Bifurcation Behaviour of the Buck Converter

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ABSTRACT

The bifurcation and chaos phenomena appeared in power system have become a focus subject at present. It has become apparent about a decade ago that power converters exhibit various types of non-linear behaviour which includes all kinds of bifurcations and chaos. Even basic DC/DC converters exhibit bifurcation and chaos phenomena as well as parallel-connected DC/DC converters and PFC system. The main source of such non-linearity is the switching mechanism of the converters. Non-linear components of the converter circuit and control scheme such as the use of naturally-sampled, constant-frequency PWM further contribute to the non-linear behaviour of converters such as a DC-to-DC buck converter. Thus, 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. This paper examines the bifurcation behaviour of the buck converter in an ideal case when the input voltage is varied. The computer simulation scheme, PSPICE is employed to model the behaviour of the ideal buck converter. For certain values of the input voltage, V_{in} instability occurs. The analysis and conclusion presented in this paper will provide an overview of the bifurcation behaviour of the DC-to-DC buck converter, aspiring to draw attention of the power electronics and the circuits and systems communities to a field that is not often researched and examined.

Keywords: Bifurcation, Chaos, Non-linear Behaviour, Buck Converter

1.0 INTRODUCTION

The mechanisms of bifurcation and chaos are so complex that there is not a unified criterion to identify them. Bifurcation is also known as the emergence of a further pattern of behaviour or string of states for a system. It can be thought of as a qualitative change in an attractor's structure when a control parameter is smoothly changed. The qualitative change is followed by a change of the stability in the attractor too [1]. A simple example would be that of a fixed attractor that might cave in to a periodic oscillation, and a periodic attractor that might become unstable and be replaced with a chaotic attractor when stress on the system is increased. Successive bifurcations are normally attained when the value of some characteristic parameter is increased. An analogy would be that of a person walking down the road. The longer the distance he travels, the more side streets or other routes appear. In other words, bifurcation establishes history. Knowledge of the paths taken or not taken would be required to identify the state of the system at any point in time. The existence of bifurcations is unavoidable in the realm of nonlinear dynamical systems, which is beyond the territory of circuitry. Rich bifurcation phenomena can be found in power systems. An example would be the oscillations and bifurcations due to the movement of the dynamics of an electric power network towards its stability boundary when the user demand for power arrives at its peaks. Voltage collapse would probably be unavoidable. Bifurcations exist in mechanical systems too [1-5]. Hopf bifurcation may be present when a road vehicle under steering control loses its stability. In the worst case, the development of chaos and hyperchaos might take place.

Period-doubling bifurcations which would ultimately lead to chaos may be experienced by a hopping robot even if it is just a simple two-degree-of-freedom, flexible, robot arm. Bifurcations may also occur when an aircraft stalls due to over a critical angle-of-attack, or reduction of speed to be below a critical speed happens while in flight [1, 2, 5]. Vibration or wave frequencies that approximate to the natural frequency of the machine can cause bifurcations in the dynamics of aero-engine compressors, vehicles and ships. This could also lead to disasters if the oscillations and chaotic motions created by the bifurcations are not controlled. Bifurcations are also observed in various fields such as chemistry, (for example, in chemical reaction and fluid dynamics), weather dynamics and biological population dynamics [1, 3, 5].

Thus, from the discussion above, it can be said that bifurcations are ever-present in most physical systems even when subject to controls. In many nonlinear systems, including some closed-loop systems which have feedback controls, do exhibit all types of bifurcation. It is surprising that local instability and complex dynamical behaviour exist in such controlled systems but in actual fact, this can happen due to the poles movement of the closed-loop transfer function over the stability border when the feedback means of the system is not robust enough [1]. The signal divergence caused due to the movement of poles when the control progress continues may eventually lead to some local self-excited oscillations, bifurcations and even chaos instead of a global unboundedness. The popular automatic gain control loops and all other types of controlled and uncontrolled pendula would be among others examples of controlled systems where complex behaviour can be observed [1, 3-5]. The three typical types of bifurcation which are known as the co-dimension-one bifurcations are the stationary, Hopf and period doubling bifurcations. Such bifurcations are termed co-dimension-one bifurcation due to the fact that there may exist a number of control parameters for which fine tuning is necessary to obtain the bifurcations intended. A stationary bifurcation involves the crossing of a single eigenvalue over the border of stability. Hopf bifurcations on the other hand involve the crossing of a conjugate pair over the border of stability. A limit cycle bifurcates in the time-continuous case. The imaginary part of the crossing pair gives the angular frequency of the bifurcations. In the discrete case however, a quasiperiodic bifurcation orbit is normally obtained [1]. The bifurcation which is possible in the discrete dynamical systems and absent in the continuous systems is known as the period doubling bifurcation. In this bifurcation, the border of stability is crossed by a real eigenvalue at period-1, while a period-2 orbit bifurcates at a period-doubling bifurcation point [6-10]. The simulations carried out in this study seek to identify the bifurcation points where the crossing of the border of stability occurs and the type of bifurcations that occur in 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 circuit is very similar to that proposed by Fossas and Olivar [6]. 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. 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 [6]. All the components used in this PSPICE model are ideal components. Both the 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_2 is off and S_1 is on, the inductor current decays while flowing through the switch 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 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 bi-directional current flow, the discontinuous conduction mode can be assumed to be avoided. Such mechanisms of the switches also cater for the existence of light load levels [6, 8-10].

Procedures in Obtaining the Waveforms for Bifurcation Behaviour – The value of V_{in} as the bifurcation parameter in the PSPICE model of the buck converter in Figure 1 is varied throughout the series of simulations carried out to obtain the bifurcation waveforms. The simulations are carried out with other circuit parameters held constant. The fixed value parameters which include the reference voltage V_{ref}, the load resistor *R*, the inductor *L*, the capacitor *C*, switching frequency *f* of the ramp generator, and the ramp

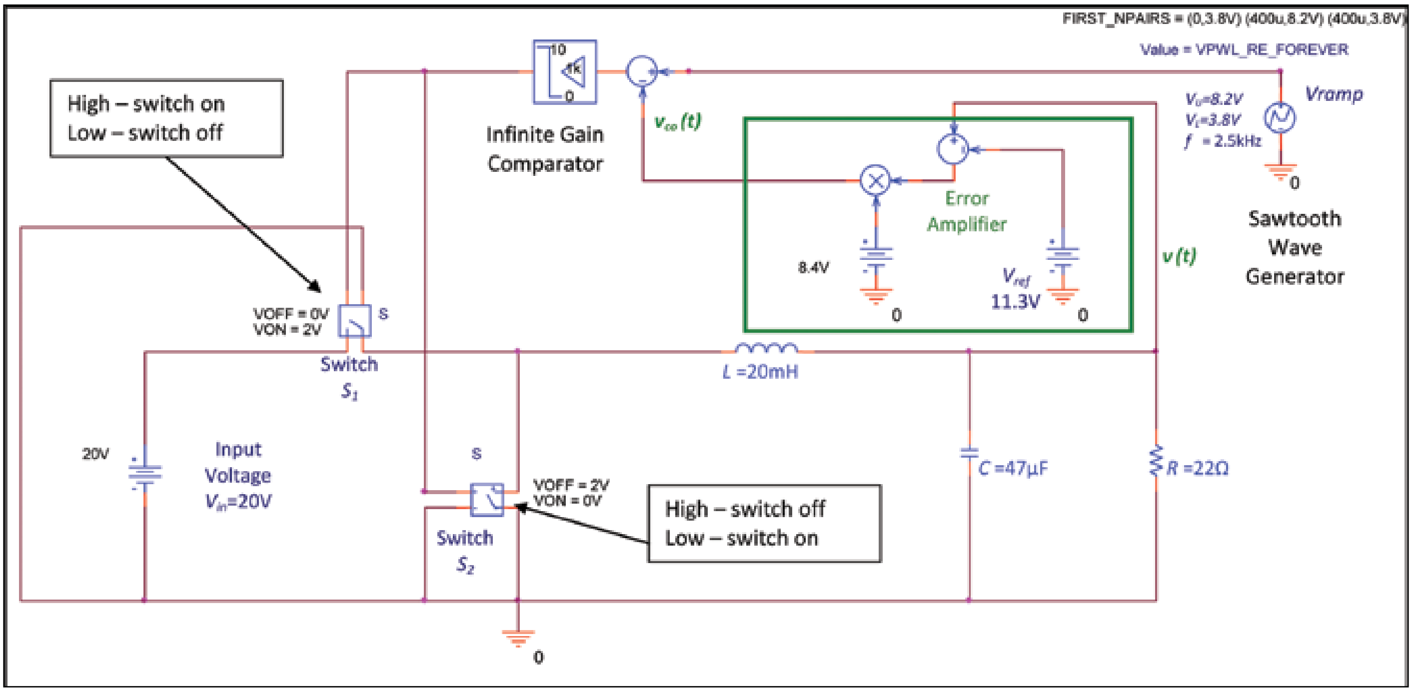

Figure 1: PSPICE Schematic of a Closed-loop Voltage Feedback DC-to-DC Buck Converter

upper and lower voltages are as summarised in the Table 1 below.

Table 1: Values of Fixed Circuit Parameters of the Buck Converter

i)	Reference Voltage, V_{ref}	11.3 V
ii)	Load Resistor, *R*	22 ohm
iii)	Inductor, *L*	20 mH
iv)	Capacitor, C	47 µF
v)	Switching Frequency, *f* (Period = 400 µs)	2.5 kHz
vi)	Ramp Upper Voltage, V_u	3.8 V
vii)	Ramp Lower Voltage, V_L	8.2 V

The input voltage V_{in} is varied from 20V to 40V and the buck converter circuit is simulated at the different values of V_{in}. The corresponding voltage and current waveforms FFT spectrum, and trajectories (phase portrait diagrams) are shown in the **Discussion and Results** section for all cases from when the circuit started out in stable state and progressed through to period-1, period-2, period-4, and thereafter to chaos via routes of period-doubling bifurcation.

3.0 DISCUSSIONS AND RESULTS

In the present case, the output voltage is fed into an error integrator. The difference comparator in the integrator compares the output voltage with a reference voltage which is chosen to be 11.3V. The difference between the two is then input into the multiplier which would amplify the output of the difference comparator by 8.4. A comparator then compares the error integrator output voltage with the output of the sawtooth generator. The switches S_1 and S_2 are controlled by the output of the comparator. If the magnitude of the sawtooth wave voltage is greater than that of the error integrator output voltage, switch S_1 is turned on and switch S_2 is turned off. On the other hand, when the sawtooth wave voltage is less than the integrator output voltage, switch S_1 will be turned off and S_2 turned on [6]. The output of the error integrator which has a gain of 8.4 would be:

$$v_{co}(t) = 8.4(v(t) - V_{ref}) \qquad \text{Equation 1}$$

The discontinuous conduction mode does not occur, a piecewise-linear vector field described by two sets of different differential equations can be used to represent the buck converter modelled as in equations 2, 3, 4, and 5 [11-15].

When $v_{co}(t) > v_{ramp}(t)$ (i.e. *S1* is off and *S2* is on):

$$\frac{dv(t)}{dt} = \frac{-v(t)}{RC} + \frac{i(t)}{C} \qquad \text{Equation 2}$$

$$\frac{di(t)}{dt} = \frac{-v(t)}{L} \qquad \text{Equation 3}$$

When $v_{co}(t) < v_{ramp}(t)$ (i.e. *S1* is on and *S2* is off):

$$\frac{dv(t)}{dt} = \frac{-v(t)}{RC} + \frac{i(t)}{C} \qquad \text{Equation 4}$$

$$\frac{di(t)}{dt} = \frac{-v(t)}{L} + \frac{V_{in}}{L} \qquad \text{Equation 5}$$

where v is the voltage through the capacitor and I is the intensity of the current in the inductor.

The sawtooth voltage is given by equation 6 below:

$$v_{ramp}(t) = V_L + (V_U - V_L)\, t/T \qquad \text{Equation 6}$$

where V_L and V_U are the lower and upper voltages of the sawtooth wave which are of the value 3.8V and 8.2V respectively, and T is its period. The operation of the buck converter can be seen from both points of view: autonomous system and nonautonomous system. Since the sawtooth wave has an externally determined periodicity, it is essentially a nonautonomous system.

The periodicity in this case would then be determined by the number of triangular ramp wave cycles in a period of the output waveform. Since the system of differential equations is linear, the exact solution for each of the differential equation is obtainable if the initial conditions are set to be $v_o = v(t_o)$ and $i_o = i(t_o)$.

Let $k = \frac{1}{2RC}$ and $\omega = +\sqrt{\frac{1}{LC} - k^2}$ and given that:

$$\frac{1}{LC} - k^2 > 0$$

The solution for the differential equations above would be equations 7 and 8:

When $v_{co}(t) > v_{ramp}(t)$ (i.e. *S1* is off and *S2* is on):

$$\begin{pmatrix} v(t) \\ i(t) \end{pmatrix} = e^{-k(t-t_0)}\left[I\cos\omega(t-t_0) + A\sin\omega(t-t_0)\right]\begin{pmatrix} v_0 \\ i_0 \end{pmatrix} \qquad \text{Equation 7}$$

When $v_{co}(t) < v_{ramp}(t)$ (i.e. *S1* is on and *S2* is off):

$$\begin{pmatrix} v(t) \\ i(t) \end{pmatrix} = \begin{pmatrix} V_{in} \\ V_{in}/R \end{pmatrix} + e^{-k(t-t_0)}\left[I\cos\omega(t-t_0) + A\sin\omega(t-t_0)\right]\begin{pmatrix} v_0 - V_{in} \\ i_0 - V_{in}/R \end{pmatrix} \qquad \text{Equation 8}$$

where I is the identity matrix.

The input voltage V_{in} is chosen as the bifurcation parameter for the study of the bifurcation behaviour of the buck converter. The PSPICE model of the buck converter is simulated for V_{in} being varied from 20V to 40V in steps of 1V with the critical waveforms when changes occur. Crucial information about the output voltage (which is also the capacitor voltage), and the inductor current and Fast Fourier Transform Spectrum are presented as follows in their respective graphs.

When V_{in} = 20V, as can be seen from Figures 2 and 3, the output voltage and the inductor current waveforms in time domain are both periodic in nature, demonstrating the period-1 stable operation of the buck converter. This observation is further strengthened by its Fast Fourier Transform (FFT) Spectrum shown in Figure 4 where narrowband, discontinuous and isolated frequency harmonics can be seen. As for the trajectory or the phase portrait when V_{in} is equal 20V in Figure 5, a normal period-1 loop is noticed [16-24].

The system continues to show period-1 behaviour until V_{in} reaches 28V. At V_{in} = 28V, the system starts to bifurcate into a period-2 domain. It can be clearly observed from the output voltage waveform, the inductor current waveform and the FFT spectrum waveforms in Figures 6, 7, and 8 respectively, where little hiccups can be seen in the voltage output and the inductor current waveforms. Moreover, the trajectory or the phase portrait when V_{in} is equal to 28V shown in Figure 9 shows a two-branch loop of a period-2 attractor [21, 23].

The period-2 bifurcation only lasted for a narrow range of V_{in} value up to 32V. Beyond and including the threshold of V_{in} = 32V, a period-4 bifurcation occurs. From the output voltage waveform and the inductor current waveform that are depicted in Figures 10 and 11, show the hiccups when V_{in} = 28V to be worse here. However, the waveforms still follow a general form of repetition [22]. The trajectory has now bifurcated into a period-4 portrait where a double image of the period-2 trajectory is observed as in Figure 13. Period-8 bifurcation lasts for the smallest range of V_{in} values from V_{in} = 32.35V to V_{in} = 33V. Period-8 bifurcation waveforms which is observed when V_{in} is set to be 32.35V can be seen in Figures 14 to 17.

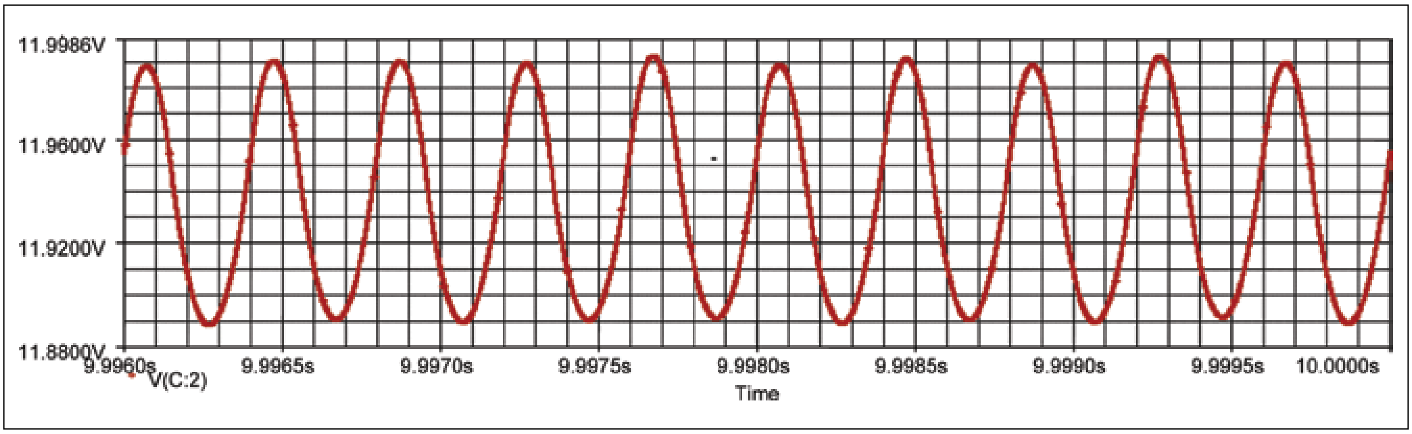

Figure 2: Output Voltage, V_C at V_{in} = 20V

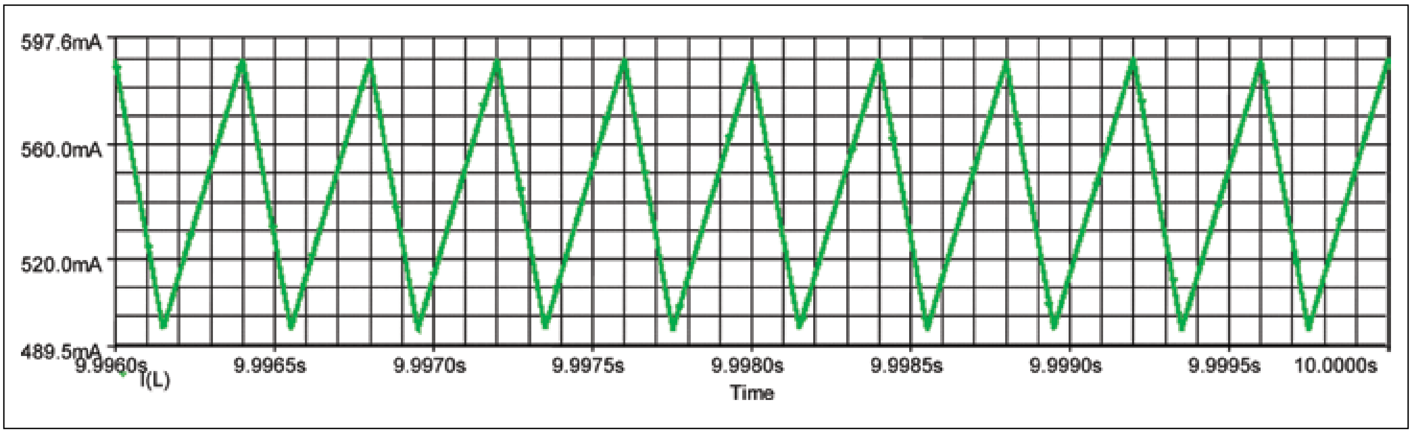

Figure 3: Inductor Current, I_L at V_{in} = 20V

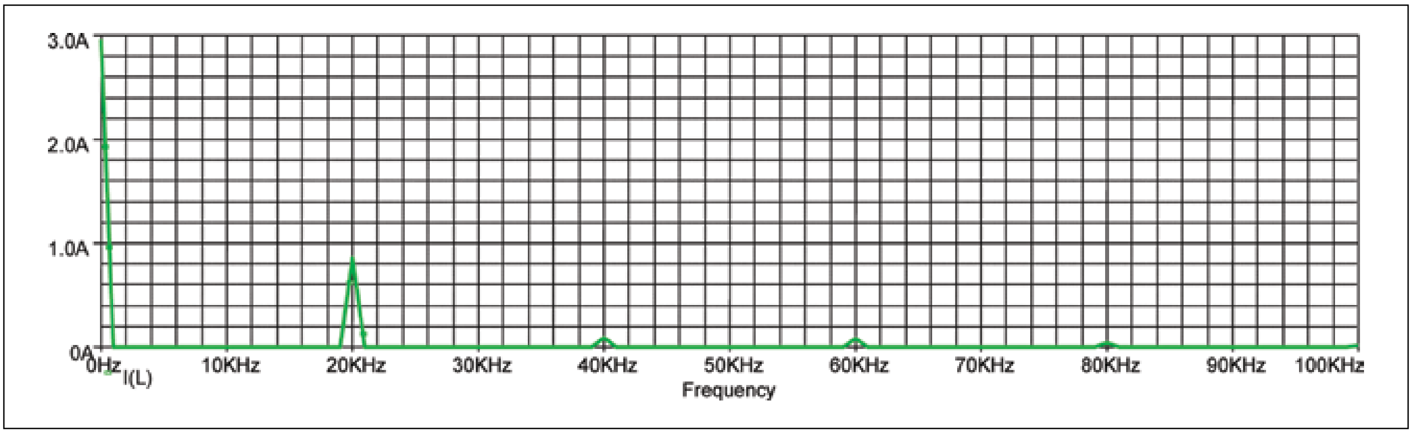

Figure 4: FFT Spectrum at V_{in} = 20V

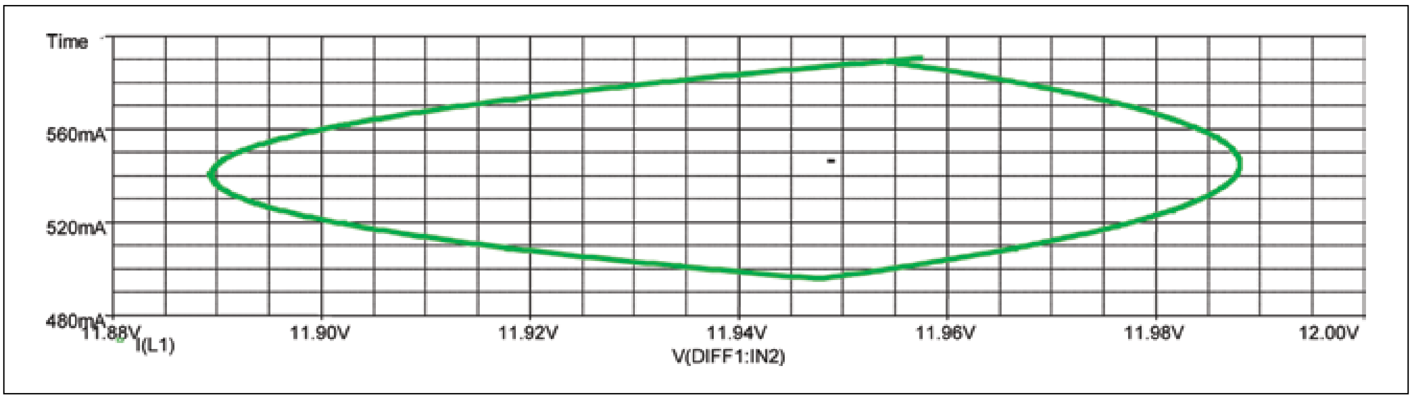

Figure 5: Trajectory when V_{in} = 20V

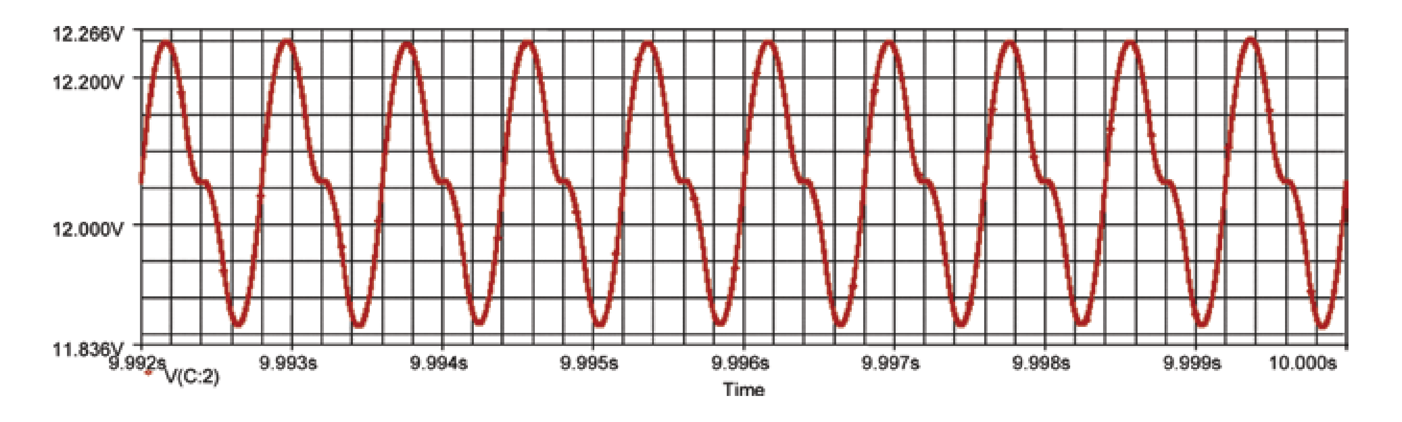

Figure 6: Output Voltage, V_C at V_{in} = 28V

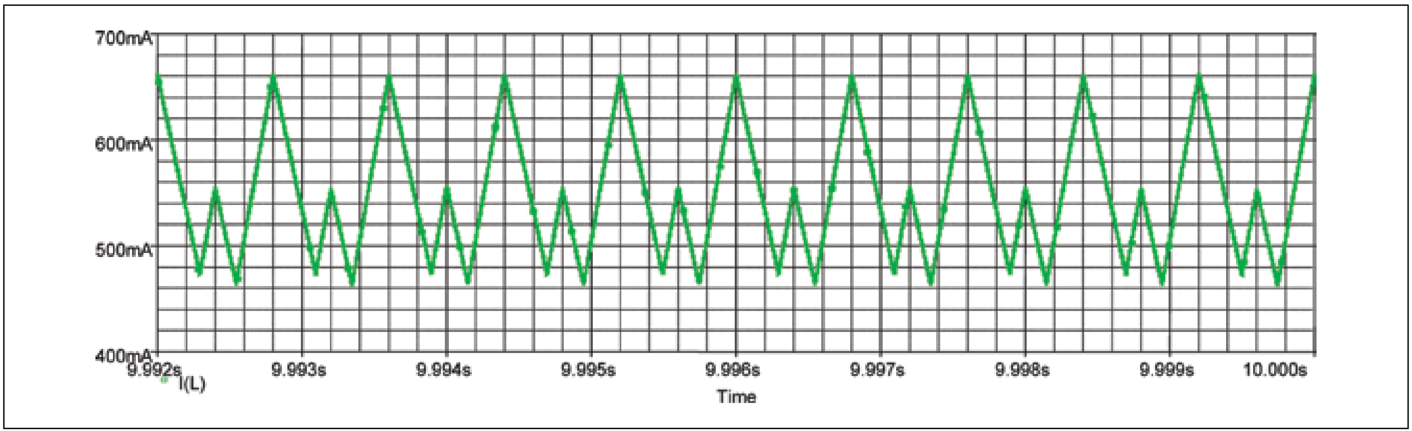

Figure 7: Inductor Current, I_L at V_{in} = 28V

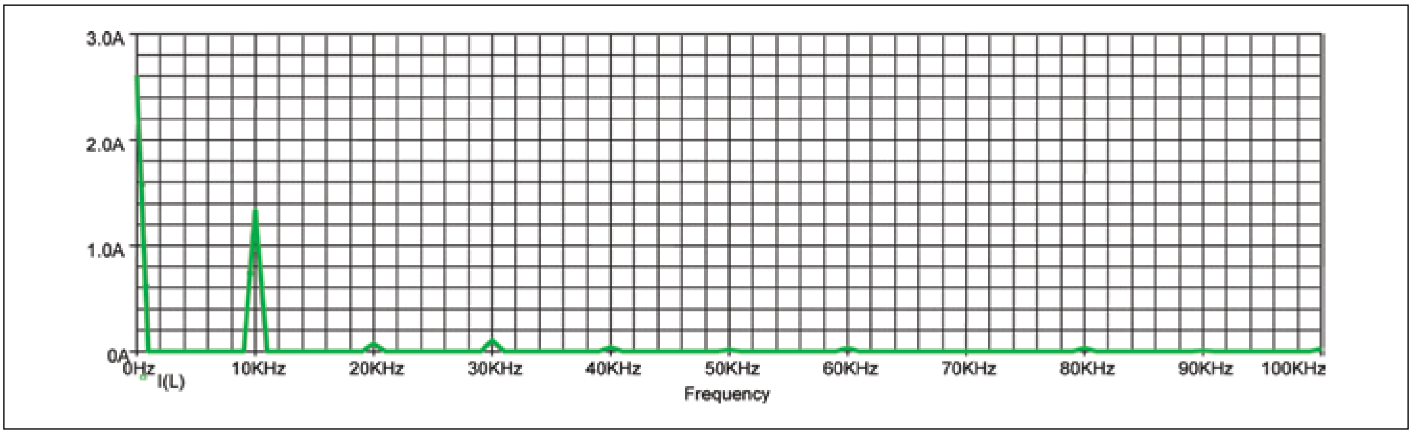

Figure 8: FFT Spectrum at V_{in} = 28V

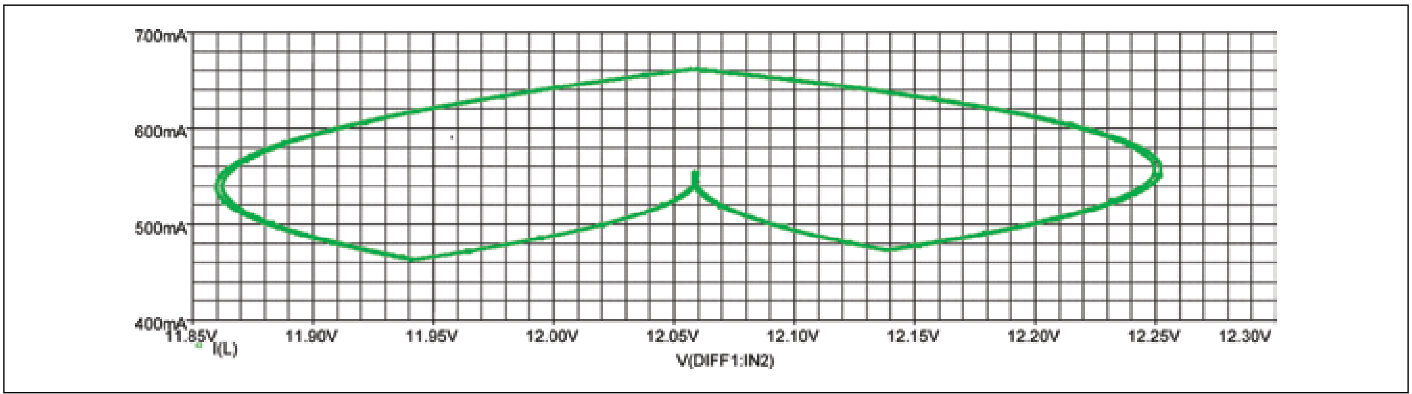

Figure 9: Trajectory when V_{in} = 28V

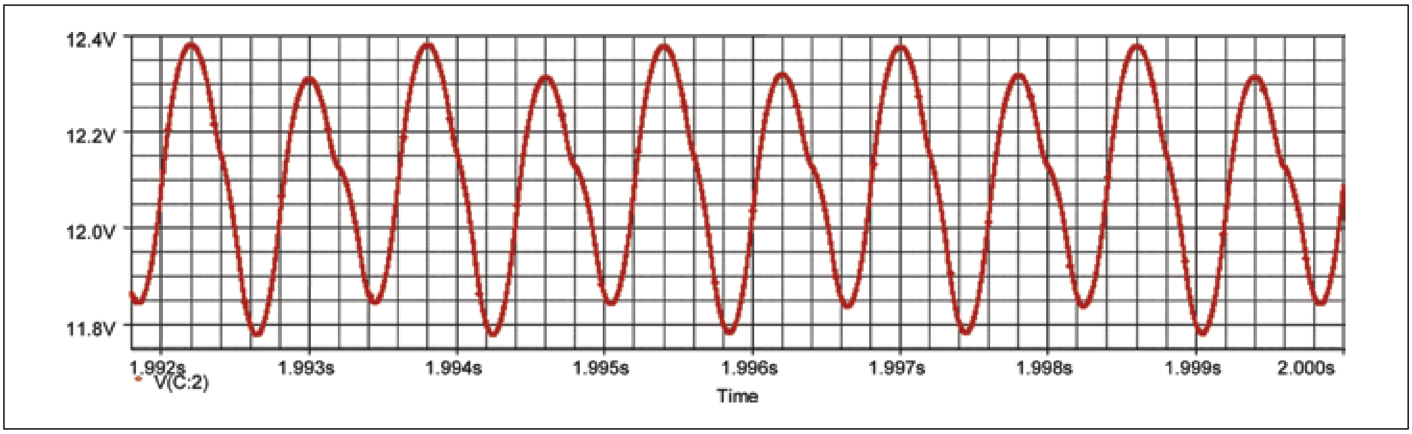

Figure 10: Output Voltage, V_C at V_{in} = 32V

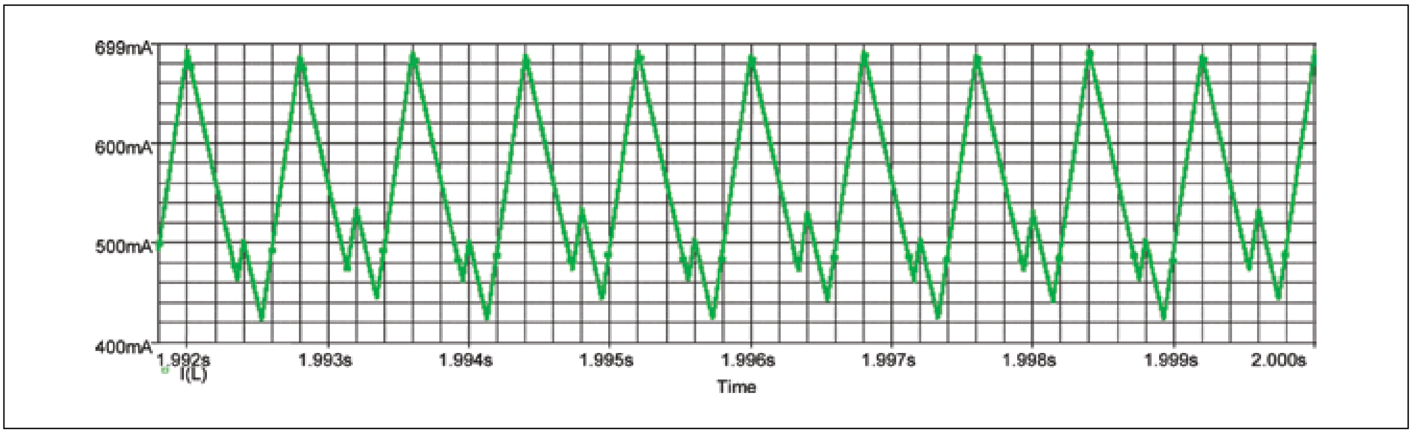

Figure 11: Inductor Current, I_L at V_{in} = 32V

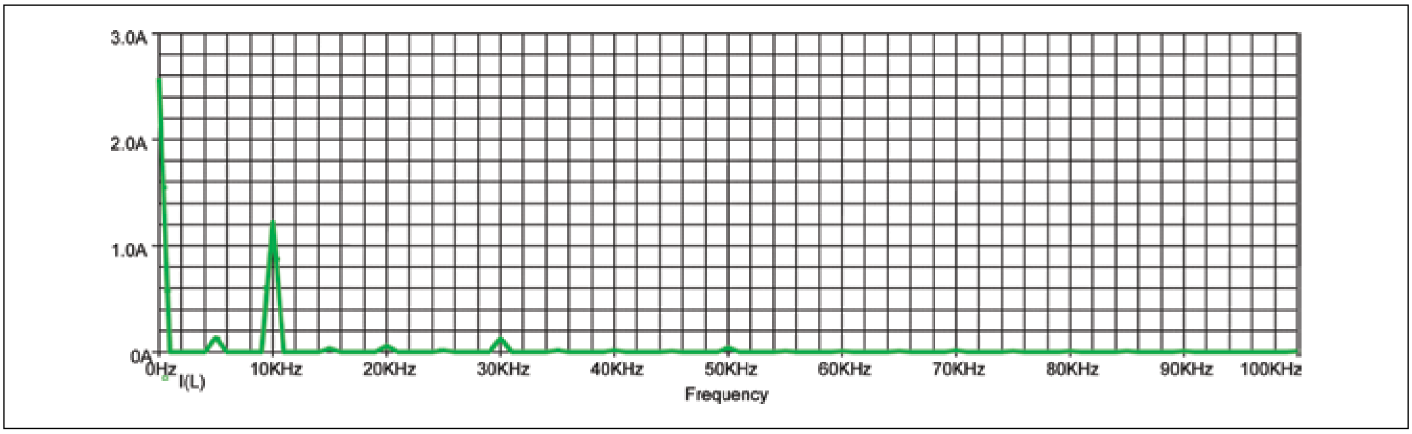

Figure 12: FFT Spectrum at V_{in} = 32V

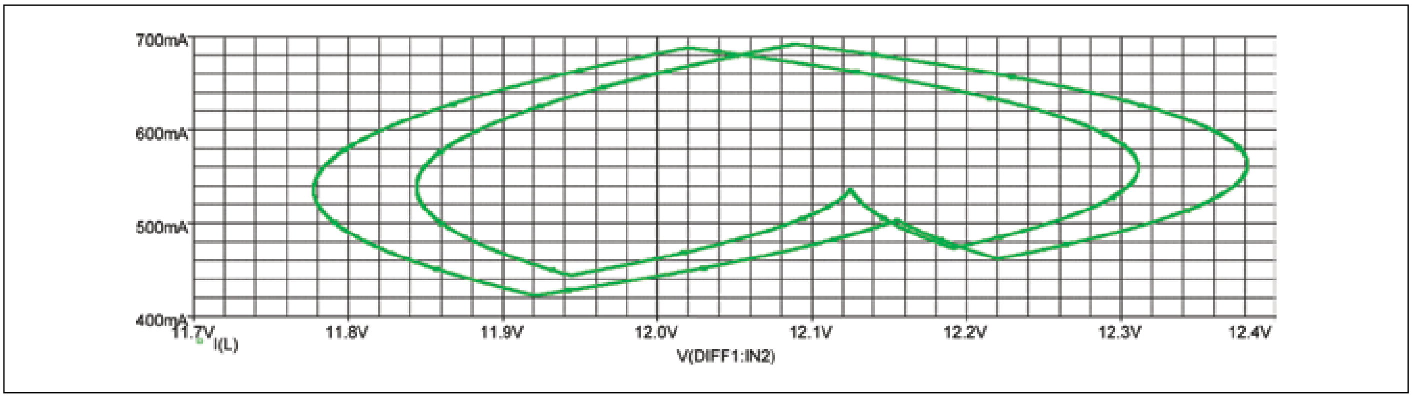

Figure 13: Trajectory when V_{in} = 32V

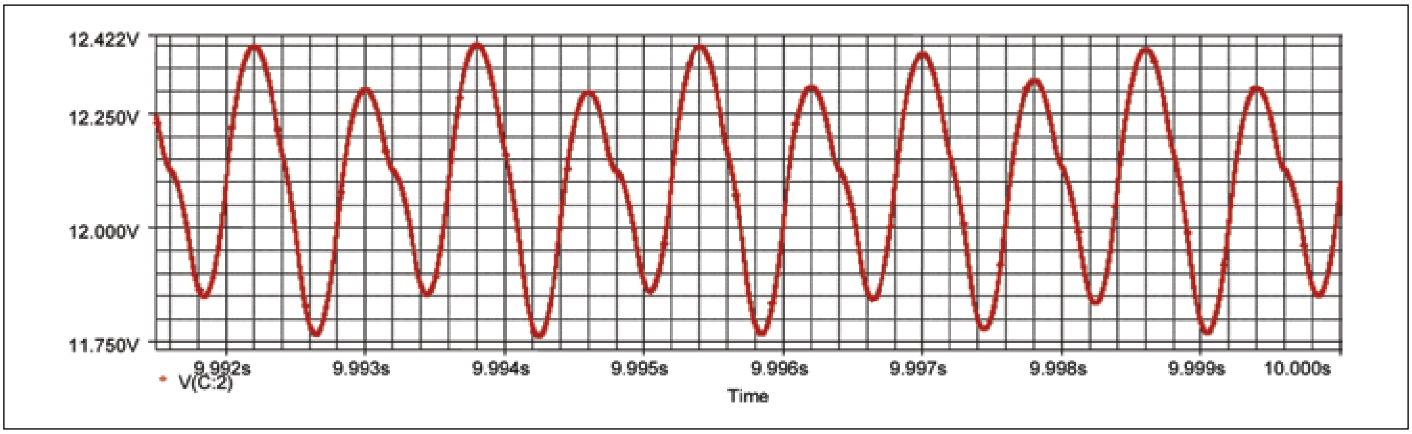

Figure 14: Output Voltage, V_C at V_{in} = 32.35V

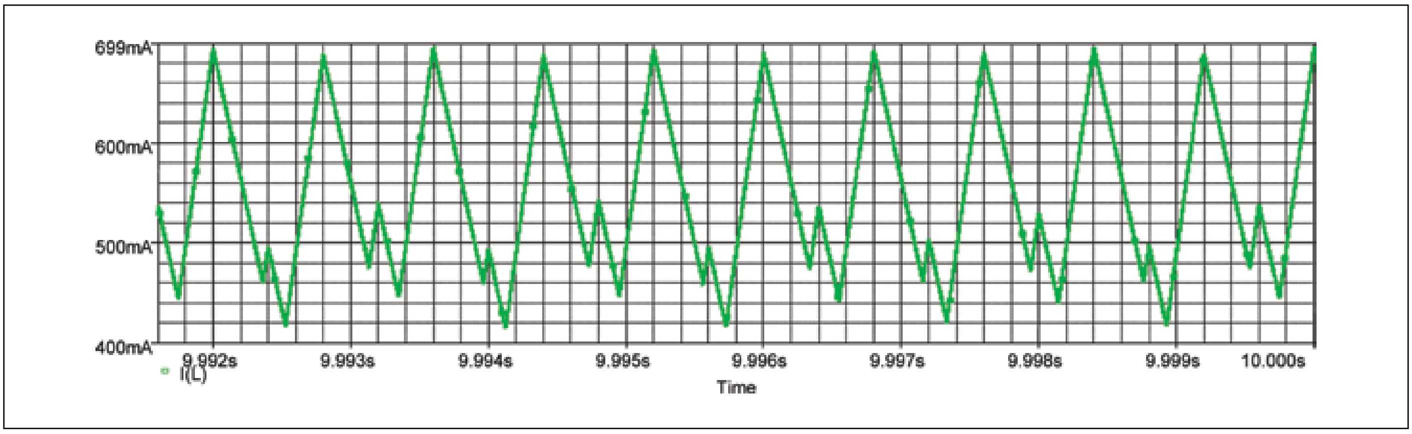

Figure 15: Inductor Current, I_L at V_{in} = 32.35V

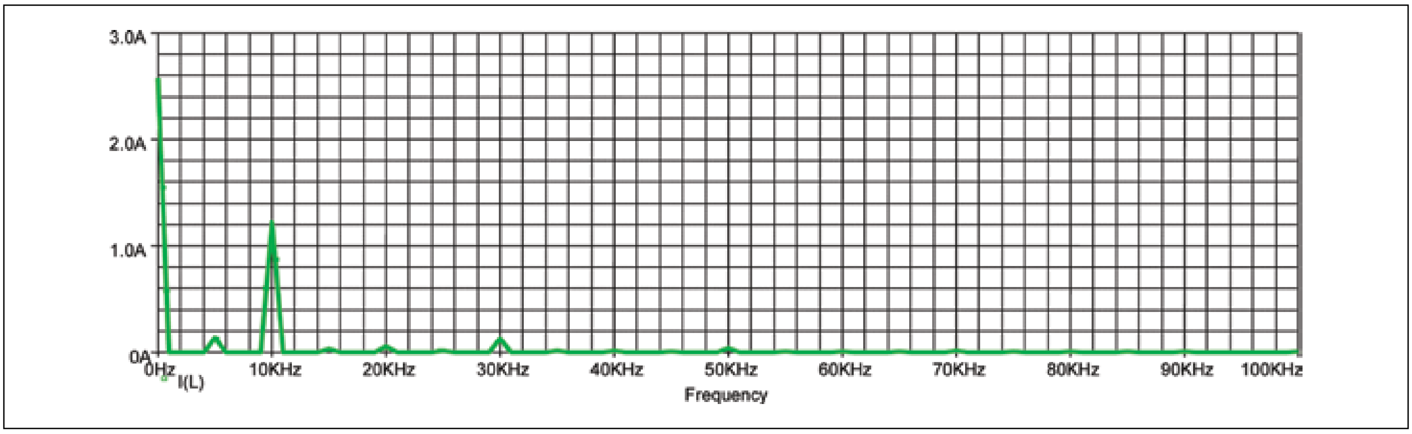

Figure 16: FFT Spectrum at V_{in} = 32.35V

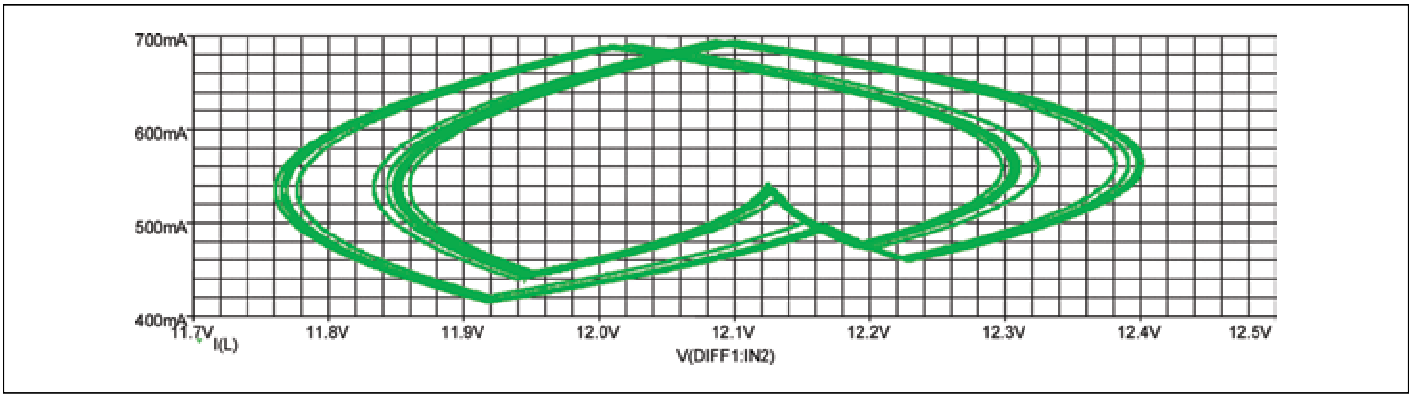

Figure 17: Trajectory when V_{in} = 32.35V

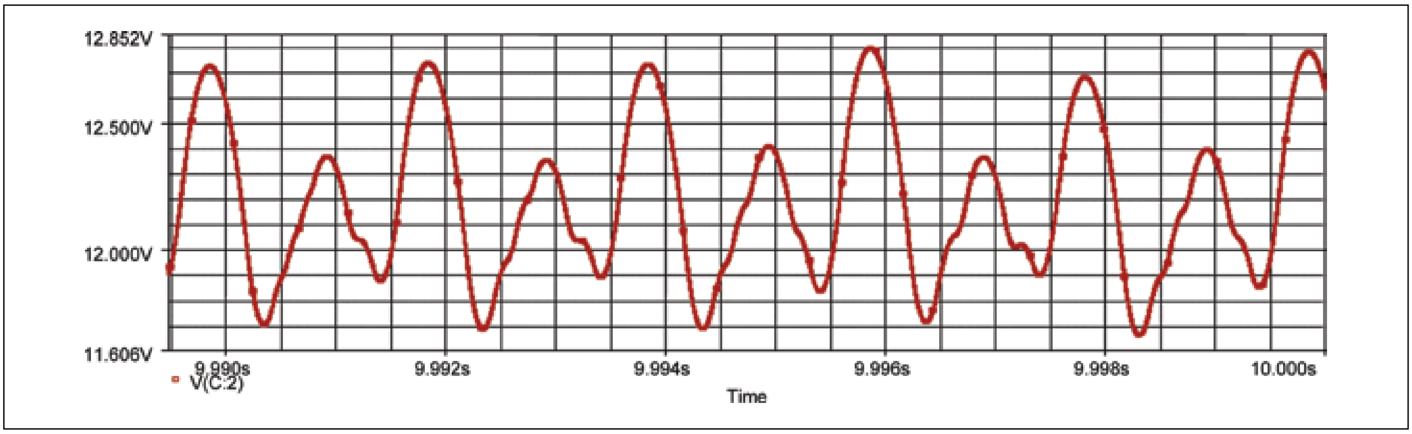

Figure 18: Output Voltage, V_C at V_{in} = 33V

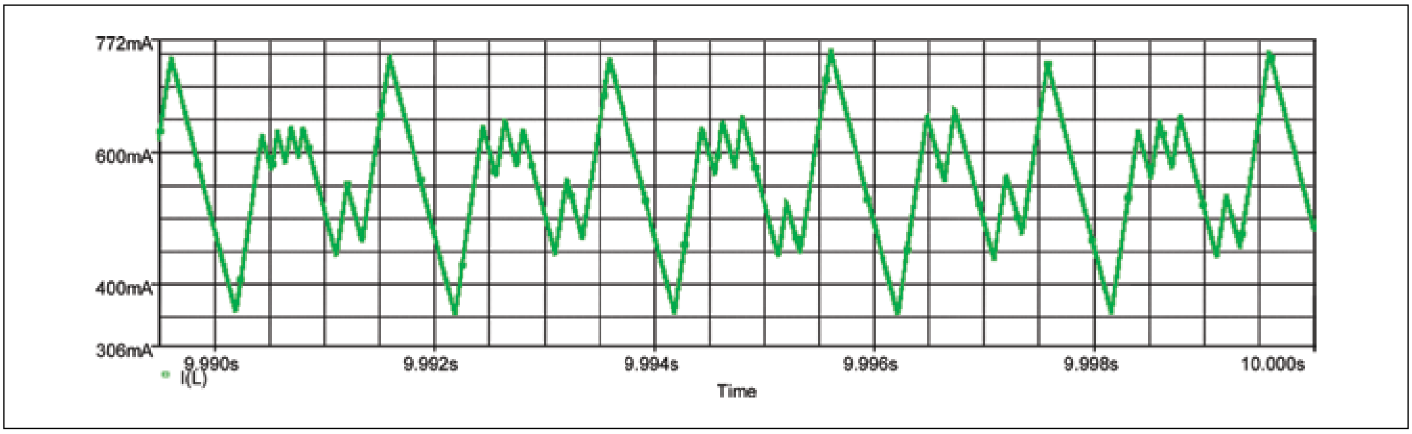

Figure 19: Inductor Current, I_L at V_{in} = 33V

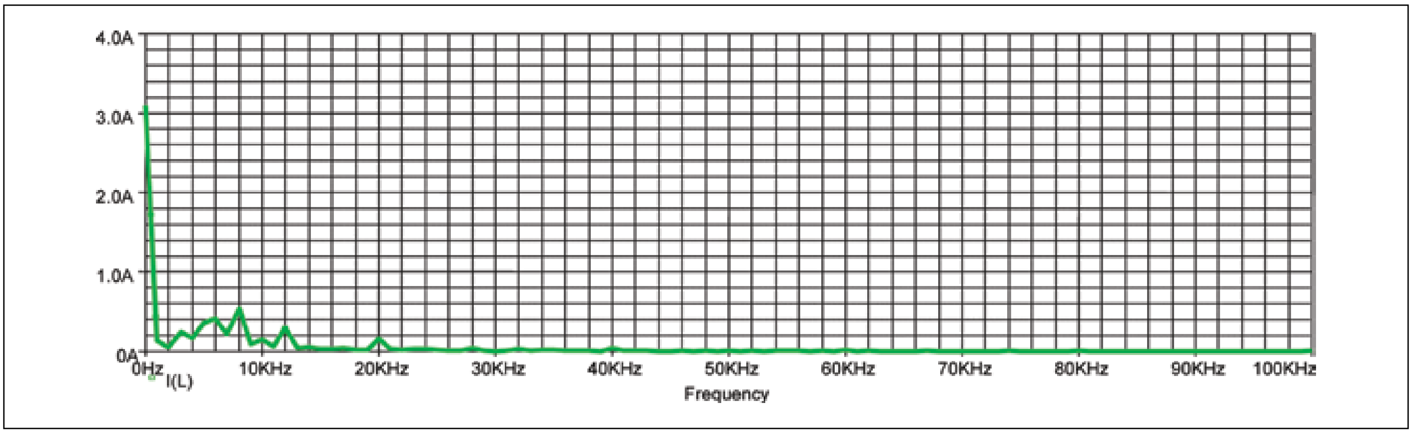

Figure 20: FFT Spectrum at V_{in} = 33V

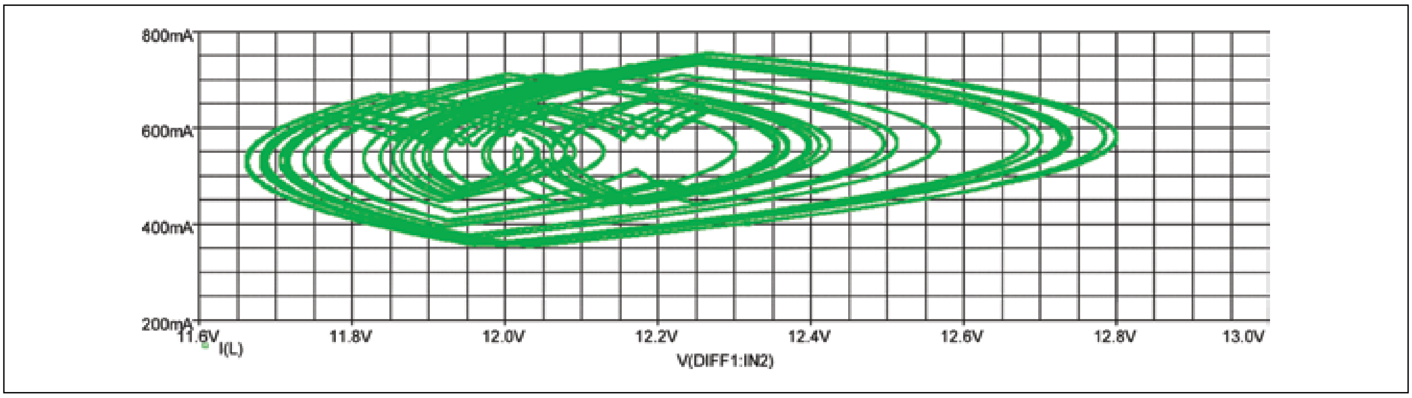

Figure 21: Trajectory when V_{in} = 33V

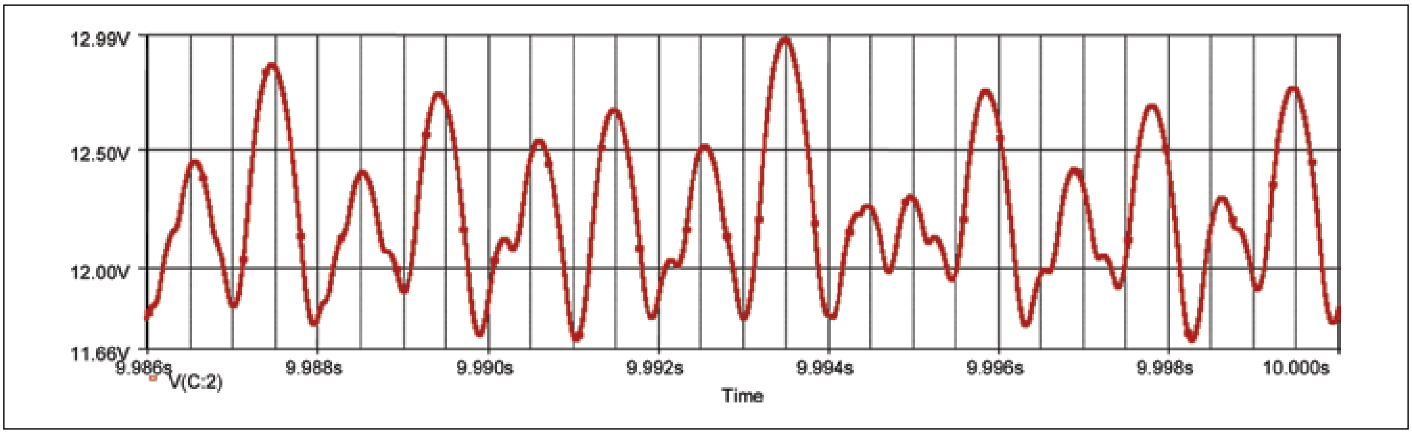

Figure 22: Output Voltage, V_C at V_{in} = 40V

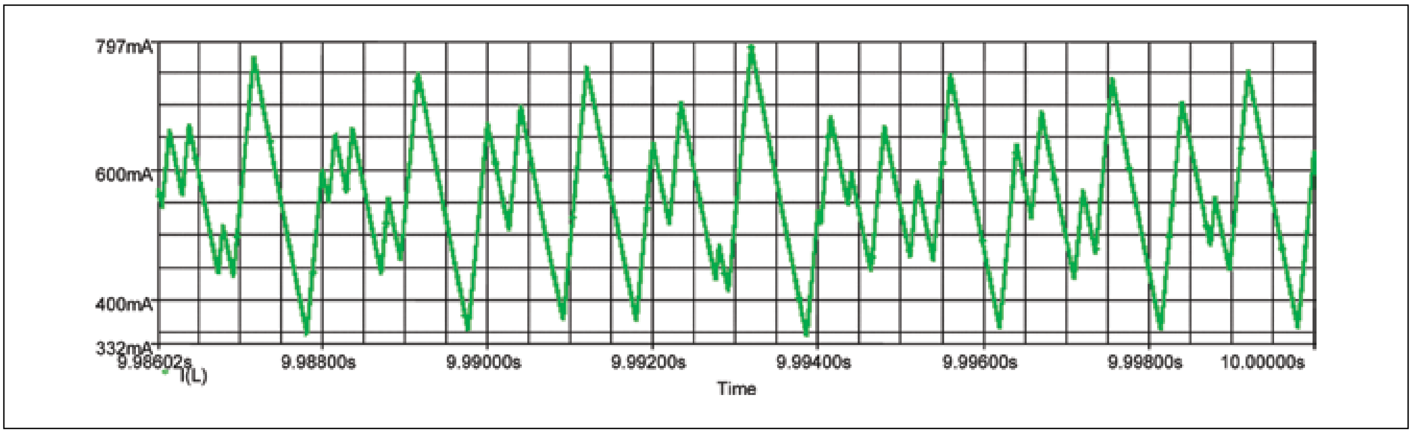

Figure 23: Inductor Current, I_L at V_{in} = 40V

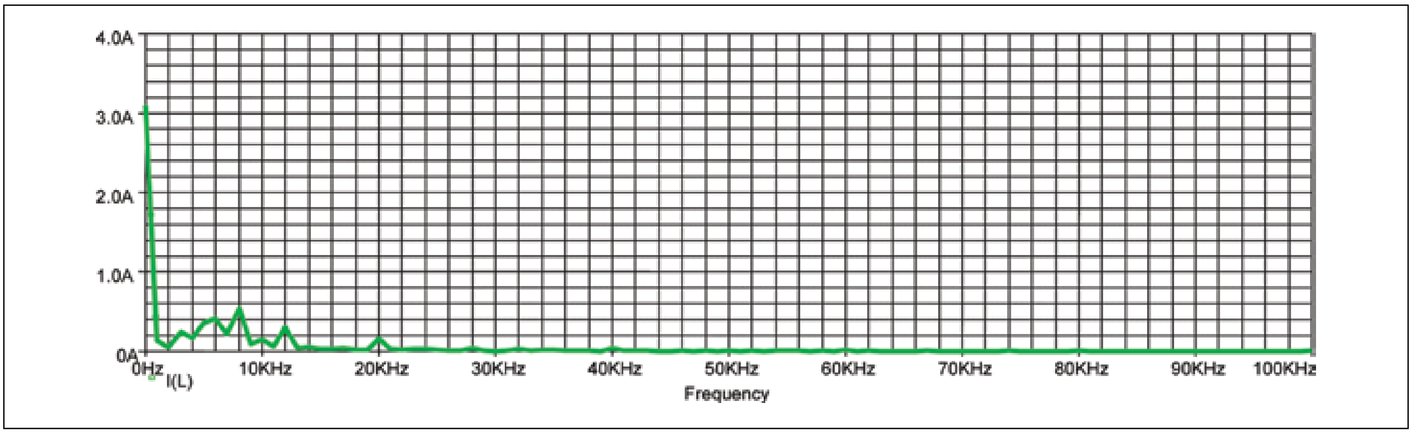

Figure 24: FFT Spectrum at V_{in} = 40V

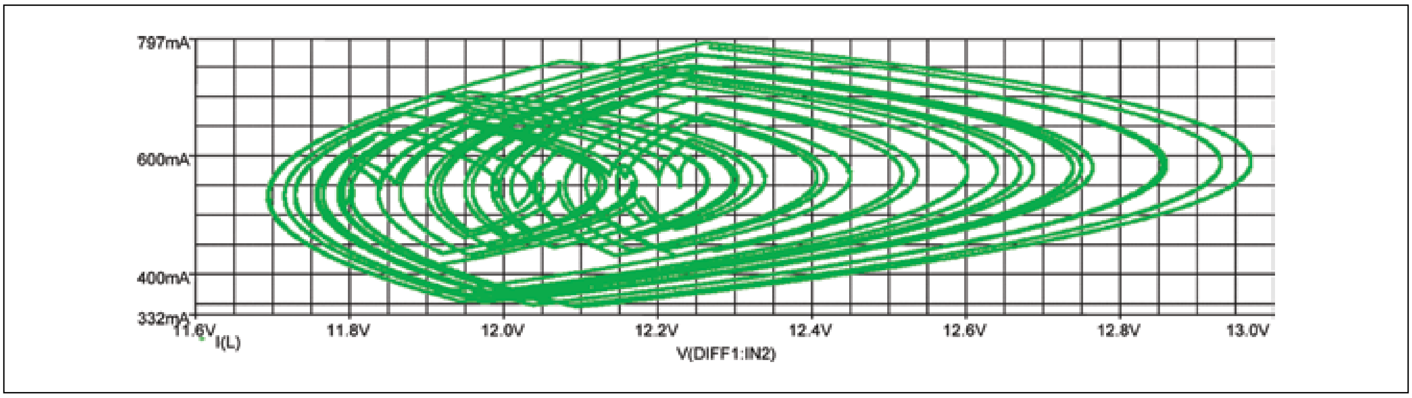

Figure 25: Trajectory when V_{in} = 40V

At V_{in} = 33V, the operation of the buck converter moves into the chaotic region. Random, unsymmetrical disjoint and aperiodic nature is evident in the waveforms of the output voltage and the inductor current of the buck converter as in Figures 18 and 19. The output voltage and the inductor current waveforms do not follow a specific form of repetition and are of random structures [24-28]. Furthermore, the Fast Fourier Transform Spectrum in Figure 20, which has a continuous and broadband nature, further emphasises that the buck converter is now operating in the chaotic region. The trajectory however, exhibits a strange attractor which signifies chaotic behaviour [16, 18-20, 25-27]. Figure 21 shows the chaotic waveform corresponding to V_{in} = 33V. To confirm that the buck converter continues to operate in the chaotic region after V_{in} = 33V, simulations when V_{in} = 40V was carried out and as expected, the results obtained as depicted in Figures 22 to 25 point to operation of the buck converter in the chaotic domain.

4.0 CONCLUSION

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. The bifurcation phenomenon and chaos in the voltage mode controlled buck converter has been investigated with the modelling and simulation of the buck converter in PSPICE in this study. It has been found that the buck converter system experiences the normal period doubling bifurcations leading to a stepwise transition from period-1 behaviour to chaos. Figures 5, 9, 13, 17, and 21 are phase portrait diagrams which show the progression of the change from period-1 to period-2, period-4, period-8, and lastly to chaotic operation of the buck converter when V_{in} is varied from 20V to 33V. For low values of the input voltage, the system is periodic, but as the input voltage is increased the system bifurcates into period-2 orbit and subsequently into period-4 and period-8 orbits when the input voltage is increased further. When border collision occurs at a much higher input voltage, the system inevitably moves into the chaotic region. The bifurcation pathway that is observed involves that of smooth period doubling. Period doubling bifurcation concerns the break of symmetry as can be seen in the trajectory waveforms. It is also known as the sudden appearance of a qualitatively different behaviour when a parameter of the circuit is changed. When period doubling recurs, an infinite period will ultimately lead to chaos. If bifurcations are under appropriate control, they can be both important and beneficial.

There are still much to be pursued both in the study of the non-linear behaviour of power electronics and the development of more effective control strategies for these behaviours. Following this study for example, future work needs to be done on investigating the bifurcation behaviour of the buck converter when other parameters besides V_{in} are varied. Other parameters in the circuit such as the load resistance, *R*, the inductance, *L*, the capacitor *C*, the switching frequency, *f* and the amplitude of the ramp voltage should be varied so as to enable the study of non-linear effects they might have on buck converter operation. The ultimate goal of all these studies on the non-linear behaviour of the DC-to-DC converters is to gain adequate information and understanding of the system behaviour for better design, functionality, reliability and performance of the converters when operating in unstable modes or even chaotically. ■

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