PERFORMANCE ANALYSIS OF LINEAR QUADRATIC REGULATOR AND MODEL PREDICTIVE CONTROL FOR DC-DC CONVERTER SYSTEMS

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CANDIDATE’S DECLARATION

I SONI KUMARI, Roll No. 2K21/C&I/07, Student of M. Tech Control and Instrumentation, hereby declare that the Dissertation titled **“PERFORMANCE ANALYSIS OF LINEAR QUADRATIC REGULATOR AND MODEL PREDICTIVE CONTROL FOR DC-DC CONVERTER SYSTEMS”** which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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ABSTRACT

This Project presents performance analysis of linear quadratic regulator and model predictive control for DC-DC Converter Systems. A DC-to-DC converter receives a DC input voltage and outputs another DC voltage. The applied input voltage may be higher or lower than the DC output voltage. These days, laptops and cell phones frequently employ DC to DC converters. To Electrical and electronic engineering has a wide range of applications where optimization can be used to reduce the goal function. Almost all in Electrical Engineering battery charging, operation cost in HRS, Filter design, controller design. In the thesis a common problem in electronic measurements and electrical engineering: Reducing “steady state error” or obtaining the “closed loop response” of the given system when no constraints or some constraints is applied to the system. The solution to this problem is the introduction of an advance controller in the control system, specifically the linear-quadratic regulator and model predictive controller. Linear-quadratic regulators (LQR) have several noteworthy properties in terms of control techniques. For instance, they can be employed methodologically independent of the system's order and they are fundamentally stable. They can also make the system behave "optimally" in accordance with the designer's needs. A new and promising control strategy for power converters and drives is model predictive control (MPC). The literature has offered a number of theoretical and practical problems that demonstrate how well this technique works. The result of a converter simulation without any regulating parameters does not quite match our rated value. To obtain an accurate outcome, a variety of optimization approaches as well as intelligent strategies might be applied. According to simulation results, we applied LQR and MPC, and the system operates satisfactorily.

Keywords: “DC-DC Converter Systems, Linear Quadratic Regulator(LQR), Small Signal State Space, Model Predictive Control(MPC), Discrete time system, Quadratic Programming, Steady State Error, Closed loop response”

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LIST OF SYMBOLS/ABBREVIATIONS

Ω	ohm
%	Percentage
V	Volt
A	Ampere
mA	Milli ampere
R	Resistance
L	Inductance
C	Capacitance
Fs	Switching Frequency
d	Duty Cycle
mH	Milli Henry
uF	Micro Farad
Vin	Input Voltage
V_0	Output Voltage
I_L	Inductor current
I_c	Capacitor Current
DC	Direct Current
SS	Steady State
CL	Closed Loop
TF	Transfer Function
PI	Proportional Integral
PD	Proportional Derivative
PID	Proportional Integral Derivative
LQR	Linear Quadratic Regulator
MPC	Model Predictive Control
CCM	Continuous Conduction Mode
DTS	Discrete Time Signal
Ts	Sampling time
EC	Electronics
OLTF	Open loop Transfer Function
MATLAB	Matrix Laboratory

ED	Energy Drives
PE	Power Electronics
QP	Quadratic Programming
LT	Laplace Theorem
DLQR	Discrete-time linear-quadratic regulator
DOFR	Dynamic output feedback regulator
CMC	Current Mode Control
MOSFET	Metal Oxide Field Effect Transistor
IC	Integrated Circuit
DOF	Degree of freedom
PSFB	Phase-shifted full bridge
AC	Alternating Current
P	Power
KCL	Kirchhoff's Current Law
KVL	Kirchhoff's Voltage Law

CHAPTER 1

INTRODUCTION

1.1. BACKGROUND

It is possible to utilize multiple objective optimal control techniques to find the optimal answer to a clearly specified problem. Finding solution that makes maximum or minimum certain research characteristics, such as making expenses minimized associated with producing a thing or utility, maximized benefits, minimizing the amount of raw materials needed to generate a good, or maximizing output, optimization techniques are often utilized. They will be explained in particular as being used to maximize thermal energy utilization while minimizing production costs. Electrical and electronic engineering has a wider area of applications where optimization could be used to reduce the goal function. Almost all in Electrical Engineering battery charging, operation cost in HRS, Filter design, controller design.

In the thesis a common problem in electronic measurements and electrical engineering: Reducing “steady state error” or obtaining the “closed loop(CL) response” of the given system when no constraints or some constraints is applied to the system[1].

Presenting examples of electrotechnical devices (DC-DC converter systems), where it is necessary to solve it.

Two methods are included:1) Linear Quadratic Regulator, 2)Model Predictive Control.

1.1.1. DC-DC converters

The “DC-to-DC converters”[2] convert the DC voltage from one level to another. It is required to specify a voltage for each device since the working voltage of various electronic components, including ICs and MOSFETs, can range over a large range. In contrast to a Boost Converter, a Buck Converter gives voltage at the output that is less than the voltage at the input.

The circuit's efficiency, ripple, and load-transient response can all be modified by using DC-to-DC converters[2]. The most effective external parts and components are typically reliant on operational circumstances like input and output requirements. As a result, when creating the products, the standard circuits must be modified or updated to meet each product's unique specification needs. A considerable deal of knowledge and experience in that area are required to design a circuit that complies with the specification and all requirements. When the volts of the cells is up or down the output voltage of the regulator, step-up or step-down “DC-to-DC converters” could be helpful. To supply a constant load, a DC to DC converter needs to be able to function as a stepping-up or stepping-down voltage supplier.

1.1.2. Steady State Error

The difference among the set input and set output of a control system after it has stabilised to its steady value is referred to as a SS error. The “steady-state error” serves as a gauge for how precisely a control system follows a command input[1]. Although non-linearized behaviour of controlling system components can cause steady errors. The layout of the CS is responsible for the steady-state problems discussed in this section. The “Laplace final value theorem” could be used to determine the SS(steady-state) error. The outcome reaction should ideally be the number that the input was set to, with no errors.

1.1.3. Closed loop response

A CL control system is one in which the system's output is fed back into the system as an input, forming a loop. Because the system's response is dependent on both input and feedback from the output, it is considered to be CL.

The CL response of a system can be described as an exchange of information at the input to the output. The output answers a query posed by the input. However, rather than ending there, the response is given back to the input, which then poses a new query in light of the answers it has already received. Until the system finds a stable state, this process continues with the input and output always interacting with one another.

This closed-loop reaction is helpful in systems where the output must be continuously monitored and adjusted in accordance with the input, such as in automation or machinery control systems. As the feedback loop may assist correct mistakes and respond to changing conditions, it enables more precise and accurate system control.

1.2. PERFORMANCE ANALYSIS OF LINEAR QUADRATIC REGULATOR FOR DC-DC CONVERTER SYSTEMS

This study focuses on power electronic converter modelling fundamentals using averaging techniques. For DC-DC “buck converters”, “boost converters”, and buck-boost converters” performing in “Continuous Conduction Mode (CCM)”[3], it explicitly covers state space averaged modelling methods. The period average method, the averaging model approach, and the power conserving guidelines are some of the modelling strategies used. The transfer function(TF) that gives the output of the converters is also obtained by the study, and this data can be applied to create trustworthy controllers. “The averaged models” produced are useful by this technology for controller design and system simulations.

The report also offers a few broad remarks about linear-quadratic regulators (LQR)[4]. To develop and implement “DC-DC Converter systems”, an LQR is specifically used. The system's performance is evaluated through simulations experiments and the findings are satisfactory.

1.3. ANALYSIS OF MODEL PREDICTIVE CONTROLLER VERSUS LINEAR QUADRATIC REGULATOR FOR DC-DC BUCK CONVERTER SYSTEMS

This paper's main objective is to compare a DC-DC buck converter's closed loop response utilising several optimisation techniques, including “Model Predictive Control (MPC)”[5] and “Linear Quadratic Regulator (LQR)”. A streamlined discrete model-based predictive control is provided for a converter running CCM[6], along with some general observations on LQR in comparison to it. The system's fundamental calculation is the control decision. The discretized system model of the converter is made simpler by linear matrix of converter model coefficients. First, a linear quadratic regulator and feedforward control are used to accomplish the control task. Second, nonlinear model predictive control is used. According to simulation results that show the validity of the predictive control method when done online and using digital technology, the output of the converter may be modified with a quick and precise response under a variety of working scenarios.

1.4. MOTIVATION

For several years, modern electronics technology has made substantial use of switching-modes power converters in a various field of markets, including industrial, commercial, utility, and consumer markets. The three important kind of power converters used in modern power conversion—buck, boost, and buck-boost—are used for low-power DC/DC conversion-based applications[7]. However, complex combinations or improved variants of the traditional topologies are used in specialised applications. There are several DC-DC converter topologies in the literature, but there is no one solution that caters to all the applications. Conversion techniques, in general, have found a wide array of applications in industry, research and development, and daily life

DC/DC converters form a key aspect of study in the field of PE and energy drives(ED) as they are highly incorporated in several applications.

The most common criteria that need to be met during the design of DC/DC converters include maximizing performance and enhancing power density while reducing the overall cost.

Some key applications where DC/DC converters are employed extensively include renewable energy integration, medical devices, vehicles, smart lighting, and other small-scale electronic appliances.

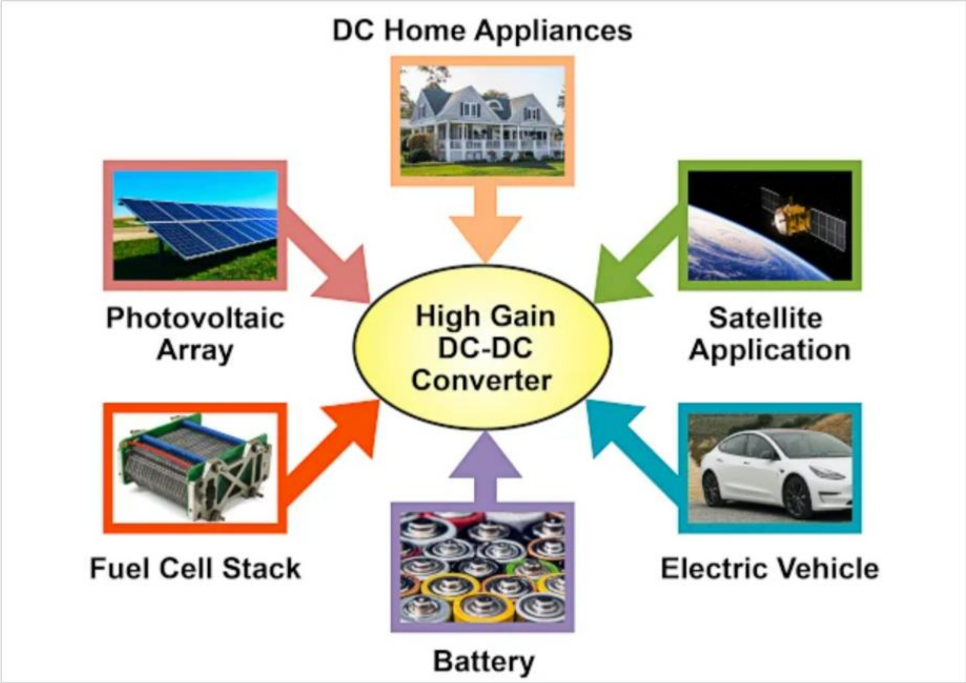


Fig 1.1:- Applications of High Gain DC-DC Converters

1.5. RESEARCH OBJECTIVE

Output voltage regulation for line and load variation is essential for optimised electronic devices. Many controlling techniques, such as "Proportional Integral and Derivative (PID) controller"[8], "Linear Quadratic Regulator (LQR)"[7], "Model Predictive Controller (MPC)", and many others, are utilised to enhance the performance of the converter. Many closed loop applications currently rely on PD, PI, and PID controllers. There are a few works for controller optimisation in the literature, and to tune the PID parameters, different classical techniques like Ziegler-Nichols are utilised. This tuning technique uses complicated mathematical computation that results in subpar performance structures. Many experts have demonstrated in their studies the new advance optimization technique that can be used to improve the performance of the converters.

These are some objectives for this Project.

- Modeling the linearized "Steady State(SS) Model" of the DC-DC Converters
- Application of "Linear Quadratic Regulator technique" on "DC-DC Converter Systems".

- Comparison of advance controlled strategies, “Model Predictive Control” and “Linear Quadratic Regulator” techniques on “DC-DC Buck Converter”.

1.6. ORGANIZATION OF THESIS

The Thesis have been categorized in seven sections.

In section 1, the introduction of DC-DC converters, Steady state error, Closed Loop Response, “Performance Analysis of Linear Quadratic Regulator for DC-DC Converter Systems”[7], “Analysis of Model Predictive Controller Versus Linear Quadratic Regulator For DC-DC buck converter systems” are discussed. This section also have the motivation and research objective.

The chapter 2 contains the literature review about overall projects. In this, discussed “Performance Analysis of Linear Quadratic Regulator for DC-DC Converter Systems” and “Analysis of Model Predictive Controller Versus Linear Quadratic Regulator For DC-DC buck converter systems”.

The chapter 3 consists the brief of Mathematical modelling of “DC-DC Converter Systems(buck converter, boost converter, buck-boost converter)”. Firstly it’s State-Space(SS) Model is derived then further showing its Small Signal Averaged State Space Model. Additionally explained the steady state error and closed loop response of any plant model.

The chapter 4 consists of brief designing and modelling “Linear Quadratic Regulator”. The origin of LQR, Riccati[9] Equation Derivation are discussed along with the transformation of CCM data to DCM data.

In the chapter 6 the results after applying both the control strategies are discussed. firstly open loop analysis is done on DC-DC Converter systems. Secondly, LQR is applied on DC-DC “Buck Converter”, “Boost Converter” and “Buck- boost converter” observed the results. Third, comparison between LQR and MPC is shown on DC-DC Buck Converters with Unconstrained and Constrained system.

In the section 7 the closure as well as upcoming scope of the suggested system has been explained.

CHAPTER-2

LITERATURE REVIEW

2.1. GENERAL

This chapter divided in two sections. In first part we discuss about background and previous work done in the area of "Performance Analysis of Linear Quadratic Regulator for DC-DC Converter Systems(buck converter, boost converter, buck-boost converter)"[7]. It also includes previous research about the optimization techniques used on converters as well as small signal state space models are determined.

In second part we discuss the background and previous research about the "Analysis of Model Predictive Controller Versus Linear Quadratic Regulator For DC-DC buck converter systems". It also includes the custom quadratic programming solver brief overview.

2.2.PERFORMANCE ANALYSIS OF LINEAR QUADRATIC REGULATOR FOR DC-DC CONVERTER SYSTEMS

The bulk of work required by the engineers to optimize the controller is reduced using the LQR algorithm. A popular technique called the LQR offers feedback gains that may be optimally regulated, allowing for the closed-loop applications robust as well as high efficient design of systems. Below are some of the reviews collected from the literature:-

Carles Jaen had presented in "A Linear-Quadratic Regulator with Integral Action Applied to PWM DC-DC Converters"[4] the averaged models produced using this method are particularly beneficial for both system simulation and controller design. This study provides some broad insights regarding linear quadratic regulators (LQR). Next, an LQR is created and used into specific circumstances of a DC-DC buck converter. PWM DC-DC converters based on LQR controller are shown in this study. This controller takes an integral stage into account in addition to one sample actuation delay. The converter's averaged model, which takes into account inductor and input power supply spurious resistors, is used by the controller. Continuous conduction mode operation has been taken into consideration. A buck converter can now be used fully with the created technology. The system performs well in simulations when starting up and changing loads. Additionally, experimental findings that support earlier models are provided. Because the LQR method is particularly intriguing for controlling multivariable systems, future study will focus on developing its applicability.

Modelling, implementing, and simulating a DC-DC converter in state space approach are covered in the paper "DC-DC Converter Modelling and Simulation using State Space Approach"[2]. Utilizing a state-space modelling technique, three "DC-DC converters—the Buck, Boost, and Buck-Boost converters"—were created and put into use in Simulink. Each converter's state space matrix is deduced in detail based on its circuit topology. The simulation findings of the state space model are equivalent to those of the circuitry model with only a tolerance of 0.0015V. In comparison to the circuits model, the simulation calculation time has increased to 7.8 times faster. The state space approach incorporates a DC-DC converter into a single block, making it simple to design and integrate buck, boost, or buck-boost into other bigger systems. Additionally, modelling a DC-DC converter does not require the use of any other Blocksets for Simulink that can be added on, such SimPowerSystems or SimElectronics. The state space system's frequency changing input element is absent, whose primary drawback is its inability to replicate ripple effects on inductor current and output voltage. The state space modeling incorporates a DC-DC converter into a singular block making it simple to simulate and analyze buck, boost, or buck-boost systems.

The work done in "Small-Signal Analysis of Boost Converter, including Parasitics, operating in CCM"[10] contains the several state space averaged modelling tenets for continuous conduction mode (CCM) functioning DC-DC Boost converters. It applies the time averaging algorithm, average model methodology, and energy conservation laws. A robust controller can be designed using the output TF of a Boost converter. On the basis of the state-space average technique, parasitic effects and losses are also taken into account. The proposed models' OLTF are generated, and the converter's behaviour is confirmed by its transient step responses. The linear and nonlinear components that make up a DC-DC converter's construction are the R, L, and C. Since these systems can be thought of as non-linearized and timedepentend systems, a linear controller must be designed using the small-signal model of the state-space averaging model.

Yoon et al. had presented application of the optimal control rule using the LQR control technique to regulate the tri-rotor UAV's altitude[11]. The system comprises of a force and moment-based linearized analytical model of single tilt dynamics. A linearized model is presupposed in order to develop a LQR control. To control roll, pitch, and yaw angles, Q and R matrices are selected during the design phase. There are flight tests performed, including hovering, altitude, and yaw control tests. According to Yoon et al. (2013), authors successfully demonstrated quick yaw control motion using an attitude controller based on LQR. In order to translate the system performance objectives into the cost function parameters, a method for solving a LQR problem was proposed (Oral et al., 2010). Instead of choosing by trial and error, the components of the Q and R performance index matrices were developed for time domain design, which describes the steady and transient responsiveness of the system. The mathematical relations were used to determine the weighting parameter ratio. However, the weighting factors need to be changed for minimum oscillations.

Satyabrata Sahoo had presented the paper, “Optimal Speed Control of DC Motor using Linear Quadratic Regulator and Model Predictive Control”[12]. In order to make comparisons, the goal of this research is to manage the angular speed in a model of a DC motor using several control systems, including model predictive control and linear quadratic regulation. Multi Parametric Quadratic Programming is used in the Model Predictive Control technique to offer online and offline computation of the optimisation law. The optimal control theory is used to develop the controllers. Utilising simulation data and the MATLAB/SIMULINK tools, the performance of these controllers has been confirmed. This study proposes a design strategy to find the best speed control utilising various controllers since speed control of a DC motor is a crucial issue. Table 2's summary of the data reveals that the model predictive controller has zero overshoot and the LQR controller has a lesser overshoot.MPC outperforms other controllers in terms of peak amplitude and settling time.

Another paper's main goal is to stabilise and balance a robot gymnast who is performing upside-down (Robogymnast)[13]. A complicated non-linear triple inverted pendulum system is the Robogymnast. Robogymnast fastened to a high bar that rotated freely and was supported by ball bearings. It has three links and three joints; the first joint is passive (an unpowered joint), while the other two are active (powered joints), mimicking the human acrobat. The passive join poses a significant problem to keeping the robot upright and balanced. The optimal control theory was applied in order to attain the needed performance. The linearized mathematical model of the plant, which was utilised to determine the state feedback control rule, was used to implement the discrete-time linear quadratic regulator (DLQR) controller. In addition, the selection of the DLQR's weighting matrices was examined. The outcomes demonstrated that Robogymnast had been successfully stabilised and balanced.

The availability of all state variables is required for the implementation of the steady-state solution for the discrete-time linear-quadratic regulator (DLQR)[14]. When all state variables are accessible, the DLQR solution is often implemented as a static state feedback control rule with an unlimited horizon. When just the plant's output is quantifiable, however, a dynamic output feedback LQ regulator is required. If a proper state observer is included in the system, the state feedback LQ control law can also be used. It should be noted that the literature does not always take into account the optimality of regularly used observers. There is one exception to this rule, in which a specific mechanism allows for the achievement of an ideal LQ output regulator. This approach, however, calls for challenging computations and intricate derivations. It is possible to use a different, simpler method to get the best regulator-observer transfer function for discrete-time systems. This approach guarantees that the closed-loop system, using the derived regulator-observer transfer function (DOFR), retains the same poles as the closed-loop system utilising the DLQR and state feedback, as well as additional poles chosen by the observer. It is demonstrated that, particularly for favourable initial conditions, the intended regulator, based on the reduced-order Luenberger observer, is similar to the one developed using this method. For systems with stepwise excitations of the plant output, it has been demonstrated that the deterministic equivalence principle is valid. The contribution of the research is to suggest a simple design approach for the closed-loop system that keeps the freely selected observer poles. This result supports the probabilistic equivalence principle's applicability in systems with progressive plant output stimulation.

In paper "State-Feedback and Linear Quadratic Regulator Applied to a Single-Link Flexible Manipulator"[14], An analysis of two various control methods for a reliable adaptable singular-link robotic manipulators are presented by the author. The rotatable base and the adaptable links are modelled as static plants applying Lagrange's formula in the dynamic model of the flexible manipulator. One degree of freedom (DOF) is present in the final system. The "State-Feedback controller" and the "Linear-Quadratic regulator (LQR)" are two different kinds of regulators that are examined and described. The state-feedback relies on the positioning of the poles, whereas the latter is derived by solving the Riccati equation. After running a simulation using MATLAB and SIMULINK, experiments using the flexible beam Quanser module were successful. At the conclusion of this study, experimental findings are provided and contrasted.

Precision systems usually use the idea of subordinate control, while the regulators frequently use PID controllers[8]. They can be used in a single system in extremely large numbers, which ultimately leads to more complex PID regulator adjustment and makes it more difficult to offer the essential parameters for the transient process quality. The answer to this problem is the introduction of a fundamentally new controller in the control system, specifically the linear-quadratic regulator. Its disadvantage is that it is a non-zero static mistake. In this study, we suggest one method to overcome this drawback, namely, the use of an integrator as an additional corrective unit in the control system's forward contour, which allowed us to create a linearquadratic speed controller with high speed control precision. When the necessary criterion for quality control was initially specified, the authors of this study synthesised the linear-quadratic regulator shaft speed of a DC motor, enabling optimal control. The authors suggested using an integrator in the control system's forward contour to lower the inaccuracy in steady-state mode. This technique for improving the regulator's precision enables error-free processing of sequential input signals. The drawback of this approach is that it is possible to lower the stability margin in phase and amplitude in the control system when utilising a compensating integrator.

In comparison to conventional controllers like PID, LQR is an optimal control regulator that more closely follows a reference trajectory. When the orbits of two dynamical systems can be projected onto one another through a homeomorphic change in coordinates, the systems are topologically similar. We'll demonstrate that all closed-loop systems originating from LQORC issues are topologically similar in general. We thereby offer fresh perspectives on the structural "tuning" of regulated behaviour.

All-inclusive, the literature review related to the robustness of LQR is compiled above which shows the classical uses of this optimization technique in various fields. In control theory the researchers have found wide future scope in this field making them read more and research.

2.3.ANALYSIS OF MODEL PREDICTIVE CONTROLLER VERSUS LINEAR QUADRATIC REGULATOR FOR DC-DC BUCK CONVERTER SYSTEMS

Two different types of optimal control techniques—model predictive control and linear-quadratic regulators—have different methodologies for determining the costs of optimization. Below are some of the reviews taken from the different aesthetic works:-

Zhaoxia Leng had presented "A Simple Model Predictive Control for Buck Converter Operating in CCM"[6]. A predictive advance control strategy for Buck converters running in CCM is provided. It is based on a reduced discrete model. The control decision computation is straightforward. From linearized modelled coefficient matrices, the discrete model of the converter is made simpler. By replacing modelled states system into the functioning and minimizing the objective function, the predictive control value is obtained. The controlled defects created by models simplifying and system's intrinsic parameters can only be addressed by changing the predicted values in the objective function based on the difference between the model's output and the real system output. The output voltage of the converter can be adjusted with a quick and accurate response under varied working situations, according to simulations and demonstrations output that demonstrate the viability of the predictive advance controlled technique when implemented online and using digital technology."

A. Wahl had presented the "tracking problem of automatic river navigation"[5] is presented. The modelling of a desired track using splines is proposed in order to achieve "track-keeping" management on rivers. The control task is first solved using feedforward control and a linear quadratic regulator. The realisation of nonlinear model predictive control comes next. A multilayer control structure including prediction is offered in addition to the "classical" model predictive control. Real-time demands are addressed because a practical application is also taken into consideration.

“Model Predictive Control of a Three-to-Five phase Matrix Converter[15]” [5], [16]proposes For a three-phase input to 5phased output matrices converters, create a model predictive control technique to simultaneously control active and reactive power as well as the source and load current. The suggested method chooses the matrix converter's actuation states in accordance with the cost function's optimization procedure. To make source side power factor management easier, the suggested cost function takes into account active and reactive input power regulation. Furthermore, both sinusoidal supply or loaded end currents are managed. Given advance controlled method allows the source side power factor to be adjusted to any value while maintaining precise monitoring of the target and actual source and load currents. The paper uses an analytical and simulation methodology.

By including inequality restrictions on the inputs and states in the “infinite-horizon linear quadratic regulator (LQR) problem[17], Pierre O. M. Scokaert and James B. Rawlings” produced a theoretical contribution that builds on the work of Sznaier and Damborg. In order to achieve the desired result, a select few finite-dimensional positive definite quadratic programmes must be solved. The restricted LQR methodology discussed here, in contrast to other conventional model predictive control (MPC) methods, eliminates the unfavourable disparity between the nominal system pathways in open-loop and closed-loop systems. By including inequality restrictions on the inputs and states in the unbounded horizon “linear quadratic regulator (LQR) problem, Pierre O. M. Scokaert and James B. Rawlings” produced a theoretical contribution that builds on the work of Sznaier and Damborg. In order to achieve the desired result, a select few finite-dimensional positive definite quadratic programmes must be solved. In contrast to other common model predictive control (MPC) methods,It is shown that the restricted LQR method is both ideal and stabilising. It is more practical than computing the ideal answer since it provides a computationally effective solution with a reasonable upper limit. Additionally, this method does away with the requirement for a control horizon, a tuning parameter used in previous MPC techniques but for which there are no valid tuning guidelines. Constrained LQR is contrasted with two additional prevalent MPC kinds in two circumstances. Constrained LQR outperforms other MPC approaches in some plant systems, as demonstrated by the examples, while still having an acceptable computing cost for online implementation.

The Riccati equation[9], which is linked to the bounded-horizon “linear quadratic regulator (LQR)”, has been extensively investigated and has made substantial contributions to control theory. However, several ways have been presented by academics to solve these drawbacks and improve management strategies. Kalman discovered that the Riccati equation has a limit in 1960 and used this knowledge to solve the infinite-horizon LQR problem, which was a significant contribution in the field of control theory. This discovery opens up new avenues for developing control principles for systems with unlimited horizons. Richalet et al. and Cutler and Ramaker made significant contributions in the late 1970s by providing the framework for model predictive control (MPC) for constrained processes. MPC is an advanced controlled technique that implements in account a finite prediction horizon and optimises control actions based on a system model. This strategy grew in popularity and influence in the field of control[18]. While developing MPC with limited horizons, it became clear that in order to create stabilising control laws, a return to an infinite-horizon formulation was required. This realisation occurred in the 1980s, when researchers faced considerable hurdles in the theory of evolution of MPC along with limitations.

Xiangdong Sun had presented in paper “The Phase-Shifted Full Bridge (PSFB) DC-DC converter”, which is frequently employed in electrochemical reactions and electric car charging systems, is the subject of this study's Model Predictive Control (MPC) analysis[19]. Based on response time, these converters' performance is evaluated. The study suggests adopting current mode control (MPC-CMC), a model predictive control technique, to improve the vigorous performance of the “PSFB DC-DC converter”. The study uses delay compensation and integral compensation to increase the model predictive control's control accuracy and response time. Calculation from simulations and experiments show how effective the suggested strategy is in increasing the converter's dynamic response speed. When there are step variations in the load's planned output current, the technique produces satisfactory dynamic performance.

Vineet kumar had presented paper, “Optimal Position Tracking for an AC Servomotor Using Linear Quadratic and Model Predictive Control”[20]. The ideal techniques for AC servomotor position control are covered in this article. This study discusses the mathematical design of an AC servo-motor along with the application of the aforementioned control approaches, beginning with a basic introduction of LQR and MPC techniques. In order to compare the results of the different strategies, transient response requirements were used. Additionally, the performance of the controllers under external disturbance has been examined. The instance track of the Alternating Current Servo-motor setting is successfully accomplished along the aid of “linear quadratic and model predictive control”, according to the findings of simulation performed in MATLAB. It is tracking the instance outcome of rotor spot in a comparatively short period of time, MPC produces better results in the situation of no disturbance. Additionally, both the “Linear Quadratic Regulator (LQR) and Model Predictive Control (MPC)” functioned well against the external disturbance once it was incorporated into the system. However, MPC's transient response to the disturbance is generally better than the LQR's.

In paper “Optimal Speed Control of DC Motor using Linear Quadratic Regulator and Model Predictive Control”[20], Under disruptions from the outside world and changes in machine parameters, the working of Proportional Integral controllers for momentum or spot regulations suffers. In order to have the required reaction, the PI controller gains must also be properly chosen. The use of sophisticated control methods like LQR and MPC can resolve this. The flexibility of Model Predictive Control to handle limitations for both control inputs and system states makes it superior to traditional PID control techniques. As in view to manage the speed of a DC motor, this introduces Model Predictive manage, LQR, and PID controllers. The remainder of the text is obtained as follows: first, a description of the plant model is given. The PID approach, the LQR design, and model predictive control are all covered in the next section. Results of the simulation are then displayed.

All inclusive review from literature shows few conclusions that is “Model predictive control and linear-quadratic regulators” are two examples of optimum control, each having a unique way of allocating the costs of optimization. The LQR analyses every linearized systems insertion along with the offers a TF that reduces overall error over the frequencies range by exchanging state-errors versus input frequency. An MPC usually considers bounded length, weighting sets of limited systems. Due of these fundamental distinctions, MPC frequently performs more locally optimally and intricately than LQR, despite having greater global stability qualities. The primary distinctions between LQR and MPC are that, LQR optimises throughout the whole time frame, and MPC optimizes in a retract interval window, and that LQR utilises a single (optimal) way for the entire time horizon as opposed to MPC, which computes new solutions often. As a result, MPC often finds an inferior solutions because it resolves the optimisation limitations in a shorter interval range than the entire horizon. However, MPC can manage severe constraints and movements of a non-linearized system far from its linearized operation point. These are the important drawbacks to LQR because it makes no assumptions about linearity. This means that when working outside of stable fixed sites, LQR can lose strength. Although MPC could plot a route into the keys, transformation of a solution is not always assured, particularly if consideration of the distension and complications of the system has been disregarded.

CHAPTER-3

MATHEMATICAL MODELING OF DC-DC CONVERTERS

3.1. INTRODUCTION

A “DC to DC converter”[2] receives a DC voltage at input and another DC voltage at the output. The applied input voltage may be higher or lower than the DC output voltage. Converters can be purchased as standalone integrated circuits (ICs), and they only need a few other parts to function. These days, laptops and cell phones frequently employ DC to DC converters. Despite having sub-circuits that manage the voltage need differently than the batteries, they nevertheless get battery power. Mathematical modelling is the process of converting difficulties from an application zone into manageable mathematical formulations using a hypothetical and arithmetic analysis to provide perception, answers, and advice for the application developer. Mathematical modelling[7] is useful in a variety of applications because it provides precision and strategy for problem solving while also allowing for a systematic understanding of the system being modelled. It also enables better system design, control, and the optimal use of modern computing capabilities.

3.2. DC/DC BUCK CONVERTER

A buck converter is a non-isolated DC converter that decreases the applied DC input voltage level immediately. It is frequently utilised in board-level circuits for local conversion. Voltage conversion is frequently required in devices such as fax machines, scanners, telephones, PDAs, laptops, and copiers. The buck converter can convert the input voltage to the precise levels needed by these devices.

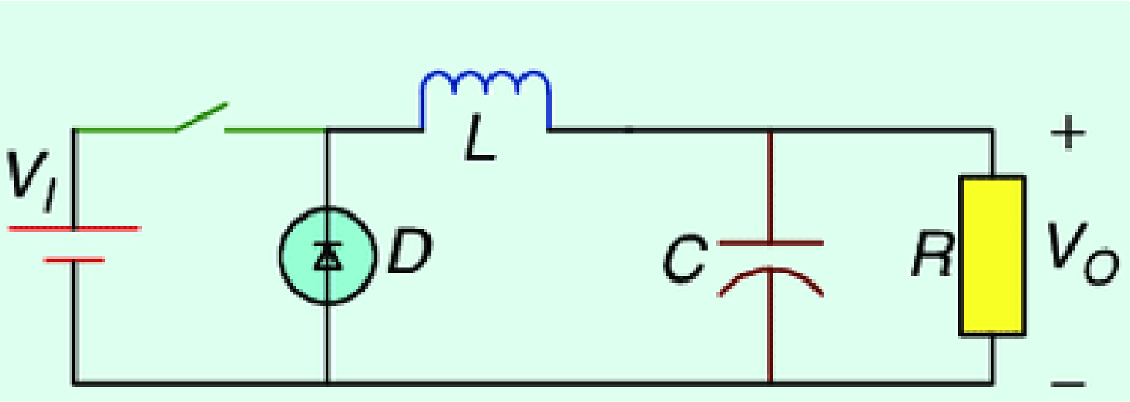


Fig 3.1. Classic DC-DC Buck Converter

3.2.1. State Space Model

The “state space model[7] of Linear Time-Invariant (LTI)” system can be given as,

$$\dot{X} = AX + BU \tag{3.1}$$

$$Y = CX + DU \tag{3.2}$$

The above equations, commonly called as the state equation(3.1) and output equation(3.2) respectively, are defined as follows:

- X = the state vector and $\dot{X}$ = differential state vector, respectively.
- The input vector is denoted by the letter U.
- A represents the system matrix.
- B denotes the input matrix.
- Y is the output vector in the output equation.
- C denotes the output matrix.
- The feed-forward matrix is denoted by D.

The buck converter functions in one of two ways, as described below:-

- First mode, when the switch is “ON”
- Second mode, when the switch is “OFF”.

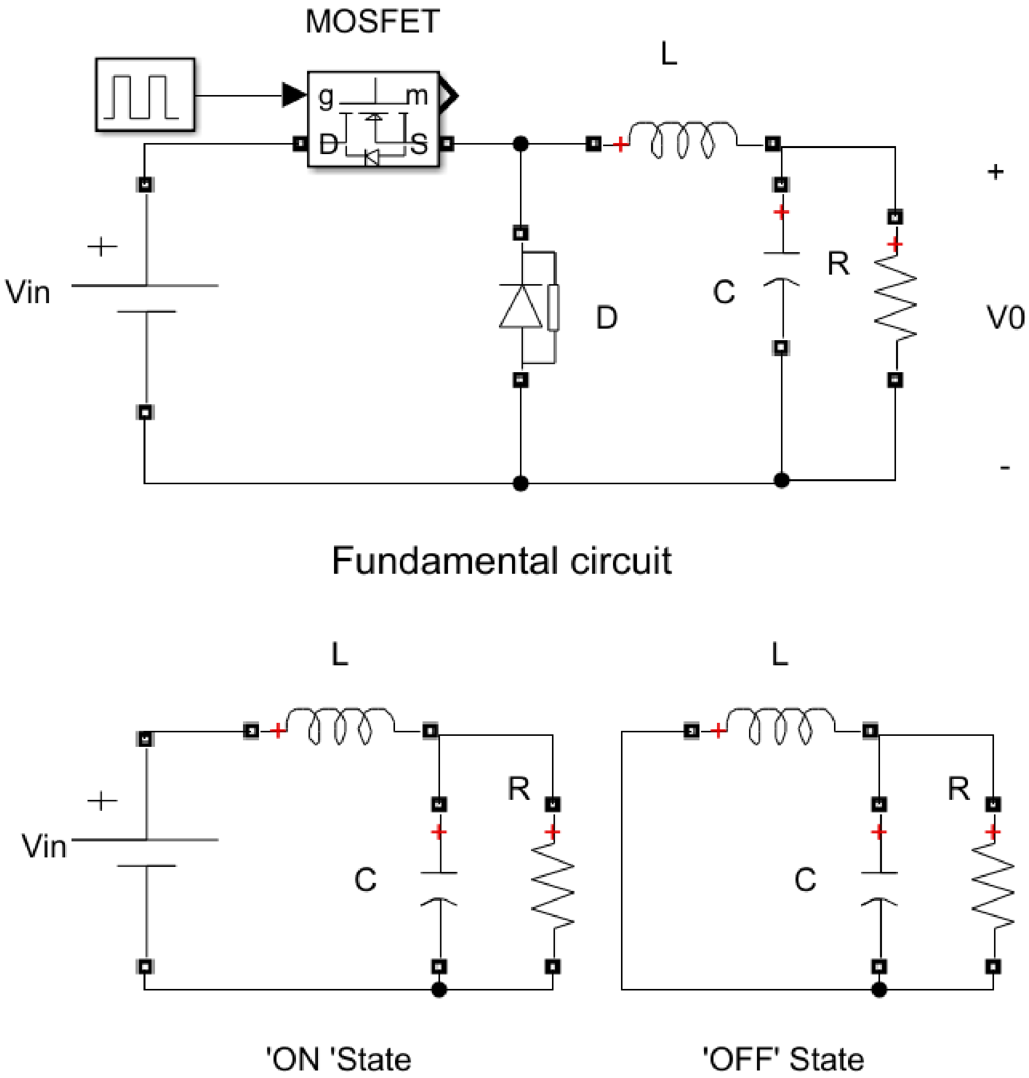


Fig 3.2. Primary buck converter circuits, and it’s ON and OFF states

Mode 1: Switch in “ON”

When you flip the switch, the diode becomes reverse biassed in proportion to the applied input. As a result, the inductor directs the input current. As a result, the DC input current (Idc) flowing in the circuit is equal to the current flowing through the inductor.

$$I_L = I_{dc}$$

The voltage difference between the output voltage Vo and the applied DC voltage Vs (Vin) during this time is known as the inductor voltage VL.

$$V_L = L\frac{di_L}{dt} = V_s - V_0$$

$$\frac{di_L}{dt} = \frac{V_L}{L} - \frac{V_0}{L} \tag{3.3}$$

$$i_L = i_0 + i_C$$

$$i_L = \frac{V_C}{R} + C\frac{dV_C}{dt}$$

where, $V_C = V_0$

$$\frac{dV_C}{dt} = \frac{i_L}{C} - \frac{V_0}{RC} \tag{3.4}$$

Where,

R= load Reasistance

C= Capacitance

Mode 2 :- Switch is "OFF"

The preceding mode, 1, switches to mode 2, when the switch is off. The inductor's polarity changes during this phase, and it begins to function as a source. In this state, the inductor's stored energy powers the current flow. The circuit relies on the inductor's released energy while the Direct Current source is detached. Because of this, the IS keeps flowing until the inductor is completely drained. During this time, the load voltage's negative polarity is represented by the voltage across the inductor.

$$V_L = -V_0$$

$$L\frac{di_L}{dt} = -V_0$$

$$\frac{di_L}{dt} = \frac{-V_0}{L} = \frac{-V_C}{L} \tag{3.5}$$

Similarly calculating like in mode 1 we get

$$\frac{dV_c}{dt} = \frac{i_L}{C} - \frac{V_C}{RC} \tag{3.6}$$

Considering all above equations from mode 1 and mode 2 we obtain the input matrix and output matrix in ON state and OFF state separately. And put them in below equations:

$$A = D * A_{on} + (1-D) * A_{off}$$

$$B = D^* B_{on} + (1-D) * B_{off}$$

Where, D=Duty Cycle

Thus obtaining the “state space model of the DC-DC Buck Converter”.

Below are the state equation(3.7) and output equation(3.8) respectively :-

$$\begin{bmatrix} \frac{\mathrm{diL}}{\mathrm{dt}} \\ \frac{dvc}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} iL \\ vc \end{bmatrix} + \begin{bmatrix} \frac{D}{L} \\ 0 \end{bmatrix} [V_s] \tag{3.7}$$

$$[v0] = [0\ 1] \begin{bmatrix} iL \\ vc \end{bmatrix} \tag{3.8}$$

3.2.2. Small Signal Averaged State Space Model

The “small signal averaged state-space”[7], [10] proficiency is a versatile analytical tool that may be implemented to both easy and complicated circuits. Even though they seemed simple enough, the linearized averaged time independent circuits created by using this method demands substantial mathematical labour to come to the right answers. To create these models, our example is implemented using the comprehensive generalised process provided in. Any electric circuit's energy storage elements, “such as the capacitance voltage as well as inductor current, are the desirable state variables for state-space modelling. A complex circuit must first be simplified in order to use the circuit rules before starting to put the state-space approach to it.”

The classical buck converter circuit and its related "ON" and "OFF" states circuits are shown in Fig.3.2. The state-space modelling of converter obtained in CCM is described above:

In the above equations lets add this small signals to variables:-

$$i_L = i_L + \tilde{i}_L$$

$$V_C = V_C + \tilde{V}_C$$

$$V_{in} = V_{in} + \tilde{V}_{in}$$

$$D = D + \widetilde{D}$$

After considering all the above equations and steps obtain the “Small Signal State Space” equations by following the similar steps as in state space model :-

$$\begin{bmatrix} \frac{\mathrm{diL}}{\mathrm{dt}} \\ \frac{dvc}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} iL \\ vc \end{bmatrix} + \begin{bmatrix} \frac{D}{L} & \frac{Vin}{L} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} vin \\ d \end{bmatrix} \tag{3.9}$$

$$[v0] = [0\ 1] \begin{bmatrix} iL \\ vc \end{bmatrix} \tag{3.10}$$

Where equations 3.9 and 3.10 gives the state equation and output equation in small signal state space of DC-DC Buck converter, respectively.

3.3. DC-DC BOOST CONVERTER

Boost converters, also called as step-up choppers, are chopper circuits that produces voltage at the output that is larger than the voltage at the input. These circuits convert DC to DC by giving voltage at the output higher in magnitude than the voltage at input .

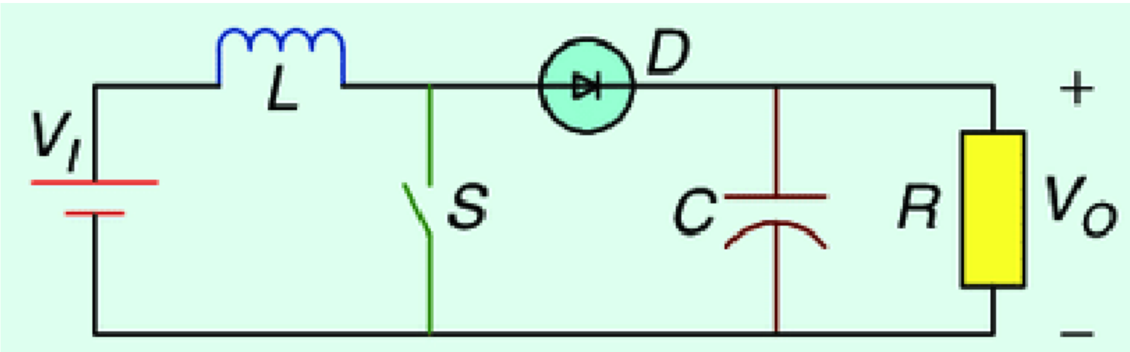


Fig 3.3. Classic DC-DC Boost Converter

3.3.1. State Space Model

Functioning of Boost Converter:-

The boost converter functions in one of two ways, as described below.

- First mode, when the switch is “ON”
- Second mode when the switch is “OFF”.

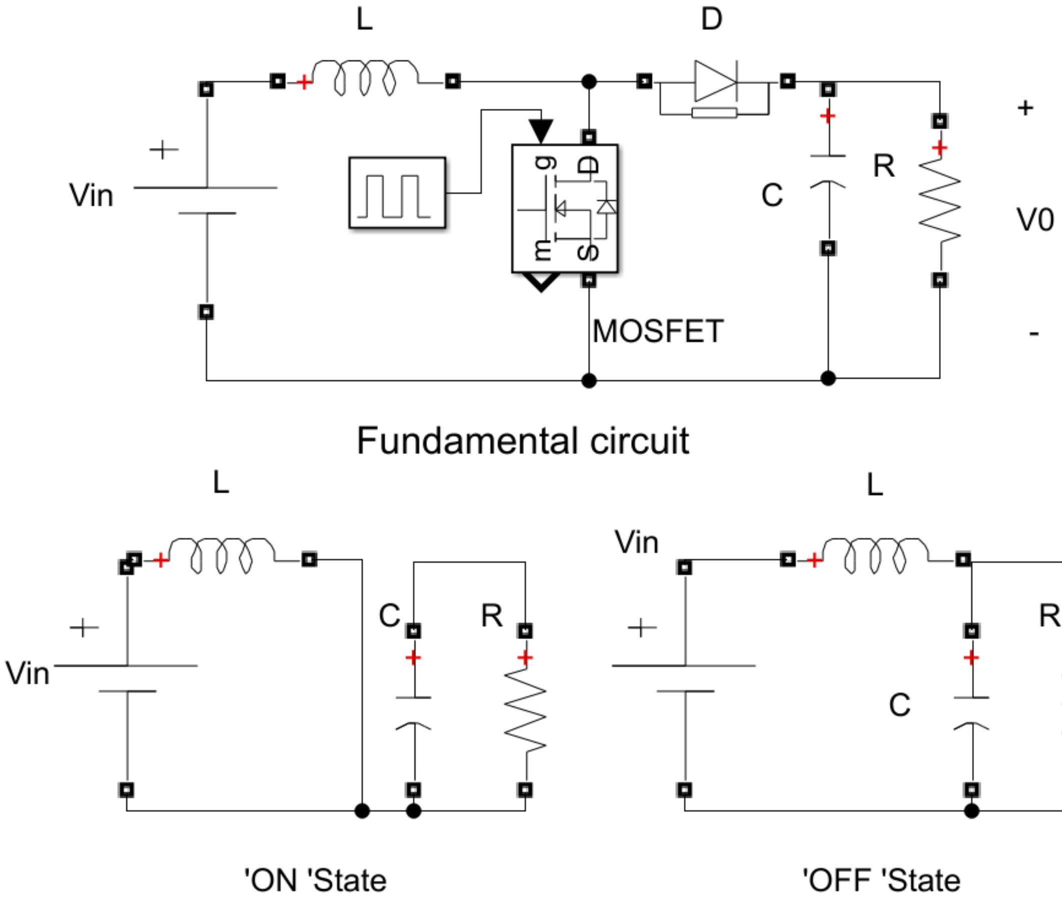


Fig 3.4. Primary boost converter circuits, and it's ON and OFF states

Mode 1:- Switch is in ON state

We "ON" the switch . When our signal source goes high, the MOSFET turns on. The inductor directs all of the current via the MOSFET. It is worth noting that the capacitor remains charged throughout this period since it cannot discharge through the now-back-biased diode. Of course, the power source isn't instantaneously shorter because the inductor causes the current to ramp up slowly. Magnetic fields are also generated in the circuit around the inductor.

$$V_s = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{V_S}{L} \tag{3.11}$$

$$\frac{dV_C}{dt} = -\frac{V_C}{RC} \tag{3.12}$$

Mode 2:- Switch is in OFF state

When the MOSFET switches off, the current to the inductor abruptly stops. The inductor's nature is to ensure a smooth current flow; it does not enjoy rapid variations in current. As a result, it replies by generating a large voltage with the opposite polarity of the voltage provided to it, utilising the power conserved in the field to keep the current flowing.

$$\frac{di_L}{dt} = \frac{V_S}{L} - \frac{V_C}{L} \tag{3.13}$$

$$i_L = i_0 + i_C$$

$$i_L = \frac{V_C}{R} + C\frac{dV_C}{dt}$$

where, $V_C = V_0$

$$\frac{dV_C}{dt} = \frac{i_L}{C} - \frac{V_C}{RC} \tag{3.14}$$

Where,

R= load Reasistance

C= Capacitance

Considering all above equations from mode 1 and mode 2 we obtain the input matrix and output matrix in ON state and OFF state separately. And put them in below equations:

$$A = D * A_{on} + (1-D) * A_{off}$$

$$B = D * B_{on} + (1-D) * B_{off}$$

Where, D=Duty Cycle

Thus obtaining the “state space model of the DC-DC Boost Converter”.

Below are the “state equation and output equation” respectively :-

$$\begin{bmatrix} \frac{\mathrm{diL}}{\mathrm{dt}} \\ \frac{dvc}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{(1-D)}{L} \\ \frac{(1-D)}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} iL \\ vc \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} [V_S] \tag{3.15}$$

$$[v0] = [0\ 1] \begin{bmatrix} iL \\ vc \end{bmatrix} \tag{3.16}$$

3.3.2. Small Signal Averaged State Space Model

The classical boost converter design and its related "ON" and "OFF" states circuits are viewed in Fig.3.4. The state-space modelled converter obtained in CCM is described in section 3.3.1.

In the above equations of DC- DC Boost Converter lets add this small signals to variables:-

$$i_L = i_L + \tilde{i}_L$$

$$V_C = V_C + \tilde{V}_C$$

$$V_{in} = V_{in} + \tilde{V}_{in}$$

$$D = D + \widetilde{D}$$

After considering all the above equations and steps obtain the "Small Signal State Space" equations by following the similar steps as in state space model :-

$$\begin{bmatrix} \frac{\mathrm{diL}}{\mathrm{dt}} \\ \frac{dvc}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{(1-D)}{L} \\ \frac{(1-D)}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} iL \\ vc \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & \frac{Vc}{L} \\ 0 & -\frac{IL}{C} \end{bmatrix} \begin{bmatrix} vin \\ d \end{bmatrix} \tag{3.17}$$

$$[v0] = [0\ 1\ ] \begin{bmatrix} iL \\ vc \end{bmatrix} \tag{3.18}$$

Where equations 3.17 and 3.18 gives the state equation and output equation in small signal state space[7], [10] of DC-DC Boost Converter.

3.4. DC-DC BUCK-BOOST CONVERTER

A "Buck-Boost Converter" is a kind of DC-to-DC converter which can step up or step down the output voltage in relation to the input voltage. The duty factor of the converter determines the magnitude of the output voltage[2]. Like its AC sibling, it is frequently referred to as a step-up or step-down transformer. The voltage at the input is changed to be more or lower than the voltage at the input. When the conversion cost- effectiveness is high, the power at the input is almost equivalent to the power at the output in this conversion process.

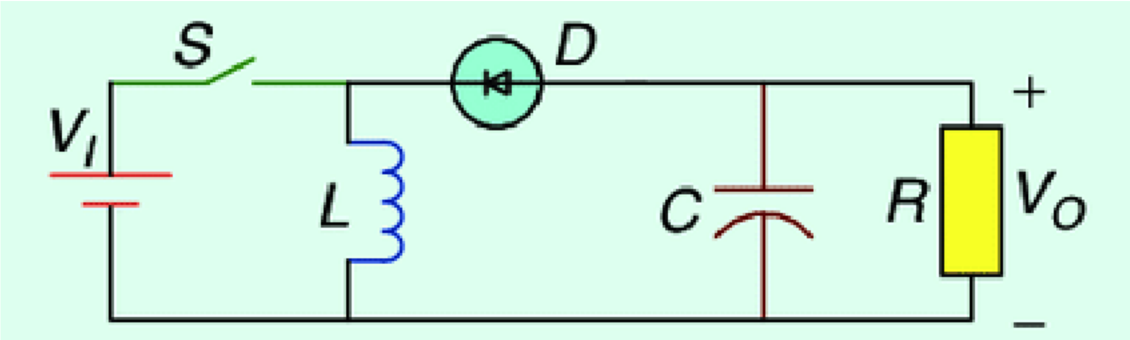


Fig 3.5. Classic DC-DC Buck-Boost Converter

3.4.1. State Space Model

Functioning of Buck- Boost Converter:-

The buck-boost converter functions in one of two ways, as described below.

- First mode, when the switch is “ON”.
- Second mode, when the switch is “OFF”.

Mode 1 : Switch is ON

From fig.3.6.

When a switch in a circuit is turned on, it creates a conduit for electricity to flow with negligible resistance. This current passes via the switch, the inductor, and back to the power supply. The inductor stores charge at this period.

At the time MOSFET is removed, the inductor's polarity upturn, causing the stored energy to discharge. The current can now travel through the load, the diode, and back to the inductor. Because of this reversal, the current flowing through the inductor remains constant during the switching process.

$$V_s = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{V_s}{L} \tag{3.19}$$

$$\frac{dV_C}{dt} = -\frac{V_C}{RC} \tag{3.20}$$

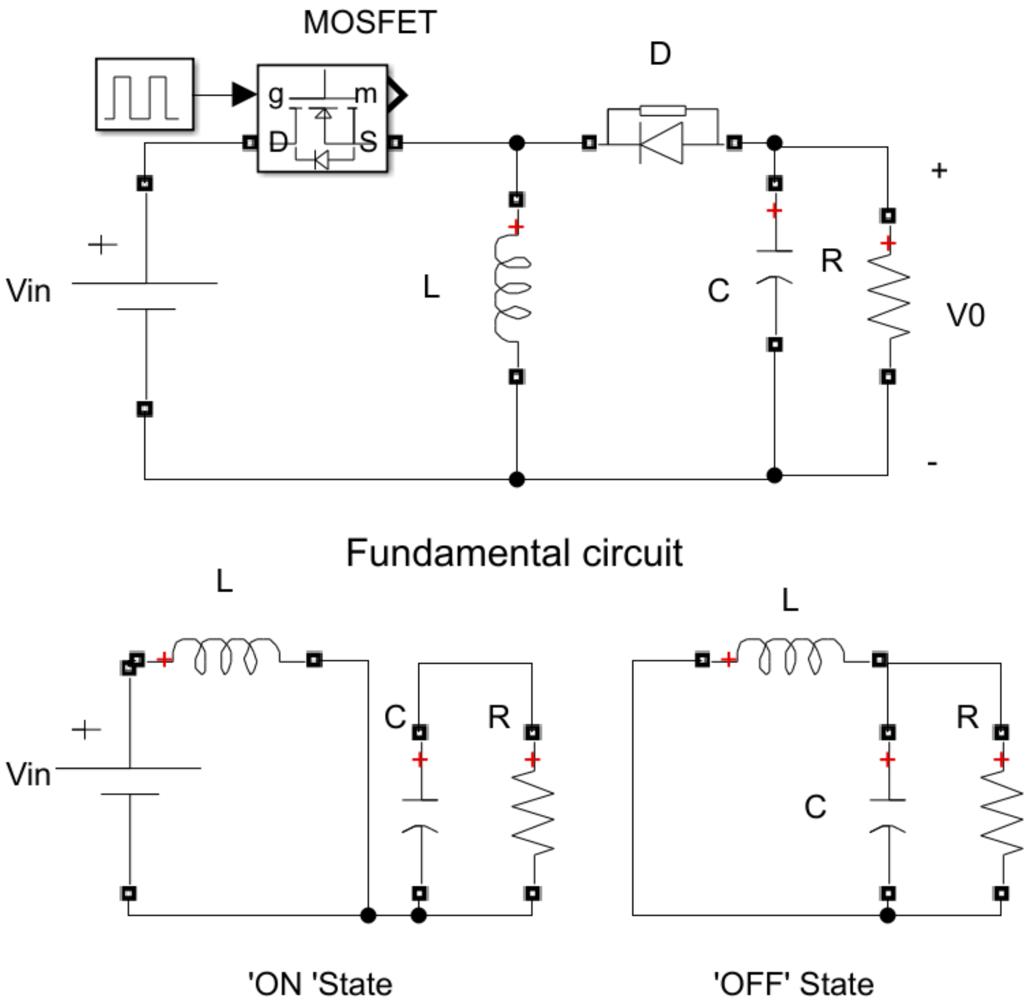


Fig 3.6. Primary buck-boost converter circuits, and it's ON and OFF states

Mode 2: Switch is OFF

The inductor's polarity is reversed in this mode, causing the stored energy to be released and dissipated in the load resistance. This energy discharge helps to keep the current flowing in the same direction across the load while also increasing the output voltage. To accomplish this step-up effect, the inductor functions as a source in concert with the input source.

When analysing the circuit with Kirchhoff's voltage law (KVL), it is critical to follow the original norms and sign conventions to ensure proper calculations and analysis.

$$V_C = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{V_C}{L} \qquad (3.21)$$

$$\frac{dV_C}{dt} = \frac{-i_L}{C} - \frac{-V_C}{RC} \qquad (3.22)$$

Where,

R= load Reasistance

C= Capacitance

Considering all above equations from mode 1 and mode 2 we obtain the input matrix and output matrix in ON state and OFF state separately. And put them in below equations:

$$A=D * A_{on} + (1-D) * A_{off}$$

$$B= D* B_{on} + (1-D) * B_{off}$$

Where, D=Duty Cycle

Thus obtaining the "state space model of the DC-DC Buck- Boost Converter".

Below are the state equation(3.23) and output equation(3.24) respectively :-

$$\begin{bmatrix} \frac{di_L}{\mathrm{dt}} \\ \frac{dv_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{(1-D)}{L} \\ -\frac{(1-D)}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_l \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{D}{L} \\ 0 \end{bmatrix} [V_s] \qquad (3.23)$$

$$[v_0] = [0\ 1\ ] \begin{bmatrix} i_L \\ v_c \end{bmatrix} \qquad (3.24)$$

3.4.2. Small Signal Averaged State Space Model

The classical "buck-boost converter" circuit and its related "ON" and "OFF" states designs are viewed in Fig.3.6. The state-space model[2], [7] converter obtained in CCM is described in section 3.4.1.

In the above equations of DC- DC Buck-Boost Converter lets add this small signals to variables:-

$$i_L = i_L + \tilde{i}_L$$

$$V_C = V_C + \tilde{V}_C$$

$$V_{in} = V_{in} + \tilde{V}_{in}$$

$$D = D + \widetilde{D}$$

After considering all the above equations and steps obtain the "Small Signal State Space equations"[7], [10] by following the similar steps as in state space model :-

$$\begin{bmatrix} \frac{di_L}{\mathrm{dt}} \\ \frac{dv_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{(1-D)}{L} \\ -\frac{(1-D)}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_l \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{D}{L} & \frac{Vin}{L} \\ 0 & \frac{IL}{C} \end{bmatrix} \begin{bmatrix} v_{in} \\ d \end{bmatrix} \tag{3.25}$$

$$[v_0] = [0\ 1\ ] \begin{bmatrix} i_L \\ v_c \end{bmatrix} \tag{3.26}$$

Where equations 3.25 and 3.26 gives the state equation and output equation of "DC-DC Buck-Boost converter" in small signal state space.

CHAPTER 4

LINEAR QUADRATIC REGULATOR

4.1. INTRODUCTION

A “DC to DC converter” receives a DC voltage at input and another DC voltage at the output. The applied input voltage may be higher or lower than the DC output voltage. Converters can be purchased as standalone integrated circuits (ICs), and they only need a few other parts to function. These days, laptops and cell phones frequently employ DC to DC converters. Despite having sub-circuits that manage the voltage need differently than the batteries, they nevertheless get battery power. PID (proportional integral and derivative) controllers are among the generally handed methods of managing converters. Precision systems usually use the idea of subordinate control, while the regulators frequently use PID controllers[8]. They can be used in a single system in extremely large numbers, which ultimately leads to much complicated PID regulator managenent and makes it more difficult to offer the essential transient process quality parameters.”The answer to this problem is the introduction of a classically new controller in the controlling system, specifically the linear-quadratic regulator. Linear-quadratic regulators (LQR) [21]have several noteworthy properties in terms of control techniques. For instance, they can be employed methodologically independent of the system's order and they are fundamentally stable. They can also make the system behave "optimally" in accordance with the designer's needs. Additionally,“LQR [22]can be obtained directly using the system's “small signal state-space averaged model”. The organisation of this essay is as follows. It is first addressed how to account for one-sample actuation delay and eliminate a null-order defect in steady-state”situations while using the LQR basis. Later, a controller for each of the three converters is created using this process. Additionally provided to support the controller's behaviour are the simulation findings.

4.2. OPEN LOOP SIMULATION OF DC-DC CONVERTER SYSTEMS

4.2.1. DC-DC Buck Converter

Definition: A buck converter is a kind of DC to DC converter that generates voltage at the output that is less than the voltage at the input. Because it reduces the source voltage, it is usually called as a step-down converter. A buck converter is normally made up of two semiconductors, specifically a diode and a transistor, as well as an energy storing parameters such as a capacitor, inductor, or a combination of the two. These components work together in the circuit to produce the desired voltage reduction.

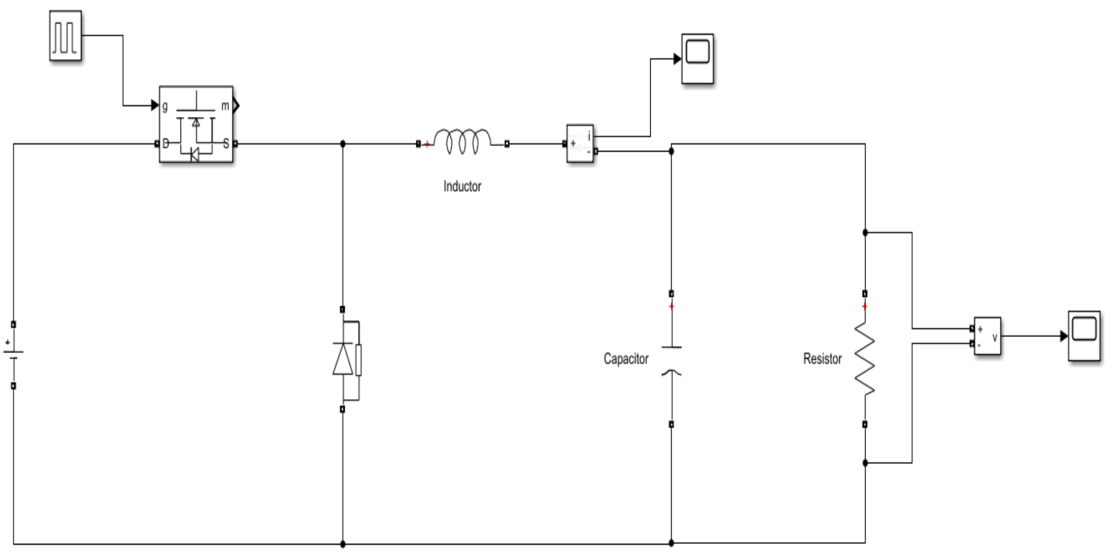


Fig 4.1. DC-DC Buck Converter model in MATLAB SIMULINK

This is an open loop "DC-DC Buck Converter" system whose performance is explained in the Results and Discussion. There is no optimization technique[23] applied on this as of now. To obtain the precise outcome, a variety of optimisation approaches as well as intelligent strategies can be applied which is discussed further.

In this LQR and MPC is used as an advance control strategy. To find solutions that maximize or minimize certain research characteristics.

TABLE 4.1. PARAMETERS OF DC-DC BUCK CONVERTER

Parameters	**Rated Values**
Voltage at the input(Vin)	12Volts
Voltage at the output(V0)	5Volts
ON/OFF Frequency	25KiloHertz

Power(P)	100Watt
Duty Factor (D)	0.4
Inductor Current at input	1.25Ampere
Inductor (L)	76.8uH
Capacitor (C)	400uF
Load Resistance(R)	4ohm

4.2.2. DC-DC Boost Converter

- A DC to DC converter called a "boost converter" has voltage at the output that is higher than the original source voltage. Step-up converter is another name for it.
- Any acceptable DC source, including solar panels, batteries, DC generators and rectifiers , can provide power to the boost converter.
- The I flowing from the output is smaller than the original source current because power that is P=VI should be preserved.

Checking the performance of the "DC-DC Boost Converter" in open loop.

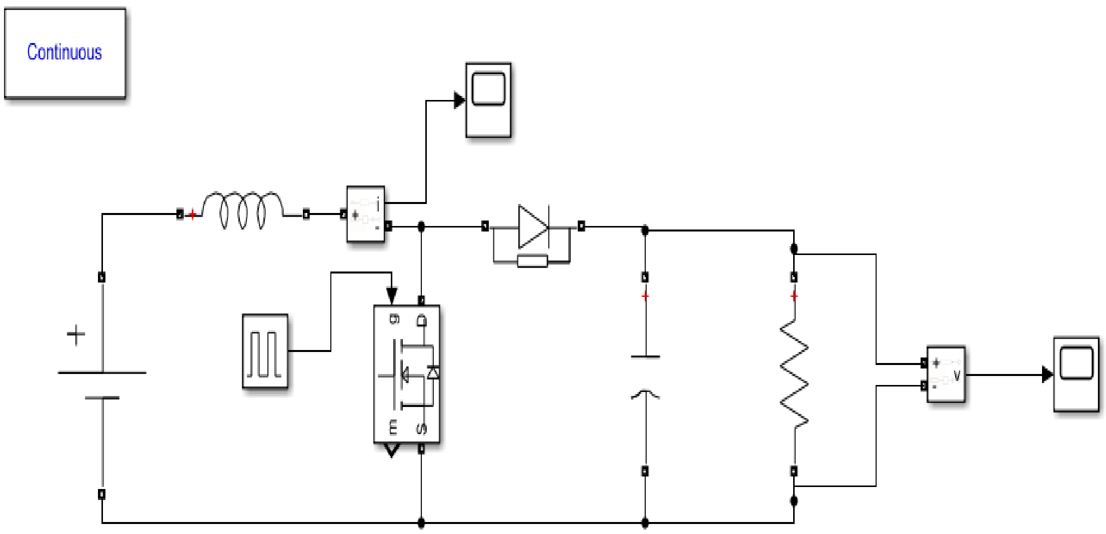


Fig 4.2. DC-DC Boost Converter Diagram in MATLAB Simulink

TABLE 4.2. PARAMETERS OF DC-DC BOOST CONVERTER

Parameters	Rated Values
Voltage at the input (Vin)	12V
Voltage at the output(V0)	20V

ON-OFF Frequency	25KHz
Power(P)	100Watts
Duty Factor(D)	0.4
Current at output(I0)	5Ampere
Current at input	8.33Ampere
Ripple in Inductor Current	2.5Ampere
Ripple in Output Voltage	0.2Volts
Inductor(L)	$76.8*10^{-6}$Henery
Capacitor(C)	$400*10^{-6}$ Farad
Load Resistance(R)	4ohm

4.2.3. DC-DC Buck-Boost Converter

A DC-to-DC converter known as a buck-boost can generate output voltages that are either greater or lower than the input voltage. The converter's duty cycle controls how much output voltage is produced. Because they can change the input voltage level, these converters, which resemble AC transformers, are occasionally called step-up or step-down transformers.

The input voltage (Vin) is less than the output voltage (Vout) in the step-up mode.

In contrast, the input voltage is greater than the output voltage in the step-down mode (Vin > Vout).

We are using the Buck-Boost converter in step-down mode in this particular scenario.

The output of a Buck-Boost converter inverts (changes from positive to negative) the DC input voltage. The MOSFET's conduction state has an impact on how the circuit functions.

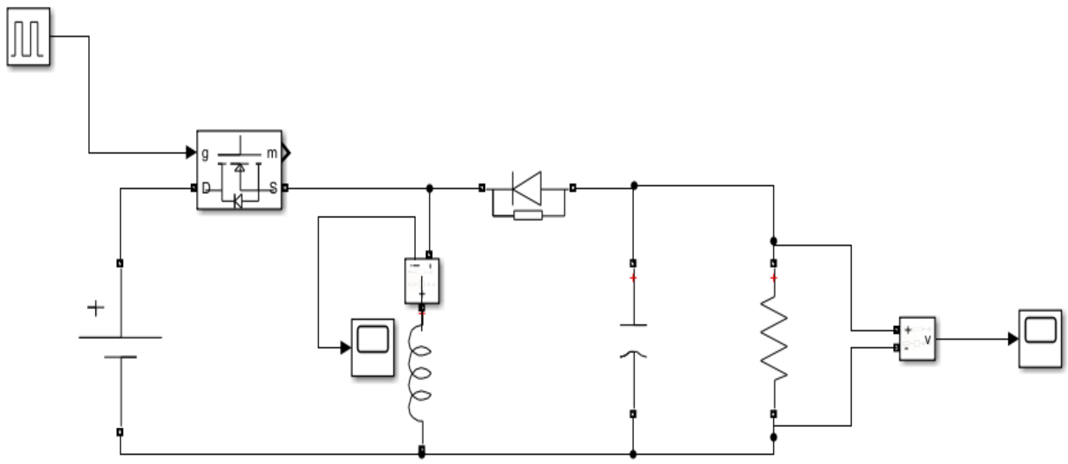


Fig 4.3. DC-DC Buck-Boost Converter Diagram in MATLAB Simulink

TABLE 4.3. PARAMETERS OF DC-DC BUCK- BOOST CONVERTER

Parameters	**Rated Values**
Voltage at the input (Vin)	12V
Voltage at the output(V0)	-8V
ON-OFF Frequency	25KHz
Power(P)	100W
Duty Factor(D)	0.4
Current at input	3A
Inductor(L)	76.8uH
Capacitor(C)	400uF
Load Resistance(R)	4ohm

Above are the open loop systems whose performance is discussed in the Results and Discussion. There is no optimization technique applied on this as of now. To obtain the precise outcome, a variety of optimisation approaches as well as intelligent strategies can be applied which is discussed further.

Likewise Linear Quadratic Regulator is used as an advance control strategy for DC-DC Converter Systems. To find solutions that maximize or minimize certain research characteristics and which has reduced the steady state error of the systems.

4.3. LINEAR QUADRATIC REGULATOR

Although it is often difficult to find a solution to the dynamic programming problem for continuous systems, there are some particular situations where this is true. The linear quadratic regulator (LQR), a system with linear dynamics and quadratic cost, is one example of such a system. The LQR is a linear system that is time-invariant and seeks to stabilise at the origin[24].

In the area of optimal control theory, the linear quadratic regulator is quite significant and influential. This chapter will examine the basic LQR technique and several upgrades that can be used to boost the tool's functionality.

The LQR control system is a type of efficient control system. This plays a key role in Control engineering. Integral performance metrics can be used to represent the behaviour of a control system[3], [13]. As a result, the system's design must focus on reducing a cost function.

Consider a linear time-invariant system in state-space form,

$$\dot{x} = Ax + Bu \tag{4.1}$$

A "quadratic performance index (J)" is to be reduced, that is what a strategy a LQR holds:

$$J = \int_0^\infty (x^T Q(t)x(t) + u^T(t)Ru(t))dt \tag{4.2}$$

Here, Q= positively semidefinite symmetric matrix, R=positively definite symmetric matrix.

The best way to solve a quadratic equation is to figure out the controlling condition u(t) resulting in J's smallest value. The state-space model for the system limits its performance:

$$\frac{d}{dt}x(t) = Ax(t) + Bu(t) \tag{4.3}$$

$$y(t) = Cx(t) + Du(t) \tag{4.4}$$

This system probably has controlled states.

$$u(t) = -Kx(t) \tag{4.5}$$

Finding gain, K (11):

$$K = R^{-1}.B^{T}.P \tag{4.6}$$

where, P is an "Algebraic Riccati equation" solution:

$$A^{T}.P + P.A - P.B.R^{-1}.P + Q = 0 \tag{4.7}$$

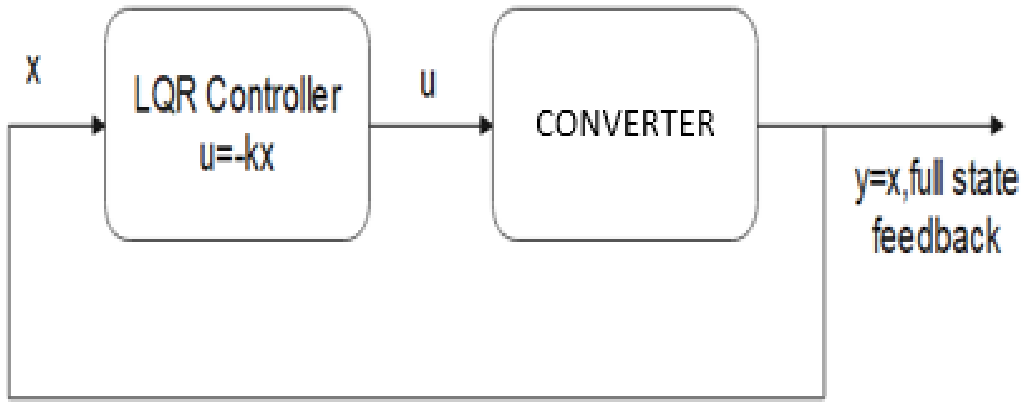


Fig.4.4. Schematic Linear Quadratic Regulator

4.3.1. "Discrete Time System"

This application uses digital control for further use on hardware, hence the study would be done on the basis of a discrete system[25].

Therefore, (4.3) and (4.4) must be transformed into discrete as shown below:

$$J = \frac{1}{2}x^{T}Mx(N) + \frac{1}{2}\sum_{K=0}^{N-1}[x^{T}(k)Qx(k) + u^{T}(k)\,Ru(k)] \tag{13}$$

And

$$x(k+1) = A_{d}x(k) + B_{d}u(k) \tag{14}$$

Here, Ad and Bd are obtained in the form

such that:

$$A_d = e^{ATs} \quad and \quad B_d = (\int_0^{Ts} e^{A\tau}\, d\tau)\, B \tag{15}$$

Afterwards a linear quadratic regulator allowed to converters to examine their function.

Creating the system modelling using equations of state and insert the numbers from table 4.1 into the small signal state-space equations of DC-DC Converters[2], [10] which is explained in chapter 3. After that convert the CCM system to DCM system referring above equations.

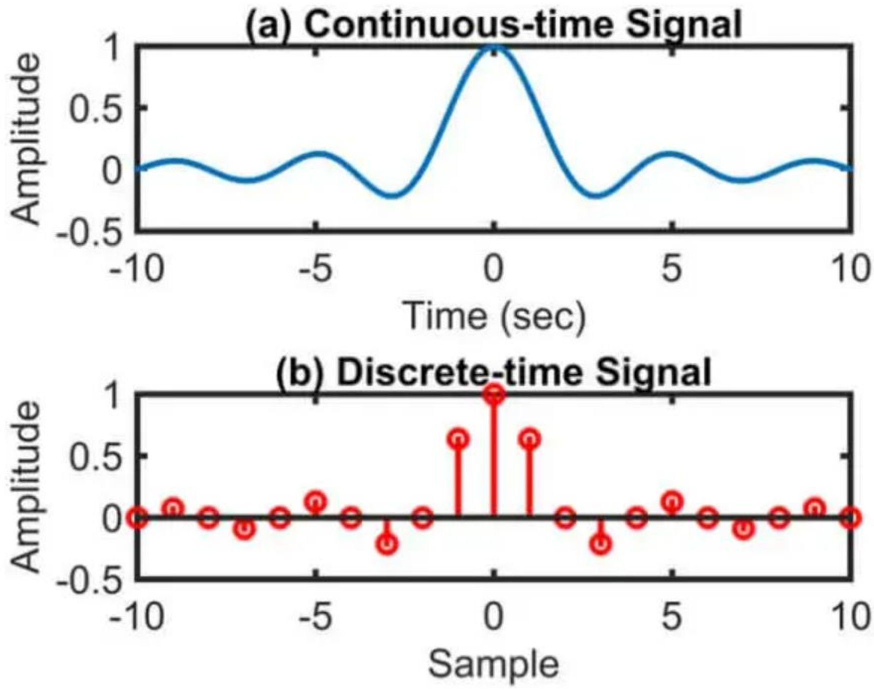


Fig 4.5: Example of Discrete vs Continuous data

TABLE 4.4 Continuous time signal versus Discrete Time Model

Continuous Time Signal	**Discrete Time Signal**
A natural signal is analogly represented by the continuous-time signal.	The discrete-time signal is a digital representation of a continuous-time signal.

The Euler's approach can transform a continuous-time signal into a discrete-time signal.	The methods of zero-order hold or first-order hold can be used to transform the discrete-time signal into a continuous-time signal.
Compared to the conversion of discrete to continuous-time signals, the conversion of continuous to discrete-time signals is simpler.	A sample and hold technique is used to convert discrete to continuous-time signals, which is a very complex procedure.
It can be defined across an infinite or finite sequence domain.	It has a bounded domain of sequence definitions.
Any arbitrary time point can be used to determine the signal's value.	The signal's value can only be determined at sampling points in time.
The method of processing of digital signals does not involve the continuous-time signals.	The processing of digital signals uses discrete-time signals.
The letter t is used to represent the continuous-time variable.	The discrete-time variable is denoted by a letter n.
The independent variable encloses in the parenthesis (.).	The independent variable encloses in the bracket [.].

CHAPTER 5

MODEL PREDICTIVE CONTROLLER

5.1. INTRODUCTION

In this study, Model Predictive Control (MPC) and Linear Quadratic Regulator (LQR) optimisation methodologies[26] are used to compare the closed-loop response of a DC-DC Buck Converter. Specifically, a condensed discrete model-based predictive control strategy is suggested for a converter running in Continuous Conduction Mode (CCM). The discrete model is made simpler by the linearization of the converter's matrix coefficients, which makes the control decision computation simple. Then, nonlinear model predictive control is used to tackle the control task. The usefulness of the predictive control method is demonstrated by simulation results, which indicate that it can quickly and accurately adjust output under different operating situations. Additionally, the use of digital technology to perform the predictive control method online demonstrates its viability.

The most common criteria that need to be met during the design of DC/DC converters[7] include maximizing performance and enhancing power density while reducing the overall cost. The process of choosing feedback gains for a closed-loop control system that adhere to design parameters is known as control system design. The majority of design techniques are iterative, incorporating parameter selection with analysis, simulation, and knowledge of the system's dynamics. Various control approaches are described in this work on DC-DC Buck Converter. The DC-DC converter topologies used for various needs are required to manage continuous inputs so ripple minimization is possible. In paper the classic ways to control converters are compared. On the converter, a feedforward control system combined with a “linear quadratic regulator (LQR)”were successfully tested. The control approach, as described in section 5, has a significant downside, though. This is the driving factor behind the use of “model predictive control (MPC)”. Model predictive controllers solve a quadratic program at each control interval to determine the best controlled variable control moves. A linear quadratic regulator with no limitations and output weighting was made. This controller acts as a comparison point for the particular MPC algorithm(Wahl & Gilles, 2015). Further Designed a unique MPC controller that applies the terminal weight at the final prediction step. Linear Quadratic Regulator Control behaviour is analyzed when applying limitations compared with MPC Controller which solves Quadratic Programming(QP)[28] problem online when implementing limitations.

5.2. MODEL PREDICTIVE CONTROL

Model Predictive Control[19] is a Dynamic System Model-Based Optimal Control Strategy. Since its inception, it has grown in popularity in industries for restrained system control. A model predictive controller employs linear plant, disturbance, and noise models to evaluate the control system state and forecast future converter's outputs. To determine control moves, the controller solves a quadratic programming optimization problem using the forecast converter outputs.

The model structure used in an MPC controller appears in the following illustration.

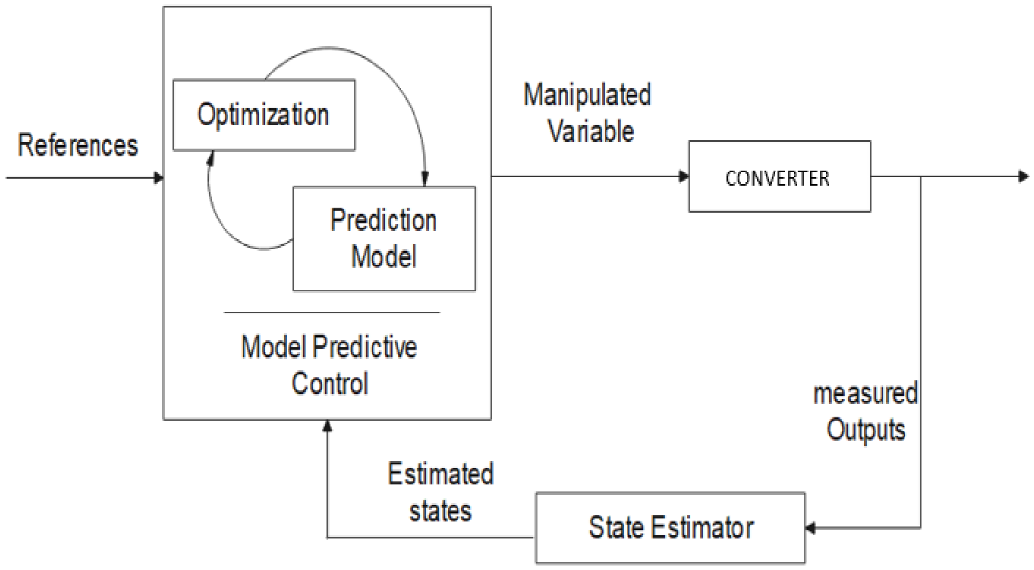


Fig. 5.1. Schematic of Model Predictive Control

A finite horizon open-loop optimum control problem[16] subject to the dynamics and constraints of the system is typically solved online in order to implement model predictive control.

Mapping the input:- $u = [u_1, u_2, \dots, u_{n_c}] \rightarrow u(t)$

Taking the performance index

$$J(u) = f^T(u) f(u) \tag{5.1}$$

Subjected to constraints

$$-u_{max} \leq u_k \leq u_{max}$$

$$-\Delta u_{max} \leq u_k - u_{k-1} \leq \Delta u_{max} \qquad where\ k = 1, \dots, n_c \tag{5.2}$$

Taking plant model for prediction

$$\dot{x}(t) = A\big(x(t)\big)x(t) + b(x(t))u(t) \tag{5.3}$$

Minimizing performance index provides the optimal control vector $u^* = [u_1^*, u_2^*, \dots, u_{n_c}^*]$ and matching the mapping of the ideal angle u*(t) over the control horizon. Additionally, the performance index can be selected from a variety of performance indexes(Institute of Electrical and Electronics Engineers & IEEE Power Electronics Society, n.d.). A quadratic cost function for optimization is given by:

$$J = \sum_{i=1}^{N} w_{x_i} (r_i - x_i)^2 + \sum_{i=1}^{N} w_{u_i} \Delta(u_i)^2 \tag{5.4}$$

Where,

x_i: i^{th} regulated variable

r_i: i^{th} reference variable

u_i: i^{th} manipulated variable

w_{xi}: weighting coefficient that reflects the relative importance of x_i

w_{ui}:weighting coefficient penalizing relative bog changes in u_i.

Figure 5.3 shows the fundamental notion underlying Model Predictive Control[5]. After defining a path of reference for the converter's output, we have to optimize it as efficiently as possible.

We specifically want to strike a balance between the path error index and different cost metrics like the ferocity with which the control action is implemented. An output prediction curve is being obtained at the moment of sampling. It shows how the output signal should proceed in order to reach the reference trajectory[18], [21].

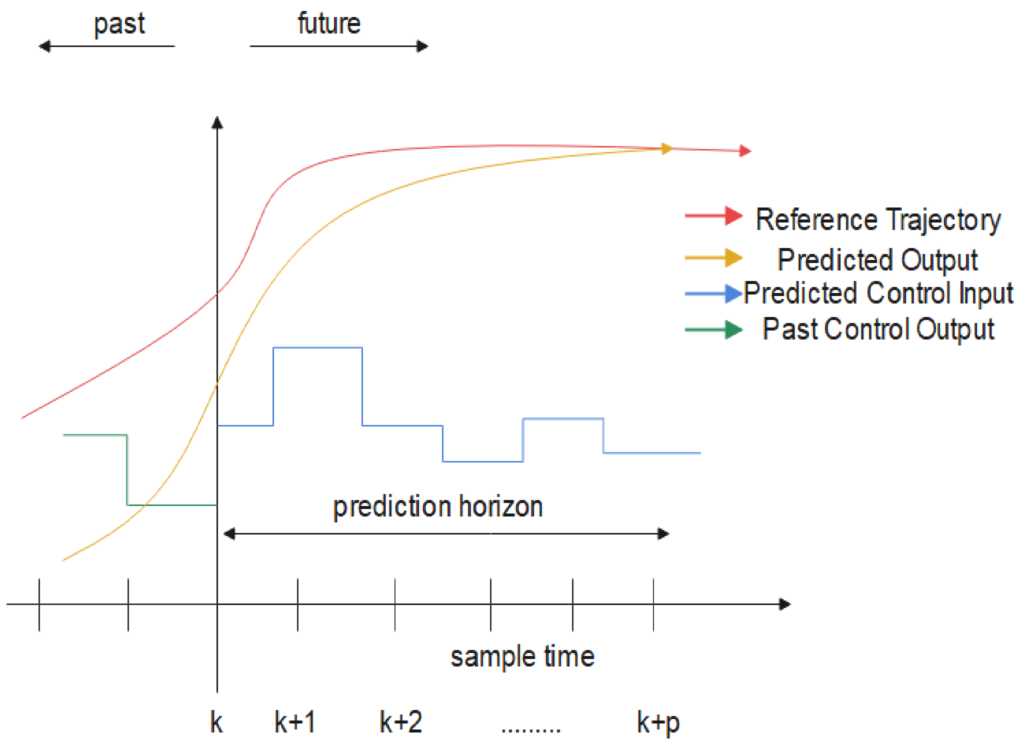


Fig. 5.2. A discrete Model Predictive Control

5.2.1. Quadratic Programming

For quadratic objective functions[28], [30] with linear constraints, there is a solver called quadratic programming(Wahl & Gilles, 2015). It determines a minimum for a problem that is given

$$min_x \frac{1}{2} x^T H x + f^T x \tag{5.5}$$

subjected to constraints

$$A.x \leq b, \quad A_{eq}.x = beq, \quad lb \leq x \leq ub \tag{5.6}$$

5.3.SUMMARY OF THE PROBLEM STATEMENT

Taking into account time-independent, linearized, and discrete systems that are characterized by converter's[31] state-

space function .

$$x_{t+1} = Ax_t + Bu_t \tag{5.7}$$

$$y(t) = Cx(t) + Du(t) \tag{5.8}$$

In which A= the state transition and B= input distribution matrices respectively, and $x_t \in R^n$ and $u_t \in R^m$. By taking the converter parameters from table 1 and putting in to obtain matrix A and B respectively.

The main goal is given over an infinite horizon and is defined as

$$\varphi(x_t, \pi) = \sum_{j=t}^{\infty} x'_{j|t}\, Qx_{j|t} + u'_{j|t} R u_{j|t} \tag{5.9}$$

In which $Q \geq 0$ and $R > 0$ are symmetric weighting matrices, such that ($Q^{1/2}$, A) is detectable, and

$$\pi = \{u_{t|t}, u_{t+1|t}, \ldots\ldots\}$$

$$x_{j+1|t} = Ax_{j|t} + Bu_{j|t}, \qquad t \leq j \tag{5.10}$$

With $x_{j|t}$ =x. On an infinite horizon, the constraints are also specified, and they take the form of

$$Hx_{j+1|t} \leq h, \qquad t \leq j$$

$$Du_{j|t} \leq d \tag{5.11}$$

Where $h \in R^{n_h}$ and $d \in R^{n_d}$ define the limitation levels, with n_h= state constraints and n_d= input constraints, and H and D are the distribution matrices of state and input constraints(Sahoo et al., 2016).

In this paper, we outline three important control problems of interest.

Problem 1__LQR:

$$min_x \varphi(x_t, \pi)$$

Subjected to:

$$x_{j+1|t} = Ax_{j|t} + Bu_{j|t} \quad , \qquad t \leq j \tag{5.12}$$

Problem 2__Constrained LQR:

$$min_x \varphi(x_t, \pi)$$

Subjected to:

$$x_{j+1|t} = Ax_{j|t} + Bu_{j|t} \quad , \qquad t \leq j$$

$$Hx_{j+1|t} \leq h, \qquad t \leq j$$

$$Du_{j|t} \leq d. \tag{5.13}$$

Problem 3__ An MPC Problem:

$$min_x \varphi(x_t, \pi)$$

Subjected to:

$$x_{j+1|t} = Ax_{j|t} + Bu_{j|t} \quad , \qquad t \leq j$$

$$Hx_{j+1|t} \leq h, \qquad t \leq j \leq t + N - 1$$

$$Du_{j|t} \leq d.$$

$$u_{j|t} = -Kx_{j|t}, \qquad t + N \leq j \tag{5.14}$$

TABLE 5.1 Parameters of DC-DC Buck Converter for the analysis of the comparison between LQR and MPC

Parameters	**Rated Values**
Input Voltage(Vin)	12Volts
Output Voltage(V0)	5Volts
Switching Frequency	25KiloHertz
Power(P)	100Watt
Duty Factor (D)	0.4

Inductor (L)	100microHenry
Capacitor (C)	1000microFarad
Load Resistance(R)	15ohm

Transforming the DC-DC Buck Converter's property to state-space[7] and then transforming the system to discrete time for applying all the three problem statements and observing the result.

CHAPTER 6

RESULTS AND DISCUSSION

6.1. OPTIMIZATION THROUGH LINEAR QUADRATIC REGULATOR

MATLAB Simulink is used to obtain the response of open loop DC-DC Converters performance analysis.

6.1.1. DC-DC Buck Converter

6.1.1.1. Open loop response

After running the open loop converter simulation mentioned in section 4.2.1 we get the following outputs:-

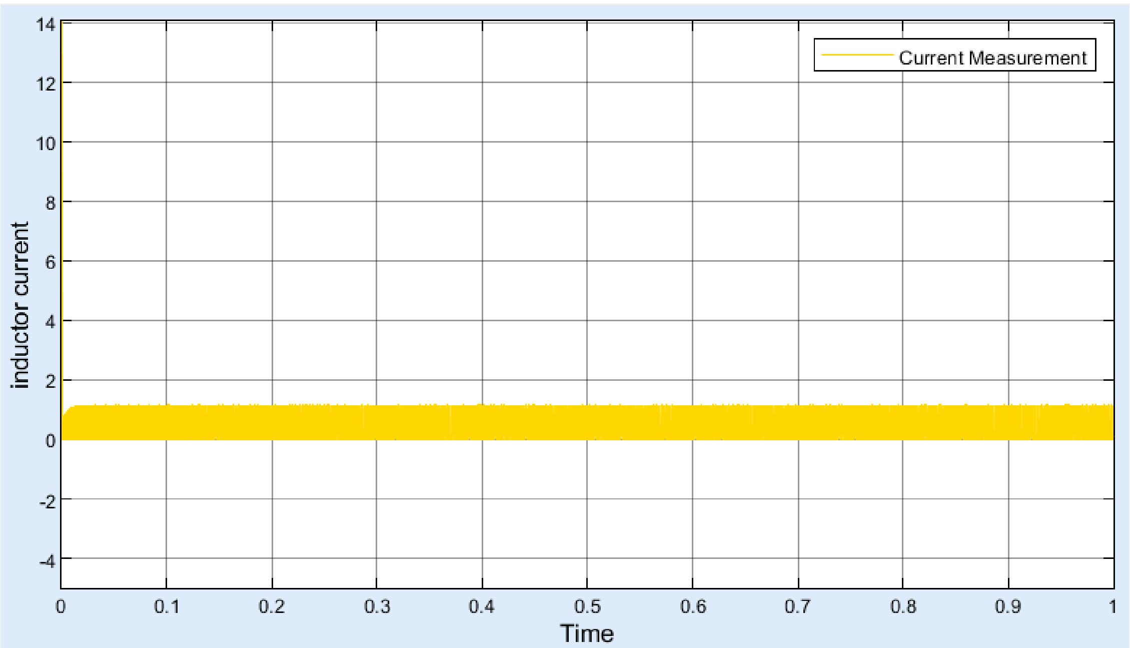


Fig 6.1. Input Inductor current of Open loop buck-converter

TABLE 6.1. Signal Statics of inductor current in dc-dc buck converter

	Value (Ampere)	**Time(second)**

Max	$1.405*10^{+01}$	$4.568*10^{-04}$
Min	$-1.105*10^{-02}$	$9.44*10^{-04}$
Peak to Peak	$1.407*10^{+01}$	
Men	$3.547*10^{-01}$	
Median	$1.436*10^{-02}$	
RMS	$6.269*10^{-01}$	

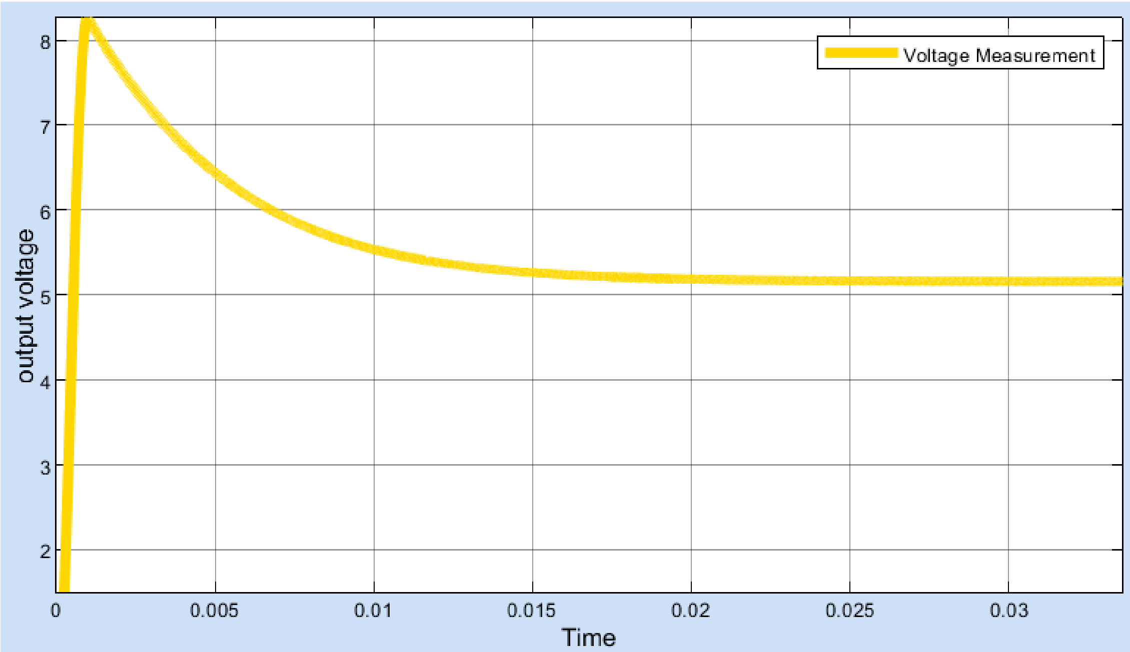


Fig 6.2. output voltage of Open loop buck-converter

TABLE 6.2: Signal Statics of output voltage in dc-dc buck converter

	Value (Volts)	**Time(second)**
Max	8.260	$9.768*10^{-04}$
Min	$1.200*10^{-03}$	$0.000*10^{-04}$
Peak to Peak	8.259	
Mean	5.240	
Median	5.160	
RMS	5.255	

By comparing the table 4.1 to table 6.1 and 6.2 we can see from the graph that we didn't get the result similar to our rated value. The input inductor current value after simulation we get is 0.35A but our rated value is 1.25A whereas output voltage obtained is 5.240 and rated output voltage is 5V.

We can see that the result obtained by simulation is not fully similar to our classified parameters. The main reason for this is due to the fact that we have designed boost converter as open loop. In open loop we need the manual tuning of the duty cycle of the pulse generator. Therefore, we need to try again and again to get the accurate result. Another method to get accurate result is to use closed loop boost converter.“ To obtain the precise outcome, a variety of optimisation approaches as well as intelligent strategies can be applied. Here we have applied LQR[4] to reduce the steady state error of the system.

6.1.1.2. Control strategy LQR on Buck Converter

The following equation (6.1) is the outcome of applying a discrete time system to the CCM models of converters in MATLAB[7]:

$$A_d = \begin{bmatrix} 0.0414 & -0.0389 \\ 0.0075 & 0.0396 \end{bmatrix},$$

$$B_d = \begin{bmatrix} 0.1114 & 3.3423 \\ 0.3834 & 11.5027 \end{bmatrix} \quad (6.1)$$

For vectors Q and R, the element values we select are (17):

$$Q = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},$$

$$R=1 \quad (6.2)$$

solving the LQR problem for gain K using the MATLAB programme:

$$K = \begin{bmatrix} 0.0000 & -0.0007 \\ 0.0003 & -0.0211 \end{bmatrix} \quad (6.3)$$

This matrix includes each value needed for LQR control.

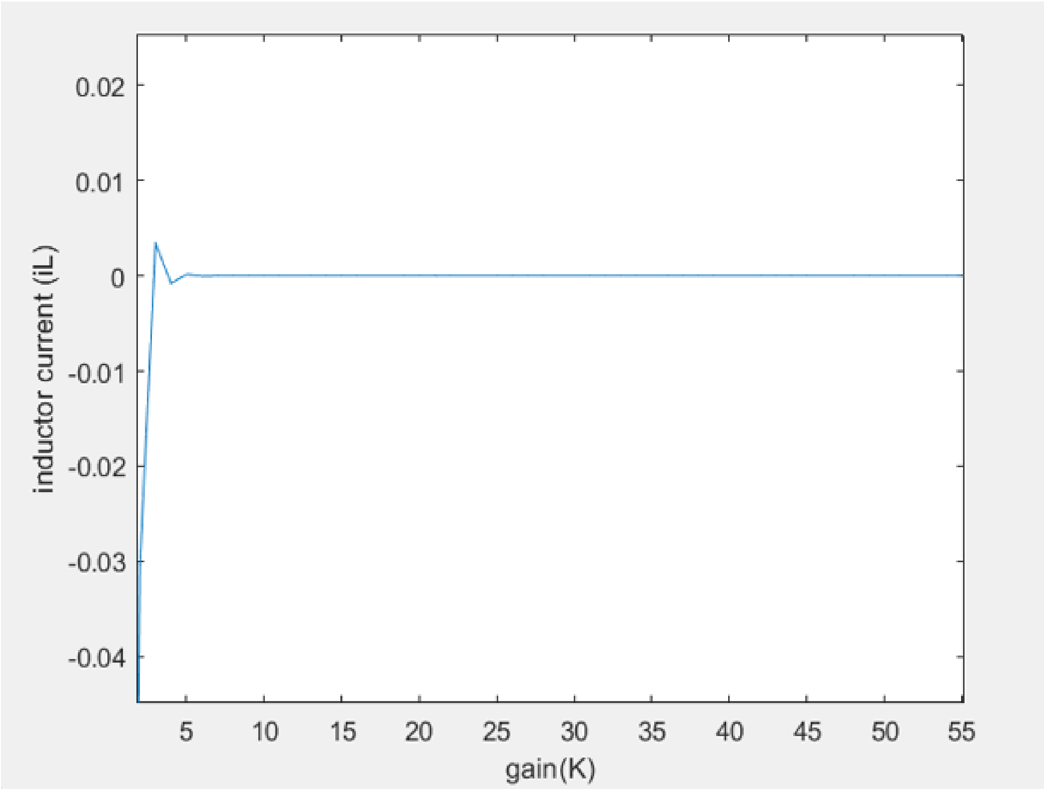


Fig. 6.3. Steady State Response of Inductor current of Buck Converter

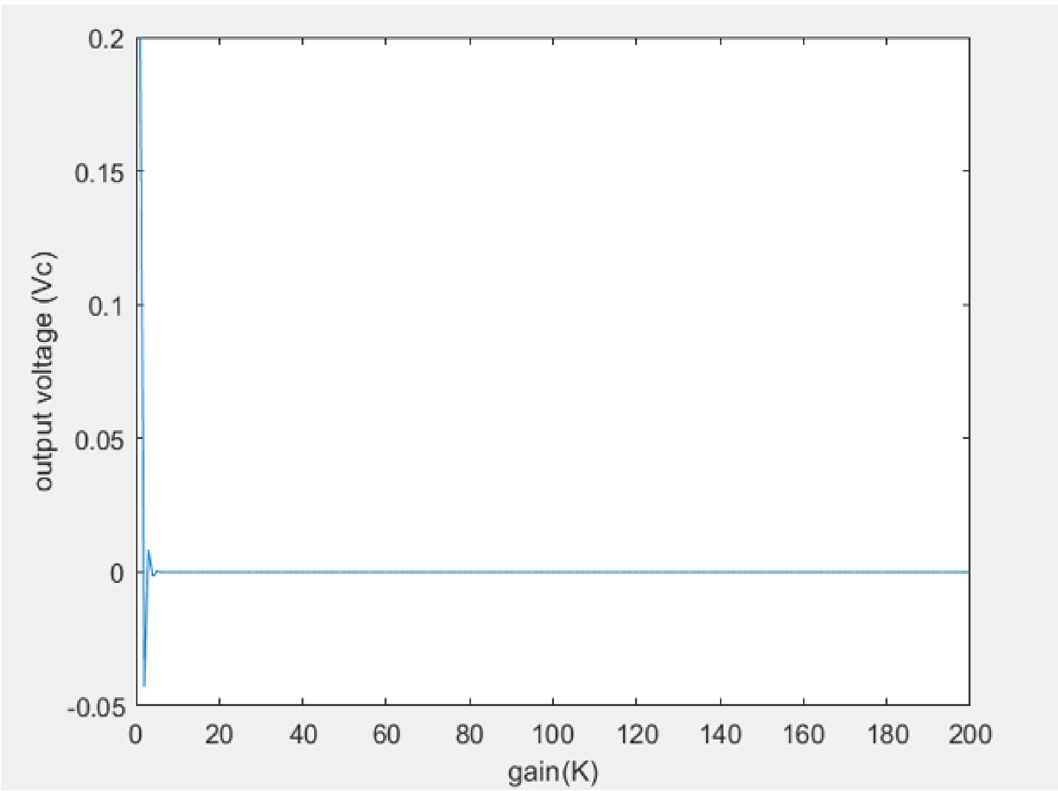


Fig 6.4 . Steady State Response of Output voltage of Buck Converter

6.1.2. DC-DC Boost Converter

6.1.2.1. Open Loop Response

After running the open loop converter simulation [7]mentioned in section 4.2.2 we get the following outputs:-

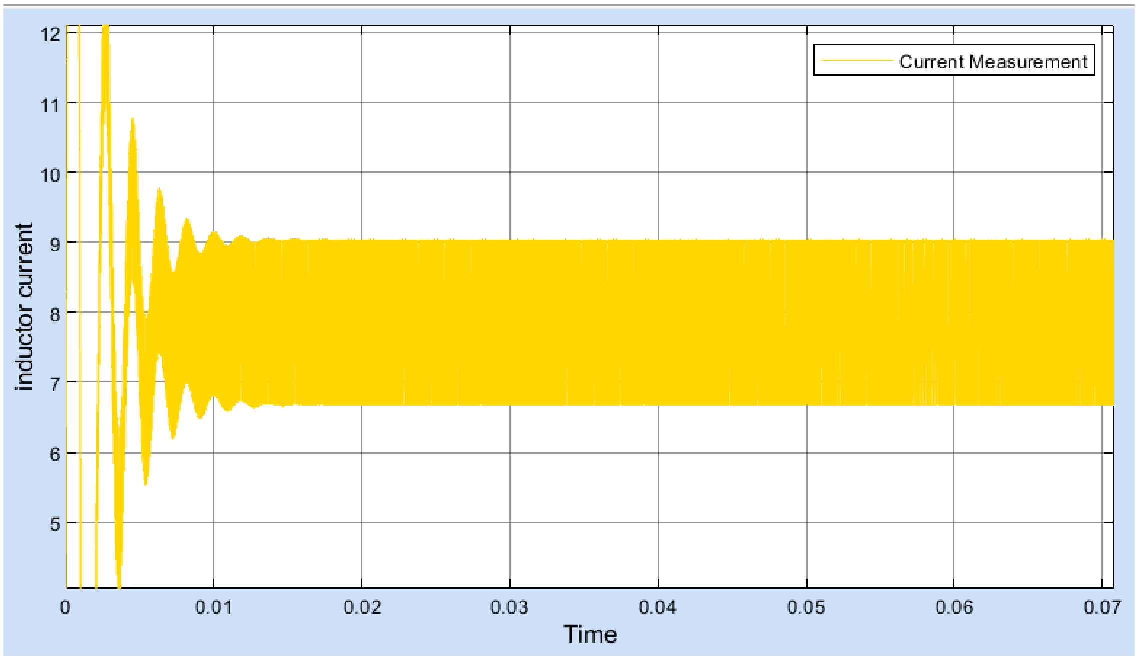


Fig 6.5. Inductor current of Open loop boost-converter

TABLE 6.3. Signal Statics of inductor current in dc-dc boost converter

	Value (Ampere)	**Time(second)**
Max	$4.119*10^{+01}$	$4.560*10^{-04}$
Min	$-1.846*10^{-02}$	$1.070*10^{-03}$
Peak to Peak	$4.121*10^{+01}$	
Men	7.794	
Median	7.466	
RMS	7.886	

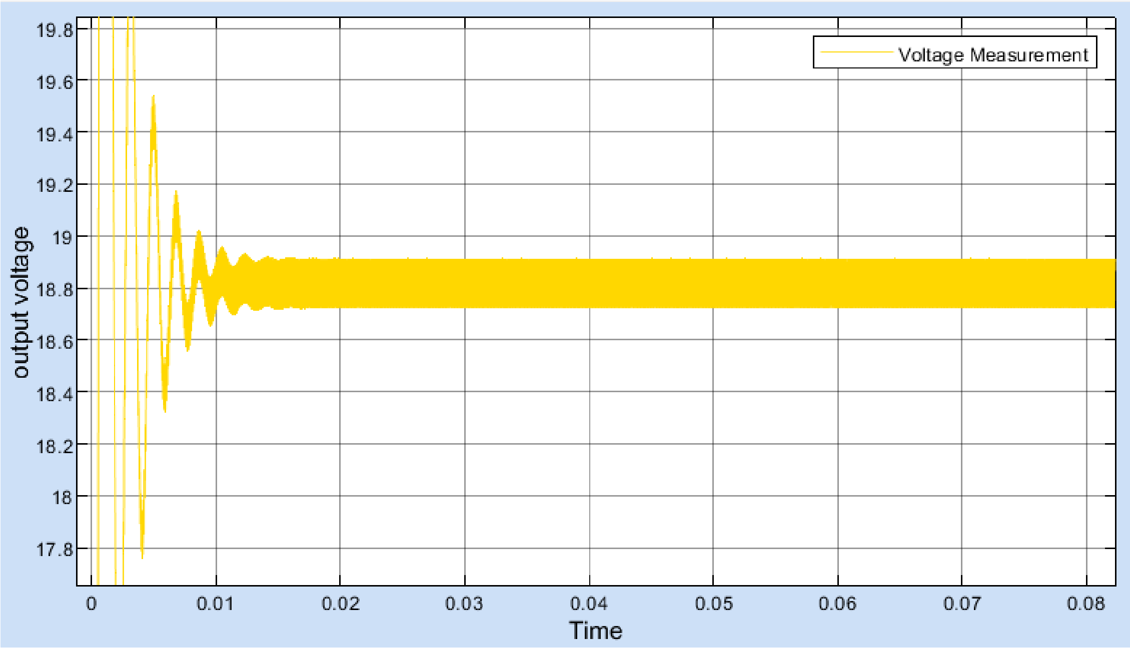


Fig 6.6. output voltage of Open loop boost-converter

TABLE 6.4. Signal Statics of output voltage in dc-dc boost converter

	Value (Volts)	**Time(second)**
Max	$2.979*10^{+01}$	$9.200*10^{-04}$
Min	$-8.869*10^{-04}$	$1.600*10^{-05}$
Peak to Peak	$2.979*10^{+01}$	
Men	$1.887*10^{+01}$	
Median	$1.887*10^{+01}$	
RMS	$1.893*10^{+01}$	

By comparing the table 4.2 to table 6.3 and 6.4 we can see from the graph that we didn't get the result similar to our rated value. The input inductor current value after simulation we get is 7.7A but our rated value is 8.33A whereas output voltage obtained is 18.87V and rated output voltage is 20V.

As stated earlier in 6.1.1. similarly applying LQR to reduce the steady state error of the system.

6.1.2.2. Control strategy LQR on boost converter

The following equation (6.4) is the result of applying the discrete time system to the CCM models of converters in MATLAB:

$$A_d = \begin{bmatrix} -0.0371 & -0.0466 \\ 0.0090 & -0.0408 \end{bmatrix},$$

$$B_d = \begin{bmatrix} 0.7978 & 20.2780 \\ 1.7285 & 34.5321 \end{bmatrix} \quad (6.4)$$

For vectors Q and R, the element values we select are in equation 6.2

solving the LQR problem for gain K using the MATLAB program:

$$K = \begin{bmatrix} 0.0190 & -0.0226 \\ -0.0009 & -0.0060 \end{bmatrix} \quad (6.5)$$

This matrix includes each value needed for LQR control."

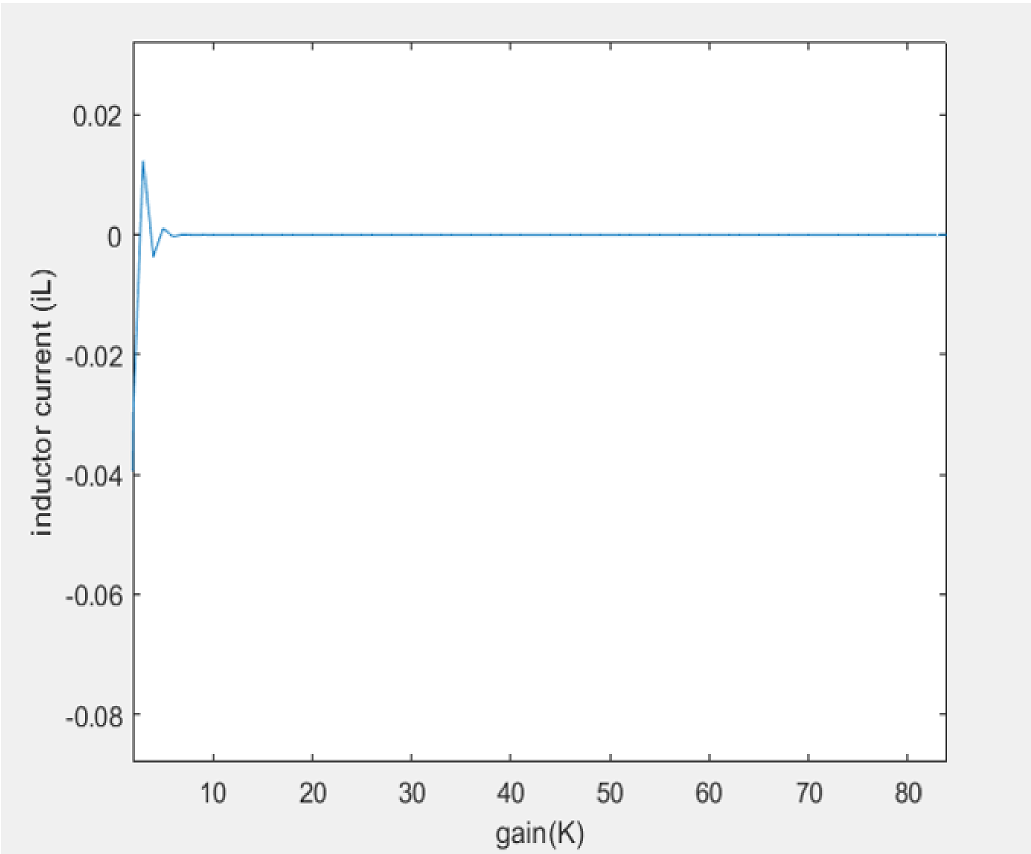
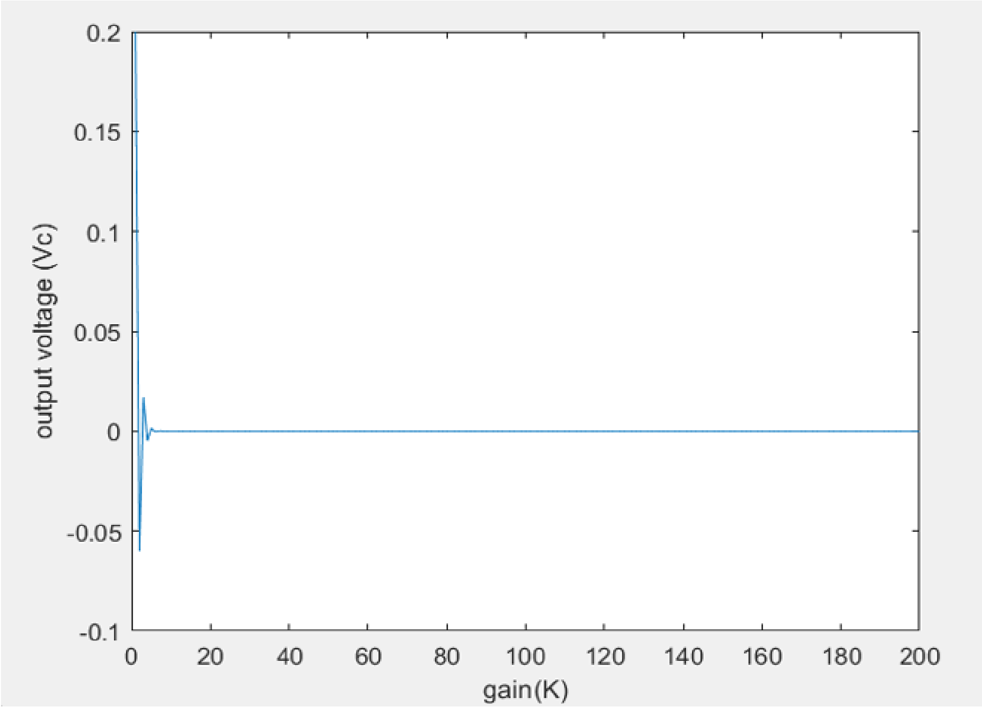


Fig 6.7. Steady State Response of Inductor current of Boost Converter



(b)

Fig. 6.8. Steady State Response of Output voltage of Boost Converter

6.1.3. DC-DC Buck-Boost Converter

6.1.3.1. Open Loop Response

After running the open loop converter simulation mentioned in section 4.2.3 we get the following outputs:-

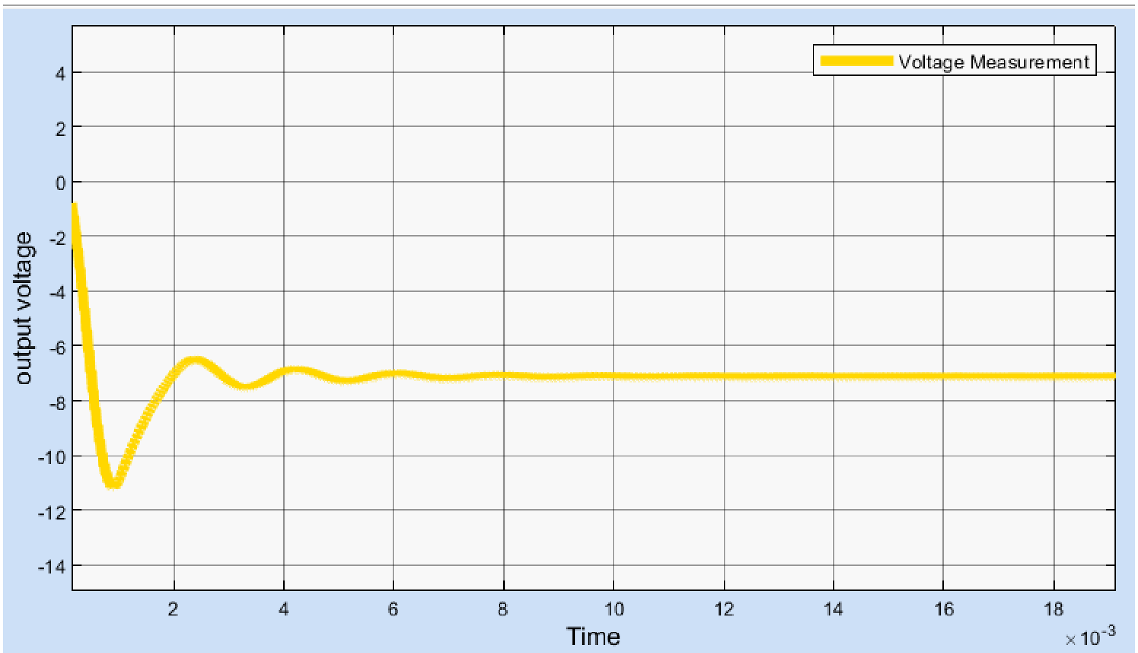


Fig 6.9. output voltage of Open loop buck-boost converter

TABLE 6.5. Signal Statics of output voltage in dc-dc boost converter

	Value (Volts)	**Time(second)**
Max	$-7.807*10^{-01}$	$1.360*10^{-04}$
Min	$-1.118*10^{+01}$	$8.800*10^{-04}$
Peak to Peak	$1.040*10^{+01}$	
Mean	-7.274	
Median	-7.129	
RMS	7.336	

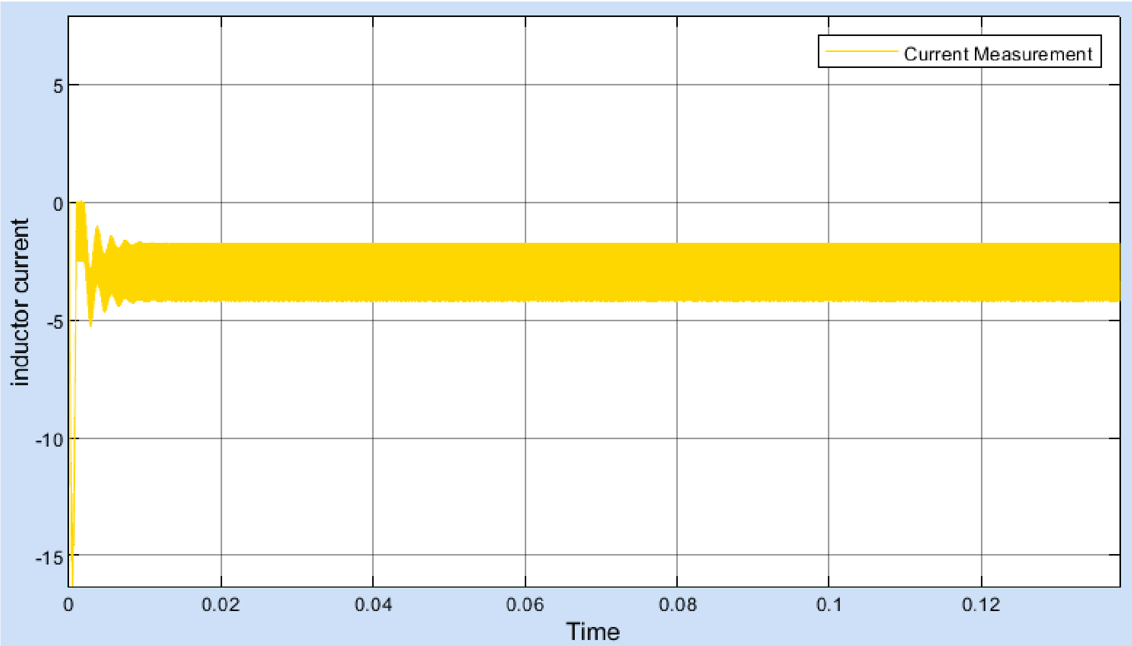


Fig 6.10. inductor current of Open loop buck-boost converter

TABLE 6.6. Signal Statics of inductor current in dc-dc buck-boost converter

	Value (Ampere)	**Time(second)**
Max	$9.919*10^{-03}$	$1.034*10^{-03}$
Min	$-1.630*10^{+01}$	$4.560*10^{-04}$
Peak to Peak	$1.631*10^{+01}$	
Mean	-2.608	
Median	-2.567	
RMS	3.122	

By comparing the table 4.3 to table 6.5 and 6.6 we can see from the graph that we didn't get the result similar to our rated value. The input inductor current value after simulation we get is 2.6A but our rated value is 3A whereas output voltage obtained is 7.2V and rated output voltage is 8V.

As stated earlier in 6.1.1. similarly applying LQR to reduce the steady state error of the system.

6.1.3.2. Control strategy LQR on boost converter

The following equation (19) is the result of applying the discrete time system to the CCM models of converters in MATLAB:

$$A_d = \begin{bmatrix} -0.0371 & 0.0466 \\ -0.0090 & -0.0408 \end{bmatrix},$$

$$B_d = \begin{bmatrix} 0.3191 & 13.8953 \\ -0.6914 & -20.7043 \end{bmatrix} \quad (21)$$

For vectors Q and R, the element values we select are in equation 6.2

solving the LQR problem for gain K using the MATLAB programme :

$$K = \begin{bmatrix} 0.0127 & 0.0177 \\ -0.0006 & 0.0108 \end{bmatrix} \quad (22)$$

7. This matrix includes each value needed for LQR control."

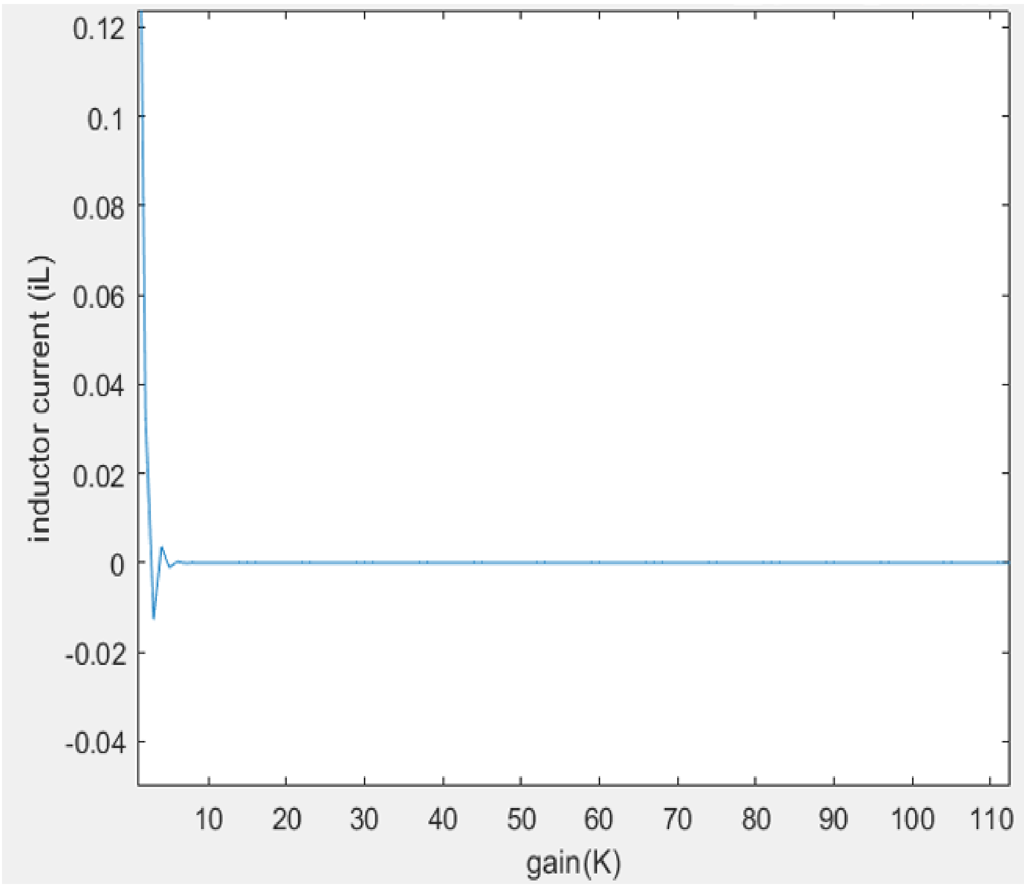


Fig 6.11. Steady State Response of Inductor current of Buck-Boost Converter

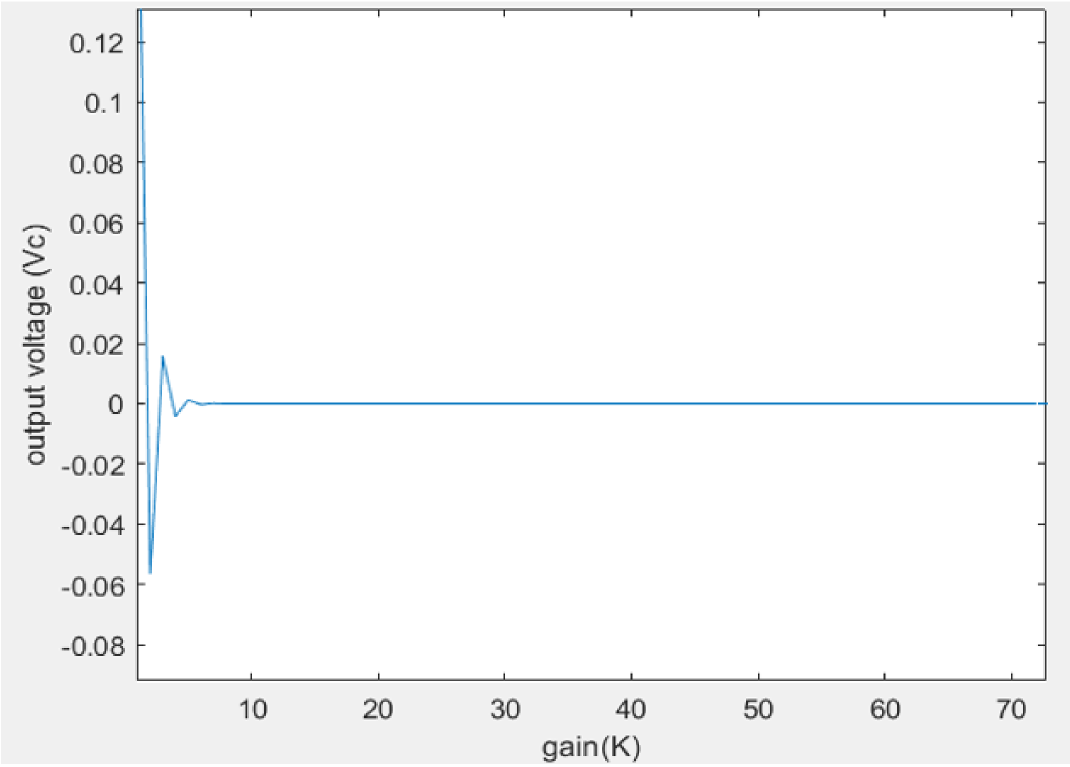


Fig. 6.12. Steady State Response of Output voltage of Buck-Boost Converter

Perform this case with MATLAB/Simulink. The results for all three converters are simulated. The primary finding is that the feedback control can be solved using LQR, according to this finding. For all three converters, K, a stabilising feedback control gain is calculated and applied. The usual solution to the LQR problem in an infinite horizon yields the static state feedback law[15], [18]. All three converters' system is permitted to operate throughout a number of time steps. We obtain all the absolute values of the eigenvalues that are less than 1 after running this system up to the number "K." This does in fact demonstrate asymptotically stable control gain[9]. Control input,u is generated at random. X is first determined using the random input u after being initialised to some modest values, such as 0.2. For the inductor current and output voltage of the buck, boost, and buck-boost converters using LQR, the steady state error is fully removed. The steady state error and the gain are inversely related. Therefore, it can be reduced by increasing the system gain.

As a result, the investigations have validated LQR's usefulness in the creation of control systems. Finally, using LQR analysis, the steady state inaccuracy of all converters' inductor current and output voltage is decreased. Its benefit is that LQR does full time-window (horizon) optimisation, proposes the transfer function that will reduce overall error, and analyses all inputs to the linear system.

6.2. Comparison of Control Strategies: Model Predictive Control and Linear Quadratic Regulator

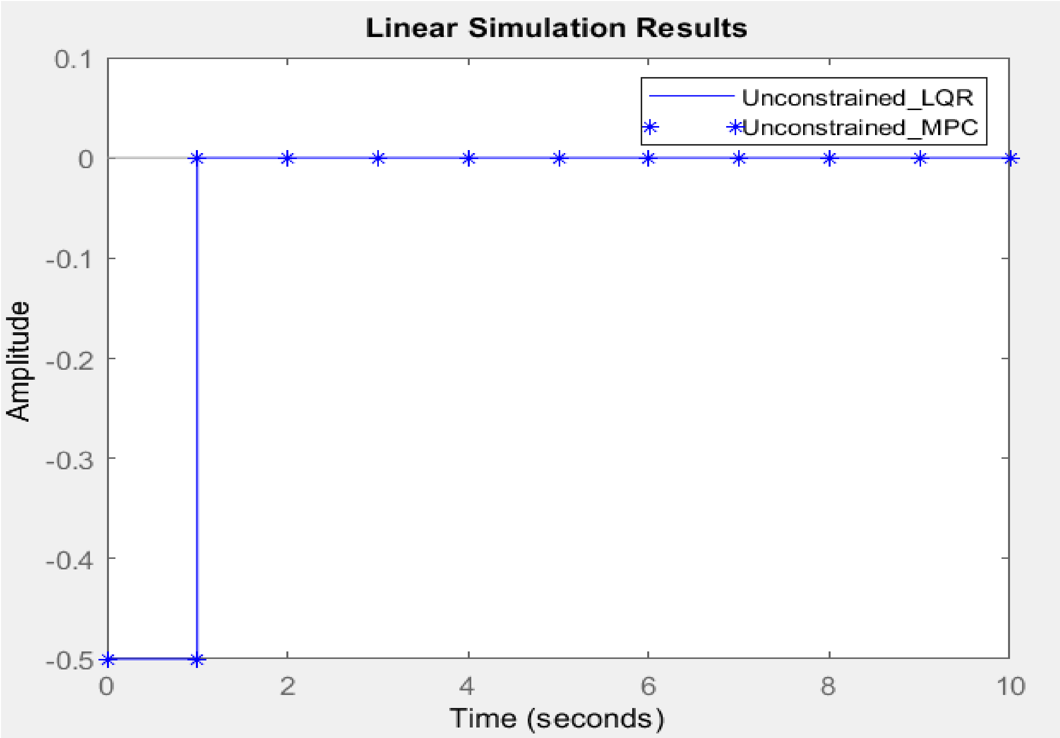
Firstly, designing of an LQR with no constraint[1]s is done. This system acts as a comparison point for the particular MPC algorithm[19]. The Linear Quadratic control law is u(k) = -K_lqr*x(k). After performing this simulation with [0.5 -0.5] beginning states. In fig. 6.13, the closed-loop response is steady.

Then, at the final prediction step, implementing a custom MPC. The linear model's predicted state sequences, X(k), and input sequence, U (k) is generated. Four prediction steps(N=4) are used in this system. Transforming the MPC issue into a typical QP issue with the objective function given by equation 5.5. The best expected input sequence U(k) produced by the MPC controller is -K*x when there are no constraints. After performing this simulation with [0.5 -0.5] beginning states. In fig. 6.13, the closed-loop response of converter is steady.

Because the control laws are the similar, both LQR and MPC controllers generate the same outcome. Therefore, the gain in both the techniques are same.

Gain in case of LQR, K_lqr = $1.0e^{-14}$*[0.2474 -0.0780]
Gain in case of MPC, K_mpc= $1.0e^{-14}$*[0.2474 -0.0780]

Limiting the range of the controller's output, u(k), to -1 and 1. Due to saturation, as illustrated in fig. 6.14 and fig 6.16 the LQR produces a sluggish and oscillating closed-loop response. Utilizing an MPC controller has many advantages, one of which is that it explicitly manages input and output limitations by resolving an optimal control problem at each regulation interval. The above-mentioned custom MPC controller is implemented using the built-in QP solver[16], [28]. The limitations of matrices are in 5.3. Invoking the QP solver on each step of a simulation. As can be seen in fig.6.15 and fig 6.17, the MPC generates a steady state response response with a quicker settling time and reduced fluctuation.



(a)

Fig. 6.13.Closed loop response of DC-DC Buck Converter obtained by (a) Unconstrained LQR, Unconstrained MPC

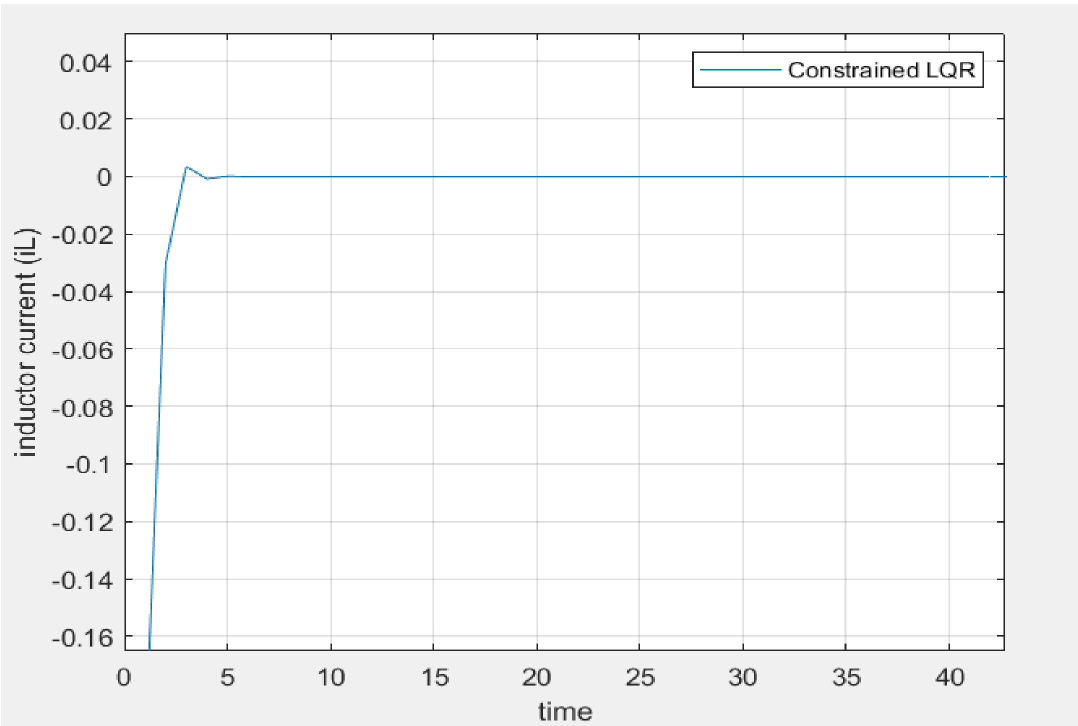


Fig. 6.14.Closed loop response of DC-DC Buck Converter obtained by Constrained LQR for inductor current

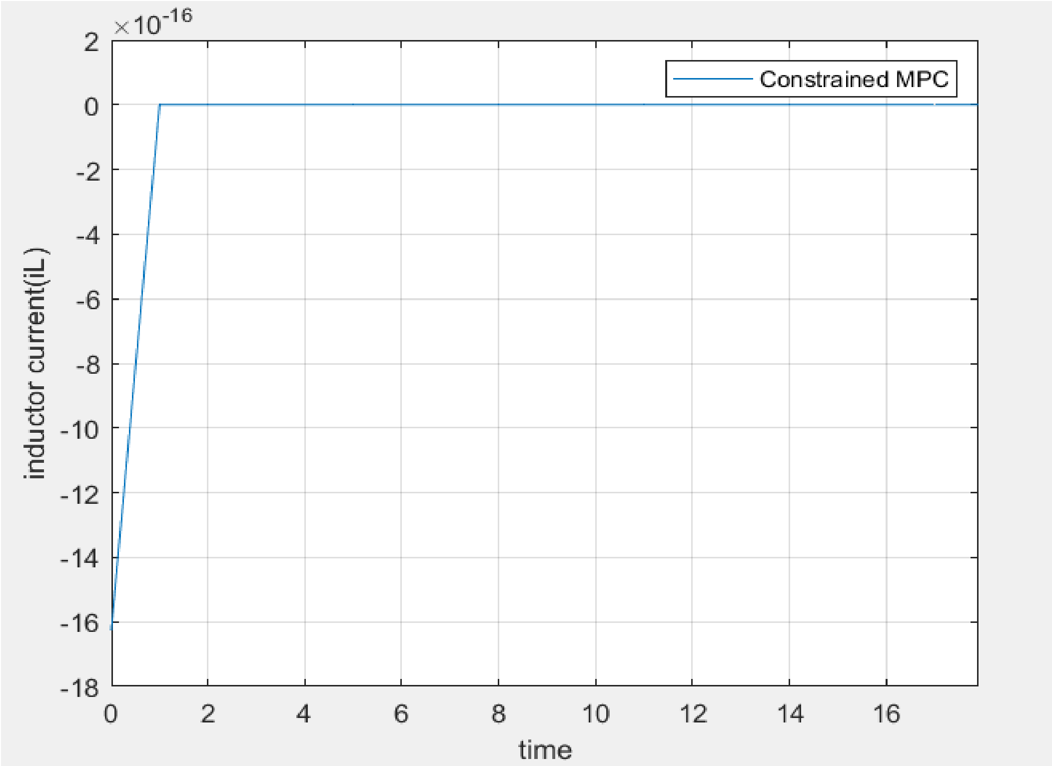


Fig. 6.15.Closed loop response of DC-DC Buck Converter obtained by Constrained MPC for inductor current

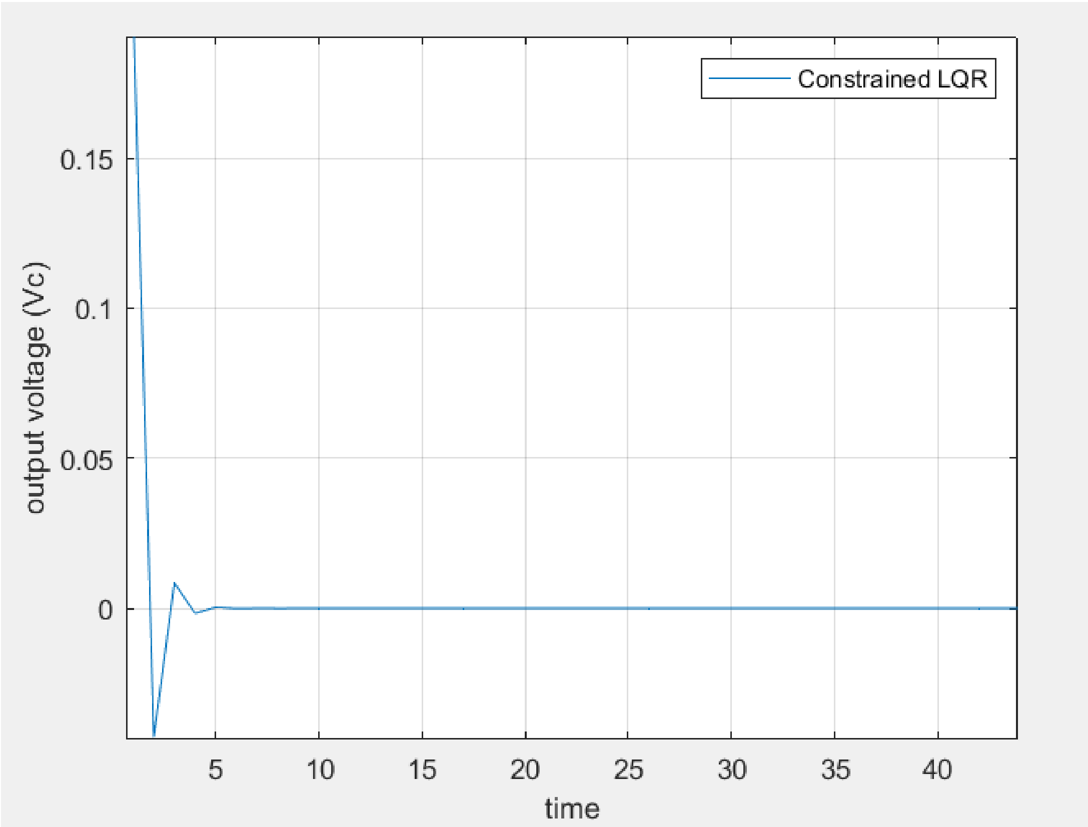


Fig. 6.16.Closed loop response of DC-DC Buck Converter obtained by Constrained LQR for output voltage

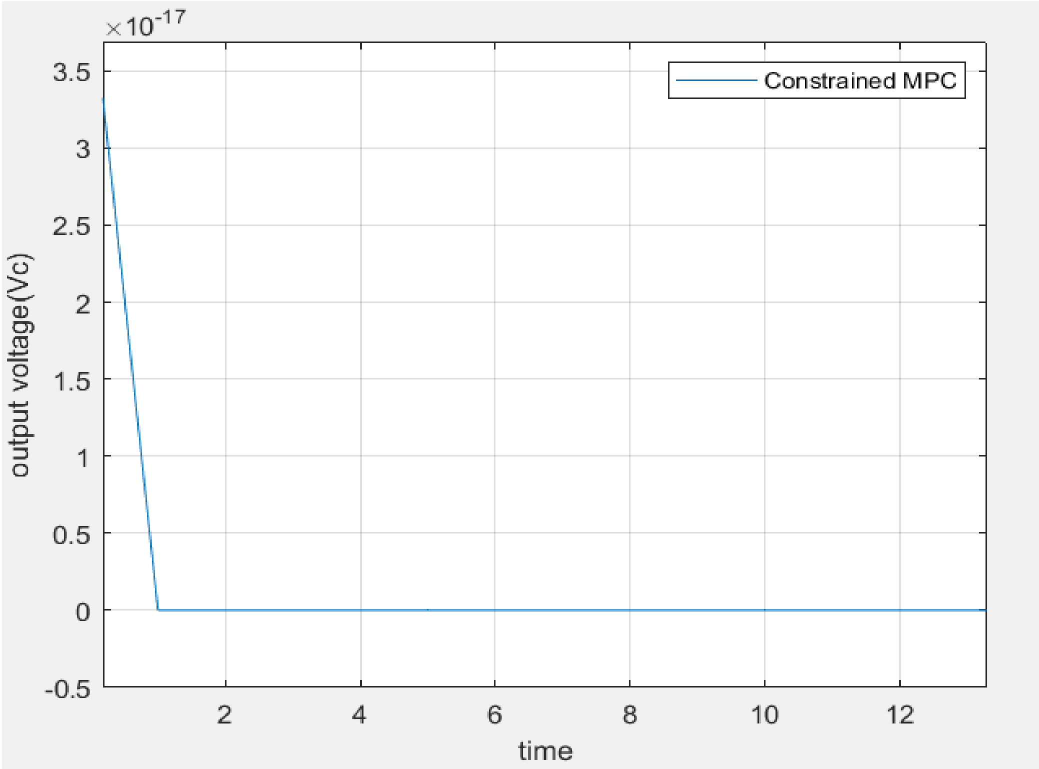


Fig. 6.17.Closed loop response of DC-DC Buck Converter obtained by Constrained MPC for output voltage

According to the outcomes of MATLAB simulation, the DC-DC Buck Converter's closed loop response is successfully realized with the aid of linear quadratic regulator and model predictive control. LQR and MPC produce the same results in the situation of no disturbance in figure 6.13. Additionally, both the Linear Quadratic Regulator and Model Predictive Control worked well when the external disturbance was added to the converter. However, the Model Predictive Control's transient reaction to the disturbance is generally better than the Linear Quadratic Regulator's. It is discovered that the model predictive controller (MPC) provides less oscillation since the LQR controller has a bigger overshoot than the MPC. MPC outperforms other controllers in terms of peak amplitude and settling time.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1. CONCLUSION

A DC-to-DC converter receives a DC input voltage and outputs another DC voltage. The applied input voltage may be higher or lower than the DC output voltage. These days, laptops and cell phones frequently employ DC to DC converters. Despite having sub-circuits that manage the voltage need differently than the batteries, they nevertheless get battery power.“PID (proportional integral and derivative) [8]controllers are among the most widely used methods of managing converters They can be used in large quantities in a single system, which leads to a more complicated PID regulator adjustment and makes it more difficult to supply the essential parameters for the transient process quality. The solution to this problem is the introduction of an entirely new controller in the control system, specifically the linear-quadratic regulator and model predictive controller.” Linear-quadratic regulators (LQR) have several noteworthy properties in terms of control techniques. For instance, they can be employed methodologically independent of the system's order and they are fundamentally stable. They can also make the system behave "optimally" in accordance with the designer's needs. An advance and promising control strategy for power converters and drives is model predictive control (MPC). The literature has offered a number of theoretical and practical problems that demonstrate how well this technique works.

The steady-state operation of any controller, one of its most important components, is the subject of the current work. It will be demonstrated that fundamental LQR and MPC formulations can be improved to provide a lower average steady-state error[24], [33].

In addition, LQR and MPC [31] can be calculated directly using the matrices of the system's small signal state-space averaged model. The Buck, Boost, and Buck-Boost topologies of DC-DC converters are modelled and implemented using Simulink. The result of a converter simulation without any regulating parameters does not quite match our rated value. To obtain an accurate outcome, a variety of optimization approaches as well as intelligent strategies might be applied. LQR analysis reduces steady state error for inductor current and output voltage of all converters. Its benefit is that LQR does full time-window (horizon) optimization, proposes the transfer function that will reduce overall error, and analyses all inputs to the linear system. This method's disadvantage is that it cannot handle severe constraints or the migration of a nonlinear system away from its linearized operating point. And here comes Model Predictive Controller which is a is a Dynamic System Model-Based Optimal Control Strategy[34]. The comparison between the MPC and LQR are made for DC-DC Buck Converters. LQR and MPC produce the same results in the situation of no disturbance. Additionally, both the "Linear Quadratic Regulator" and "Model Predictive Control" worked well when the external disturbance was added to the converter. However, the Model Predictive Control's transient reaction to the disturbance is generally better than the Linear Quadratic Regulator's. It is discovered that the model predictive controller (MPC) provides less oscillation since the LQR controller has a bigger overshoot than the MPC. MPC outperforms other controllers in terms of peak amplitude and settling time.

5.2. FUTURE SCOPE

Disruptive end-product innovations keep moving the goalposts on the shared objectives of better power efficiency, higher power density, and lower cost across almost all segments of the power supply business. Many industries, like the automotive industry as it transitions to electric vehicles and the medical field as ever-smaller equipment demand effective battery management, call for efficient solutions for DC/DC converter power control. There is an increasing demand for wide-range, high-voltage DC/DC converters to be utilized in both monitoring and control units, as well as to supply low-voltage rails to power inverters. LQR and MPC are such ideal controllers that they not only give good stability, but also ensure the system's stability margin. When compared to PID and fuzzy controllers, it gives superior optimal energy. We don't need to apply any loop-shaping to get the gain settings. These methods lessen the amount of work required by the control systems engineer to optimize the controller.

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LIST OF PUBLICATIONS

[1] S. Kumari, M. M. Rayguru and S. Upadhyaya, "Performance analysis of Linear Quadratic Regulator for DC-DC Converter Systems," 2023 International Conference on Power, Instrumentation, Energy and Control (PIECON), Aligarh, India, 2023, pp. 1-5, doi: 10.1109/PIECON56912.2023.10085906.

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