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Intelligent Controller Design for a Dspace-Controlled Dc-Dc Buck Converter Using the Spotted Hyenas Optimizer

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Abstract

Power electronics circuits are well-known for their nonlinear dynamics, which arise from cyclic switching between the circuit topologies. This work explores the nonlinear behavior of voltage mode controlled Buck converters in continuous conduction mode (CCM) through a mathematical model developed and tested in MATLAB. The behavior of the system is studied using time domain waveforms and phase portraits. Through systematic changes in the converter's variables, it is shown that the switching converter may exhibit fundamental, quasi-periodic, and chaotic oscillations. A Hopf bifurcation causes the one-periodic orbit to become unstable, leading to a quasi-periodic orbit. The Spotted Hyena Optimizer (SHO) is used to control the chaotic characteristics of a buck converter by obtaining optimal parameters for the PID controller. This is done by reducing the difference between the reference and output, as well as the difference between the inductor current readings, during switch openings. To validate the proposed solution, a dSPACE-controlled Buck converter prototype is constructed and subjected to experimental studies. The results of both the computational and experimental studies demonstrate the effectiveness of the proposed solution to enhance the dynamics of the converter.

Keywords: *Buck Converter, Nonlinear Behaviors, Intelligent Controller Design, Spotted Hyena Optimizer.*

1. INTRODUCTION

Switched-mode power supplies (SMPS) are often used in domestic and industrial appliances, such as computers, telecommunication instruments, automation industries and robotics. As opposed to other conventional linear power supplies, SMPS offer a number of advantages, including reduced size and weight of the power supplies and improved efficiency. This is because the solid-state devices in SMPS operate as switches, turning either completely on or completely off, meaning they don't need to operate in the active region. As a result, energy efficiency can reach up to 95%. Additionally, higher switching speeds and larger power-handling capabilities can be achieved at a much lower cost.

Due to the presence of control strategies and nonlinear elements, the converters may display complex phenomena with the variation of circuit parameters, resulting in unusual nonlinear oscillations. The study of nonlinear phenomena in static converters began in the 1980s, when [1] presented a paper demonstrating the existence of chaos in a Buck converter. Following that, the author of [2] examined bifurcation and chaos through dynamic analysis in a voltage-mode-controlled converter. Since then, research into such phenomena has been conducted around the world.

In 2005, Cafagna et al [3] conducted an experimental study on bifurcation and chaos for the Boost converter. Subsequently, Kaveh et al [4] conducted a similar study to investigate the emergence of bifurcation (type Hopf) in a Buck converter. The same team also conducted an additional study to analyze the nonlinear phenomena of the Luo converter [5]. Hong [6] further explored the spectrum of the chaotic signals of the converter to reduce the interference between components, utilizing the Prony method for determining the spectrum of chaotic signals.

In their work, Ghosh et al. [7] explored chaotic behavior in buck converters and found the subharmonic and chaotic oscillation regions for certain parameter values. They further assessed the chaos and bifurcation of a DC-DC switched-mode flyback converter regulated by peak current mode (PCM) by adjusting the converter circuit parameters in [8]. Additionally, they conducted research on the theoretical and practical chaos for Type III controller based VMC boost converter circuit through a dSPACE based controller in [9].

Recent advances in nonlinear phenomena control have suggested a variety of possible solutions, such as discrete-time models of boost converters utilized in [10] to predict the nonlinear behavior of digitally current-mode-controlled power converters, in [11], a novel approach has been proposed for the design of a robust and stable feedback control system for boost converters, which involves the use of bifurcation analysis of the linearized average model and constraining stabilization principles, and in [12], a controller is proposed that follows the concepts of the contraction theory of switched systems. While these solutions are sophisticated, they can be challenging to implement in a real-world environment.

Controllers that are based on Fuzzy logic have been employed in a number of studies [13-21] to control chaos. However, the complexity of the fuzzy logic-based control system, as well as the requirement for a large computation time and memory space, makes its use complicated and costly. On the other hand, the optimized controllers that are based on metaheuristic algorithms can provide similar performance with less complexity and cost [22,23].

Although many works use this kind of controller, they usually employ integral absolute error (IAE) as a parameter for adaptation, which is not enough to evaluate the effectiveness of each solution during the search process.

Despite the various solutions that have been discussed by prior researchers in this field, eliminating nonlinear phenomena in power converters remains an ongoing research topic. The presented work has added some contributions, which are the study, analysis, and exploration of the chaos of a PID controller-based voltage mode controlled buck converter using the dSPACE real-time controller. This approach is conceptually simple to implement, and the designers can easily find out the probable operating zone for quasi-periodic and chaotic oscillation within a specific range of parameter values that will help to design a chaos free power supply. Additionally, an approach has been suggested to extend the stability range of converters without requiring complex analysis or extra circuitry. A PID controller was developed using MATLAB and the state-space model of the buck converter to ensure the global stability of the system. The spotted hyena optimizer was used to determine the optimal gains of the controller, with suitable adaptation coefficients. The effectiveness of the proposed solution was validated through both experimental and simulated results.

2. BUCK CONVERTER

A buck converter is a power electronic circuit that transforms a high DC voltage to a lower DC voltage. As illustrated in Fig. 1, the circuit includes a controlled switch (MOSFET) sw, a diode D, an inductor L, an output capacitor C, and a load resistance R.

Typically, buck converters are controlled using voltage mode control; in this, the difference between the output voltage (V_o) and the desired reference voltage (V_{ref}) is applied to the PID controller to get the control signal. This signal is then compared to a triangular waveform to create the Pulse Width Modulation (PWM) signal at the output of the comparator, which is necessary to drive the switch.

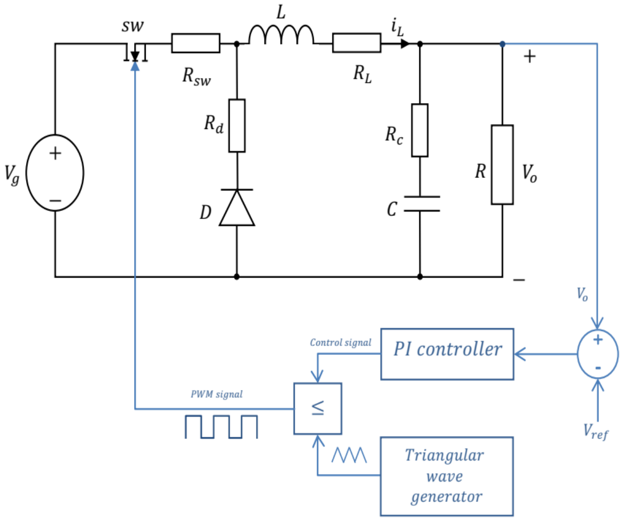

Fig 1: Voltage controlled buck converter

The vector $X = [i_L, V_c]^T$ is used to represent the state of the system with:

$$\dot{X}_i = A_i X_i + B_i \qquad (1)$$

Where for each configuration, the state matrices A_i and B_i are given as follow:

$$A_1 = \begin{bmatrix} -\frac{\left(R_{sw}+R_L+\left(\frac{R_C R}{R_C+R}\right)\right)}{L} & \frac{-R}{L(R+R_C)} \\ \frac{R}{C(R+R_C)} & \frac{-1}{C(R+R_C)} \end{bmatrix}, B_1 = \begin{bmatrix} \frac{V_g}{L} \\ 0 \end{bmatrix} \qquad (2)$$

$$A_2 = \begin{bmatrix} -\frac{\left(R_D+R_L+\left(\frac{R_C R}{R_C+R}\right)\right)}{L} & \frac{-R}{L(R+R_C)} \\ \frac{R}{C(R+R_C)} & \frac{-1}{C(R+R_C)} \end{bmatrix}, B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad (3)$$

$$A_3 = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-1}{C(R+R_C)} \end{bmatrix}, B_3 = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad (4)$$

Equation (5) represents the solution of (1)

$$X_i(t) = e^{A_i(t-t_0)}(X_i(t_0) + A_i^{-1}B_i) - A_i^{-1}B_i \qquad (5)$$

Equation (5) will be used to described the behavior of the system in each configuration.

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3. SPOTTED HYENA OPTIMIZER

The SHO follows an organized group hunting technique based on the natural hunting behavior of the spotted hyena, which includes encircling, chasing, and attacking [24], [25].

In this study, the optimization algorithm was implemented to find the optimal parameters for the PID controller to enhance the converter's performance. This method was based on minimizing the difference between the reference voltage and the measured voltage, as well as between the peak values of the inductor current.

A flowchart illustrating the algorithm employed in the optimization process is presented in Fig. 2.

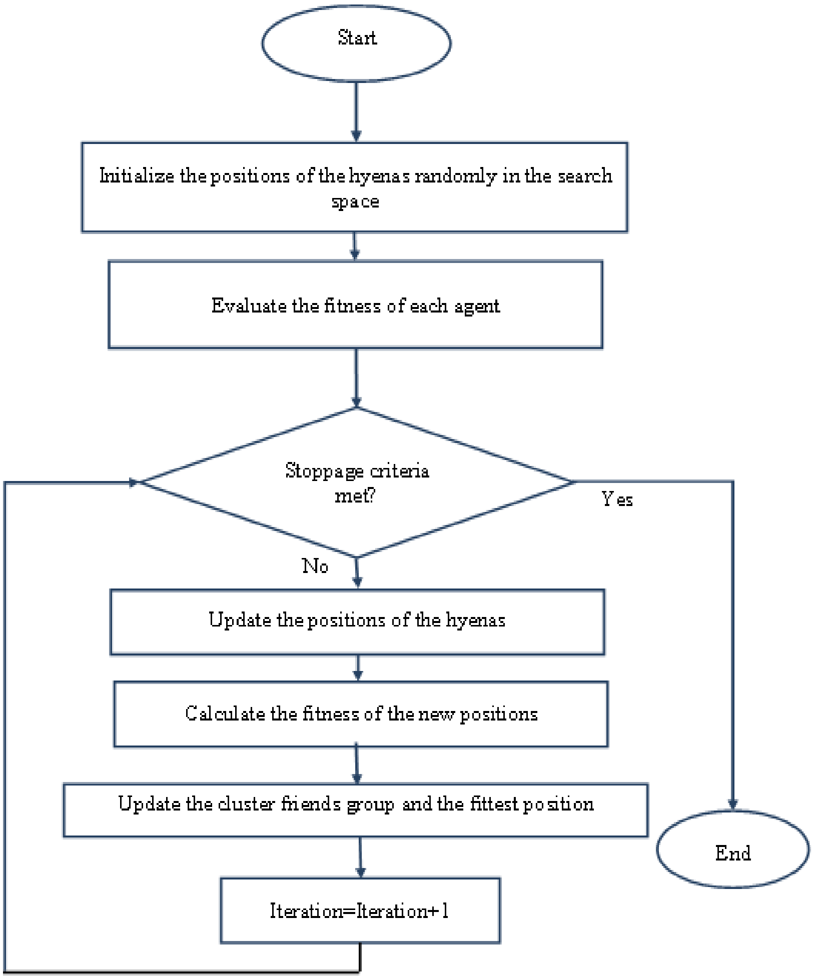


Fig 2: Flowchart of the SHO algorithm

4. SIMULATION RESULTS

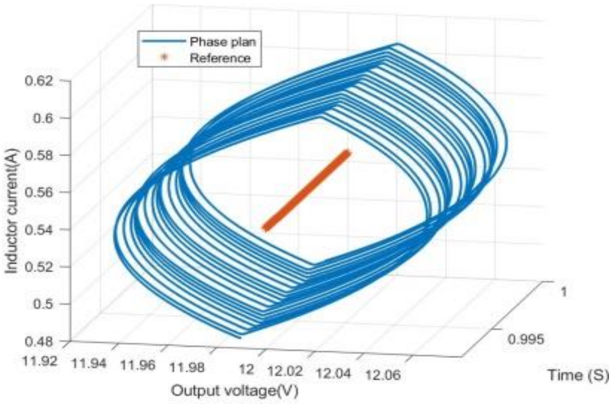
The converter is simulated in MATLAB using (2) -(5). Table 1 specifies the parameters of the switching circuit [26,27].

Table 1: The parameters of the study circuit

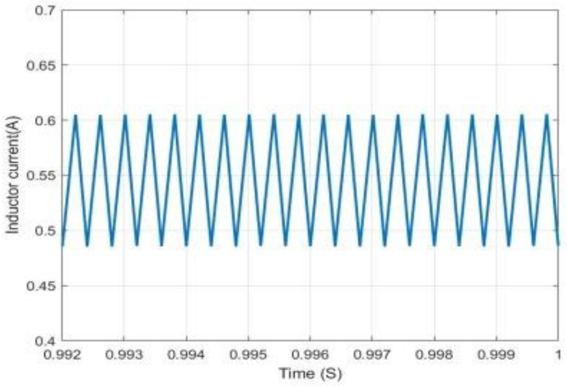
Parameter	Value
V_g	$24\ \Omega$
F	$2500\ Hz$
$R_{sw} = R_D$	$0.0177\ V$
L	$0.02\ H$
R_L	$2\ \Omega$
C	$47\ \mu F$
R_C	$0.2\ \Omega$
R	$22\ \Omega$

To analyze the nonlinear behavior of the converter, the input voltage (V_g) is considered as the bifurcation parameter, while the other parameters of the circuit have been fixed. The phase plane is used to observe the various periodicities of the limit cycles when V_g is altered within a certain range, while the remaining circuit parameters have fixed values.

Fig. 3 shows the phase plan and time-domain waveform (i_L-V_c) of the converter when V_g is set to 24 V. It has been observed from the phase plan that the converter has a stable periodic behavior, and this type of dynamics is known as the fundamental periodic operation mode (period 1).



(a) Phase plan



(b) Inductor current

Fig 3: Response of the system for $V_g = 24V$

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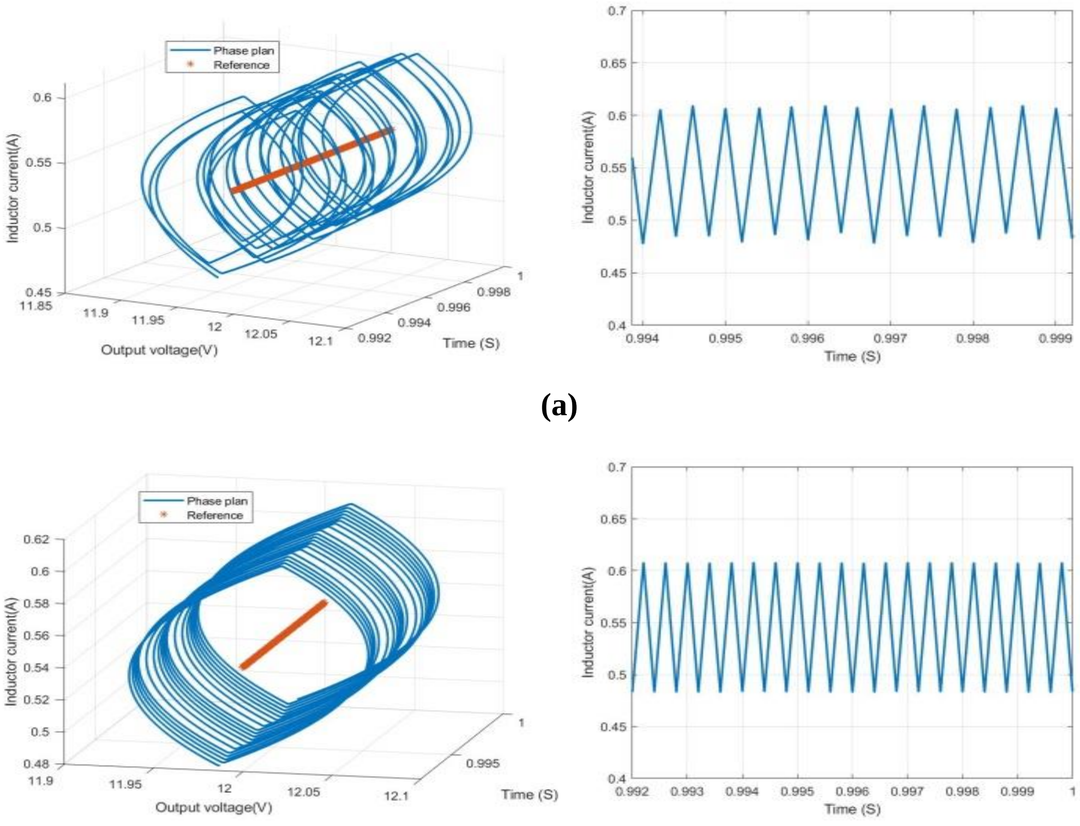
When the input voltage is equal to 25V, the converter is no longer stable and enters slow-scale instability, as seen in Fig. 4(a). The resulting trajectory follows a quasi-periodic orbit which is characterized by a finite number of frequencies. The use of the optimized in the other hand, stabilize the converter and keep it in the desired period 1 behavior as it clear in Fig. 4(b).

As the input voltage rises above 25 V, the system has an additional periodicity that is not related to the first limit cycle. This leads to slower-scale instability and low-frequency oscillations in a power supply. When the voltage is at 30 V, chaotic dynamics occur, resulting in a bounded aperiodic oscillation in the phase plane. These chaotic dynamics cause each loop of the phase plane to traverse a new trajectory, forming a strange attractor as it is clear in Fig. 5(a). Meanwhile, the optimized controller stabilizes the converter and maintains the desired **period 1 behavior, as is evident in Fig. 5(b).**



(a)

(b)

Fig 4: Response of the system for $V_g = 25V$, (a) Original behavior, (b) Optimized behavior

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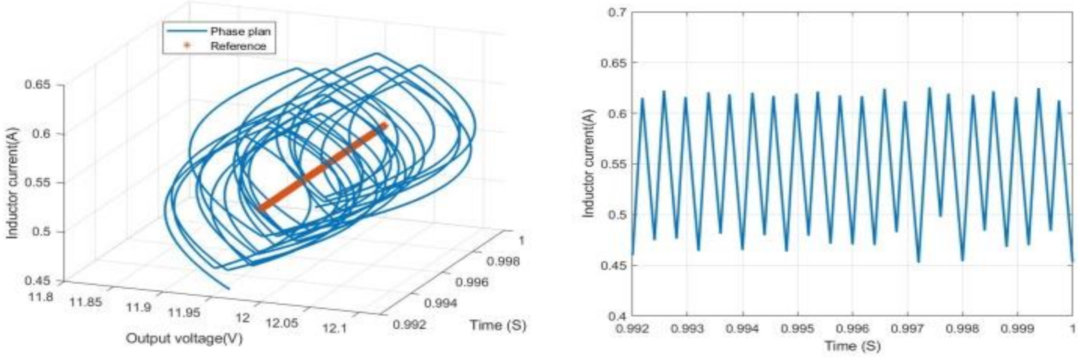
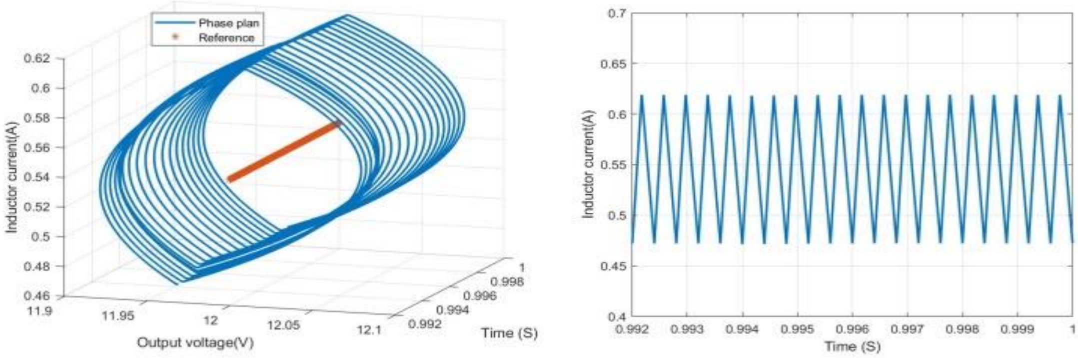


(a)

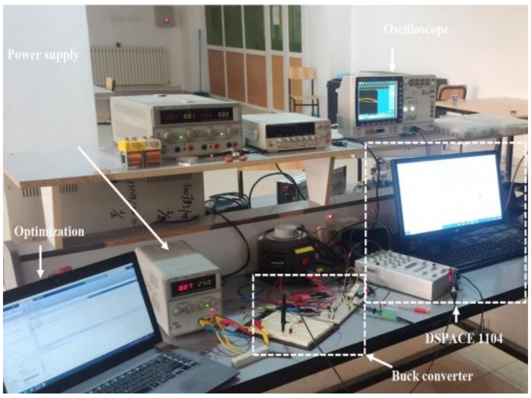


(b)

Fig 5: Response of the system for $V_g = 30V$, (a) Original behavior, (b) Optimized behavior

5. EXPERIMENTAL RESULTS

An experimental setup of the VMC buck converter was constructed and applied in a real-time platform using the dSPACE controller in order to validate the previous analysis and results. Parameters of the circuit can be found in Table 1, and Fig. 6(a) and 6(b) show the experimental setup and schematic circuit diagram, respectively.



(a)

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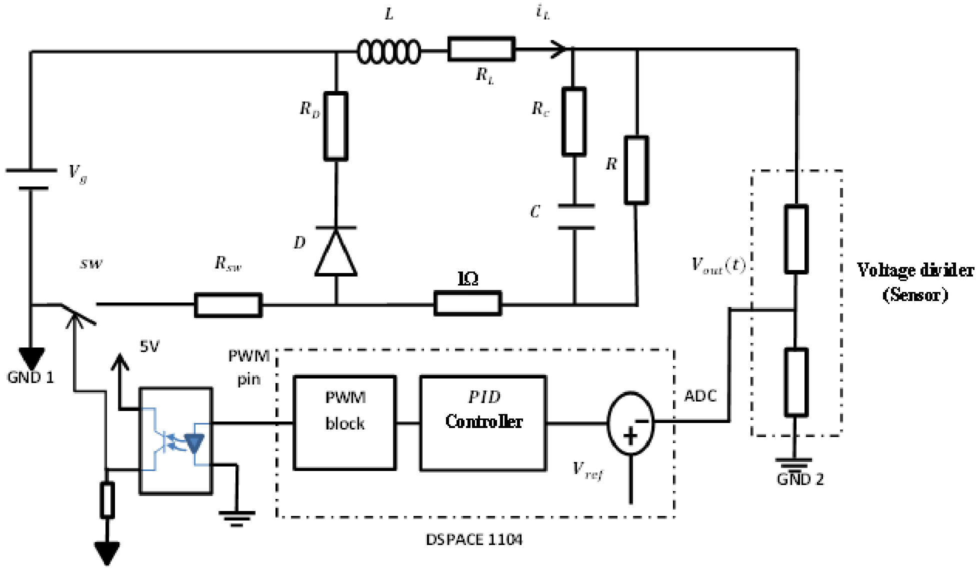


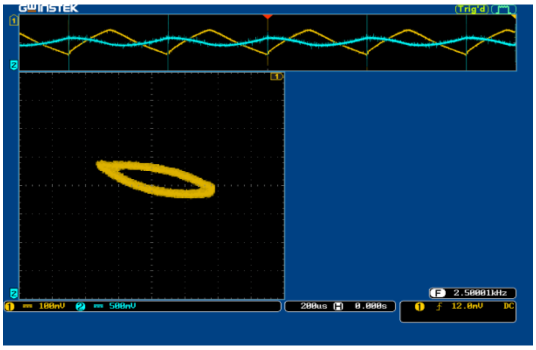
(b)

Fig 6: VMC buck converter controlled by dSPACE controller, (a) Experimental setup, (b) Circuit diagram

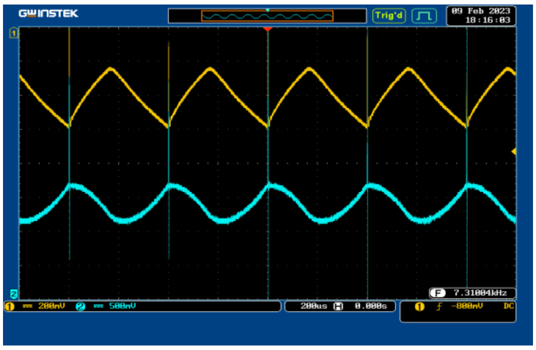
The dSPACE DS1104 is a controller board that is inserted into the PCI slot of a PC. It is comprised of an MPC8240 PowerPC processor with 32 kB of internal cache memory, which is set to a clock speed of 250 MHz and serves as the master processor. Additionally, it has a TMS320F240 DSP as the slave, which has 4 KB of dual-port RAM.

The control system is implemented on a dSPACE-based real-time interface platform, where the reference is compared with the digital output voltage coming from the ADC port of dSPACE. To sense the output voltage of the converter, a voltage divider is used and the scaled voltage is then fed to the ADC port of the dSPACE controller, limited to a maximum of 10 volts. An error signal is generated by the comparison, and then passed through the PID controller to obtain a control signal. This signal is fed to the PWM generation module of the dSPACE board, configured for the switching frequency. Finally, an opto-isolator is utilized to transfer the PWM signal from dSPACE to the gate of the MOSFET.

At a voltage of 24 V, the converter operates in a repeating pattern, as seen in the phase plane in Fig. 7. The waveform of the inductor current in the time domain displays the waveforms recurring after one cycle of the clock, also referred to as Period 1.



(a) Phase plan

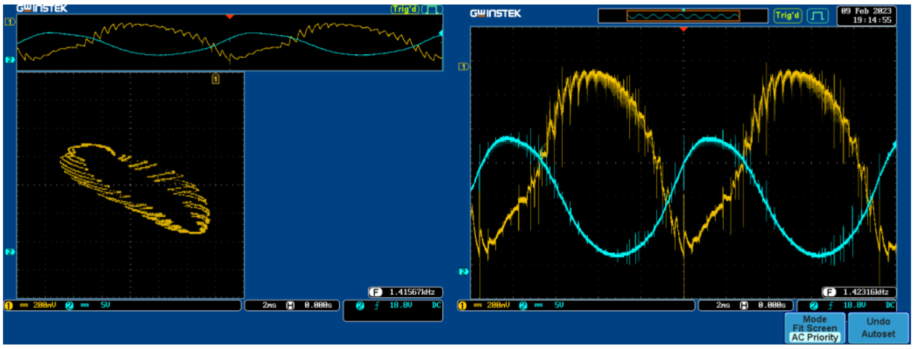


(b) Inductor current

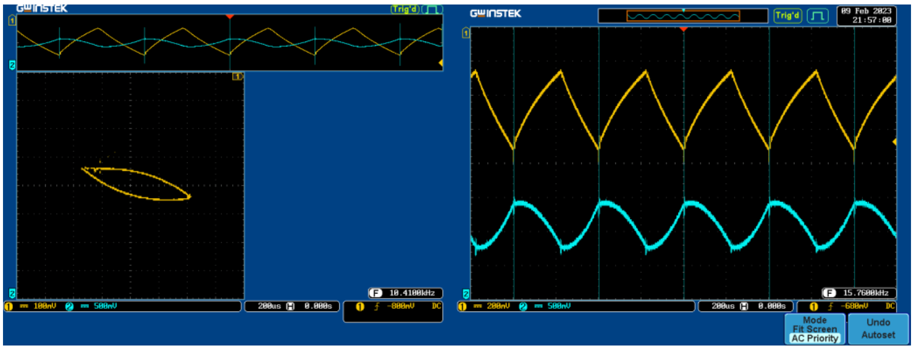
Fig 7: Response of the system for $V_g = 24V$

When the input voltage is increased to 25 V, the converter exhibits quasi-periodic behavior, as illustrated in Fig. 8(a). This shift is due to the occurrence of slow-scale instabilities, which give rise to many other possible limit cycles. However, as shown in Fig. 8(b), the optimized controller keeps the system stable regardless of changes in the input voltage.

In chaotic mode operation, the system dynamics form an oscillation inside a particular area of the phase space that is never repeated; it takes a new path for each cycle in the phase plane. This phenomenon can be seen in an electronic circuit when the system appears to be undergoing random oscillations. Our experiments, illustrated in Fig. 9, which show the phase plan of the experimental chaotic orbits and the corresponding time domain waveform of the inductor current, display this effect when the input voltage is set to 30 V.



(a)



(b)

Fig 8: Response of the system for $V_g = 25V$, (a) Original behavior, (b) Optimized behavior

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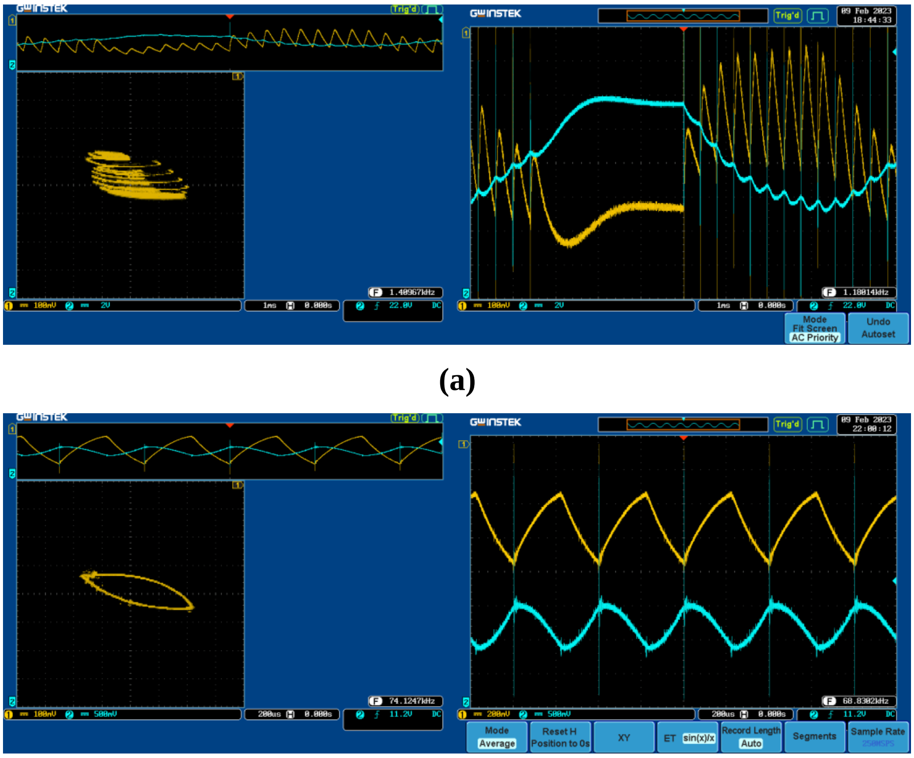

(a)

(b)

Fig 9: Response of the system for $V_g = 30V$, (a) Original behavior, (b) Optimized behavior

6. CONCLUSION

A dSPACE-based real-time controller was used to study the complex dynamics of a voltage mode-controlled PID controller-based buck converter circuit. The mathematical model of the circuit and the corresponding experimental results confirmed the converter's complex dynamic behavior. This enabled designers to easily identify the probable operating zone and design a chaos-free power supply. Parametric variation of the converter demonstrated a gradual instability that gave rise to a Hopf bifurcation, a quasi-periodic oscillation, and finally a chaotic state. Employing the experimental outcomes, it was possible to identify areas of quasi-periodic oscillation and practical chaos. For practical design of power supplies, these types of nonlinear oscillations should be avoided, and the system dynamics should be guaranteed to have a fundamental periodic behavior for better stability.

In order to achieve this, this paper suggests a technique for shifting nonlinear occurrences and widening the stability range of converters without using intricate analysis techniques or additional circuits. Using MATLAB and the state-space model of the buck converter, a PID regulator was designed to ensure the global stability of the system. The spotted hyena optimizer was employed to determine the optimal controller gains. Both experimental and simulated results showcase the effectiveness of the optimized controller in addressing nonlinear behaviors and achieving the intended periodic behavior.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

1) Brockett, R. -W., and J. -R. Wood.: Understanding power converter chaotic behavior mechanisms in protective and abnormal modes. *Proc. Powercon*. 11(4), 1-15(1984)

2) Hamill, D. -C., & Jeffries, D. -J.: Subharmonics and chaos in a controlled switched-mode power converter. IEEE Transactions on Circuits and Systems. 35(8), 1059-1061(1988)

3) Cafagna, D., & Grassi, G.: Experimental study of dynamic behaviors and routes to chaos in DC–DC boost converters. Chaos, Solitons & Fractals. 25(2), 499-507(2005)

4) Kavitha, A., & Uma, G.. Bifurcation Analysis of DC-DC Converters using Discrete Time Model. International Conference on Power System Technology and IEEE Power India Conference. 1-7(2008, October)

5) Kavitha, A., & Uma, G.: Experimental Verification of Hopf Bifurcation in DC--DC Luo Converter. IEEE transactions on power electronics. 23(6), 2878-2883(2008)

6) Li, H., Li, Z., Halang, W. -A., & Chen, G.: Analyzing chaotic spectra of DC-DC converters using the Prony method. In International Symposium on Power Electronics, Electrical Drives, Automation and Motion, IEEE. 195-199(2006)

7) Ghosh, A., & Banerjee, S.: Study of complex dynamics of DC-DC buck converter. International Journal of Power Electronics. 8(4), 323-348(2017).

8) Ghosh, A., & Banerjee, S.: Study on chaos and bifurcation in DC-DC flyback converter. International Journal of Industrial Electronics and Drives. 3(3), 161-174(2017).

9) Ghosh, A., Rana, N., & Banerjee, S.: Study of complex dynamics in DC-DC boost converter with dSPACE-based real time controller. International Journal of Power Electronics, 11(2), 160-178(2020)

10) Singha, A. -K., Kapat, S., Banerjee, S., & Pal, J.: Nonlinear analysis of discretization effects in a digital current mode controlled boost converter. IEEE Journal on Emerging and selected Topics in Circuits and Systems, 5(3), 336-344(2015)

11) Yfoulis, C., Giaouris, D., Stergiopoulos, F., Ziogou, C., Voutetakis, S., & Papadopoulou, S.: Robust constrained stabilization of boost DC–DC converters through bifurcation analysis. Control Engineering Practice, 35, 67-82(2015)

12) Angulo-Garcia, D., Angulo, F., Osorio, G., & Olivar, G.: Control of a dc-dc buck converter through contraction techniques. *Energies*. *11*(11), 3086(2018).

13) Guesmi, K., Essounbouli, N., Hamzaoui, A., Zaytoon, J., & Manamanni, N.: Shifting nonlinear phenomena in a DC–DC converter using a fuzzy logic controller. Mathematics and computers in simulation. 76(5-6), 398-409(2008)

14) Guesmi, K., Essounbouli, N., & Hamzaoui, A.: Systematic design approach of fuzzy PID stabilizer for DC–DC converters. Energy Conversion and Management. 49(10), 2880-2889(2008).

15) Mehran, K., Giaouris, D., & Zahawi, B.: Stability analysis and control of nonlinear phenomena in boost converters using model-based Takagi–Sugeno fuzzy approach. IEEE Transactions on Circuits and Systems I: Regular Papers. 57(1), 200-

Volume 63 | Issue 01 | January 2024
DOI: 10.5281/zenodo.10669384

212(2009)

16) Hu, W., Zhang, B., & Yang, R.: Bifurcation mechanism and stabilization of V 2 C controlled buck converter. IEEE Access. 7, 77174-77182(2019)

17) Gozim, D., Guesmi, K., & Mahi, D.: On the elimination of nonlinear phenomena in DC/DC converters using type-2 fuzzy logic controller. Diagnostyka. 19(2018)

18) Ayati, M., Bakhtiyari, A., & Gohari, A. Chaos control in buck converter using fuzzy delayed-feedback controller. 4th International Conference on Control, Instrumentation, and Automation (ICCIA), IEEE. 362-365(2016).

19) Yuan, Y., Chang, C., Zhou, Z., Huang, X., & Xu, Y.: Design of a single-input fuzzy PID controller based on genetic optimization scheme for DC-DC buck converter. International Symposium on Next-Generation Electronics (ISNE), IEEE. 1-4(2015)

20) Duranay, Z. B., Guldemir, H., & Tuncer, S.: Fuzzy sliding mode control of DC-DC boost converter. Engineering, Technology & Applied Science Research. 8(3), 3054-3059(2018)

21) Behih, K., Benmahammed, K., Bouchama, Z., & Harmas, M. N.: Real-time investigation of an adaptive fuzzy synergetic controller for a DC-DC buck converter. Engineering, Technology & Applied Science Research. 9(6), 4984-4989(2019)

22) Fu, C. -B., Tian, A. -H., Yu, K. -N., Lin, Y. -H., & Yau, H. -T.: Analyses and control of chaotic behavior in DC-DC converters. Mathematical Problems in Engineering. 1-13. (2018).

23) Abdelgawad, H., & Sood, V.: Boost Converter Controller Design Based On Particle Swarm Optimization. International Journal on Power Engineering and Energy (IJPEE). 7, 647-659(2016)

24) Dhiman, G., & Kumar, V.: Spotted hyena optimizer: a novel bio-inspired based metaheuristic technique for engineering applications. Advances in Engineering Software. 114, 48-70(2017).

25) Dhiman, G., & Kaur, A.: Spotted hyena optimizer for solving engineering design problems. *International conference on machine learning and data science (MLDS)* IEEE. 114-119(2017)

26) Giaouris, D., Banerjee, S., Zahawi, B., & Pickert, V. Stability analysis of the continuous-conduction-mode buck converter via Filippov's method. *IEEE Transactions on Circuits and Systems I: Regular Papers*. *55*(4), 1084-1096(2008).

27) Bakria, D., Gozim, D. & Korich, B. Chaos Elimination for a Buck Converter Using the Multi-Objective Grey Wolf Optimiser. Power Electronics and Drives.8(1), 165-173(2023).