A Combined Control for Fast and Smooth Performance of IPM Motor Drives Over Wide Operating Conditions

Ehsan Daryabeigi, Student Member, IEEE, and Sadegh Vaez-Zadeh, Senior Member, IEEE

Abstract—This paper presents a new combined vector and direct torque control (CC) system for interior permanent magnet motor drives to achieve improved motor performance. High-performance motor control systems are always aimed at fast and smooth motor performances. Also, simplicity and parameter independence are much anticipated in motor control systems. The proposed system uses fast production of torque producing current command and smooth production of flux producing current command, in connection with a switching table. The CC enjoys minimal parameter dependence and controller tuning challenges. Analysis of motor performance under the control system shows rapid motor dynamics with low torque and flux linkage ripples and current harmonics, in addition to rather uniform inverter switching. Simulation and experimental results obtained from a 1 hp motor under the proposed control system confirm the above-mentioned performance merits. Also, extensive simulation results show the control performance superiority in comparison with vector control, direct torque control, and an existing CC.

Index Terms—Permanent magnet synchronous motors, ac motor drives, switching frequency, steady state operation, dynamic response.

I. INTRODUCTION

Among AC machines, interior permanent magnet (IPM) motors have attractive features including mechanical robustness, smooth air gap, high flux weakening capability, and high efficiency [1], [2]. IPM motor drives are being increasingly used in industrial applications under the two competing control methods, i.e., vector control (VC) and direct torque control (DTC) [3], [4], [5]. Despite their similarities, VC and DTC are different in mathematical treatment and practical implementation. Also, the performance characteristics of motor drives are different at least under the original VC and DTC schemes. VC generally enjoys current control loops and provides smooth motor operation; while, DTC has attractive features such as minimal parameter dependency and very fast dynamic response [6], [7]. However, VC based systems need tuned controllers and rather intensive calculations for PWM, while DTC suffers from torque and flux pulsations and control problems at low speeds [8], [9].

Demanding applications such as anti-lock braking systems (ABSs) and drones require very fast motor dynamics and smooth performance needed for extra maneuverability and silent operation. IPM motors are excellent candidates for use in these applications, particularly if they operate under a control system with the main advantages of both VC and DTC. Attempts have been reported in this direction by focusing on the improvement of either of the two methods [10], [11], [12]. VC for instance is treated with hysteresis controllers instead of PI ones to achieve faster dynamic response. On the other hand, DTC is implemented with space vector modulation (SVM) to ensure smoother performance [13].

A direct flux vector control strategy is proposed by combining some futures of DTC and VC [14]–[15]. It does not need tuning of regulators, but requires parameter estimation, which makes it complex. Also, a sensorless induction motor drive is presented by combining sliding-mode control, DTC, and SVM [16]. Although the method aims at system simplicity, it has two sliding mode PI controllers. Thus, it has the difficulty of tuning PI controllers and provides moderate dynamic response due to the controllers delay.

In an alternative approach, a combined control (CC) method, using selected features of VC and DTC, has been presented for induction motors [17]–[20]. As a result, rather fast motor dynamics and smooth motor performance are achieved. The method has also been applied to doubly fed induction generators and linear induction motors [21]–[23]. A CC control system is presented for IPM motors with intelligent current controllers, where the limited simulation results confirm partial improvement of the motor performance [24]. In [25], using common base of DTC and VC, a combined control method is proposed in which a SVM controlled five-level inverter is used. All the CC systems reviewed above suffer from either high parameter dependency and/or challenges of tuning PI controllers.

In this paper, a novel CC system is proposed for IPM motors, with minimal parameter dependency and without PI controller for torque control. The simulation and experimental results confirm that the motor performance under the proposed CC system is superior over the one under VC, DTC, and existing CC in a wide range of operation in terms of torque response and/or torque and flux-linkage pulsations. In addition, since...
the employed equations in the CC are common in modelling synchronous motors, the proposed control may be extended to other types of synchronous motors including surface-mounted permanent magnet and synchronous reluctance [26].

The paper continues in Section II by developing a deviation model for IPM machines after the conventional models appropriate for VC and DTC are briefly recalled. Using the deviation model, the fundamental basis of CC is investigated. The CC system is then proposed in Section III. Finally, in Section IV, extensive performance evaluation of the motor drive system under the proposed CC is carried out, before providing some concluding remarks in Section V.

II. THEORETICAL BASIS

A. Vector Control (VC)

The developed torque and stator current components of IPM motors in stator reference frame can be given as [5]:

\[
T_e = \frac{3}{2} P \lambda_s i_y, \quad (1)
\]

\[
i_y = \left(1 - \frac{L_d}{L_q}\right) \frac{\lambda_s \sin 2\delta}{2} + \frac{\lambda_f}{L_d} \sin \delta, \quad (2)
\]

\[
i_x = \frac{\sin^2 \delta}{L_q} + \frac{\cos^2 \delta}{L_d} \lambda_s - \frac{\lambda_f}{L_d} \cos \delta, \quad (3)
\]

where \(\lambda_s\), \(i_y\), and \(i_x\) are the amplitude of stator flux linkage vector and the torque and the flux linkage producing components of stator current vector, respectively. In addition, \(\lambda_f\) is the maximum rotor flux linkage magnitude due to the magnet poles and \(\delta\) is the load angle. Also, \(L_d\) and \(L_q\) are the stator inductances and \(P\) is the number of pole pairs.

Considering (1)-(3), the torque deviation can be written as:

\[
\Delta T_e = k_1 \Delta i_y + k_2 \Delta i_x, \quad (4)
\]

where:

\[
k_1 = \frac{3P}{2} \lambda_s, \quad k_2 = \frac{T_e}{L_d}, \quad (5)
\]

and, \(\Delta\) denotes a small deviation of the respective variable from the equilibrium point. Referring to (4), it is seen that the torque of IPM machines can be controlled by current vector deviation components as occurs in VC [4], [5].

B. Direct Torque Control

In DTC systems, there is not any current controller, instead the machine torque and flux linkage are controlled directly.

By substituting \(i_y\) from (2) into (1), the torque deviation expression in the polar coordinates is obtained as:

\[
\Delta T_e = k_3 \Delta \lambda_s + k_4 \Delta \delta, \quad (6)
\]

where:

\[
k_3 = \frac{3P}{4L_d L_q} \left[2 \lambda_f L_q \sin \delta - \lambda_s (L_q - L_d) \sin 2\delta\right],
\]

\[
k_4 = \frac{3P \lambda_s}{2L_d L_q} \left[\lambda_f L_q \cos \delta - \lambda_s (L_q - L_d) \cos 2\delta\right]. \quad (7)
\]

Equation (6) shows that the torque dynamics depend on the variation of \(\delta\) only, when \(\Delta \lambda_s \cong 0\) by a closed-loop control. Hence, a fast torque control can be achieved by rapidly changing \(\delta\). Also, the machine voltage equation can be represented in a short interval of \(\Delta t\) as [17]:

\[
\vec{V}_s \Delta t \cong \Delta \vec{\lambda}_s = \Delta \lambda_s + j \Delta \lambda_y, \quad (8)
\]

where,

\[
\Delta \lambda_s = \Delta \lambda_x, \quad \Delta \lambda_y \cong \lambda_s \Delta \delta. \quad (9)
\]

Since, \(\Delta \delta\) is considered as a step change corresponding to a change of voltage vector, the goal of DTC is to control flux linkage amplitude and torque within the predefined hysteresis bands.

C. Fundamental Basis of CC

In this section, the analogy of VC and DTC methods and a common basis for these two control methods are introduced [17]. In steady state \(\delta\) is constant corresponding to load torque, and both stator and rotor flux linkage vectors rotate at the synchronous speed. In transient operation however, the stator and rotor flux linkage vectors rotate at different speeds. Since the motor mechanical time constant is usually more than 10 times the electrical time constant, the rotating speed of stator flux linkage with respect to the rotor flux linkage can be easily changed by applying proper voltage vectors.

Fig. 1 shows the rotation of stator flux linkage vector, \(\vec{\lambda}_s\), towards \(\vec{\lambda}_s\) in an inverter-switching period. Here, \(\Delta \vec{\lambda}_s\) is decomposed into a radial component \(\Delta \lambda_x\), and a tangential component \(\Delta \lambda_y\). By considering (6) and (9), a good approximation of torque deviation can be obtained as:

\[
\Delta T_e = k_3 \Delta \lambda_s + \frac{k_4}{\lambda_s} \Delta \lambda_y \quad (10)
\]

The deviations of flux linkage vector and current vector are shown in more detail in Fig. 1(b). The flux linkage deviation...
components ($\Delta \lambda_x$, $\Delta \lambda_y$) and current deviation components ($\Delta i_x$, $\Delta i_y$) are aligned with the y-axis and x-axis, respectively. In addition, both the pairs ('$\Delta \lambda_x$, $\Delta i_y$) and ($\Delta \lambda_y$, $\Delta i_x$) are responsible for providing the stator flux linkage and motor torque deviations. Furthermore, (4) and (10) denote that the torque deviation is a linear sum of either current deviations or flux linkage deviations. Therefore, it is concluded that:

$$\Delta \lambda_x \propto \Delta i_x, \quad \Delta \lambda_y \propto \Delta i_y. \quad (11)$$

It means that the radial and tangential components of the stator flux linkage vector deviations, which are controlled in DTC, are proportional to the direct and quadrature components of the stator current vector deviations, which are controlled in VC, respectively. Therefore, there is an analogy between VC and DTC in a sense that in both motor control methods, a set of two perpendicular deviation variables control the flux linkage and torque, resulting in fast dynamic responses. Moreover, the components of the sets are proportional, respectively. Therefore, it is possible to replace each component of a set by its proportional component of the other set. This analogy provides the same motor performances under the two control methods if the number of inverter voltage vectors would have not been limited.

### III. Motor Control System

According to Section II, there is an analogy between the control of electromagnetic torque by flux linkage control in DTC and the current control in VC when deviation variables instead of actual variables are considered as confirmed by (11).

The first proportionality in (11) may lead us to a simple control law to develop flux-producing component of current vector deviation as a PI controller. Thus:

$$\Delta i_x = \left(\frac{k_i}{s} + k_p\right) \Delta \lambda_x, \quad (12)$$

where $k_i$ and $k_p$ are integral and proportional coefficients of PI flux linkage controller, respectively. The integral term is included in the control law to smooth the system performance. The y-axis current deviation is obtained from (1) as:

$$\Delta i_y = \frac{2}{3P} \frac{\left|\lambda_s\right|}{\left|\lambda_s\right|} \frac{\Delta T_r - T_1 \Delta \lambda_s}{s} \quad (13)$$

It is emphasized that (13) lacks any dynamic. Therefore, it facilitates a fast torque response. In addition (13) does not depend on motor parameters other than the stator winding resistance, which is used in stator flux linkage estimation as in DTC. Consequently, (12) and (13) are implemented by a new combined control system as proposed in Fig. 2. The figure shows that torque and flux linkage deviations for (12) and (13) are provided by using the reference and actual values of the torque and flux linkage signals. The current deviations are applied to an optimal switching table, similar to the one used in VC as seen in Table I. Selection of voltage vectors is done according to the table by considering the position of stator flux linkage vector and sign of current deviations provided by the hysteresis controllers. In contrast to DTC, in the CC, torque and flux linkage deviations are indirectly controlled by deviations of the current components. As a result, there are two current hysteresis controllers (equivalent to those in DTC) and just one PI flux linkage controller (like in VC). Therefore, the resulting control system is not much complex than either VC or DTC system.

Since fast and smooth motor performance is the main objective of selecting voltage vectors, the proposed system is analyzed in this regard in comparison with DTC.

Considering (8) and (9), it is seen that the y-axis component of the stator voltage is proportional to the load angle deviation. In the proposed CC, the switching table determines a voltage vector such that:

$$V_x \propto \Delta i_x, \quad V_y \propto \Delta i_y. \quad (14)$$

In addition, the y-axis current deviation can be approximately as [27]:

$$\Delta i_y = K_d \Delta \delta \quad (15)$$

where, $K_d = \frac{2}{\left|\lambda_s\right|} \frac{\Delta i_y}{\Delta \lambda_x}$

Relationships (14) and (15) yield:

$$V_y \propto \Delta \delta, \quad (16)$$

which further matches with (8) and (9).

On the other hand, as discussed above, in DTC the stator flux linkage deviation is neglected. Thus, the torque deviation can

![Fig. 2. The proposed control system.](Image)

**TABLE I**

<table>
<thead>
<tr>
<th>$\Delta i_x$</th>
<th>$\Delta i_y$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha(1)$</td>
<td>$\alpha(2)$</td>
<td>$\alpha(3)$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>V2</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>V3</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>V5</td>
</tr>
</tbody>
</table>
be given as proportional to the load angle deviation, i.e., [5]:

$$\Delta T_e = k_t \Delta \delta.$$  (17)

By assuming that the rotor movement during a very short interval of the inverter switching time is fixed, and substituting (9) and (17) into (8), the selected inverter voltage vector satisfies the following relationship:

$$\Delta \lambda_y = \lambda_y + j \lambda_s \Delta T_e$$  (18)

Substituting “$\Delta T_e$” from (1) and “$\Delta i_y$” from (15) into (18), yields:

$$\Delta \lambda_y = \lambda_y + j \frac{3}{2} P (\lambda_s K_e \Delta \delta + i_y \Delta \lambda_s),$$  (19)

where it is seen that the $y$-axis voltage component, in contrast to (8) and (9), is not proportional to the load angle due to an extra term having the flux linkage deviation. This matter might momentarily cause DTC to select improper voltage vector, which leads to apply additional voltage vector to compensate that malfunction. This results in an increase in the inverter switching frequency and even in motor torque ripples by DTC.

The proposed CC uses current controllers like VC. However, it does not have any subsystem to cause time-delay in the main torque control path in contrast to most VC systems. The system uses hysteresis controllers in connection with a switching table like DTC. However, it employs a PI controller in flux-linkage control loop, to provide low current harmonics and overall smooth performance [28]. In addition, using a switching table instead of a pulse width modulation (PWM) block leads to ease of implementation and less computation burden, and low tonal acoustic noise [29]. The performance features of the CC will be evaluated in the next section.

### IV. Evaluation

#### A. Simulation

In order to verify the proposed control system, the performance of an IPM motor drive under the control system is investigated by simulation at different operating conditions. The motor specifications are given in Table II. In addition, for the sake of comparison, the same IPM motor is simulated under VC, DTC, and conventional CC. The evaluation is carried out in two control modes including torque control mode (TCM) and speed control mode (SCM).

For TCM study, the torque command “$T_e^*$” and the stator flux linkage command are given in Table III. Simulation results under VC, DTC and the proposed CC are shown in Figs. 3–5, respectively. Fig. 3(a) shows actual torque under VC that converges to a step of $+3$ Nm at 5 ms without any considerable overshoot; while steady state error is close to zero. Furthermore, average torque ripple is about 1%.

In addition, the value of stator flux linkage, $\lambda_s$, shown in Fig. 3(b) converges to its reference value properly and tracks the step command. To satisfy a suitable behavior, a decoupling signal is included into the $y$-axis voltage reference.

Fig. 4 shows the results obtained under DTC. It can be seen that there is not any steady state error. Moreover, fast dynamic torque response is achieved at about 1.5 ms. Furthermore, the controlled signals do not show any coupling. Nevertheless, there are significant ripples in the developed torque (2.5%) and stator flux linkage.

Fig. 5 presents the results under the proposed CC and conventional CC denoted by “CC Con.” [24]. The results of the proposed CC, as shown in Fig. 5(a), are more desirable in terms of fast dynamics, about 1.7 ms, and low ripples in both torque (2.2%) and stator flux linkage signals. This indicates that the system performance under the proposed CC combines good features of the performances under VC and DTC. In fact, the torque and stator flux linkage ripples are low by the contribution of the current control. The system also retains fast dynamics and

### TABLE II

<table>
<thead>
<tr>
<th>Parameters of the IPM Motor Drive</th>
<th>Value</th>
<th>Quantity</th>
<th>Value</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Phase Number</td>
<td>4</td>
<td>Poles</td>
<td></td>
</tr>
<tr>
<td>3.8 Nm</td>
<td>Torque (Max)</td>
<td>60 Hz</td>
<td>Frequency</td>
<td></td>
</tr>
<tr>
<td>0.311 Wb</td>
<td>Magnetic flux</td>
<td>2.7 A</td>
<td>Stator current</td>
<td>rated</td>
</tr>
<tr>
<td>2.95 ohm</td>
<td>Stator resistance</td>
<td>208 V</td>
<td>Voltage rated</td>
<td></td>
</tr>
<tr>
<td>0.002 Nm/rad/s</td>
<td>Friction Coefficient</td>
<td>0.0002</td>
<td>kg·m²</td>
<td></td>
</tr>
<tr>
<td>42.4 mH</td>
<td>d-axis inductance $L_d$</td>
<td>79.6 mH</td>
<td>q-axis inductance $L_q$</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE III

<table>
<thead>
<tr>
<th>Reference Commands</th>
<th>Time [s]</th>
<th>$T_e^*$ [Nm]</th>
<th>$T_{Load}$ [Nm]</th>
<th>$\lambda_s^*$ [Wb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.2</td>
<td>0.2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2</td>
<td>1</td>
<td>1.8</td>
<td>2.8</td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Simulation results under VC in TCM test. (a) Electromagnetic torque. (b) Stator flux linkage.
Fig. 4. Simulation results under DTC in TCM test. (a) Electromagnetic torque. (b) Stator flux linkage. 

Fig. 5. Simulation results under the proposed CC and CC Con methods in TCM test. (a) Electromagnetic torque. (b) Stator flux linkage. 

shows decoupled performance by the contribution of the hysteresis controllers and the switching table. Fig. 5(b) shows the stator flux linkage with acceptable ripples. Furthermore, a comparison of the motor performance under both the proposed and the conventional CC systems are shown in Fig. 5(a), where the torque step response corresponding to the two control systems are presented. The PI controllers in the conventional CC, though provide smooth torque during steady state, cause moderate dynamic responses compared with that of the proposed CC. This can be seen in Fig. 5(a), where the motor torque under the conventional CC lags behind the one under the proposed one with a delay of about 1.8 ms at a step torque command. Nevertheless, torque ripples and flux quality are very close to those of the proposed CC.

For SCM study, the proposed CC system of Fig. 2 is cascaded by a PI speed controller, which generates the torque reference. 

The main purpose of this test is to evaluate the motor performance under the CC at low speed. In this speed, the steady state ripples are of important concern, which is a major challenge with DTC [4]. Therefore, the system commands consisting of the speed command, \( \omega_r \), and flux linkage command, \( \lambda_s \), are given as constant values as presented in Table IV and the results are presented for CC and DTC methods in Fig. 6. One can see a good speed tracking of both methods. Although the CC shows a torque ripple comparable to that of DTC, its flux linkage ripple is significantly lower in comparison with that of DTC.

Switching frequency is a very important issue in general, particularly in methods with variable switching frequency such as DTC. It causes harmonics and affects profiles of the motor currents, flux, and torque. In practical operations, a variable frequency is limited by hardware capability [13]. In order to evaluate switching frequency, bandwidth of the hysteresis controllers in the CC are changed and torque and flux ripples are kept as same as those of DTC in steady state, to make a fair comparison. This study is done under SCM conditions with a speed reference of 188.5 rad/s and a flux linkage reference of 0.25 Wb.

In order to define the switching frequency, switching pulse train of phase-a is measured for DTC and CC in steady state.
The stator current under the CC, DTC & VC. The switching frequency is near 4.5 kHz, 6.7 kHz, and 12 kHz for CC, DTC and VC respectively. Therefore, the switching frequency is significantly lower under the CC in comparison with the other methods. The stator currents are depicted for the methods in Fig. 7. The current total harmonic distortion (THD) is equal to 2.84%, 3.18% and 1.75% for the CC, DTC and VC methods, respectively. Therefore, a better profile of the stator current is achieved under VC. However, the CC method outperforms DTC in this regard as shown in Fig. 7. Additionally, details of a FFT analysis of the stator current are presented in Fig. 8. According to these results, the CC shows a better performance over DTC with a lower and more regular switching frequency, which decreases current harmonics, while keeping fast dynamics. It seems that the current control in CC helps decrease the current THD. Note, in order to investigate the switching frequency, some 0.01s intervals is examined. The numbers of pulses (0,1) are counted in the intervals for each control method. Then, the frequency is calculated by averaging the numbers. Maximum deviation of the counted pulses is 3 pulses and 34 pulses for CC and DTC, respectively. It means that the distribution of switching pulse train is almost uniform under CC method. An index is introduced to show density of the switching pulses as the following:

\[ \eta_{sw} = \frac{n_{pulse}}{\Delta t}, \]  

where \( \eta_{sw} \), \( n_{pulse} \) and \( \Delta t \) are density of switching, number of the pulses and the time interval, respectively. This index shows pulse density. For \( \Delta t = 0.001 \) s, the maximum density is equal to 6 kHz, 20 kHz and 12 kHz under CC, DTC and VC, respectively, as shown in Fig. 9. Consequently, not only CC has a lower THD under a lower switching frequency, but also it enjoys a uniform switching in comparison with those of DTC. It means that CC can offer lower harmonic and switching losses than those of DTC.

B. Experimental Implementation

The theoretical findings and the simulation results of CC are confirmed in real time by a prototype system, as shown in Fig. 10. The experimental results are presented for the TCM and the SCM test in Figs. 11 and 12, respectively. Fig. 11 shows the results under the CC method in response to a step command for electromagnetic torque. In this case, torque command changes at \( t = 0.12 \) s from \(-3 \) Nm to \(+3 \) Nm while flux linkage reference is kept constant at 0.25 Wb, as shown in Fig. 11(a) and (d), respectively. Transient response of torque is shown in Fig. 11(b). The torque follows its command appropriately in about 1.7ms. Fig. 11(d) displays flux linkage signal that tracks its reference properly and not affected significantly by the torque step. As can be seen, the behavior of the motor is similar to that of Fig. 5, namely \( \lambda_s \) is not affected by the torque transient. Furthermore, Fig. 12 shows the results of the SCM test under the CC at low speed conditions. Both flux linkage and speed...
comments are set at zero until \( t = 0.2 \) s, and then change to 0.25 Wb and 2 rad/s, respectively. It is easily seen in Fig. 12(a) that the speed tracking is satisfactory. Fig. 12(b) and (c) show that the torque and flux linkage ripples are higher in comparison with those of the normal conditions as expected. The results agree with those of simulation in Fig. 6. Considering the above-mentioned results, it can be concluded that the experimental results adequately confirm those of the simulation and well prove the validity of CC.

V. CONCLUSION

A deviation model for IPM motors is derived to show that vector control and direct torque control of the motors are basically the same when deviation signals instead of actual ones are considered in the modeling. A novel combined VC and DTC system is then proposed for an IPM motor by using selective features of VC and DTC. The components of current deviation vector in a stator flux linkage reference frame are obtained on line and applied to hysteresis controllers, which provide decoupled current component control with no extra means for decoupling. The system gets rid of PWM block and uses a switching table to quickly supply the machine with optimal voltage vectors. The machine performance under the proposed control method is evaluated in a wide range of operating conditions. Extensive simulation results show superiority of the CC over DTC in terms of lower torque and flux ripples, lower switching frequency and THD especially at low speed range. The CC also facilitates a rather uniform switching frequency. In addition, the method provides faster dynamics than that of VC. The experimental results confirm the simulation results. In fact, the combined method keeps high dynamic response close to that of DTC, while it enjoys low torque and flux ripples comparable to those of VC.

In other words, the proposed method contributes, in view point of the both structure and performance, a good compromise between the advantages of VC and DTC without some of their deficiencies.

REFERENCES

viable schemes for induction motors torque control,” IEEE Trans. Power
strategy to reduce torque ripples and improve low speed performance of a
vol. 64, no. 4, pp. 2709–2721, Apr. 2017.
an IPM motor with real-time MTPA operation,” IEEE Trans. Energy
mode, direct torque control and space-vector modulation in a high-
strategy to reduce torque ripples and improve low speed performance of a
vol. 64, no. 4, pp. 2709–2721, Apr. 2017.
vol. 51, no. 4, pp. 3126–3136, Jul. 2015.
[16] C. Lascu and A. M. Trznadlowski, “Combining the principles of sliding
mode, direct torque control, and space-vector modulation in a high-
control method for high performance induction motor drives,” Energy
vector control and direct torque control an experimental review and eval-
torque ripple minimization in combined vector and direct controls for
high performance of IM drive,” J. Electr. Eng. Technol., vol. 7, no. 4,
“Hybrid field orientation and direct torque control for electric vehicle
motor drive with an extended Kalman filter,” in Proc. IEEE Energytech,
2012, pp. 1–6.
ned vector and direct power control for dfig-based wind turbines,” IEEE
torque ride through strategy for doubly fed induction generator based wind
turbines under both symmetrical and asymmetrical grid faults,” IET Renew.
[23] H. Karimi, S. Vaez-Zadeh, and F. Rajaei Salmasi, “Combined vector and
direct thrust control of linear induction motors with end effect compensa-
control methods for ipm motor drives using emotional controller (BEL-
BIC),” in Proc. 2nd Power Electron., Drive Syst. Technol. Conf., Tehran,
Iran, 2011, pp. 145–150.
DTC and FOC based control for medium voltage induction motor drive in
[27] G. Foo and X. N. Zhang, “A constant switching frequency based direct
torque control of interior permanent magnet synchronous motors with
reduced ripples and fast torque dynamics,” IEEE Trans. Power Electron.,
hysteresis band amplitude in direct torque control of induction machines,”
in Proc. 20th Int. Conf. Ind. Electron., Control Instrum., 1994, pp. 229–
304.
[29] L. Xu, Z. Q. Zhu, and D. Howe, “Acoustic noise radiated from di-
Appl., vol. 147, no. 6, pp. 491–496, Nov. 2000. [Online]. Available:
http://ieeexplore.ieee.org/xpl/tocresult.jsp?isnumber=19353

Ehsan Daryabeigi received the B.Sc. degree in elec-
trical engineering from the Islamic Azad University
(IAU), Yazd, Iran, in 2005, and the M.Sc. degree in
electrical engineering from the IAU, Najafabad, Iran,
in 2009. He is currently working toward the Ph.D.
degree at Yazd University, Yazd, Iran.
He has been the Head of the R&D Department,
Sarcheshmeh Industrial Power Co., Kerman, Iran,
since 2014. In addition, he has been an Associate
Researcher with the Advanced Motion Systems Re-
search Laboratory, University of Tehran, Tehran, Iran,
since 2011. His research interests include applications of advanced control
and optimization techniques in electric drive control, and power electronics. He
has been a Student Member of the Young Researchers and Elite Club, since 2008,
and a Member of the American Association for the Advancement of Science,
since 2012. Furthermore, he has been a Reviewer for the Journal of Intelligent
and Fuzzy Systems, since 2013.

Sadegh Vaez-Zadeh (S’95–A’03–SM’05) received
the B.Sc. degree from the Iran University of Science
and Technology, Tehran, Iran, in 1985, and the M.Sc.
and Ph.D. degrees from Queens University, Kingston,
ON, Canada, in 1993 and 1997, respectively.
Since 2005, he has been a Full Professor with
the University of Tehran, Tehran, Iran, where he has
served as the Head of the Power Department and is
currently the Director of the Advanced Motion Sys-
tems Research Laboratory. He has co-authored more
than 150 technical papers in these areas and holds one
U.S. patent. He is the Author of Control of Permanent Magnet Synchronous Mo-
tors (Oxford Univ. Press, 2018). His research interests include electrical drives,
contactless power transfer, renewable energy, and energy policy. He is an Ed-
itor for the IEEE TRANSACTIONS ON ENERGY CONVERSION and an Associate
Editor for the IET Renewable Power Generation. He has been active in IEEE
sponsored conferences as the General Chair, Keynote Speaker, Member of the
technical and steering committees, etc. He has also served as the first President
of the Power Electronics Society of Iran. He was a recipient of a number of awards
including the International Khwarizmi Award, and the First Prize of the
Commission on Science and Technology for Sustainable Development in the
South in 2011.
Q1. Author: Please check whether abbreviation “(CC)” is okay here.
Q2. Author: The equations have been renumbered so as to arrange them in sequential order. Please check for correctness.
A Combined Control for Fast and Smooth Performance of IPM Motor Drives Over Wide Operating Conditions

Ehsan Daryabeigi, Student Member, IEEE, and Sadegh Vaez-Zadeh, Senior Member, IEEE

Abstract—This paper presents a new combined vector and direct torque control (CC) system for interior permanent magnet motor drives to achieve improved motor performance. High-performance motor control systems are always aimed at fast and smooth motor performances. Also, simplicity and parameter independence are much anticipated in motor control systems. The proposed system uses fast production of torque producing current command and smooth production of flux producing current command, in connection with a switching table. The CC enjoys minimal parameter dependence and controller tuning challenges. Analysis of motor performance under the control system shows rapid motor dynamics with low torque and flux linkage ripples and current harmonics, in addition to rather uniform inverter switching. Simulation and experimental results obtained from a 1.1 HP motor under the proposed control system confirm the above-mentioned performance merits. Also, extensive simulation results show the control performance superiority in comparison with vector control, direct torque control, and an existing CC.

Index Terms—Permanent magnet synchronous motors, ac motor drives, switching frequency, steady state operation, dynamic response.

I. INTRODUCTION

Among AC machines, interior permanent magnet (IPM) motors have attractive features including mechanical robustness, smooth air gap, high flux weakening capability, and high efficiency [1], [2]. IPM motor drives are being increasingly used in industrial applications under the two competing control methods, i.e., vector control (VC) and direct torque control (DTC) [3], [4], [5]. Despite their similarities, VC and DTC control methods, i.e., vector control and direct torque control, are different at least under the original VC and DTC schemes. Also, the performance characteristics of motor drives are different in mathematical treatment and practical implementation. As a result, rather fast motor dynamics and smooth motor performance are achieved. The method has also been applied to doubly fed induction generators and linear induction motors [21]–[23]. A CC control system is presented for IPM motors with intelligent current controllers, where the limited simulation results confirm partial improvement of the motor performance [24]. In [25], using common base of DTC and VC, a combined control method is proposed in which a SVM controlled five-level inverter is used. All the CC systems reviewed above suffer from either high parameter dependency and very fast dynamic response [6], [7]. However, VC based systems need tuned controllers and rather intensive calculations for PWM, while DTC suffers from torque and flux pulsations and control problems at low speeds [8], [9].

Demanding applications such as anti-lock braking systems (ABSs) and drones require very fast motor dynamics and smooth performance needed for extra maneuverability and silent operation. IPM motors are excellent candidates for use in these applications, particularly if they operate under a control system with the main advantages of both VC and DTC. Attempts have been reported in this direction by focusing on the improvement of either of the two methods [10], [11], [12]. VC for instance is treated with hysteresis controllers instead of PI ones to achieve faster dynamic response. On the other hand, DTC is implemented with space vector modulation (SVM) to ensure smoother performance [13].

A direct flux vector control strategy is proposed by combining some futures of DTC and VC [14]–[15]. It does not need tuning of regulators, but requires parameter estimation, which makes it complex. Also, a sensorless induction motor drive is presented by combining sliding-mode control, DTC, and SVM [16]. Although the method aims at system simplicity, it has two sliding mode PI controllers. Thus, it has the difficulty of tuning PI controllers and provides moderate dynamic response due to the controllers delay.

In an alternative approach, a combined control (CC) method, using selected features of VC and DTC, has been presented for induction motors [17]–[20]. As a result, rather fast motor dynamics and smooth motor performance are achieved. The method has also been applied to doubly fed induction generators and linear induction motors [21]–[23]. A CC control system is presented for IPM motors with intelligent current controllers, where the limited simulation results confirm partial improvement of the motor performance [24]. In [25], using common base of DTC and VC, a combined control method is proposed in which a SVM controlled five-level inverter is used. All the CC systems reviewed above suffer from either high parameter dependency and/or challenges of tuning PI controllers.

In this paper, a novel CC system is proposed for IPM motors, with minimal parameter dependency and without PI controller for torque control. The simulation and experimental results confirm that the motor performance under the proposed CC system is superior over the one under VC, DTC, and existing CC in a wide range of operation in terms of torque response and/or torque and flux-linkage pulsations. In addition, since
the employed equations in the CC are common in modelling synchronous motors, the proposed control may be extended to other types of synchronous motors including surface-mounted permanent magnet and synchronous reluctance [26].

The paper continues in Section II by developing a deviation model for IPM machines after the conventional models appropriate for VC and DTC are briefly recalled. Using the deviation model, the fundamental basis of CC is investigated. The CC system is then proposed in Section III. Finally, in Section IV, extensive performance evaluation of the motor drive system under the proposed CC is carried out, before providing some concluding remarks in Section V.

II. THEORETICAL BASIS

A. Vector Control (VC)

The developed torque and stator current components of IPM motors in stator reference frame can be given as [5]:

\[
T_e = \frac{3}{2} P \lambda_s i_y, \\
i_y = \left( \frac{1}{L_q} - \frac{1}{L_d} \right) \frac{\lambda_s \sin 2\delta}{2} + \frac{\lambda_f \sin \delta}{L_d}, \\
i_x = \frac{\sin^2 \delta}{L_q} + \frac{\cos^2 \delta}{L_d} \lambda_s - \frac{\lambda_f \cos \delta}{L_d},
\]

where \( \lambda_s, i_y, \) and \( i_x \) are the amplitude of stator flux linkage vector and the torque and the flux linkage producing components of stator current vector, respectively. In addition, \( \lambda_f \) is the maximum rotor flux linkage magnitude due to the magnet poles and \( \delta \) is the load angle. Also, \( L_d \) and \( L_q \) are the stator inductances and \( P \) is the number of pole pairs.

Considering (1)-(3), the torque deviation can be written as:

\[
\Delta T_e = k_1 \Delta i_y + k_2 \Delta i_x,
\]

where:

\[
k_1 = \frac{3P}{2} \lambda_s, \quad k_2 = \frac{T_e}{i_x},
\]

and, \( \Delta \) denotes a small deviation of the respective variable from the equilibrium point. Referring to (4), it is seen that the torque of IPM machines can be controlled by current vector deviation components as occurs in VC [4], [5].

B. Direct Torque Control

In DTC systems, there is not any current controller, instead the machine torque and flux linkage are controlled directly.

By substituting \( i_y \) from (2) into (1), the torque deviation expression in the polar coordinates is obtained as:

\[
\Delta T_e = k_3 \Delta \lambda_s + k_4 \Delta \delta,
\]

where,

\[
k_3 = \frac{3P}{4L_d L_q} \left[ 2 \lambda_f L_q \sin \delta - \lambda_s (L_q - L_d) \sin 2\delta \right],
\]

\[
k_4 = \frac{3P}{2L_d L_q} \left[ \lambda_f L_q \cos \delta - \lambda_s (L_q - L_d) \cos 2\delta \right].
\]

Equation (6) shows that the torque dynamics depend on the variation of \( \delta \) only, when \( \Delta \lambda_s \equiv 0 \) by a closed-loop control. Hence, a fast torque control can be achieved by rapidly changing \( \delta \). Also, the machine voltage equation can be represented in a short interval of \( \Delta t \) as [17]:

\[
\frac{V_s}{\Delta t} = \Delta \lambda_s = \Delta \lambda_x + j \Delta \lambda_y,
\]

where,

\[
\Delta \lambda_x = \Delta \lambda_{sx}, \quad \Delta \lambda_y = \lambda_{sy} \Delta \delta.
\]

Since, \( \Delta \delta \) is considered as a step change corresponding to a change of voltage vector, the goal of DTC is to control flux linkage amplitude and torque within the predefined hysteresis bands.

C. Fundamental Basis of CC

In this section, the analogy of VC and DTC methods and a common basis for these two control methods are introduced [17]. In steady state \( \delta \) is constant corresponding to load torque, and both stator and rotor flux linkage vectors rotate at the synchronous speed. In transient operation however, the stator and rotor flux linkage vectors rotate at different speeds. Since the motor mechanical time constant is usually more than 10 times the electrical time constant, the rotating speed of stator flux linkage with respect to the rotor flux linkage can be easily changed by applying proper voltage vectors.

Fig. 1 shows the rotation of stator flux linkage vector, \( \lambda_s \), towards \( \lambda_x \) in an inverter-switching period. Here, \( \Delta \lambda_x \) is decomposed into a radial component \( \Delta \lambda_{sx} \), and a tangential component \( \Delta \lambda_{sy} \). By considering (6) and (9), a good approximation of torque deviation can be obtained as:

\[
\Delta T_e = k_3 \Delta \lambda_x + \frac{k_4}{\lambda_{sx}} \Delta \lambda_{sy}
\]

The deviations of flux linkage vector and current vector are shown in more detail in Fig. 1(b). The flux linkage deviation...
components \( (\Delta \lambda_x, \Delta \lambda_y) \) and current deviation components
\( (\Delta i_x, \Delta i_y) \) are aligned with the y-axis and x-axis, respectively.
In addition, both the pairs \( (\Delta \lambda_x, \Delta i_x) \) and \( (\Delta \lambda_y, \Delta i_y) \) are responsible for providing the stator flux linkage and motor torque deviations. Furthermore, \( (4) \) and \( (10) \) denote that the torque deviation is a linear sum of either current deviations or flux linkage deviations. Therefore, it is concluded that:
\[
\Delta \lambda_x \propto \Delta i_x, \quad \Delta \lambda_y \propto \Delta i_y. \tag{11}
\]
It means that the radial and tangential components of the stator flux linkage vector deviations, which are controlled in DTC, are proportional to the direct and quadrature components of the stator current vector deviations, which are controlled in VC, respectively. Therefore, there is an analogy between VC and DTC in a sense that in both motor control methods, a set of two perpendicular deviation variables control the flux linkage and torque, resulting in fast dynamic responses. Moreover, the components of the sets are proportional, respectively. Therefore, it is possible to replace each component of a set by its proportional component of the other set. This analogy provides the same motor performances under the two control methods if the number of inverter voltage vectors would have not been limited.

### III. Motor Control System

According to Section II, there is an analogy between the control of electromagnetic torque by flux linkage control in DTC and the current control in VC when deviation variables instead of actual variables are considered as confirmed by (11).

The first proportionality in (11) may lead us to a simple control law to develop flux-producing component of current vector deviation as a PI controller. Thus:
\[
\Delta i_x = \left( \frac{k_i}{s} + k_p \right) \Delta \lambda_x, \tag{12}
\]
where \( k_i \) and \( k_p \) are integral and proportional coefficients of PI flux linkage controller, respectively. The integral term is included into the control law to smooth the system performance.

The y-axis current deviation is obtained from (1) as:
\[
\Delta i_y = \frac{2}{3P} \left[ \lambda_s |AT_e - T_e| \Delta \lambda_s \right] \frac{1}{|\lambda_s|^2} \tag{13}
\]
It is emphasized that (13) lacks any dynamic. Therefore, it facilitates a fast torque response. In addition (13) does not depend on motor parameters other than the stator winding resistance, which is used in stator flux linkage estimation as in DTC. Consequently, (12) and (13) are implemented by a new combined control system as proposed in Fig. 2. The figure shows that torque and flux linkage deviations for (12) and (13) are provided by using the reference and actual values of the torque and flux linkage signals. The current deviations are applied to an optimal switching table, similar to the one used in DTC as given in Table I. Selection of voltage vectors is done according to the table by considering the position of stator flux linkage vector and sign of current deviations provided by the hysteresis controllers. In contrast to DTC, in the CC, torque and flux linkage deviations are indirectly controlled by deviations of the current components. As a result, there are two current hysteresis controllers (equivalent to those in DTC) and just one PI flux linkage controller (like in VC). Therefore, the resulting control system is not much complex than either VC or DTC system.

Since fast and smooth motor performance is the main objective of selecting voltage vectors, the proposed system is analyzed in this regard in comparison with DTC.

Considering (8) and (9), it is seen that the y-axis component of the stator voltage is proportional to the load angle deviation. In the proposed CC, the switching table determines a voltage vector such that:
\[
V_x \propto \Delta i_x, \quad V_y \propto \Delta i_y. \tag{14}
\]
In addition, the y-axis current deviation can be approximately as [27]:
\[
\Delta i_y = K_{\delta} \Delta \delta \tag{15}
\]
where \( K_{\delta} = \frac{\lambda_s}{L_{d2}} \).

Relationships (14) and (15) yield:
\[
V_y \propto \Delta \delta, \tag{16}
\]
which further matches with (8) and (9).

On the other hand, as discussed above, in DTC the stator flux linkage deviation is neglected. Thus, the torque deviation can be controlled by the current controller. Therefore, the resulting control system is not much complex than either VC or DTC system.
be given as proportional to the load angle deviation, i.e., [5]:
\[ \Delta T_e = k_1 \Delta \delta. \]  
(17)

By assuming that the rotor movement during a very short interval of the inverter switching time is fixed, and substituting (9) and (17) into (8), the selected inverter voltage vector satisfies the following relationship:
\[ \overrightarrow{V_s} \Delta t = \Delta \lambda_x + j \frac{\lambda_s}{K_s} \Delta T_e \]  
(18)

Substituting “\( \Delta T_e \)” from (1) and “\( \Delta i_y \)” from (15) into (18), yields:
\[ \overrightarrow{V_s} \Delta t = \Delta \lambda_x + j \frac{3}{2} P \left( \lambda_s K_s \Delta \delta + i_y \Delta \lambda_x \right), \]  
(19)
where it is seen that the y-axis voltage component, in contrast to (8) and (9), is not proportional to the load angle due to an extra term having the flux linkage deviation. This matter might momentarily cause DTC to select improper voltage vector, which leads to apply additional voltage vector to compensate that malfunction. This results in an increase in the inverter switching frequency and even in motor torque ripples by DTC.

The proposed CC uses current controllers like VC. However, it does not have any subsystem to cause time-delay in the main torque control path in contrast to most VC systems. The system uses hysteresis controllers in connection with a switching table like DTC. However, it employs a PI controller in flux-linkage control loop to provide low current harmonics and overall smooth performance [28]. In addition, using a switching table instead of a pulse width modulation (PWM) block leads to ease of implementation and less computation burden, and low tonal acoustic noise [29]. The performance features of the CC will be evaluated in the next section.

### IV. Evaluation

#### A. Simulation

In order to verify the proposed control system, the performance of an IPM motor drive under the control system is investigated by simulation at different operating conditions. The motor specifications are given in Table II. In addition, for the sake of comparison, the same IPM motor is simulated under VC, DTC, and conventional CC. The evaluation is carried out

<table>
<thead>
<tr>
<th>Value</th>
<th>Quantity</th>
<th>Value</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Phase Number</td>
<td>4</td>
<td>Poles</td>
</tr>
<tr>
<td>3.8 Nm</td>
<td>Torque (Max)</td>
<td>60 Hz</td>
<td>Frequency</td>
</tr>
<tr>
<td>0.311 Wb</td>
<td>Magnetic flux</td>
<td>2.7 A</td>
<td>Stator current</td>
</tr>
<tr>
<td>2.95 ohm</td>
<td>Stator resistance</td>
<td>208 V</td>
<td>Voltage rated</td>
</tr>
<tr>
<td>0.002 Nm/rev</td>
<td>Friction Coefficient</td>
<td>kg·m²</td>
<td>Rotor inertia</td>
</tr>
<tr>
<td>42.4 mH</td>
<td>d-axis inductance ( L_d )</td>
<td>79.6 mH</td>
<td>q-axis inductance ( L_q )</td>
</tr>
</tbody>
</table>

### Table III

<table>
<thead>
<tr>
<th>Time, [s]</th>
<th>0</th>
<th>0.2</th>
<th>0.2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T^* ) [Nm]</td>
<td>-3</td>
<td>-3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>( T_{Load} ) [Nm]</td>
<td>1</td>
<td>1</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>( \lambda^* ) [Wb]</td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Simulation results under VC in TCM test. (a) Electromagnetic torque. (b) Stator flux linkage.

For TCM study, the torque command “\( T^* \)” and the stator flux linkage command are given in Table III. Simulation results under VC, DTC and the proposed CC are shown in Figs. 3–5, respectively. Fig. 3(a) shows actual torque under VC that converges to a step of +3 Nm at 5 ms without any considerable overshoot; while steady state error is close to zero. Furthermore, average torque ripple is about 1%.

In addition, the value of stator flux linkage, \( \lambda_s \), shown in Fig. 3(b) converges to its reference value properly and tracks the step command. To satisfy a suitable behavior, a decoupling signal is included into the y-axis voltage reference.

Fig. 4 shows the results obtained under DTC. It can be seen that there is not any steady state error. Moreover, fast dynamic torque response is achieved at about 1.5 ms. Furthermore, the controlled signals do not show any coupling. Nevertheless, there are significant ripples in the developed torque (2.5%) and stator flux linkage.

Fig. 5 presents the results under the proposed CC and conventional CC denoted by “CC Con.” [24]. The results of the proposed CC, as shown in Fig. 5(a), are more desirable in terms of fast dynamics, about 1.7 ms, and low ripples in both torque (2.2%) and stator flux linkage signals. This indicates that the system performance under the proposed CC combines good features of the performances under VC and DTC. In fact, the torque and stator flux linkage ripples are low by the contribution of the current control. The system also retains fast dynamics and
shows decoupled performance by the contribution of the hysteresis controllers and the switching table. Fig. 5(b) shows the stator flux linkage with acceptable ripples. Furthermore, a comparison of the motor performance under both the proposed and the conventional CC systems are shown in Fig. 5(a), where the torque step response corresponding to the two control systems are presented. The PI controllers in the conventional CC, though provide smooth torque during steady state, cause moderate dynamic responses compared with that of the proposed CC. This can be seen in Fig. 5(a), where the motor torque under the conventional CC lags behind the one under the proposed one with a delay of about 1.8 ms at a step torque command. Nevertheless, torque ripples and flux quality are very close to those of the proposed CC.

For SCM study, the proposed CC system of Fig. 2 is cascaded by a PI speed controller, which generates the torque reference. The main purpose of this test is to evaluate the motor performance under the CC at low speed. In this speed, the steady state ripples are of important concern, which is a major challenge with DTC [4]. Therefore, the system commands consisting of the speed command, $\omega_r$, and flux linkage command, $\lambda_s$, are given as constant values as presented in Table IV and the results are presented for CC and DTC methods in Fig. 6. One can see a good speed tracking of both methods. Although the CC shows a torque ripple comparable to that of DTC, its flux linkage ripple is significantly lower in comparison with that of DTC. Switching frequency is a very important issue in general, particularly in methods with variable switching frequency such as DTC. It causes harmonics and affects profiles of the motor currents, flux, and torque. In practical operations, a variable frequency is limited by hardware capability [13]. In order to evaluate switching frequency, bandwidth of the hysteresis controllers in the CC are changed and torque and flux ripples are kept as same as those of DTC in steady state, to make a fair comparison. This study is done under SCM conditions with a speed reference of 188.5 rad/s and a flux linkage reference of 0.25 Wb.

In order to define the switching frequency, switching pulse train of phase-a is measured for DTC and CC in steady-state.
Fig. 7. The stator current under the CC, DTC & VC.

Fig. 8. Harmonic order of stator current, under (a) CC, (b) DTC, (c) VC.

The switching frequency is near 4.5 kHz, 6.7 kHz, and 12 kHz for CC, DTC and VC respectively. Therefore, the switching frequency is significantly lower under the CC in comparison with the other methods. The stator currents are depicted for the methods in Fig. 7. The current total harmonic distortion (THD) is equal to 2.84%, 3.18% and 1.75% for the CC, DTC and VC methods, respectively. Therefore, a better profile of the stator current is achieved under VC. However, the CC method outperforms DTC in this regard as shown in Fig. 7. Additionally, details of a FFT analysis of the stator current are presented in Fig. 8. According to these results, the CC shows a better performance over DTC with a lower and more regular switching frequency, which decreases current harmonics, while keeping fast dynamics. It seems that the current control in CC helps decrease the current THD. Note, in order to investigate the switching frequency, some 0.01s intervals is examined. The numbers of pulses (0,1) are counted in the intervals for each control method. Then, the frequency is calculated by averaging the numbers. Maximum deviation of the counted pulses is 3 pulses and 34 pulses for CC and DTC, respectively. It means that the distribution of switching pulse train is almost uniform under CC method. An index is introduced to show density of the switching pulses as the following:

$$\eta_{sw} = \frac{n_{pulse}}{\Delta t},$$ (20)

where $\eta_{sw}$, $n_{pulse}$, and $\Delta t$ are density of switching, number of the pulses and the time interval, respectively. This index shows pulse density. For $\Delta t = 0.001 \text{s}$, the maximum density is equal to 6 kHz, 20 kHz and 12 kHz under CC, DTC and VC, respectively, as shown in Fig. 9. Consequently, not only CC has a lower THD under a lower switching frequency, but also it enjoys a uniform switching in comparison with those of DTC. It means that CC can offer lower harmonic and switching losses than those of DTC.

B. Experimental Implementation

The theoretical findings and the simulation results of CC are confirmed in real time by a prototype system, as shown in Fig. 10. The experimental results are presented for the TCM and the SCM test in Figs. 11 and 12, respectively. Fig. 11 shows the results under the CC method in response to a step command for electromagnetic torque. In this case, torque command changes at $t = 0.12 \text{s}$ from $-3 \text{Nm}$ to $+3 \text{Nm}$ while flux linkage reference is kept constant at 0.25 Wb, as shown in Fig. 11(a) and (d), respectively. Transient response of torque is shown in Fig. 11(b). The torque follows its command appropriately in about 1.7ms. Fig. 11(d) displays flux linkage signal that tracks its reference properly and not affected significantly by the torque step. As can be seen, the behavior of the motor is similar to that of Fig. 5, namely $\lambda_s$ is not affected by the torque transient.

Furthermore, Fig. 12 shows the results of the SCM test under the CC at low speed conditions. Both flux linkage and speed...
Fig. 11. Experimental results using the proposed method in TCM test. (a)–(c) Electromagnetic torque (including transient and steady state). (d) Stator flux linkage.

Fig. 12. Experimental results using the proposed method in SCM test. (a) Rotor speed. (b) Electromagnetic torque. (c) Stator flux linkage.

V. Conclusion

A deviation model for IPM motors is derived to show that vector control and direct torque control of the motors are basically the same when deviation signals instead of actual ones are considered in the modeling. A novel combined VC and DTC system is then proposed for an IPM motor by using selective features of VC and DTC. The components of current deviation vector in a stator flux linkage reference frame are obtained on line and applied to hysteresis controllers, which provide decoupled current component control with no extra means for decoupling. The system gets rid of PWM block and uses a switching table to quickly supply the machine with optimal voltage vectors. The machine performance under the proposed control method is evaluated in a wide range of operating conditions. Extensive simulation results show superiority of the CC over DTC in terms of lower torque and flux ripples, lower switching frequency and THD especially at low speed range. The CC also facilitates a rather uniform switching frequency. In addition, the method provides faster dynamics than that of VC. The experimental results confirm the simulation results. In fact, the combined method keeps high dynamic response close to that of DTC, while it enjoys low torque and flux ripples comparable to those of VC. In other words, the proposed method contributes, in view point of the both structure and performance, a good compromise between the advantages of VC and DTC without some of their deficiencies.

REFERENCES


[33] H. Karimi, S. Vaez-Zadeh, and F. Rajaei Salmasi, “Combined vector and direct thrust control of linear induction motors with end effect compensa-

tion,” in Proc. 20th Int. Conf. Ind. Electron., Control Instrum., 1994, pp. 229–
304.


Sadeqh Vaez-Zadeh (S’95–A’03–SM’05) received the B.Sc. degree from the Iran University of Science and Technology, Tehran, Iran, in 1985, and the M.Sc. and Ph.D. degrees from Queens University, Kingston, ON, Canada, in 1993 and 1997, respectively.

Since 2005, he has been a Full Professor with the University of Tehran, Tehran, Iran, where he has served as the Head of the Power Department and is currently the Director of the Advanced Motion Systems Research Laboratory. He has co-authored more than 150 technical papers in these areas and holds one U.S. patent. He is the Author of Control of Permanent Magnet Synchronous Motors (Oxford Univ. Press, 2018). His research interests include electrical drives, contactless power transfer, renewable energy, and energy policy. He is an Editor for the IEEE TRANSACTIONS ON ENERGY CONVERSION and an Associate Editor for the IET RENEWABLE POWER GENERATION. He has been active in IEEE sponsored conferences as the General Chair, Keynote Speaker, Member of the technical and steering committees, etc. He has also served as the First President of the Power Electronics Society of Iran. He was a recipient of a number of awards including the International Khwarizmi Award, and the First Prize of the Commission on Science and Technology for Sustainable Development in the South in 2011.

Ehsan Daryabeigi received the B.Sc. degree in electrical engineering from the Islamic Azad University (IAU), Yazd, Iran, in 2005, and the M.Sc. degree in electrical engineering from the IAU, Najafabad, Iran, in 2009. He is currently working toward the Ph.D. degree at Yazd University, Yazd, Iran.

He has been the Head of the R&D Department, Sarcheshmeh Industrial Power Co., Kerman, Iran, since 2014. In addition, he has been an Associate Researcher with the Advanced Motion Systems Research Laboratory, University of Tehran, Tehran, Iran, since 2011. His research interests include applications of advanced control and optimization techniques in electric drive control, and power electronics. He has been a Student Member of the Young Researchers and Elite Club, since 2008, and a Member of the American Association for the Advancement of Science, since 2012. Furthermore, he has been a Reviewer for the Journal of Intelligent and Fuzzy Systems, since 2013.
Q1. Author: Please check whether abbreviation “(CC)” is okay here.
Q2. Author: The equations have been renumbered so as to arrange them in sequential order. Please check for correctness.