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# DTCSVM Fault Tolerant Control of PMSM

Mongi Moujahed, Hechmi Benazza, Mohamed Jemli, and Mohamed Boussak. Sr., *Member, IEEE*

***Abstract*—This paper presents a MRAS observer applied to fault-tolerant PMSM drive system. It proposes a fast method of fault switches detection in the power converters, whose objective is to eliminate the mechanical sensor and ensure continuity of service even fault presence opening a phase. A MRAS observer is used to replace the mechanical sensor and a redundant inverter leg is used to replace the faulty leg.**

***Index Terms*—Permanent Magnet Synchronous Machine (PMSM), Direct Torque Control (DTC-SVM), FTC, MRAS.**

## I. Introduction

Recently, permanent magnet synchronous motors are applied to various applications such as electric vehicle, aerospace, medical service, and military applications due to several outstanding characteristics. If any failure of the drive system occurs in these applications, cost and damages to the human life should become very high. Because of the importance of high reliable operation in these areas.Therefore, there is an urgent need to research fault control for electrical motor performance [1], [2]. Multitudes of control solutions for PMSM have been studied. The DTC-SVM controls is a powerful control, not sensitive to parameters changes in machines and robust to disturbance and reduce the ripples of the flux and torque in comparison with classical DTC [3], [4].
The objective of this method is to make a monitor of stator flux vector in a fixed (α,β) reference and we consider two flux vectors, the estimated flux and its reference. The polar forms of these two vectors are obtained by their projections on the reference frame (α, β). From these components, the increment desired stator flux vector at a given time is calculated. SVPWM will be applied to this vector to get the inverter switching states. Consequently, the block of the DTC-SVM has been defined and presented.
Moreover, a sensorless control with MRAS is presented in order to reduce the hardware complexity, the size of the drives. Also, it eliminates the sensor cable, increase the reliability, and decrease the maintenance requirements [5].
In this paper, DTC-SVM control sensorless fault tolerant of PMSM (case of open phase) is presented.

M. Moujahed, H. Benazza and M. Jemli : Unite de Recherche en Commande, Surveillance et Surete de Fonctionnement des Systemes (C3S) –Equipe Developpement des Systemes Electrotechniques – Ecole Nationale Superieure d'Ingenieurs de Tunis (ENSIT) –5 Avenue Taha Hussein, Tunis 1008, Tunisia. e-mail: mongi.moujaheed@yahoo.com,benazzahechmi@yahoo.

## II. PMSM Equations

When The equations will be developed in the park reference (d, q). The electromagnetic torque equation (3) is based on id and iq currents [6].

$$\frac{di_d}{dt} = \frac{R_s}{L_d} i_d + \frac{L_q}{L_d} \omega_r i_q + \frac{V_d}{L_d} \quad (1)$$

$$\frac{di_q}{dt} = -\frac{R_s}{L_q} i_q - \frac{L_d}{L_q} \omega_r i_d - \frac{K_e}{L_q} \omega_r + \frac{V_q}{L_q} \quad (2)$$

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

$$\frac{d\omega_r}{dt} = n^2{}_p \left(\frac{L_d - L_q}{J}\right) i_d + n^2{}_p \frac{K_e}{J} i_q - \frac{f}{J}\omega_r - \frac{n_p T_L}{J} \quad (4)$$

$$J\frac{d\Omega}{dt} + f\Omega = T_e - T_e \quad (5)$$

Where $\omega_r = n_p \Omega$

## III. Fault tolerant inverter

The principle of the method is illustrated by Fig. 1 which is a DTC-SVM fault tolerant control of a PMSM. Fig. 1 shows that the control presented is none other than a standard three-phase six-switch inverter, endowed with three fuses and three TRIACs. In healthy mode, the structure of the presented DTC-SVM fault tolerant inverter is the same as a standard three phases six switches inverter. The adopted inverter fault tolerant control has the objective of accommodation the opening of a phase fault or short circuit. We considered only in this paper the open phase fault (phase A) case. The same procedure is applied to the phase B and phase C. Fig.2 shows the new inverter topology, after the fast detection and isolation of the open phase (phase A) [7]. In this paper, we studied two cases; healthy and faulty mode.

## .IV. MODEL REFERENCE ADAPTATIVE SYSTEM

During operation of an electrical machine, its parameters can be changed. Therefore its performance decreases. The MRAS can eliminate this problem. The model reference adaptive system (MRAS) is a significant observer [8].By using equations (1) and (2), the state model were the stator current are chosen as the state variable is:

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$$\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \frac{L_q}{L_d}\omega_r \\ -\frac{L_d}{L_q}\omega_r & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{V_d}{L_d} \\ \frac{V_q}{L_q} - \frac{K_e}{L_q}\omega_r \end{bmatrix} \quad (6)$$

Whether

$$i_d^* = i_d + \frac{K_e}{L_d}, \quad i_q^* = i_q \quad (7)$$

$$V_d^* = V_d + \frac{K_e}{L_d} R_s, \quad V_q^* = V_q \quad (8)$$

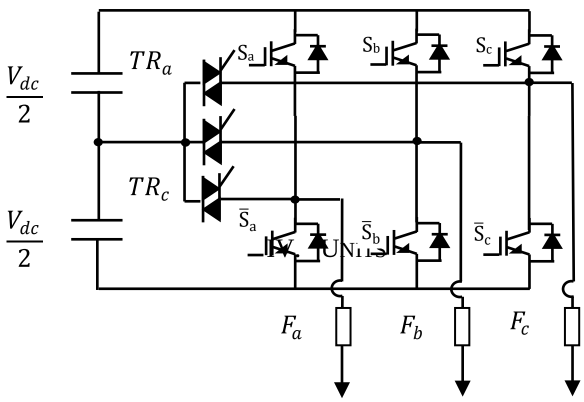



Fig.1 Healthy mode inverter

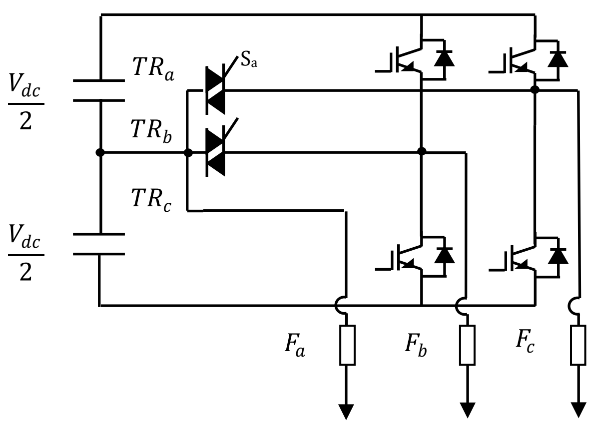



Fig.2 Fault tolerant inverter fed PMSM drive

According to the general structure of the adaptation law, the $\widehat{\omega}_r$; can be expressed in the form of (11).

$$\widehat{\omega}_r = \int_0^t \psi_1(v,t,\tau)d\tau + \psi_2(v,t) + \widehat{\omega}_r(0) \quad (11)$$

Where v is the output of the block.

$\psi_1$ et $\psi_2$ area as follow.

$$\begin{cases} \psi_1(v,t) = K_1 e^T L \hat{\imath}^* \\ \psi_2(v,t) = K_2 e^T L \hat{\imath}^* \end{cases} \quad (12)$$

Where

$$L = \begin{bmatrix} 0 & \frac{L_q}{L_d} \\ -\frac{L_d}{L_q} & 0 \end{bmatrix}, e = \begin{bmatrix} i_d{}^* - \hat{\imath}_d{}^* \\ i_q{}^* - \hat{\imath}_q{}^* \end{bmatrix}, \hat{\imath}^* = \begin{bmatrix} \hat{\imath}_d{}^* \\ \hat{\imath}_q{}^* \end{bmatrix} \quad (12)$$

So with replace equation (10) into equation (9), the estimated is as follows:

$$\hat{\omega} = \left(K_p + \frac{K_i}{p}\right)\left[\frac{L_q}{L_d} i_d \hat{i}_q - \frac{L_d}{L_q}\hat{i}_d i_q - \frac{K_e}{L_q}\left(i_q - \hat{i}_q\right) + \hat{i}_d \hat{i}_q \left(\frac{L_d}{L_q} - \frac{L_q}{L_d}\right)\right] + \hat{\omega}(0)$$

By these equations, block diagram control of the PMSM based on MRAS can be gotten, and it is shown as Fig. 3

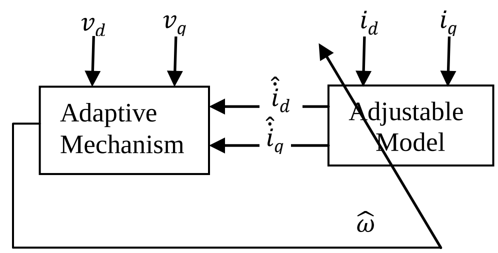



Fig.3 The block diagram control of the PMSM based on MRAS

## V. DIRECT TORQUE CONTROL SPACE VECTOR MODULATION

The DTC-SVM greatly improves torque and flux performance by achieved fixed switching frequency and decreased torque and flux ripplises.

$$T_e = \frac{3}{2} n_p \left[ \frac{|\underline{\Phi}_s| K_e \sin\delta}{L_d} - \frac{|\underline{\Phi}_s|^2 \left(L_q - L_d\right)\sin(2\delta)}{2 L_d L_q} \right] \quad (14)$$

From equation (14) we can see that for constant stator flux amplitude $|\underline{\Phi}_s|$ and flux produced by permanent magnet $K_e$, the electromagnetic torque can be changed by control of the torque angle δ. This is the angle between the stator and rotor flux linkage, when the stator resistance is neglected.

The torque angle, in turn, can be changed by changing position of the stator flux vector $\theta_s$ in respect to PM vector using the actual voltage vector supplied by PWM inverter. In the steady state, δ is constant and corresponds to a load torque, whereas stator and rotor flux rotate at synchronous speed. In transient operation, δ varies and the stator and rotor flux rotate at different speeds (Fig. 4)

The relation between torque error and increment of load angel δ is nonlinear. Therefore, we used PI controller which generates the load angel increment required to minimize the instantaneous error between reference $T_{e\_ref}$ and actual $T_e$ torque.

The torque error signal $\Delta T_e$ is delivered to the PI controller, which determines the increment of torque angle δ. Based on this signal and reference amplitude of stator flux $\Phi_{s\_ref}$, the reference voltage vector in stator coordinates α,β is calculated. The calculation block of reference voltage vector also uses information about the actual stator flux vector (amplitude $\Phi_s$ and position $\theta_s$) as well as measured current vector $I_s$. The reference stator voltage vector is delivered to space vector modulator (SVM), which generates the switching signals $S_a, S_b$ et $S_c$ for power transistors of inverter. The calculation block of reference voltage vector is shown in Fig. 5.

Based on $\Delta\delta$ signal, reference of stator flux amplitude $|\Phi_{s\_ref}|$ and measured stator flux vector position $\theta_s$(Fig. 5) the reference flux components $\Phi_{s\alpha\_ref}, \Phi_{s\beta\_ref}$ in stator coordinate system are calculated as:

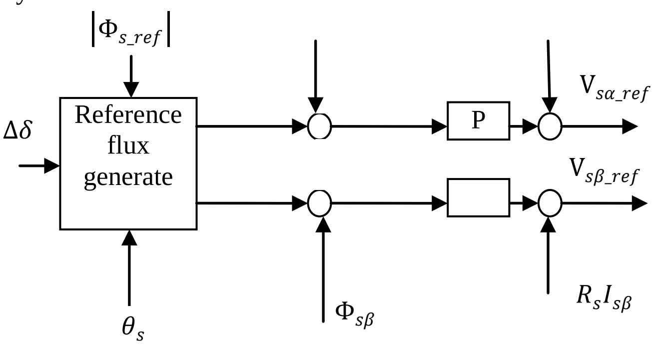



Fig.4 Calculation block of reference voltage vector

$$\begin{cases} \Phi_{s\alpha\_ref} = |\Phi_{s\_ref}|\cos(\theta_s + \Delta\delta) \\ \Phi_{s\beta\_ref} = |\Phi_{s\_ref}|\sin(\theta_s + \Delta\delta) \end{cases} \quad (15)$$

For constant flux operation region the reference value of stator flux amplitude $|\Phi_{s\_ref}|$ is equal flux amplitude of permanent magnet $K_e$.

The command voltage can be calculated from flux errors in $\alpha,\beta$ coordinate system as follows

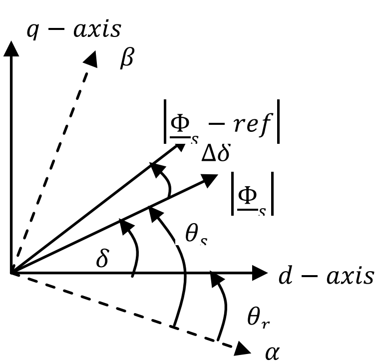



Fig.5 Space vector diagram illustrating torque control conditions

$$\begin{cases} V_{s\alpha\_ref} = \frac{\Delta\Phi_{s\alpha}}{T_s} + R_s I_{s\alpha} \\ V_{s\beta\_ref} = \frac{\Delta\Phi_{s\beta}}{T_s} + R_s I_{s\beta} \end{cases} \quad (16)$$

Where $T_s$ is the sampling time, $\Delta\Phi_{s\alpha} = \Phi_{s\alpha\_ref} - \Phi_{s\alpha}$ et $\Delta\Phi_{s\beta} = \Phi_{s\beta\_ref} - \Phi_{s\beta}$.

The structure of the proposed control scheme presented in this paper is shown in the Fig.6.

## VI. FAULT TOLERANT CONTROL( FTC)

The design and modeling of some types of faults in the electric actuators and particularly in the inverter faults (component faults) are very important task. So, the development of control strategy able to detect, to isolate and to ensure continuity of functioning of the system becomes a necessity. Many studies have already been conducted on the detection of an electrical fault in the machine, inverter and power circuits. Each fault is the cause of one or more perturbations. Therefore, the detection thereof should be traceable to the fault. The choice and the desired signature extraction method differ from one technique to another. Open circuit faults are identifiable from their observed by measuring currents and result in a decrease of current (or voltage) on the faulty phase signatures.

When the abnormal operation is detected, the fault is localized with some specific test loop at each leg inverter, which allows knowing the IGBT module where the fault occurred. Fig.2 shows the technique used (series of tests) for fault detection and localization by the same operations and signal generation for the intervention of these fault tolerant control [9].

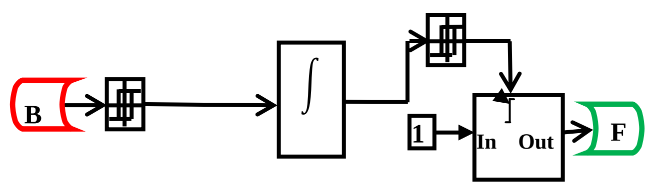



Fig.6 Fault detection isolation algorithm (FDI)

B: Represents the signal of the measured current on phase b. (same thing for a and c phase)
F: Represents the signal (1or 0 logic) for passing the command to fourth leg of the IGBT, if F=1.

## VII. SIMULATION RESULTS

The simulation results of the proposed control, under inverter fault discussed previous has been carried out with the scheme block fig.6, using Matlab/Simulink. The drive system is composed of a PMSM (parameters are listed in Table 1) and a fault tolerant inveter shown in Fig.1.

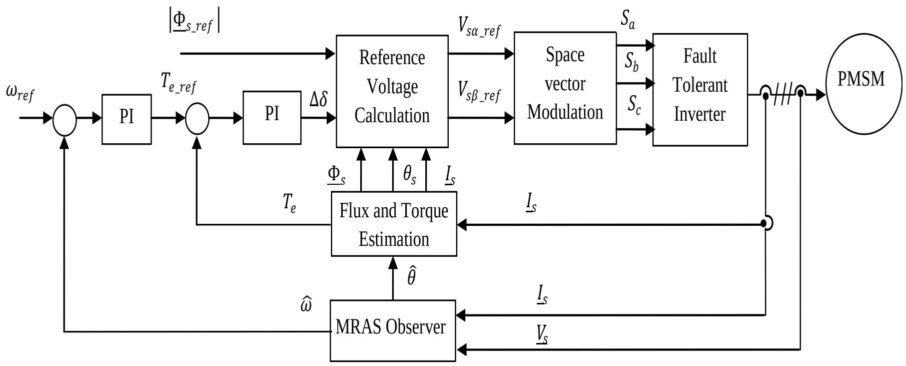
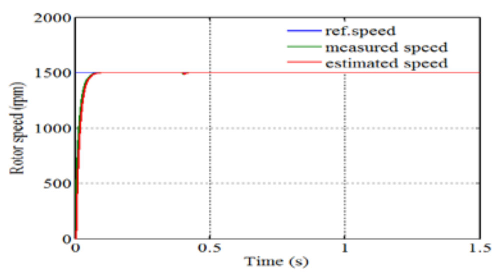
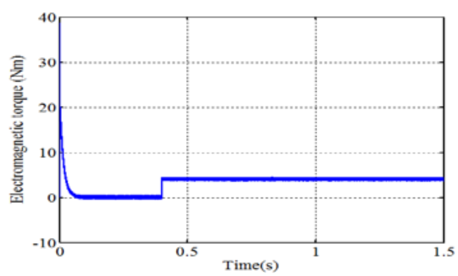



Fig.7 Block diagram of the fault tolerant control of PMSM drive with MRAS-based rotor speed estimator.

## *A. Healthy mode*




(a)




(b)

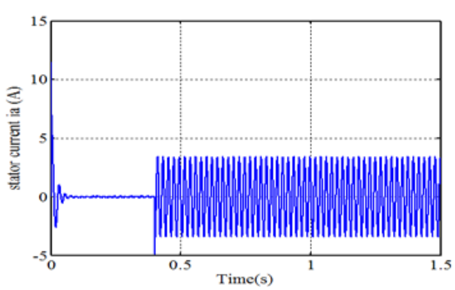
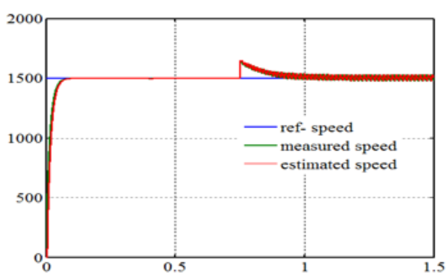
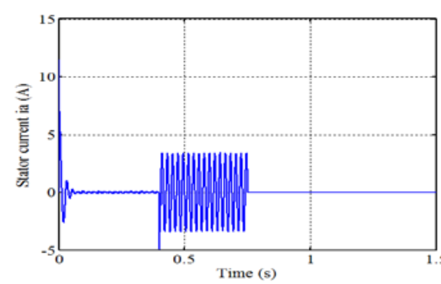



Fig.8 waveforms of speed, torque and stotor current Ia in case of healthy mode

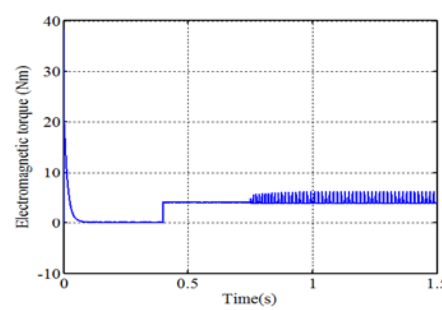
## *C. Faulty mode*




(a)



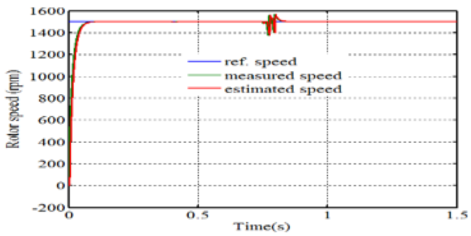

(b)



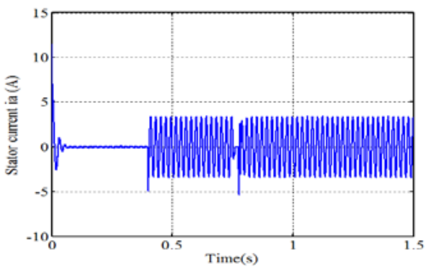

(c)

Fig.9 Waveforms of speed, torque and stotor current Ia; case of open phase fault.

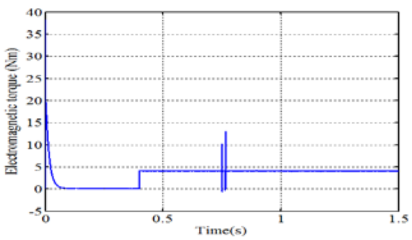
### D. *FTC Mode*




(a)




(b)




(c)

Fig.10 Waveforms of speed, torque and stotor current Ia; FTC mode

The capacitors in the DC-link are assumed to be infinite so that the voltage on both capacitors is constant and equal to $\frac{V_{dc}}{2}$.

As a first test, fig.8 shows a typical start-up of the PMSM without fault. The reference rotor speed is set at 1500 rpm with step nominal load torque Tl=4 Nm applied to the system at time t=0.4s. Fig.8 (a) show that the speed drop at the time of applying a load torque does not exceed 4%, while the duration of the disturbance does not exceed 0.6 s. Fig.8 (b) shows the waveforms of the electromagnetic torque Fig.8 (c) illustrates the waveform of the currents ia.

In the second test (Fig. 9), the PMSM started without load torque, and then a nominal load torque is applied at 0.4 s.

An open phase fault is created by a cutting of motor power phase. The fig.9 shows the rotor speed, stator currents, electromagnetic of the PMSM to an open phase fault. Like it's shown in the fig. 9 (c), the machine continues to rotate with oscillations as a consequence of the huge oscillations in the torque.

Fig. 10 shows the simulation results under the same conditions (the reference rotor speed is set at 1500 rpm with step nominal load torque Tl=4 Nm) but with an open phase. We note a presence of disturbances in the amplitudes of the currents at the time of fault and the removal of the alternating positive of ia current returns to its nominal value after a few milliseconds (fig 10.b), when the changeover takes place (response time of the tolerant control faults - time required for diagnosis). Note also large variations in the torque of the machine that accompanies a slowdown in speed (fig. 10.c).

This controller is capable of tolerating a fault. Based on the results obtained during the application of our FTC, there is a conservation of its performance since all variables return to their nominal states.

## VIII. Conclusion

This paper has presented a fault tolerant voltage source inverter which can compensate faults in the switching devices. A comparison between the behavior of the machine corresponding to the operate in a healthy and degraded mode in the presence of the fault and in his absence is presented. A sensorless control based on MRAS is also presented. The simulation results demonstrate that the proposed algorithms have good static and dynamic performance.

TABLE.I
PMSM PARAMETERS

| Parameters | | Specification | |
|---|---|---|---|
| $R_s$ | 0.5Ω | Rated power | 1.570kW |
| $L_d$ | 3.9 mH | Rated voltage | 400V |
| $L_q$ | 3.7 mH | Rated current | 5.9A |
| $K_t$ | 0.910 Nm/A | $V_{dc}$ | 540V |
| $K_e$ | 0.2275V.s/rad | Number of pole pairs | 4 |
| $J$ | $5.810^{-4}$ Kg.m² | Rated speed | 3000 rpm |
| $f$ | 0.00374 Nm./rad | Rated torque | 5 Nm |

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**Mongi Moujahed** was born in Sbikha, Tunisia, on march 4, 1966. he received the B.S. master degrees and Ph,d. degrees from the Ecole Superieure des Sciences et Techniques de Tunis (ESSTT), Tunis, Tunisia, in 1992, 2010 and 2016, respectively,, all in electrical engineering. he is currently an Aggregate Teacher with the Institut Superieur des Etudes Technologiques (ISET) of Kairouan, Tunisia He has published many papers in international conference proceedings and technical journals. His current research interests include electrical machines, power conversion systems, sensorless vector control of AC motor drives, and diagnostics. His current research interests include electrical machines, sensor less dtc control and fault tolerant control (F.T.C) ac motor drives.

**Hechmi Ben Azza** was born in Bizerte, Tunisia, in 1978. He received the B.S., master's, and Ph.D. degrees in electrical engineering from Ecole Supérieure des Sciences et Techniques de Tunis (ESSTT), University of Tunis, Tunis, Tunisia, in 2002, 2006, and 2011, respectively.

He is currently an Assistant Professor with ESSTT. He has published more than 16 papers in international conference proceedings and technical journals. His current research interests include electrical machines, power conversion systems, sensorless vector control of AC motor drives, and diagnostics

**Mohamed Jemli** was born in Nasr'Allah, Tunisia, in 1960. He received the B.S. and D.E.A. degrees in electrical engineering from Ecole Normale Supérieure de l'Enseignement Technique de Tunis, University of Tunis, Tunis, Tunisia, in 1985 and 1993, respectively, the Ph.D. degree in electrical engineering from Ecole Nationale d'Ingénieurs de Tunis, University of Tunis, in 2000, and the Habilitation à Diriger des Recherches in electrical engineering from Ecole Supérieure des Sciences et Techniques de Tunis (ESSTT), Tunis, in 2010. He was an Aggregate Teacher with the ISET of Radès, Rades, Tunisia, from 1998 to 2001. He served as an Assistant Professor with ESSTT from 2001 to 2009. He is currently a Senior Professor with ESSTT. He has authored or co-authored more than 70 papers published in international conference proceedings and technical journals. He holds many patents. His current research interests include electrical machines, sensorless vector control of AC motor drives, advanced digital motion control, and renewable energy.

**Mohamed Boussak** was born in El Haouaria, Tunisia, on 28 December 1958. He received the B.S. and D.E.A. degrees from Ecole Normale Supérieure de l'Enseignement Technique de Tunis, Tunis, Tunisia, in 1983 and 1985, respectively, the Ph.D. degree from Pierre et Marie Curie University, Paris, France, in 1989, and the Habilitation à Diriger des Recherches from Aix-Marseille III University, Marseille, France, in 2004, all in electrical engineering. He was a Researcher with Ecole Supérieure d'Ingénieurs de Marseille (ESIM) from 1989 to 1990. Between 1990 and 1991, he was a Research Teacher of electrical engineering with Claude Bernard University, Lyon, France. From 1991 to 2004, he was an Associate Professor with ESIM. From 2004 to 2008, he was an Associate Professor of electrical machines with Ecole Centrale Marseille, Marseille, where he has been a Senior Professor since 2009. He has published more than 150 papers on top rank international journals and refereed conferences. His current research interests include electrical machines, power conversion systems, sensorless vector control ac motor drives, advanced digital motion control, diagnosis faults, and fault tolerant control. Dr. Boussak is currently serves as a member of the technical program committees of several international conferences and scientific journals in the areas of power electronics and motor drives fields. He is a member of the IEEE Industry Application, the IEEE Industrial Electronics, and the IEEE Power Electronics Societies.