Comparative Analysis of Different Control Schemes for DC-DC Converter: A Review

Ferrarison B. Lynser[1], Morningstar Sun[2], Maiarta Sungoh[3], Nuki Taggu[4], Pushpanjalee Konwar[5]

[1,2,3,4,5]Department of Electrical and Electronics Engineering, School of Technology, Assam Don Bosco University
Airport Road, Azara, Guwahati-781017, Assam, India
[1]ferlynser123@gmail.com, [2]msun413@gmail.com, [3]maiaz1302@gmail.com, [4]nukitaggu.aru@gmail.com,
*[5]pushpanjalee.konwar@dbuniversity.ac.in**

Abstract: ***DC-DC converters are some power electronic circuits that convert the DC voltage from one level to another. They have a very large area of applications ranging from computing to communication. They are widely used in appliance control transportations and high-power transmission. Its increasing demand is based on its capability of electrical energy conversion. The basic topologies of DC-DC converter are Buck converter and Boost converter, other topologies are derived from these two basic topologies. Mathematical modelling of both Buck converters is done. Some of the control schemes are summarized in this paper. Current mode control (CMC), PID, Sliding Mode (SM) control including their advantages and disadvantages are highlighted in this paper.***

Keywords: DC-DC converter, PID, Sliding Mode Control and Buck converter.

1. Introduction

The switch mode DC-DC converters are the simplest power electronic circuit that efficiently converts an unregulated DC voltage into a regulated DC voltage. Solid state device such as transistors and diodes are used as switching power supplies. They operate as switch either in completely ON or completely OFF state. The energy storing elements such as inductor and capacitor are used for energy transfer and work as a low pass filter. The buck and boost converters are the two fundamental topologies of switch mode DC-DC converter. DC-DC converters have a wide area of applications. The drastic use of these converters in appliances control, telecommunication equipment, DC-motor drives, automotive, aircraft, etc. increases its interests in many fields.

The analysis along the control of switching converters is the main factor to be considered. Various control schemes are used to control the switch-mode DC-DC converter. There are many advantages and disadvantages related to every control methods. Preference is always given to the methods under which the best performance is obtainable. The most commonly used control technique is PWM voltage mode control, PWM current mode control, PID controller. The disadvantage of these controllers is that satisfied results are not achievable under large parameter or variation of load. Therefore the utilization of non-linear

2. Literature Review

R. Priewasser *et al.* [1] in 2010 derived a linear PID (proportional-integral-derivative) control loop, both in analog and digital domain and compared its performance to a non-linear regulation loop. A goal of this research work was to point out potential advantages and drawbacks of the different solutions. This exploration forms the starting point for the implementation of the most promising concepts in CMOS technology. Mike Wens *et al.* [2] in 2012 discussed a brief mathematical steady state model for fully-integrated boost and buck DC-DC converters, which takes all the significant resistive and dynamic power losses into account. The maximization of output power and power density parameters is the main goal of this work. K. Bhattacharyya *et al.* [3] in 2012 implemented an integral DC-DC converter to reduce the energy lost and to reduce the output voltage ripple. Apart from ripple reduction, its power efficiency is improved by reducing short-circuit currents in the switched capacitor converter. A combination of non-overlap switching phase and a dip-reducer helps to reduce short circuit current without degrading the output ripple. The converter has been used to observe the power efficiency and ripple variation at different frequency of operations. In another research work by D. Sutanto *et al.* [4] in 2010, two topologies for the buck converter are presented and the first converter consisting of two active switches and the second one derived from the parent two switch converters which consist of only one active switch. This new converter can operate a constant switching frequency using a simple PWM control.

This converter has a good efficiency, as is proved by the experimental results. The operation of the two-switch converter, derived from the new single-switch converter is presented to gain insight designing of the new converter. Yogesh V. HOTE in 2012[5], presented, using Kharitonov's theorem, an analytical technique for time domain analysis used for the transient and steady-state response of Pulse Width Modulation (PWM) push-pull DC-DC converter. Even though the transfer function model of a PWM push-pull DC-DC converter is disturbed; the complete analysis has been done on a linear transfer function model of a PWM push-pull DC-DC converter which is the main advantages of the proposed analysis. In the research work by T. B Petrovic *et al.* [6] in 1999, the design for a single operating dc/dc converter using robust controller has been investigated. Using H∞ optimization procedure with Glover-Doyle algorithm, the controller is designed. Stability and performance robustness is achieved in the presence of unstructured multiplicative (input) uncertainty using this designed controller. While maintaining robustness properties, a simple technique is used to reduce the controller order. Using computer simulation, the performance of the closed-loop system is evaluated, and the results are compared with previously designed classical PI controller and IMC controller. Xile Wei *et al.* [7] in 2009, proposed the internal model control of a conditional integrator in order to get the robust output regulation of a DC-DC buck converter. Based on the input-output linearization from the state-space averaged model of a DC-DC buck converter, the robust output regulation problems of the converter can be converted into a robust stabilization problem of a system consisting of the given buck converter and the internal model by introducing a proper internal model. In the research work done by Carlos Olalla *et al.* [8] in 2012, a new digital robust control law for dc-dc converters is analyzed and implemented in this paper which has been successfully used with analog implementation, has been adapted to the digital domain. Concretely, this paper considers the design of a power conditioning unit, which must consider the uncertainty of the converter, as the conduction mode, the load, the input voltage or the storage elements while assuring that the specifications of a well-known standard are met.

3. Background Study

3.1 Switch mode DC-DC Converter

The switch mode DC-DC converters are those which convert the unregulated DC voltage to a regulated DC voltage with high efficiency and flexibility. The various types of DC-DC converters comprise of buck converter, boost converter, buck-boost converter etc. Buck and boost converters are the two fundamental topologies of switch mode DC-DC converter whereas buck-boost converter is the combination of buck and boost converter topologies.

DC-DC converter usually operates in two modes of operation: continuous mode and discontinuous mode. In case of continuous mode, the current through the inductor never falls to zero whereas in case of discontinuous mode the current through the inductor falls to zero as the switch is turned off.

3.2 Buck Converter

The buck converter is shown in figure 1. It is the step-down converter in which a fixed high voltage is step down to a desired low voltage level. It consists of a non-dissipative switch, inductor, and capacitor. The switches will operate at the rate of PWM switching frequency. The ratio of ON time when the switch is closed to the entire switching period is known as the duty cycle and is represented as:

$$d = \frac{t_{ON}}{T}$$

and the output voltage is controlled by varying the duty cycle. During steady state, the ratio of output voltage over input voltage is d, which is given by:

$$d = \frac{V_{out}}{V_{in}}$$

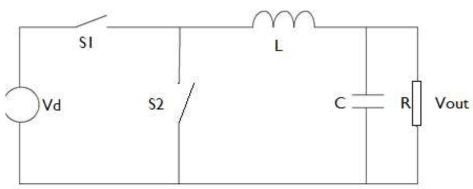

Figure 1: Basic Buck Converter

In the first sub-circuit state when the switch S1 is closed, the diode is reversed biased and the energy is transferred from the source to the inductor and the current through the inductor gradually increases during this time interval as shown in figure 2(a). In the next sub-circuit state when the switch S2 is closed, the source is disconnected from the network. The diode will be forward biased and the current will flow through the freewheeling diode. During the second time interval, the current through the circuit decreases linearly as the energy in the inductor discharges as shown in figure 2(b).

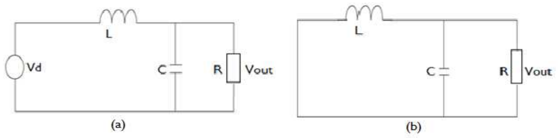

Figure 2: Buck Converter when (a) Switch is ON (b) Switch is OFF

3.3 Control techniques used in DC-DC Buck Converter

In DC-DC converter for a given input voltage, the output voltage can be controlled by controlling the ON or OFF duration of the switch. Pulse Width Modulation (PWM) is one of the methods in which the control circuit regulates the output by varying the ON time of the switch and by fixing the switching frequency.

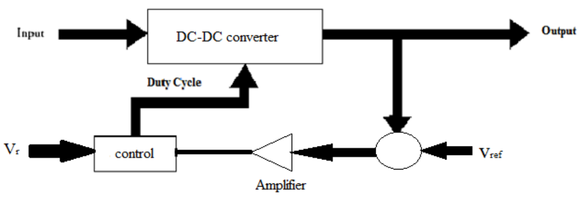

Figure 3: Elements of switching-mode regulator

3.4 Voltage Mode Control of DC-DC Converter

It is a type of single loop controller, where the output voltage is sensed and subtracted from the reference voltage in an error amplifier. The error amplifier will generate a control signal which is compared with constant amplitude saw-tooth waveform. A PWM signal is generated from the comparator is fed to the drivers of the controller switch of the converter. The duty ratio of the PWM signal depends on the value of the control voltage. The frequency of the PWM signal will remain the same as that of the control signal.

Some of the advantages of voltage mode control are its simple hardware implementation and flexibility and voltage mode provides good load regulation, that is, regulation against variation in load.

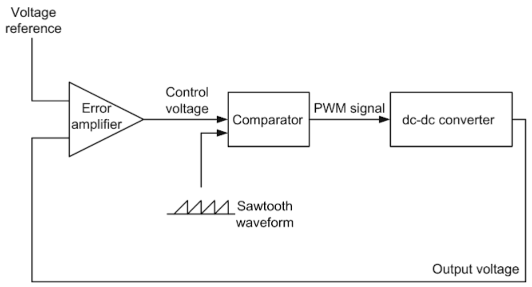

Figure 4: Control schemes for dc-dc converters: Voltage-Mode Control [13]

3.5 Current Mode Control of DC-DC Converter

Current mode control method contains dual loop including voltage and current control loop. Here an additional inner loop control loop feedbacks an inductor current signal. The current signal is converted into its voltage analog and is compared with the control voltage. The modification of replacing saw-tooth waveform voltage mode control scheme by converter current signal significantly alters the dynamic behavior of the converter.

Some of the advantages of current mode control scheme include: good and improved performance in the line regulation, self-protection opposes overload, shows improved transient response.

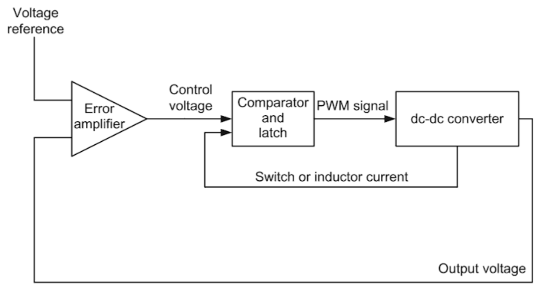

Figure 5: Control schemes for dc-dc converters: Current-mode Control [13]

3.6 Linear Control Design for dc-dc Converters

The design of the DC-DC converter using linear control method is presented. For designing a linear controller, an accurate model is essential which can be obtained using the state-space averaging technique. In the case of the buck converter, the control law is based on the small signal model.

Designing of PID and PI controllers were executed using small signal models. To achieve high loop gain, the system was compensated, wide bandwidth and sufficient phase margin. Transformation of the PID and PI controllers was possible using the backward integration method. PID and PI controllers were altered into digital controllers transform.

3.6.1 PID Controller design for Buck Converters

To design a controller using the frequency response method, phase-lead, phase-lag or lead-lag compensation is usually used. A proportional-derivative (PD) controller is phase-lead compensation. The advantage of using PD controllers is that it leads to the increase of phase margin and improvement of cross-over frequency. The transfer function of a PD controller is:

$$G_C(s) = K_P + K_D(s)$$

A proportional-integral (PI) controller is a phase-lag controller. A PI controller is used to increase the low-frequency loop gain, therefore reducing steady-state error. The transfer function of a PI controller is:

$$G_C(s) = K_p + \frac{K_I}{s} = \frac{K_p s + K_I}{s}$$

The PI controller has a pole at the origin. Both PD and PI controllers are first-order controllers.

By using a lead-lag compensator, the advantages of lead compensation and lag compensation can be combined to obtain sufficient phase margin, high loop gain, and wide control bandwidth. A proportional-integral-derivative (PID) controller is a lead-lag compensator. It is the most widely used compensator in feedback control systems. The PID controller is defined as:

$$u(t) = K_P e(t) + K_I \int_0^\tau e(t)dt + K_D \frac{de(t)}{dt},$$

where e(t) is the compensator input and u(t) is the compensator output.

The Laplace transform of the above equation yields the transfer function:

$$G_C(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D(s)$$

The integral term is phase-lag and the derivative term is phase-lead. The low-frequency gain is improved by the integral term, and the low-frequency components of the output voltage are accurately regulated. At high frequency, the phase margin and cross-over frequency are improved by the derivative term, which improves the system's stability and the speed of the transient response. An increase in the proportional term will increase the speed of system response; however, too much proportional gain will make the system unstable.

For operation during a startup transient and steady state, a PID and a PI controller were designed for the buck converter respectively. The derivative term in a PID controller is susceptible to noise and measurement error of the system, which could result in oscillation of the duty cycle during steady state. However, the derivative term is needed during a transient period to reduce the settling time by predicting the changes in error. Therefore, to obtain the desired response the system switches between PID and PI controllers during transient and steady-state period. The PID controller is applied during startup to obtain a fast-transient response. The PI controller is applied during steady state to reduce oscillation of the duty cycle and improve the system's stability.

3.6.2 Implementation of Digital PID and PI Controllers

Frequency response technique is used for designing the PID and PI controller, which will be based on the small signal model of the DC-DC Buck converter. These are transformed into digital controller using back integration method.

The digital PID controller can be deduced from the PID controller equation as:

$$u(t) = K_P e(t) + K_I \int_0^\tau e(t)dt + K_D \frac{de(t)}{dt}$$

The difference equation to calculate a new duty cycle for the digital PID controller given as:

$$u[k] = K_P e[k] + K_I T \sum_{i=0}^{k} e[i] + \frac{K_D}{T}\{e[k] - e[k-1]\}$$

The digital PID controller can be deduced from the PID controller equation as:

$$u(t) = K_P e(t) + K_I \int_0^\tau e(t)dt$$

The difference equation to calculate a new duty cycle for the digital PI controller given as:

$$u[k] = K_P e[k] + K_I T \sum_{i=0}^{k} e[i]$$

In the above equations, u[k] is the controller output, e[k] is the error of k^th sample, $\sum_{i=0}^{k} e[i]$ is the sum of the error and $\{e[k] - e[k-1]\}$ is the difference between the error of the k^th sample and (k-1)^th sample.

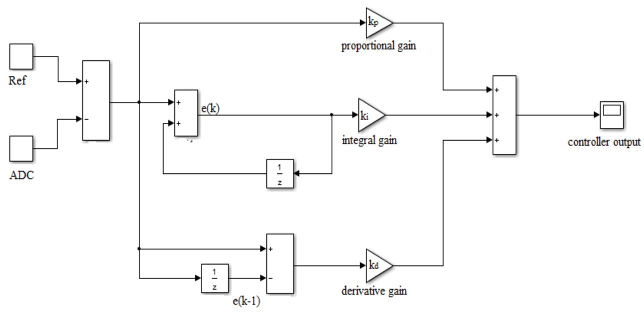

Figure 6: Block diagram of digital PID controller.

3.7 Sliding Mode Control (SMC)

Sliding mode control is the only non-linear method. Sliding mode controller is a systematic approach to solve the stability problem and consistency performance. Switch mode controller could be implemented for switch mode power supplies. Switching control action is required to drive the non-linear plants' state trajectory into a specified surface in the state space and to maintain the plants' state trajectory for subsequent time. The gain of the feedback path depends upon the position of the trajectory w.r.t surface. If the trajectory is above the surface feedback path has one gain and the gain will change as the trajectory move below the surface. The surface is known as the sliding surface. Ideally, a response is made to slide along a predefined trajectory with the help of the control algorithm. The control detects the deviation of actual trajectory from the reference trajectory and correspondingly changes the trajectory to restore the tracking.

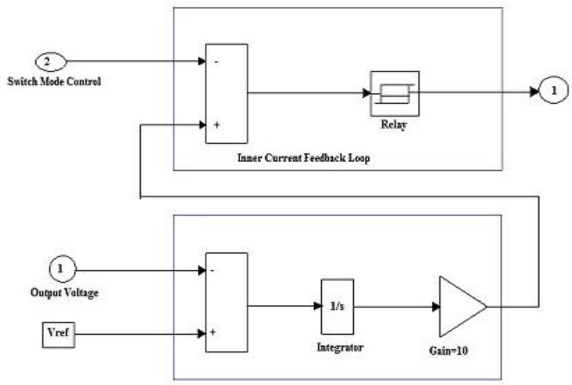

Figure 7: Block Diagram of SMC

4. Conclusion

In this review, we provided a control technique used for DC-DC converters. The basic concepts behind every adaptive control schemes have been highlighted. A comparison is made between the different control schemes. The selection of controller depends on the purpose for which it is required. The development of a more reliable and efficient control technique will be possible in the upcoming days.

References

[1] R. Priewasser, M. Agostinelli, S. Marsili, D. Straeussnigg and M. Huemer, "Comparative study of linear and non-linear integrated control schemes applied to a Buck converter for mobile applications", *e & I Elektrotechnik und Informationstechnik*, Vol. 127, Issue No. 4, April 2010, pp. 103–108. Retrieved from: https://link.springer.com/article/10.1007/s00502-010-0705-6

[2] M. Wens and M. Steyaert, *Design and Implementation of Fully-Integrated Inductive DC-DC Converters in Standard CMOS*, 2011 edition, Springer, Dordrecht, Netherlands, 2011.

[3] K. Bhattacharyya and P. Mandal, "Design and implementation of a switched capacitor-based embedded hybrid DC-DC converter", *International Journal of Electronics,* Vol. 99, Issue No. 6, 2012, pp. 823-849. Doi: http://dx.doi.org/10.1080/00207217.2011.647290

[4] B. P. Divakar IV and D. Sutanto, "Novel topologies for DC-DC converter with PWM control", *International Journal of Electronics,* Vol. 87, Issue No. 6, 2010, pp. 741-756. Doi: http://dx.doi.org/10.1080/002072100131931

[5] Y. V. HOTE, "A new approach to time domain analysis of perturbed PWM push-pull DC-DC converter", *Journal of Control Theory and Applications*, Vol. 10, Issue No. 4, November 2012, pp.465–469. Retrieved from https://link.springer.com/article/10.1007/s11768-012-0064-4

[6] T. B. Petrovic and A. T. Juloski, "Robust H∞ controller design for current mode-controlled dc/dc converters", *Electrical Engineering*, Vol. 82, Issue No. 2, November 1999, pp. 83–88. Retrieved from https://link.springer.com/article/10.1007/s002020050079

[7] X. Wei, K. M. Tsang and W. L. Chan, "DC/DC Buck Converter Using Internal Model Control", *Electric Power Components and Systems*, Vol. 37, Issue No. 3, 2009, pp. 320-330. Retrieved from https://www.tandfonline.com/doi/abs/10.1080/15325000802454500

[8] C. Olalla, C. Carrejo, R. Leyva, C. Alonso and B. Estibals, "Digital QFT robust control of DC-DC current-mode converters", *Electrical Engineering,* Vol. 95, Issue No. 1, 2012, pp. 21-31. Retrieved from https://link.springer.com/article/10.1007/s00202-012-0236-8

[9] A. B. Ponniran, *A study on optimization of circuit components in high boost dc-dc converter with hybrid-based configuration*, Ph.D. Thesis, Nagaoka University of Technology, Japan, June 2016. Retrieved from http://hdl.handle.net/10649/814

[10] H. S. Ramirez and R. S Ortigoza, *Control Design Techniques in Power Electronics Devices*, 1st Edition, Springer-Verlag, London, 2006.

[11] K. Kayisli, S. Tunner and M. Poyrax, "A Novel Power Factor Correction System Based on Sliding Mode Fuzzy Control", *Electric Power Components and Systems,* Vol. 45, Issue No. 4, February 2017, pp. 430-441. Doi: http://dx.doi.org/10.1080/15325008.2016.1266418

[12] Wang Feng-yan and Xu Jian-ping, "Modeling and Analysis of V~2C Controlled Buck Converter", *Proceedings of the Chinese Society of Electrical Engineering: CSEE 2006-02*, Vol. 2006, Issue No. 2, 2006, pp. 121. Retrieved from http://en.cnki.com.cn/Article_en/CJFDTOTAL-ZGDC200602021.htm

[13] M. H. Rashid (ed.), *Power Electronics Handbook*, 4th Edition, pp. 285, Butterworth-Heinemann, Oxford, UK, 2017.

Authors' Profile

Ferrarison B. Lynser

Morningstar Sun

Maiarta Sungoh

Nuki Taggu

B.Tech. 8th Semester, Dept. of Electrical and Electronics Engineering, School of Technology, Assam Don Bosco University

Ms. Pushpanjalee Konwar is an Assistant Professor in the department of Electrical and Electronics Engineering, School of Technology, Assam Don Bosco University, Guwahati. She received her M. Tech. degree from Assam Don Bosco University in 2014 and pursuing Ph.D. from NIT Nagaland. She has authored one book chapter published by IGI Global Journals and has published many research papers in journals and conferences. Her area of research is biomedical instrumentation and power systems.