Comparative analysis of switch mode power supplies using Proportional plus integral, sliding mode and artificial neural network controllers

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Abstract

DC DC converters are used as switch mode converters that increasing rapidly in switch mode power supplies. To improve the performance of these power supplies various control techniques have been investigated. The buck converter is also used in switched mode power supplies. The Buck converter is a highly under damped system due to its variable structure system. Due to switching operation, this converter generates oscillations. To minimize the oscillations in a buck converter, various control techniques have been investigated and analyzed.

This paper presents the comparative analysis of buck DC DC topology using proportional plus integral (PI), sliding mode (SM) and artificial neural network (ANN) controllers. These control schemes are implemented and simulated in MATLAB. The performance of the buck converter is tested during transient, line and load variations. The SM controller in line and load variation well damped the oscillations compared to PI and ANN controllers, while the SM controller has longer settling time. The ANN controller has less settling time during transient, line and load variation when compared to the PI and SM controllers.

Keywords
Buck converter, cascade loop, PI, SMC, ANN

1. Introduction

The regulated power supplies are classified as linear and switch mode regulators. The linear regulators are less efficient compared to switch mode regulators (Sum, 2017). Moreover, the transformer used in linear regulators is bulky and expensive.

DC DC topologies have developed very rapidly due to high efficiency and compact size. They can be found in various applications such as wind farms, solar systems, fuel cells and vehicles, switch mode power supplies, mobile chargers, dc drives systems, computer systems, and telecommunication equipment etc (Sum, 2017; Chang et al., 2013; Ma et al., 2015; Yang et al., 2018). The Buck converter has fast switching actions, high efficiency and is available in compact size. Buck converter is a highly underdamped system and contains non- linearities which leads to the generation of oscillation during its operation (Syed and Patra, 2016; Yan et al., 2011; Abro et al., 2009; Mahar et al., 2009). Many controllers (Abro et al., 2009; Tsang and Chan, 2005; Ding et al., 2018; Al-Nussairi et al., 2017; Alaoui and Magrez, 2015; Kumar et al., 2008) have been proposed to minimize the oscillations in the output voltage during line and load variations.

This work focuses on a cascaded scheme for the buck converter which is developed in MATLAB. To control the dynamics of buck converter with cascade controller, it is decomposed into two first-order systems. The details of the cascade controller are given in (Abro et al., 2009; Tsang and Chan, 2005). The Cascade controller composed of inner (current) and outer (voltage) loops. In this research work, initially, the cascade control scheme is developed with PI controllers. Later, the same scheme is developed with a sliding mode controller (SMC) and artificial neural network controller.

2. Modelling of buck converter

The output voltage of buck converter is regulated with pulse width modulator through switching of switch. The circuit of a buck topology is illustrated in Figure 1. It consists of a low pass filter (L and C), a solid-state switch (S) and a diode (D). The turn ON and OFF period of solid state switch is controlled with pulse width modulation control technique. The diode is reverse biased when a switch is closed. The diode conducts when switch is off.

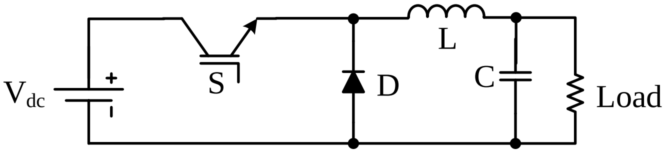

Figure 1. Buck DC DC converter

An state space model of the buck topology when operated in CCM is modeled with the following equations (Mahar et al., 2009; Tsang and Chan, 2005). As shown in Figure 1, when switching signal is turned-ON the solid state switch S, the inductor current i_L is obtained by Equation 1.

$$i_L = i_C + i_O \tag{1}$$

where, capacitor current i_C is

$$i_C = C\frac{d}{dt}v_C \quad ; \; v_C \text{ is capacitive voltage} \tag{2}$$

and load current i_O is given as

$$i_O = \frac{v_C}{R} \tag{3}$$

From Equation 2 and 3, the Equation 1 can be rewritten as

$$i_L = C\frac{d}{dt}v_C + \frac{v_C}{R} \tag{4}$$

From Fig. 1 it is also found that

$$V_{dc} = L\frac{d}{dt}i_L + v_C \tag{5}$$

The state space equation of buck topology when solid state switch is conducting is given by Eq. (6).

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{dc} \tag{6}$$

Where, L is inductor, C indicates capacitor, R is resistor and Vdc represent input voltage.

Similarly, state space equation of buck topology when solid state switch is turned off is given by Eq. (7) and state space averaging model is given in Eq. (8).

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{\mathrm{L}} \\ \frac{1}{C} & -\frac{1}{\mathrm{RC}} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{dc} \tag{7}$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{\mathrm{L}} \\ \frac{1}{C} & -\frac{1}{\mathrm{RC}} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{D}{L} \\ 0 \end{bmatrix} V_{dc} \tag{8}$$

From Eq. (8), the state variable x_1 is the inductor current. Its first derivative is given as

$$\dot{x}_1 = \frac{D}{L} V_{dc} - \frac{1}{L} x_2 \;; \qquad \text{D is duty ratio} \tag{9}$$

or

$$\frac{d_{i_L}}{dt} = \frac{(D \times V_{dc}) - V_O}{L} \tag{10}$$

Similarly, the first derivative of the state variable x_2 (capacitor voltage) is given by

$$\frac{dV_O}{dt} = \frac{i_L - i_O}{C} \tag{11}$$

3. Simulation of buck converter

A buck converter is implemented according to Eqs. (10) and (11) in Simulink toolbox of MATLAB software. The buck topology simulated with parameters like input dc voltage, V_{dc} = 50 V, load resistor, R = 10 Ω, inductor, L = 1 mH, capacitor, C = 120 µF and output voltage, Vo =10 V (Abro et al., 2009).

3.1 Simulation of buck converter with PI controllers

The simulation of buck topology is based on the cascade control scheme which is obtained by decomposing the dynamics of buck converter into two first-order systems (Abro et al., 2009; Tsang and Chan, 2005). The Figure 2 illutrates the detail simulation model of the buck topology with PI controllers. The Vo and I_L are taken as feedback parameters for outer and inner loops respectively. The outer loop is controlled by the PI voltage controller while the inner loop is controlled by the current loop controller. The step change in line voltage is obtained with switch S1 while the load variation is changed with S2.

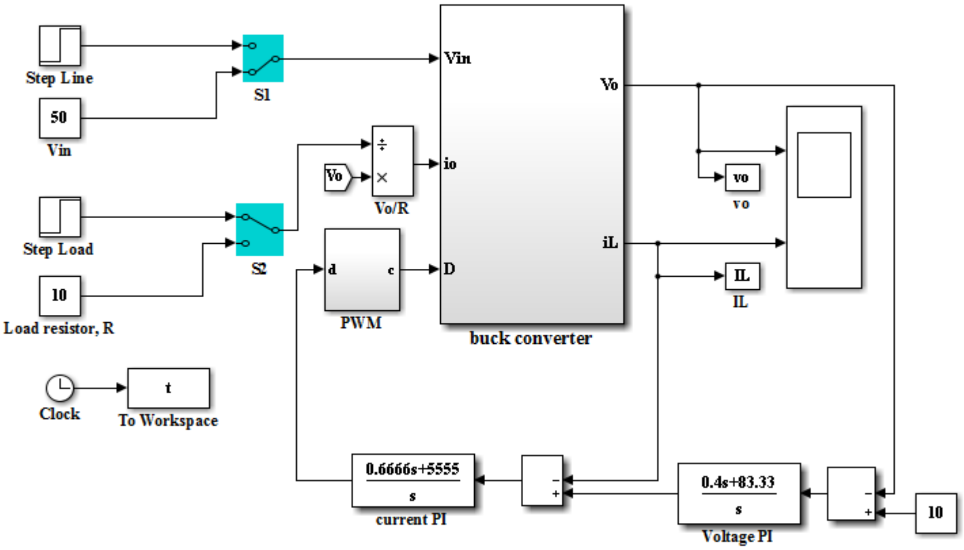

Figure 2. Simulation model of PI controller for buck converter

3.2 Simulation of buck converter with SM controller

The sliding mode control scheme is shown in Figure 3 which is composed of linear and nonlinear part. The PI controller is used for linear part while nonlinear part of the SMC is controlled by hysteresis controller. The output of the hysteresis controller used to derive the solid state switch of buck converter. The hysteresis controller parameters can be selected by using the peak to peak inductor current as given in Eq. (12), while linear part is tuned to get optimum values.

$$\Delta i_L = \frac{v_L \times D \times T_S}{L} \qquad (12)$$

Where V_L is voltage across inductor, L represent the inductor, D indicates duty ratio, Δ_{iL} represent inductor current ripple and Ts indicates switching time period.

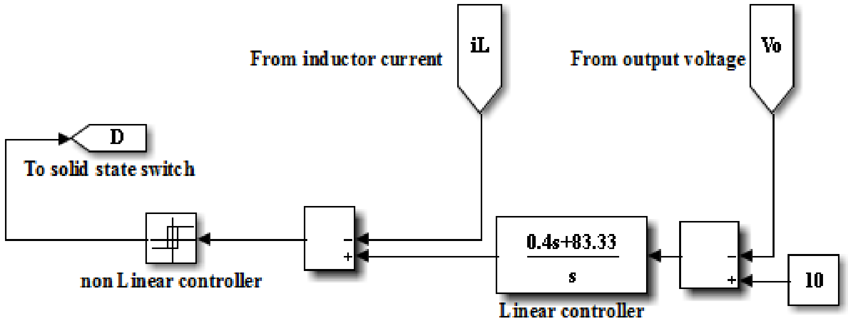

Figure 3. Simulation model of SM controller for buck converter

3.3 Simulation of buck converter with ANN controller

Due to several advantages of neural network controller it is widely used in power electronic converters.The ANN controllers have good dynamic behavior, robustness, self-adapting capabilities, increase system speed, enhance the system performance and reduce the system complexity (Kumar et al., 2008; Maruta et al., 2017; Bicer et al., 2016; Wai et al., 2015; Guellal et al., 2015; Buswig et al., 2018).

In this work, the buck topology is also simulated with feedforward neural network controller. The data for ANN controllers is achieved from PI controllers during training. The successful training is achieved in 5000 epochs for voltage and current loops at one neuron in the output layer and five neurons in single hidden layer. The ANN controller is constructed for each loop from weights and biases values obtained during the training. Figure 4 shows the feedforward neural network composed of two inputs, one output layer and single hidden layer.

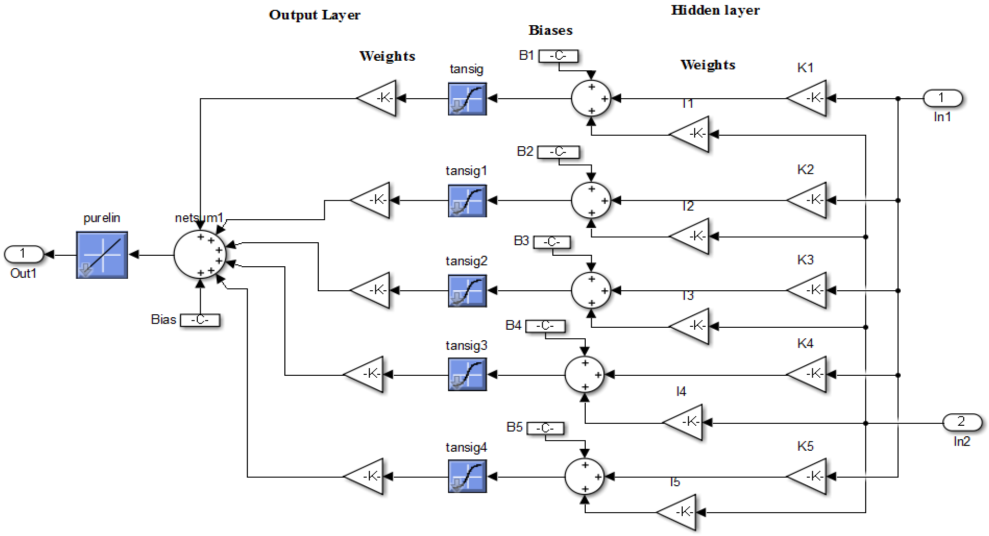

Figure 4. The simulink model of neural network controllers

4. Results and discussion

The performance of buck topology is analyzed with PI, SM and ANN controllers under transient region, line and load voltage variations.

4.1. Transient analysis of buck converter

The waveforms shown in Figure 5 indicate the behavior of buck topology in transient region. Table 1 shows the comparison of buck converter with three controllers in transient region. It is clear from the output voltage waveforms, there is no any overshoot when buck converter controlled with these controllers. But the settling time is longer with SMC. The buck converter with ANN controller has less settling time in output voltage compared to other controllers.

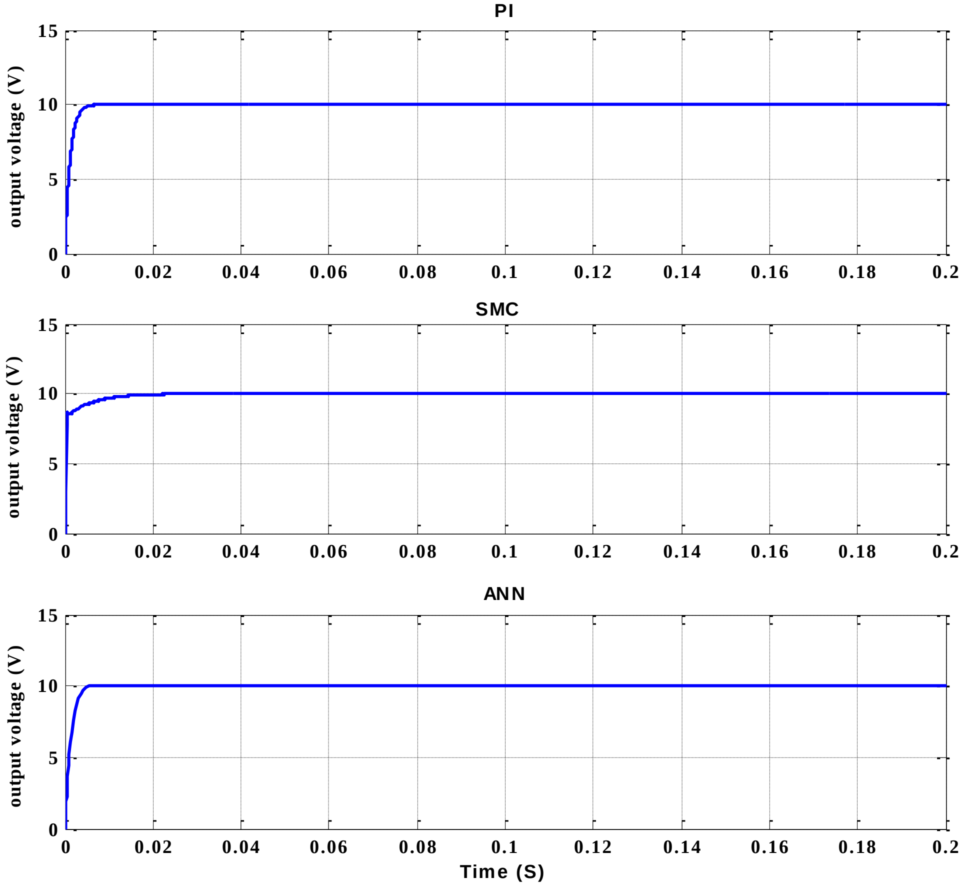

Figure 5. Waveforms of buck converter with PI, SM and ANN controllers in transient region

Table 1. Output voltage of buck converter in transient region

Controller	**Settling time (msec)**	**Maximum overshoot in output voltage**
PI	5	No overshoot
SMC	12.5	No overshoot
ANN	4.5	No overshoot

4.2. Analysis of buck converter under line voltage variation

To analyze the performance of buck topology with line variation, a step change from the input voltage is applied to all three controllers. It is illustrated from Figure 6 the only buck converter with PI is affected with this change while SM and ANN controllers well damped the oscillations in output voltage during line variation. The results of line variation of buck converter are tabulated in Table 2.

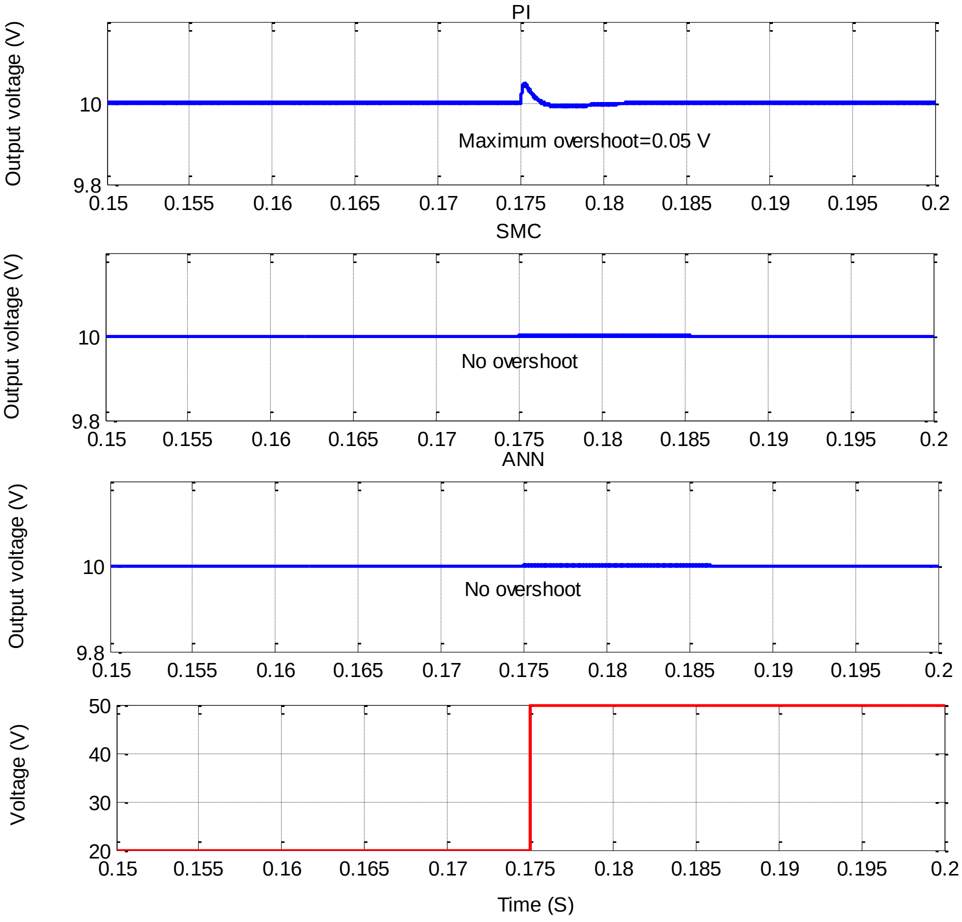

Figure 6. Waveforms of buck converter with PI, SM and ANN controllers during line variation.

Table 2. Output voltage of buck converter under line variation

Controller	**Settling time (msec)**	**Maximum overshoot in output voltage (V)**
PI	**6**	0.05
SMC	**---**	No overshoot
ANN	**---**	No overshoot

4.3. Analysis of buck converter under load variation

The dynamic operation of the buck converter is simulated under load variations. Figure 7 shows the simulated results of buck topology with PI, SM and ANN controllers. To observe the effect on output voltage, an input step change of load current (1.25 A to 1 A) is given to buck converter. With PI controller, the maximum overshoot in the output voltage of 0.92 V is observed during the step change in load variation. The overshoot in output voltages comes to steady state within 8.5 msec. With SMC, the overshoot of output voltage is 0.45 V which is less than PI and ANN controllers. This overshoot settles downs in 20 ms which is longer as compared to PI and ANN controllers. During the same load variation, the buck converter with ANN controller has taken less time to reach at steady state compared to PI and SM controllers. Table 3 shows the comparison results of buck converter with three controllers in this region.

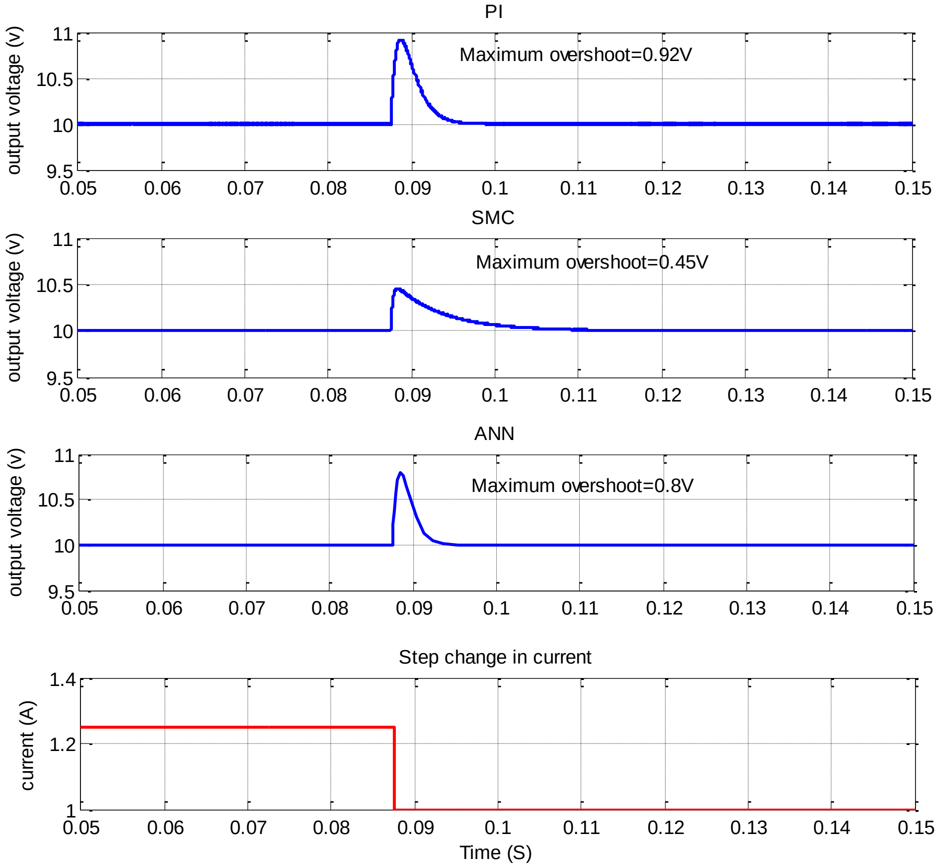

Figure 7. Waveforms of buck converter with PI, SM and ANN controllers during load variation.

Table 3. Output voltage of buck converter under load variation

Controller	**Settling time (msec)**	**Maximum overshoot in output voltage (V)**
PI	8.5	0.92
SMC	20	0.45
ANN	6	0.8

5. Conclusion

The buck converter was successfully simulated and analyzed with PI, SM and ANN controllers under transient, line and load variations. Under transient region, these controllers show similar characteristics with no overshoot in output voltage. The sliding mode controller both in line and load variation well damped the oscillations as compared to PI and ANN controllers while it takes longer settling time. The ANN controller has less overshoot in output voltage compared to PI controllers. The ANN controller has fast dynamic response during transient, line and load variation compared to PI and SM controllers.

References

Al-Nussairi, M.K., Bayindir, R., Hossain, E., Fuzzy logic controller for DC-DC buck converter with constant power load, 6th International Conference on Renewable Energy Research and Applications (ICRERA), pp. 1175-1179, San Diego, CA, USA, 5-8 November, 2017.

Alaoui, M.C., Magrez, H., DC Motor Velocity Neural Network Sliding Mode Controller for the Combined Pumping Load-DC Motor-Buck Converter System, Journal of Mechatronics, vol.3, no.3, pp.253-7, 2015.

Abro, M.R., Mahar, M.A., Larik, A.S., Non-Linear controller design of dc-dc buck converter to assess the performance under steady state and dynamic operation, Mehran University Research Journal of Engineering & Technology vol. 28, pp. 549-554, 2009.

Bicer, Y., Dincer, I,, Aydin, M., Maximizing performance of fuel cell using artificial neural network approach for smart grid applications. Energy, pp.1205-17, 2016.

Buswig, Y.M., Othman, A.K., Julai, N., Yi, S.S., Utomo, W.M., Siang, A.J., Voltage Tracking of a Multi-Input Interleaved Buck-Boost DC-DC Converter Using Artificial Neural Network Control. Journal of Telecommunication, Electronic and Computer Engineering (JTEC),pp. 29-32, 2018.

Chang, C. H., Chang, E.C., Cheng, H. L., A high-efficiency solar array simulator implemented by an LLC resonant dc dc converter, IEEE Transaction on Power Electronics, vol.28, no.6, pp.3039-3046, 2013.

Ding, S., Zheng, W.X., Sun, J., Wang, J., Second-Order Sliding-Mode Controller Design and Its Implementation for Buck Converters, IEEE Transactions on Industrial Informatics, vol.14, no.5, pp.1990-2000, 2018.

Guellal, A., Larbes, C., Bendib, D., Hassaine, L., Malek, A., FPGA based on-line artificial neural network selective harmonic elimination pwm technique, International Journal of Electrical Power & Energy Systems, pp.33-43, 2015.

Kumar, N.S., Sadasivam, V., Sukriya, H.M., A comparative study of PI, fuzzy, and ANN controllers for chopper - fed dc drive with embedded systems approach, Electric Power Components and Systems, vol.36. no.7, pp. 680 – 695, 2008.

Mahar, M. A., Abro, M.R., Larik, A.S., Simulation analysis of cascade controller for buck dc dc converter. Mehran University Research Journal of Engineering & Technology, vol. 28, pp. 349-356, 2009.

Ma, K., Tutelea, L., Boldea, I., Ionel, D.M., Blaabjerg, F., Power electronic drives, controls, and electric generators for large wind turbines–an overview, Electric Power Components and Systems, vol. 43, no.12, pp.1406-1421, 2015.

Maruta, H., Taniguchi, H., Furukawa, Y., Kurokawa, F., Improved transient response for wide input range of DC-DC converter with neural network based digital controller, 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe), Warsa, Poland, 11-14 September, 2017.

Sum, K.K., Switch mode power conversion: basic theory and design, Routledge; 2017.

Syed, A.E., and Patra, A., Saturation Generated Oscillations in Voltage-Mode Digital Control of DC–DC Converters, IEEE Transactions on Power Electronics, vol. 31, no.6, pp.4549-64, 2016.

Tsang, K.M., Chan, W.L., Cascade controller for dc dc buck converter, IEE Proceedings-Electric Power application, vol.152, no. 4, pp. 827-831, 2005.

Wai, R.J., Lin, Y.F., Liu, Y.K., Design of adaptive fuzzy-neural-network control for a single-stage boost inverter, IEEE Transactions on Power Electronics, vol.30, no.12, pp.7282-98, 2015.

Yan, W., Li, W., Liu, R., A noise-shaped buck DC–DC converter with improved light-load efficiency and fast transient response, IEEE Transactions on Power Electronics, vol. 26, no.12, pp.3908-24, 2011.

Yang, Y., Wang, H., Sangwongwanich, A., Blaabjerg, F., Design for reliability of power electronic systems, In Power Electronics Handbook, 4th Edition, 2018, pp. 1423-1440.

Biographies

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