Direct Phase Digital Control Method in Power Inverters Based on Dumping Frequency Analysis

Ljupco Karadzinov  
Faculty of Electrical Engineering and IT  
Sts. Cyril and Methodius University  
Skopje, Republic of Macedonia  
l.karadzinov@feit.ukim.edu.mk

Goce Stefanov  
Faculty of Electrical Engineering  
University Goce Delcev  
Stip, Republic of Macedonia  
goce.stefanov@ugd.edu.mk

Abstract—Direct phase or indirect frequency control methods are used in series-resonant bridge power inverters for induction heating to maintain maximum power transfer as the load equivalent electrical parameters change during the heating process. The paper presents mathematical analysis of the output voltage and current phase angle dependence on the resonant circuit dumping frequency when it is excited with pulse voltage with a different frequency than the resonant one. Based on this analysis and using only measurements of the deviation of the phase angle from its reference value, an improved control method is derived that calculates the new bridge switching frequency. An algorithm for digital implementation is presented. The improved method is verified by simulations and experiments on a prototype.

Keywords—series-resonant bridge inverter; direct phase control method; digital control algorithm; dumping frequency.

I. INTRODUCTION

Series-resonant bridge inverters are used in a variety of applications. Maximum energy is transferred to the load when the converter switching frequency is the same as the resonant one. In some applications, like direct induction heating, the heated work-piece equivalent electrical parameters are part of the resonant circuit [1–4]. As the temperature of the work-piece is increased, the resonant tank inductance and resistance change, thus changing the circuit resonant frequency. To ensure maximum energy transfer, the inverter control circuitry must adjust the switching frequency so that it follows the change of the resonant frequency. Different control algorithms are used to adjust the switching to the resonant frequency. Several of them are based on direct frequency control [5–6] and other use indirect frequency control by controlling the phase angle $\phi$ between the inverter output voltage and current [7–15]. The last control type, instead of indirect frequency, is more often called direct phase control method. Phase control provides reliable drive of the resonant converter in the presence of large dynamic changes in the load impedance during start-up, natural tracking of component variations with temperature and time, simplified control to output dynamics and a more linear relationship between phase command and output current when compared to frequency control [10, 11].

In the analysis of serial resonant converters it is usual to use the resonant circuit frequency $\omega_0$ for two reasons: 1) assuming that the value of the resistance of the resonant tank is very small the dumping is negligible and thus resonant $\omega_0$ and damping $\omega_d$ angular frequencies have very close values; 2) active power is calculated using the phase angle between voltage and current first harmonics. However, in bridge resonant converters the voltage waveforms are pulse and the current has a damped sinusoidal form. In such cases the phase angle is calculated in respect to the dumping frequency and derived expressions show qualitatively different behavior. Based on dumping frequency analysis of the dependence of the phase angle $\phi$ on the switching frequency $\omega_s$ we develop improved direct phase control method and verify its performance with simulations and measurements on a prototype of a full-bridge series resonant inverter for induction heating.

II. DIRECT PHASE CONTROL METHOD

Fig. 1 shows a block diagram of the feedback control circuit used in the direct phase control of full-bridge series-resonant inverter. It comprises of a current transformer that measures the resonant circuit (output) current, a zero crossing detector that gives zero voltage when $i_{\text{out}}(t) < 0$ and positive voltage when $i_{\text{out}}(t) > 0$, a microcontroller that implements the control algorithm, optocoupler galvanic isolation, a driver circuit that supplies firing pulses to the IGBT switches and a feedback circuit for IGBT overload protection measuring collector-emitter voltages $v_{\text{CE}}$ to limit currents through T1 to T4.

Fig. 1. Block diagram of the full-bridge series-resonant inverter.
The microcontroller program has predefined values for the initial value of the switching frequency $f_{s,ref}$ (or period $T_{s,ref} = 1/f_{s,ref}$) and the desired or the reference phase difference between the output voltage and current $\varphi_{s,ref}$. This phase difference would be zero or close to zero if maximum power transfer is needed, or have a specific value that corresponds to the desired output power when we like to control the power transfer.

Fig. 2 shows the output voltage and current waveforms in the more usual above-resonance mode of operation. In induction heating/melting and similar applications the heated work-piece equivalent electrical parameters are part of the resonant circuit. As the work-piece temperature increases, its equivalent resistance and inductance change, thus changing the circuit resonant frequency. Consequently, the deviation of the switching frequency from the resonant one is also changed, which results in undesired change of output power.

To maintain the desired output power the switching frequency needs to be adjusted. Control methods [10, 11] achieve this by adjusting the interval $T_{\text{delay}}$ (after which T3 and T4 are switched off, and T1 and T2 switched on) according to (1).

$$T_{\text{delay}} = \frac{T}{2} - T_{\text{p,ref}} = \frac{T}{2} - \varphi_{\text{ref}} \frac{T}{360^\circ} \quad (1)$$

The new values of the positive half-period and consequently the new switching frequency are determined by the desired phase angle which makes this method a direct phase control. The new switching frequency are determined by the desired phase angle dependence on the deviation of the switching from the resonant damping frequency.

III. PHASE ANGLE DEPENDENCE ANALYSIS

Analysis of the series-resonant converters usually use the voltage and current first harmonics to determine the circuit parameters and behavior. Assuming that the resistance in the circuit is small, the resonant frequency $\omega_0$ is used in the calculations. To show the difference in these two approaches we first review the results with sine-wave voltage excitation and then elaborate the square-pulse excitation case.

A. Sine-wave excitation

When a series resonant circuit is excited by a sine wave voltage, all waveforms have the same shape and the current phase $\varphi$ in respect to the voltage is a well known relation (2):

$$\varphi = \arctg \left[ \frac{\omega_0 - \omega_s}{\omega_0 + \omega_s} \right] \quad (2)$$

where $\omega_s$ is the switching, $\omega_0 = 1/(LC)^{1/2}$ the resonant angular frequency and the quality factor is $Q = \omega_0 L/R = 1/(\omega_0 RC)$.

The range of values for $Q$ and $\omega_0$ can be obtained using the real parameter values of the prototype resonant inverter for induction heating (used for method verification at the end of this paper) with rated power of 10 kW: $R = 0.24 \, \Omega$, $L = 26.5 \, \mu\text{H}$, $C = 26.6 \, \mu\text{F}$. Using these parameters' values it is obtained that $\omega_0 = 37664 \, \text{rad/s}$ ($f_0 = 5994 \, \text{Hz}$) and $Q = 4.16$. Table I summarizes $\omega_0$, $f_0$ and $Q$ values with typical R and L change of ±50% during metal-piece induction melting. Fig. 3 shows the phase $\varphi$ change dependence on normalized switching frequency $x = \omega_0/\omega_s$ for three values for $Q = 3, 4$ and 5.

<table>
<thead>
<tr>
<th>R (Ω)</th>
<th>$\Delta R/%$</th>
<th>L (µH)</th>
<th>$\Delta L/%$</th>
<th>$\omega_s$(rad/s)</th>
<th>$f_0$ (Hz)</th>
<th>Q</th>
<th>$\Delta\omega_s/%$</th>
<th>$\Delta Q/%$</th>
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<td>0.12</td>
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<td>13.25</td>
<td>-50</td>
<td>33 266</td>
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<td>26.50</td>
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<td>5994</td>
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<tr>
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<td>39.75</td>
<td>-50</td>
<td>30 753</td>
<td>4 895</td>
<td>3.35</td>
<td>-18</td>
<td>-18</td>
</tr>
</tbody>
</table>

![Fig. 3. Phase angle $\varphi$ dependence on $x = \omega_0/\omega_s$ for $Q = 3, 4$ and $5$.](image)

B. Square pulse excitation

Let us now consider the series-resonant circuit excited by voltage pulses. If the voltage is in form of the Heaviside step function, then the current oscillates around zero with angular dumping frequency $\omega_0$ as shown in Fig. 4. When the voltage has square pulses waveform (duty ratio $D = 0.5$) and amplitude $\pm V_{DC}$ then in every half-period the current is a piece of the dumped oscillation of Fig. 4 and looks like the waveform shown in Fig. 2. In the steady state the negative half-period waveform is symmetrical to the positive one in respect to the
Dividing (9) by (7) we obtain:

\[(8) \frac{d(t)}{dt} = \frac{\epsilon \sin(\omega t)}{L C} \]

The solution in this case is the under-damped one \((\alpha < \omega_0)\) since the current oscillates (Fig. 4), it has no DC component and \(\phi\) is not taken into account in many analysis and papers. The figure shows that there is a considerable difference, especially further away from the resonance point. However, making PSpice simulations and measuring the phase angle time equivalents \(T_p\) it was noticed that they have very close values in the above-resonance region as can be clearly seen in Fig. 8. Analyzing this fact lead us to a very interesting conclusion. Namely \(\phi_0\) is calculated in a different way in both cases. When the circuit excitation is sinusoidal, the current is in the form:

\[i(t) = I_{max} \sin(\omega_0 t - \phi) = I_{max} \sin(\omega_0(t - t_p)) \]

and finally: \(\phi = \arctan \left( \frac{\sin(\pi \frac{\omega_1}{\omega_0})}{\epsilon \frac{\omega_1}{\omega_0} + \cos(\pi \frac{\omega_1}{\omega_0})} \right) \)

Relation (12) is graphed in Fig. 5 for \(Q = 3, 4\) and 5 and shows considerably different behavior than (2) and Fig. 3. The function is not monotoneous and it "oscillates" below resonance \((x = \omega_1/\omega_0 < 1)\) having negative, but also positive values for \(\phi\).

To verify this rather strange dependence, Fig. 6 gives PSpice simulation results of steady-state for several values of the switching frequency below and above resonance. Phase angles measured in these waveforms match and verify results obtained by (12). Also, the current waveform for \(f_s = 0.5f_d\) or \(f_s = 0.6f_d\) shows that it is very much distorted deep below resonance, the first harmonic is no longer dominant, which reflects to the amount of active power transferred to the load. This explains why below-resonance mode of power control is less desirable. The first diagram in Fig. 6 for \(f_s = 0.5f_d\) shows that (12) gets zero values every time the switching period \(T_s\) is multiple of the dumping one \(T_d\), in this case \(T_s = 2T_d\).

C. Comparison of the sine and the pulse excitation cases

A comparison of the phase angle \(\phi\) dependence on \(\alpha_0\) in both cases, with sinusoidal and pulse excitation, is given in Fig. 7. The switching angular frequency \(\alpha_0\) is normalized, in the first case with the resonant \(\alpha_0\), and in the second with the dumping angular frequency \(\alpha_d\). To verify this rather strange dependence, Fig. 6 gives PSpice simulation results of steady-state for several values of the switching frequency below and above resonance. Phase angles measured in these waveforms match and verify results obtained by (12). Also, the current waveform for \(f_s = 0.5f_d\) or \(f_s = 0.6f_d\) shows that it is very much distorted deep below resonance, the first harmonic is no longer dominant, which reflects to the amount of active power transferred to the load. This explains why below-resonance mode of power control is less desirable. The first diagram in Fig. 6 for \(f_s = 0.5f_d\) shows that (12) gets zero values every time the switching period \(T_s\) is multiple of the dumping one \(T_d\), in this case \(T_s = 2T_d\).

\[t_p = \frac{\phi}{\omega_0} = \frac{T_d}{2\pi} \]

Relations (14) and (16) are similar, but profoundly different: \(\alpha_0\) and \(T_d\) are constants determined by the circuit parameters, while \(\alpha_d\) and \(T_s\) are variables that are changed by the control method and are used as x-axis in Figs. 7 and 8. This also shows that in the case with voltage pulses, the correct way to measure and calculate the phase angle is by using (16) which is not taken into account in many analysis and papers.

IV. NEW METHOD DEVELOPMENT

The main objective of the control method is to adjust the switching frequency so that the desired phase angle and power transfer are obtained. To do so, the feedback circuit in Fig. 1...
Fig. 5. Dependence of the phase angle $\phi$ on the normalized value $\omega_0/\omega_s$ for $Q = 3, 4$ and $5$, when excited by voltage pulses.

Fig. 6. Steady state voltage and current waveforms below and above resonance ($R = 0.24 \Omega$, $L = 26.5 \mu H$, $C = 26.6 \mu F$ and $Q = 4$).

Fig. 7. Comparison of the phase angle $\phi$ dependence on $\omega_0$ for $Q = 4$: (a) sinusoidal excitation, $x = \omega_0/\omega_d$; (b) pulse excitation, $x = \omega_0/\omega_d$.

Fig. 8. Comparison of the phase angle time equivalent $t_\phi$ dependence on $\omega_0$: (a) sinusoidal excitation, $x = \omega_0/\omega_d$; (b) pulse excitation, $x = \omega_0/\omega_d$.

has possibilities to measure the time between current zero crossings and instants when the switches are turned on or off. This means that the control method as input has the values of the previous cycle switching period $T_{s,i-d}$ and the current cycle phase angle time equivalent $t_{\phi,i}$. Having these measured values, the method should determine the new switching frequency $T_{s,i}$ at which the $\phi_i$ and $t_{\phi,i}$ have the desired or reference values.

To determine $T_{s,i}$ knowing $T_{s,i-1}$ and $t_{\phi,i}$, the implicit equation (18) can be used, that now has the form:

$$t_{\phi,i} = T_{s,i} \cdot \arctg \left( \frac{\sin(\frac{\pi}{T_{s,i}} T_{s,i-1})}{\cos(\frac{\pi}{T_{s,i}} T_{s,i-1})} \right)$$

Then $T_{s,i}$ is determined using now the implicit equation (12) and $T_{s,i}$ and $\phi_{ref}$ as known parameters:

$$\phi_{ref} = \arctg \left( \frac{\sin(\frac{\pi}{T_{s,i}} T_{s,i})}{\cos(\frac{\pi}{T_{s,i}} T_{s,i})} \right)$$

Finally, the interval $T_{delay,i}$ is calculated using (1):

$$T_{delay,i} = \frac{T_{s,i}}{2} - t_{\phi,i}$$

All these calculations should be solved numerically before the positive half-period ends, i.e. during $T_{delay}$ time. Having in
mind that $T_r/2$ is less than 100 μs and $t_o$ in the order of 10 μs, it is not possible to do the calculations with low cost microcontrollers, so the equations need to be simplified.

A. Linearization of phase angle equations

One common approach in electrical engineering and electronics to simplify nonlinear equations is linearization using derivatives at the operating point ($x = 1$). This way a simple linear equation is obtained that matches the nonlinear curve very good around the operating point, and no so well away from that point. In the above-resonance region this linearization can be done on any of the two excitation cases since the curves almost overlap. Having in mind that the method uses time intervals ($T_r$ and $t_o$) the linearization is done on the $t_o = f(T_r)$ function, resulting in (23) and graphically presented in Fig. 9.

$$t_o = \frac{Q}{\mu} T_r (1 - \frac{T_r}{T_d})$$

Another way is to make linearization is to position the linear dependence in such a way so that there is smallest deviation from the curve on the entire range of $t_o$ change. To do so, the linear equation has to have a smaller slope, which can be achieved by multiplication by an additional coefficient $a < 1$, as in (24) and illustrated in Fig. 9 with the dashed line for $a = 0.75$ and the dotted line for $a = 0.5$.

$$t_o = a \frac{Q}{\mu} T_r (1 - \frac{T_r}{T_d})$$

B. Algorithm for the proposed direct phase control method

Based on the above analysis the method for the direct phase control consist of an algorithm with 8 steps:

1. Switch-off T1 and T2, and switch-on T3 and T4, (positive half-period starts, reset the $t_{o,i}$ register);
2. Wait for current zero crossing moment $i(t) > 0$ and measure time interval $t_{o,i}$;
3. Calculate $T_{\text{delay},i}$ using following equations:

$$T_{d, \text{ref}} = \frac{\mu}{Q} T_r; \quad T_{\text{delay},i} = \frac{\phi_{\text{ref}}}{2\pi} T_{d, \text{ref}}$$

$$T_{d,i} = T_{d, \text{ref}} - \frac{\phi_{\text{ref}}}{2\pi} T_{\text{delay},i} = \frac{T_{d,i}}{2} - t_{o,i}$$

4. Wait for time interval $T_{\text{delay},i}$;
5. Switch-on T1 and T2, and switch-off T3 and T4 (negative half-period starts, reset the $t_{o,i}$ register);
6. Wait for current zero crossing moment $i(t) < 0$ and measure time interval $t_{o,i}$;
7. Calculate $T_{\text{delay},i}$ using (25);
8. Wait for time interval $T_{\text{delay},i}$ and go to step 1.

The algorithm is graphically shown in Fig. 10.

V. VERIFICATION

To verify the improved method series of investigations have been done including mathematical calculations, PSpice simulations, code simulations in Proteus and hardware implementation. The method was tested in situations when there is abrupt change of $L$ and $R$ values, as well as with abrupt changes of the reference angle $\phi_{\text{ref}}$. Due to limited space in this paper only few of the simulations and experiments are presented.

Fig. 11 shows results for the change of $\phi_i$ obtained by a PSpice simulation of the method when there are simultaneous abrupt changes of the inductance value $L$ from 26.5 μH to 31.5 μH and the resistance $R$ from 0.24 Ω to 0.29 Ω, with the reference phase angle set to $\phi_{\text{ref}} = 5^\circ$. Results obtained for the method in [10, 11] are shown on the same graph to make a comparison. The amplitude of the oscillation of $\phi_i$ with the new method is smaller, and also the transient interval is shorter. A comparison and verification when the reference angle $\phi_{\text{ref}}$ is abruptly changed from 5° to 35° is shown in Fig. 12. Again, the amplitude of oscillation of $\phi_i$ before it settles to the new value with the new method is smaller and the transient interval is shorter, too.

Practical verification was done with algorithm implementation on a PIC18F4542 microcontroller and an IGBT full-bridge resonant inverter prototype shown in Fig. 13 [14, 15]. The prototype initially works with $f_c = 1.268$ Hz ($T_s = 788$ μs), resonant circuit parameters are $R = 0.5$ Ω, $L = 315$ μH, $C = 55$ μF ($Q = 4.77$) and the control circuitry is set to work with $\phi_{\text{ref}} = 22^\circ$ ($t_o = 0.80$ μs) to have output power of 40VA (Fig 14.a).
The inductor in this experiment is a coil with a moving ferromagnetic coil. When the coil is moved so that its inductance changes to \( L = 426 \mu\text{H} \) (35% change), the control algorithm successfully changes the switching frequency to \( f_s = 1.207 \text{Hz} \) (\( T_s = 828 \mu\text{s} \)) with \( \phi = 21.6^\circ \) (\( t_p = 58 \mu\text{s} \)) (Fig.14.b).

\[
\text{Fig. 11. PSpice results of the change of } \phi \text{ due to an abrupt changes of } L \text{ from } 26.5 \mu\text{H to } 31.5 \mu\text{H and } R \text{ from } 0.24 \Omega \text{ to } 0.29 \Omega \text{ with } \phi_{\text{ref}} = 5^\circ: (a) \text{ the new method and (b) the method in } [10, 11].
\]

\[
\text{Fig. 12. PSpice results of the change of } \phi \text{ due to an abrupt change of } \phi_{\text{ref}} \text{ from } 5^\circ \text{ to } 35^\circ: (a) \text{ the new method and (b) the method in } [10, 11].
\]

\[
\text{Fig. 13. Prototype of the series-resonant full-bridge inverter with the feedback, control and drive circuits.}
\]

\[
\text{Fig. 14. Oscillograms of the prototype } v_{\text{out}}(t) \text{ and } i_{\text{out}}(t) : (a) } L = 315 \mu\text{H with } T_s \text{ = } 788 \mu\text{s}, \text{ (b) after inductance change to } L = 426 \mu\text{H the period adjusts to } T_s = 828 \mu\text{s}. \text{ Ch1: } 5V/\text{div}, 250 \mu\text{s/}\text{div}; \text{ Ch2: } 2A/\text{div}, 250 \mu\text{s/}\text{div.}
\]

V. CONCLUSION

The analysis of the series resonant circuit excited by a square pulse voltage, obtained from a full-bridge converter, shows a considerably different dependence of the current phase angle on the switching frequency than in the case of sinusoidal excitation. More over, the phase angle in this case has to be calculated in respect to the damping frequency, which depends on circuit parameters, rather then in respect to the switching one, which is constantly varied by the control method. This fact is usually neglected in many analysis and papers.

Phase control provides reliable drive of the series-resonant inverters in the presence of large dynamic changes in the load impedance. Based on above analysis, improvements to the direct phase control method are made. Linearization of the method equations has been made to facilitate its implementation with low cost microcontrollers. An algorithm for digital implementation and method verification with simulations and a prototype are presented at the end of the paper.

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EUROCON 2015

08-11 September 2015
Salamanca, Spain

IEEE Catalog Number: CFP15EUR-CDR

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Ivan Androcec, Hrvatska elektroprivreda d.d., Croatia
Ivan Rajšl, University of Zagreb, Croatia
Ivan Kastelan, University of Novi Sad, Serbia
Ivan Macia, Vicomtech, Spain
Ivars Beinarts, LATNET, Latvia
J. David Nuñez-Gonzalez, University of Basque Country, Spain
Jaime Ramirez-Angulo, New Mexico State University, USA
Jan Verveckken, Catholic University of Leuven, Belgium
Jan Haase, Helmut Schmidt University of the Federal Armed Forces, Germany
Jarmila Pavlovičová, Slovak University of Technology in Bratislava, Slovakia
Javier Perez, Genomics and Bioinformatics Platform of Andalusia (GBPA), Spain
Jean Marie Darmanin, University of Malta, Malta
Jean-Marie Vella, University of Malta, Malta
Jesus Alonso, University of Las Palmas de Gran Canaria, Spain
Jesus Fraile-Ardanuy, Universidad Politecnica de Madrid, Spain
Jianguo Ding, University of Skövde, Sweden
Joao Matos, Instituto de Telecomunicacoes - Polo de Aveiro, Portugal
Joao Paulo Papa, UNESP - Univ Estadual Paulista, Brazil
Jon Andoni Barrena, Mondragon University, Spain
Jordi Sole-Casals, University of Vic, Spain
Jordi Solé-Casals, University of Vic - Central University of Catalonia, Spain
Jorge Sevilla, University of Extremadura, Spain
Jose Antonio-Daviu, Universitat Politècnica de Valencia, Spain
José Ángel Sánchez, Technical University of Madrid, Spain
José M. de La Rosa, CSIC, Spain
Jose Manuel Lopez-Guede, Basque Country University, Spain
José Miguel Franco-Valiente, Ciemat, Spain
Josu Antinda, Ingeteam Technology, Spain
Josu Maioria, University of the Basque Country, Spain
Jozef Pokusny, Pokusna, Slovakia
Juan C. Dueñas, Universidad Politécnica de Madrid, Spain
Juan Pedro Lopez, Universidad Politècnica de Madrid, Spain
Juergen Mottok, LaS³, OTH Regensburg, Germany
Julia Merino, Tecnalia, Spain
Kaminski Marcin, Wroclaw University of Technology, Poland
Karmele López, University of the Basque Country, Spain
Khaled Mohamed, Mentor Graphics, Egypt
Kim Grutfner, OFFIS, Germany
Krunoslav Ivesić, FER, Croatia
Krzysztof Szabat, Wroclaw University of Technology, Poland
Ksenia Lomovskaya, National Research University of Electronic Technology (MIET), Russia
Kuljaca Ognjen, Brodarski institut, Croatia
Lakhllef Hicham, University Of Franche-Comte, France
Lars Svensson, Chalmers University of Technology, Sweden
Larysa Globa, National Technical University of Ukraine "KPI", Ukraine
Laszlo Lengyel, BME DAAI, Hungary
Leire Ozaeta, University of the Basque Country, Spain
Lekic Nedjeljko, University of Montenegro, Montenegro
Liu Yu-Sian, National Chiao Tung University, Taiwan
Luciano Agostini, Universidade Federal de Pelotas, Brazil
Luís Cruz, Instituto de Telecomunicações - Coimbra, Portugal
Lukasz Kulas, Gdańsk University of Technology, Poland

M

M. Slanina, Brno University of Technology, Czech Republic
Mabed Hakim, University of Franche-Comté, France
Maglaras Athanasios, Technological Educational Institute of Larissa, Greece
Majda Petric, University of Belgrade, Serbia
Maksim Shudrak, Siberian State Aerospace University, Russia
Malyutin Alexandr, JSC “Concern “Sozvezdie”, Russia
Manuel Graña, ENGINE centre, Wroclaw University of Technology, Poland
Manuel Vázquez, ICMMA-CSIC, Spain
Marcos Faundez-Zanuy, Tecnocomputación, Spain
Marcus Svoboda, Politechnical University of Timisoara, Romania
María Botín-Fernández, Ciemat, Spain
María Julia Fernández-Getino, Charles III University of Madrid, Spain
María-Alexandra Paun, University of Cambridge, United Kingdom
Mario Cifrek, University of Zagreb, Croatia
Mario Alvarado, MINES ParisTech, France
Marjan Gusev, Faculty of Natural Science and Mathematics, Macedonia
Marta Pla-Castells, Universitat de Valencia, Spain
Mathinus Booyse, Stellenbosch University, South Africa
Matthias Sauppe, Technische Universität Chemnitz, Germany
Matthias Wolff, Brandenburg University of Technology, Germany
Maxim Dybko, Novosibirsk State Technical University, Russia
Michaël Bourdoulis, University of Patras, Greece
Michele Albanò, CISTER/ISEP, Politecnico Institute of Porto, Portugal
Miguel Angel Guevara, University of Aveiro, Portugal
Mihail Antchev, Technical University - Sofia, Bulgaria
Mihail Galanu, West University of Timisoara, Romania
Mile Jovanov, Faculty of Natural Science and Mathematics, Skopje, Macedonia
Milica Pejanovic-Djurisic, University of Montenegro, Montenegro
Milos Oravec, Slovak University of Technology Bratislava, Slovakia
Milos Borenovic, University of Westminster, United Kingdom
Minas Dasygénis, University of Western Macedonia, Greece
Mirko Palazzo, ABB Switzerland, Switzerland
Mohammad Hasan, University of North Carolina at Charlotte, USA

N

Najeeb Ullah, Politecnico Di Torino, Italy
Nariman Rahmanov, CPEE, Azerbaijan

P

Padma Iyenghar, University of Osnabrueck, Germany
Paul Micalef, University of Malta, Malta
Pawel Ksieniewicz, Wroclaw University of Technology, Poland
Pedro Valero, BACM, Spain
Pedro A. Amado Assuncão, Portugal
Peter Glosekovtzeff, University of Munster, Germany
Petre - Marian Nicolae, University of Craiova, Romania
Pilar Calvo, University of the Basque Country, Spain
Poles Damir, Croatia Control, Croatia
Premek Brada, University of West Bohemia, Czech Republic

R

Radonjic Milutin, University of Montenegro, Montenegro
Raman Ramsin, Sharif University of Technology, Iran
Reuben A. Farrugia, University of Malta, Malta
Reza Malekian, University of Pretoria, South Africa
Riaan Stopforth, University of KwaZulu-Natal, South Africa
Richard Lipka, University of West Bohemia, Czech Republic
Roberto Alvaro-Hernana, UPM, Spain
Roberto Dominguez, University of Seville, Spain
Roc Berenguer, CEIT, Spain
Roger Achkar, AUST, Lebanon
Rosa Guadalupe Gonzalez, Pontificia Universidad Católica de Valparaíso, Chile
Ruth Leao, Universidade Federal do Ceará, Brazil
Ruxandra Mihaela Botez, École de Technologie Supéérieure, Canada

S

Samia Loucif, ALHOSN University, United Arab Emirates
Salvatore Cannella, University of Seville, Spain
Sameer Alawnah, American University of Sharjah, United Arab Emirates
Sandhya Pattanayak, Narula institute of technology, India
Sandra Castaño, Universidad Carlos III de Madrid, Spain
Sarunas Paulikas, Vilnius Gediminas Technical University, Lithuania
# Table of Contents

Welcome ......................................................................................................................... 1
Committees ..................................................................................................................... II
Program Committee ......................................................................................................... III
Partners .......................................................................................................................... VII
Table of Contents .......................................................................................................... VIII
Plenary Speakers ............................................................................................................ 1

## Track 1: Information and Communication Technology

- **Computational intelligence: general** ................................................................. 8
- **Radio** .................................................................................................................. 9
- **Image and video processing** .............................................................................. 10
- **Coding** ............................................................................................................... 11
- **Networks** ........................................................................................................... 12
- **Security and reliability** .................................................................................... 13
- **Database systems and webservices** ................................................................. 14

## Track 2: Circuits, Systems, and Signal Processing

- **Circuits and systems** ....................................................................................... 15
- **Systems and applications** .............................................................................. 16
- **Signal processing** ........................................................................................... 17

## Track 3: Power Resources and Systems

- **Electric vehicle, active demand control and distributed storage** .................. 20
- **Electrical machines** ....................................................................................... 21
- **Power electronics applications** ...................................................................... 22
- **Electric market applications** ......................................................................... 23
- **Smart grids and power systems modelling** .................................................. 24
- **Renewable energy applications** .................................................................. 25

Student Paper Contest ................................................................................................. 26
Intelligent Systems and Applications ......................................................................... 28

Computer: Tool for Signal/Image/Video Processing and Intelligent Systems ........... 30

Image and Signal Processing for High Performance Computing environments .... 32
Workshop on Magnetic Materials for Energy Applications .................................... 34
Workshop on Micro/Nanoelectronic Circuits and Systems ...................................... 36

Author Index ............................................................................................................... 38
Track 3: Power Resources and Systems

Chair:
  Jesús Fraile-Ardanuy
Session 03
Power electronics applications

Primary Control Operation Modes in Islanded Hybrid ac/dc Microgrids
Eneko Unamuno and Jon Andoni Barrena.

Small Signal Assessment of an AC System Integrated with a VSC-HVDC Network
Duc Nguyen Huu.

Adaptive Coordinated Droop Control for Multi-Battery Storage
Duc Nguyen Huu and Hung Truong Nam.

An Ultra-Low-Power Boost Converter for Micro-Scale Energy Scavenging
Mahmoud R. Elhebeary, Mohamed M. Aboudina and Ahmed Nader Mohieldin

Harmonic and Imbalance Voltage Mitigation in Smart Grids: A DSTATCOM Based Solution
Pedro Roncero-Sanchez and Enrique Acha.

Control and Stability Analysis of Interfaced Converter in Distributed Generation Technology

Direct Phase Digital Control Method in Power Inverters Based on Dumping Frequency Analysis
Ljupco Karadzinov and Goce Stefanov.