Torque Feedforward Control Technique for Permanent-Magnet Synchronous Motors

Bing Cheng, Member, IEEE, and Tod R. Tesch, Member, IEEE

Abstract—This paper proposes a torque control method for interior permanent-magnet (IPM) motors operating in a wide speed range requiring high torque/power accuracy and a fast dynamic response. Using the fact that the motor parameters are nonlinear and significantly vary with direct and quadrature current operating points, a new optimal operating plane is generated. This operating plane combines the maximum torque per ampere (MTPA) curve, current limit circle, and maximum torque per volt (MTPV) curve, voltage limitations, and torque calculation under the nonlinear parameter variations. As a result, new feedforward tables are generated, which make full use of measured motor parameters. The new torque and flux regulators built around the feedforward tables provide a fast dynamic response and accurate steady-state torque/power production. The proposed controller was implemented and successfully tested on a 105-kW IPM motor electric drive used in a fuel-cell vehicle program.

Index Terms—Motor parameter variation, optimal operating plane, permanent-magnet synchronous motor, torque feedforward control.

I. INTRODUCTION

INTERIOR permanent-magnet (IPM) synchronous motors are widely used in electric vehicle traction drives due to their positive features such as high efficiency and high power density. Such applications require the motor drives to work in a wide speed range while maintaining high efficiency. The vehicles are also subject to large variations in the dc bus voltage, particularly in the case of fuel-cell vehicles. In the high-speed range, or in field-weakening mode operation, the optimal motor current commands are not only a function of torque requested and speed but also a function of motor parameters, dc bus voltage, and motor temperature.

Some prior research work proposed the optimal operating plane for an IPM motor based on its motor parameter, dc bus voltage, and motor speed [1]–[3]. The operating plane is bounded by the maximum torque per ampere (MTPA) curve, current limit circle, and maximum torque per volt (MTPV) curve. Due to the multiple optimal curves and boundaries imposed on the motor current commands, a simple regulator that can precisely and quickly control the motor torque output in the high-speed or field-weakening region does not exist. To have a stable and fast motor torque/power output response, feedforward controllers were utilized within the optimal operating plane for IPM motors [4]. The operating plane and feedforward controls are all based on constant motor parameters. However, over the entire motor direct and quadrature current range, the saturation and cross-magnetization of the IPM motor make the motor parameter highly nonlinear and varying in a very large range [6]–[8]. Under such conditions, the aforementioned optimal operating plane and feedforward tables are no longer accurate or optimal. The torque and voltage ellipses are away from their constant parameter curves as well. The inaccurate feedforward control loses its fast reference command purpose. In this paper, a new optimal operating plane is generated, which makes full use of measured IPM motor parameters, combined with MTPA curve, current limit circle, MTPV curve, voltage limits, and torque calculations. Feedforward tables for reference currents are created as a result of the new operating plane. A torque regulator and a flux regulator are built around the feedforward tables, which improve torque output accuracy and dynamic response.

II. TORQUE FEEDFORWARD CONTROL

A. Motor d–q Model

In the synchronous frame, the steady-state voltage equation of an IPM motor and the motor torque can be expressed as

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \begin{bmatrix} r_s & -\omega_r L_q \\ \omega_r L_d & r_s \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_r \lambda_{PM} \end{bmatrix}$$

(1)

$$T_{em} = (3P/2) (\lambda_{PM} q_{qs} + (L_d - L_q) i_{ds} i_{qs})$$

(2)

where $i_{ds}$, $i_{qs}$, $v_{ds}$, and $v_{qs}$ are the motor currents and voltages in the $d$–$q$ reference frame; $\omega_r$ is the rotor electrical frequency; $T_{em}$ is the motor torque output; $L_d$ and $L_q$ are the stator $d$- and $q$-axis inductances; $r_s$ is the stator resistance; $\lambda_{PM}$ is the permanent-magnet flux linkage; and $P$ is the number of pairs of poles of the motor.

B. Some Basic Equations/Boundaries [1]

1) Voltage ellipse equation: In steady state, if the motor stator resistance in (1) is ignored, the magnitude of the motor voltage squared for convenience is

$$v_{ds}^2 + v_{qs}^2 = \omega_r^2 (L_d^2 q_{qs}^2 + (L_d i_{ds} + \lambda_{PM})^2) \leq v_d^2.$$  

(3)
2) **Current limit circle**: If the output current is limited by \( i_{\text{max}} \)

\[
i_d^2 + i_q^2 \leq i_{\text{max}}^2. \tag{4}
\]

3) **MTPA curve** [3]: For a given torque \( T \), the minimum current is the shortest distance from the torque curve to the origin in the current \( d-q \) coordinate, and the MTPA curve is

\[
i_d = \frac{\lambda_{PM}}{2(L_d - L_q)} - \sqrt{\frac{\lambda_{PM}^2}{4(L_d - L_q)^2}} + i_q^2. \tag{5}
\]

4) **MTPV control** [3]: For a given flux linkage \( \lambda_0 = \sqrt{\lambda_d^2 + \lambda_q^2} \), if the dc-bus voltage is \( V_{dc} \), the optimal currents for the maximum torque are

\[
i_d^2 = \frac{-\lambda_{PM} + \lambda_d}{L_d} \quad i_q = \frac{\lambda_0^2 - \lambda_d^2}{L_q} \quad \lambda_0 = \frac{2V_{dc}}{\pi \omega_r}. \tag{6}
\]

To maximize the torque with respect to \( \lambda_d \)

\[
\lambda_d = \frac{-L_q \lambda_{PM} + \sqrt{(L_q \lambda_{PM})^2 + 8(L_q - L_d) L_d \lambda_0^2}}{4(L_q - L_d)}. \tag{7}
\]

Fig. 1 shows all the aforementioned equations and boundaries. The shaded area is the optimal operating plane for the IPM motor current. For any given torque, dc bus voltage, and motor speed, there exist a torque curve and a voltage ellipse curve, as shown in Fig. 1. The torque curve intercepts with the voltage ellipse and the boundaries such as the MTPA curve, MTPV curve, and current limit circle. A unique set of optimal reference currents \( i_d \) and \( i_q \) within the optimal operational plane can be calculated.

**C. Feedforward Tables**

Note that the aforementioned operating plane calculations, as well as the torque and voltage ellipse calculations, are typically based on the assumption that the motor parameters are constant. However, in reality, mainly due to the saturation and cross-magnetization of the IPM motor, the parameters \( L_d, L_q, \) and \( \lambda_{PM} \) have a wide range of change with respect to different motor currents. Using finite-element analysis (FEA) calculation, Fig. 2 shows the variations of the IPM motor parameters \( L_d, L_q, \) and \( \lambda_{PM} \) within the motor current range.

When the motor parameters change in a wide range, for example, close to 40% for \( L_q \), all the optimal curves and
boundaries, as shown in Fig. 1, are no longer accurate, nor are the torque and voltage ellipse calculations. The current commands from feedforward table outputs are away from the ideal positions. The actual outputs could be outside of the area, or inside, but away from the optimal points. Therefore, it will increase the burden of the torque and current regulators and possibly saturate the regulator outputs.

To accommodate the parameter-varying situation, a recursive calculation method [10] is used for the feedforward outputs. Assume that the motor parameters can be characterized by either analytical expressions or lookup tables from experimental data, i.e.,

\[ L_d = f(i_d, i_q) \]
\[ L_q = g(i_d, i_q) \]
\[ \lambda_{PM} = w(i_d, i_q). \tag{8} \]

The model parameters in (8) can be as simple as constants or be as complicated as multivariable nonlinear functions. They can also be the lookup tables whose data come from real motor parameter measurements. In the following discussions, the motor parameters being used are experimentally measured in the form of 3-D curves. The measured parameters cover the entire current operating range at different current \((i_d \text{ and } i_q)\) levels. The parameters are determined based on the steady-state measurements of motor voltage, current, and torque produced in a similar way to [8]. The measured parameters have a similar format to the motor parameter obtained by finite-element analysis, as shown in Fig. 2.

For a given torque command and flux feedback, starting with default parameters, one set of feedforward outputs \(i_d\) and \(i_q\) is obtained, which is a result of the intersections between the torque curve and the voltage ellipse, the MTPA curve, the MTPV curve, or the current limit circle, as shown in Fig. 1. The obtained currents are used for a new set of motor parameter calculation using (8) or using a parameter table lookup. Another set of current outputs is calculated with the new parameters. This recursive calculation is carried out until the differences between the new output currents and the previous ones have reached a defined minimum error. Starting from the default motor parameters, for a given torque command, motor speed, and dc-bus voltage, the recursive calculation of the feedforward outputs follows six steps [10].

1) Choose a torque and a flux inputs in the operating plane in Fig. 1.
2) Calculate one set of feedforward outputs \(i_d\) and \(i_q\) with one set of constant motor parameters within the operating plane, as described in Fig. 1. The calculations apply to all the boundaries, MTPV, MTPA, torque curves, voltage ellipses, and intersections.
3) Using (8), in our case, three measured parameter tables, calculate the motor parameters with the current outputs from step 2.
4) Calculate one set of feedforward currents with a new set of constant motor parameters from step 3.
5) If the current output errors are within tolerances between the outputs in the current step and the previous step, optimal outputs are obtained. Otherwise, go back to step 2.
6) Choose a new input point and go back to step 1 until the complete operating plane is covered.

With measured motor parameters, a new optimal operating plane is plotted in Fig. 3. A group of torque and voltage ellipses is also plotted in the same chart. As shown in the figure, with the default constant motor parameters, the operating plane is bounded by the black dotted curves, i.e., MTPA and MTPV, and the torque and the voltage ellipses are also in dotted lines. Using the measured motor parameters, the optimal operating plane is bounded by the solid MTPA and MTPV curves and the current limit circle, as shown in the shaded area. The new MTPA curve has huge changes in the high current range due to the parameter changes. The MTPV curve shifted leftward as current increases.

The new torque curves, in thick solid lines, have very large changes in both magnitude and trend as \(i_q\) changes. It also shows torque reduction in most of the operating plane due to the parameter change. The MTPA curve has significant changes at high current levels; therefore, the optimal operating range is significantly reduced. The new voltage ellipses, in dark solid lines, are no longer ellipses. The distorted voltage ellipses show size shrinkage due to the motor parameter variations in the high-speed or field-weakening range, where the feedforward torque controller is mostly effective and needed. The changes in both torque and voltage ellipses due to the motor parameter variations demonstrate that a more field-weakening current is needed for the same torque output at high speed. In addition, torque output reduction occurs in most of the speed range.

Fig. 4 shows the voltage ellipses in the entire current range using experimentally measured motor parameters. The new optimal operating plane of motor currents, i.e., \(i_d\) and \(i_q\), is shown in the dark area, same as the shaded area in Fig. 3. The torque command curves are not plotted in this figure. The voltage “ellipses” now become highly distorted in regions of parameter saturation.

The 3-D feedforward currents \(i_d\) and \(i_q\) are shown in Figs. 5 and 6, where the 2-D inputs are torque command and flux linkage. The feedforward tables contain all the boundary or
optimal conditions and generate accurate current command signals under variations of motor parameter conditions. The dark portions of Figs. 5 and 6 are the boundaries from the current limit circle and/or the MTPV curve.

D. Feedforward Torque Controller

Fig. 7 shows the block diagram for the proposed torque feedforward control system for IPM motors for a 105-kW integrated power train (IPT) unit used in a fuel-cell vehicle. The proposed new controller consists of five primary parts: 1) the motor parameter estimate; 2) the torque regulator; 3) the generated current feedforward tables; 4) the current regulators; and 5) the saturation controller that prevents the current regulators from deep saturation in steady state. The inputs for the feedforward tables are torque command and flux feedback, which is a function of dc bus voltage and rotor speed.

Motor Parameter Estimate: As discussed in the previous section, motor parameters $L_d$, $L_q$, and $\lambda_{PM}$ are functions of motor currents $i_d$ and $i_q$. Here, the motor parameters are measured as functions of feedback currents $i_d$ and $i_q$, and they are stored in the memory as 2-D lookup tables. As shown in Fig. 7, the motor parameter estimate block uses feedback currents and experimental motor parameter lookup tables to estimate the parameters in real time. The estimated parameters are used in the torque feedback estimate and feedforward voltage calculations in current regulator blocks.

Torque Regulator and Its Limit: Due to the uncertainty nature of the motor parameter estimates, the feedforward controls will typically contain steady-state errors. A torque control regulator is used here to dynamically regulate the torque. As shown in Fig. 7, the output of the torque regulator goes to the feedforward tables, and it generates nearly optimal $i_d$ and $i_q$ simultaneously. Therefore, it produces a fast response at both low- and high-speed ranges. The torque estimator uses feedback currents and the parameters from the lookup tables to estimate the motor electromagnetic torque using (2). At each motor speed and given dc bus voltage, the torque is also limited by the MTPV curve, as in (6) and (7), and the maximum current limit circle, as in (4).

Saturation Control: The outputs of the feedforward tables not only generate optimal current commands but also push the motor output to its maximum boundaries when it is commanded at high speed. This will send the pulsewidth-modulated (PWM) output into deep saturation, or in six-step mode. In this case, depending on the current regulator outputs, it may slow the current/torque responses and introduce harmonics for the motor. To prevent deep saturation from happening in steady state, a saturation controller is used, as indicated in Fig. 7. The modulation index output $M_i$ is compared with the steady-state modulation index reference $M_{i\text{ref}}$ and is controlled by a flux regulator, typically a proportional–integral regulator. If the PWM output tends to go to deep overmodulation, the saturation controller output will reduce the flux input to the feedforward tables, which, consequently, will shrink the voltage ellipse, as shown in Fig. 3. As a result, the output voltage and the PWM modulation index will be reduced, and therefore, the motor current controller will stay out of deep saturation. To provide high power output for a fast motor transient response, the saturation controller runs at a slower rate so that it only controls the steady-state modulation output. This way, during transients, the current regulator can still go into deep saturation and produce maximum output power for fast dynamic responses.
III. EXPERIMENTAL RESULTS

The proposed torque feedforward controller is implemented in an IPT unit. It is a liquid-cooled inverter and motor with an integrated single-ratio gearbox (8.3:1). The maximum peak output power is 105 kW, 70 kW continuous. The input dc voltage range is 170–430 V. The maximum motor operating speed is 13 500 r/min, and the maximum output torque at motor shaft is 332 N·m.

The full-speed range torque and power capabilities are verified on the laboratory dynamometer and in field testing on a fuel-cell vehicle. With the feedforward tables generated the very first time by measured motor parameters, the motor output torque accuracy is within 5% of the commanded torque in almost the entire speed range.

Fig. 8 shows the torque step response at 170 r/min. The test data are collected by CANape’s CCP tool, which is used to communicate between vehicle modules and personal computers. The variables and their color definitions captured in the figure are listed in the left column. They are the torque command G_in_tqmcu, the torque feedback G_torque, the current reference signals id_ref and iq_ref, and their corresponding feedback signals id_fdk and iq_fbk. The motor speed G_speed is also shown in the captured data. The torque step is from 0 to 287 N·m. In Figs. 8 and 9, the step responses of the motor torque, id, iq, and motor speed are captured from top to bottom.

Fig. 9 shows similar step responses tested in the field-weakening range, at 6225 r/min, with a torque step of 157 N·m. This is at full power output, about 100 kW. The motor speed is also captured in this figure. Both of the responses show that the motor output torque precisely follows the command. The current feedback matches the feedforward controller’s outputs, namely, the reference id and iq commands, when the output torque matches the command torque. This also indicates that the feedforward tables generate correct current reference commands for the commanded step torque under the current flux linkage condition. Notice that the dynamo-
the current reference signals id_ref and iq_ref, as shown in the figure. During the transient, the current regulators briefly go into deep saturation. That is, the modulation index reaches 1. To maintain fast torque dynamic responses, the flux regulator is tuned such that the modulation index is maintained at over-modulation mode I [11], i.e., 95%, in steady state when the current regulators tend to saturate. This provides high enough output power and more stability margins. The results clearly demonstrate that, although the motor parameters change in a wide range, the proposed feedforward controller generates very accurate outputs, which not only reduces the current feedback controller’s burden but also reduces the torque response time.

IV. CONCLUSION

A new feedforward control technique for IPM motors has been presented for a fast dynamic response and high torque/power outputs in a wide speed range. A new optimal operating plane for IPM motors with nonlinear parameter variations has been obtained. The resulted feedforward tables for the reference currents, combined with the proposed torque and flux regulators, provide accurate field-weakening commands, which is critical for the applications with wide dc bus voltage range and large variation of motor parameters that is typical for electric vehicle applications. Since the feedforward tables use only motor parameters, this new control technique dramatically reduces product development time. The proposed controller has been implemented in a 105-kW IPT unit in a fuel-cell vehicle. The dynamometer experiment and vehicle field test results showed a very fast dynamic response with high accurate torque and power output in all speed ranges.

REFERENCES


Bing Cheng (S’90–M’97) received the B.S. and M.S. degrees from Northeastern University, Shenyang, China, in 1982 and 1984, respectively, and the Ph.D. degree from the University of Massachusetts, Amherst, in 1992, all in electrical engineering. From 1992 to 1994, he was with Cleveland Machine Controls, where he was responsible for ac induction motor control development for industrial drives. In 1994, he joined Ford Motor Company—Ecostar Electric Drives, LLC, which was acquired by Ballard Power Systems in 2001, by Siemens VDO in 2007, and by Continental Corporation in 2008. During this time, he performed research and development work on automotive applications of electric drives and power electronics, and their control. He is currently a Principal Engineer with the Controls and Software Department, Hybrid and Electric Drives, Continental Automotive, Dearborn, MI, where he is responsible for motor control and software development, and power electronic and system simulation for fuel-cell and hybrid vehicles. His interests include control systems, electric machines, and power electronics in electric/hybrid vehicle applications.

Dr. Cheng is a member of the IEEE Industry Applications Society.

Tod R. Tesch (S’93–M’95) received the B.S. and M.S. degrees in electrical engineering and the Ph.D. degree in mechanical engineering from the University of Wisconsin, Madison, in 1989, 1996, and 2005, respectively, with focus on electric machines, power electronics, and control systems. In 2001, he joined Ford Motor Company—Ecostar Electric Drives, LLC, which was acquired by Ballard Power Systems in 2001, by Siemens VDO in 2007, and by Continental Corporation in 2008. During this time, he performed research and development work on automotive applications of electric drives and power electronics, and their control. He was responsible for motor control, power electronic, and system simulation for fuel-cell and hybrid vehicle applications. In 2008, he joined Woodward Governor, where he worked on inverter development for hybrid applications. In 2009, he joined Generac Power Systems, Waukesha, WI, working in the area of generator research and development. He is currently a Senior Principal Engineer with the Corporate Research and Development Engineering Group, Generac Power Systems, Waukesha, WI, where he is responsible for motor control, power electronic, and system development of generator systems. His interests include control systems, electric machines, power electronics, and mechatronics.

Dr. Tesch is a member of the IEEE Industry Applications Society.