Critical Review: Adaptive Pole Assignment PID Controller on DC-DC Converters

A W N Husna 1, M H Mat 2, M N M Yasin 3, M Juso4, Y M Irwan5, M S Abdul Rahim5 and S Md Esa5

1School of Electrical System Engineering, Universiti Malaysia Perlis, Malaysia
2Bioelectromagnetics Research Group (BioEM), Centre for Diploma Studies, Universiti Malaysia Perlis, Malaysia
3Bioelectromagnetics Research Group (BioEM), School of Computer and Communication Engineering, Universiti Malaysia Perlis, Malaysia
4Bioelectromagnetics Research Group (BioEM), School of Microelectronic Engineering, Universiti Malaysia Perlis, Malaysia
5Centre for Diploma Studies, Universiti Malaysia Perlis, Malaysia

nurulhusna.awb@gmail.com

Abstract. Recently, control usages of DC-DC converters have been widely investigated particularly in renewable energy; as the primary sources. Discovering the most appropriate control method to be applied in DC-DC converter topologies is the most significant interest of research and development in this field. Thus, the review is carried out in selecting a control method that capable to improve the functioning of the converters as well as reducing the effect of disturbances and load variances.

1. Overview of DC-DC converters

Recently, control applications of DC-DC converters have been widely investigated particularly in renewable energy; as the primary sources. The most important interest of research and development in this area is constantly to discover the very appropriate control technique to be employed in DC-DC converter topologies.

This paper reviews past work done for DC-DC converters controlled by an adaptive PID controller with the application of pole assignment method which is required on demand to achieve better performance of the overall system. Its rising importance in industrial applications and green technology is due to the need to improve the system so that it can be adapted with existing technology of renewable energy and become more efficient in manufacturing. All reviews come from different sources which consist of various methods, in order to obtain a comprehensive view about the latest technique and technology of controller for DC-DC converters. Thus, a comparative study can be done amongst converters and controllers involved so that a better performance can be obtained. Thus, the most important goal of this review is to study a recent method of adaptive pole assignment PID to control DC-DC converters.
2. Critical Review

PID controller has been designed in 1890s and since that there is a lot of improvement has been done on it thus more approaches were developed to adapt to the latest technology. From conventional method, nowadays PID was improved to the digital controllers that widely implemented with microcontroller, field-programmable gate array (FPGAs), or digital signal processor (DSP). This method has successfully developed through the design of DC-DC converters that controlled by DSP based on the implementation of a digital controller. Beginning by a DC-DC buck converter and a given set of functioning specifications, a digital PID controller is employed in TMS320F2812 DSP. In this work, the effectiveness of the design is established to analyze the steady state and dynamic response performance of the controller. A digital based PID control approach for a DC–DC buck converter has been introduced along with a digital implementation of the controller using DSP. At the end of this work, the experimental performance shows that; steady-state accuracy and settling time are consistent with the simulation results [1].

The classic technique for tuning a PID loop has become even more popular with the beginning of controllers capable of tuning themselves. The tuning techniques namely as Ziegler-Nichols, are still used nowadays even it was published in 1942. As referred to [2], specified that John “Zeke” Ziegler and Nathaniel Nichols may not have developed the proportional-integral-derivative (PID) controller, even though the PID system is the most common of entirely feedback control approaches used in industrial applications, but the well-known loop tuning methods designed by John “Zeke” and Nathaniel Nichols facilitated a lot in creating the PID controller as an outstanding controller. In fact, by tweaking a PID loop the responses of the controller to faults between the determined process variable besides desired set point can be tweaked. Doubt the controlled procedure happens to be fairly sluggish, the design of PID process will take instantaneous and remarkable actions whenever a random disturbance shifts the method variable, or an operator shifts the set point. These reviews stated that an adaptive technique that applied in DC-DC converters show an improvement in transient response besides it produced a superior performance in terms of system improved stability, disorder elimination and yield control. Nevertheless, all this can be achieved using PID controller. Furthermore, ringing and oscillation occurrence in transient response can be averted by smoothly transitioning between steady-state operation as well as dynamic transient operation. The proposed controller; PID has proven that the operation of DC-DC converters is not depending on any further hypothesis of the transient magnitudes or kinds.

In past a decade, the appliance of an adaptive PID controller has been attracting other researchers [3]. An immediate pole assignment control approach is announced during this workplace yet because the execution of a discrete-time controller within the model of a DC-DC buck converter has been used. The answer involves a feed forward component within the control strategy so as to remove steady-state inaccuracies. The worth of the feedback gain that's eliminates the steady-state error depends upon the gain of the plant, which cannot be known precisely. In their model, the feedback gain is adjusted adaptively to drive the steady state inaccuracy to zero. This method allows precise placement of the closed-loop poles as anticipated. so as for the steady-state error to be exactly zero using this feedback technique, the feedback gain must be determined exactly. As this can be impossible, they adapt the feedback gain using least-mean-square (LMS) techniques, so the control error is forced back to zero. The direct pole-placement could be a possible approach for DC-DC converter model which is permitting the choice of an easy complex conjugate pair of closed-loop poles, yet on establish a completely unique technique to achieve a zero steady-state error. With this work, the performance of a prototype compared very favorably with standard design methods. An adaptation of the feedback gain using LMS techniques was proven to be effective in driving the steady-state control error to zero.

A straightforward auto-tuning procedure for digitally dictated DC-DC synchronous buck converters was introduced by [4]. In this effort, the intended method is based on the relay feedback technique as well as the authors were presenting perturbations on the output voltage throughout converter soft start. Via utilizing an iterative method, the fine-tuning of PID parameters is achieved precisely by incorporating the controller in the relay feedback and by tweaking the controller factors based on control loop bandwidth along with the phase margin. A nice property of the planned solution is that output
voltage perturbations are presented as preserving the closed loop control of the digitally controlled converters. The suggested algorithm is minimal, involves minor tuning times and it is compatible with the complexity constraint of integrated digital ICs. Experimental investigation has been performed using discrete components, employing the digital control in an FPGA. Simulation and experimental results of a 1.5V–5A synchronous buck converter confirms the effectiveness of the proposed solution.

H. and Ran, Z. have discovered the study centered on the integrated circuit version for DC-DC converters [5]. In this work, the planned new controller is an altered single-neuron self-adaptive PID controller invented by applying the ‘Hebbian Learning Rule’ (HLR). Moreover, mimicking the PID control implementation as well as vigorous responses designed for the given DC-DC converter than evaluated by using Simulink. To assess the control implementations, an investigational on buck converter has been applied. discover out a rapid, simple and effective design method for the controller of DC-DC converters are well attained are the purpose of this work. Constructed on the aim, the integrated circuit model is utilized to develop new conventional prototypes for PWM DC-DC converters. Additionally, a straightforward single-neuron controller has been designed by utilizing the planned control scheme. The modeling and investigational outcomes are attained to demonstrate that the new controller has improved operations competed to the conventional PID device and the control approach might reduce to bare bones of the inventing method of standard smart controllers.

The application of fuzzy logic and PID controller has been explored by [6]. The state-space averaged prototype, is an appraised prototype, is utilized toward produce PWM DC-DC converters. As an Alternative, a process built on Orthogonal-Function Approach (OFA) merely relating arithmetic calculation is recommended in this work to exactly resolve the irregular vigorous calculations of the PWM DC to DC converters. The optimum fuzzy-immune-PID controller model challenge for a group of PWM DC to DC converters is changed into a constant optimizing parameters challenge that is characterized by algebraic equivalents based on the OFA. Instead, a PWM DC to DC converter, a fuzzy-immune-PID controller by merging the conventional PID controller, the fuzzy logic theory as well as the immune feedback law are considered to be a self-adaptive controller in their work to adapt the load variation. But then the Hybrid Taguchi-Genetic Algorithm (HTGA) is used for the static optimization challenge to discover the best possible parameters of the fuzzy immunizing PID controllers used by the PWM DC to DC converters. The recommended integrative technique, fusing the OFA together with the HTGA, is non-differential, non-integral, straightforward and well-adapted to computer application. The outputs from this proof that the recommended method yields an effective approach to synthesizing the best parameters of the PWM DC to DC converters ‘ fuzzy-immune-PID controllers. An algorithm engaged in this study, based on the OFA, is merely algebraic calculation to accurately resolve the uneven dynamic calculations of the DC to DC PWM converters. In addition, the algorithm presented is combined with the HTGA to synthesize the optimal parameters of the fuzzy immune PID controllers under the minimisation of an integral quadratic cost functional. Since the proposed method requires mere algebraic computation, the design methods of the ideal fuzzy-immune-PID controllers for the PWM DC to DC converters can be either completely reduced or significantly streamlined appropriately.

It shows at the conclusion of this work that the proposed methodology is effective in synthesizing the PWM DC to DC converters optimum fuzzy immune PID controllers.

Another alternative approach has been discovered by [7], introduces a form of enhanced fuzzy-PID control technique which approves linear quadratic regulator (LQR) methodology. There is some model of a system is unspecified or complex in most of industrial control systems. Due to this problem, PID parameters are rather difficult to find hence the authors take this opportunity designed the advanced controller with LQR in improving the control performance. An achievement of better performance has been found even according to the fact that the output voltage is always heavy harmonic pollution in DC-DC converter using a traditional PID controller. In addition, it be able to alter the PID parameters online and be considerably improved than standard PID on steady state as well as anti-jamming; consequently it proves the system is achievable, effective and practical. This work indicates that the combination of LQR algorithm and the fuzzy reasoning control can significantly improve the final control effect. Likewise, the output voltage of the optimized DC-DC buck converter has a better load-disturbance
rejection capability than the traditional PID control or LQR method. The overshoot at start-up and the steady state error are eliminated using the new approach. Consequently, it has faster and dynamic responded and smaller overshoot under the load change condition.

Jen-Ta, S. discuss a fully digital controller for interleaving DC-DC converter [8]. Adaptive control architecture was presented based on a PID controller with pole-zero cancellation method to optimize the transient response under different load conditions as well to improve the dynamic performance in rapid load current slew rate requirement. According to PID controller, the control architecture with gain scheduling which is based on pole-zero cancellation method is used to construct the parameters of the PID in optimizing the transient response. The proposed digital controller is tested on a 12V input with 1.2V, 30A buck converter by FPGA based. Furthermore, the control method has verified in an FPGA board and the experimental results demonstrate a substantial improvement in transient response.

Although adaptive control mostly applied to the PID controller, there are other works which introduced this method collaborated with another controller as presented by [9]. As a DC-DC converter is strongly nonlinear, a fuzzy self-adaptive adjusting of PID controller is presented in this work, which is a control mode which employs fuzzy control rules to modify the PID parameters online. The equivalent small signal circuit of the phase-shifted full-bridge converter is derived based on a small signal model of buck converter. The performance of the converter has been proved to be perfect by using the program of fuzzy self-adaptive adjusting of PID control using MATLAB simulation. Due to the self-adaptive adjusting of the PID control parameters, the system can steadily quickly in the condition of perturbation.

Another type of adaptive control such as adaptive voltage positioning (AVP) is also taken into account which is operated inside DC-DC switch over energy converters used for driving unified circuits exactly to this one improvements of applying permissible production energy acceptance whilst reducing the production screen capacitance requisite, combined with attaining a more rapidly transient response. To reduce the right half plane (RHP) 0 consequence the rapid Boost DC to DC Converter is constructed through AVP method [10]. A common model theory in former works with AVP design is the concept of steady production impedance. Nevertheless, achievement of constant output impedance complicated by the “RHP zero” exists in controller to production transfer function of the Boost Converter (BS). To attain comparative continuous production impedance as well as achieve the AVP specific inside BS. The AC altering skill suggested in this article is showed, throughout the load transient contrasted with every control scheme introduced in the past. The boost converter model along with the AVP procedure offers reduced voltage overshoots or undershoots and far quicker response time. Once the load current alterations from 100mA to 400mA. The replication outcomes are shown to demonstrate exceptional performing of faster than the 4µs response time then the 40mV voltage drop. In this study, the proposed AC modification method relieves this constraint from the well-known RHP zero which occurs in the transfer function to output control. The presence of the RHP zeroes slows the energy supplied to the output and causes great fluctuations in voltage during a transient load. The output voltage will settle down within a few micro-seconds using the AVP control technique and have a much smaller drop in voltage than other control schemes. The results verify the proposed technique successfully and obtain an excellent result of decreasing voltage by 40mV when the load current changes from 100mA to 400mA.

Giustina della, D. And Liberali, V. analyzed the sensitivity of the adaptive filter used to control pulse width modulation DC-DC converters to the discrete and continuous parameters [11]. Measuring and digitizing input variables of the structures are selected as the optimum transition method to compensate the power cell. A digitally programmable switching capacitor circuit is used for its synthesis. It discusses the effects that can lead to an incorrect estimation of the operating point and miss the external feedback dynamic behavior of the target. To investigate limitations in the synthesis of the transfer function, an adaptive switched condenser filter using multiplying digital-to-analog converters (MDACs) was analysed. The results of both quantization and inconsistency cause poles and zeros to change from their theoretical position.
Although PID and Fuzzy controller become the priority controller until nowadays, sliding mode still gives a great performance on DC-DC converters. Sliding mode PID approach has discovered by [12], to control DC-DC converter. The integrated vigorous design of DC to DC buck converter has been set up along with 2 slipping method controllers are presented so-called the traditional “sliding mode (SM) controller” The constancy is examined for the DC to DC converter system controlled by the SM PID as well as the optimal SM PID limits are clarified. The system simulation is employed plus simulation findings demonstrate that SM PID controlled DC to DC buck converter requires improved vigorous combined with constant performing compare with the procedure operated by the traditional SM controller. An integrated dynamic design of DC to DC buck converter is initially configured later their work is applied to developing the SM PID optimal considerations when the system is packed various opposition. To inhibit output voltage disruption as well as the merging of lengthy time SM at the instantaneous of the rapidly changeable load, hence the altered SM PID controller is invented.

Additionally, there are some impressive reviews written by [13], have improving the vigorous performing of DC to DC energy converter an method aimed at an adaptive PID device. The control adjustable namely the proportionate constant (Kp) and integral constant (Ki) vary such as a purpose of the uncompensated inaccuracy voltage in improving the dynamic transient response of the energy converter,. It shows that by comparing the conventional PID there is a decline during undershoot or overshoot as well as settling time from their experimental outcomes. The effectiveness of adaptive PID control method in a reduction in the settling time and overshoot/undershoot of the power converter output voltage, dynamically and adaptively variable the proportional and integral constants as a function of the error signal has been proved. Furthermore, any ringing and oscillations have been averted by the smoothly transitioning between steady-state operation and dynamic transient operation. The idea is continued by presenting an adaptive digital proportional–integral–derivative (AD-PID) controller scheme to enhance the vigorous implementation of energy converters in closed-loop structure from their previous work [14]. The controller smartly modifies the Kp and Ki subsequent a latest control rule. The control rule is a purpose of the magnitude adjustment in the inaccuracy signal as well as that one highest rate through vigorous transients. Same as their previous controller, the proposed AD-PID controller smartly identifies the highest rate of the inaccuracy signal, which is a purpose of the magnitude and transient nature and utilizes it in the control rule as a consequence of the smart-process such that no fluctuations are produced. Consequently, there are reduction occurred in the settling time of the output voltage and vigorous output of the voltage divergence. The concept and architecture of the anticipated AD-PID are stated and its intended control rule is considered besides validated with investigational findings. By applying the AD-PID, it has been proved that the vigorous outcome voltage variation coupled with the settling time are diminished with a straightforward plan then minus the must to know every extra info. The AD-PID controller utilizes a system that ensures the switch among the steady-state plus transient process approaches is easy and unrestricted of extra fluctuations as well as reverberating.

The model of the strong Digital PID (DPID) controller for H-bridge soft-switching boost converter was proposed by [15]. In this paper, a strong DPID controller is suggested for the H-bridge soft-switching boost converter (HSBC). The DPID device remains intended to certify load voltage regulation and give a vigorous execution along with step loads plus source decrease. The statistical simulations of the H-bridge boost converter are articulated applying the method identification apparatus in addition to use in DPID model.

A smart prediction error filter (PEF) in the control system response loop are introduced by [16]. This study explains the concept of the use of an adaptive PEF and statistical study of core principles, such as the Auto-Regressive (AR) cycle generator and the Moving Average (MA) identifier. In addition, authors also submit the direct relation between an adaptive PEF and a digital Proportional-Derivative (PD) controller. This leads to the development of the adaptive control structure Proportional-Derivative + Integral (PD+I) which is an important replacement for a traditional PID controller. In this work, the relation between the PEF and a PD controller are described, including its suitability for usage in an adaptive PD+I control structure. The superior performance of this controller over a classical PID approach; in terms of system disturbance rejection, improved stability, and output regulation proved in
this work. The experimental validation has proven that the approach results in a fast-adaptive controller with self-loop compensation.

The design and structure of a fuzzy logic based on a PID controller for the control of a PWM of DC-DC buck converter working in continuous conduction mode (CCM) was introduced by [17]. In this work, the converter is set to use at a swapping frequency of 100KHz. Computer replications are complete to fuzzily the responses plus association tasks, therefore rapid the corollary regulations combining the output and input and variables to de-fuzzify the outcome limit. No linearized prototype of the buck converter is needed this methodology is straightforward. As of the simulation findings, the fuzzy-logic constructed on PID control method offers tough control for non-linear power electronic flexible shifting assembly.

In some cases, negative impedance instability compensation in buck converter using state space pole placement control has been taken as one of the control methods in improving the satisfactory operation of the converter [18]. In atmosphere energy systems, numerous voltage-power-systems and power-convertisers work together along with each one in addition be able to be resulting wobblily process. It demonstrates volatility once a DC to DC converter is inserted by a continuous power load (PL),. This is as of the undesirable impedance specific of the continuous PL [19]. Several poles of the converter with a continual PL are in the RHP. The work represents a reimbursement procedure used for buck converter utilizing SSP positioning control. Through a SSP position control, the unpredictable poles have transferred to the steady section. The traditional PI controlled buck converter is volatile once it is packed with continuous PL. Buck converter packed with continuous PL is remunerated with pole positioning control.

Though, fast transient (FT) control in conjunction with the Adaptive Phase Margin (APM) to achieve a high transient response in current DC-DC buck converters under different load conditions was uncovered by [20]. The over-shoot / undershoot voltage and the transient recovery time are reduced efficiently. The APM control enables the system phase margin to be continuously maintained at an appropriate value below distinct load circumstance. That is, the pole-zero compensation pair is modified to load current to broaden the bandwidth of the system and get an adequate phase margin. Research findings indicate that the overshoot / undershoot voltage is lower than 60mV (3%) and the transient period is lower than 12μs as the load current changes abruptly from 100mA to 500mA, or vice versa. The undershoot voltage and recovery time are increased by 45 percent and 85 percent compared with traditional models without any fast-transient method

Yushan, L. analyzed how exactly the current mode control delivers dynamic damping for improve converters by continual power loads [21]. Small-signal control-to-output transfer functions are obtained for peak or valley current mode-controlled boost converter with a downstream regulated converter developed as continuous power load. Moreover, this one is demonstrated how load current feedforward grants an efficient way to enhance energy capacity transient responses. Developing coupled with model methodologies are proven with examine circuit imitations, exhibiting balanced processes utilizing current-mode control in steady energy loads. The specified that John “Zeke” Ziegler and Nathaniel Nichols may not have developed the proportional-integral-derivative (PID) controller, even though the PID system is the most common of entirely feedback control approaches used in industrial applications, but the well-known loop tuning methods designed by John “Zeke” and Nathaniel Nichols facilitated a lot in creating the PID controller as an outstanding controller. In fact, by tweaking a PID loop the responses of the controller to faults between the determined process variable besides desired set point can be tweaked. Doubt the controlled procedure happens to be fairly sluggish, the design of PID process will take instantaneous and remarkable actions whenever a random disturbance shifts the method variable, or an operator shifts the set point.

3. Summary
Since DC-DC converters are strongly nonlinear, a conventional PID controller is simply to adapt with ‘small-signal control-to-output’ transfer function through a compensation technique using state space pole position control. This control procedure will be applied in this work and may lead in improving the
satisfactory performance of the converters. The unstable poles will be repositioned to the stable region through a SSP position control. The pole position controller imprints the anticipated outcome relatively good if adjusting the converters boundary to converge with load current remains constructive.

These reviews stated that an adaptive technique that applied in DC-DC converters show an improvement in transient response besides it produced a superior performance in terms of system improved stability, disorder elimination and yield control. Nevertheless, all this can be achieved using PID controller. Furthermore, ringing and oscillation occurrence in transient response can be averted by smoothly transitioning between steady-state operation as well as dynamic transient operation. The proposed controller; PID has proven that the operation of DC-DC converters is not depending on any further hypothesis of the transient magnitudes or kinds. That One can adapt its process for any transient magnitude and kind, as it continuously utilizes it in its control principle such as per a product of the adaptive process and finds the greatest value of the voltage error signal.

References
[1] Tajuddin M F N bin, Rahim N A and Daut I 2009 Design and Implementation of a DSP Based Digital Controller for a DC-DC Converter Second International Conference on Computer and Electrical Engineering (IEEE) 209–13.
[2] Anon Control Engineering 2016 Understanding PID control and loop tuning fundamentals.
[3] Kelly A and Rinne K 2005 Control of DC-DC converters by direct pole placement and adaptive feedforward gain adjustment Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC.
[4] Stefanutti W, Mattavelli P, Saggini S and Ghioni M 2005 Autotuning of digitally controlled buck converters based on relay feedback PESC Record - IEEE Annual Power Electronics Specialists Conference.
[5] Hui J and Zhao R 2007 Single-neuron self-adaptive PID control based on unified circuit model of DC/DC converters ICIEA 2007: Second IEEE Conference on Industrial Electronics and Applications 1994–7.
[6] Hsieh C H 2007 Optimal fuzzy-immune-PID controllers design of PWM DC-DC converters Annual Conference of the North American Fuzzy Information Processing Society - NAFIPS.
[7] Wei K, Sun Q, Liang B and Du M 2008 The research of adaptive fuzzy PID control algorithm based on LQR approach in DC-DC converter Proceedings Pacific-Asia Workshop on Computational Intelligence and Industrial Application.
[8] Su J-T, Liu D-M, Liu C-W and Hung C-W 2009 An adaptive control method for two-phase DC/DC converter International Conference on Power Electronics and Drive Systems (PEDS) (IEEE) pp 288–93.
[9] Jiang Z and Liu Y 2009 Design of DC/DC Converter Based on Fuzzy Self-Adaptive Adjusting of PID Control International Conference on Information Engineering and Computer Science (IEEE) 1–4.
[10] Liao J Y, Huang H H and Chen K H 2010 Minimized right-half plane zero effect on fast boost DC-DC converter achieved by adaptive voltage positioning technique ISCAS 2010 - 2010 IEEE International Symposium on Circuits and Systems: Nano-Bio Circuit Fabrics and Systems.
[11] Della Giustina D and Liberali V 2010 Practical design considerations on adaptive controllers for PWM DC/DC converters 2010 International Conference on Microelectronics (IEEE) pp 212–5.
[12] Li Q and Ye X 2010 Sliding-mode PID control of DC-DC converter Proceedings of the 2010 5th IEEE Conference on Electrical and Applications, ICIEA 2010.
[13] Arikatla V and Qahouq J A A 2011 DC-DC Power Converter with digital PID controller Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC) (IEEE) 327–30.
[14] Arikatla V P and Abu Qahouq J A 2012 Adaptive digital proportional-integral-derivative
controller for power converters *IET Power Electron.*

[15] Mummadi V 2011 Design of robust digital PID controller for H-bridge soft-switching boost converter *IEEE Trans. Ind. Electron.*

[16] Algreer M, Armstrong M and Giaouris D 2012 Predictive PID controller for DC-DC converters using an adaptive prediction error filter *IET Conference Publications.*

[17] Rabbani M, Maruf H M M, Ahmed T, Kabir M A and Mahbub U Fuzzy 2012 logic driven adaptive PID controller for PWM based buck converter *International Conference on Informatics, Electronics and Vision.*

[18] Kim S and Williamson S S 2012 Negative impedance instability compensation in buck converter using state space pole placement control *25th IEEE Canadian Conference on Electrical and Computer Engineering: Vision for a Greener Future, CCECE 2012.*

[19] Husna A W N, Siraj S F and Mat M H 2011 Effect of load variations in DC-DC converter *Proceedings - CIMSIm 2011: 3rd International Conference on Computational Intelligence, Modelling and Simulation.*

[20] Lee Y H, Huang S C, Wang S W and Chen K H 2012 Fast transient (FT) technique with adaptive phase margin (APM) for current mode DC-DC buck converters *IEEE Trans. Very Large Scale Integr. Syst.*

[21] Li Y, Vannorsdel K R, Zirger A J, Norris M and Maksimovic D 2012 Current Mode Control for Boost Converters With Constant Power Loads *IEEE Trans. Circuits Syst. I Regul. Pap. 59* 198–206.