Control of Bifurcation Behaviour of the Buck Converter via a Resonant Parametric Perturbation Circuit

(Date received: 24/01/2014/Date accepted: 6/5/2015)

Ir. Dr Ng Kok Chiang*[1], Dr Michelle Tan Tien Tien[2], Dr Nadia Tan Mei Lin[3]

[1]R&D Centre, Leong Hing Sdn. Bhd., No. 1, Jalan P4/7, Seksyen 4, Bandar Teknologi Kajang, 43500 Semenyih, Selangor, Malaysia. [2]The University of Nottingham Malaysia Campus, Jalan Broga, 43500 Semenyih, Selangor, Malaysia.
[3]Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia.
**Corresponding author: kokchiang.ng@leonghing.com*

ABSTRACT

Nonlinear circuits and systems research has been growing very quickly over the past two decades. Actively pursued in almost every branch of science and engineering, nonlinear systems theory has found wide applications in a variety of practical engineering problems. Engineers, scientists and mathematicians have similarly advanced from the passive role of simply analyzing, or identifying chaos to their present, active involvement in controlling chaos – control directed not only at suppression, but also at exploiting its enormous potential. We now stand at the threshold of major advances in the control and synchronization of chaos for new applications across the range of engineering disciplines. All feedback controlled power converters exhibit certain non-linear phenomena over a specific breadth of parameter values. Despite being commonly encountered by power electronics engineers, these non-linear phenomena are by and large not thoroughly understood by engineers. Such phenomena remaining somewhat mysterious and hardly ever been examined in a formal way. As the discipline of power electronics becomes more matured, demand for better functionality, dependability and performance of power electronics circuits will inevitably force researchers to engage themselves in more detailed study and analysis of non-linear phenomena and complex behaviour of power electronics converters. The bifurcation behaviour of the buck converter occurs when the input voltage is varied. In this study, the computer simulation scheme, PSPICE is employed to model the behaviour of the ideal buck converter. For certain values of the input voltage Vin instability occurs. The resonant parametric perturbation method is then applied to control the bifurcation behaviour of the voltage-mode controlled buck converter. Analysis and simulations are presented to provide theoretical and practical evidence for the proposed control method. As the buck converter has wide industrial application, it would be deemed necessary for designers to know about its bifurcation behaviour and how to control such behaviour.

Keywords: Bifurcation, Chaos, Control, Buck Converter, Parametric Perturbation

1.0 INTRODUCTION

Bifurcations control involves the designing of a controller to curb or lessen the bifurcation dynamics of a given system to attain desirable dynamical behaviour. There have been proposals for control methods to bifurcation and chaos behaviour for a variety of engineering applications [1-3]. The objectives of the control methods can be divided into two groups. The first is the identification of one of the unstable periodic orbits within a chaotic attractor as the control target and the utilisation of a control technique to specifically stabilise the system on the targeted periodic orbit [2]. The second group involves the control action to attain the required operating state (target) without much emphasis on which unstable orbit that is stabilised in the chaotic attractor. The feedback scheme is used to for the first category of control objective, while the non-feedback scheme is employed mostly for the second category [2, 3].

For the feedback method, some parameters of the control mechanism are changed to attain the required control objective after the establishment and implementation of control laws. These control laws are established from the collection and examinations of the system variables via experiments and simulations [2, 3]. Among the techniques that are currently employed to counter the bifurcation behaviour using the feedback method are the deferral of the incident of an intrinsic bifurcation, the modification of the shape or nature of the bifurcation, the introduction of a new bifurcation phenomena, the fine tuning of the system performance around a bifurcation point, the supervision of the multiplicity, amplitude and frequency of some limit cycles surfacing from a bifurcation process, and the adjustment of the parameter sets or values of an existing bifurcation point [1].

As for the non-feedback scheme, there is no need for any system variables to be gauged, and it is of no necessity to identify any specific periodic orbit as the control target [4, 5]. Among the known techniques of controlling bifurcation behaviour without feedback are the resonant parametric perturbation technique [4-6], the weak periodic perturbation, and the entrainment and migration control [7, 8]. Contrasting the non-feedback scheme to the feedback scheme, the method that is more suited for practical implementation and for anti-jamming ability is that of the non-feedback scheme [7, 9].

Implementation of bifurcations and chaos control with specific objectives have been successful in various experimental systems and numerical simulations in a wide range of fields and disciplines, the former including electrical, mechanical, chemical, and the latter, aeronautical studies, biology, meteorology, physics and chemistry [10]. Bifurcation control usually paves the way to the identification of chaos control as bifurcation is a generic route to chaos in most nonlinear dynamical systems [10-12]. In the course of this study, the non-feedback type of control, namely the resonant parametric perturbation method, will be examined in detail for the control of chaotic and bifurcation behaviour of the buck converter.

2.0 METHODOLOGY

The PSPICE Model for this study –The PSPICE schematic of the closed-loop voltage feedback buck converter used in this study is depicted in Figure 1. The changes made in this PSPICE circuit however are the replacement of one of the comparators with a gain of 8.4 in the Fossas and Olivar's paper with an ideal multiplier and a difference comparator, which forms the error amplifier circuit of the buck converter to generate the birfucation behaviour and the replacement of V_{ref} with the $V_{ref-}(1+\alpha \sin 2\pi f_r t)$ function as the control which forms the Resonant Parametric Perturbation Circuit as indicated in Figure 1 [13, 14]. The PWM controls the ideal switch, S_1 and it is the most complex part of the switched regulator of the buck converter [13, 15]. The switched buck converter circuit in this study uses a PWM integrator circuit. The PWM circuit consists of the wave generator, the error amplifier and an infinite gain comparator. The PWM controls the ideal switch, S_1 and is the most complex part of the switched regulator of the buck converter [13, 14]. All the components used in this PSPICE model are ideal components. Both switches, S_1 and S_2 have zero on and infinite off resistance, and can switch instantaneously. Both the S_1 and S_2 switches work in a complementary manner. When S_1 is on, S_2 will be off and the input voltage supplies energy to the load resistance and the inductor. On the other hand, when S_1 is off and S_2 is on, the inductor current decays while flowing through S_2 and at the same time transfers some of the stored energy to the load resistor. The output voltage is controlled by setting the frequency of the sawtooth generator to be of constant switching frequency and by altering the on-interval of the switch. The switch ratio, d which can be characterised as the ratio of the on-time to the switching period is changed through the PWM switching. As the switches turn off and turn on in a complementary way, instantaneously allowing the current flow in two different directions, the discontinuous conduction mode can be assumed to be avoided. Such mechanisms of the switches also cater for the existence of light load levels [13-15].

In this work, the circuit parameter with the strongest effect on the system is employed to be the perturbation parameter, i.e. the reference voltage, V_{ref} of the buck converter circuit. The circuit used to study the effectiveness of the resonant parametric perturbation method in controlling the chaos and bifurcation behaviour of the buck converter will be further discussed in the Results and Discussion section of this paper. The waveforms obtained are then observed and analysed to establish the effects of the changes of the perturbation amplitude, in the newly introduced function, $V_{ref}(1+\alpha \sin 2\pi f_r t)$ on the typical circuit characteristics.

The perturbation frequency f_r is set to the driving frequency and the perturbation amplitude, α is varied from 0 to 0.25. The chaotic behaviour of the buck converter when V_{in} = 33 V is examined in this study. Simulation of the buck converter for each value of α is presented in three main categories of waveforms namely, the time-domain voltage and current waveforms, the Fast Fourier Transform (FFT), and the phase portrait (better known as the Trajectory).

Procedures in Controlling the Bifurcation Behaviour – The value for α of the resonant parametric perturbation function $V_{ref}(1+\alpha \sin 2\pi f_r t)$ in the PSPICE model of the buck converter in Figure 1 is varied while other circuit parameters are held constant to obtain the required waveforms. The fixed value parameters, which include the input voltage, V_{in} (when the circuit exhibits chaotic behaviour), the load resistor, R, the inductor, L, the capacitor, C, switching frequency, f of the ramp generator, the perturbation frequency, f_r, and the ramp upper and lower voltages are as summarised in the Table 1.

i) Reference Voltage, V_{ref}	11.3 V
ii) Input Voltage, V_{in}	33 V
iii) Load Resistor, R	22 Ohm
iv) Inductor, L	20 mH
v) Capacitor, C	47 μF

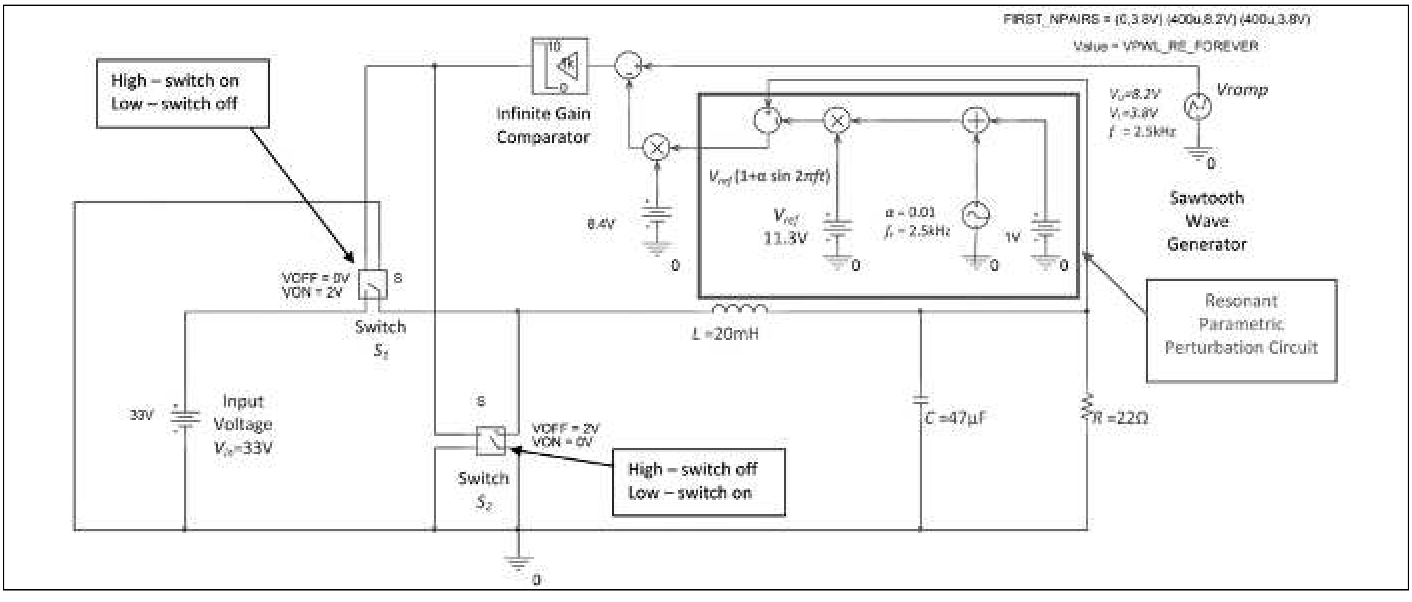

Figure 1: PSPICE Schematic of the Modified Voltage Feedback Buck Converter with Resonant Parametric Perturbation Control Circuit

vi) Switching Frequency, f (Period = 400 μ s)	2.5 kHz
vii) Perturbation Frequency, f_r (Period = 400 μ s)	2.5 kHz
viii) Ramp Upper Voltage, V_U	8.2 V
ix) Ramp Lower Voltage, V_L	3.8 V

Table 1: Values of Fixed Circuit Parameters of the Modified Circuit of the Buck ConverterCircuit

The perturbation amplitude, α is varied from 0 to 0.25 and the new circuit is simulated at each of the different values of α. The corresponding voltage and current waveforms, FFT spectrum, and trajectories (phase portrait diagrams) are shown in the Results and Discussion section. All cases are described as is increased from when the circuit started out in the chaotic state progresses through to period-2, lastly to period-1.

3.0 RESULTS AND DISCUSSION

The resonant parametric perturbation method is highly effective in controlling chaos and bifurcations in periodically driven systems. Although this method requires non-zero control power even when the system has been reduced to its steady state, the viability of its implementation to control chaos and bifurcations in various systems is very encouraging [16-18]. Nonetheless, even though by and large, parametric perturbation can lead to chaotic behaviour of a system, it can also be used to suppress chaos if the right frequencies and amplitudes are selected. Thus, a chaotic system or a system which is in its period-doubling domain can be converted into a normal period-1 operation through the perturbation of some parameters at the right frequencies and amplitude [16, 18].

The parameter that will be selected to be perturbed using this technique is usually the parameter that has characteristics such as strong influence on the system, and can be easily varied. In the circuit developed in PSPICE for the control of chaos and bifurcation behaviour of the buck converter, (see Figure 1), V_{ref} is chosen to be the perturbation parameter. This parameter is perturbed with the function $(1+\alpha\sin 2\pi f_r t)$ where α and f_r is the perturbation frequency. This is to ensure the Lyapunov exponent is kept below zero [16]. Lima & Pettini's paper in 1990 [4], proves that the largest Lyapunov exponent will approach zero from positive which leads to the taming of the chaos. The period-1 operation then appears when the Lyapunov exponent falls further below zero if the perturbation frequency f_r is the set to be the same as the periodic driving frequency of the circuit [4, 5]. The PSPICE model of the modified buck converter to which includes the resonant parametric perturbation circuit is simulated for the perturbation amplitude, α being varied from 0 to 0.25 in steps of 0.01. The chaotic reduction effect by the resonant parametric perturbation circuit when V_{in} = 33 V is examined here. Crucial information about the output voltage (the capacitor voltage), the inductor current and Fast Fourier Transform Spectrum are collected.

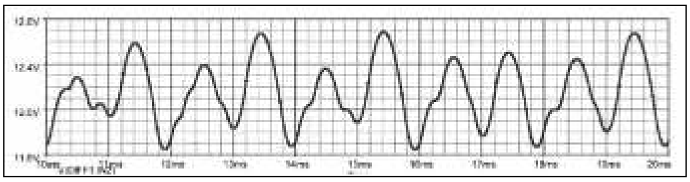

Figure 2: Output Voltage at α = 0.00

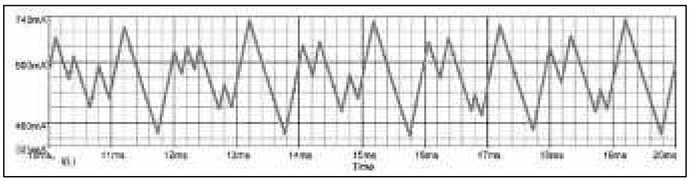

Figure 3: Inductor Current, I_L at α = 0.00

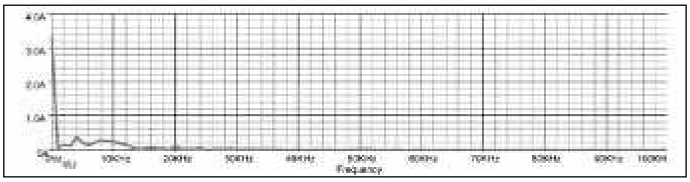

Figure 4: FFT Spectrum at α = 0.00

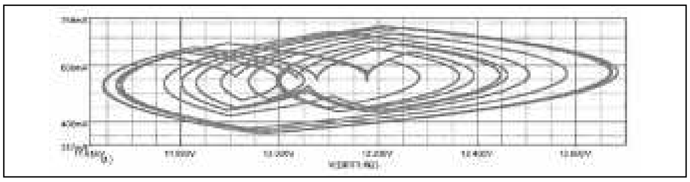

Figure 5: Trajectory when α = 0.00

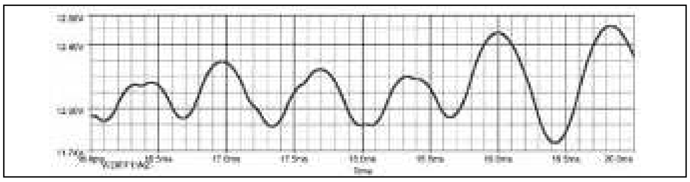

Figure 6: Output Voltage, V_C at α = 0.01

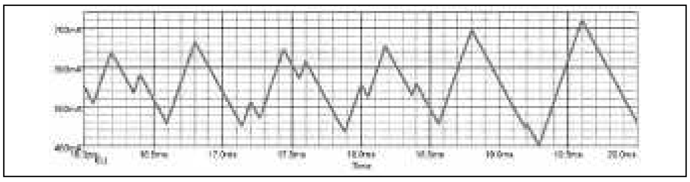

Figure 7: Inductor Current, I_L at α = 0.01

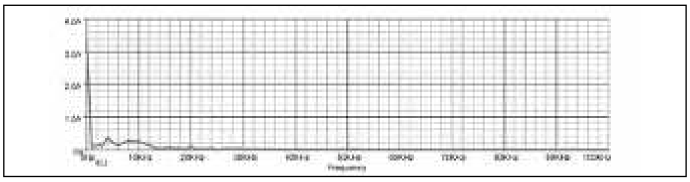

Figure 8: Broadband FFT Spectrum at α = 0.01

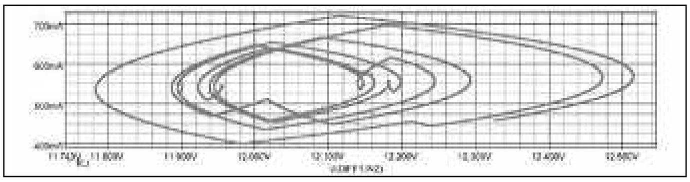

Figure 9: Chaotic Trajectory when α = 0.01

When α = 0.00, the operation of the buck converter is in the chaotic region where V_{in} = 33 V. This is very much the same operation as in the case of chaotic operation of the buck converter when V_{in} = 33 V as previously reported [19-21]. This is because at α = 0.00, the resonant parametric perturbation circuit remains dormant and does not affect the operation of the buck converter significantly. When α is increased to 0.01 however, we can see some improvement in the waveforms as compared to that when α = 0.00. Random, unsymmetrical disjoint and aperiodic nature that are evident in the waveforms of the output voltage and the inductor current of the buck converter as in Figure 6 and 7, have improved a little. Nonetheless, as expected, the output voltage and the inductor current waveforms still do not follow a specific form of repetition. Improvement is also evident in the phase portrait in Figure 9 where the trajectory is less chaotic when compared to that in Figure 5. As for the Fast Fourier Transform Spectrum in Figure 8, a continuous and broadband nature can still be observed suggesting that the buck converter is still operating in the chaotic region.

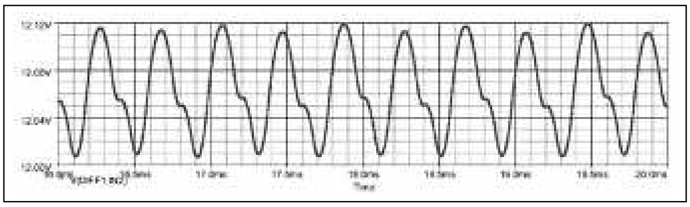

Figure 10: Output Voltage, V_C at α = 0.02

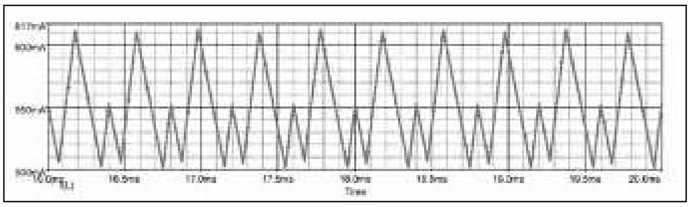

Figure 11: Inductor Current, I_L at α = 0.02

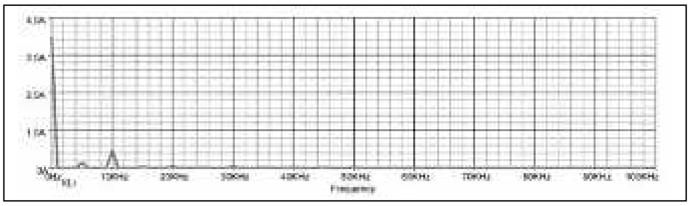

Figure 12: FFT Spectrum at α = 0.02

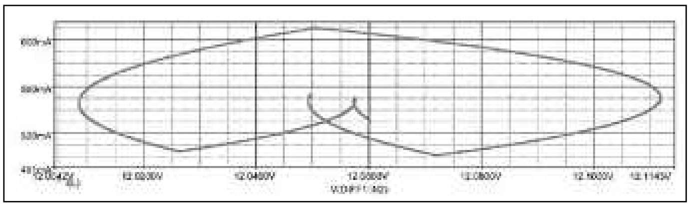

Figure 13: Period-2 Trajectory when α = 0.02

As α is increased to 0.02, the waveforms of the output voltage and the inductor current of the buck converter show great improvement. The unsymmetrical and disjoint waveforms of the output voltage and inductor current when α is equal to 0.01 are now showing a constant repetition of waveforms despite having little hiccups in them. The output voltage and the inductor current waveforms when α = 0.02 are very much the same as when the buck converter was operating in its period-2 region as if when V_{in} = 28 V as previously reported [19, 21]. Hence, by just changing the□□□, the operation of the buck converter as if V_{in} is equal to 28 V (as been reported previously [19-21]) can be achieved even at V_{in} = 33 V, which would have been chaotic if it was not for the resonant parametric perturbation circuit. The Fast Fourier Transform Spectrum (see Figure 12) is now no longer continuous and of a broadband nature as before. Moreover, to strengthen the argument that the buck converter is now operating in the period-2 region, the trajectory or the phase portrait in Figure 13 is a two-branch loop of a period-2 attractor.

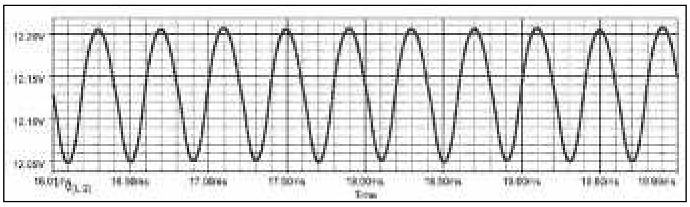

Figure 14: Output Voltage, V_C at α = 0.04

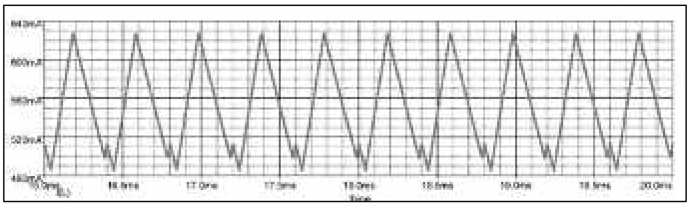

Figure 15: Inductor Current, I_L at α = 0.04

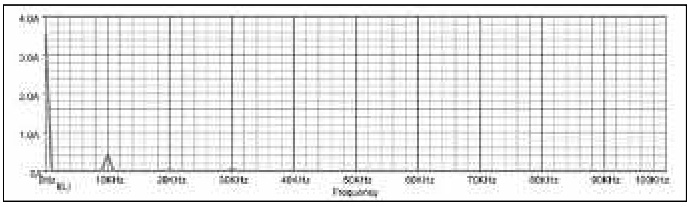

Figure 16: FFT Spectrum at α = 0.04

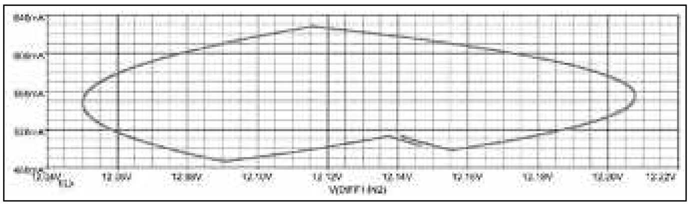

Figure 17: Trajectory when α = 0.04

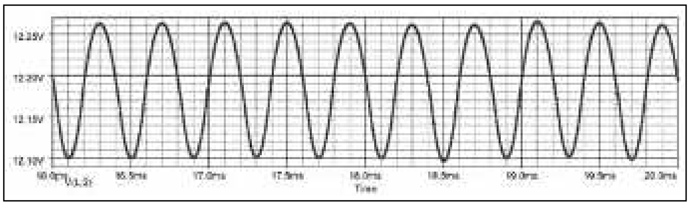

Figure 18: Output Voltage, V_C at α = 0.06

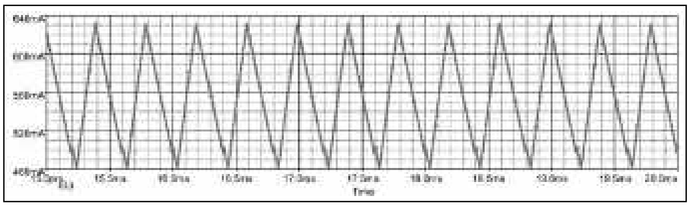

Figure 19: Inductor Current, I_L at α = 0.06

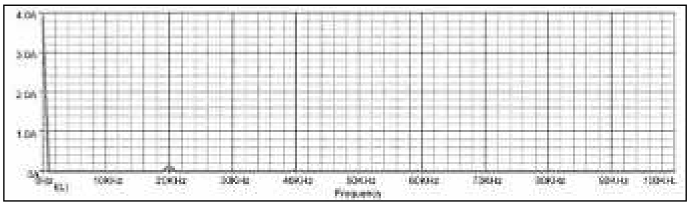

Figure 20: FFT Spectrum at α = 0.06

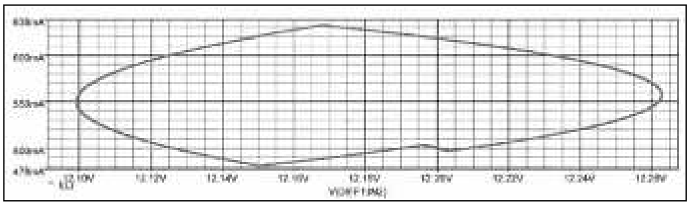

Figure 21: Trajectory when α = 0.06

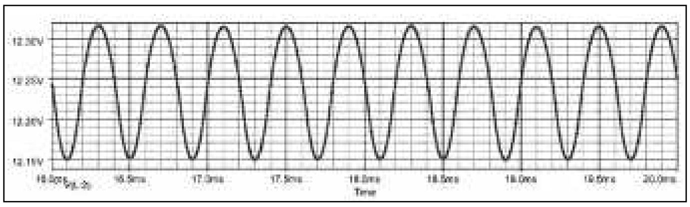

Figure 22: Output Voltage, V_C at α = 0.08

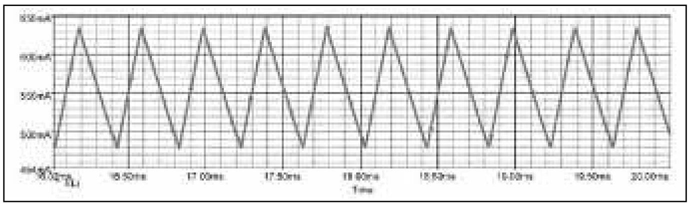

Figure 23: Inductor Current, I_L at α = 0.08

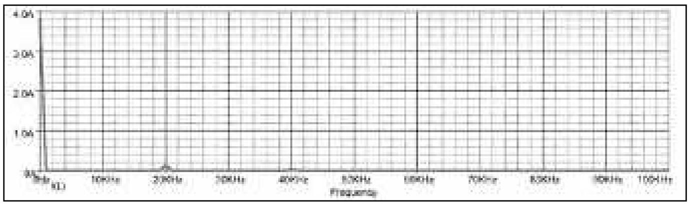

Figure 24: FFT Spectrum at α = 0.08

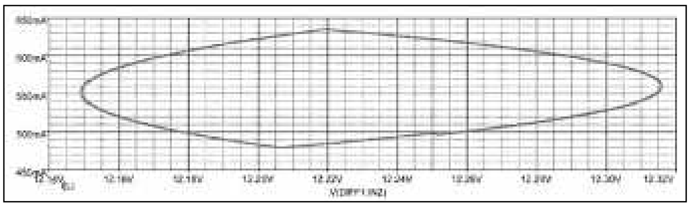

Figure 25: Trajectory when α = 0.08

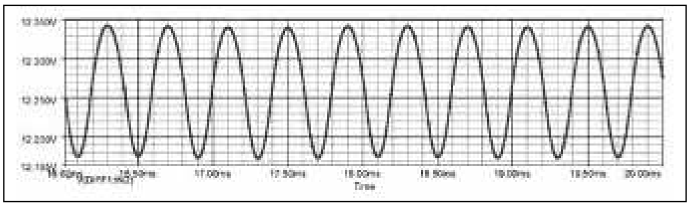

Figure 26: Output Voltage, VC at α = 0.09

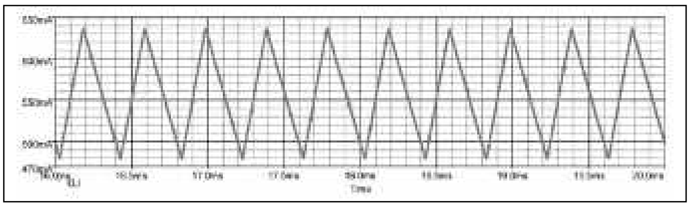

Figure 27: Inductor Current, I_L at α = 0.09

As α is increased further to 0.04, the output voltage and the inductor current waveforms show an even better improvement than before as can be seen in Figures 14 and 15. The waveforms are experiencing the smoothing effect of the resonant parametric perturbation circuit. The hiccups become less evident in the waveforms, and the trajectory now has the shape of a period-1 trajectory except for the little disjoint at the right bottom corner of the graph (see Figure 17). The Fourier Transform Spectrum too has narrowband, discontinuous and isolated frequency harmonics as in Figure 16. Figures 18 to Figure 21 and Figures 22 to 25 show the waveforms as α is changed to 0.06 and 0.08 respectively. As α is increased further and further, the waveforms of the output voltage and the inductor current show better and better symmetry and improvement. The graphs have indeed become smoother and smoother. When α is 0.08, the waveforms shown are already as good as those of period-1 operation except for occasional small flaws and hiccups.

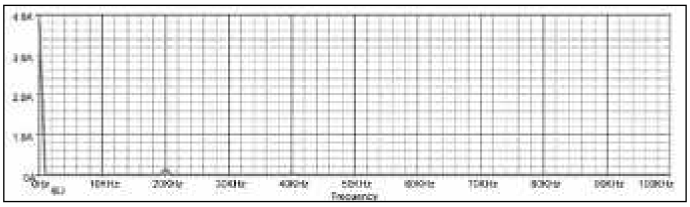

Figure 28: FFT Spectrum at α = 0.09

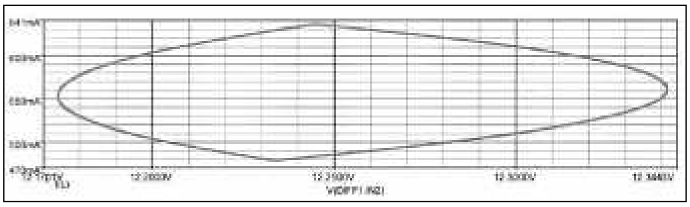

Figure 29: Trajectory when α = 0.09

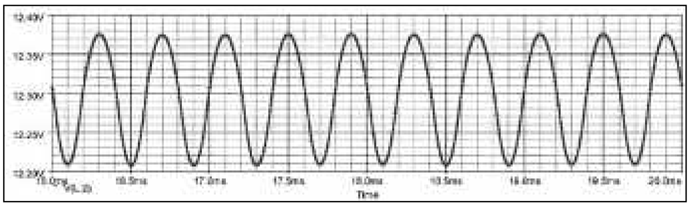

Figure 30: Output Voltage, V_C at α = 0.10

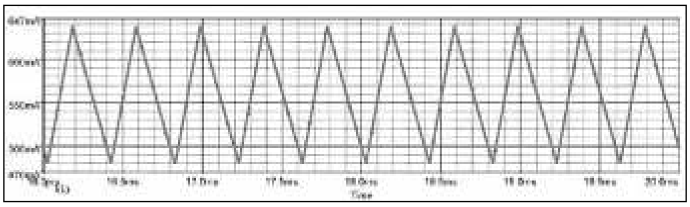

Figure 31: Inductor Current, I_L at α = 0.10

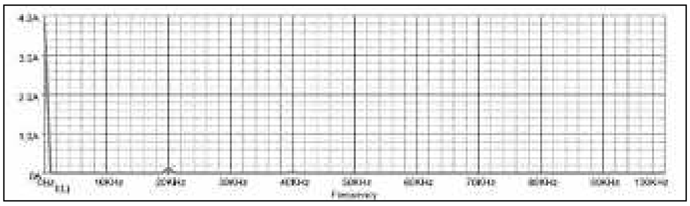

Figure 32: FFT Spectrum at α = 0.10

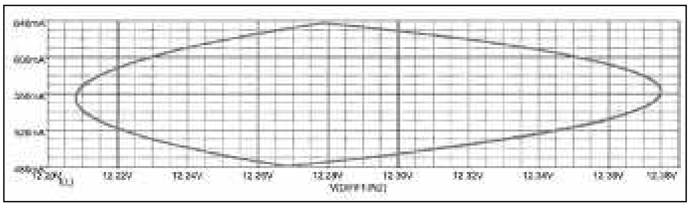

Figure 33: Trajectory when α = 0.10

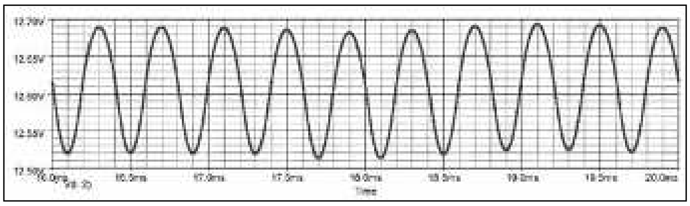

Figure 34: Output Voltage, V_C at α = 0.20

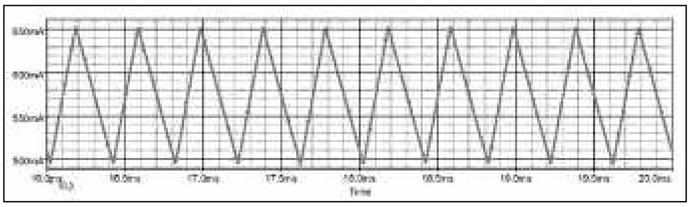

Figure 35: Inductor Current, I_L at α = 0.20

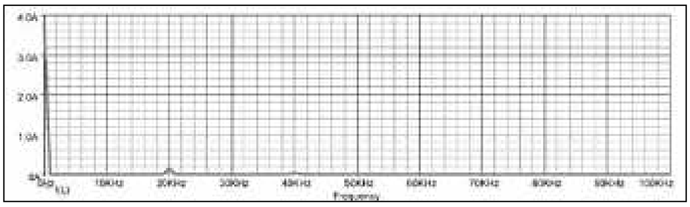

Figure 36: FFT Spectrum at α = 0.20

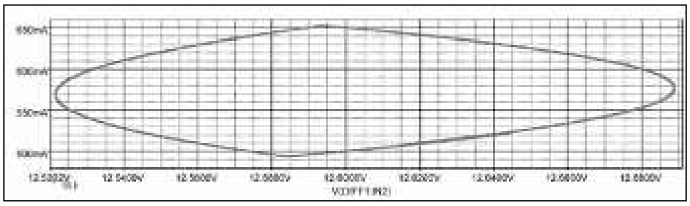

Figure 37: Trajectory when α = 0.20

Finally, when α is equal to 0.09, output voltage and the inductor current waveforms in the time domain both appear to be very smooth and periodic in nature, demonstrating that the period-1 stable operation of the buck converter has been achieved. This observation is further verified by its Fast Fourier Transform Spectrum in Figure 28 where narrowband, discontinuous and isolated frequency harmonics are very obvious. Furthermore, the very small hiccup in the trajectory of the buck operation when α= 0.08, is now gone, and the only thing left is a smooth period-1 trajectory signifying that the operation of the buck converter is in its stable region similar to its operation with V_{in} = 20V has been reported elsewhere [19, 20-28]. Here however, the only difference is that the buck converter is now operating in period-1 region at V_{in} = 33 V with α = 0.09 for the resonant parametric perturbation circuit. The input voltage of 33 V and switching frequency of 2.5 kHz were chosen because the bifurcation behaviour that was present in an earlier study [29] used the input voltage 33 V at the switching frequency of 2.5 kHz. This study attempts to solve the bifurcation problem that was present in the earlier study [29]. Thus, α= 0.09 is found to be the smallest effective perturbation amplitude to bring the chaotic operation of the buck converter circuit back to its period-1 operation. To confirm that the operation of the buck converter continues in the stable period-1 region after α= 0.09, simulations when α = 0.10 and α= 0.20 are carried out and as expected, the results obtained as depicted in Figures 30 to 37 point to operation of the buck converter in the stable period-1 domain. Thus, results show that the resonant parametric perturbation circuit functions effectively in smoothing out the curves and the waveforms of the output voltage and the inductor current of the buck converter circuit to bring it back to its period-1 operation in a non-feedback manner.

4.0 CONCLUSION

Power electronics has always been known to exhibit complicated behaviour, even in very simple circuits. This is due to their inherent non-linear and time-varying nature. Throughout the years, it has been experimentally found that a large number of non-linear systems in power electronics demonstrate 'strange behaviour' which includes subharmonic oscillations, bifurcations and chaos. But due to the normal reaction of engineers who wish to avoid such behaviours through some trial-and-error procedures these phenomena have remained rather puzzling and rarely examined in a formal manner. However, it is only with detailed examination and study of these non-linear behaviours that better controls of these non-linear behaviours can be found instead of just sticking to traditional trial-and-error methods.

This paper dealt with the modelling and simulation of the buck converter in PSPICE to simulate its bifurcation behaviour and to examine a control technique to counter such behaviour. Being one of the simplest of the DC-to-DC converters, the buck converter is chosen to be the subject of this study because of its widespread representation of the circuit to many practical DC-to-DC converters. Also, due to its extensive applications in industrial and engineering applications, the knowledge of the system behaviour in different regions of parameter space should be crucial, especially in designing the buck converter for sensitive equipment.

As the buck converter is expected to function under a generous range of input voltage, V_{in}, additional control may be essential to control chaos and bifurcations. The resonant parametric perturbation method has been chosen in this study as the non-feedback control strategy to counter the chaotic and bifurcation behaviour of the buck converter when it is operating in its chaotic region at V_{in} = 33V. Figures 5, 9, 13, 17, 21, 25, and 29 are phase portrait diagrams which shows the progression of the change from chaotic to period-2 and lastly to period-1 operation of the buck converter when α is varied from 0 to 0.09. Thus, the addition of the resonant parametric perturbation circuit has indeed turned out to be effective in suppressing the chaotic and bifurcation behaviour of the buck converter, bringing its operation back to its period-1 state. The resonant parametric perturbation method is a method easy to apply when it is compared to those of the feedback types as no prior knowledge of the system behaviour is required. Besides that, as evident from the layout of the circuit in Figure 1, resonant parametric perturbation control allows easy incorporation of the perturbation circuit with the existing buck converter circuit.

With better understanding of the system's behaviour under different operating circumstances, better control strategies can be developed and furthermore, profitable exploitation of the non-linear operating region for engineering purposes may also be possible. There are also a number of papers on the control of chaos and bifurcation behaviours now being actively published. Better knowledge of non-linear behaviour of the system has paved way for such publications. Bifurcation and chaos control via the resonant parametric perturbation method is now becoming more and more useful in engineering applications. Examples can be found in areas such as power network control and stabilisation, axial flow compressors and jet engine control, cardiac alternans and rhythms control, and stabilisation in tethered satellites and bearing systems. Successful implementation of this method in controlling chaos and bifurcation is now not in doubt anymore as to its effectiveness in a wide range of systems. ■

REFERENCES

[1] G. Chen, J. L. Moiola and H. O. Wang "Bifurcations: Control and Anti-Control," IEEE Circuits and Systems Society Newsletter, vol. 10, no. 2, pp. 4-31, June/July 1999.

[2] M. H. Rashid, Power Electronics Circuits, Devices, and Applications, (Third Edition) University of West Florida: Pearson – Prentice Hall International Edition, 2004.

[3] C. K. Tse, "Recent Development in the Study of Nonlinear Phenomena in Power Electronics Circuits", IEEE Circuits and Systems Society Newsletter, pp. 14-48, March , 2000.

[4] R. Lima and M. Pettini "Suppression of chaos by resonant parametric perturbations," Phys. Rev. A41, 726-733, 1990.

5] J. Baillieul, R. W. Brockett, and R. B. Washburn, "Chaotic Motion in Nonlinear Feedback Systems," IEEE Transactions on Circuits and Systems, vol. 27, no. 11, pp. 990-997, November 1980.

[6] D. C. Hamill and D. J. Jefferies, "Subharmonics and Chaos in a Controlled Switched-mode Power Converter," IEEE Transactions on Circuit Systems I, vol. 35, pp. 1059-1061, August 1988.

[7] Y. Zhou, C. K. Tse, S. Qiu and F. C. M. Lau, "Applying Resonant Parametric Perturbation to Control Chaos in the Buck DC/DC Converter with Phase Shift and Frequency Mismatch Consideration," International Journal of Bifurcation and Chaos, vol. 13, no. 11, pp. 3459-3471, 2003.

[8] J. H. B. Deane and D. C. Hamill, "Instability, subharmonics and chaos in power electronics systems," in IEEE Power Electronics Specialists Conference Record, pp.34-42, 1989.

[9] J. H. B. Deane and D. C. Hamill, "Instability, subharmonics and chaos in power electronics systems," IEEE Transactions on Power Electronics, vol. 5, no. 3, pp.260-268, 1990.

[10] G. Chen, "Chaos: Control and Anti-Control," IEEE Circuits and Systems Society Newsletter, pp. 1-5, March 1998.

[11] P. T. Krein and R. M. Bass, "Types of Instability Encountered in Simple Power Electronics Circuits: Unboundedness, Chattering, and Chaos," in APEC'90, IEEE Applied Power Electronics Conference Proceedings, pp. 191-194, 1990.

[12] J. H. B., Deane and D. C. Hamill, "Analysis, Simulation and Experimental Study of Chaos in the Buck Converter," PESC'90, IEEE Power Electronics Specialists Conference Record, Vol. II, pp.491-498, 1990.

[13] E. Fossas and G. Olivar, "Study of chaos in the buck converter," IEEE Transactions on Circuits Systems I, vol. 43, pp. 13–25, Jan 1996.

[14] K. Chakrabarty, G. Podder, and S. Banerjee, "Bifurcation behaviour in buck converter," IEEE Transactions on Power Electronics, vol. 11, pp. 439–447, May 1996.

[15] Poddar, Gautam, K. Chakrabarty and S. Banerjee, "Experimental Control of Chaotic Behavior of a Buck Converter," IEEE Transactions on Circuits and Systems I, vol. 43, no. 8, pp. 502-504, August 1995.

[16] P. Colet and Y. Braiman, "Control of chaos in multimode solid state lasers by the use of small periodic perturbations," Phys. Rev., E53, pp. 200-206, 1996.

[17] Y. Braiman and I. Goldhirsch, "Taming chaotic dynamics with weak periodic perturbations," Phys. Rev. Lett. 66, pp. 2545-2548, 1991.

[18] R. Chacón and J. Díaz Bejarano, "Routes to suppressing chaos by weak periodic perturbations," Phys. Rev. Lett. 71, pp. 3103-3106, 1993.

[19] H. B. J. Deane and D. C. Hamill. "Analysis, simulation and experimental study of chaos in the buck converter." IEEE Power Electronics Specialists Conference, 2. 1990.

[20] K. A. Mirus and J. C. Sprott "Controlling chaos a high dimensional system with periodic parametric perturbations," Phys. Lett. A254, pp. 275-278, 1999.

[21] W. C. Y. Chan and C. K. Tse, "Study of Bifurcations in Current-Programmed DC/DC Boost Converters: From Quasi-Periodicity to Period-Doubling," IEEE Transactions on Circuits and Systems I, vol. 44, no. 12, pp. 1129-1142, December 1997.

[22] R. Gavagsaz-Ghoachani, M. Phattanasak, J.-P. Martin, S. Pierfederici and B. Davat

"Predicting the onset of bifurcation and stability study of a hybrid current controller for a boost converter," Mathematics and Computers in Simulation, vol. 91, pp. 262-273, May 2013.

[23] S. Hebertt, L. Alberto and C. John, "Robust input–output sliding mode control of the buck converter," Control Engineering Practice, vol. 21, pp 671–678, May 2013.

[24] W. Lu, L. Zhou, Q. Luo and J. Wu, "Non-invasive chaos control of DC–DC converter and its optimization," International Journal of Circuit Theory and Applications, vol. 39, pp 159–174, Feb 2011.

[25] E. Meyer, Z. Zhang and Y. Liu, "Digital Charge Balance Controller to Improve the Loading/Unloading Transient Response of Buck Converters," IEEE Transactions on Power Electronics, vol. 27, pp. 1314 – 1326, March 2012.

[27] K. Karama, J. Pelaez-Restrepo, M. Feki, B. G. M. Robert and A. El Aroudi, "Improved static and dynamic performances of a two-cell DC–DC buck converter using a digital dynamic time-delayed control," vol 40, pp 395–407, April 2012.

[28] C. K. Tse and M. di Bernardo, "Complex Behavior in Switching Power Converters," Proceedings of IEEE, Special Issue on Application of Nonlinear Dynamics to Electronic and Information Engineering, vol. 90, no. 5, pp.768-781, May 2002.

[29] K. C. Ng, N. M.L. Tan and M. T. T. Tan, " Bifurcation of Buck Converter," Journal of the Institutions of Engineers, Malaysia, vol. 75, no. 1, June 2014.

PROFILES

IR. DR NG KOK CHIANG graduated from the University of Western Australia with first class honours in Bachelor of Engineering in Electrical & Electronics and Bachelor of Commerce majoring in Accounting, Investment Finance (Derivatives), and Managerial Accounting. He then furthered his studies to the University of Nottingham, UK and graduated with a PhD in Engineering having worked in the area of renewable energy and its storage for three and a half years. Ir. Dr Ng Kok Chiang in his course of research and work had liaised with various organisations such as E.ON (Power and Gas), Lockheed Martin, Jaguar/Land Rover (supercapacitors in automotive industry/electric cars), Battelle (lab management and commercialisation), Malaysia Rubber Board (energy management, artificial intelligent, control, and electronics), and MOSTI (Fabrication of Advanced Supercapacitors). He is currently the Chief Technology Officer of MyBig Sdn. Bhd. and a Professional Engineer with the R&D Centre at Leong Hing Sdn. Bhd. involved in research and prototyping projects in collaboration with various Malaysian Government Agencies and research bodies. Among the prominent solutions founded were the advanced switching mechanism in the Nexcap storage to efficiently capture minuscule trickle of charges, intelligent control systems incorporating power electronics device, and the advanced Sunopy solar system.

DR NADIA TAN MEI LIN was born in Kuala Lumpur, Malaysia. She received the B.Eng. (Hons.) degree from the University of Sheffield, Sheffield, U.K., in 2002, the M.Eng. degree from Universiti Tenaga Nasional, Kajang, Malaysia, in 2007, and the Ph.D. degree from Tokyo Institute of Technology, Tokyo, Japan, in 2010, all in electrical engineering. Since October 2010, she has been a Senior Lecturer in the Department of Electrical Power Engineering, Universiti Tenaga Nasional. Her current research interests include power conversion systems and bidirectional isolated dc–dc converters. Dr. Tan is a Graduate Member of the Institution of Engineers Malaysia (IEM), a Member of the Institution of Engineering and Technology (IET), and a Member of the Institute of Electrical and Electronics Engineers (IEEE).

DR MICHELLE TAN TIEN TIEN is an Assistant Professor in the Department of Electrical & Electronic Engineering at the University of Nottingham Malaysia Campus. She received her BEng. degree in Electrical & Electronic Engineering at Swansea University, Wales, UK where she also completed her PhD on using one dimensional Zinc Oxide nanowires for bio-sensing application. Michelle's current research focuses on the synthesis and characterisation of nanomaterials for bio-sensing applications, with emphasis on graphene, metal oxide and graphene/metal oxide composites. Besides that, her research also focuses on incorporating graphene composites for application in critical and hard environments, such as aerospace applications, of which is currently funded by the Ministry of Science Technology & Innovation (MOSTI), Malaysia.