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Development of Electric Scooter Driven by Sensorless Motor Using D-State-Observer

Ichiro Aoshima[1], Masaaki Yoshikawa[1], Nobuhito Ohnuma[1], Shinji Shinnaka[2]
[1]*PUES corporation*
1516 Aiko, Atsugi, Kanagawa 243-0035 Japan
E-mail: aoshima.ichiro@pues.co.jp
[2]*Dept. of Electrical Engineering, Kanagawa University*
3-27-1, Rokkakubashi, Kanagawaku, Yokohama 221-8686 Japan
E-mail: shinnaka@kanagawa-u.ac.jp

Abstract

This paper presents a newly developed sensorless electric scooter, whose traction motor (IPMSM of non-sinusoidal magnetization) is controlled by a sensorless vector control method using the "D-state-observer." Through an actual development, this paper verifies that sensorless electric scooters can be realizable, and re-verifies that the D-state-observer has a potential applicable to other EVs. Detailed experimental results confirming the verification are also shown.

Keywords: Electric Vehicles, Scooter, Position Sensorless, Sensorless Vector Control, Permanent magnet motor, Synchronous motor

1 Introduction

Permanent-magnet synchronous motors (PMSMs) have an advantage in size and energy efficiency as traction motors of electric vehicles (EVs). As a high-performance control method for PMSM drives, so-called "vector control method" has been known. However, the vector control requires information of the rotor phase (in other words, position of the N-pole of the rotor permanent magnet), and an encoder or a resolver is widely used for detecting the rotor phase. In addition, the installation of such position sensors has disadvantages in cost, reliability and space. In order to solve the sensor caused problems, so-called "sensorless vector control methods" have been developed, which can control PMSMs efficiently just like vector controls, but with no use of the position sensor.

From the aforementioned viewpoints, the authors developed an electric scooter with a PMSM whose drive is controlled by a sensorless vector control method using the "D-state-observer."

2 Electric scooter

As a base of the newly developed scooter, the authors employed an electric scooter called "ELE-ZOO" made by PUES Corporation. ELE-ZOO has a PMSM as a traction motor, but its drive is controlled by "120-degree rectangular current method" using a potion sensor. The drive system shows performances equivalent to that of gasoline-engine. Fig. 1 illustrates a view of ELE-ZOO.

The new sensorless-driven electric scooter utilizes the body, motor, and battery of ELE-ZOO, but drive control apparatus is newly developed.

Fig. 1: Based Electric Scooter “ELE-ZOO”.

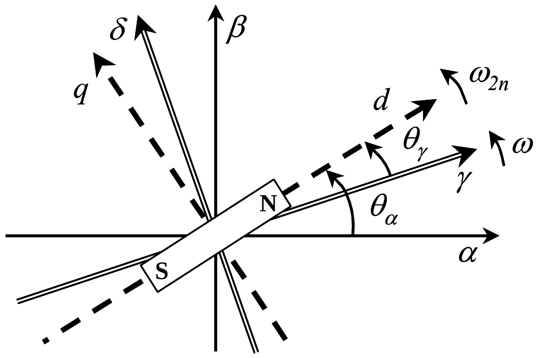

Fig. 2: Phase of rotor N-pole in γ-δ general reference frame rotating at arbitrary velocity ω.

3 Mathematical model of PMSM

Consider the general reference frame where orthogonal γ-δ coordinates rotating at an arbitrary instant angular velocity ω as shown in Fig. 2. A mathematical model of PMSMs that describes the circuital electro-magnetic dynamics can be given as follows.

$$\boldsymbol{v}_1 = R_1 \boldsymbol{i}_1 + [s\boldsymbol{I} + \omega \boldsymbol{J}]\boldsymbol{\phi}_1 \tag{1}$$

$$\boldsymbol{\phi}_1 = \boldsymbol{\phi}_i + \boldsymbol{\phi}_m \tag{2}$$

$$\boldsymbol{\phi}_i = [L_i \boldsymbol{I} + L_m \boldsymbol{Q}(\theta_\gamma)]\ \boldsymbol{i}_1 \tag{3}$$

$$\boldsymbol{\phi}_m = \Phi \boldsymbol{u}(\theta_\gamma)\ ;\ \Phi = \text{const} \tag{4}$$

$$\boldsymbol{Q}(\theta_\gamma) = \begin{bmatrix} \cos 2\theta_\gamma & \sin 2\theta_\gamma \\ \sin 2\theta_\gamma & -\cos 2\theta_\gamma \end{bmatrix} \tag{5}$$

$$\boldsymbol{u}(\theta_\gamma) = \begin{bmatrix} \cos\theta_\gamma \\ \sin\theta_\gamma \end{bmatrix} \tag{6}$$

$$s\theta_\gamma = \omega_{2n} - \omega \tag{7}$$

where $\boldsymbol{v}_1 = [v_\gamma \quad v_\delta]^T$ is stator voltage; $\boldsymbol{i}_1 = [i_\gamma \quad i_\delta]^T$ is stator current; $\boldsymbol{\phi}_1$ is stator flux (stator flux linkage); $\boldsymbol{\phi}_i$ is reaction flux evolve directly by the stator current $\boldsymbol{i}_1$; $\boldsymbol{\phi}_\text{m}$ is flux due to the rotor magnet; ω_2n is the electrical speed of the rotor; $\boldsymbol{I}$ is a identity matrix and $\boldsymbol{J}$ is a skew symmetric matrix such as

$$\boldsymbol{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}; \tag{8}$$

L_i, L_m is the “in-phase and mirror-phase inductances” having the following relation to the d, q-axes inductances

$$\begin{bmatrix} Ld \\ Lq \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} Li \\ Lm \end{bmatrix}; \tag{9}$$

“s” indicates a differential operator d/dt.

4 Sensorless control method

As a rotor-phase estimation method for sensorless vector controls, the “D-state-Observer” was employed, which was originally proposed by one of the authors [1], [3]. The D-state-observer has the following attractive characteristics.

1) It is a flux state-observer requiring no additional steady-state condition to the dynamic mathematical model of PMSMs.
2) Its order is the minimum second.
3) The Observer gain guaranteeing proper estimation in four quadrants over wide operating range except singular zero speed is a simple constant, and can be easily designed.
4) It utilizes motor parameters in a very simple manner.
5) Its structure is very simple, and it can be realized at very low computational load.
6) It can be applied to both of salient pole and non-salient pole PMSMs.

In addition to the above characteristics, the D-state-observer has nice phase-estimate convergence properties about error between actual and estimated speeds, error between actual and nominal motor parameters, error between sinusoidal and non-sinusoidal magnetization of the rotor magnet. The D-state-observer has contributed to development of sensorless and transmissionless EV using batteries [2], [3].

The D-state-observer can be described as follows [1], [3].

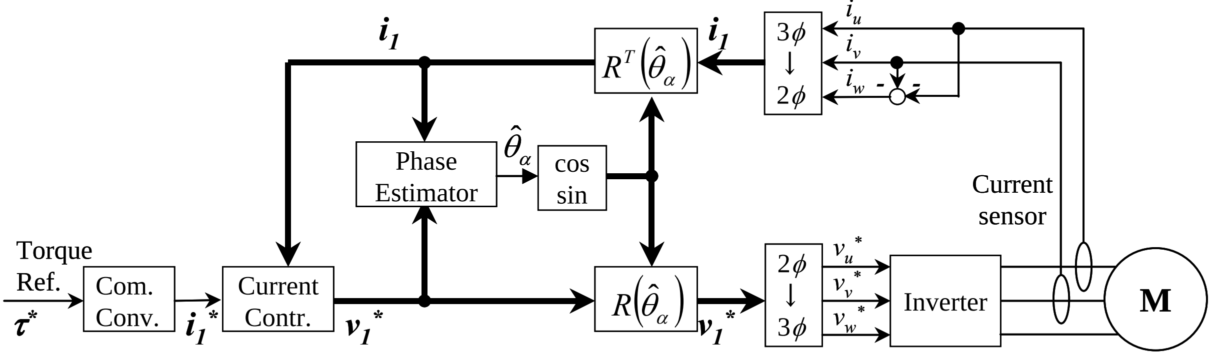

Fig. 4: A configuration of the sensorless vector control system.

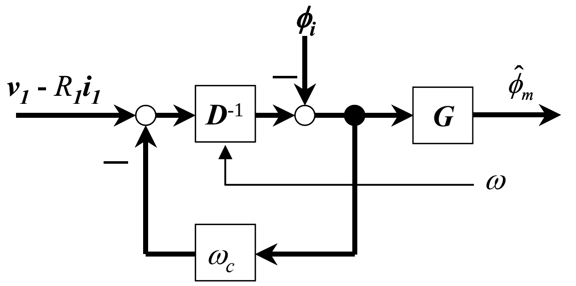

Fig. 3: A basic configuration of the D-state-observer.

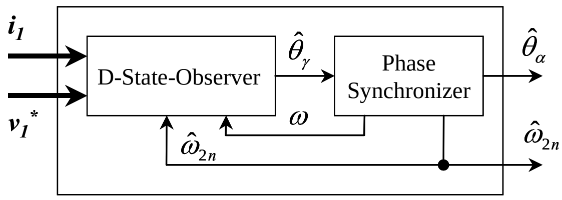

Fig. 5: A configuration of the phase-speed estimator.

D-State-Observer

$$\boldsymbol{D}(s,\omega)\tilde{\boldsymbol{\phi}}_1 = \boldsymbol{G}[\boldsymbol{v}_1 - R_1\boldsymbol{i}_1] + \omega_{2n}[\boldsymbol{I} - \boldsymbol{G}]\boldsymbol{J}\hat{\boldsymbol{\phi}}_m \quad (10)$$

$$\hat{\boldsymbol{\phi}}_m = \tilde{\boldsymbol{\phi}}_1 - \boldsymbol{G}\boldsymbol{\phi}_i \quad (11)$$

Here $\boldsymbol{D}(s,\omega)$ is so-called "D-matrix" defined as

$$\boldsymbol{D}(s,\omega) = s\boldsymbol{I} + \omega\boldsymbol{J}\,; \quad (12)$$

$\boldsymbol{G}$ is an observer gain; and $\hat{\boldsymbol{\phi}}_m$ is a rotor phase estimate.

The observer gain $\boldsymbol{G}$ is a 2x2 matrix and is constructed as

$$\boldsymbol{G} = \boldsymbol{I} - \frac{\omega_c}{\omega_{2n}}\boldsymbol{J} \quad (13)$$

where ω_c is a design parameter to be determined by a designer. Note that the observer gain in (13) and $\boldsymbol{J}$ are mutually commutative.

Applying (13) to (10) yields [3]

$$\hat{\boldsymbol{\phi}}_m = [\boldsymbol{D}(s,\omega) + \omega_c\boldsymbol{I}]^{-1}\boldsymbol{G}[\boldsymbol{v}_1 - R_1\boldsymbol{i}_1 - \boldsymbol{D}(s,\omega)\boldsymbol{\phi}_i]\,. \quad (14)$$

In the case that a scalar design parameter ω_c is selected such as

$$\omega_c = |\omega_{2n}|g \quad ; g = \text{const} > 0\,, \quad (15)$$

the observer gain $\boldsymbol{G}$ turns to be constant such as

$$\boldsymbol{G} = \boldsymbol{I} - \text{sgn}(\omega_{2n})g\boldsymbol{J} \quad ; g = \text{const} > 0\,. \quad (16)$$

Because the observer gain $\boldsymbol{G}$ in (16) is constant overall positive or negative speeds, it can be commutative with the D-matrix, i.e.

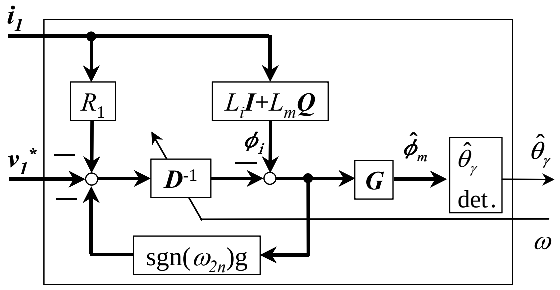

Fig. 6: A detailed configuration of the D-state-observer in the phase-speed estimator.

$$\boldsymbol{D}(s,\omega)\boldsymbol{G} = \boldsymbol{G}\boldsymbol{D}(s,\omega)\,. \quad (17)$$

Equations (14) and (17) yields another form of the D-state observer such as [3]

$$\hat{\boldsymbol{\phi}}_m = \boldsymbol{G}[\boldsymbol{D}(s,\omega) + \omega_c\boldsymbol{I}]^{-1}[\boldsymbol{v}_1 - R_1\boldsymbol{i}_1 - \boldsymbol{D}(s,\omega)\boldsymbol{\phi}_i]\,. \quad (18)$$

Fig. 3 shows a basic configuration of the D-state observer in (18).

Fig. 4 shows a configuration of the sensorless vector control systems, where the block of phase-speed estimator plays the role estimating rotor phase and speed instead of rotor position/speed sensors such as encoder and resolver. Note that the phase-speed estimator is constructed in the in γ-δ general coordinates expected to track d-q coordinates with no phase difference (refer to Fig. 2).

Table 1: Specification of the target IPSM

Item	Unit	Description
Size	[mm]	ϕ100 x L100
Weight	[kg]	6
Rated current	[A rms]	50
Pole pairs	[pairs]	2
R_1	[Ω]	0.021
L_d / L_q	[mH]	0.20 / 0.41
Φ	[V s/rad]	0.032

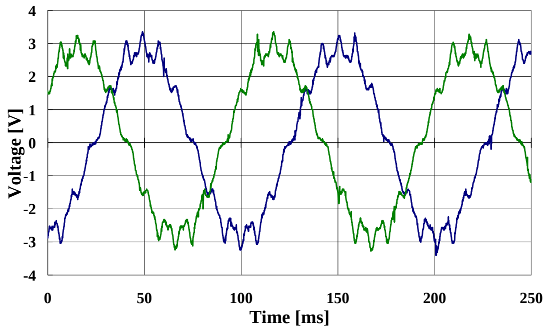

Fig. 7: Back EMF waveforms.

Fig. 5 shows a configuration of the phase-speed estimator. As shown, it consists of two sub-blocks of D-State-Observer and "Phase Synchronizer." The phase synchronizer is realized according to so-called the "generalized integral-type Phase-Locked Loop (PLL) method" [1], [3].

Fig. 6 shows an actual structure of the D-state-observer used in Figs 5, 6 where a voltage command is used as voltage information instead of actual voltage signal; a rotor speed estimate is used instead of actual rotor speed; and the observer gain takes the form in (16).

5 Evaluation on test bench

5.1 Configuration of the evaluation system

A target traction motor of the scooter is an IPMSM of non-sinusoidal magnetization. Table 1 indicates nominal characteristics of the motor. Fig. 7 shows back EMF waveforms of the motor at 62.8 [rad/s], which was measured in a line-to-line manner using open three-phase terminals. The waveforms show that although they are roughly trapezoidal, the associated magnetization is strongly non-sinusoidal, consequently has strong harmonics.

Fig. 8 is a picture of the target motor on a test bench. An optical encoder mounted on the target

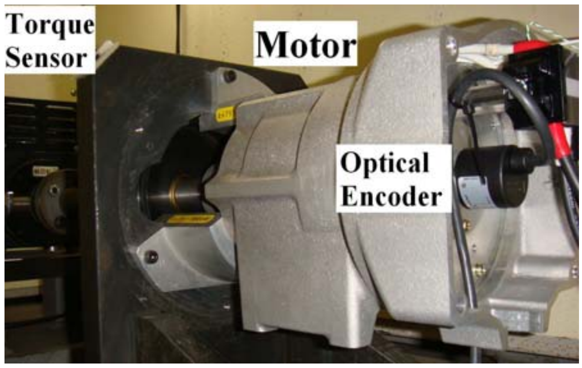

Fig. 8: A picture of the target motor on a test bench.

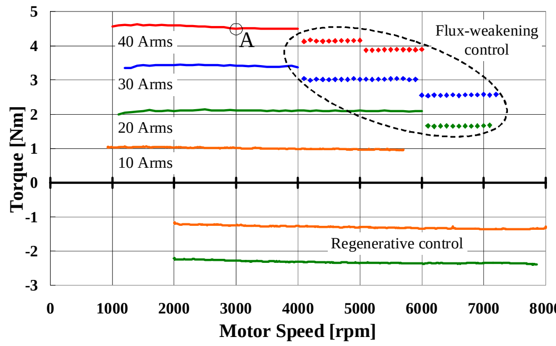

Fig. 9: Experiments result of sensorless drive.

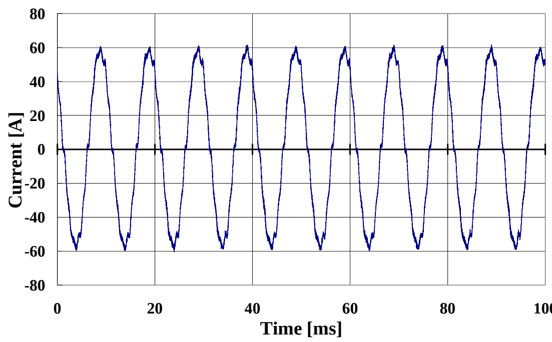

Fig. 10: Steady state U-phase current at point A.

motor is just for measurement of the actual rotor phase, and is not used for the drive control. This motor is the same as that of the base electric scooter (refer to Fig. 1), which uses the 120-degree rectangular current method for motor drives.

5.2 Evaluation results on test bench

Fig. 9 shows experiment results of the sensorless drive system, which are arranged as torque vs. speed characteristics. The colors of waveform data indicate amplitude of the associated stator currents. A torque-speed characteristic of same color was obtained using constant amplitude of the stator

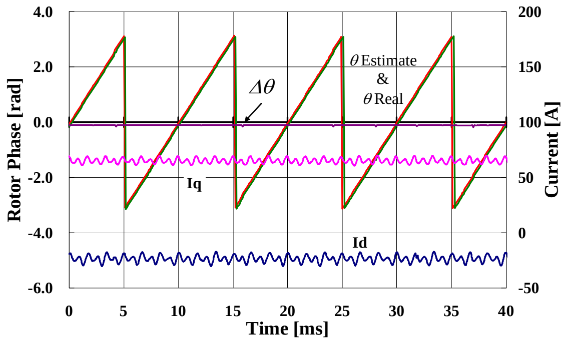

Fig. 11: Rotor phase, rotor phase estimate, rotor phase estimation error, and d, q-currents.

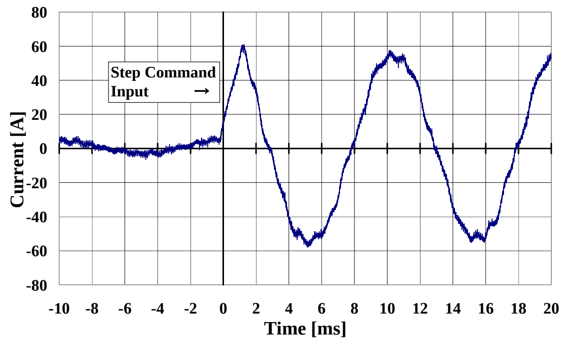

Fig. 12: A response of U-phase current to a instantly-injected command.

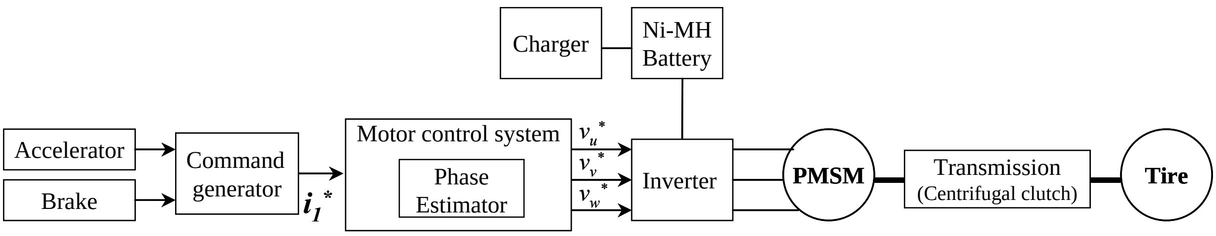

Fig. 13: A configuration of the proposed vehicle drive system

current. In the high speed range, the command of negative d-current was increased for flux-weakening control (indicates by dot lines). The negative torque means regenerative control. Since the sensorless vector control using D-state-observer cannot operate properly in low-speed region including zero speed, the condition of rotor speed were over 1000 rpm.

Fig. 10 shows steady-state U-phase current at 3000 [rpm] and 4.5 [Nm] (point A in Fig. 9).

Fig. 11 shows internal variables of the motor controller. It indicates, from the top, actual rotor phase, its estimate, rotor phase estimation error, q-current, and d-current. The rotor estimate contains few noises. Average value of the rotor phase estimation error is about -0.1 [rad], and peak-to-peak value is about 0.01 [rad].

Fig. 12 shows a response to a constant current command that is injected at an instant on the γ-δ coordinates tracking the d-q ones. Note that even for instant command, the senseless vector control system in Fig.4 does not lose control and operates properly.

Table 2: Components of the developed electric scooter.

Item	Description
Traction Motor	IPMSM
Transistor of inverter	MOS-FET
Transmission	Using centrifugal clutch
Battery	Ni-MH output DC 72V
Battery charger	700W mounted Charger Input AC 100V
Microcomputer for Motor control	SH7047 50MHz (Renesas Tech. Corp.)

6 Development of sensorless-motor-driven electric scooter

6.1 Configuration of vehicle system

Fig. 13 shows a configuration of the proposed vehicle drive system. The transmission employs a centrifugal clutch that is usually used in gasoline-engine scooters. Because of equipment of the transmission, a simple starting method can be used for starting up from standstill.

Table 2 shows main components of the developed electric scooter. The employed microcomputer that controls the sensorless vector

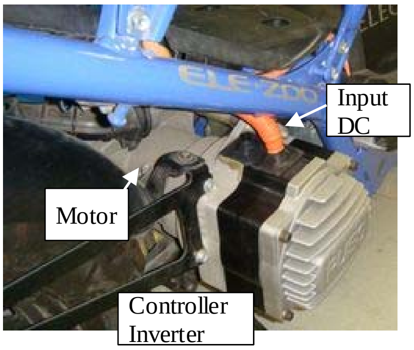

Fig. 14: Developed drive controller mounted on the scooter.

control drive system is relatively old and a low cost type.

6.2 Development of electric scooter

Main changes made to the base electric scooter in order to develop the new sensorless scooter are summarized as follows.

1) Addition of current sensors.
2) Change of the motor controller.

It is apparent that the modifications are small and the developed scooter is similar to the base one.

Fig. 14 is a picture of the motor and inverter equipped on the electric scooter. Amplitude of the current command is specified by the accelerator. The current amplitude is separated into negative d-current and positive q-current commands according to a certain rule that is obtained from the evaluation on the test bench. The brake signal is also converted into the current command amplitude, but it is separated into negative d, q-current commands. When the brake signal is injected in middle-to-high speed range, the vector control goes into the regenerating mode, and the regenerated power is charged in the battery.

6.3 Riding-test of developed scooter

Drive-tests of the developed scooter have been done at a test course in the authors company. It was verified through drive-tests that the performance by the sensorless vector control drive is practically equivalent to that of traditional sensor-used vector control drive.

After completion of the drive-tests, a license plate for the developed scooter was applied in order to drive it on public roads. Fig. 15 is a picture of the developed scooter driving on a public road.

Fig. 15: The developed scooter riding on public road

7 Conclusion

This paper presented a new sensorless electric scooter using the D-state observer, verified that such a scooter can be realizable, and re-verified the usefulness of the D-state observer. The authors are convinced that the technologies used in the developed scooter can be also applied to other EVs.

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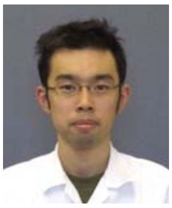

Ichiro Aoshima joined in PUES Corporation in 2006. He has been working in field of motor control system.

Masaaki Yoshikawa was Deputy director of Engineering, PUES Corporation. He joined Tokyo R&D Co., Ltd. in 1984.

Nobuhito Ohnuma is currently an executive vice-president of PUES Corporation since 2008. He joined Tokyo R&D Co., Ltd. in 1982. He commenced EV development in 1989. He appointed as a director of Tokyo R&D in 1990. He was a director of PUES Corporation additionally in 1999.

Shinji Shinnaka has been a professor of Dept. of Electrical Engineering, Kanagawa University. Prof. Shinnaka has been working in field of motor drives and has established important fundamental patents especially in sensorless drives. He has received Best Paper, Best Book, and Best Technology Awards from the Society of Instrument and Control Engineers, Japan, and a Prize Paper Award from the IEEE Transactions on Industry Applications. His current interests are application of motor drive technologies to EVs.