THE NTV-SV-PWM METHOD USING AN IMPROVED LOOK-UP TABLE FOR DC-LINK MID-POINT BALANCING APPLIED FOR OCEAN WAVE ENERGY CONVERSION SYSTEM

Ilknur Colak* and Derya A. Kocabas**

Abstract

The research activities for maximum energy absorption from wave energy converters (WECs) are very often limited to hydrodynamic control and performance of the power take-off (PTO) which mostly simplifies the power electronics conversion systems. There are only few studies that show deep analysis of connecting the generated voltage to the grid by using the most developed power electronics technologies. The main objective of this study is (i) to develop a full wave-to-grid model to show all conversion stages from ocean waves to the electricity network, (ii) to combine the WEC with neutral point clamped (NPC) inverter which uses advanced nearest three vector–space vector–pulse width modulation (NTV-SV-PWM) method based on a look-up table that can build up a sinusoidal voltage waveform at the inverter output with the least number of switching in the power circuit and the best possible harmonic spectrum without the need for any big filtering.

Key Words

Nearest three vector–space vector–pulse width modulation, DC-link mid-point balancing, multilevel converter, wave energy conversion

1. Introduction

Harnessing energy from ocean waves to generate electrical or mechanical power has occupied the scientific thinking starting from the 18th century. First patent on wave energy conversion was submitted already on 27 July 1799 [1]. The wave energy represents more predictable and higher potential compared with solar and wind energy; however, it has to cope with many challenges which slow down its development and thereof reveal the low maturity level of the sector. The control of wave energy converters (WECs) is crucial to overcome the essential issues of energy output optimization and survivability. In last couple of decades, new technologies have been developed aiming to expand the use of renewable energy sources. Most of the prior research studies focused on operating principle of WECs; contribution to the understanding of the complex wave structure interactions, influence of hydro-pneumatic chamber geometry, mechanical to electrical energy conversion, optimization of the absorption of wave energy and maximization of the generated electrical power. However, there are only few which combine WECs with the most developed power electronics technologies, and they mostly focus on partial mathematical models [1]–[10]. Compared with the existing studies in the literature [7]–[16], in this research paper, three-level active rectifier and nearest three vector–space vector–pulse width modulation (NTV-SV-PWM)-controlled three-level inverter, operating with an improved look-up table for DC-link mid-point balancing, are applied to an ocean wave energy conversion system to improve the power quality. In the paper, Section 2 presents the hydrodynamic model of oscillating water column (OWC), control diagram of three-level active rectifier, operating principle of NTV-SV-PWM-controlled three-level neutral point clamped (3L-NPC) inverter and the DC-link mid-point balancing method based on a look-up table; Section 3 shows the numerical model of the system and the simulation results of the entire model; and Section 4 summarizes the findings of the study.

2. Model Description

In this research study, a full system model was developed in MATLAB and Simulink in order to analyse the system behaviour in detail. The simulation model consists of three main parts. In the first section, a fixed-type OWC (see Fig. 1), together with Wells turbine on the air outlet...
reservoir, takes place to capture the ocean waves and transform the wave energy from hydraulic to mechanical energy. In the second part, Wells turbine’s shaft is coupled with a synchronous generator to transform the mechanical energy into electric power (given in Fig. 1). Because the obtained voltage from turbine/generator group does not produce the waveform that fulfils the grid requirements, a power conversion interface system is required at the generator’s terminals. Therefore, in the third part an active rectifier/inverter (see Fig. 2(a) and (b)) group is used to convert the non-sinusoidal voltage into sinusoidal voltage that fulfils the grid power quality requirements. Finally, the generated voltage was filtered and synchronized to the grid voltage.
2.1 Mathematical Model of Oscillating Water Column

As shown in Fig. 1, OWC devices consist of a large open-end wave capture chamber made of concrete or steel that is partly immersed in the sea and a platform for an air turbine. The incoming wave field produces an oscillating hydrodynamic pressure distribution inside the closed housing. Changing air pressure results in bidirectional airflow that drives the volume of air through a constriction containing an air turbine which is connected to a generator to generate electrical energy. The amount of useful convertible energy depends on the flow behaviour inside the air chamber and the orifice. In this study, it is assumed that air inside the chamber is an ideal gas and air compression is isentropic [7]–[13].

According to Bocotti, the wave length inside the chamber, $\lambda_w$, is calculated as in (1) [13]:

$$\lambda_w = \frac{\pi h_o}{3L} \cdot \frac{1}{\sqrt{g h_o}} \cdot \frac{T}{2} \cdot \frac{\pi h_o}{L}$$

The displacement of wave inside the chamber, $H_o$, is calculated as in (2) based on the length of the chamber and the wave height [13].

$$H_o(t) = \frac{H}{2} \cdot \cos \left( \frac{2\pi}{T} \cdot t \right) \cdot \frac{1}{\theta} \cdot \sin \left( \frac{\theta}{2} \right)$$

$$\theta = 2\pi \cdot \frac{\lambda_o}{L}$$

The extracted wave energy inside the OWC depends on both air pressure drop inside the air chamber and the heaving motion of the water column. The time-averaged hydrodynamic energy stored by the OWC device, $E_{OWC}(t)$, can be calculated by (4) ($w$: width of the OWC chamber, $g$: gravitational acceleration, $\rho_w$: density of the seawater surface).

$$E_{OWC}(t) = \frac{1}{T} \int_0^T \frac{1}{2} \rho_w \cdot g \cdot (H_o(t))^2 \cdot w \cdot dt$$

The instantaneous extracted power in the orifice, $P_p(t)$, is defined as the product of the airflow rate through the turbine, $q(t)$, and the pneumatic pressure drop between the chamber and the open air ($\Delta p)$.

$$P_p(t) = \frac{E_p(t)}{T} = \frac{\Delta p \cdot q(t)}{T} = \frac{1}{T} \int_0^T \Delta p \cdot q(t) \cdot dt$$

$$\Delta p = p_{owc}(t) - p_o$$

where $p_{owc}$ is the pressure transferred from OWC to Wells turbine, and $p_o$ is air pressure relative to atmospheric pressure. The airflow rate can be written in terms of the cross-sectional area of the OWC surface and the air velocity in the chamber, $\vartheta_{owc}(t)$, as in (7) ($\omega_o$: OWC natural oscillation frequency).

$$q(t) = \frac{d}{dt} \vartheta_{owc}(t) \cdot w \cdot L$$

$$\vartheta_{owc}(t) = \frac{H_o}{2} \cdot \omega_o \cdot \cos(\omega_o \cdot t)$$

$$\omega_o = \sqrt{\frac{g}{H_o + x}}$$

$$q(t) = \frac{H_o}{2} \omega_o \cdot w \cdot L \cdot \cos(\omega_o \cdot t)$$

The airflow rate in the orifice can be expressed also as in (11) in terms of turbine and the orifice diameters and the velocity of air in the orifice ($\vartheta_a$). The influence of turbine diameter on the annual power can be seen in Fig. 2(d).

$$q(t) = \frac{\pi}{4} \cdot (D_a^2 - D_t^2) \cdot \vartheta_a(t)$$

Based on volume flow rate principle, the velocity of air in the orifice is given with (12).

$$\vartheta_a = \frac{4}{\pi} \cdot \frac{\vartheta_{owc}(t) \cdot A_{owc}}{D_a^2 - D_t^2}$$

When the Bernoulli equation [17] is used for the air pressure inside the OWC chamber, the relation between the pressure inside the chamber and the pressure inside orifice can be written as in (13) ($h_1 - h_2$: vertical displacement of the air between water surface and the orifice, $\rho_a$: air density, $p_w$: pressure on the water inside the chamber).

$$p_w + \rho_a \cdot g \cdot h_1 + \frac{1}{2} \rho_a \cdot \vartheta_{owc}^2 = p_{owc} + \rho_a \cdot g \cdot h_2 + \frac{1}{2} \rho_a \cdot \vartheta_a^2$$

$$p_{owc} = p_w + \rho_a \cdot \frac{d}{dt}(h_1 - h_2) + \frac{1}{2} \rho_a \cdot \vartheta_{owc}^2 - \frac{1}{2} \rho_a \cdot \vartheta_a^2$$

The pressure difference between orifice and the air can be expressed as in (14) ($h_o - h_1$: vertical displacement of the air inside the orifice).

$$p_w - p_o = \rho_a \cdot \frac{d}{dt}(h_o - h_1) + \frac{1}{2} \rho_a \cdot \vartheta_a^2 - \frac{1}{2} \rho_a \cdot \vartheta_{owc}^2$$

If the air velocity outside of OWC is assumed zero, and (14) is used in (13), then the pressure distribution on the Wells turbine can be found as in (15) in terms of OWC dimensions and water displacement inside OWC.

$$\vartheta_{owc} = -\rho_a \cdot \frac{H_o^2}{4} \cdot \omega_o^2 \cdot (2 \cdot \cos^2(\omega_o \cdot t) - 1)$$

$$\frac{A_{owc}}{(A_a - A_t)} - \frac{1}{2} \rho_a \left( \frac{H_o^2}{4} \cdot \omega_o^2 \cdot \cos^2(\omega_o \cdot t) \cdot \left( \frac{A_{owc}}{(A_a - A_t)} \right)^2 \right)$$

When (11) and (15) are used in (5), the instantaneous power take-off (PTO) value can be found as below:

$$P_p(t) = \begin{cases} -\rho_a \cdot \frac{H_o^2}{4} \cdot \omega_o^2 \cdot (2 \cdot \cos^2(\omega_o \cdot t) - 1) & \frac{A_{owc}}{(A_a - A_t)} \end{cases}$$

$$\sqrt{\frac{g}{H_o + x}}$$

$$\times \left( \frac{H_o}{2} \omega_o \cdot A_{owc} \cdot \cos(\omega_o \cdot t) \right)$$

In this study, a Wells turbine with linear characteristics curve is used to convert the hydraulic energy to mechanical
energy where the turbine motion is independent of the fluid direction [18].

The performance characteristics of Wells turbine define the relation between the pressure, flow rate and the extracted power from the turbine. The dimensionless turbine characteristics are given below where \( N_t \) is the rotational speed, \( T_t \) is the turbine torque and \( P_t \) is the power taken from the turbine shaft [18], [19]:

Dimensionless pressure rate (see Fig. 2(b)):

\[
\Psi = \frac{p}{\rho_a N_t^2 D_t^2}
\]

Dimensionless pressure drop coefficient:

\[
\Delta^* = \frac{\Delta p}{\frac{1}{2} \rho_a N_t^2}
\]

Dimensionless flow rate coefficient:

\[
\phi = \frac{Q}{A_a N_t^2} = \frac{\dot{m}}{\rho_a N_t^2 D_t^3}
\]

Dimensionless torque coefficient (see Fig. 2(c)):

\[
\Pi = \frac{P_t}{\rho_a N_t^3 D_t^5} = \frac{T_t}{\rho_a N_t^2 D_t^5}
\]

Efficiency (see Fig. 2(a)):

\[
\eta = \frac{P_t}{\Delta p Q} = \frac{T_t N_t}{\Delta p Q}
\]

The transformation from mechanical to electrical energy is realized by a synchronous generator due to its favourable characteristics: easy to use, high power density and high torque-to-inertia ratio.

### 2.2 Neutral Point Clamped Active Rectifier

In this study, 3L-NPC topology is used for both active rectifier (AFE) and inverter because it provides better energy capture system, lower harmonic distortion, there of smaller filter requirement [20]. The active rectifier is controlled with sinusoidal pulse width modulation (SPWM) method

where a sinusoidal reference voltage waveform is compared with two triangular carrier signals to keep the input harmonics at low level. The control diagram of active rectifier is illustrated in Fig. 3(a). Active rectifier control scheme includes two cascaded loops where one of them is used to regulate the active power produced by the synchronous generator and the second one keeps the DC voltage at the rated value at the DC bus. In the control diagram, the d and q axis currents are obtained by applying Park’s transformation to the phase currents. Here the value of \( i_d \) is forced to zero. In this study, the reactive power control introduces complexity into the system because it requires the PTO to supply energy to change the hydrodynamic stiffness and damping [21], [22].

### 2.3 Nearest Three Vector–Space Vector–Pulse Width Modulation -Controlled Neutral Point Clamped Inverter

Space vector modulation provides higher DC voltage utilization, better harmonic performance and less switching losses [23]. Therefore in this study, NTV-SV-PWM method is applied to control the three-phase 3L-NPC inverter (shown in Fig. 3(b)) based on 27 voltage vectors (6 large vectors, 6 medium vectors, 12 small vectors, 3 zero vectors). The main steps of the method can be listed as below [24]–[27].

(I) Determination of the sector of reference voltage: Space vector diagram is formed in hexagonal shape with six equal sectors. In order to find out in which sector the switching will take place, it is necessary to know the displacement angle (\( \theta \)) of the reference vector, \( V_{ref} \), in (22) as given in Table 1.

\[
V_{\text{ref}} = \sqrt{V_{\text{ref}a}^2 + V_{\text{ref}b}^2} e^{-i(\theta - \pi)}
\]

(II) Determination of the nearest three vectors: Each sector consists of four triangles called sections as shown in Fig. 4(a). The reference vector is built based on the three nearest stationary vectors in the sector where the reference vector lies. Depending on the amplitude and \( \alpha \) and \( \beta \) of

![Figure 3. Control block diagram of (a) 3L-NPC-AFE and (b) 3L-NPC inverter.](image-url)
Table 1

<table>
<thead>
<tr>
<th>Angle</th>
<th>Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ &lt; \theta \leq 60^\circ$</td>
<td>Sector I</td>
</tr>
<tr>
<td>$60^\circ &lt; \theta \leq 120^\circ$</td>
<td>Sector II</td>
</tr>
<tr>
<td>$120^\circ &lt; \theta \leq 180^\circ$</td>
<td>Sector III</td>
</tr>
<tr>
<td>$180^\circ &lt; \theta \leq 240^\circ$</td>
<td>Sector IV</td>
</tr>
<tr>
<td>$240^\circ &lt; \theta \leq 300^\circ$</td>
<td>Sector V</td>
</tr>
<tr>
<td>$300^\circ &lt; \theta \leq 360^\circ$</td>
<td>Sector VI</td>
</tr>
</tbody>
</table>

the reference vector, the region of the vector and thereof the nearest three vectors can be found as below by using (23), (24) and (25).

- if the imaginary component of reference vector, $V_{ref\alpha}$, is less than the threshold values of $\alpha_{12}$ and $\alpha_2$, then $V_{ref}$ is located in the first region (see Fig. 4(b)),
- if $V_{ref\alpha}$ is greater than $\alpha_{11}$ and $\alpha_{12}$ and less than $\alpha_2$, the reference vector is located in the second region,
- if $V_{ref\alpha}$ is less than $\alpha_{11}$ and $\alpha_2$, the reference vector is in the third region,
- if $V_{ref\alpha}$ is greater than $\alpha_2$, then the vector is located in the fourth region.

\[
\begin{align*}
\alpha_{11} &= V_d - \sqrt{3} V_{ref} \cos \theta \\
\alpha_{12} &= \sqrt{3} V_{ref} \cos \theta - V_d \\
\alpha_2 &= \frac{V_d}{2}
\end{align*}
\]  

(III) Defining the switching time period: Three vectors in the arbitrary sector and region are applied for their dwell time during the sampling period. The dwell time specifies the duty cycle period of each applied vector where the switching period of each vector is defined as in (26).

$$\frac{1}{T} \int_0^T V_{ref} \, dt = \frac{1}{T} \left( \int_0^{T_x} V_x \, dt + \int_{T_x}^{T_x+T_y} V_y \, dt + \int_{T_x+T_y}^{T_x+T_y+T_z} V_z \, dt \right)$$  

(26)

$$d_{x,y,z} = \frac{T_{x,y,z}}{T}$$  

(27)

where; $V_x$, $V_y$, $V_z$ are the three nearest vectors from arbitrary sector and region, $T$ is the sampling period, $T_x$, $T_y$, $T_z$ are the dwell times for the three nearest vectors. For instance, when the reference vector lies in region 4 in Fig. 4(b), the duty ratios can be found as n (30), (31) and (32):

\[
\begin{align*}
V_{ref\beta} &= V_{ref} \cos \theta = d_2 V_2 \cos 60^\circ + d_7 V_7 \cos 30^\circ + d_{14} V_{14} \cos 60^\circ \\
V_{ref\alpha} &= V_{ref} \sin \theta = d_2 V_2 \sin 60^\circ + d_7 V_7 \sin 30^\circ + d_{14} V_{14} \sin 60^\circ \\
d_2 &= 2 - \frac{V_{ref}}{V_d} \left( \sqrt{3} \cos \theta + \sin \theta \right) \\
d_7 &= \frac{V_{ref}}{V_d} \left( \sqrt{3} \cos \theta - \sin \theta \right) \\
d_{14} &= 2 \frac{V_{ref}}{V_d} \sin \theta - 1
\end{align*}
\]  

(28) (29) (30) (31) (32)

(IV) Defining the switching sequence: The switching sequence is defined to have a minimum number of switching actions when moving from one switching state to another to minimize the switching losses. It is ensured that when the switching state is changed, the DC link voltage deviation at the neutral point is kept minimum and the sequence of connection of each phase to the DC link point is symmetrical. The direction of the switching sequence is given in Fig. 4(a).

Figure 4. (a) Directions of the switching sequence rotation and (b) defining the region of the three nearest vector.
2.4 DC-Link Mid-Point Balancing

In 3L-NPC converters, when the DC-link mid-point is not balanced, it creates changes on the voltage vectors. The redundant small vectors’ magnitudes change while their total value and phase angle remain the same. When it comes to medium vectors, both the magnitude and the angle of the vectors change whilst for large vectors, both remain the same. In the unbalanced situation, the regions in the sectors become uneven instead of being equilateral triangles. The number of regions in one sector increases from 4 to 12 as illustrated in Fig. 5 which makes the given calculations in the previous section more complicated [26], [27]. In this study, a look-up table is created for the unbalanced situation to implement it directly in the SV-PWM modulator.

The parameters, $\gamma_1$ and $\gamma_2$, in Fig. 5 are used to define the new dwell times for the resized regions. The total value of the parameters is equal to the large vector’s magnitude as given in (33).

$$\gamma_1 + \gamma_2 = \frac{2V_d}{\sqrt{3}}$$  (33)

Figure 5. Resized regions for unbalanced DC-link mid-point (a) Case I, (b) Case II, (c) Case III and (d) Case IV.

<table>
<thead>
<tr>
<th>Case</th>
<th>Vector</th>
<th>$V_2$</th>
<th>$V_7$</th>
<th>$V_{14}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Duty Ratio $d_2' = 1 - \frac{V_{ref}}{\sqrt{3}\gamma_2}.(\sqrt{3}.\cos \theta + \sin \theta)$</td>
<td>$d_7' = \frac{V_{ref}}{\sqrt{3}\gamma_2}.(\sqrt{3}.\cos \theta - \sin \theta)$</td>
<td>$d_{14}' = \frac{2V_{ref}}{\sqrt{3}\gamma_2}.\sin \theta$</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Vector $V_2$</td>
<td>$V_7$</td>
<td>$V_{14}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Duty Ratio $d_2' = 1 - \frac{V_{ref}}{\sqrt{3}\gamma_1}.(\sqrt{3}.\cos \theta + \sin \theta)$</td>
<td>$d_7' = \frac{V_{ref}}{\sqrt{3}\gamma_2}.(\sqrt{3}.\cos \theta - \sin \theta)$</td>
<td>$d_{14}' = \frac{V_{ref}}{\sqrt{3}\gamma_1}.(\sqrt{3}.\cos \theta + \sin \theta)$ [- \frac{V_{ref}}{\sqrt{3}\gamma_2}.(\sqrt{3}.\cos \theta - \sin \theta)$</td>
<td></td>
</tr>
</tbody>
</table>
By using geometry and the mathematical equations, the new duty ratios \( d_{x,y,z} \) are calculated as in Table 2 for the nearest three vectors when the reference vector lies in the resized fourth region as in Case I and Case II. The new duty ratios are calculated for 12 regions in similar way, and the new look-up table is integrated in the system model. By applying this method, the subsequent corrections are not needed anymore which simplifies the control loops, achieves a wide linear modulation range and less total harmonic distortion and improves the system response time [24]–[25].

3. Design Validation and Simulation Results

The main dimensions of the OWC such as \( D_t, D_a, L \) and \( w \) were optimized carefully in the simulations to maximize the power extraction from the incoming wave. The parameters given in Table 3 were used for the system computation. In the design formulation, the linear wave theory is considered.

Pressure drop on the Wells turbine and the airflow rate are given in Fig. 6(a) and (b), respectively. Figure 6(c) shows the rectifier’s input current waveform, whereas the instantaneous power that is taken from the output terminals of the synchronous generator is shown in Fig. 6(d). Figure 6(e) and (f) show the inverter voltage without filter before and after the look-up table–based balancing control respectively.

Figure 7(a), (b), (d) and (e) give the three-level inverter output current and voltage waveforms for resistive load and inductive load, respectively. Even though the voltage generated at the synchronous generator’s terminals has changing amplitude and frequency and the current is discontinuous, sinusoidal current/voltage waveforms and continuous power (in Fig. 7(c) and (f)) are achieved on the AC grid coupling point by using voltage conditioning system and an output filter.

Output current and voltage harmonic spectra for reactive load are presented in Fig. 8(a) and (b) respectively. As seen in Fig. 8(a), the current waveform contains high third-order harmonic. However, all individual current harmonic components and current and voltage total harmonic distortion (THD) values (current THD: 3.86%, voltage THD: 0.23%) are below the limits that are described in IEEE 519 standard [28].

4. Conclusion

In this research study, a comprehensive wave-to-grid mathematical model was built for a fixed OWC wave energy conversion system where a self-rectifying air turbine coupled with cylindrical synchronous generator is used in air outlet reservoir. First, a set of numerical simulations were carried out for different turbine diameter and sea wave characteristics aiming to determine the optimum hydro-pneumatic chamber shape of the OWC and maximize the PTO value. Later, the AC terminals of synchronous generator were coupled with a 3L-AFE to control active and reactive power components and to regulate the DC-link voltage while reducing the harmonic components on the AC side of the rectifier, so that the lifespan of the generator can be increased. In order to integrate the output voltage of the rectifier to the grid, a 3L-NPC inverter controlled by NTV-SV-PWM method is used to bring the advantage of better harmonic performance, higher efficiency and higher DC voltage utilization on the wave energy conversion system. The NTV-SV-PWM method is advanced by using a modified look-up table strategy to control the DC-link mid-point. In the updated control method, the dwell times for the three nearest vectors are modified based on the fluctuation on the DC-link mid-point. Thus, it became possible to reduce the computation efforts and the interpolating errors, improve the performance of the 3L-NPC within the power conversion chain and keep the voltage deviation at minimum level by using less control loop. In addition, the power fluctuation from wave energy to the grid, which is a typical problem for wave energy conversion systems, is minimized by using the proposed methodology. The results proved that NTV-SV-PWM scheme provides optimal output and reduces the harmonic content of the output current.
Figure 6. (a) Pressure distribution on the Wells turbine; (b) airflow rate; (c) 3L-NPC rectifier input current; (d) 3L-NPC rectifier instantaneous input power; (e) inverter output voltage before balancing (wo filter); and (f) inverter output voltage after balancing (wo filter).

Figure 7. 3L-NPC inverter: (a) Output current; (b) output voltage; (c) instantaneous output power at resistive load respectively; (d) output current; (e) output voltage; and (f) instantaneous output power at reactive load respectively.
and voltage, which are below the given values in the IEEE standards.

References


Figure 8. Harmonics spectrum of (a) inverter output current and (b) inverter output voltage.
Biographies

Ilknur Colak (Senior Member, IEEE) studied B.Sc., M.Sc. and Ph.D. in electrical engineering program in Istanbul Technical University, Istanbul, Turkey. In the last 20 years, she worked in industry and research centres such as ABB, Ansaldo Richerhe, TUBITAK and CERN. Since November 2016, Colak has been working for Maschinenfabrik Reinhausen (MR) as Head of Power Electronics R&D Team. Her research area includes multilevel converter topologies, modulation schemes, solid-state transformers, high-power resonant converters, insulation-coordination, EMC and grounding, reliability and wave energy conversion systems.

Derya A. Kocabas (Member, IEEE) received B.S. degree in electrical engineering from ITU, Istanbul, Turkey, in 1994, and M.Sc. and Ph.D. degrees from the Electrical Engineering Program, Institute of Science and Technology, ITU, in 1997 and 2004, respectively. His main subjects of concern are design and control of electrical machines, space harmonics, drive systems and power electronics. In 1995, he joined the Department of Electrical Engineering, Electrics and Electronics Faculty, ITU, where he has been an Assistant Professor, since January 2009.