STUDY OF CHAOTIC BEHAVIOR BASED ON DISCRETE ITERATIVE MAPPING FOR DC-DC BOOST AND SEPIC CONVERTERS

A PROJECT REPORT

MASTER OF TECHNOLOGY

IN

POWER ELECTRONICS AND SYSTEMS

Submitted by

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I hereby certify that the project Dissertation titled "Study of Chaotic Behavior Based on Discrete Iterative Mapping for DC-DC Boost and SEPIC Converters" which is submitted by SANDHU GANESH, Roll No. 2K21/PES/12 Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

Power electronic systems in switched-mode DC-DC converters exhibit complex behaviors such as rapid adjustments, bifurcation and chaotic performance. These unexpected behaviors are often attributed to random external influences, leading to issues like sensor failure, electromagnetic interference and reduced efficiency and in the worst cases it leads to converter failure. The growing demand for affordable DC-DC power conversion requires reliable operation in all loading conditions, including extreme scenarios. In the past decade, researchers have focused on studying these boundary conditions in power electronic converters, employing various analytical and theoretical approaches. However, the most intriguing findings are based on abstract mathematical structures that cannot be directly applied to the development of practical industrial applications.

In this thesis utilizes the discrete time Iterative mapping method to investigate the dynamics of non-linear behavior in DC-DC Boost and SEPIC converters. By establishing a state space and discrete iterative mapping, the stability of the system can be demonstrated incorporating comprehensive information about closed-loop control and DC converter parameters. The discrete iterative mapping technique enables further analysis of stability considering the impact of nonlinear loads and potential extensions to different types of converters. Based on the findings, modern control algorithms can be developed to ensure the converter's proper functionality and prevent complex behaviors, including rapid and slow-scale bifurcations. The Boost and SEPIC converters are both theoretically derived and analyzed with simulation results focusing on doublet and chaotic bifurcations.

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$\Phi_k(\xi)$

LIST OF SYMBOLS

A	State Matrix
B	System Matrix
I	Identity Matrix
R	Resistor
L	Inductor
C	Capacitor
D	Diode
d	duty ratio
f_s	Switching frequency
g	Mapping Function
K	Feedback Factor
V_{in}	Input Voltage
V_c	Capacitor Voltage
V_{ref}	Reference Voltage
I_{ref}	Reference Current
I_L	Inductor Current
V_o	Output Voltage
T	Time period
n	Number of Variables
$\Phi_k(\xi)$	Transition Matrix

d_n	duty cycle for nth period
Ω	Ohm
μ	micro
H	Henry
F	Farad
V	Volts
A	Amps
K_p	Gain of proportional
K_I	Gain of Integral
K_D	Derivative Coefficient
S	Switch
X	State Vector
V_{con}	Control Voltage

CHAPTER I

INTRODUCTION

1.1 Overview of Power Electronics:

Power electronics is a branch of electrical engineering that deals with the study, design, and application of electronic devices and circuits for the control, conversion, and conditioning of electric power. Power electronic systems rely on specialized semiconductor devices capable of handling high power levels. Common power semiconductor devices include diodes, thyristors (such as SCRs and TRIACs), power MOSFETs, IGBTs (Insulated Gate Bipolar Transistors). These devices provide the foundation for power conversion and control. Power electronic systems often involve energy storage elements such as capacitors and inductors. Inductors stores energy in their magnetic field, whereas capacitors store it in their electric field. Energy storage elements play a vital role in smoothing out voltage and current waveforms, providing transient response, and maintaining system stability.

Power electronic circuits employ various topologies to convert electrical energy from one form to another. Some common power conversion topologies include AC-DC rectifiers, DC-DC converters (for example buck, boost, and buck-boost converters), DC-AC inverters, and AC-AC converters (like Cycloconverters). Each topology has a specific function in applications such as electric car drives, power supplies, renewable energy systems and more.

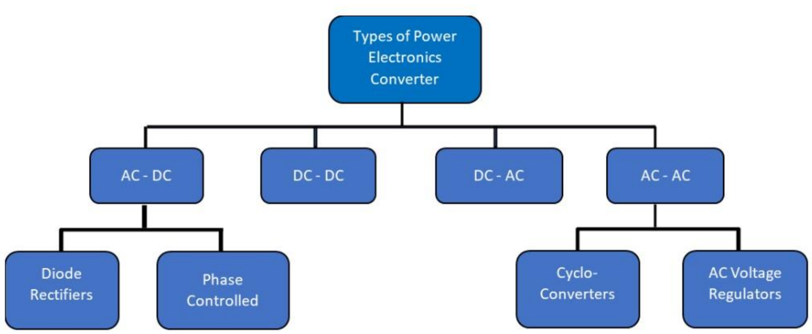


Figure 1.1-Various types of Power Electronic Converters

Power electronics finds applications in various industries and systems. It is integral to renewable energy systems, such as solar photovoltaic (PV) inverters and wind power converters, enabling efficient conversion of renewable energy into usable electricity. Power electronics is also crucial in motor drives for electric vehicles, industrial machinery and robotics. Other applications include uninterruptible power supplies (UPS), supplies power for electronic devices, electric grid systems, and more. Power electronic systems aim to achieve high efficiency in power conversion, minimizing losses and improving energy utilization. Efficient power conversion is essential for reducing energy consumption, optimizing system performance, and minimizing environmental impact. Power electronics also plays a role in improving power quality by reducing harmonics, mitigating voltage fluctuations, and providing power factor correction. Power electronics is a rapidly evolving field, with ongoing research and development in emerging technologies.

DC-DC converters offer several advantages over other types of power conversion methods. Here are some of the key benefits of using DC-DC converters:

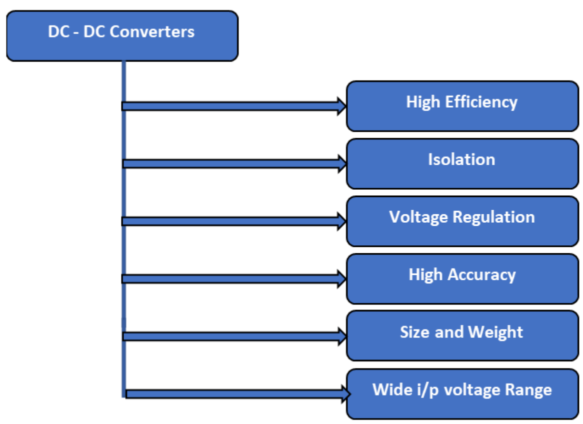


Fig. 1.2 – Advantages of DC-DC Converters

High Efficiency:

DC-DC converters are highly efficient, with conversion efficiencies typically above 90%. This is due to the absence of a bulky transformer, which can result in lower losses and higher efficiency.

Isolation:

Some DC-DC converters provide isolation between the input and output, which can improve safety and protect sensitive electronic components.

Voltage Regulation:

DC-DC converters can regulate output voltage irresepective of input voltage fluctuations. This feature is especially useful in battery-powered applications, where the voltage of the battery drops over time.

High Accuracy:

Some DC-DC converters can provide output voltages with high accuracy and low ripple. This is especially important in sensitive applications, such as medical devices or aerospace systems.

Size and Weight:

DC-DC converters are typically smaller and lighter than their AC counterparts. This makes them ideal for use in portable and mobile devices.

Wide Input Voltage Range:

DC-DC converters can operate over a wide scope of input voltages, from a few volts to several hundred volts. This feature makes them suitable for a wide range of applications, inclusive of renewable energy systems and electric vehicles.

Overall, DC-DC converters offer a range of benefits, including high efficiency, small size and weight, wide input voltage range, flexibility and high accuracy. These advantages make them a popular choice in a wide range of applications like consumer electronics, industrial automation, renewable energy systems and more.

1.2 Nonlinear Phenomena in Switching Power Converters:

Nonlinearity in power electronic converters arises from various factors related to the components, circuit topology, and control strategies.

Here are some common causes of nonlinearities in power electronic converters:

Switching Nonlinearities:

Power electronic converters involve switching operations, where the switching devices (transistors or thyristors) turn on and off to control the flow of current. The switching process introduces nonlinearities, including voltage spikes, ringing, and switching losses. These nonlinearities can lead to electromagnetic interference (EMI) affect the efficiency of the converter and introduce disturbances in the output voltage or current.

Nonlinear Characteristics of Semiconductor Devices:

Power electronic converters rely on semiconductor devices, such as diodes, transistors, and thyristors, which exhibit nonlinear characteristics. For example, the voltage-current relationship of a diode is nonlinear, and the current-voltage relationship of a MOSFET or IGBT can exhibit nonlinear behavior in certain operating regions. These nonlinearities impact the operation and efficiency of power electronic converters.

Nonlinear Loads:

Power electronic converters are often connected to nonlinear loads, such as rectifiers, motor drives, or LED lighting systems. Nonlinear loads draw non-sinusoidal current waveforms, introducing harmonic content and nonlinearity in the input current of the converter. It can lead to distortion, increased losses, and challenges in power quality management.

Nonlinear Control Techniques:

Control strategies employed in power electronic converters can introduce nonlinearity. Pulse Width Modulation (PWM), which is popularly used for regulating the output voltage or current, is inherently nonlinear. The switching signals and control algorithms used in PWM introduce nonlinearities in the converter operation. Additionally, the implementation of feedback control and the limitations of the control circuitry can introduce nonlinear behavior.

Nonlinearities in power electronic converters can impact the performance, efficiency, and stability of the system. Engineers employ various techniques to mitigate these nonlinear effects, including careful component selection, advanced control strategies, filtering techniques, and system-level design considerations.

DC-DC converters are nonlinear systems that exhibit complex dynamics. When the operating conditions, such as input voltage, output load, or control parameters, are within certain ranges, the converter can enter chaotic behavior. Chaotic behavior arises from the nonlinearity of the system and the interaction between its components [1, 2]. DC-DC converters are highly sensitive to changes in their operating parameters. Small variations in component values, such as inductors, capacitors or resistors, can lead to significant changes in the system behavior. When the parameters reach certain thresholds or fall within specific ranges, chaotic behavior may emerge. DC-DC converters can undergo bifurcations, which are sudden qualitative changes in system behavior as a parameter is varied.

Bifurcations can lead to the onset of chaos, where the system transitions from stable or periodic behavior to unpredictable and irregular dynamics. Examples of bifurcations include period-doubling bifurcations and saddle-node bifurcations [3-6]. DC-DC converters are typically controlled using feedback control techniques to control the output voltage or current. If the control loop is not properly designed or the feedback gains are set incorrectly, it can result in instability and chaotic behavior. Control instability can cause the system to oscillate, exhibit irregular voltage ripple, or fail to settle into a steady-state. DC-DC converters operate by rapidly switching power semiconductor devices, such as transistors or diodes, to regulate the flow of energy. The switching action introduces nonlinearities and can lead to complex switching dynamics. When the switching frequency or duty cycle approaches certain values, the converter may enter chaotic behavior due to the intricate interactions between the switching components. External noise and disturbances, such as electromagnetic interference or variations in the input voltage or load, can influence the behavior of DC-DC converters. In the presence of noise, the system response can become unpredictable and chaotic, especially when the noise magnitude is significant or resonates with the system's natural frequencies.

Chaotic behavior in DC-DC converters is generally undesired, as it can lead to issues such as excessive voltage ripple, electromagnetic interference, reduced efficiency or instability. Therefore, careful design and analysis techniques are employed to ensure stable and predictable operation.

Several researchers have studied the chaotic behavior of DC-DC converters.

The work of Brockett and Wood [7] published in 1980s is a significant contribution to the understanding of chaos phenomena in power electronic converters. In their research, Brockett and Wood investigate the dynamic behavior of a class of power electronic converters, particularly DC-DC converters. Moreover, Brockett and Wood highlight the potential implications of chaos in power electronic converters. They discuss challenges in control design, such as the difficulty of stabilizing chaotic behavior and the need for robust control strategies. They also explore the impact of chaos on electromagnetic interference (EMI) and harmonic distortion in power electronic systems. The work of Brockett and Wood on chaos in power electronic converters contributed to the broader understanding of the dynamics of these systems and the presence of chaotic behavior.

The chaotic behavior in the buck converter Fossas and Oliva [8] typically analyze the system's behavior through numerical simulations or experimental measurements trajectory evolution near the chaotic attractors is examined by considering initial conditions that are close to each other and observing the subsequent divergence of trajectories over time. Hongwei Xu and Yanyan Huang [9] are published about the nonlinear behavior by using discrete time iterative mapping technique. After that many researchers worked in DC-DC converters like Buck Converter [10-13], Boost Converter [14-16], Cuk Converter [17-19] and Forward Converter [20-21]. These researchers, along with many others have contributed to our understanding of chaotic behavior in DC-DC converters through theoretical analysis, simulation studies and experimental validations. Their work has provided valuable insights into the underlying mechanisms, control techniques and stability considerations of chaotic dynamics in these systems.

CHAPTER II

LITERATURE REVIEW

2.1 Problem Formulation on power switching converters:

Nonlinearity is a fundamental characteristic of power switching converters due to their inherent switching action and nonlinear components. The nonlinearity in power switching converters arises from various sources, including the switching devices (like transistors or diodes), energy storage elements (like capacitors or inductors) and control strategies employed in the converters. The switching action in power converters can result in the generation of high-frequency harmonics. These harmonics introduce nonlinear distortion in the converter's output voltage or current waveform, affecting the quality of the output signal and potentially causing electromagnetic interference (EMI) issues.

Stability analysis techniques for DC-DC converters are methods used to assess the stability of these power electronic systems. Stability analysis is crucial in ensuring the reliable and safe operation of DC-DC converters.

Averaged modeling is a widely used technique for stability analysis of DC-DC converters. It involves simplifying the converter's nonlinear dynamics by obtaining an averaged or reduced-order model that captures the essential behavior of the system. By employing an averaged model, stability analysis techniques that are applicable to linear systems can be applied to the simplified representation of the converter. This approach allows for easier analysis of stability criteria such as gain and phase margins, Eigen value analysis, or frequency response characteristics. Averaged modeling for stability analysis is a valuable tool in understanding the stability characteristics of DC-DC converters and aids in the design and optimization of control strategies for improved system performance.

State-space averaging [22-25] is a technique used to derive a simplified averaged model of a DC-DC converter based on its state-space representation. It provides a reduced-order model that captures the essential dynamics of the converter while maintaining accuracy for stability analysis and control design. State-space averaging simplifies the dynamics of the converter by replacing the fast-switching variables with their averaged values, resulting in a reduced-order model that is easier to analyze. However, it is important to note that state-space averaging relies on certain assumptions, such as the assumption of continuous conduction mode or certain control strategies, which may limit its applicability to specific operating conditions or converter topologies. State-space averaging technique is a valuable tool in stability analysis and control design for DC-DC converters, allowing for a more manageable analysis while retaining the critical dynamics of the system.

Frequency-dependent averaged modeling [26] is a technique used to derive a more accurate representation of the dynamics of a DC-DC converter by considering the frequency dependence of certain components or parameters in the averaged model. It extends the traditional time-averaging approach by incorporating frequency-dependent effects, which can be particularly relevant in high-frequency switching converters or when dealing with specific component characteristics. By considering the frequency-dependent effects in the averaged model, the frequency-dependent averaged modeling technique provides a more accurate representation of the converter's behavior, particularly at higher frequencies where the effects of parasitic elements, losses, or control dynamics become more significant. This can be useful for assessing stability, designing control strategies, and analyzing the converter's performance in the frequency domain.

Multi-frequency averaged modeling [27-29] is a technique used to derive a more accurate representation of the dynamics of a DC-DC converter by considering the effects of multiple frequencies in the averaged model. It takes into account the harmonics and inter modulation components that arise from the switching action of the converter. By incorporating the effects of multiple frequencies, the multi-frequency averaged modeling technique provides a more accurate representation of the converter's behavior, particularly in systems with high-frequency switching or significant harmonic content. It allows for the assessment of system performance, stability, and control design at different frequency components. Frequency-selective averaged modeling [30] is a technique used to derive a simplified averaged model of a DC-DC converter that considers the frequency-dependent behavior of certain components or parameters. It allows for a more accurate representation of the converter's dynamics by incorporating the selective effects of specific frequency ranges or frequency bands. By considering the frequency-selective behavior of specific components or frequency ranges, the frequency-selective averaged modeling technique provides a more accurate representation of the converter's dynamics. It allows for the analysis of stability, control design, and performance within the specific frequency ranges that are most relevant to the converter's operation.

Discrete nonlinear modeling is a technique used to describe and analyze the behavior of systems that exhibit nonlinear dynamics in discrete-time domains. It is particularly applicable to systems with digital or discrete-time control, such as digital controllers for power electronic converters or digital signal processing systems. Discrete nonlinear modeling provides a valuable tool for understanding and analyzing the behavior of systems with nonlinear dynamics in discrete-time domains. It allows for the study of stability, performance, and control design in digital systems, and it is particularly useful in applications where accurate representation of nonlinear behavior is essential. Nonlinear map-based modeling [31-33] is a technique used to describe and analyze the behavior of systems with nonlinear dynamics using maps or discrete-time iterations. It is a mathematical approach that represents the system's behavior through iterative equations, capturing the evolution of the system from one state to another.

Nonlinear map-based modeling provides a useful tool for understanding and analyzing the behavior of systems with nonlinear dynamics. It simplifies the description of the system by capturing its dynamics through a set of iterative equations, allowing for the study of stability, bifurcations, and other nonlinear phenomena. A stroboscopic map [34] is a nonlinear map-based modeling technique used to describe the behavior of a dynamical system by considering its response at discrete time intervals or stroboscopic instants. It is particularly useful for systems with periodic or quasi-periodic dynamics. The stroboscopic map captures the relationship between the system's state at one time instant and its state at the next stroboscopic instant, allowing for the analysis of long-term behavior and stability properties.

An S-switching map [35] is a type of nonlinear map used to model systems with switching behavior or hybrid dynamics. It describes the evolution of the system's state based on different modes or regimes of operation associated with the switching events. The S-switching map captures the transitions between different modes and characterizes the system's behavior in each mode, providing insights into stability, bifurcations, and other nonlinear phenomena. An A-switching map [36] is another type of nonlinear map used to model systems with switching behavior or hybrid dynamics. Similar to the S-switching map, it represents the evolution of the system's state based on different modes or regimes of operation associated with the switching events. The A-switching map, however, considers asynchronous or arbitrary switching events that do not follow a predefined pattern or synchronization. It captures the system's behavior under these arbitrary switching events, enabling the analysis of stability, transient behavior, and other nonlinear effects.

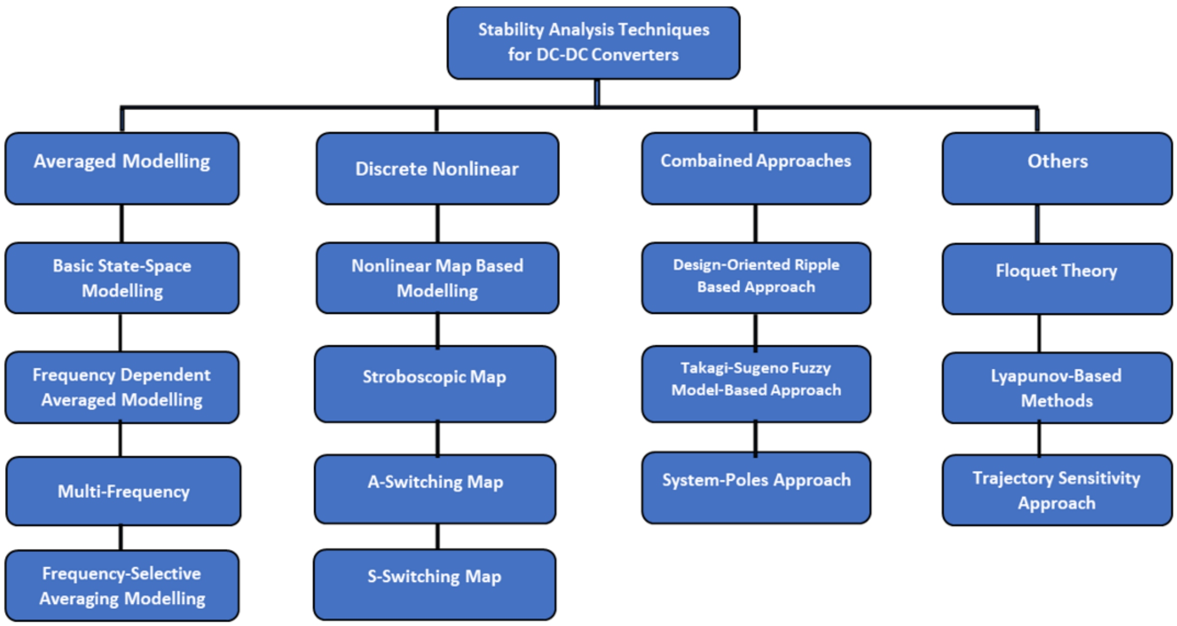


Fig 2.1- Various approaches are employed to assess the stability of power switching converters.

Both S-switching and A-switching maps are valuable tools for understanding and analyzing systems with switching dynamics, such as power electronic converters, hybrid control systems, or biological systems with intermittent behavior. These maps provide a discrete-time representation of the system's behavior, allowing for the study of stability, transient response, and bifurcations, and facilitating the design and optimization of control strategies. Floquet theory [37-40] is a mathematical technique used to analyze the stability of periodic systems. It is particularly useful for studying the stability properties of time-varying systems, such as those encountered in power electronic converters with periodic switching. Floquet theory provides a way to determine the stability of the system by examining the eigen values of the Floquet matrix. The Floquet matrix captures the dynamics of the system over one period and helps identify stability regions or conditions for stability. Floquet theory is often used to analyze stability, bifurcations, and limit cycle behavior in periodically driven systems.

Lyapunov-based methods [41-46] are a family of techniques used to analyze stability and convergence properties of nonlinear systems. These methods rely on Lyapunov's stability theory, which states that if a function (called a Lyapunov function) can be found that satisfies certain properties, then the system is stable or asymptotically stable. Lyapunov-based methods can be used to prove stability, convergence, and robustness properties of nonlinear systems, including power electronic converters. Common Lyapunov-based methods include the direct method, indirect method, and energy function methods. These methods often involve finding a Lyapunov function and analyzing its derivative or rate of change to establish stability or convergence properties. Both Floquet theory and Lyapunov-based methods are powerful tools in stability analysis for nonlinear systems.

Floquet theory is well-suited for analyzing the stability of periodic systems, such as power electronic converters with periodic switching. Lyapunov-based methods, on the other hand, offer a more general framework for analyzing stability and convergence properties of nonlinear systems, including those with time-varying dynamics. These methods are widely used in control system design and analysis to ensure stability and robustness. The trajectory-sensitive approach [47] provides valuable insights into the behavior of nonlinear systems and helps in designing control strategies that can enhance stability and robustness.

The design-oriented ripple-based approach [48-49] is a method used in the design and analysis of power electronic converters to assess and control the ripple components in the system. It focuses on understanding and managing the ripple currents or voltages that occur in the converter's operation, which can affect the system's performance, efficiency, and stability. The system-poles approach [50, 51] is a method used in stability analysis and control system design to evaluate the stability and performance characteristics of a system based on the location of its poles in the complex plane. The poles of a system represent the values of the system's transfer function where its response becomes unbounded or unstable. By analyzing the pole locations, stability margins, and pole-zero cancellations, the system-poles approach provides insights into the stability and dynamic behavior of the system.

2.2 Non-linear Control Methods in Power Switching Converters:

Nonlinear control methods play a crucial role in achieving high-performance and robust operation in power switching converters. These methods are designed to handle the inherent nonlinearity, uncertainties, and disturbances that are present in power electronics systems. These nonlinear control methods offer advanced techniques to deal with the challenges associated with nonlinear dynamics, uncertainties, and disturbances in power switching converters. By employing these methods, it is possible to achieve precise control, improved efficiency, and enhanced robustness in power electronic systems.

Feedback-based control utilizes feedback signals from the converter's output or intermediate stages to regulate and stabilize the system. Proportional-Integral-Derivative (PID) control is a commonly used feedback-based control technique in power converters. Nonlinear control techniques, such as sliding mode control, can also be applied within the feedback loop to handle nonlinear dynamics and uncertainties. The Ott-Grebogi-Yorke (OGY) approach [52] is a nonlinear control method used for stabilizing chaotic systems. It involves adding a small perturbation signal to the system's state variables to drive the chaotic behavior towards a desired stable orbit. In the context of power switching converters, the OGY approach can be employed to control and stabilize the converter's output voltage or current, particularly when the system exhibits chaotic or unpredictable behavior. Time-delayed feedback control [53] is a technique that introduces a delayed version of the system's output or state variables into the control loop. By carefully choosing the delay time and control gain, this method can stabilize or suppress unwanted oscillations in the system.

Washout filter-aided control [54] is a technique that utilizes a washout filter to remove unwanted high-frequency components from the system's signals. This method is commonly used in power switching converters to reduce harmonics, noise, or disturbances in the output voltage or current. By applying washout filter-aided control, the converter's performance can be improved, and the effects of nonlinearities and disturbances can be mitigated. Filter-based non-invasive [55-57] methods are control techniques that utilize filtering or signal processing approaches to estimate or extract specific parameters or signals without the need for invasive measurements. In power switching converters, these methods can be used for state estimation, fault detection, or condition monitoring. By employing advanced filtering techniques, such as Kalman filters, particle filters, or wavelet transforms, accurate estimation and control of the converter's variables can be achieved, enhancing the system's performance and robustness.

The self-stable chaos control method is a technique used to stabilize chaotic behavior in nonlinear systems. It involves designing a control strategy that allows the system to self-adjust and achieve a stable state. This method takes advantage of the inherent dynamics of chaotic systems to guide them towards desired attractors or orbits, thereby achieving stability. In the context of power switching converters, the self-stable chaos control method can be applied to regulate and stabilize the converter's output voltage or current, even in the presence of chaotic behavior. Predictive control is particularly effective in handling nonlinearities, constraints, and uncertainties in power switching converters. By predicting the future behavior of the system, predictive control can make proactive adjustments to maintain desired performance and stability. The frequency-domain approach in control design involves analyzing the system's behavior and designing control strategies based on frequency response characteristics. This approach utilizes techniques like Nyquist plots, Bode plots and frequency response analysis to understand the system's stability, phase margin, gain margin and frequency characteristics. In power switching converters, the frequency-domain approach can be used to design compensators or filters to achieve desired frequency response and stability.

The two-parameter chaotic approach is a control method that exploits the chaotic behavior of a system to achieve control objectives. It involves adjusting two control parameters in a controlled manner to induce chaotic behavior, which can then be controlled to achieve desired system performance or stabilization. This approach can be implemented to power switching converters to regulate the converter's output voltage or current by exploiting the chaotic dynamics of the system. The chaotic SPO (State-Position Output) algorithm is a control method that utilizes chaos theory and bifurcation analysis to achieve control objectives. It involves adjusting system parameters to induce chaotic behavior, and then using bifurcation analysis to identify stable regions or attractors within the chaotic system. By controlling the system's parameters within these stable regions, desired performance or stabilization can be achieved. In power switching converters, the chaotic SPO algorithm can be applied to control the converter's output voltage or current by exploiting the chaotic dynamics and stable regions of the system.

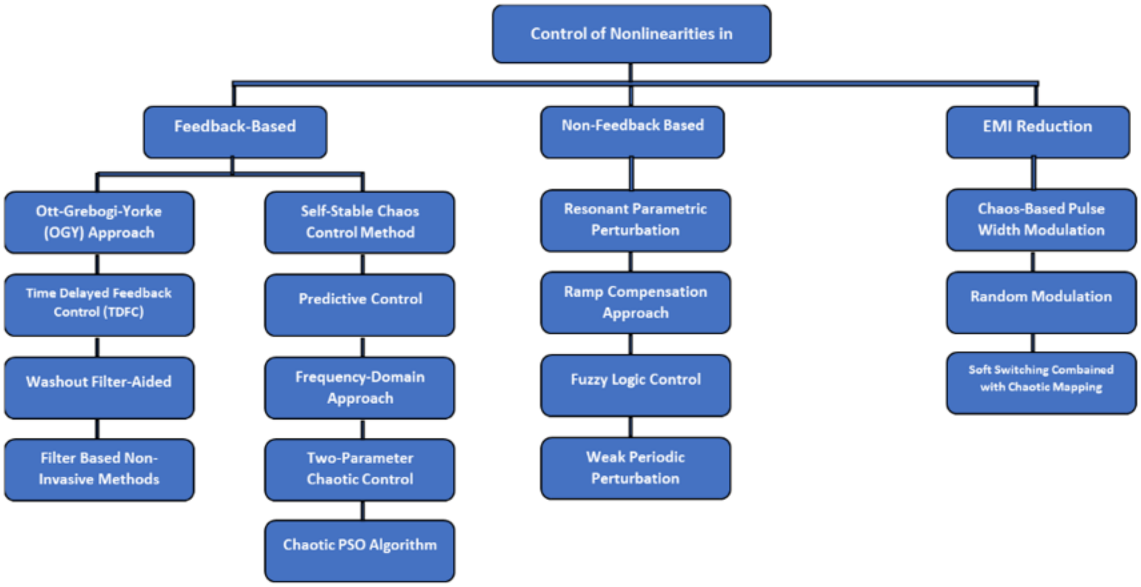


Fig.2.2- Switching power converters utilize non-linear control techniques to enhance their performance.

Non-feedback control methods aim to regulate the power switching converter without explicit feedback from the output or intermediate stages. These techniques often rely on feed forward control or open-loop control strategies. Nonlinear control methods, such as adaptive control or neural network control, can be used in non-feedback control to address uncertainties and enhance performance. Resonant parametric perturbation is a control method that utilizes periodic perturbations to stabilize or control the behavior of a system. By introducing specific parametric perturbations at resonant frequencies, the system's dynamics can be manipulated to achieve desired control objectives. In power switching converters, resonant parametric perturbation can be employed to stabilize the system's operation, enhance performance or mitigate undesired oscillations. The ramp compensation approach is a control technique used to compensate for voltage or current ramps in power switching converters. It involves modifying the control signal or parameters to account for the variations in the system's behavior due to ramp effects. This approach helps in achieving a more accurate and stable output voltage or current, especially during transient or dynamic conditions.

Power switching converters are prone to electromagnetic interference (EMI) generation due to fast switching transitions. EMI reduction techniques are employed to minimize the emission of undesirable electromagnetic noise. These techniques include filtering, shielding, grounding, and the use of soft-switching or zero-voltage switching (ZVS) techniques. Nonlinear control methods can be integrated into the control algorithms of these techniques to improve their effectiveness and address nonlinear dynamics. Chaos-based pulse width modulation is a technique that utilizes chaotic systems or chaotic maps to generate modulation signals for power switching converters. Instead of using conventional modulation techniques, chaos-based PWM employs the unpredictable and pseudo-random behavior of chaotic systems to generate modulation patterns. This approach can improve the spectral characteristics of the converter's output, reduce harmonic distortion, and enhance efficiency.

Random modulation is a technique that introduces randomness or noise into the modulation signals of power switching converters. By incorporating random variations in the switching patterns, random modulation can distribute the energy of the converter's output over a wide frequency spectrum, reducing the concentration of energy at specific frequencies. This approach helps in mitigating electromagnetic interference (EMI) and improving the converter's performance. Soft switching is a technique used in power switching converters to minimize switching losses and improve efficiency by ensuring that the switches operate under zero-voltage or zero-current conditions during the switching transitions. Combining soft switching techniques with chaotic mapping involves using chaotic dynamics to determine the optimal switching instants or patterns for achieving soft switching. By exploiting chaotic behavior, this approach can optimize the converter's operation and minimize losses.

2.3 Thesis Organization:

Bifurcation and chaotic phenomena are frequently encountered in power electronics circuits and systems. In power electronics, altering any parameter be it input, output or load, often results in nonlinear behaviors. These behaviors may include the emergence of coexisting attractors, Hopf bifurcation, period-doubling bifurcation, and boundary collisions. Extensive research has been conducted in the field of power electronics and systems regarding bifurcation behavior, leading to a mature understanding of this phenomenon. Numerous studies have reported various bifurcation behaviors and identified the theoretical parameters responsible for their occurrence, as well as the associated side effects. In the past decade, research papers have focused on harnessing the complex behaviors observed in power electronics for practical applications in industrial settings within the field of power electronics and systems. One of my research interests involves developing methodologies to mitigate bifurcation behavior in practical applications of power electronics and systems. While abstract mathematical formulations can provide detailed insights into bifurcation outcomes, they cannot be directly applied to the design of industrial systems. Therefore, future study and research work should focus on exploring more practical, design-oriented approaches that can be experimentally tested and implemented in real-world applications.

This thesis focuses on the analysis and regulate of rapid nonlinear behaviors in DC-DC power electronic switching converters, with the aim of enhancing our understanding of nonlinear modeling and bridging the gap between theoretical research and practical applications. It provides comprehensive details on feedback control system implementation and stability analysis, addressing the specific timescale dynamics of these converters. By doing so, it contributes to advancing knowledge in this field and improving the practicality of research findings. The research employs a method of nonlinear analysis based on the Iterative Mapping Matrix. This approach provides a comprehensive understanding of boundary operation conditions and facilitates the development of new control methodologies to address instability issues. By adopting a design-oriented strategy, this research offers practical options that can be readily applied in the conceptual design process and expedite progress at a practical scale.

CHAPTER III

METHODOLOGIES:

3.1 A comprehensive review of the analysis of nonlinear dynamics in power switching converters:

Nonlinear dynamics refers to the study of complex behaviors exhibited by systems with nonlinear relationships between inputs and outputs. In the context of power switching converters, nonlinear dynamics can arise due to factors such as switching losses, magnetic core saturation, parasitic elements, and nonlinear loads. There are different power switching converter topologies like buck, boost, buck-boost, flyback and forward converters. Each topology has unique characteristics that can affect the nonlinear dynamics. Review various modeling techniques used to describe the behavior of power switching converters, such as state-space averaging, small-signal modeling, and discrete-time models. Examine the nonlinear phenomena observed in power switching converters, including sub harmonic oscillations, chaos, bifurcations, and limit cycles. These phenomena can occur due to the nonlinearity introduced by the converter's components and control schemes.

Methods for analyzing the stability of power switching converters, such as Lyapunov stability analysis, describing functions and frequency response analysis. Investigate the impact of nonlinear dynamics on the converter's stability and the design of stabilizing control strategies. Analysis of nonlinear dynamics in power switching converters would involve a thorough exploration of the theoretical foundations, modeling approaches, control strategies, and experimental findings related to the nonlinear behavior of these converters.

3.2 Information about switching power converters:

Switching power converters are electronic devices that efficiently convert electrical energy from one form to another by rapidly switching power semiconductor devices like transistors or diodes, on and off. These converters play a vital role in various applications inclusive in power supplies, renewable energy systems, motor drives and electric vehicles. Switching power converters operate by employing high-frequency switching techniques to control the flow of energy. They typically consist of several key components, including an input power source, power semiconductor devices, energy storage elements (like inductors and capacitors), control circuitry, and an output load. The operation of switching power converters involves cyclically switching the power semiconductor devices between on and off states. During the on-state, energy is stored in the energy storage elements, while during the off-state, this energy is transferred to the output load. This switching action enables efficient voltage or current transformation, allowing for voltage regulation, power factor correction, isolation, and other desired functionalities.

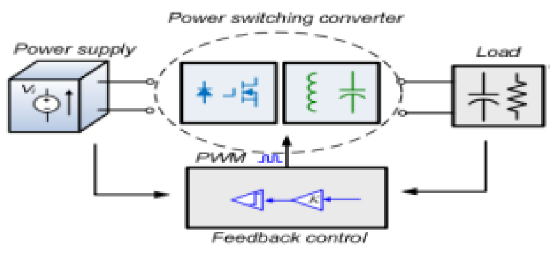


Fig.3.1- Non-isolated DC-DC power switching converters

Switching power converters offer several advantages over traditional linear converters, including higher efficiency, smaller size, and improved control capabilities. However, they also introduce challenges due to their nonlinear characteristics. These nonlinearities arise from various factors, including the nonlinear behavior of the power semiconductor devices, parasitic elements, magnetic core saturation, and interactions between control loops. Understanding the behavior and characteristics of switching power converters is crucial for their design, analysis, and control. It involves modeling the converter's dynamics, analyzing its transient and steady-state responses, investigating stability issues, and developing control strategies to achieve desired performance objectives.

3.3 Control Methods:

Voltage mode control and current mode control are regularly used control schemes in power electronics for regulating the output voltage or current of switching converters.

(i) Voltage Mode Control Method:

Voltage mode control alternatively known as voltage loop control is a control scheme where the output voltage of the converter is detected and compared to a reference voltage. The control circuit adjusts the duty cycle of the power switch to sustain the output voltage at the desired level.

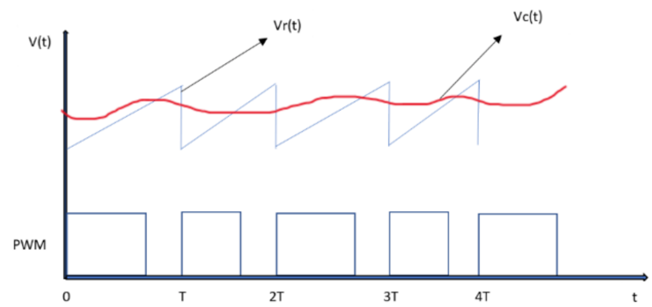


Fig.3.2- Voltage Mode Control Technique

Here's how voltage mode control typically works:

- An error amplifier compares the detected the output voltage with the reference voltage and generates an error signal proportional to the difference between the two.
- The sensed output voltage can be obtained using a voltage divider network connected to the output of the converter.
- The error signal is processed by a compensator or a control loop filter to shape the response and provide stability.
- The output of the compensator is fed into a pulse-width modulation (PWM) generator, which generates the control signal for the power switch. The duty cycle of the PWM signal is altered based on the error signal to regulate the output voltage.

Voltage mode control offers good dynamic response and stability. It is commonly used in applications where voltage regulation is the primary requirement, such as power supplies, DC-DC converters, and voltage regulators.

(ii) Current Mode Control Method:

Current mode control, also referred to as current loop control, is a control scheme where the current flowing through a sensing element (usually an inductor or a current-sensing resistor) is sensed and used as the primary feedback signal for control. The control circuit adjusts the duty cycle of the power switch to maintain a stable current level.

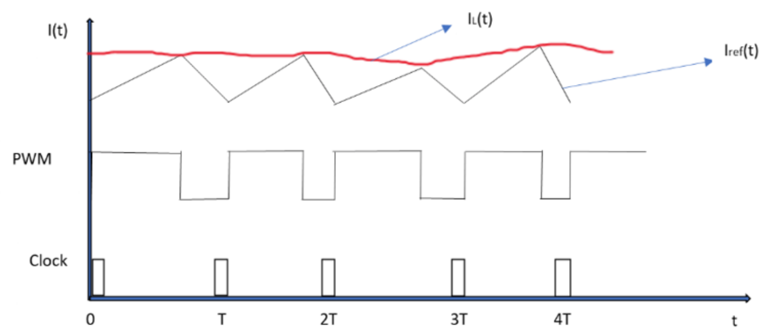


Fig. 3.3- Current Mode Control Technique

Here's an overview of current mode control:

- A current sense amplifier measures the current flowing through the sensing element and generates a proportional voltage signal.
- The current sense amplifier provides the current feedback signal to the control circuit.
- Similar to voltage mode control, a compensator or control loop filter processes the current feedback signal to shape the response and ensure stability.
- The output of the compensator is used to generate the PWM signal, adjusting the duty cycle of the power switch based on the current feedback.

Current mode control delivers inherent cycle-by-cycle current limiting and faster transient response evaluated to voltage mode control. It is commonly used in applications where current regulation, current limiting, or fast load transient response is critical, such as motor drives, LED drivers, and high-frequency power converters.

Both voltage mode control and current mode control have their advantages and are suitable for different applications. The choice of control scheme depends on the specific prerequisites of the power converter and the desired performance characteristics.

3.4 Modeling of Power Electronic Switching Converters:

The state-space averaging approach is a commonly used technique for modeling power electronic switching converters. It provides a systematic procedure for deriving average-value state-space models, which capture the steady-state behavior of the converter.

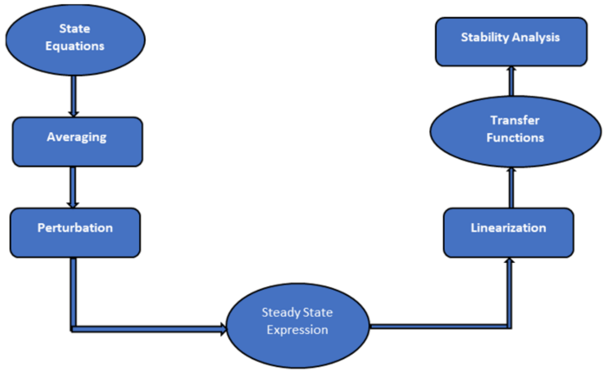


Fig. 3.4 - The procedural scheme of the state-space averaging approach

State equations describe the dynamic behavior of a system in terms of its state variables. In the context of power electronic systems, state equations represent the relationships between the system's inputs, outputs and the time derivatives of the state variables. These equations are typically formulated as first-order differential equations in state-space form, where the states represent variables like inductor currents and capacitor voltages.

$$\frac{dx(t)}{dt} = f(x(t), t) \tag{1}$$

Averaging is a technique used to obtain the average behavior of a power electronic system over a switching period. By averaging the system's equations, the fast switching dynamics are smoothed out resulting in simplified average-value equations that capture the steady-state behavior. Averaging is often used in conjunction with the state-space averaging approach to derive average-value models of switching converters.

$$\frac{dx(t)}{dt} = f(x(t), d) \tag{2}$$

Perturbation refers to small deviations or disturbances from the steady-state operating conditions of a system. In power electronic systems, perturbations can arise due to changes in the input voltage, load variations, or control signal variations. Analyzing the system's response to these perturbations helps evaluate the stability and performance of the system.

$$\frac{d\hat{x}(t)}{dt} = f(X + \hat{x}(t), D + \hat{d}) \tag{3}$$

Steady state refers to the operating condition of a system where the system's variables no longer change with time. In the context of power electronic systems, steady state represents a condition where the system's voltages, currents, and other variables have reached a stable and constant value. Steady-state analysis is essential for understanding the behavior and performance of power electronic converters under normal operating conditions.

$$\hat{x}(t) = f(\hat{d}) \tag{4}$$

Linearization is the process of approximating the nonlinear behavior of a system by considering small deviations around a given operating point. In power electronic systems, linearization is commonly used to linearize the system's equations and obtain linear small-signal models. Linearized models enable the application of linear control techniques, such as transfer function analysis and stability analysis.

$$\frac{d\hat{x}(t)}{dt} = f(\hat{x}(t), D + \hat{d}) \tag{5}$$

A transfer function is a mathematical portrayal of the relationship between the input and output signals of a system in the frequency domain. In power electronic systems, transfer functions are derived from linearized models and describe the frequency response characteristics of the system. Transfer function analysis helps evaluate stability, gain and phase margins, and frequency-domain performance.

$$X = f(D) \tag{6}$$

Stability analysis is an essential aspect of analyzing power electronic systems. It involves evaluating the stability of the system's response to perturbations or disturbances. Stability analysis techniques, such as Bode plots, Nyquist plots, and root locus plots, are used to assess the stability margins, determine stability criteria, and design stable control systems for power electronic converters.

3.5 The Equilibrium points Solution's Stability:

The stability of equilibrium points refers to the behavior of the system around its steady-state operating points. An equilibrium point, also known as a steady-state solution, is a set of values for the system's variables (such as voltages and currents) where the system remains constant over time in the absence of external perturbations.

It's important to note that stability analysis is based on the assumption of small perturbations around the equilibrium points. Nonlinear effects, large disturbances, or parameter variations may require more advanced stability analysis techniques, such as Lyapunov stability analysis or direct time-domain simulations. By solving this state-space representation, one can analyze the behavior, stability, and response of the linear system to different inputs and disturbances. It is a powerful framework for modeling and controlling a wide range of dynamic systems, including power electronic converters.

$$\dot{X} = Ax + BE \tag{7}$$

Where, A represents the system matrix it captures the dynamics of the system and describes how the state variables evolve over time. It is an n x n matrix, where n is the dimension of the state vector X and B represents the input matrix B relates the inputs of the system to the rate of change of the state variables. It is an n x m matrix, where m is the number of input variables or control signals affecting the system and E represents the external input vector E represents any external disturbances.

The expression $\dot{X} = Ax + BE$ represents the dynamic evolution of the state vector X over time. It states that the rate of change of the state variables (Ax) is influenced by both the internal dynamics described by the system matrix A and the external inputs represented by the product of the input matrix B and the external input vector E.

In state-space models, the stability of equilibrium points can be analyzed by examining the eigen values of the system's state matrix. The eigen values provide information about the system's stability characteristics. The stability of equilibrium points can be determined based on the location of the eigen values in the complex plane. An equilibrium point is considered stable if all eigen values of the state matrix have negative real parts. This means that any small perturbations from the equilibrium point will decay over time, and the system will return to the steady state. An equilibrium point is unstable if at least one eigen value of the state matrix has a positive real part. In this case, small perturbations will grow over time, causing the system to diverge from the steady state.

$$\left| AI - \lambda \right| = 0 \tag{8}$$

If the state matrix has eigen values with zero real parts, the equilibrium point is marginally stable. Perturbations at this equilibrium point neither decay nor grow exponentially, resulting in a bounded response.

Stability analysis can also be performed using transfer functions derived from linearized models. For linear time-invariant systems, stability can be determined based on the poles of the transfer function.

3.6 Characterization of Dynamical Systems:

The characterization of dynamical systems involves a combination of analytical, numerical, and graphical techniques to understand the behavior, stability, and response of systems over time. The combination of analytical approaches, numerical methods, and experimental verifications provides a comprehensive approach to characterizing dynamical systems. Analytical methods provide insights into system behavior and can offer simplified models for initial analysis. Numerical methods allow for more accurate and detailed simulations, especially for complex and nonlinear systems. Experimental verifications provide practical validation and real-world insight, helping to bridge the gap between theory and practice.

The averaging approach is particularly useful for obtaining simplified models and understanding the steady-state behavior of power electronic systems. It allows for the analysis of systems without explicitly considering the fast switching dynamics, which can be computationally intensive. However, the approach assumes that the slow variations dominate the system's behavior, and it may introduce some approximation errors. The perturbation method is valuable in gaining insights into the effects of small disturbances or nonlinearities on system behavior. It allows for the analysis of nonlinear systems without the need for complex numerical simulations or solving the equations exactly.

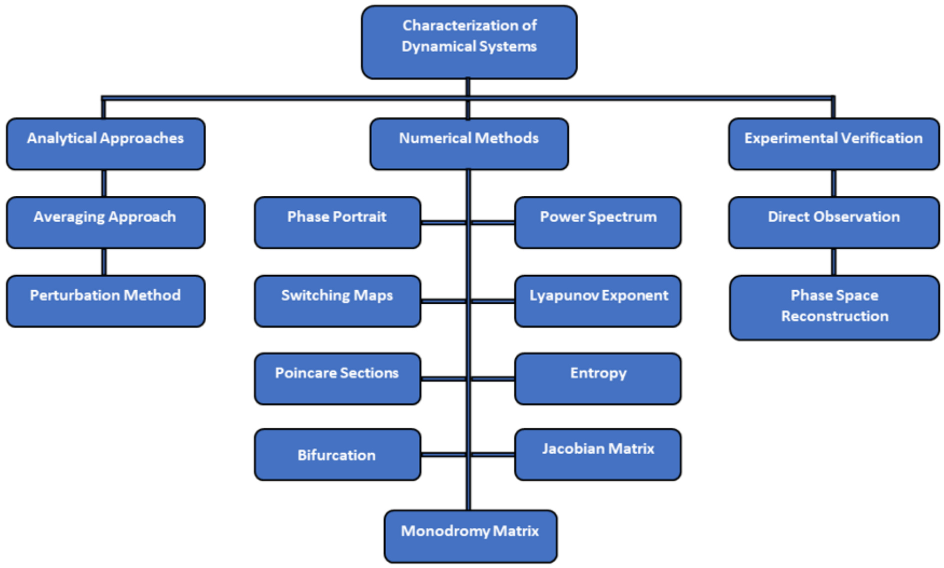


Fig. 3.5- A common way to describe a dynamical system is through its typical characterization.

A phase portrait is a graphical representation of the trajectories or orbits of a dynamical system in the state space. It provides a visual depiction of the system's behavior and helps in understanding its qualitative properties. In a phase portrait, each point represents a unique state of the system, and the trajectories show how the system evolves over time. The shape, stability, and attractors of the system can be inferred from the phase portrait. Switching maps are used to analyze and understand the behavior of systems with discrete or switching dynamics, such as power electronic converters. These maps capture the evolution of the system's variables between consecutive switching events or discrete time instants. The switching map represents the relationship between the system's states before and after each switching event, allowing for the analysis of stability, periodic behavior, bifurcations, and other dynamic properties. By plotting the state variables of the system at the instances they cross the Poincare section, a reduced-dimensional representation of the system's behavior can be obtained. Poincare sections help in identifying periodic orbits, stability and chaotic behavior of the system.

A bifurcation diagram is a graphical representation that shows the qualitative changes in a dynamical system as a parameter of the system is varied. It helps in understanding how the system's behavior changes with different parameter values. The bifurcation diagram typically plots the system's equilibrium points, periodic orbits, or other key features against the varying parameter. It reveals information about stability, the onset of bifurcations (such as period-doubling, saddle-node bifurcation, or Hopf bifurcation), and the existence of different dynamical regimes in the system. These tools and techniques play a crucial role in the analysis and characterization of dynamical systems. They provide insights into the system's behavior, stability, periodicity, chaos, and the effects of parameter variations.

3.7 Bifurcation Diagram:

Bifurcation patterns are characteristic structures or patterns observed in the bifurcation diagram. These patterns reflect the different dynamic regimes or behaviors exhibited by the system. Common bifurcation patterns include period-doubling bifurcations, saddle-node bifurcations, Hopf bifurcations, pitchfork bifurcations and more. When examining the bifurcation diagram of a switching power electronic converter, the horizontal axis represents the parameter of interest, such as the control parameter or the operating conditions. The vertical axis represents a relevant output characteristic, such as the output voltage or current.

Period 1 behavior is often desirable in power electronic converters as it represents a stable and predictable operating mode. It indicates that the system is operating in a controlled manner, providing a consistent output waveform over time. Stable period 1 operation is typically associated with a specific parameter range in the bifurcation diagram where the system is stable and exhibits regular periodic behavior. Understanding the presence and location of period 1 points in the bifurcation diagram of switching power electronic converters helps in designing stable and efficient converter operation. It provides insights into the parameter ranges where the system operates in a predictable and controlled manner.

A "period 2" point on the bifurcation diagram indicates that the system exhibits stable periodic behavior with a period of two. This means that the output waveform of the converter repeats itself exactly after completing two cycles, and then repeats the same pattern again. This behavior is characterized by a doubling of the period compared to the period 1 behavior. Period 2 behavior can occur as a result of a period-doubling bifurcation in the system. As the control parameter or operating conditions are varied, the system transitions from a stable period 1 behavior to a stable period 2 behavior. This bifurcation point in the bifurcation diagram represents the onset of the period-doubling phenomenon. Understanding the presence and location of period 2 points in the bifurcation diagram of switching power electronic converters helps in analyzing the stability and dynamic behavior of the system. However, it's important to note that the system can exhibit further bifurcations leading to higher-order periodic behavior, such as period 4, period 8, and so on, as the control parameter is further varied.

Chaotic behavior in the bifurcation diagram indicates the presence of regions where the system exhibits chaotic dynamics. Chaotic behavior occurs when the system undergoes a bifurcation, such as a period-doubling bifurcation or other types of bifurcations, leading to the onset of irregular and unpredictable output waveforms.

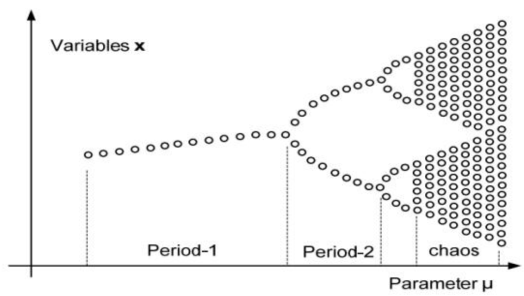


Fig.3.6 - An illustration of a bifurcation plot depicting the behavior of a dynamical system.

In a bifurcation diagram, chaotic regions can be identified by their fractal-like patterns, where fine-scale structures are repeated on different scales. These regions reflect the sensitivity of the system to small changes in initial conditions or parameter values, resulting in significantly different output behavior. Chaotic behavior in switching power electronic converters can arise due to a combination of nonlinear dynamics, feedback effects, and the interaction between different components of the converter. It can have various negative effects, such as increased output ripple, reduced efficiency, or electromagnetic interference.

CHAPTER-IV

Chaotic Behavior of DC-DC Boost Converter:

The chaotic behavior of a DC-DC boost converter refers to the occurrence of complex and unpredictable dynamics in its operation. It manifests as irregular and aperiodic output waveforms, exhibiting sensitive dependence on initial conditions and parameter values. Chaotic behavior in a DC-DC boost converter can arise due to the nonlinear dynamics of the system, which result from the interaction of the various components such as the inductor, capacitor, switch, and diode.

The inductor and capacitor in a boost converter exhibit nonlinear characteristics, such as magnetic hysteresis in the inductor core and voltage-dependent capacitance. These nonlinearities can introduce complex dynamics and contribute to the onset of chaos. The switching action in the boost converter, where the switch transitions between on and off states, can introduce nonlinear effects and generate complex behavior. Rapid changes in voltage and current during the switching events can lead to bifurcations and the emergence of chaotic dynamics. The control parameters of the boost converter, such as the switching frequency, duty cycle, and feedback control gains, can influence its dynamic behavior. Small variations in these parameters can result in significant changes in the system's output, leading to chaotic behavior. Parasitic elements in the converter, such as stray capacitance, inductance, and resistance, can contribute to nonlinear behavior and instability. These effects, coupled with the inherent nonlinearity of the system, can lead to chaotic dynamics. Understanding and analyzing chaotic behavior in a DC-DC boost converter is important for system design, control, and optimization. It allows identifying parameter ranges and operating conditions where chaos occurs, and take appropriate measures to mitigate its effects. Techniques such as nonlinear control methods, feedback stabilization, and parameter optimization can be employed to suppress or avoid chaotic behavior in the converter, ensuring stable and reliable operation.

4.1 Mathematical Analysis of Boost Converter by Using Discrete Iterative Mapping:

The mathematical analysis of a boost converter can be performed using discrete iterative mapping techniques. These techniques involve modeling the converter's behavior as a discrete-time dynamical system and applying iterative equations to describe the system's state evolution over time.

The boost converter is represented by a set of nonlinear difference equations that describe the relationships between the system's input, output, and control variables. These equations capture the switching dynamics, energy storage elements (inductor and capacitor), and control mechanisms of the converter. The discrete-time equations obtained from the discretization process form the basis of the iterative mapping. Starting from an initial condition, the system's state variables (such as the inductor current and capacitor voltage) are updated iteratively based on the discrete equations. The iterative mapping allows the simulation of the system's behavior over multiple time steps. The mathematical analysis of a boost converter using discrete iterative mapping provides valuable insights into the converter's behavior, stability, and performance characteristics. It allows engineers and researchers to understand the system's dynamics, optimize the control strategy, and design efficient and reliable power conversion systems.

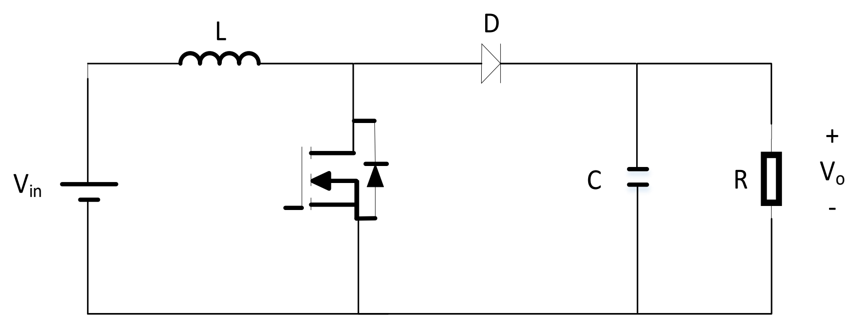


Fig.4.1 - The Circuit diagram of Boost converter

The Boost converter's state space equations can be stated as follows:

$$\dot{x} = A_1 x + B_1 E \quad \text{for} \quad t_n \le t < t_n^{'} \tag{1}$$

$$\dot{x} = A_2 x + B_2 E \quad \text{for} \quad t_n^{'} \le t < t_n^{''} \tag{2}$$

$$\dot{x} = A_3 x + B_3 E \quad \text{for} \quad t_n^{''} \le t < t_{n+1} \tag{3}$$

Where,

$$A_1 = \begin{bmatrix} \frac{-1}{RC} & 0 \\ 0 & 0 \end{bmatrix}, B_1 = \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} \quad (4)$$

$$A_2 = \begin{bmatrix} \frac{-1}{RC} & \frac{1}{C} \\ \frac{-1}{L} & 0 \end{bmatrix}, B_2 = \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} \quad (5)$$

$$A_3 = \begin{bmatrix} \frac{-1}{RC} & 0 \\ 0 & 0 \end{bmatrix}, B_3 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, x = \begin{bmatrix} V_c \\ i_L \end{bmatrix} \quad (6)$$

Integrating the RHS of (2) and replacing the t $= t_n^{'}$ will get the common solution to the switch on interval. This results in the end value of the switch on period after substitution.

$$V_C(t_n^{'}) = V_C(t_n)e^{-dT/CR} \quad (7)$$

$$i_L(t_n^{'}) = i_L(t_n) + \frac{EdT}{L} \quad (8)$$

Where, V_c represents the voltage of the capacitor (C) and I_L represents the current of the inductor (L). Apply the Laplace transformation to the switch-off interval equation to obtain the solution.

$$X(s) = \left[sI - A_2\right]^{-1}[x(t_n^{'}) + B_2E(s)] \quad (9)$$

$$= \frac{\begin{bmatrix} s & \frac{1}{C} \\ \frac{-1}{L} & s + \frac{1}{RC} \end{bmatrix}}{s^2 + \frac{s}{CR} + \frac{1}{LC}} \begin{bmatrix} V_C(t_n^{'}) \\ i_L(t_n^{'}) + \frac{E}{sL} \end{bmatrix} \quad (10)$$

Where, X(s) represents the Laplace transform of x(t). Therefore, the s-domain expression for the capacitor's voltage (V_c) and the inductor's current (I_L) in the above Laplace equation can be written as

$$V_c(s) = \frac{E}{s} + \frac{K_I s + K_{II}}{H(s)} \tag{11}$$

$$I_L(s) = \frac{E}{Rs} + \frac{K_{III} s + K_{IV}}{H(s)} \tag{12}$$

Where,

$$K_I = V_C(t_n^{'}) - E \tag{13}$$

$$K_{II} = \frac{1}{C} i_L(t_n^{'}) - 2\sigma E \tag{14}$$

$$K_{III} = i_L(t_n^{'}) - \frac{E}{R} \tag{15}$$

$$K_{IV} = \frac{1}{C} i_L(t_n^{'}) - \frac{1}{L} V_C(t_n^{'}) + \left(\frac{R}{L} - 2\sigma\right)\frac{E}{R} \tag{16}$$

$$2\sigma = \frac{1}{CR} \tag{17}$$

$$H(s) = s^2 + \frac{s}{CR} + \frac{1}{LC} \tag{18}$$

The inverse Laplace transformation can be used to get the time-domain equations for the capacitor voltage $V_c(s)$ and inductor current $I_L(s)$ in the interval of $t_n^{'} < t < t_{n+1}$

$$V_C(t) = E + K_I e^{-\sigma(t-t_n^{'})} \cos\omega(t - t_n^{'}) + \frac{K_{II} - K_I \sigma}{\omega} e^{-\sigma(t-t_n^{'})} \sin\omega(t - t_n^{'}) \tag{19}$$

$$i_L(t) = \frac{E}{R} + K_{III} e^{-\sigma(t-t_n^{'})} \cos\omega(t - t_n^{'}) + \frac{K_{IV} - K_{III}\sigma}{\omega} e^{-\sigma(t-t_n^{'})} \sin\omega(t - t_n^{'}) \tag{20}$$

Where,

$$\omega = \sqrt{\frac{1}{LC} - \sigma^2} \tag{21}$$

Where, K_I, K_{II}, K_{III} and K_{IV} are the functions of $x(t_n^{'})$ which a function is in turn off $x(t_n)$ and d. The difference equation's basic form is represented by the

$$x(t_{n+1}) = f(x(t_n), d) \tag{22}$$

The function f (.) in this case is provided by

$$f(x,d) = \begin{bmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{bmatrix} x + \begin{bmatrix} g_1 \\ g_2 \end{bmatrix} E \tag{23}$$

Where,

$$f_{11} = e^{\frac{-dT}{RC} - \sigma(1-d)T} \left[\cos(1-d)\omega T - \frac{\sigma}{\omega} \sin(1-d)\omega T \right] \tag{24}$$

$$f_{12} = \frac{1}{\omega C} e^{-\sigma(1-d)T} \sin(1-d)\omega T \tag{25}$$

$$f_{21} = -\frac{1}{\omega L} e^{\frac{-dT}{RC} - \sigma(1-d)T} \sin(1-d)\omega T \tag{26}$$

$$f_{22} = e^{-\sigma(1-d)T} \left[\cos(1-d)\omega T + \frac{1}{\omega}\left(\frac{1}{CR} - \sigma\right) \sin(1-d)\omega T \right] \tag{27}$$

$$g_1 = 1 - e^{-\sigma(1-d)T} \left[\cos(1-d)\omega T - \frac{1}{\omega}\left(\frac{dT}{LC} - \sigma\right) \sin(1-d)\omega T \right] \tag{28}$$

$$g_2 = \frac{1}{R}\{1 + e^{-\sigma(1-d)T} \left[\left(\frac{RdT}{L} - 1\right) \cos(1-d)\omega T \;\; \frac{1}{\omega}\left[\left(\frac{1}{CR} - \sigma\right) \frac{RdT}{L} + \frac{R}{L} - \sigma \right] \sin(1-d)\omega T \right] \tag{29}$$

$$x(t_{n+1}) = f(x(t_n), d) \tag{30}$$

The boost converter's discrete-time state equation for continuous mode operation is provided by the equations above. To assure that the circuit functions in discontinuous mode, the inductance's value must be appropriately low. It has been suggested that the inductance value L should not be larger than $\frac{1}{2}D(1-D)^2RT$ for a discontinuous conduction mode operation, where T indicates the switching period and D indicates the duty cycle.

There are three basic topologies, and each of them has a state equation with an explicit solution. Using the interval $t_n \le t < t_n^{'}$ as an example, the solution is given by

$$x(t) = \Phi_1(t-t_n)x(t_n) + \int_{t_n}^{t} \Phi_1(t-T)B_1E.dT$$

$$= \Phi_1(t-t_n)\left(x(t_n) + \int_{t_n}^{t} \Phi_1(t_n-T)B_1E.dT \right) \tag{31}$$

A map that iteratively represents $x(t_{n+1})$ in terms of x would be produced by "stacking" successive solutions over a switching period $x(t_n)$,i.e.,

$$x(t_{n+1}) = \Phi_3(t_e)\Phi_2(t_d)\Phi(t_c)\left(x(t_n) + \int_{t_n}^{t_n^{'}} \Phi_1(t_n-T)B_1E.dT \right) + \Phi_3(t_e)\Phi_2(t_d)\int_{t_n^{'}}^{t_n^{''}} \Phi_2(t_n^{'}-T)B_2E.dT$$

$$+\Phi_3(t_e)\int_{t_n^{''}}^{t_{n+1}} \Phi_2(t_n^{''}-T)B_3E.dT \tag{32}$$

Where, $t_c = t_n^{'} - t_n, t_e = t_{n+1} - t_n^{''}, t_d = t_n^{''} - t_n^{'}$ and $\Phi_k(\xi)$ is the transition matrix which is provided by the series of equations below:

$$\Phi_k(\xi) = 1 + \sum_{n=1}^{\infty} \frac{1}{n!} A_k^n \xi^n \quad \text{for} \quad k=1,2,3. \tag{33}$$

After computing and substituting each transition matrix in equation (33), an iterative map is produced

$$x(t_{n+1}) = f\left(x(t_n), d_n\right) \tag{34}$$

Where, d_n represents the duty cycle for the nth period, which is defined as

$$d_n = \frac{t_c}{T} \tag{35}$$

Typical switching regulator applications have switching periods that are significantly less than the time constant for capacitance-load-resistance. The examination of the transition matrix $\Phi_k(.)$ is significantly streamlined by this condition yields a finite series representation of $\Phi_k(.)$ that is quite accurate.

$$\Phi_k(\xi) = 1 + A_k^2 \xi + \frac{1}{2} A_k^2 \xi^2 \qquad \text{for} \quad k = 1,2,3 \tag{36}$$

Moreover, the inductance current I_L grows linearly throughout the time period $t_n \le t < t_n^{'}$ at a rate of E/L from zero to a value of $i_{\max}$ and linearly declines throughout the time period $t_n^{'} \le t < t_n^{''}$ from $i_{\max}$ to zero at the rate of $\frac{x-E}{L}$ in order to write

$$\frac{t_d}{t_c} = \frac{E}{x-E} \tag{37}$$

Using equations from (4)-(6), (36) and (37), and aware that the $i_L(t_n) = 0$, $\forall$ n in equation (33) can estimated be classified as

$$x_{n+1} = \alpha x_n + \frac{\beta d_n^2 E^2}{x_n - E} \tag{38}$$

Where,

$$x_n = v_c(t_n) = v_c(nT) \tag{39}$$

$$\alpha = 1 - \frac{T}{RC} + \frac{T^2}{2R^2C^2} \tag{40}$$

$$\beta = \frac{T^2}{2LC} \tag{41}$$

Here, we're concentrating on the system that is managed by the simple feedback system shown below:

$$\Delta d_n = -k.\Delta x_n \tag{42}$$

Where, the closed-loop dynamics can be changed by using the feedback parameter k. The preceding equation suggests the usage of a uniform sampling strategy, where in Δd is determined for each switching period using the value of $\Delta x(t_n)$, which is sampled at the beginning of each switching period.

The closed-loop system's Poincare map may now be obtained by substituting (18) in (14), which results in

$$x_{n+1} = \alpha x_n + \frac{h(d_n)^2 \beta E^2}{x_n - E} \tag{43}$$

Where,

$$d_n = D - k(x_n - X) \tag{44}$$

$$h(d_n) = \begin{cases} 0 & if \quad d_n < 0 \\ 1 & if \quad d_n > 0 \\ d_n & , \quad otherwise \end{cases} \tag{45}$$

4.2 Feedback Control Loop of Boost Converter:

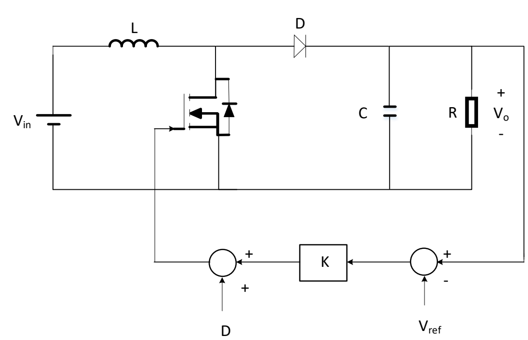


Fig.4.2 Circuit diagram for Closed-loop Boost Converter

There are several ways to modulate the output voltage of Boost converter. In this study, a voltage mode control system was used to adjust the output voltage. The feedback loop serves as the main component of this control, monitoring changes in output voltage (V_c) and adjusting the duty cycle as necessary. In a compensation network, a control signal (V_{con}) is produced particularly from the variance between the reference voltage (V_{ref}) and the output voltage (V_c).

$$V_{con}(t) = g(V_{ref} - V_c) \tag{46}$$

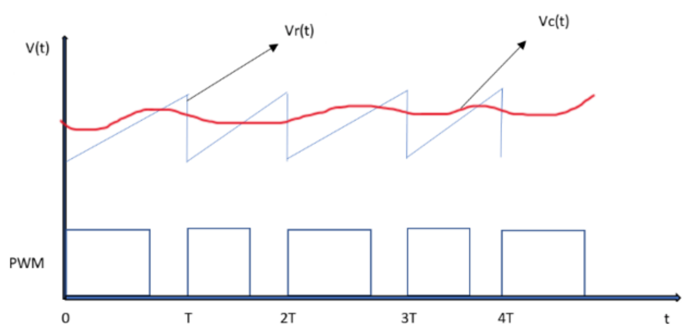


Fig. 4.3 – Voltage Mode Control Technique

Where the compensation network's determination of g(.) is the function. This control signal efficiently indicates how to modify the duty cycle (D) is to provide the output voltage with the optimal transient dynamics.

4.3 Bifurcation Diagram of Boost Converter:

The bifurcation diagram with different feedback gain, one can gain insights into the system's behavior as the feedback gain is varied. It helps to understand the stability boundaries, parameter regions that induce bifurcations, and the effects of feedback on the system's performance. This information can guide the design and optimization of the control system for improved stability, performance, or desired dynamic behavior. To determine the initial and final conditions under which the converter may operate securely, the bifurcation diagram is plotted. Bifurcation can be examined using this graphic depiction as well. In this case, computer simulations are a great tool for figuring out the chaotic behavior. In the simulation from the computer, one parameter is altered while the other parameters are held constant.

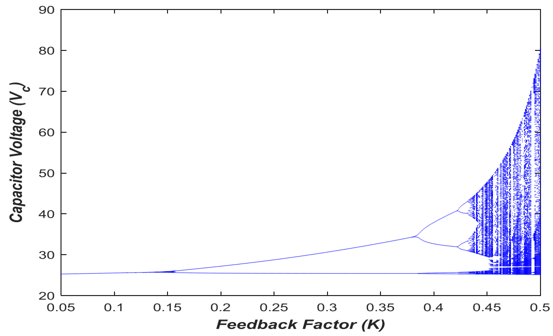


Fig.4.4. Diagram for bifurcation with different feedback gain

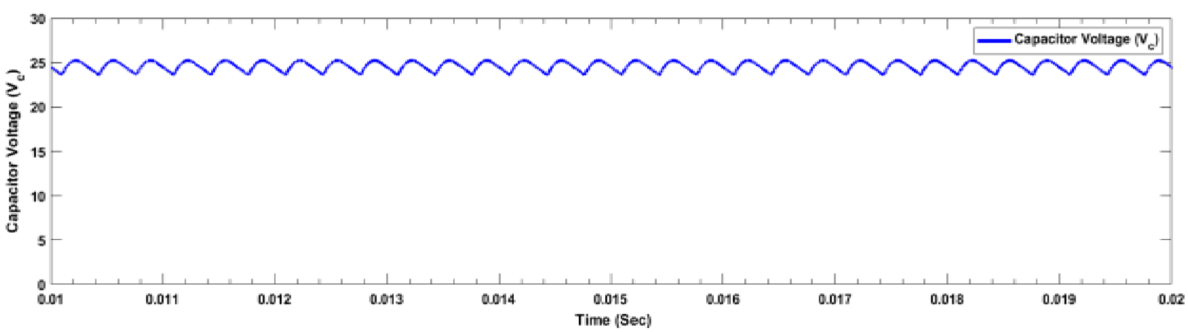
In the above Fig.3, a stable period up to about 0.15 can be noticed, and the diagram of bifurcation with reference to feedback gain is visible. Double bifurcation, often known as 2T, happens after k= 0.15. Up until k=0.37, this occurs. Moreover, the output voltage splits into period 4 (or 4T) after k = 0.38, continuing until almost k = 0.42. At some point after k = 0.43, this finally moves into a chaotic area.

Table 4.1 - Simulation Parameters of Boost Converter

Switching frequency (f_s)	3000Hz
Inductance (L)	208 μH
Input Voltage (E)	16V
Capacitance (C)	222 μF
Output Voltage (X)	25V
Load Resistance (R)	12.5Ω

4.4 Results:

(i) Time Domain waveforms of Boost Converter:



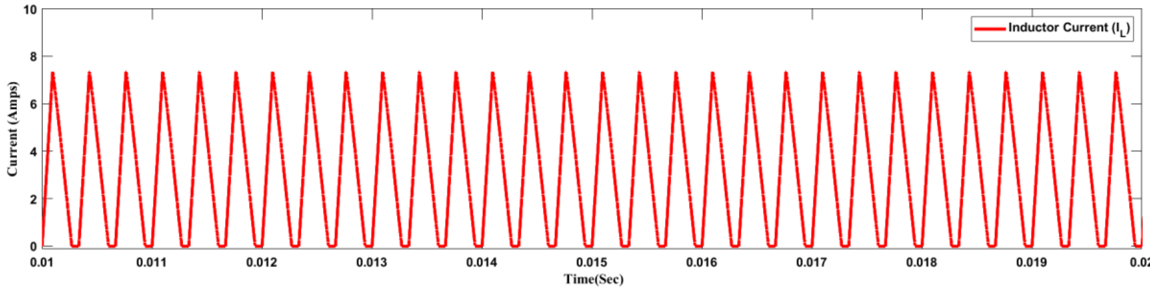
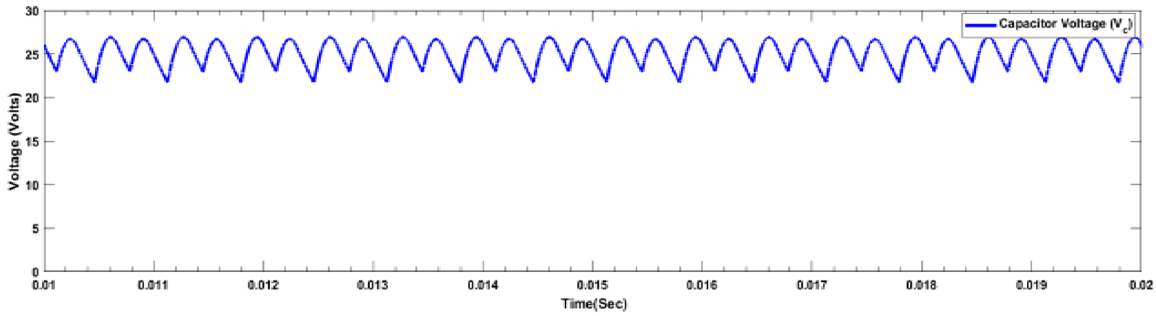


Fig.4.5 - Fundamental waveforms of V_c and I_L at 5ms interval from the simulation at k=0.13



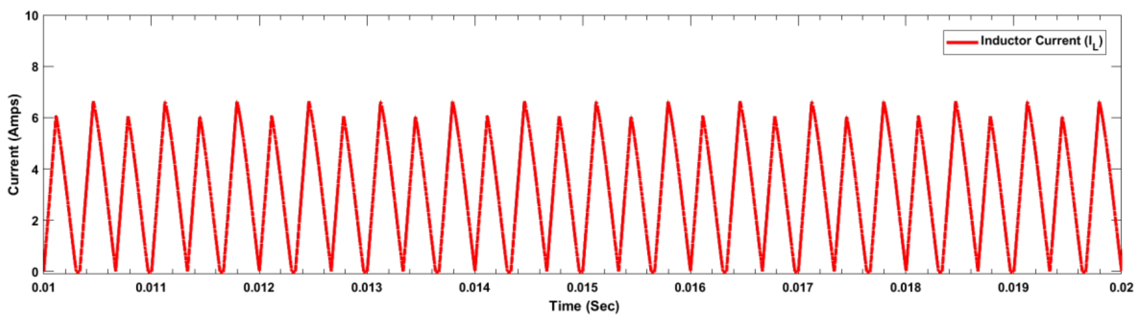
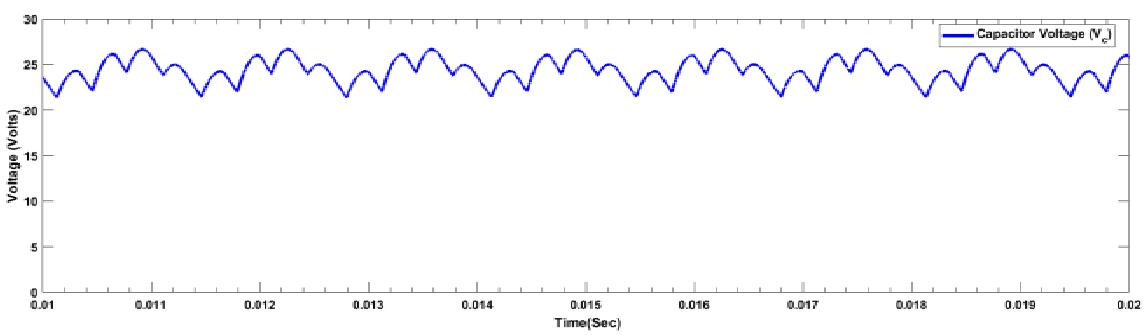


Fig.4.6 - Period-II waveforms of Vc and I_L at 5ms interval from the simulation at k=0.2



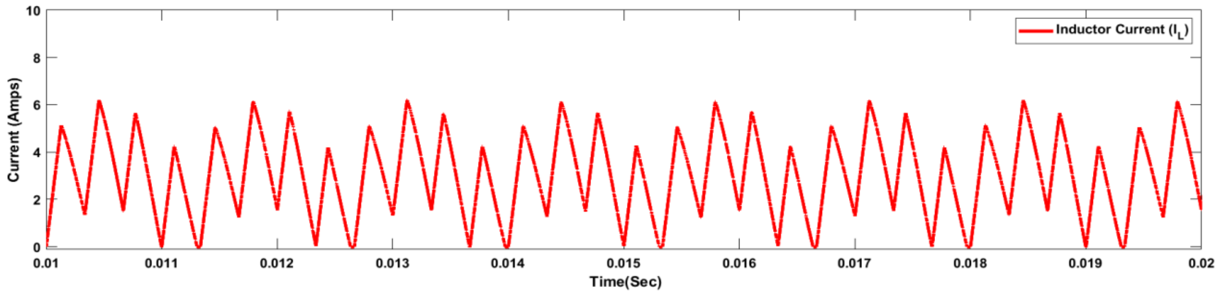


Fig.4.7 period-IV waveforms of V_c and I_L at 5ms interval from the simulation at k=0.4

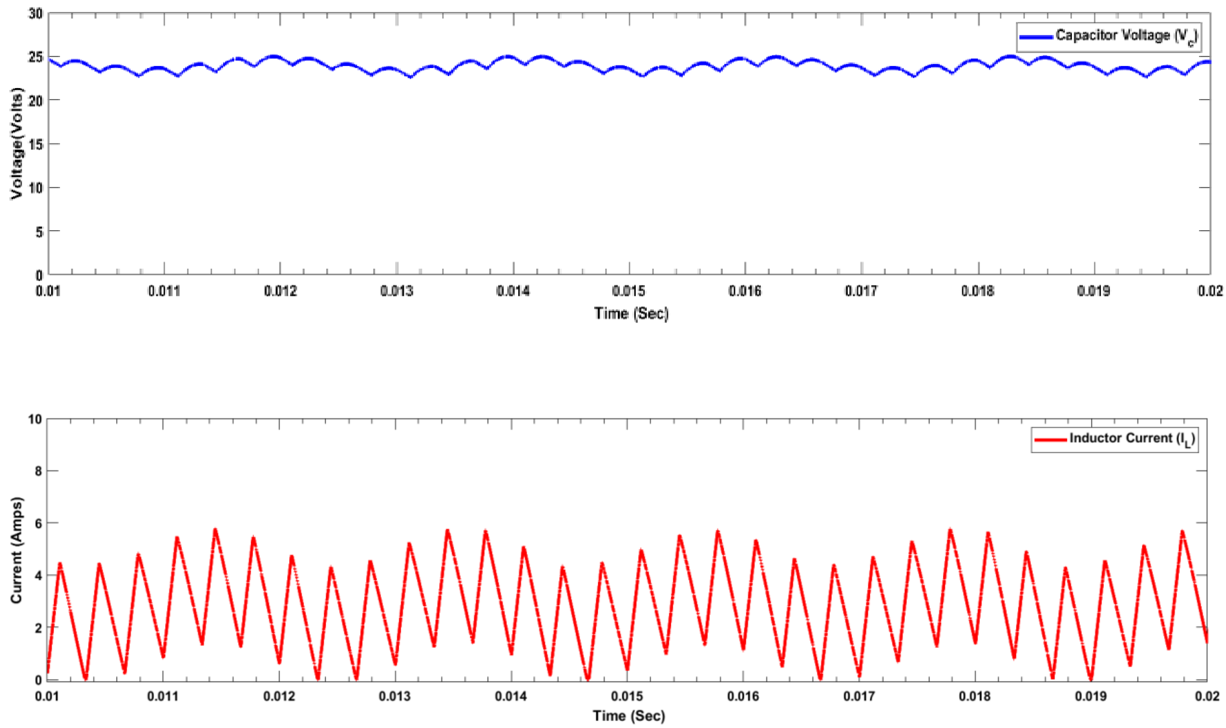


Fig.4.8- Waveforms of V_c and I_L at 5 ms intervals chaos sampled at k=0.45

Time domain waveforms can be used to confirm the bifurcation diagram. Here, the voltage waveform of the capacitor and the current waveform of the inductor have been recorded. The system shown in fig.4 operates in stable mode when the voltage and current waveforms of capacitor and the inductor have been replicate or mirror each other for every one time period. Moreover, fig.5 shows that the system contains period-doubling bifurcations of the voltage waveform of the capacitor and the current waveform of the inductor duplicates themselves for every two time periods. Figure 6 show that the voltage and current waveforms of capacitor and the inductor time domain waveforms, which are similar in that they repeat for every four cycles. Hence, the system has four bifurcations in total. And finally in Fig. 7, the system has no repeating cycles, indicating that chaos has taken over. The bifurcation diagram's phase portraits are covered in more detail in the next section.

(ii) Phase Portrait Diagrams of Boost Converter:

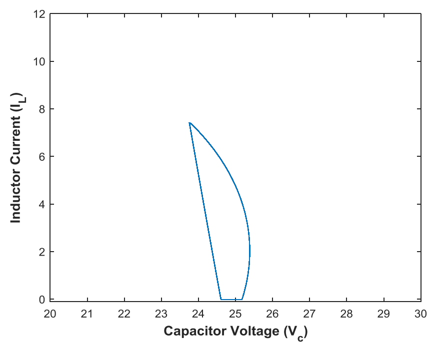


Fig .4.9- Diagram of Phase Portrait for Vc and I_L at stable 1 period (1T)

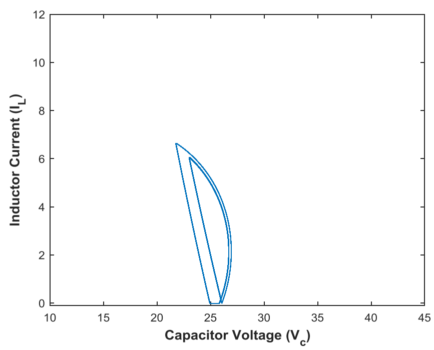


Fig .4.10- Diagram of Phase portrait for V_c and I_L at period 2 (2T)

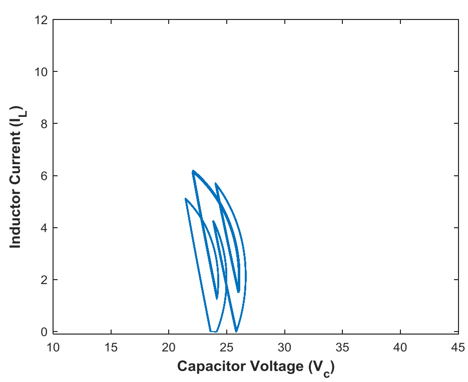


Fig .4.11- Diagram of Phase portrait for V_c and I_L at period 4 (4T)

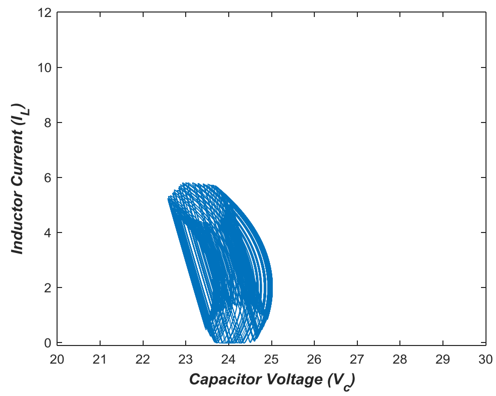


Fig.4.12- Diagram of Phase portrait for V_c and I_L at chaos

Phase portrait diagrams of the Capacitor's voltage (V_c) Vs Inductor's current (I_L) at various system stages (period-I, period-II (2T), period-IV (4T) and chaotic) are shown in Figures 8, 9, 10, and 11.

CHAPTER V

Chaotic Behavior of SEPIC Converter

The SEPIC (Single-Ended Primary Inductor Converter) converter is a type of DC-DC converter that can exhibit chaotic behavior under certain conditions. Chaotic behavior in the SEPIC converter refers to the occurrence of irregular and unpredictable dynamics in its operation, characterized by aperiodic and sensitive dependence on initial conditions and parameter values, it consists of nonlinear components such as inductors, capacitors, and switches. The nonlinear characteristics of these components, coupled with the switching action of the converter, can give rise to complex and chaotic dynamics.

The SEPIC converter can undergo bifurcations as the control parameters are varied. Bifurcations are points in the parameter space where the system's behavior changes qualitatively, leading to the onset of chaotic dynamics. Bifurcations can occur due to period doubling, fold bifurcations, or other nonlinear phenomena. Understanding and analyzing chaotic behavior in a SEPIC converter is important for system design, control, and stability techniques such as numerical simulations, bifurcation analysis, and Lyapunov exponent calculations to detect and analyze chaotic behavior in the converter. By studying the chaotic dynamics, we can design appropriate control strategies, parameter ranges, and stability measures to mitigate or avoid chaotic behavior and ensure reliable and predictable operation of the SEPIC converter.

5.1 Operating Principle and Control Strategy:

The SEPIC Converter is a type of DC-DC converter that allows both step-up and step-down voltage conversion. It is commonly used in power electronics applications where the input voltage may vary or needs to be regulated. The basic operation of a SEPIC converter involves the use of two inductors (L_1 and L_2), two capacitors (C_1 and C_2), and a switch (typically a MOSFET or a diode). The converter topology allows for the isolation of the input and output. When the switch is closed, current flows through inductor L_1 storing energy in its magnetic field. At the same time, capacitor C_1 charges building up voltage across it. When the switch opens, the energy stored in the inductor's magnetic field seeks a path to discharge. The diode connected in parallel with inductor L_1 allows the current to circulate. The energy from the inductor is transferred to capacitor C_2 and the load.

Average current mode control is a control method where the average inductor current is sensed and used as a feedback signal to regulate the converter's operation. At the start of each cycle, the switch S is activated (turned on). The current through the switch gradually increases until it reaches the specified reference current value (i_{ref}). Once the reference current is reached, the switch S is deactivated (turned off) and remains in the off state until the beginning of the next cycle.

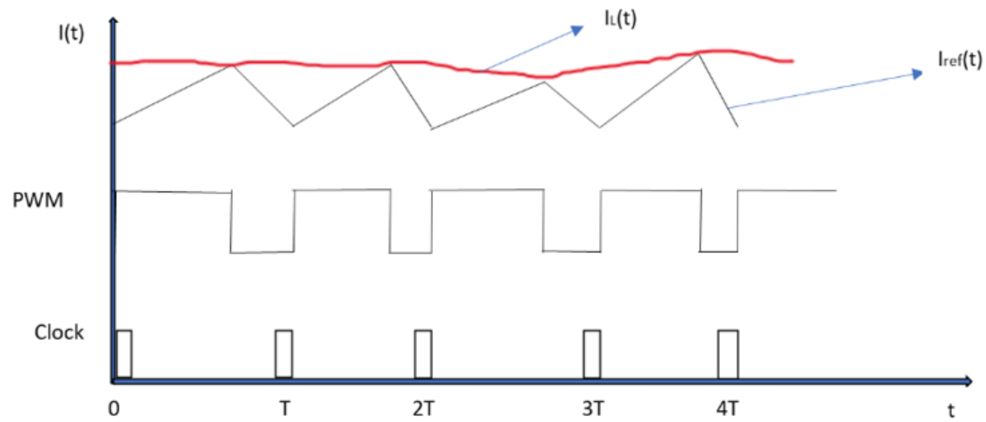


Fig.5.1- Current Mode Control Technique

5.2 Mathematical Analysis of SEPIC Converter by Using Discrete Iterative Mapping

The mathematical analysis of a SEPIC (Single-Ended Primary Inductor Converter) converter can be performed using discrete iterative mapping. This approach allows us to analyze the converter's behavior in discrete time steps, making it suitable for simulation and analysis purposes. Begin by writing down the circuit equations that describe the SEPIC converter, including the voltage and current relationships for the inductors, capacitors, and switches. Convert the continuous-time circuit equations into discrete-time equations by approximating derivatives as differences between consecutive time steps. This involves replacing differential equations with iterative update equations. Express the state variables (such as inductor currents and capacitor voltages) at time step [n+1] in terms of their values at time step [n] and other relevant parameters. This iterative mapping defines how the state variables evolve from one time step to the next. Start with initial conditions for the state variables and iteratively update their values using the iterative mapping equation. Repeat this process for multiple time steps to simulate the converter's behavior over time.

Examine the time-domain waveforms of the state variables and observe the converter's transient response, steady-state operation, and other characteristics of interest. Adjust the parameters of the converter, such as duty cycle, inductance, and capacitance, to achieve desired performance metrics. Iterate the analysis process to evaluate different operating conditions and optimize the converter's behavior. Discrete iterative mapping provides a mathematical framework to study the behavior of SEPIC converters in discrete time steps. It allows for simulation, analysis, and optimization of the converter's performance. By iteratively updating the state variables based on the mapping equation, you can gain insights into the converter's dynamics and make informed design decisions.

The SEPIC converter's state space equations can be stated as follows:

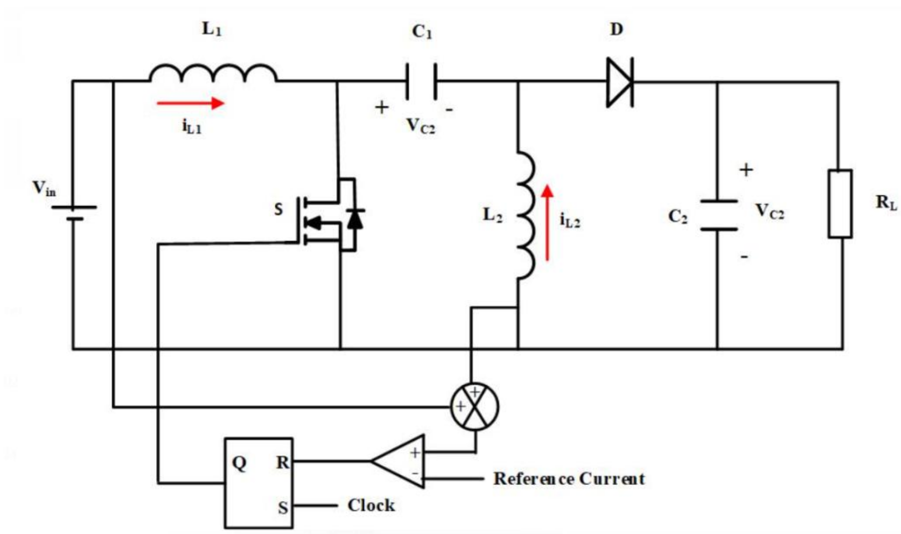


Fig. 5.2 - Block Diagram of DC-DC SEPIC Converter

$$\dot{x} = A_1 x + B_1 E \qquad \text{for} \qquad t_n \le t < t_n^{'} \tag{1}$$

$$\begin{bmatrix} \frac{dV_{C2}(t)}{dt} \\ \frac{di_{L2}(t)}{dt} \\ \frac{dV_{C1}(t)}{dt} \\ \frac{di_{L1}(t)}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-1}{RC_2} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L_2} & 0 \\ 0 & \frac{-1}{C_1} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{C2} \\ i_{L2} \\ V_{C1} \\ i_{L1} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{L_1} \end{bmatrix} V_{in}$$

$$\dot{x} = A_2 x + B_2 E \qquad \text{for} \qquad t_n^{'} \le t < t_{n+1} \tag{2}$$

$$\begin{bmatrix} \frac{dV_{C2}(t)}{dt} \\ \frac{di_{L2}(t)}{dt} \\ \frac{dV_{C1}(t)}{dt} \\ \frac{di_{L1}(t)}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-1}{RC_2} & \frac{1}{C_2} & 0 & \frac{1}{C_2} \\ \frac{-1}{L_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{C_1} \\ \frac{-1}{L_1} & 0 & \frac{-1}{L_1} & 0 \end{bmatrix} \begin{bmatrix} V_{C2} \\ i_{L2} \\ V_{C1} \\ i_{L1} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{L_1} \end{bmatrix} V_{in}$$

In above equation, 'X' represents the state vector of the system. It typically consists of various state variables that describe the system's behavior A_1 and A_2 is a square matrix representing the system's state transition matrix, which defines how the state variables change over time. B_1 and B_2 is a matrix that relates the system's input vector V_{in} to the state variables.

In a SEPIC converter, there are typically two capacitors (C_1 and C_2), two inductors (L_1 and L_2), and a switch (usually a MOSFET or a diode). The input voltage is denoted as V_{in}, and the output voltage is denoted as V_{out}.

The main objective is to create an iterative function that relates the state variables at a specific sampling instant to their values at a previous sampling instant. This discrete-time model allows for accurate analysis of system stability. Different methods, such as stroboscopic map, S-switching map or A-switching map, can be employed to develop the discrete-time model. In this study, a stroboscopic map [58] is utilized to derive the discrete-time model for the SEPIC converter. The stroboscopic map involves uniformly sampling the system's state at the switching frequency. This approach provides a comprehensive understanding of how the SEPIC converter behaves in discrete time.

The stroboscopic map [59] can be generated by if A_i (i=1, 2), the system matrix of the converter, is invertible.

$$x_{n+1} = \Phi_2(T - t_n)(\Phi_1(t_n)x_n + \Psi_1(t_n)) + \Psi_1(T - t_n) \quad (3)$$

Where,

$$\Psi_1(\xi) = A_i^{-1}(\Phi_i(\xi)t_n - I)B_i \quad (4)$$

When the system matrix A_i (i=1, 2) of the converter is not invertible, the stroboscopic map can be expressed as follows:

$$x_{n+1} = \Phi_2(T - d_nT)\Phi_1(d_nT)x_n + \int_{nT}^{nT+d_nT} \Phi_1(nT - \tau)B_1V_{in}d\tau + \Phi_2(T - d_nT)\int_{nT+d_nT}^{(n+1)T} \Phi_2(nT + d_nT - \tau)B_2V_{in}d\tau \quad (5)$$

Where, the transition matrix $\Phi_i(\xi)$ in equations (3), (4) and (5) corresponds to the system matrix A_i and is expressed by,

$$\Phi_i(\xi) = 1 + \sum_{m=1}^{\infty} \frac{1}{m!} A_i^m \xi^m \quad , \qquad \text{for m=1, 2….} \quad (6)$$

The discrete iterative mapping equations for the SEPIC Converter can be expressed as follows:

$$V_{C1}(n+1) = V_{C1}(n) + T_S * \frac{1}{C_1} * (i_{L1}(n+1) - i_{L2}(n+1)) \quad (7)$$

$$i_{L1}(n+1) = i_{L1}(n) + T_S * (\frac{1}{L_1}) * (V_{in} - V_{C1}(n+1)) - T_S * (\frac{1}{L_1}) * (1 - D) * (V_{C1}(n+1) - V_O) \quad (8)$$

$$V_{C2}(n+1) = V_{C2}(n) + T_S * (\frac{1}{C_2}) * (i_{L2}(n+1)) \quad (9)$$

$$i_{L2}(n+1) = i_{L2}(n) + T_S * (\frac{1}{L_1}) * (V_{C1}(n+1) - V_O) - T_S * (\frac{1}{L_2}) * (1 - D) * (V_{C2}(n+1) - V_O) \quad (10)$$

The system matrix of the SEPIC converter is invertible has been taken into account. Therefore, using a truncated series for $\Phi_i(\xi)$, the mapping could be determined based on equation (1). The mapping f_x obtained has the following format:

$$\begin{bmatrix} v_{C1(n+1)} \\ i_{L1(n+1)} \\ v_{C2(n+1)} \\ i_{L2(n+1)} \end{bmatrix} = \begin{bmatrix} f_{11} & f_{12} & f_{13} & f_{14} \\ f_{21} & f_{22} & f_{23} & f_{24} \\ f_{31} & f_{32} & f_{33} & f_{34} \\ f_{41} & f_{42} & f_{33} & f_{44} \end{bmatrix} \begin{bmatrix} v_{C2n} \\ i_{L2n} \\ v_{C1n} \\ i_{L2n} \end{bmatrix} + \begin{bmatrix} g_{11} \\ g_{21} \\ g_{31} \\ g_{41} \end{bmatrix} V_{in} \tag{11}$$

To find the Jacobian matrix, we differentiate above equations (7), (8), (9) and (10) with respect to the state variables:

$$f_{11} = 1 \tag{12}$$

$$f_{12} = T_s * \frac{1}{C_1} \tag{13}$$

$$f_{13} = 0 \tag{14}$$

$$f_{14} = -T_s * \frac{1}{C_1} \tag{15}$$

$$f_{21} = -T_S * (\frac{1}{L_1}) \tag{16}$$

$$f_{22} = 1 + T_S * (\frac{1}{L_1}) * (1 - D) \tag{17}$$

$$f_{23} = 0 \tag{18}$$

$$f_{24} = 0 \tag{19}$$

$$f_{31} = 0 \tag{20}$$

$$f_{32} = 0 \tag{21}$$

$$f_{33} = 1 \tag{22}$$

$$f_{34} = T_S * (\frac{1}{C_2}) \tag{23}$$

$$f_{41} = T_S * (\frac{1}{L_2}) \tag{24}$$

$$f_{42} = -T_S * (\frac{1}{L_2}) * (1 - D) \tag{25}$$

$$f_{43} = -T_S * (\frac{1}{L_2}) \tag{26}$$

$$f_{44} = 1 + T_S * (\frac{1}{L_2}) * (1 - D) \tag{27}$$

5.3 Stability Analysis:

To analyze the stability of the SEPIC converter, we utilize the Jacobian matrix derived from the discrete-time model. The Jacobian matrix is obtained by taking the derivatives of the mapping equations, as described in equation (9), with respect to the state variables. The stability of the converter is determined by examining the characteristic multipliers, which correspond to the eigen values of the Jacobian matrix Df_x. For the converter to be stable, it is necessary for the magnitude of all characteristic multipliers to be less than one. During the simulation, the specific component values mentioned in the appendix are utilized.

The Jacobian matrix is derived by differentiating the discrete iterative mapping equations, as expressed in the following equation.

$$Df_x = \frac{\partial f_x}{\partial x_n} + \frac{\partial f_x}{\partial t_n} \cdot \frac{\partial t_n}{\partial x_n} \tag{28}$$

By applying the implicit function theorem, the equation mentioned above can be transformed or expressed in the following form.

$$Df_x = \frac{\partial f_x}{\partial x_n} - \frac{\partial f_x}{\partial t_n} \left(\frac{\partial \sigma}{\partial t_n} \right)^{-1} \frac{\partial \sigma}{\partial x_n} \tag{29}$$

The given equation defines the switching function (σ), which is utilized to determine the operation of the circuit.

$$\sigma(x_n, t_n, i_{ref}) = i_{ref} - k\left(\Phi_1(t_n)x_n + \psi_1(t_n)\right) \tag{30}$$

From the circuit diagram,

$$i_{ref} - (i_{L1} + i_{L2}) = \left(\frac{V_{in}}{L_1} + \frac{V_{C1}}{L_2}\right)DT \tag{31}$$

The duty ratio can be obtained by solving the above equation.

$$D = \frac{i_{ref} - (i_{L1} + i_{L2})}{\left(\frac{V_{in}}{L_1} + \frac{V_{C1}}{L_2}\right)T} \tag{32}$$

5.4 Bifurcation Diagram of SEPIC Converter:

When system parameters are changed, the behavior of the inductor current and load resistance can be plotted to create the bifurcation diagram of a SEPIC converter. The diagram displays the steady-state values or periodic orbits of various variables as a function of a control parameter. The resulting bifurcation diagram provides insight into the dynamic behavior of the SEPIC converter and demonstrates the existence of steady-state values, periodic orbits or any other interesting phenomena that appear as the control parameter evolves.

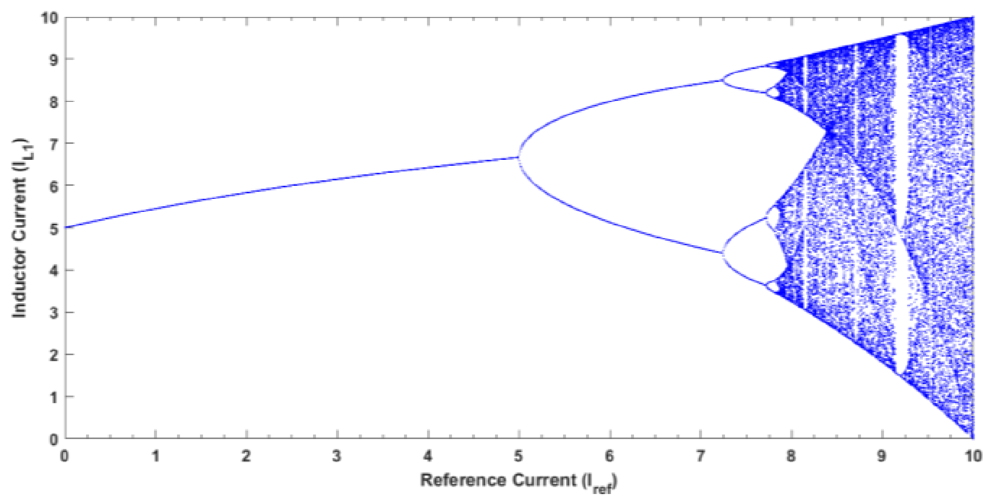


Fig. 5.3- Bifurcation Diagram with respect to Reference Current (I_{ref})

Table 5.1 - Simulation Parameters of SEPIC Converter

Switching Time Period (T_s)	2 μ sec
Inductance (L_1)	17.8 μ H
Input Voltage (E)	24V
Capacitance (C_1)	0.4 μ F
Load Resistance (R)	10 Ω
Inductance (L_2)	37 μ H
Capacitance (C_2)	47 μ F

5.5 Results:

(i) Time Domain waveforms of SEPIC Converter:

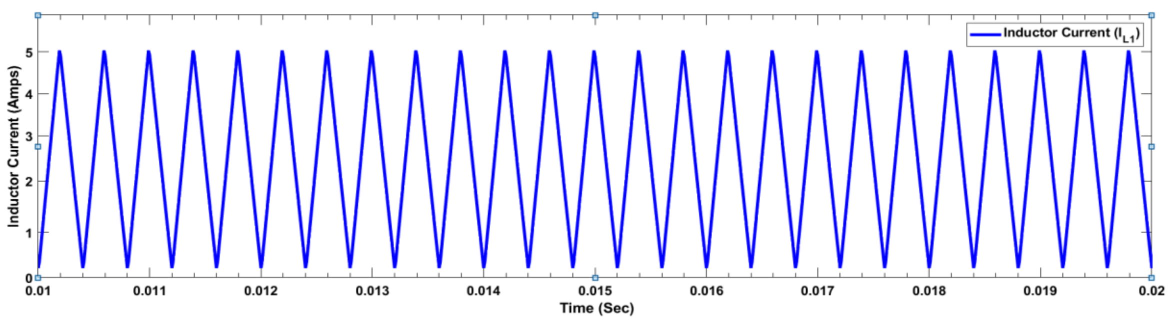


Fig.5.4-Fundamental waveforms (1T) of I_{L1} from the simulation at I_{ref}=5Amps

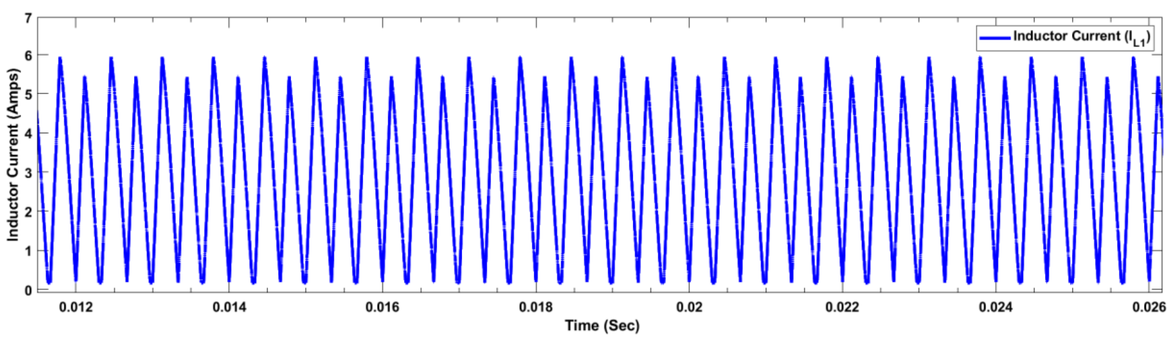


Fig.5.5-Two-Period waveform (2T) of I_{L1} from the simulation at I_{ref}=6Amps

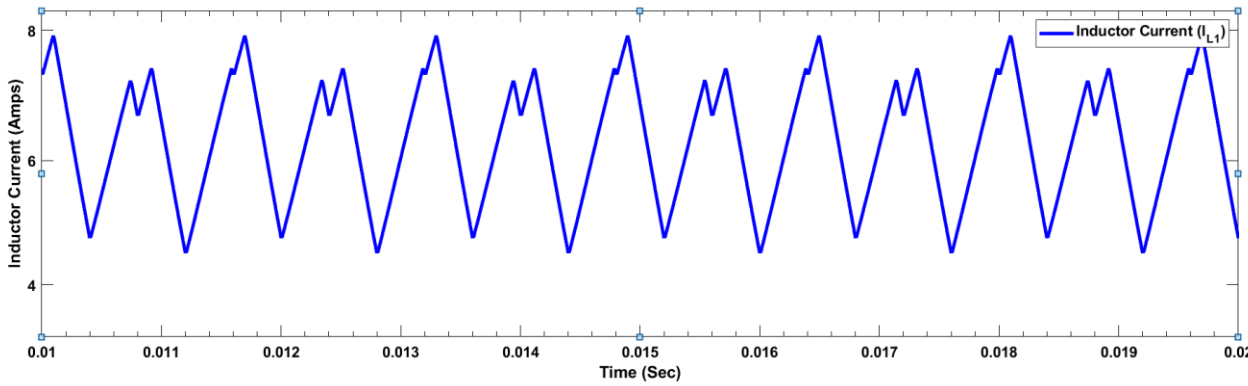


Fig.5.6-.Four-Period waveform (4T) of I_{L1} from the simulation at I_{ref}=7Amps

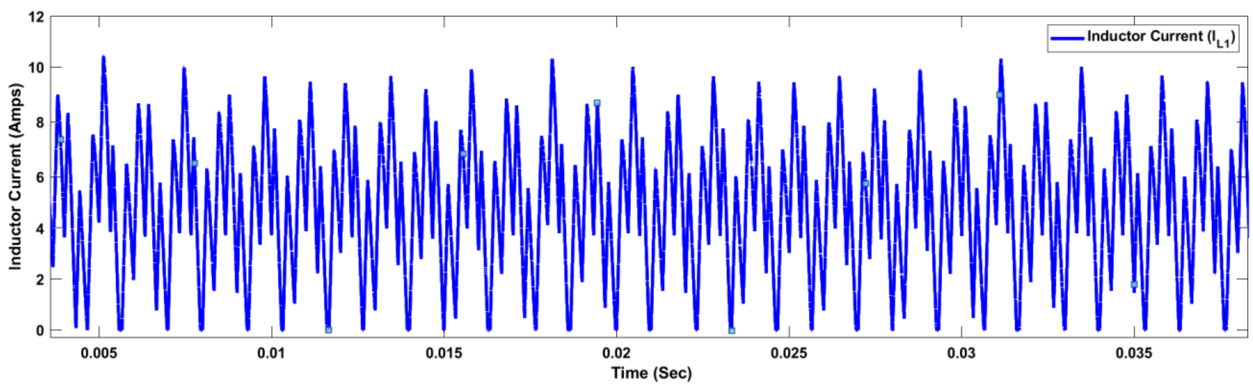


Fig.5.7-Chaotic waveform of I_{L1} from the simulation at I_{ref}=8Amps

Time domain waveforms can be used to confirm the bifurcation diagram. Here, the current waveform of the inductor has been recorded. The system shown in fig.4 operates in stable mode when the current waveform of inductor has been replicate or mirrors each other for every one time period. Moreover, fig.5 shows that the system contains period-doubling bifurcations of the current waveform of the inductor duplicates themselves for every two time periods. Figure 6 show that the current waveforms of inductor time domain waveforms, which are similar in that they repeat for every four cycles. Hence, the system has four bifurcations in total. And finally in Fig. 7, the system has no repeating cycles, indicating that chaos has taken over. The bifurcation diagram's phase portraits are covered in more detail in the next section.

(ii) Phase Portrait Diagrams of SEPIC Converter:

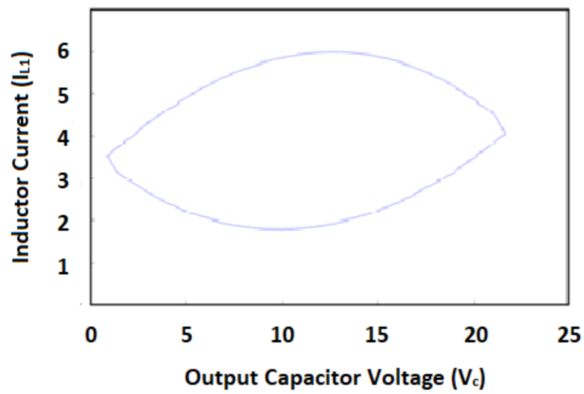


Fig .5.8- Diagram of Phase Portrait for Vc and I_{L1} at stable 1 period (1T)

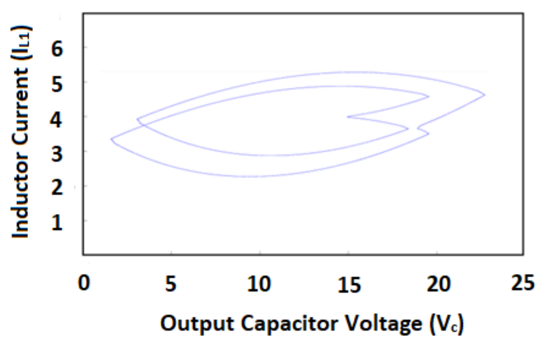


Fig .5.9- Diagram of Phase portrait for V_c and I_{L1} at period 2 (2T)

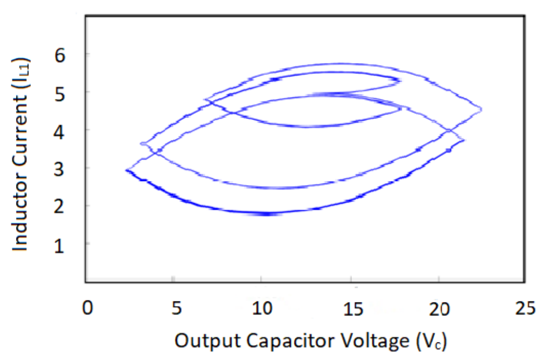


Fig .5.10- Diagram of Phase portrait for V_c and I_{L1} at period 4 (4T)

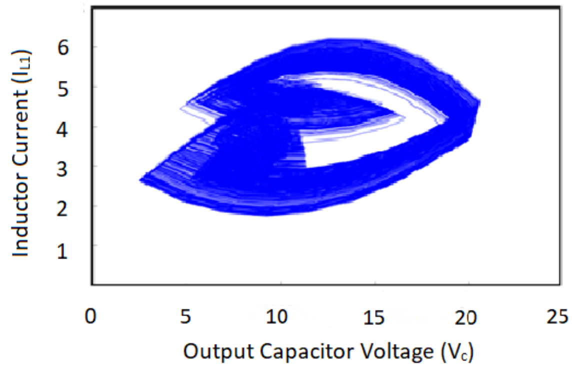


Fig .5.11- Diagram of Phase portrait for V_c and I_{L1} at chaos

Phase portrait diagrams of the Capacitor's voltage (V_c) Vs Inductor's current (I_L) at various system stages (period-I, period-II (2T), period-IV (4T) and chaotic) are shown in Figures 8, 9, 10, and 11.

CONCLUSION

This study focuses on the nonlinear analytic approach based on discrete iterative mapping for the stability analysis and control of DC-DC converters. The generated matrix includes circuit characteristics and control coefficients, allowing system performance to be evaluated with a range of input and output parameters. Advanced control strategies are suggested to improve stability performance in DC-DC converters together with specific derivations of the Discrete Iterative Mapping. A wider variety of converters, such as interleaved or multiphase converters, can be converted using the techniques mentioned. A novel method of combining digital controllers with the suggested control system is also shown. The size of DC-DC converter inductors is also reduced with the help of the discrete iterative mapping. Simulators and experimental data are used to illustrate the theoretical analysis and effectiveness of the suggested methodologies.

This study provides information on the chaotic behavior of Boost and SEPIC Converters. The analysis includes the examination of phase portraits, time-domain waveforms and bifurcation diagrams. Bifurcation analysis proves to be a robust method for understanding chaos in the system. The next voltage and current state is predicted using the discrete iterative mapping and analysis is done using numerical methods. A closed-loop converter with a voltage control loop and current control loop is subjected to input voltage and feedback gain variations and the resulting bifurcation diagram shows the behavior across various time periods, phase portrait and including chaos. The accuracy of the bifurcation diagram is verified by comparing it with time-domain waveforms and phase portraits. The results provide valuable information on the boundary conditions and the maximum operating point.

FUTURE SCOPE

The work presented in this thesis opens up potential areas for future research. Building upon the methods provided, nonlinear analysis can be extended to encompass other types of non-isolated or isolated converters with higher orders. For instance, exploring the creation of the Discrete Iterative Mapping matrix while considering transformer nonlinearities would be an interesting avenue of investigation. Additionally, the application of the proposed methods to develop new control techniques based on emerging control regulations warrants further exploration. Investigating the relationship between switching conditions and different control algorithms, along with their corresponding modifications in the Discrete Iterative Mapping matrix is another potential research direction.

In terms of practical implementation, enhancing the existing platform to incorporate additional features and expand its universality for testing different types of converters at varying power ratings can be pursued. Lastly, constructing a representation of system stability that provides detailed information about all system parameters and external conditions can greatly assist in product design and development.

REFERENCES

[1] G. Poddar, K. Chakrabarty and S. Banerjee, "Experimental control of chaotic behavior of buck converter," in IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, vol. 42, no. 8, pp. 502-504, Aug. 1995, doi: 10.1109/81.404067.

[2] L. Premalatha and P. Vanajaranjan, "Spectral Analysis of DC-DC Buck Converter with Chaotic Dynamics," 2005 Annual IEEE India Conference - Indicon, Chennai, India, 2005, pp. 605-608, doi: 10.1109/INDCON.2005.1590243.

[3] V. Kovanis, A. Gavrielides, T. B. Simpson, J. M. Liu and P. H. Alsing, "Chaos, period-doubling and reverse bifurcations in an optically injected semiconductor laser," Proceedings of 1994 Nonlinear Optics: Materials, Fundamentals and Applications, Waikoloa, HI, USA, 1994, pp. 30-32, doi: 10.1109/NLO.1994.470892.

[4] Chung-Chieh Fang and E. H. Abed, "Harmonic balance analysis and control of period doubling bifurcation in buck converters," ISCAS 2001. The 2001 IEEE International Symposium on Circuits and Systems (Cat. No.01CH37196), Sydney, NSW, Australia, 2001, pp. 209-212 vol. 2, doi: 10.1109/ISCAS.2001.921284.

[5] Yue Ma, C. K. Tse, T. Kousaka and H. Kawakami, "Connecting border collision with saddle-node bifurcation in switched dynamical systems," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 52, no. 9, pp. 581-585, Sept. 2005, doi: 10.1109/TCSII.2005.850488.

[6] Yue Ma, C. K. Tse, T. Kousaka and H. Kawakami, "A subtle link in switched dynamical systems: saddle-node bifurcation meets border collision," 2005 IEEE International Symposium on Circuits and Systems (ISCAS), Kobe, Japan, 2005, pp. 6050-6053 Vol. 6, doi: 10.1109/ISCAS.2005.1466019.

[7] Brockeet.R.W. and W. J.R., "Understanding power converter chaotic behaviour mechanisms in protective and abnormal modes," in POWERCON'11, Eleventh Annual International Power Electronics Conference, 1984, pp. E-4 1 to 15.

[8] E. Fossas and G. Olivar, "Study of chaos in the buck converter," Circuits and Systems I: Fundamental Theory and Applications, IEEE Transactions on, vol. 43, pp. 13-25, 1996.

[9] H. Xu and Y. Huang, "Optimal Iterative Learning Control for Nonlinear Discrete-Time Systems," 2010 International Conference on Computing, Control and Industrial Engineering, Wuhan, China, 2010, pp. 190-193, doi: 10.1109/CCIE.2010.56.

[10] K. Chakrabarty, G. Poddar and S. Banerjee, "Bifurcation behavior of the buck converter," in IEEE Transactions on Power Electronics, vol. 11, no. 3, pp. 439-447, May 1996, doi: 10.1109/63.491637.

[11] G. Olivar, M. di Bernardo and F. Angulo, "Discontinuous bifurcations in DC-DC converters," IEEE International Conference on Industrial Technology, 2003, Maribor, Slovenia, 2003, pp. 842-845 Vol.2, doi: 10.1109/ICIT.2003.1290768.

[12] I. Flegar, D. Pelin and D. Zazeck, "Bifurcation diagrams of the buck converter," 9th International Conference on Electronics, Circuits and Systems, Dubrovnik, Croatia, 2002, pp. 975-978 vol.3, doi: 10.1109/ICECS.2002.1046412.

[13] Chung-Chieh Fang and E. H. Abed, "Harmonic balance analysis and control of period doubling bifurcation in buck converters," ISCAS 2001. The 2001 IEEE International Symposium on Circuits and Systems (Cat. No.01CH37196), Sydney, NSW, Australia, 2001, pp. 209-212 vol. 2, doi: 10.1109/ISCAS.2001.921284.

[14] A. Kavitha and G. Uma, "Bifurcation Analysis of DC-DC Converters using Discrete Time Model," 2008 Joint International Conference on Power System Technology and IEEE Power India Conference, New Delhi, India, 2008, pp. 1-7, doi: 10.1109/ICPST.2008.4745342.

[15] S. Iqbal, X. Zang, Y. Zhu and J. Zhao, "Study of bifurcation and chaos in DC-DC boost converter using discrete-time map," 2014 International Conference on Mechatronics and Control (ICMC), Jinzhou, China, 2014, pp. 1813-1817, doi: 10.1109/ICMC.2014.7231874.

[16] S. Banerjee and K. Chakrabarty, "Nonlinear modeling and bifurcations in the boost converter," in IEEE Transactions on Power Electronics, vol. 13, no. 2, pp. 252-260, March 1998, doi: 10.1109/63.662832.

[17] W. Siu Chung, W. Xiaoqun, and C. K. Tse, "Sustained Slow-Scale Oscillation in Higher Order CurrentMode Controlled Converter," Circuits and Systems II: Express Briefs, IEEE Transactions on, vol. 55, pp. 489-493, 2008.

[18] X. Fan, Z. Bo, Q. Dongyuan, Y. Ru, and H. H. C. Iu, "Complex bifurcation and torus breakdown in higher order converters with an inductive impedance load," in Industrial Electronics Society, IECON 2013 - 39th Annual Conference of the IEEE, pp. 8362-8366, 2013.

[19] P. Deivasundari, G. Uma, and S. Ashita, "Chaotic dynamics of a zero average dynamics controlled DC-DC Cuk converter," Power Electronics, IET, vol. 7, pp. 289- 298, 2014.

[20] H. Fei-Hu, W. Hen-Kung, C. Po-Lun, S. Ming-Hong, and Y. Ying-Kuei, "Study of nonlinear phenomena and chaotic control in current-programmed forward converters," in Industrial Technology, 2009. ICIT 2009. IEEE International Conference on, pp. 1-6. 2009.

[21] L. Premalatha and G. M. Sneha, "Experimental analysis of power density spectrums in a forward converter with nonlinear dynamics," in Advances in Engineering, Science and Management (ICAESM), 2012 International Conference on, 2012,pp. 553-557.

[22] H. H. C. Iu, C. K. Tse, V. Pjevalica, and Y. M. Lai, "Analysis of Hopf bifurcation in parallel-connected boost converters via averaged models," 2002 Ieee International Symposium on Circuits and Systems, Vol V, Proceedings, pp. 305-308, 2002.

[23] H. H. C. Lu and C. K. Tse, "Study of low-frequency bifurcation phenomena of a parallel-connected boost converter system via simple averaged models," IEEE

Transactions on Circuits and Systems IFundamental Theory and Applications, vol. 50, pp. 679-686, May 2003.
[24] P. T. Krein, J. Bentsman, R. M. Bass, and B. C. Lesieutre, "On the Use of Averaging for the Analysis of Power Electronic Systems," Pesc 89 Record, Vols 1 and 2, pp. 463- 467, 1989.
[25] C. Jingquan, R. Erickson, and D. Maksimovic, "Averaged switch modeling of boundary conduction mode DC-to-DC converters," in Industrial Electronics Society, 2001. IECON '01. The 27th Annual Conference of the IEEE, 2001, pp. 844-849 vol.2.
[26] B. Lehman and R. M. Bass, "Switching frequency dependent averaged models for PWM DC-DC converters," Power Electronics, IEEE Transactions on, vol. 11, pp. 89- 98, 1996.
[27] V. A. Caliskan, G. C. Verghese, and A. M. Stankovic, "Multifrequency averaging of DC/DC converters," IEEE Transactions on Power Electronics, vol. 14, pp. 124-133, Jan 1999.
[28] A. Kumar and S. K. Valluru, "Bifurcation Analysis of Current-mode controlled CUK converter," 2022 2nd Asian Conference on Innovation in Technology (ASIANCON), Ravet, India, 2022, pp. 1-5, doi: 10.1109/ASIANCON55314.2022.9909370.
[29] P. Fei and A. M. Cramer, "Reduced-order multifrequency averaging in naturally sampled PWM converters," in Energy Conversion Congress and Exposition (ECCE), 2014 IEEE, 2014, pp. 3010-3015.
[30] Y. Gao, Y. Wang, J. Huang, M. Li, and X. Yang, "Modeling of single-HB PWM modulated dual active bridge DC-DC converter with multifrequency average approach," in Energy Conversion Congress and Exposition (ECCE), 2014 IEEE, 2014, pp. 2588-2593.
[31] S. R. Sanders, J. M. Noworolski, X. Z. Liu, and G. C. Verghese, "Generalized averaging method for power conversion circuits," Power Electronics, IEEE Transactions on, vol. 6, pp. 251-259, 1991.
[32] M. di Bernardo and F. Vasca, "Discrete-time maps for the analysis of bifurcations and chaos in DC/DC converters," IEEE Transactions on Circuits and Systems I-Regular Papers, vol. 47, pp. 130- 143, Feb 2000.
[33] Y. Sun, A. P. Hu, X. Dai, and Y. G. Su, "Discrete time mapping modeling and bifurcation phenomenon study of a ZVS converter," 2004 International Conference on Power System Technology - POWERCON, Vols 1 and 2, 2004, pp. 1015-1018.
[34] Z. Suto, E. Masada, and I. Nagy, "Discontinuous iterated map model of bifurcation phenomena in DTC drives," in Electrical Machines and Systems, 2009. ICEMS 2009. International Conference on, 2009, pp. 1-6.
[35] S. Jian and R. M. Bass, "A new approach to averaged modeling of PWM converters with currentmode control," in Industrial Electronics, Control and Instrumentation, 1997. IECON 97. 23rd International Conference on, 1997, pp. 599-604 vol.2.

[36] M. di Bernardo and F. Vasca, "Discrete-time maps for the analysis of bifurcations and chaos in DC/DC converters," IEEE Transactions on Circuits and Systems I-Regular Papers, vol. 47, pp. 130- 143, Feb 2000.
[37] Y. Sun, A. P. Hu, X. Dai, and Y. G. Su, "Discrete time mapping modeling and bifurcation phenomenon study of a ZVS converter," 2004 International Conference on Power System Technology - POWERCON, Vols 1 and 2, 2004, pp. 1015-1018.
[38] D. Giaouris, S. Banerjee, O. Imrayed, K. Mandal, B. Zahawi, and V. Pickert, "Complex Interaction Between Tori and Onset of Three-Frequency Quasi-Periodicity in a Current Mode Controlled Boost Converter," IEEE Transactions on Circuits and Systems I-Regular Papers, vol. 59, pp. 207-214, Jan 2012.
[39] D. Giaouris, A. Elbkosh, S. Banerjee, B. Zahawi, and V. Pickert, "Control of switching circuits using complete-cycle solution matrices," 2006 IEEE International Conference on Industrial Technology, Vols 1-6, 2006, pp. 2935-2940.
[40] D. Giaouris, S. Banerjee, B. Zahawi, and V. Pickert, "Stability Analysis of the ContinuousConduction-Mode Buck Converter Via Filippov's Method," Circuits and Systems I: Regular Papers, IEEE Transactions on, vol. 55, pp. 1084-1096, 2008.
[41] O. Imrayed, B. Zahawi, D. Giaouris, and V. Pickert, "Reduced Inductance in DC-DC Converter Circuits via the Application of Filippov's Method," in IUTAM Symposium on Nonlinear Dynamics for Advanced Technologies and Engineering Design, 2013, pp. 295-311.
[42] K. Pyragas, "Control of Chaos Via Extended Delay Feedback," Physics Letters A, vol. 206, pp. 323- 330, Oct 16 1995.
[43] S. K. Mazumder and K. Acharya, "Multiple Lyapunov Function Based Reaching Condition for Orbital 43 | P a g e Existence of Switching Power Converters," Power Electronics, IEEE Transactions on, vol. 23, pp. 1449-1471, 2008.
[44] M. Spinetti, E. Fossas, and D. Biel, "Stabilitiy analysis of a Lyapunov-based controlled boost converter," Proceedings of the 48th Ieee Conference on Decision and Control, 2009 Held Jointly with the 2009 28th Chinese Control Conference (Cdc/Ccc 2009), pp. 6544-6548, 2009.
[45] T. S. Hu, "A Nonlinear-System Approach to Analysis and Design of Power-Electronic Converters With Saturation and Bilinear Terms," Ieee Transactions on Power Electronics, vol. 26, pp. 399-410, Feb 2011.
[46] B. Grzesik and P. Siewniak, "Lyapunov Stability Analysis of DC-DC Power Electronic Converters: A Brief Overview," Przeglad Elektrotechniczny, vol. 88, pp. 162-166, 2012.
[47] C. Yfoulis, D. Giaouris, S. Voutetakis, and S. Papadopoulou, "Constrained switching stabilization of a dc-dc boost converter using piecewise-linear Lyapunov functions," 2013 21st Mediterranean Conference on Control and Automation (Med), pp. 814-823, Reference 145 2013.
[48] I. A. Hiskens and M. A. Pai, "Trajectory sensitivity analysis of hybrid systems," IEEE Transactions on Circuits and Systems I-Regular Papers, vol. 47, pp. 204-220, Feb 2000.

[49] A. El Aroudi, E. Rodriguez, R. Leyva, and E. Alarcon, "A Design-Oriented Combined Approach for Bifurcation Prediction in Switched-Mode Power Converters," IEEE Transactions on Circuits and Systems Ii-Express Briefs, vol. 57, pp. 218-222, Mar 2010.

[50] J. Reina, Rodri, x, E. guez, E. Alarcon, and A. El Aroudi, "Ripple-based approach for predicting fastscale instability in multi-level converters," in Control and Modeling for Power Electronics (COMPEL), 2010 IEEE 12th Workshop on, 2010, pp. 1-8.

[51] E. Rodriguez, A. El Aroudi, F. Guinjoan, and E. Alarcon, "A Ripple-Based DesignOriented Approach for Predicting Fast-Scale Instability in DC-DC Switching Power Supplies," Ieee Transactions on Circuits and Systems I-Regular Papers, vol. 59, pp. 215-227, Jan 2012.

[52] K. H. Wong, "Output capacitor stability study on a voltage-mode buck regulator using system-poles approach," IEEE Transactions on Circuits and Systems Ii-Express Briefs, vol. 51, pp. 436-441, Aug 2004.

[53] E. Ott, C. Grebogi, and J. A. Yorke, "Controlling chaos," Physical review letters, vol. 64, p. 1196, 1990.

[54] C. Batlle, E. Fossas, and G. Olivar, "Time-delay stabilization of the buck converter," in Control of Oscillations and Chaos, 1997. Proceedings., 1997 1st International Conference, 1997, pp. 590-593 vol.3.

[55] M. A. Hassouneh, L. Hsien-Chiarn, and E. H. Abed, "Washout filters in feedback control: benefits, limitations and extensions," in American Control Conference, 2004. Proceedings of the 2004, 2004, pp. 3950-3955 vol.5.

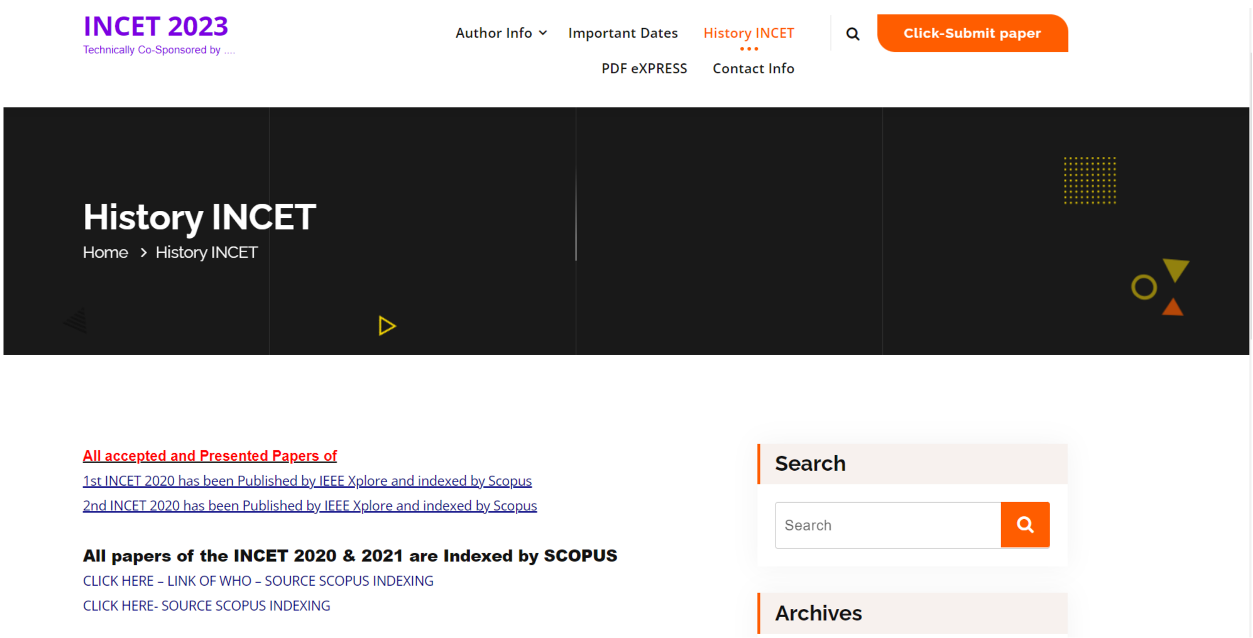
[56] W. G. Lu, L. W. Zhou, and Q. M. Luo, "Notch filter feedback controlled chaos in buck converter," Chinese Physics, vol. 16, pp. 3256-3261, Nov 2007.

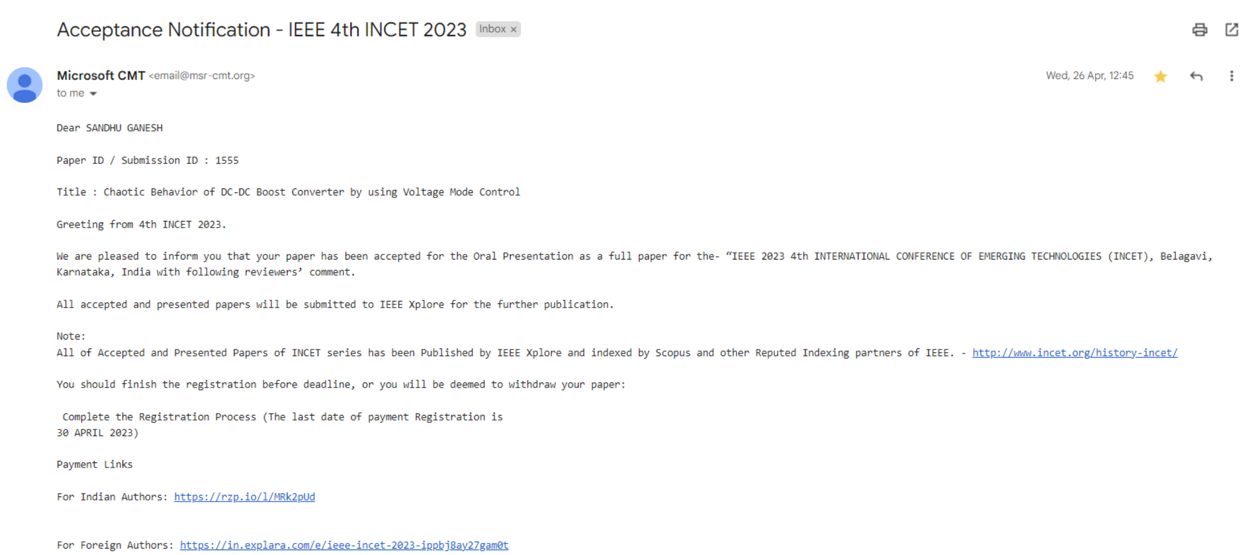
[57] W. G. Lu, L. W. Zhou, Q. M. Luo, and X. F. Zhang, "Filter based non-invasive control of chaos in Buck converter," Physics Letters A, vol. 372, pp. 3217-3222, Apr 28 2008.

PAPER PUBLICATIONS

[1] Sandhu Ganesh, Sudarshan K Valluru "Chaotic Behavior of DC-DC Boost Converter by using Voltage Mode Control ", *IEEE 4th International Conference of Emerging Technologies 2023*, Belgaum, Karnataka, India (26-28 May 2023) **(Presented)**

[2] Sandhu Ganesh, Sudarshan K Valluru "Chaotic Behavior of SEPIC Converter by using Current Mode Control", 2023 *IEEE 3rd ASIAN conference on Innovation in Technology*, Pune, India **(Communicated)**





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