in figure 1, if the neural network has more than one hidden layers, the neural network is considered as a deep neural network. Otherwise, the neural network is a conventional shallow neural network. Since the deep neural networks have more hidden layers than the shallow ones, it possesses a stronger ability to approximate the complex relationship between the inputs and outputs [5]. According to (3), the electromagnetic torque is a function of d- and q-axis currents. Therefore, the inputs of the deep neural network are the d- and q-axis currents, and the outputs of the deep neural network is the electromagnetic torque. By training the deep neural network with different sets of d- and q-axis currents and their corresponding electromagnetic torque, the nonlinear relationship between torque and d- and q-axis currents can be fitted by the deep neural network. More details of the modelling and training of the DNN can be found in [5].

#### 3.2. MTPA control of IPMSM drives assisted by a deep neural network

According to Section 2, the main idea of the virtual signal injection based MTPA control is to virtually inject a disturbance into a motor torque model and to extract the information of  $\partial T_e / \partial \beta$  through signal processing of the motor torque model outputs. Meanwhile, as mentioned in Section 3.1, the nonlinear relationship between torque and d- and q-axis currents can be modelled by a deep neural network. Therefore, based on this principle, in this paper, the motor torque model of conventional virtual signal injection based MPTA, i.e., the (9), is substituted by a motor torque model based on DNN. Since the training of the DNN only requires sets of d- and q-axis currents and their corresponding torque, which can be easily obtained by experiments, thus the difficulties of obtaining the machine parameters in [4] are avoided.

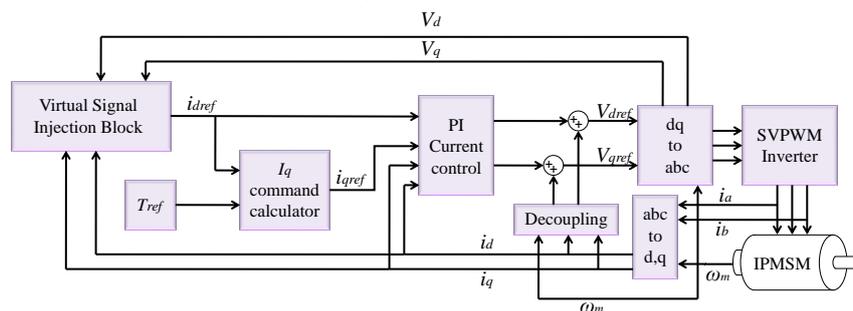
The schematic of the proposed signal processing blocks of virtual signal injection assisted by a deep neural network is shown in figure 2.



**Figure 2.** The schematic of the proposed signal processing blocks of virtual signal injection assisted by a deep neural network

As can be seen in figure 2, a virtual signal  $\Delta\beta = A\sin(\omega_h t)$  is added to the motor current angle  $\beta$  mathematically and the resultant d- and q-axis currents with the high-frequency components are calculated by (7) and (8), respectively. The resultant d- and q-axis currents with the high-frequency components are fed to a DNN to calculate the torque with high-frequency component  $T_{e,2}^h$ . The  $T_{e,2}^h$  was processed by signal processing blocks and the output of the low-pass filter will be proportional to the  $\partial T_{e,2} / \partial \beta$  and will be fed to the integrator to adjust the reference d-axis current until the MTPA point is reached.

It worth to notice that since the nonlinear relationship between d- and q-axis currents and motor torque is fitted by the DNN accurately, the  $\partial T_{e,2} / \partial \beta$  contains the components of the derivative of machine parameters with respect to current angle. Therefore the MTPA control error caused by the neglect of the derivative of machine parameters with respect to current angle [4] can be avoided. The overall schematic of the proposed MTPA control is shown in figure 3.

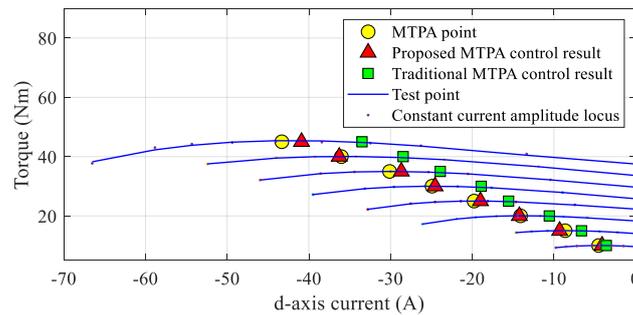


**Figure 3.** The overall schematic of the proposed MTPA control

As can be seen from figure 3, the resultant reference d-axis current generated by figure 2 is fed to the PI current controllers together with the reference q-axis current as the d- and q-axis current commands to regulate the motor current efficiently.

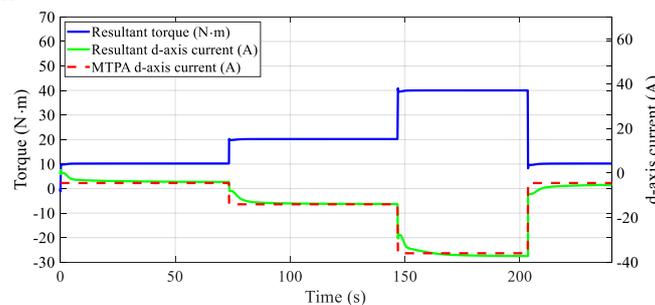
#### 4. Simulation Result

In order to verify the proposed MTPA control scheme, simulations have been performed based on a 10 kW IPMSM drive which is designed for traction applications for wide constant power operation. Tests were first performed to track the MTPA points when the motor speed was 1000 r/min and the reference torque varied from 10 N·m to 45 N·m in steps of 5 N·m. figure 4 shows the real MTPA points obtained by curve-fitting of the constant current amplitude locus, the control trajectory based on the proposed control scheme and the control trajectory based on conventional mathematical model based MTPA control scheme without the compensation of the derivative terms. As can be seen from figure 4, due to the neglect of the derivatives of machine parameters with respect to current angle, the resultant control trajectory of the existing mathematical model based MTPA control contains large errors even if the parameters used are accurate. In contrast, due to the DNN models the nonlinearities between d- and q-axis current and motor torque accurately, the control accuracy of the proposed control scheme was significantly increased. The relatively small error between the MTPA control trajectory of the proposed control scheme and the real MTPA trajectory was caused by the relatively small modelling error of DNN.



**Figure 4.** Torque versus current angle of different control trajectories when speed was 1000 r/min.

The MTPA tracking performance of the proposed control scheme was also simulated. In order to illustrate the performance of the proposed control scheme during payload torque changes, the response of d-axis current to a step-change in torque command from 10 N·m to 20 N·m and to 40 N·m then back to 10 N·m at speed of 1000 r/min is shown in figure 5. The resultant torque and the MTPA d-axis currents are also shown in figure 5. It can be seen that with the proposed control scheme the d-axis current tracks the MTPA d-axis currents automatically and the resultant d-axis current is very close to the MTPA d-axis current.



**Figure 5.** The MTPA tracking performance of the proposed control scheme at 1000 r/min.

## 5. References

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