©2016 Published in 4th International Symposium on Innovative Technologies in
Engineering and Science 3-5 November 2016 (ISITES2016 Alanya/Antalya - Turkey)

An Efficient Control Approach for DC-DC Buck-Boost Converter

*[1]Faruk Yalçın and [2]Felix A. Himmelstoss
*[1]Faculty of Technology, Department of Mechatronics Engineering Sakarya University, Turkey
[2]Department of Electronic Engineering University of Applied Sciences Technikum Wien, Austria

Abstract

In this paper, an efficient control structure based on a PI controller for DC-DC buck-boost converter operation is proposed. By the proposed approach, accurate pulse width modulation (PWM) switching based operation duty ratio of the buck-boost converter is achieved by the closed-loop PI controller. The control law based on instantaneous values of the input voltage and the desired output voltage is used to support the PI controller to achieve an efficient and fast operation duty ratio. So the efficiency of the converter is improved to gain the desired high quality output voltage when the parameters of the converter operation are changed. Simulation studies have been done in MATLAB-Simulink to prove the efficiency of the proposed control approach based on the PI controller supported by the control law. The obtained results have shown that the proposed control approach achieves accurate and efficient operation for the buck-boost converter under different system conditions.

Key words: Buck-boost converter, control law, PI controller, PWM

1. Introduction

The improving technology needs continuously various forms of the electrical energy. So, different types of converters were developed based on the improvements in power electronics. DC-DC converters are used to convert a DC source from one voltage level to another. These converters are widely used in many industrial applications where direct voltage regulation is required [1-3].

The DC-DC buck-boost converter produces an output direct voltage value lower or higher than the input voltage value [4]. The voltage transformation is achieved by pulse width modulation PWM. The duty ratio controls the buck-boost converter as is the case in other DC-DC converters e.g. in buck and boost converters [5, 6]. Considering ideal devices and continuous inductor current mode conditions, the relation between the converter input and output voltages in steady state can be derived as an algebraic equation which depends on the PWM duty ratio alone. But in practice, discontinuous current mode converter operation and non-ideal converter components prevent to achieve a certain duty ratio for converter operation for the related operating point through mathematical computation. Thus, a feedback control structure for practical converter operation depending on the actual and the reference output voltage values is obviously required for accurate converter operation [7].

The researchers have studied the control of the DC-DC buck-boost converter on many different controllers. The controller processes the error between the converter reference and the real output

*Corresponding author: Address: Faculty of Technology, Department of Mechatronics Engineering Sakarya University, 54187, Sakarya TURKEY. E-mail address: farukyalcin@sakarya.edu.tr, Phone: +902642956473

voltage and eliminates the error by generating the necessary duty cycle. The conventional PI and PID controllers are generally used to control DC-DC buck-boost converters [8, 9]. Modern control techniques such as the Sliding Mode Controller are also successfully applied to many studies, where the PI and PID controllers are not sufficient for the required converter responses [10]. The designs of these mentioned controllers are achieved through the mathematical models for the defined converter operating points. So, any change of the converter system parameters forces the change of the mathematical model of the converter. As the mathematical model of the converter is changed, it is impossible to achieve the same performance of the system response by the designed controller parameters obtained for the previous converter operating point. This statement is valid for classical and modern designs. A non-adaptive controller has to be designed especially for one working point, but must be able to control the system in a precise and stable way and within a time restriction for the whole area of working points where the converter is planned to work.

A major pitfall in controlling the buck-boost converter (and also in the fly-back converter which is a buck-boost with the possibility to get an isolation between input and output) is its right-side zero. Different ways were used to improve the control [11, 12].

In this study, a novel DC-DC buck-boost converter control strategy based on the PI controller and an open-loop control law is proposed. In this control structure, the operating duty ratio for the converter is achieved by the PI controller and the proposed open-loop control law. The open-loop control law supports the PI controller to eliminate the converter operating error in a fast and efficient manner. Thus, the open-loop control law accelerates the system response. So, the control law prevents the requirement of changing the determined controller parameters for various converter operating points. The control law is the switching duty ratio depending on the converter input voltage and the reference output voltage and has an algebraic structure. So, the control law can be achieved easily and fast. Thus, it does not cause additional design challenges and complexity. Simulation studies have been done for the proposed control approach for the DC-DC buck-boost converter in MATLAB-Simulink environment. The obtained simulation results for different operating points have proved that the proposed control structure based on the open-loop control law allows a robust and efficient DC-DC buck-boost converter operation.

2. Design of the Proposed Converter Control Structure

2.1. The open-loop control law

The DC-DC buck-boost converter topology is given in Fig. 1 [13]. In Fig. 1, $V_i(t)$, $V_o(t)$, S, D, L and C represent the input direct voltage, the output direct voltage, the switch that is one way conductive and capable of being turned on and turned off, the diode, the inductor, and the capacitor, respectively.

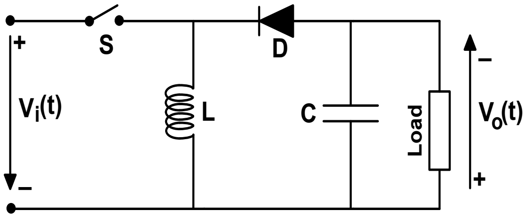

Figure 1. The topology of the DC-DC buck-boost converter

An IGBT device is used as switch S in this study. The DC-DC buck-boost converter circuit using a controllable IGBT as switching device is demonstrated in Fig. 2. In Fig. 2, $I_o(t)$, $I_L(t)$ and $I_C(t)$ represent load current, inductor current, and capacitor current, respectively.

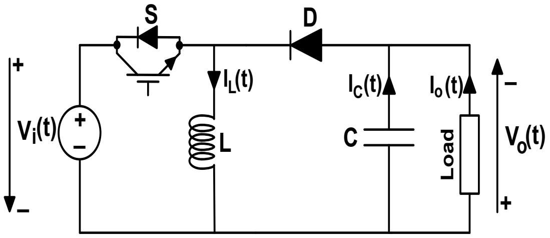

Figure 2. The DC-DC buck-boost converter circuit using IGBT as switching device

The operation of the DC-DC buck-boost converter can be clarified by the converter circuit given in Fig. 2. When S is turned on, diode D is off because of reverse biasing. In this case, converter input voltage supplies the inductor, thus the inductor is energized. When S is turned off, the diode is forward biased and turned on. In this case, the energized inductor supplies both the capacitor and the load. Thus, a voltage value lower or higher than the input voltage value is obtained at the output of the converter depending on the switching duty ratio of S [14]. By assuming the continuous current mode (CCM) and ideal converter components, the relation between the converter input and output voltages can be given as [15]:

$$V_o(t) = \frac{d(t)}{1-d(t)} V_i(t), \tag{1}$$

where $d(t)$ determines the PWM switching duty ratio of S. It is defined as the ratio of the turn-on time of S to the switching period of S:

$$d(t) = \frac{t_{on}}{T}. \tag{2}$$

The open-loop duty ratio that provides the converter operation can be achieved through (1) considering the mentioned ideal conditions above. Thus, the open-loop duty ratio, which is used as control law and can be given as:

$$d_{CL}(t) = \frac{V_r}{V_r + V_i(t)}, \tag{3}$$

where V_r is the reference value of the desired converter output direct voltage.

2.2. The proposed closed-loop converter control structure

Because of the unideal reasons mentioned before, the derived open-loop control law is not enough to achieve the required converter output voltage value in practice. Because of the non-ideal converter components and discontinuous inductor current situation caused by different load values, the duty ratio of the converter providing the required output voltage is different from the duty ratio obtained by the open-loop control law. So, the real converter duty ratio that eliminates the error between the reference and real output voltage must be obtained from the closed-loop controller. For this aim, the PI controller is chosen in this study. The proposed control structure for the control of the DC-DC buck-boost converter is given in Fig. 3.

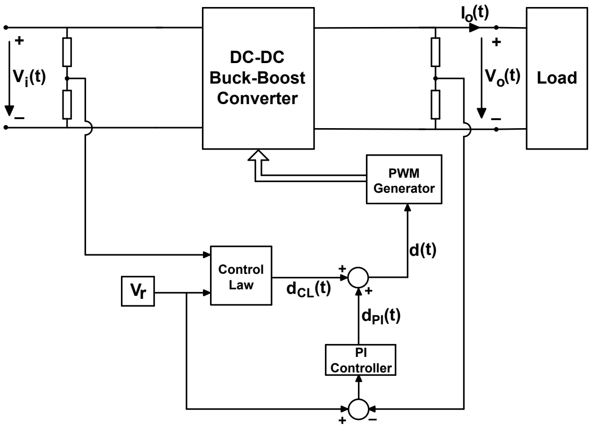

Figure 3. The proposed closed-loop control structure for the DC-DC buck-boost converter

As can be seen from Fig. 3, the PI controller produces a feedback duty ratio $d_{PI}(t)$ from the error between the reference and actual converter output voltages. The open-loop duty ratio $d_{CL}(t)$ given in (3) supports the feedback duty ratio $d_{PI}(t)$ achieved by the PI controller. Thus, the effective duty ratio $d(t)$ for accurate converter operation is produced by

$$d(t) = d_{CL}(t) + d_{PI}(t). \tag{4}$$

As seen from Fig. 3, the PWM generator produces the control signal of the switch S depending on the duty ratio derived by (4).

2.3. Mathematical model of the converter for the PI controller

The PI controller can be designed by the mathematical model of the converter circuit given in

Fig. 2. The mathematical model of the idealized converter (no loss mechanisms included) can be derived from the equivalent converter circuits given in Fig. 4.

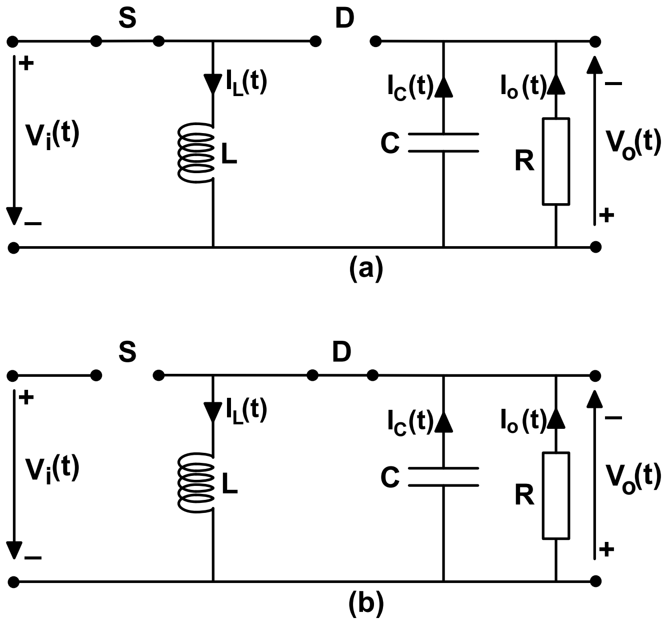

Figure 4. Equivalent circuits of the converter: a) Switch S is on – mode I, b) Switch S is off – mode II

The dynamic equations for mode I where S is on in Fig. 4(a) can be given as:

$$L\frac{dI_L(t)}{dt}=V_i(t) \tag{5}$$

$$C\frac{dV_o(t)}{dt}=-\frac{V_o(t)}{R}. \tag{6}$$

The dynamic equations for mode II where S is off in Fig. 4(b) can be written as:

$$L\frac{dI_L(t)}{dt}=-V_o(t) \tag{7}$$

$$C\frac{dV_o(t)}{dt}=I_L(t)-\frac{V_o(t)}{R}. \tag{8}$$

The state-space equations for mode I and mode II can be obtained from (5)-(8) respectively as:

$$\frac{d}{dt}\begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix}=\begin{bmatrix} 0 & 0 \\ 0 & -1/RC \end{bmatrix}\begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix}+\begin{bmatrix} 1/L \\ 0 \end{bmatrix}V_i(t) \tag{9}$$

$$\frac{d}{dt}\begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} = \begin{bmatrix} 0 & -1/L \\ 1/C & -1/RC \end{bmatrix}\begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_i(t). \tag{10}$$

and the average state-space model of the DC-DC buck-boost converter can be derived from (9) and (10) as:

$$\frac{d}{dt}\begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} = \begin{bmatrix} 0 & -(1-d)/L \\ (1-d)/C & -1/RC \end{bmatrix}\begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} + \begin{bmatrix} d/L \\ 0 \end{bmatrix} V_i(t). \tag{11}$$

The closed-loop control block diagram of the system is shown in Fig. 5 according to the closed-loop control structure given in Fig. 3.

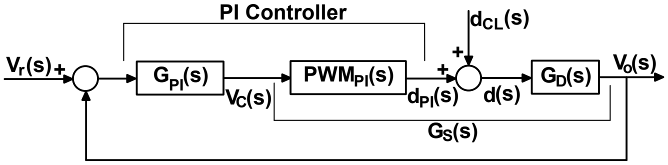

Figure 5. The closed-loop control block diagram of the system

The transfer function between $V_o(s)$ and $d(s)$ can be obtained from Fig. 5 and (11) (the working point values are marked with an index W) as:

$$\frac{V_o(s)}{d(s)} = \frac{-s\dfrac{I_{LW}}{C} + \dfrac{(V_{oW}+V_{iW})(1-d_W)}{LC}}{s^2 + s\dfrac{1}{RC} + \dfrac{(1-d_W)^2}{LC}} \tag{12}$$

The converter transfer function shows that the buck-boost converter is a non-phase-minimum system. Therefore, we have an additional phase shift due to the right half-plane zero. The model described by (12) is a linearized model, and therefore enables us to use the linear control theory. As seen in Fig. 5, the duty ratio of the control law $d_{CL}(s)$ has an effect upon the operation duty ratio $d(s)$. By considering $d_{CL}(s)$ is zero (assuming there is no support from the control law), $d_{PI}(s)$ can be derived as:

$$d_{PI}(s) = d(s). \tag{13}$$

$PWM_{PI}(s)$ is the transfer function of the PWM stage between $d_{PI}(s)$ and the PI control signal $V_C(s)$ and can be given as:

$$PWM_{PI}(s) = \frac{d(s)}{V_C(s)} = \frac{1}{V_{PWM}}. \tag{14}$$

Here, V_{PWM} is the amplitude of the ramp in the PWM conversion of the PI controller. The PWM stage can be interpreted as a proportional element. So the transfer function of the system, which the transfer function of the PI controller $G_{PI}(s)$ has to control, is the product of (12) and (14).

The influence of the input voltage on the output voltage can be described by the disturbance model:

$$\frac{V_o(s)}{V_i(s)} = \frac{\dfrac{d_W(1-d_W)}{LC}}{s^2 + s\dfrac{1}{RC} + \dfrac{(1-d_W)^2}{LC}} \tag{15}$$

A PI controller has a dynamic structure. So it requires a response time. But the proposed control law has a static behavior as seen from its algebraic structure. The control law produces a duty ratio value close to the necessary operation duty ratio simultaneously with the error change. Thus, the control law leads the PI controller to compensate the system from the duty ratio point obtained by the control law. So the control law accelerates the system response. After that, the PI controller takes over the task from the control law to eliminate the system error. One has to keep in mind, however, that a too fast change in the duty cycle leads to an overshot in the current (and also in the voltage) and has therefore be omitted. This can be done similar to the soft-start of the system.

3. Simulation Results

The proposed control approach for the DC-DC buck-boost converter has been tested in MATLAB-Simulink environment for different system operating conditions. The obtained simulation results for the proposed approach are given with the results of the conventional PI controller based converter to show the accuracy and the efficiency of the proposed control approach for the DC-DC buck-boost converter operation. The comparison studies have been done for three different operation conditions: changing the reference output direct voltage, changing the input direct voltage and changing the load.

The switching frequency is chosen as 20 kHz for the simulation studies. The capacitance value of the capacitor and the inductance value of the inductor the in the converter circuit are determined as $\mathrm{C=330\,\mu F}$ and $\mathrm{L=50\,\mu H}$, respectively. The parameters of the PI controller are kept constant for all operation conditions. The analog PI constants determined for an operating point are used as $\mathrm{K_P=1.2}$ and $\mathrm{K_I=0.053}$.

For the first case, the reference output voltage is changed during the DC-DC buck-boost converter operation. The converter input voltage and the load values are kept constant. The input voltage and the load values are $\mathrm{V_i=30\,V}$ and $\mathrm{R=20\,\Omega}$, respectively. The reference output voltage is decreased from $V_r = 40\,\text{V}$ to $V_r = 25\,\text{V}$. The comparative results of the proposed approach and the conventional PI controller based converter operation for case 1 are given together in Fig. 6.

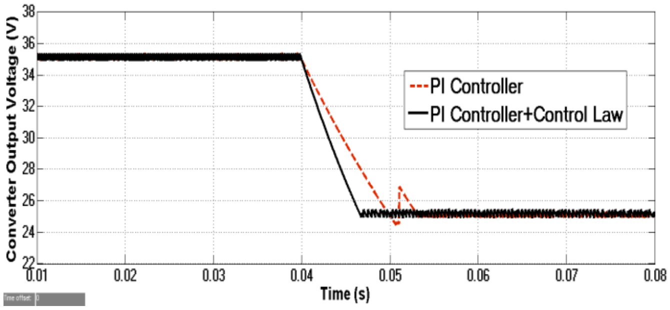

Figure 6. The comparative converter operation results for the change of the reference output direct voltage

Fig. 6 shows that the converter controlled by the proposed approach, where the proposed control law supports the PI control reaches the new reference output voltage faster than the converter controlled by the conventional PI controller. On the other hand, the proposed control approach prevents the overshot where the conventional method can not.

For case 2, the converter input voltage is changed during the reference output voltage and the load values are kept constant. The reference output voltage and the load values are $V_r = 30\,\text{V}$ and $R = 20\,\Omega$, respectively. The input voltage is changed from $V_i = 20\,\text{V}$ to $V_i = 35\,\text{V}$. The comparative results of the proposed approach and the conventional PI controller based converter operation for case 2 are given together in Fig. 7.

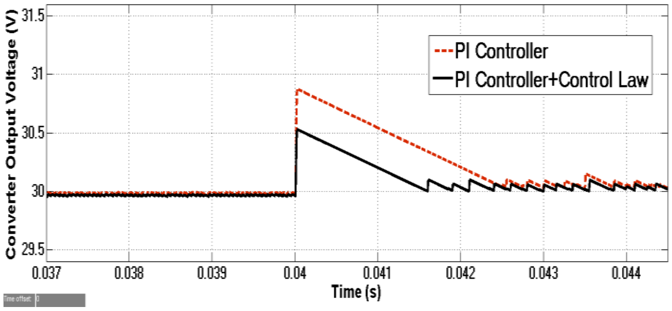

Figure 7. The comparative converter operation results for the change of the input direct voltage

Fig. 7 shows that the sudden rise of the input voltage affects the increase of the output voltages of both of the two converters. But it is clear that the proposed approach provides the converter output voltage to reach the reference value with less overshot in a less response time.

In case 3, the load is forced to change during the converter operation, while the reference output voltage and the input voltage of the converter are kept constant. The reference output voltage and the input voltage values are $V_r = 30\,\text{V}$ and $V_i = 45\,\text{V}$, respectively. The load is decreased from $R = 20\,\Omega$ to $R = 30\,\Omega$. The comparative results of the proposed approach and the conventional PI controller based converter operation for case 3 are given together in Fig. 8.

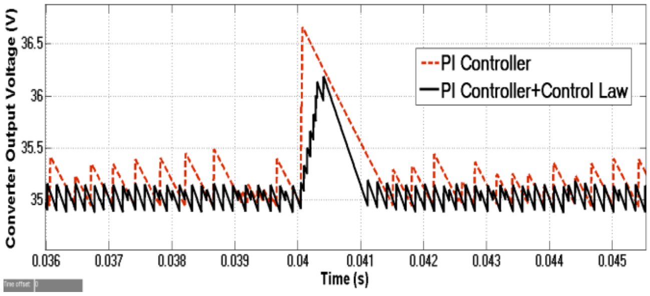

Figure 8. The comparative converter operation results for the change of the load

It is clear from Fig. 8 that the sudden increase in the load value affects the decrease of the output voltage in both of the two converter operations. At the beginning of the load change, the converters output voltages increase. After that, the output voltages decrease immediately. The proposed control structure based on control law provides the converter output voltage to return to the reference value with less overshot in a less response time.

The results for three different operation cases show that the proposed control law approach improves the DC-DC buck-boost converter operation efficiently through supporting the closed-loop PI controller structure. So a higher quality of the converter output voltage is achieved in comparison with the conventional PI controller based system.

4. Conclusions

In this study, contrary to the control structure based on the conventional PI controller, an improved control structure based on open-loop control law that supports the PI controller is proposed for the control of the DC-DC buck-boost converter. The proposed control law is obtained as an algebraic one depending on the reference output voltage and the input voltage of the converter. So it supports the PI controller and thus a better quality of the converter operation for different operation parameters of the PI controller is achieved. The obtained comparative simulation results have shown that the proposed approach has improved the converter operation.

References

[1] K.C. Wu, H.H. Wu, and C.L. Wei, “Analysis and design of mixed-mode operation for noninverting buck-boost DC-DC converters,” IEEE Trans. Circuits Syst. II-Express Briefs, vol. 62, pp. 1194-1198, December 2015.
[2] H. Zhang, M. Zhao, and X. Wu, “Zero-current switching method for dc-dc buck converter in portable application,” Electron. Lett., vol. 51, pp. 1913-1914, November 2015.
[3] E. Babaei and O. Abbasi, “Structure for multi-input multi-output dc-dc boost converter,” IET Power Electr., vol. 9, pp. 9-19, February 2016.
[4] Y. Ma, “Integrated lossless load current sensing method for buck-boost DC-DC converters,” Electron. Lett., vol. 51, pp. 88-90, January 2015.

[5] C.L. Kok, X. Li, L. Siek, D. Zhu, and J.J. Kong, “A switched capacitor deadtime controller for DC-DC buck converter,” IEEE Int. Symp. Circuits and Syst., p. 217-220, 2015.
[6] M. Hejri and H. Mokhtari, “Hybrid predictive control of a DC-DC boost converter in both continuous and discontinuous current modes of operation,” Optim. Contr. Appl. Met., vol. 32, pp. 270-284, May/June 2011.
[7] Z. Wu and J.H. Zhao, “Nonlinear output feedback control for DC/DC buck-boost power converters,” 6th Int. Symp. Test and Meas., p. 491-494, 2005.
[8] Z. Wu, J.H. Zhao, and J.Y. Zhang, “PI-adaptive cascade controller design for DC/DC buck-boost power converters,” 7th Int. Conf. Electron. Meas. Instrum., p. 426-430, 2005.
[9] Z. Wu and W. Chou, “Adaptive-PID cascade controller design for DC/DC buck-boost PWM power converters,” 3rd Int. Conf. Impul. Dynam. Syst. Appl., p. 896-901, 2006.
[10] M. Salimi, J. Soltani, A. Zakipour, and N.R. Abjadi, “Hyper-plane sliding mode control of the DC-DC buck/boost converter in continuous and discontinuous conduction modes of operation,” IET Power Electr., vol. 8, pp. 1473-1482, August 2015.
[11] F.A. Himmelstoss, J.W.Kolar, and F.C.Zach, “A Bidirectional DC-DC Converter - Analysis and Control Design,” Journal of Electronics and Telecommunication Engineers, Vol.37, No.1 1991, pp. 124-132.
[12] F.A. Himmelstoss, J.W. Kolar, and F.C. Zach, “Analysis of a Smith-Predictor Based Control Concept Eliminating the Right-Half Plane Zero of Continous Mode Boost and Buck-Boost DC/DC Converters,” Proceedings of the IEEE Industrial Electronics Conference IECON'91, Kobe, Oct.28 - Nov.1, 1991, pp. 423- 428.
[13] A. Ajami, H. Ardi, and A. Farakhor, “Design, analysis and implementation of a buck-boost DC/DC converter,” IET Power Electr., vol. 7, pp. 2902-2913, December 2014.
[14] M.R. Banaei, H. Ardi, and A. Farakhor, “Analysis and implementation of a new single-switch buck-boost DC/DC converter,” IET Power Electr., vol. 7, pp. 1906-1914, July 2014.
[15] J. Dey, T.K. Saha, and S.N. Mahato, “Robust voltage regulation of DC-DC PWM based buck-boost converter,” IEEE Int. Conf. Ind. Tech., p. 229-234, 2014.

Faruk Yalçın was born in Sakarya, Turkey in 1984. He received M.Sc. and Ph.D. degrees in electrical and electronics engineering from Sakarya University, Turkey, in 2009 and 2013, respectively. He is assistant professor at the Department of Mechatronics Engineering at the Faculty of Technology at Sakarya University, Turkey. His current research interests are power systems, smart grids, power electronics and control systems.

Felix A. Himmelstoss was born in 1956 in Moedling, Austria. He received the Dipl.-Ing. and Dr. (PhD) degrees from Technical University of Vienna, in 1981 and 1990, respectively. Since 1982 he has been working on different projects for Austrian companies developing power supplies and electrical drives. He is author and coauthor of numerous technical and scientific papers and patents. Dr. Himmelstoss is professor and head of the Industrial Electronics section of the University of Applied Sciences Technikum Wien.