SYNOPSIS OF THE THESIS

Sliding Mode Control for Power Converters with Modified Sliding Function for Improved Performance

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CERTIFICATE

This is to certify that the the synopsis of the thesis titled **Sliding Mode Control for Power Converters with Modified Sliding Function for Improved Performance** submitted by Mr. Brijesh Naik (Enrollment No. 119997117001) is satisfactory. The synopsis is recommended for the final submission and the thesis can be submitted based on it.

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SYNOPSIS

Introduction

The Sliding Mode Control(SMC) technique has its roots in Soviet Union. But it was not well known to the world until Itkis[1] published a book and a research article by Utkin[2] in IEEE Transactions. However, many scientists [3],[4],[5],[6] and [7] in Soviet Union have worked enough for creating the strong background for the evolvement of the SMC technique. The SMC was derived from the relay feedback control technique. The most significant factors of SMC technique are so called Reaching Mode (RM), Sliding Mode (SM) and Steady State Mode (SS). The terms have very specific meanings. Under SMC law the phase trajectory is forced to be directed to the origin of the phase plane via sliding manifold. Starting from the initial condition, the phase trajectory is attracted to the sliding manifold during the RM. Once the phase trajectory hits the manifold it slides towards the origin of the phase plane and it is called SM. Then the phase trajectory *stays* at the origin and steady state is achieved. The whole exercise of designing SMC law requires a fairly good mathematical model of the system. The switching component in SMC law is desired in most of the cases to ensure the phase trajectory doesn't leave the sliding manifold and thus it reaches origin in presence of certain uncertainties in the system.

The SMC provides robustness for matched uncertainties. The SMC technique deals with differential equations with discontinuous right hand side. As the theory of SMC proved to be quite promising its application to the real system was a bit challenging due to the involvement of high frequency switching component and other issues like noise. Implementation of SMC law for real systems are now a days facilitated by high quality electronics systems and variety of programming tools. Of course, the SMC can be applied to a wide class of systems like Linear Time Invariant, Linear Time Variant, Nonlinear and delayed systems, the chattering or high frequency switching is not desirable. But in past few years Higher Order SMC (HOSMC) came in to existence [8],[9],[10] which alleviates chattering.

There is a vast scope of SMC and its applications to electrical systems and chemical processes. Power Electronics being a specific domain in power engineering make use of various control techniques. For many applications Pulse Width Modulation (PWM) based controllers are quite popular. Majority of Power Electronic Converters (PEC) are controlled with PWM based PI or PID controllers. However Utkin [11],[12] proposed SMC for many PEC like Buck, Boost converters and rectifiers in his book in 1999. Since then many researchers have contributed in the field.

The SMC is inherently suitable to PEC because of the switching action is involved in operation. The increasing usage of robotic and other mobile electrical-electronic systems imposed the great demand for stable and well controlled PEC. These type of systems frequently exposed to changes in electrical load, supply side variations and parameter variations. The SMC can be the choice as it can provide robustness against the same. It is not always easy to design a good control systems with classical techniques [13],[14]. However, many tools are available for design and those are some professional software tools [15],[16]. There are many types of analog compensators available named as Type I, II and III in the wide variety of literature.

The modeling and control techniques for PEC are available in the wide variety of literature[12],[13]. Cuk[17] proposed a general unified approach to modeling switching power converters. The control and modeling of various PECs can be also be found in [18] with various control methodologies including linear and non linear control techniques. The important task in many of the PECs is control of the output/load voltage. In [19], a large-signal nonlinear control technique(One Cycle Control) of switching power converters is developed to dynamically control the duty ratio of a switch such that in each cycle the average value of the controlled variable is proportional to the control reference. The technique is good at rejecting source power perturbations. However, the load disturbances are remained to study. The voltage regulation of Pulse Width Modulation(PWM) based DC-DC switching converter is discussed in [20] with the controller designed in frequency domain. It uses the averaged small signal model of the converter. The SMC tightened its grip in the field of Power Electronics after Utkin[12] discussed about wide class of PECs which may be controlled with the SMC technique. Since then SMC is applied to the various PEC and Electromechanical Systems[12],[21]. The fundamentals of SMC can be found in [22]. The SMC has been the choice of many researchers to control the output voltage of PECs. Caceres and Barbi[23] presented design, analysis and experimentation of DC-AC boost converter with SMC. The technique is useful for design of Uninterruptible Power Supply(UPS) and Inverters. The SMC for DC-DC PEC is available in [24] with graphical and analytical explanations. Maity[25] proposed Fixed Frequency Hysteresis Controller(FFHC) that uses both SMC and FFHC with hysteresis band. In [26] and [27] they have described SMC based technique for control of PECs. Hasan[28] suggested the Adaptive Terminal SMC for DC-DC buck converter having non-linear sliding surface with finite time reaching law. But the Region Of Existence(ROE)of sliding modes was not defined. However, the load variation is examined for its effects on load voltage.

Tan [29],[30],[31] proposed a sliding mode control with hybrid modeling for different PEC. The conditions for existence of sliding modes are also derived and the term Region Of Existence (ROE) is coined. It is also identified that the higher values of controller parameters can lead to sustained oscillations especially for PEC with high power applications [32]. Moreover, the conventional SMC for PEC suffers from steady state error in load voltage for a given reference. Also, the ROE is not fixed on the phase plane and in fact varies according to the load disturbances. For that Tan [29] suggested adaptive tuning but it required the measurement of load current. For steady state error elimination they have suggested double integral sliding surface. However, chattering alleviation is still a challenge. In general, steady state error and chattering alleviation need more attention from the research fraternity.

With this background, this report focuses the work to minimize the steady state error and chattering alleviation. A modified sliding function is proposed. in which the Proportional Integral type function of sliding surface is used. Further modification is suggested to facilitate finite time reaching. Some PECs like Buck, Boost and Buck Boost (Zeta converter) are tested with this proposed SMC law. The proposed SMC proved to be better in elimination of steady state error. The ROE and robustness against load disturbances are also examined. The need for adaptive tuning due to load requirement no longer exists with this proposed SMC and hence no measurement of load current is required. It is proved that the proposed SMC leads to minimization of steady state error. The complete analysis for stability and switching frequency is presented. Moreover, some efforts are put to use some of the most modern techniques like HOSMC-Second Order SMC (2-sliding mode control) for PEC for chattering alleviation. The analysis of the buck converter under control is proposed. The overall research effort is to improve the tracking response of various PEC like Buck, Boost, Zeta, DC-AC Inverters, and Power Factor Controller (PFC) with the SMC.

Contributions of the thesis

The main contributions of this thesis is summarized as below:

∗Introduction to Sliding Mode Control and Review of classical control of Power Electronic Converters

The continuous time SMC technique is discussed. The invariance of SMC for matched uncertainties is illustrated. Idea of modeling of PEC is presented with state space and transfer function approaches. The model averaging technique is discussed and model is obtained for buck converter. The Buck converter is controlled with state feedback and PI/PID controller using PWM technique. The graphical method Bode diagrams are used to design compensator for Buck converter to improve the performance of the converter with load and supply side disturbances. The simulation results are presented.

∗Sliding Mode Controller with PI type sliding function for DC DC Buck Converter

The SMC is proposed with a Proportional Integral type sliding function for buck converter. The proofs of stability and zero steady state error is presented. The simulation and experimental results are presented. It is shown that the proposed SMC law for Buck converter results in better steady state response of load voltage than conventional SMC for a given reference. The efficacy of the proposed SMC law is evaluated for load disturbances. It is shown that the proposed SMC law provides robustness against load disturbances. Effects of variations in controller parameters explored. The discussion of stability, frequency limits of the switching device and steady state performance of the load voltage is presented. Moreover to facilitate finite time reaching the Integral SMC with Finite Time Reaching (ISMCFTR) is proposed. With ISMCFTR, the load voltage is forced to be equal to reference voltage within finite time. The guidelines for tuning parameters of the ISMCFTR is given. Simulation results demonstrate the efficacy of the system under ISMCFTR.

∗Sliding Mode Control for DC DC Boost Converter with Adaptive Mechanism

The proposed SMC is applied to DC DC Boost or step up converter. Here the adaptive mechanism is used to improve the performance of the converter in terms of load voltage quality in presence of load disturbances. The ROE is defined for a given SMC law. It is shown with simulation results that the load disturbance rejection is quite faster with the proposed adaptive SMC law.

∗The Modeling and control of zeta converter with conventional and proposed SMC

The Zeta converter is a type of Buck Boost Converter with non-inverting output. It is complex fourth order non-linear (bilinear) system. The modeling of the converter is presented. The limitations in the choice of sliding manifold is identified. The proposed SMC is applied to Zeta converter to reduce steady state error in load voltage for a given reference. It is shown that the proposed SMC contribute considerable reduction in the steady state error.

∗Applications of SMC for Power Factor Controller and Inverter

The idea of designing sine wave inverter with Zeta converter as a pre stage is proposed. The performance is evaluated with proposed and conventional SMC law. The results are satisfactory but there is a scope of improvement. The performance of Power Factor Controller using Boost converter is also evaluated for PWM/PI control and proposed SMC laws. The results of comparison are presented. It is shown that proposed PI function based SMC perform better as power factor controller.

∗Second order sliding mode controller for DC DC Buck converter with output feedback

The SOSMC law with output feedback for the Buck converter is proposed. The performance of SOSMC is evaluated and compared with that of conventional SMC. The procedure for state estimation is given. Analysis of the system is proposed. The implementation guidelines are provided. The bounds of tuning parameters for stability are estimated. The effects of the tuning parameters on load voltage are explored. It is shown through simulation and experimental results that the SOSMC outperforms the conventional SMC in terms of chattering alleviation.

Organization of the thesis report

The thesis examines DC DC Buck, Boost and Zeta converters with the proposed and conventional SMC law. The thesis provide implementation guidelines for real applications. It addresses the limitations of the conventional SMC law. Also, the modern techniques known as Higher Order SMC or 2-sliding mode control is also applied to the Buck converter for chattering alleviation.

The theory of continuous time SMC is presented. The robustness against the matched uncertainties is discussed. The modeling of DC DC Buck converter is presented. The AC equivalent model is also presented. The classical approaches of designing compensator for the PEC are discussed. Also, the step by step design procedures are given for the same. The state feedback controller design is also discussed. Moreover the guidelines for designing compensator to reject the supply and load side disturbances are also presented.

The Chapter 3 discusses about the proposed Proportional Integral type sliding function based control law for DC DC Buck converter. The simulation and experimental results are presented.

In Chapter 4, the DC DC Boost converter is controlled with proposed SMC law with adaptive mechanism. The efficacy of the control strategy is evaluated with simulation results.

Chapter 5 and 6 presents the Zeta converter and its application to design sine wave inverter for low power AC applications. The performance of Power Factor Controller is also tested with PWM+PI and SMC laws.The simulation results are presented.

Chapter 7 presents the application of 2-sliding mode controller to DC DC Buck converter. The comparison of load voltage responses with proposed SMC law and 2-sliding mode control law is presented. Contains the simulation and experimental results.

Finally, the conclusions of the research work is summarized in Chapter 8 with the scope for future work.

CONCLUSION AND FUTURE WORK

The thesis report discussed about applications of conventional SMC and its limitations especially for PEC. With the use of proposed modified SMC, the steady state error is minimized. Moreover, the variations in ROE due to system parameters variations can also be counteracted in case of Buck and Boost converters. The proof of stability is given. The improvement in load disturbance rejection is demonstrated with simulation and experimental results. To facilitate finite time reaching the Integral SMC with Finite Time Reaching (ISMCFTR) is proposed for buck converter. It is shown that the ISMCFTR results in better steady state and dynamic performance. The comparison results are presented. For Boost converter the adaptive mechanism is incorporated to compensate load variations. Due to the proposed SMC for Boost converter the load voltage settles quickly to reference compared to conventional SMC when load disturbance occurs. The Zeta converter is also controlled with conventional and proposed SMC. The idea of designing sine wave inverter with Zeta converter is also proposed. The results are presented and seems satisfactory. The Power Factor Controller based on Boost topology are also tested for performance with the use of SMC and PWM+PI control. The simulation results are quite better in case of SMC. The quality of load voltage is assessed in terms of THD.

Use of Second Order Sliding Mode Control(SOSMC) for DC DC Buck or step down converter is also proposed. The experimental and simulation results are presented. The experimental results confirms that the chattering alleviation is quite effective with the SOSMC. It is shown that the chattering amplitude is reduced 1.5 times compared to the conventional SMC case. The implementation guidelines are also presented. The use of Digital Signal Controller(DSC) proved to be feasible while executing complex algorithms and state estimation.

Overall observations of simulation and experimental results depicts that the proposed SMC is quite effective for various types of PEC. The proposed SMC is quite better for load disturbance rejection. It also improves the steady state performance. The suitable choice of SOSMC for PEC can be the so called Prescribed Convergence Law (PCL). Because of the discontinuous nature of PCL, it is inherently suitable for the PEC. The conditions for application of PCL specifically for DC DC Buck converter are derived. The output feedback is used for implementation. The bounds of controller parameters are obtained with analysis.

The digital implementation can be preferred over analog due to obvious reasons. The proposed SMC can be applied for multilevel converters. The application of SOSMC/HOSMC for higher order and non linear converters like Buck Boost, Zeta and Cuk can be carried out in future. The proposed SMC can be applied to more complex systems like three phase converters and inverters. The feasibility of various available HOSMC techniques for PEC should be evaluated. The use of HOSMC with PWM technique can also be explored.

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