A SHORT PREDICTIVE MODEL PREDICTIVE CONTROL (MPC) APPROACH FOR HYBRID CHARACTERISTICS ANALYSIS IN DC-DC CONVERTER

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ABSTRACT

Historically, the MPC has been successfully applied in drives system for over a decade. Furthermore, the DC-DC converter naturally deals with high switching phenomenon that contributes to the challenging in control approach. Its operation conventionally associated with PI/PID controller in order to meet the desired output. However, the PI/PID controller lacking in getting a good transient response since this controller highly depends on the controller gains. Recently, an advanced controller has been proposed in the literature for the purpose to enhance the DC-DC converter performance. Hence, in this thesis, the short prediction horizon of MPC using search tree optimization that generates low switching states phenomenon is proposed. The MPC algorithm is developed based on the hybrid characteristic signals from the DC-DC converter. The load changes due to the increasing or decreasing the loads (could be happened of heating effect) will affect the tracking of the output voltage. The Kalman Filter (KF) is used for load estimation for smoothing and tracking the output voltage. The performance of short prediction horizons is being compared to PI controller in terms of transient response during the start-up scenario. The results show that the proposed controller has a better response than PI controller, which is the overshoot has been reduced to more than 50% and the settling time more faster about 25% than PI controller during start-up scenario. Therefore, this control approach for DC-DC buck converter has produced the promising output transient performance when compared with the conventional PI controller while also minimizing the switching sequence phenomenon.

ABSTRAK

Dari segi sejarah, MPC telah berjaya digunakan dalam sistem pemacu selama lebih satu dekad lagi. Tambahan pula, penukar DC-DC secara semula jadinya berkaitan rapat dengan fenomena pensuisan yang tinggi yang menyumbang kepada kesukaran dalam proses pendekatan kawalan.Secara konvetional, penukar DC-DC menggunakan pengawal PI / PID dalam menghasilkan output yang dikehendaki. Walaubagaimanapun, PI/PID mempunyai kekurangan dalam mendapatkan hasil kawalan yang baik disebabkan oleh kebergantungan terhadap gandaan kawalan. Baru-baru ini, pengawal maju telah dicadangkan dalam kesusasteraan bagi tujuan meningkatkan prestasi penukar DC-DC. Dalam tesis ini, ramalan ufuk pendek MPC menggunakan pengoptimuman secara pokok carian yang menjana fenomena pensuisan rendah telah dicadangkan. Algoritma MPC dihasilkan berdasarkan ciri-ciri hybrid yang terdapat pada penukar DC-DC. Perubahan beban yang berlaku disebabkan oleh penambahan atau pengurangan beban (berlaku akibat kesan pemanasan) akan memberi kesan kepada pengesanan voltan keluaran. Penapis Kalman (KF) digunakan untuk membuat anggaran beban bagi menurangkan ralat dan pengesanan voltan keluaran. Prestasi ufuk ramalan pendek kemudiannya dibandingkan dengan pengawal PI dari segi sambutan fana semasa scenario permulaan. Hasil daripada perbandingan itu menunjukkan bahawa MPC mempunyai tindak balas lebih baik daripada pengawal PI dimana overshoot telah dikurangkan kepada lebih daripada 50% dan masa penyelesaian lebih cepat kira-kira 25% daripada pengawal PI pada senario permulaan. Pendekatan MPC sebagai kawalan penukar DC-DC telah menghasilkan prestasi output yang lebih baik berbanding dengan pengawal PI yang konvensional. Selain itu, MPC juga dapat mengurangkan fenomena pensuisan urutan dalam penukar DC-DC.

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LIST OF SYMBOLS

$v_g(t)$	DC input voltage
$v_o(t)$	DC output
P_T	Total power loss on a power semiconductor device
$P_{c(on)}$	Conduction losses during on state
P_{off}	Turning off loses
$P_{b(off)}$	Blocking mode during off state
P_{on}	Turning on losses
L	Inductor
r_1	Internal Resistor
C	Capacitor
r_2	Capacitors Resistor
R	Load Resistor
S	Controllable Switch
D	Diode
V_C	Voltage Across The Output Capacitor
I_L	Current Through The Inductor
$e(t)$	Tracking Error
ξ_p	Vector
η_p ,	Scalar
x_k	Signal Value
z_k	Measurement Value
K_k	Kalman Gain
$\hat{X}_k^-$	Prior Estimation
P_k^-	Prior Error Covariance

LIST OF ABBREVIATIONS

MPC	Model Predictive Control
KF	Kalman Filter
PWM	Pulse Width Modulation
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching
PHEV	Plug-In Hybrid Electric Vehicles
HBBFF	Hybrid Buck–Boost Feedforward
QZSI	Quasi-Z- Source Inverter
EKF	Extended Kalman Filter
KCL	Kirchhoff’s Current Law
KVL	Kirchhoff’s Voltage Law

CHAPTER 1

INTRODUCTION

1.1 Introduction

In recent years, there is an increasing interest in advanced control techniques in power electronics applications. One of them is a Model Predictive Control (MPC) that has been used in improving the performance of DC-DC converters (Yan, Shu, & Sharkh, 2015)(Stellato, Geyer, & Goulart, 2016)(Yan et al., 2015).

Historically, the MPC has been successfully applied in plant process control for over a decade (Zanoli, Pepe, & Rocchi, 2016)(Rosero, Alama, & Silupu, 2015) and (Angeli, Amrit, & Rawlings, 2012). The slow response of the process plant had made the MPC is possible to apply. Moreover, the multiple parameters and plant's constraints of process plant had made the MPC is suitable to implement in order to increase the efficiency of the plant process. Due to the slow response of the process plant, the optimization of the MPC control objective could be performed in long prediction horizon. This has contributed to the more precise of control output. However, the long prediction horizon gives scrutiny to the algorithm to be done. Since that, the exploration of using and enhancing the MPC algorithm for other applications is increasing time to time. For power electronics applications, the MPC is first started to explore in drives system and then further investigation to the high switching circuits, for example the family of DC-DC converters.

The high switching frequency in converters gives another challenging to the control approach that wants to implement. This means that the sampling time in DC-DC converters done in very short period (microsecond and below). Thus, made any control approach need to response fast and efficiently. Since the MPC had shown the effectiveness in other applications, the further investigation of using MPC in DC-DC converters could bring an interesting topic to study. Even though the PI/PID controllers had shown a maturity in controlling DC-DC converters, the performance response showed a lot of improvement could be imposed. The tuning of the gains is also needed to be done if the operating points are changes. Thus, with the advancement of the controller processor has made the utilization of MPC is possible in fast response applications.

Basically, there are two main group of control techniques for closed-loop operation in DC-DC converters, i.e., voltage-mode and current-mode controllers as shown in Figure 1.1 While the voltage-mode controller can be achieved by using a single loop control that controls the output voltage from the difference between measured and the reference voltage. The voltage-mode control is difficult to get a good response since it involves a second order with non-minimum phase behaviour, where the transfer function contains a right half-plane zero. Meanwhile, the current-mode controller is using two loops for inner and outer loops. The outer loop is for regulating the voltage to manipulate the current reference so that the voltage error could be improved. The inner loop is for regulating the current that controls the inductor current. This current-mode controller is often used since the minimum phase behavior of the controller is presented, which is a first order system.

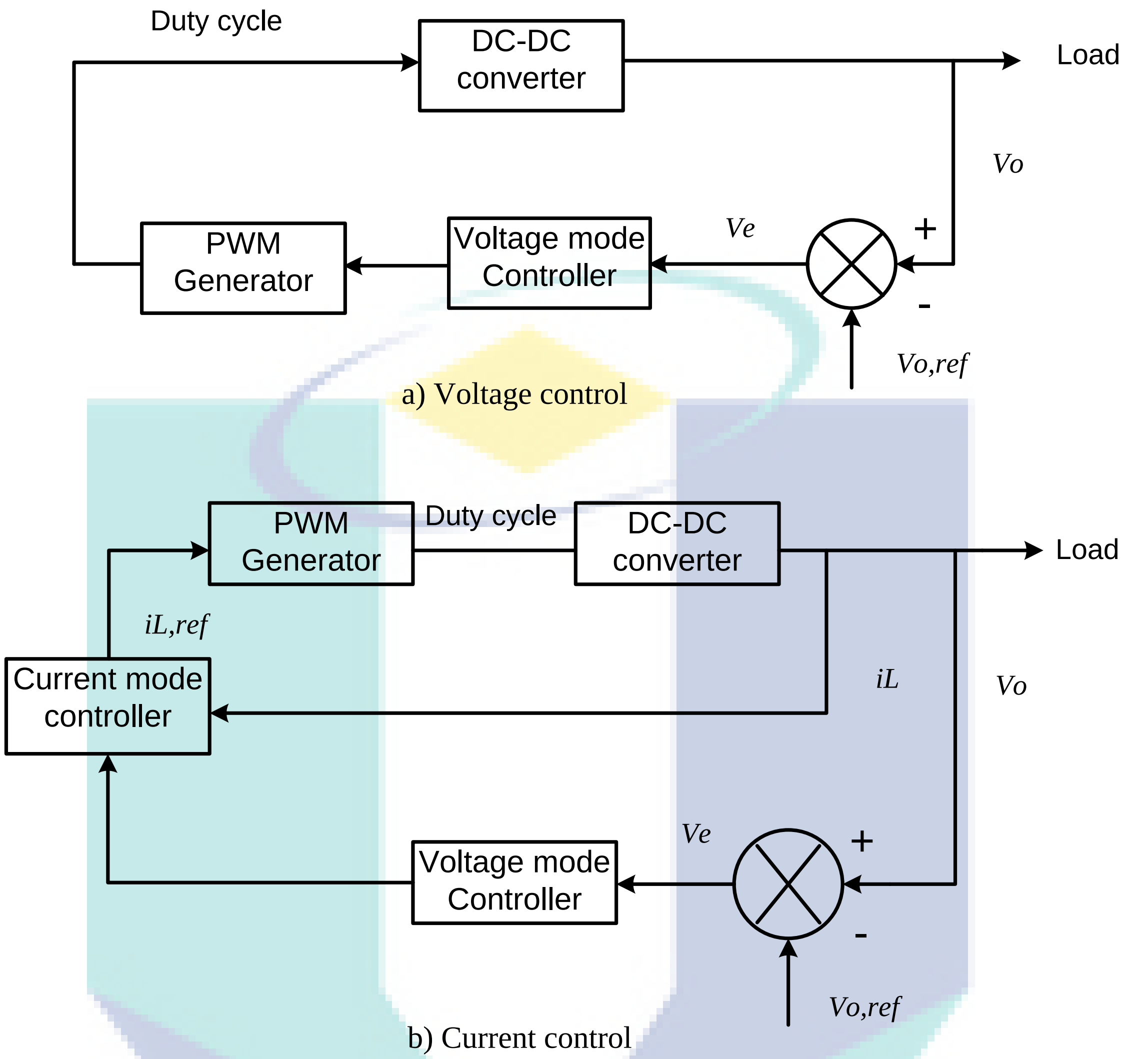


Figure 1.1 a) Voltage-mode control, b) Current-mode control

Recently, there are many researchers had proposed MPC for improving the performance DC-DC converters (Stellato et al., 2016)(Forbes et al., 2015) and (Karamanakos, Geyer, & Manias, 2014). Many of them are focusing on the effectiveness of implementing MPC in DC-DC converters. However, lately the researchers have started to study for improving the MPC's algorithm so as the optimization algorithm could be performed in light computation hence improving the controller effectiveness. This study needs to come out with the reformulation of the MPC strategy in DC-DC converters. Essentially, the DC-DC converters in nature can be classified as a hybrid signal, which is consist of discrete and continuous signals (i.e., switching ON/OFF signal and continuous output signal)(Karamanakos, Geyer, & Manias, 2014). So, this hybrid signal must be formulated in MPC model so as the precise control approach could be proposed.

The purpose of controlling DC-DC converters is to track the output voltage with the reference. This could be analysis with using the transient response and steady state error. The tracking problem will occur if the load changes due to the increasing or decreasing of the loads (could be happened of heating effect)(Q. Zhang et al., 2014)(G. G. Rigatos et al., 2013). With using the conventional PI/PID controllers, no big issue on the load changes since the PI/PID just uses the output error as an input control signal. However, there is another concern in using MPC for load changes. The load changes would effect to the tracking response (Arnab et al., 2014). Another control strategy could be used for identify the load changes.

In this thesis, a reformulation of the MPC to DC-DC buck converter is carried out. The MPC is derived based on the hybrid nature behaviour of the DC-DC converter and formulate the control objective so as the optimization could be performed in analytical. The analytical optimization could be performed by introducing a short prediction horizon of control objective MPC. Then, the Kalman filter (KF) is adapted for load identification of load changes problem. It could be defined as MPC-KF for the controller proposed. The effectiveness of the controller is compared with the PID controller for several cases.

1.2 Motivation & Problem Statement

Recently, DC-DC converters have been broadly used in a variety of applications, ranging from computer to electronic medical systems, electronic devices, power systems and telecommunication tools (A. Simon and O. Alejandro, 2005)(H. Sira-Ramirez and R. Silva-Ortigoza, 2006). Even the development and improvement of the DC-DC converters have been much implemented by many researchers and engineers; the room of improvement study is still fascinating since the modern applications nowadays are more complicated, which are much depends on the stability and high-performance converter.

Theoretically, the principle control approaches are mostly based on the averaged model and small-signal linearization of DC-DC converters, which are widely used in controller development of DC-DC converters (Sosa & Mart, 2013)(Pavlovi, Bja, & Ban, 2013). It is then usually incorporated with PI/PID/enhancement of PID based compensator to compensate the converter output response (Converter, Li, & Chen,

2012) and (Priewasser et al., 2014). However, there are still relying on the linearization technique, which is restricted the dynamic analysis that can be done. To more detail, DC-DC converters in nature presenting a hybrid behavior, i.e., encompasses a set of discrete modes (switched nonlinear) and continuous dynamics (output voltage) (Molla-ahmadian, Karimpour, Pariz, & Tahami, 2012)(Mariéthoz et al., 2010). Therefore, in such case, an accuracy of the dynamic analysis that taking into account the hybrid problem can be granted for DC-DC converters. However, for simplicity, this hybrid problem is usually omitted in controlling DC-DC converters. Therefore, this hybrid problem has posed a challenging task. In addition, the inherently of high switching frequency in DC-DC converters have originated the switching control problem, in which the highly nonlinear is produced.

Furthermore, the constraints are also available, resulting from the DC-DC converter topology such as the manipulated variable of duty cycle that bounded between zero and one, current limiting and soft starting for safety concern. These would be more complex if the constraints are included in controller development, which is not applicable for a conventional controller such as PI/PID.

In the last decade, new advanced control techniques such as nonlinear based control techniques (Tan, Lai, & Tse, 2008)(Linares-flores, Méndez, & García-rodríguez, 2014) intelligent based controller (Wai, Member, & Shih, 2012) and predictive based controller (Karamanakos, Geyer, & Manias, 2014)(Xie, Member, Ghaemi, Sun, & Freudenberg, 2012) have been increasingly investigated in power electronics applications which including DC-DC converters. It has made an outcome of improvement for converter's efficiency and robustness. However, these control methods deal with a complex control algorithm that made the controller cost higher and computational burden. Among these, MPC is one of the promising control approaches that can be served to the power electronics applications. MPC as a brief is using a model to predict the future evolution of the control output by optimizing the control objective in each sampling instant along the prediction horizon, which is sometimes called *receding control*. As a result, the hybrid nature characteristic of the DC-DC converter can be subdued. Furthermore, the constraint parameter (such as duty ratio constraint) of DC-DC converter also can be handled in control objective. Nonetheless, again, the computational burden of controller's algorithm is the big concern in MPC since the processing of the control index is performed at each sampling time. It is noted, by nature the MPC consume high computational burden on the processor that is contributing to the main shortcoming of MPC especially in a fast response system.

In the past, MPC has been successfully applied in slow response systems. However, with the growth of high processor, an application of the high switching system is possible (Karamanakos, Geyer, & Manias, 2014)(Xie et al., 2012). Nevertheless, the ultimate problem then returns back to the complexity of optimization algorithm of MPC control objective, which is the converter constraints is included (Tran & Quang, 2013). Therefore, in this thesis, the reformulated MPC algorithm is proposed using a hybrid nature of DC-DC converters with the aim to perform the control objective optimization in the analytical method. This will involve the knowledge of mathematical derivation to propose a new control objective of MPC and finite optimization algorithm. The key idea is to solve the constraint optimization directly using the analytic solution in order to achieve the aim of high-efficiency DC-DC converters with a simple controller. In order to attain this, the short prediction horizon $(l \leq 3)$ is intended to propose by fundamentally revising the new control objective of MPC for DC-DC converters control and analytical solution of optimization algorithms.

Since the MPC is depended on the converter's model, any changes in load will affect the output performance. It is noted that in power electronic application, the load resistor in the power electronics circuit element is the most vulnerable components (Izadian & Khayyer, 2010). The load can be changed in the present of transient that develops from environmental and heavy load strains. Furthermore, the load uncertainty that produced has been resulting in a model mismatch and therefore in a steady state output voltage error. Several approaches have been developed in order to detect the load uncertainty behavior in the DC-DC converter. However, their performance has demonstrated poor performance during the transient and significantly resulting in the noise. In estimating the load changes, the Kalman Filter (KF) is perhaps the most suitable approaches to estimating the changes of load resistor with the combination of MPC. Thus the adoption of KF in the controller will be proposed.

1.3 Objectives

The aims of this thesis are to propose the controller for DC-DC buck converter based on an analytical model predictive control. In accomplishing this; some objectives are identified to embark as follows;

1) To develop a short prediction horizon of model predictive control approach to DC-DC buck converters.

2) To propose a simple load identification of DC-DC buck converter using Kalman filter for load uncertainty.

3) To verify the effectiveness of the proposed controller through simulation using Matlab/Simulink

1.4 Contribution

The main contributions of this proposed research are described:

i) The new method of MPC, which is by using MPC and analytical optimization are presented. This method describes the parameter and hybrid behaviour of DC-DC converter. The MPC is developing in short prediction horizons which offer a lower number of switching turn on and off that benefitted to the cost effectiveness of DC-DC converter applications.

ii) The load identification for load changes is developed by using KF that identify the load changes and smoothing the output signals.

1.5 Thesis Overview

This thesis encompasses the explanation and discussion of the proposed method. It divided into five chapters. The chapters are arranged as follow:

Chapter 1 introduces the whole idea of the project. It consists of an introduction, problem statement, objective and contribution.

Chapter 2 discusses the literature review. Previous researcher's work in the same area and the relevant issue related to the DC-DC converter, Kalman Filter and PID controllers that can be helped in developing the project and finding the research gap of the studies.

Chapter 3 provides the entire step of developing proposed controller for DC-DC buck converter based on an analytical Model Predictive Control. This chapter also represents the development of Kalman Filter in solving the load variations.

Chapter 4 presents the results of proposed method which consists of the results of the best prediction horizons and the comparison of the proposed studies are being compared with conventional PI controller. The discussion is prepared to validate the performance results.

Chapter 5 concludes and summarizes the overall studies and future recommendation is carried out.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews the related work that has been done for controlling the DC-DC converters. Various works of using MPC also discussed. In MPC, the DC-DC converter has to be modelled in order to formulate the MPC. The modelling techniques are explained and review in this chapter. Afterward, the use of conventional PID controller in the DC-DC converter is being reviewed. Besides, the comparison of various methods to tackle load variation is deliberated

2.2 DC-DC Converter Controller

Generally, DC-DC converter broadly used in industrial application due to its ability in changing and regulate the voltage (Qiang et al., 2010)(Babu et al., 2011)(Martin et al., 2013)(Guida & Cavallo, 2012) and (Mane & Jain, 2015). High-efficiency regulators, wide supply voltage operation range, very low current consumption operation, short circuit operation and over temperature protection are some of the switching converter industrial applications.

Furthermore, the DC-DC converter has received much attention for more than four decades due to its important role in power electronics industries. Commonly, the DC-DC converters have been used as the electrical circuit that transfers the energy to a load from the DC source. It is a switching converter of a power converter. The output voltage of DC-DC converter can be greater than the input voltage or vice versa (J. Zhang et al., 2016). The process of adjusting of desired output voltage of the DC-DC converter is consists of temporarily stored and released of DC-DC converter input energy using proper manipulating of the switches. The converter output voltages are used to match the power supply required to the loads. The connection and disconnection of power supply to the load can be controlled using a switch in the simple DC-DC converter circuit (Petros Karamanakos, 2013). Figure 2.1 shows a DC-DC converter as a center box. It converts a DC input voltage, $v_g(t)$ to a desired DC output, $v_o(t)$ conducted by switching action.

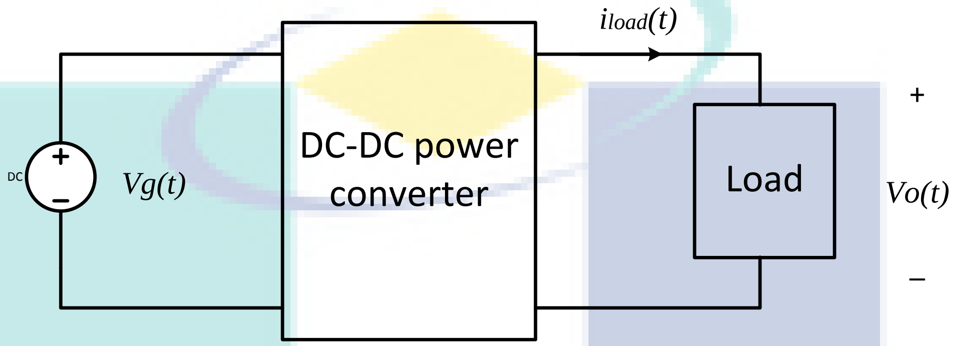
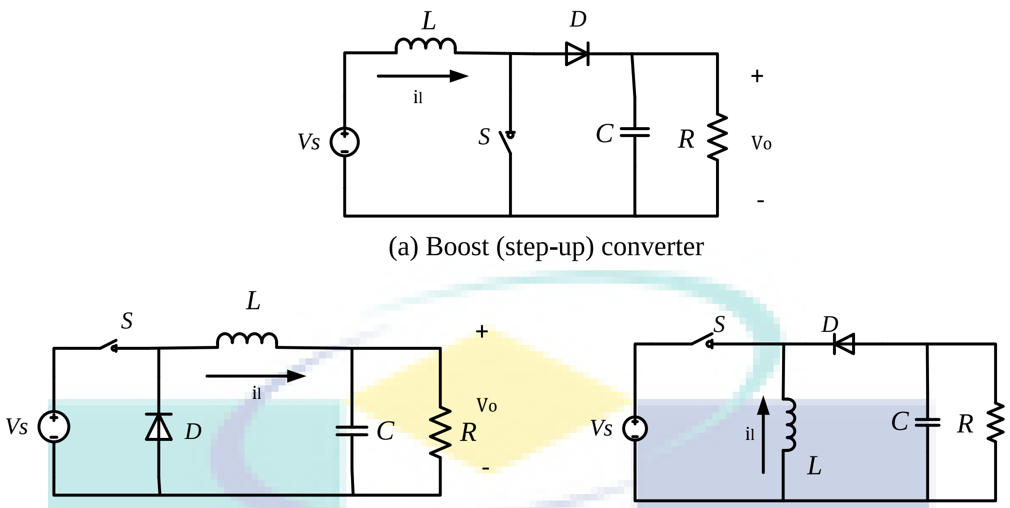


Figure 2.1 A DC-DC converter
Sources : Johansson, (2004)

DC-DC converter usually consists of few electrical components such as a transistor, resistor and switches. The electrical components can be combined and connected to each other in different ways, called topologies, each one having different properties. Figure 2.2 shows the three basic converter topologies that are a buck, boost, and buck-boost converters.



(a) Boost (step-up) converter

(b) Buck (step-down) converter

(c) Buck-Boost converter

Figure 2.2 DC-DC converter topologies

Sources : A. Simon and O. Alejandro, (2005)

One of the most important circuits within the family of power electronics circuits are the DC-DC converters. The DC-DC converter has been widely used in the variety application (A. Simon et al., 2005). Despite these well-established technologies, the applications and their closed loop controlled performance arose with concrete and theoretical challenges. The regulations of the output voltage a converter to the desired value of should be achieved by appropriate control strategy (Petros Karamanakos, 2013).

In the DC-DC converter, the switching behavior consists of hybrid systems or switched linear. Furthermore, the hybrid nature of the DC-DC converter occurred at the discrete mode of the switch (MOSFET) and the continuous dynamics of the output voltage.

The control of power converters has been widely studied, and new control schemes are founded every year. Several control schemes have been proposed for the control of power converters and drives. There are various different approaches to the control problem can be found in the literature. It divided into two main groups that are the linear and nonlinear controllers. In this project, the DC-DC buck converter is being used. It is a nonlinear control. Recently, several nonlinear controllers have been proposed. Some of them are predictive control, hysteresis, fuzzy logic, sliding mode controller, backstepping control, current mode control and voltage mode controller

(Verma et al., 2013). Other control schemes found in the literature include neural networks, neuro–fuzzy, and other advanced control techniques (Cortés et al., 2008). Within this kind of controller, the researcher found the most conventional controller is hysteresis and linear controls with pulse width modulation (PWM) (Kazmierkowski et al., 2002).

Moreover, the literature on DC-DC converter schemes shows another approach that is to use a small-signal linearization of the hybrid model (Priewasser et al., 2014)(Kuntal, Soumitro, & Chakraborty, 2014). Nevertheless, it is clear that the simplified models are slightly restricted in their ability to characterize the hybrid system dynamics. Instantly, it thus narrows the control performance and its accuracy in these control techniques.

In literature (Iqbal et al., 2016), the fuzzy logic can use as controller of DC-DC buck converter. It is suitable for applications where the controlled system or some of its parameters are unknown. DC-DC buck converters have a few weaknesses features such as uncertainty response, parameter variation and load disturbance. The fuzzy controller can capture these features and improve the performance of DC-DC buck converter. Gupta (1997) found that the fuzzy logic controller also provides a smaller time constant by choosing the best sampling frequency. The fuzzy controller has been used by the researcher by Jia (2006). Nevertheless, this scheme control does not study on a dynamic characteristic of the switching non-linear in a DC-DC buck converter.

Sliding mode presents robustness and takes into account the switching nature of the power converters. It is achieved by controlling the nonlinear switching or ideal switching devices to guarantee the desired steady state mode and stability (M. Ergin et al., 2015). This control schemes can handle the load uncertainty, applicable control error and dynamics response variation (Cid-pastor et al., 2011). Besides, the load parameter variations and the peak current controller are the important factors that generate robustness of sliding mode controller. It makes the characteristic current limiting characteristic of the DC-DC converter can tackle the overload damage, rapid dynamics response and fixed to switch frequency (Lachichi, Pierfedirici, Martin, & Davat, 2005).

Additionally, the backstepping controller is one of the well-known non-linear controllers in literature. It has been used in DC-DC converter application such as a PV array. The previous researchers mention that the backstepping controller able to track the maximum power of the PV array and to synchronize the grid current with the grid voltage depending on integral backstepping approach and Lyapunov stability tools (Skik & Abbou, 2016)(Martin et al., 2013). Furthermore, in terms of hybrid behavior uncertainty, the backstepping controller provides the same method with the sliding mode controller and the Model Predictive Control (MPC) in solving the problem by using the state-space averaging technique (Nizami & Mahanta, 2015).

Current and voltage-mode control are basically the DC-DC converter controller. Additionally, the previous study indicates that the current mode has a higher loop bandwidth compared to the voltage-mode controller. The higher loop bandwidth is related to the good performance of characteristics response of the control systems. The current model of hysteresis control is commonly used for controlling these DC-DC converters that need fast response characteristics. As for voltage-mode control, the high-precision prediction is difficult due to slope of output voltage waveform is non-linear, (Liu et al., 2012). Based on these authors, the key limitation of this research is the voltage-mode is difficult to use in controlling the DC-DC buck converter. Due to the existence of hybrid behavior and parameter uncertainty.

Although the aforementioned approaches have been shown to a reasonable effective, several challenges have not been fully addressed yet. It includes robustness of parameters load and computational burden. Furthermore, the current theoretical improvements are concerns to controlling hybrid systems, as well as the appearance of fast microprocessors. This will support the implementation of more computationally challenging algorithms that allow this method to capture these difficulties in a novel approach. Though, the employments of new and more complex control method are promising also due to the growth of great microprocessors. Since MPC is a particularly promising scheme to tackle those entire problems, several algorithms have been offered at these current centuries.

2.2.1 Hybrid Nature of DC-DC converter

There are several researchers that conduct new research related to the characteristics of the DC-DC converter, which is hybrid behavior. The DC-DC converter is essentially challenging to control due to both the continuous and the discontinuous conduction mode.

Figure 2.3 shows a simple DC-DC buck converter circuit consists of two semiconductor switches that are switching transistors and one switching diode. DC–DC converters are fundamentally difficult to control due to the nature of hybrid behaviour in the circuit operation. It exists from a set of discrete modes of nonlinear switching that switch *on* and *off* at high-frequency associated with continuous dynamics of the output voltage (Karamanakos, Geyer, & Manias, 2014). The limitation of hybrid behaviour of DC-DC converter occurs using the conventional modelling and control scheme (Chen, Fu, Xu, & Ding, 2014). Moreover, the high switching characteristic has originated the switching control problem. Motivated by these, the fundamental study of the control approach in hybrid system analysis is essential in DC-DC converters.

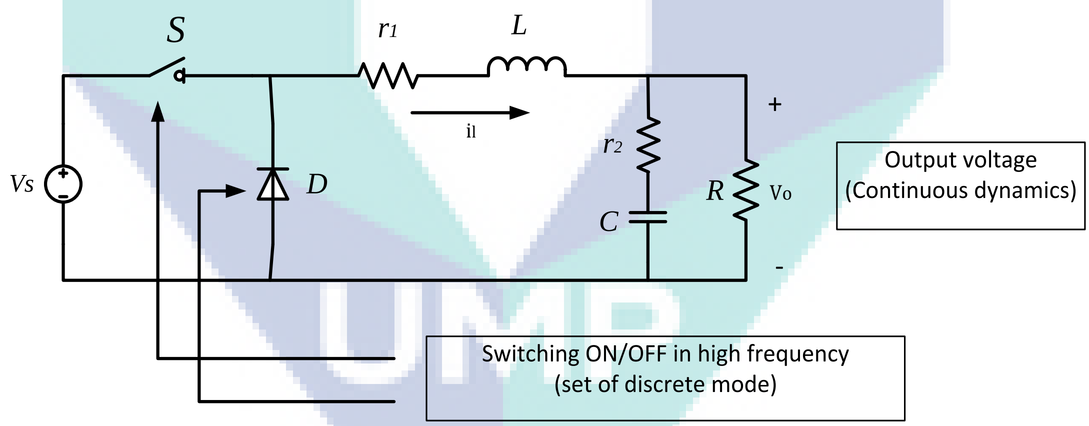


Figure 2.3 Illustration of Hybrid Behavior of DC-DC Converter

The state space averaging techniques is one of the significant modelling techniques for hybrid behavior. A new model of switched linear system of DC-DC converters, in which continuous variable and the discrete variable is being modelled using state space averaging equation (Y. Zhang et al., 2006). These techniques represent all of the DC-DC converter parameters and constraints as switched linear systems.

In Aghili-ashtiani & Menhaj, (2015), a novel inventive modelling scheme is introduced for modelling hybrid dynamical systems, which contains both continuous and discrete mode dynamics. Thus, in this method a finite number of switching can be modelled in every closed time interval. Another research related to hybrid behaviour is being discussed in Guida & Cavallo, (2012) for Bidirectional DC-DC converter for intelligent fuel cell vehicles energy management, which consists of the hybrid system from the interaction between continuous plants and discrete events supervisors. In addition, X. Wang & Zhang, (2013) claimed that DC-DC converters are typical hybrid systems consisting of interacting discrete and continuous process. This scheme controlled the boost converter by using the PWM hybrid control strategy.

Karamanakos et al., (2014), Asano et al., (2006) and Hanene et al., (2015) also claimed that the hybrid nature of DC-DC converter exist from the input of the considered system that restrained to discrete value whereas the output to be controlled is a continuous value. In additions, both researchers controlled the DC-DC converters by using the MPC method, which handling the difficulties of hybrid behaviours. Moreover, this proposed scheme will directly regulate the output voltage along its reference by calculating the optimizations problem.

2.2.2 State Space Averaging Techniques

Over the centuries, a great effort of improvement has been made in developing mathematical descriptions of power converters. Basically, modelling of the systems is compulsory in developing control method of power converters. The state space averaging techniques is widely used in the various controllers to represent many systems in the industry.

Generally, the combinations of PWM and linear controller or its modification controller for regulating the voltage of the DC-DC converter are widely used. Lots of the analysis for switching circuits is counted on averaging or discretization techniques, due to the nonlinearities of the power converter (Sosa & Mart, 2013)(Pavlovi et al., 2013). Various papers have documented that the state space averaging is the most prominent averaging technique that models the converters as a single equation (Antip Ghosh & Kandpal, 2010)(Tan et al., 2008)(Wissenschaften, 2014)(V. S. Rajguru, 2012). The state space averaging is describing the characteristics of the converter over a switching cycle, by accepting the switching duty ratio as an input as stated in Tajuddin et al., (2009) and Zhang et al., (2016).

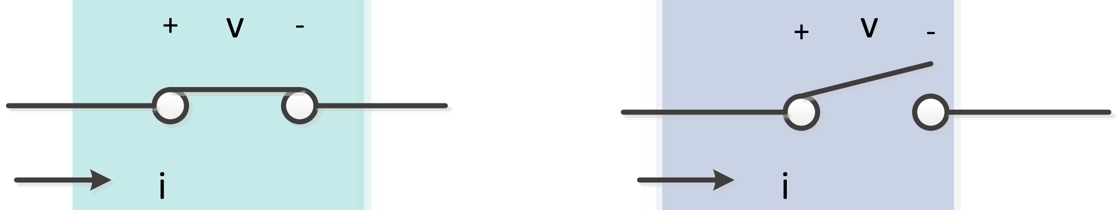
The DC-DC converter characterizes as switching between different time-invariant systems during each switching period and is afterward a time-variant system. Nowadays, there are numerous approaches that estimated this time-variant system with a linear continuous time-invariant system (Johansson, 2004). In Haripriya & Alivelu Manga Parimi, (2013) and Behjati et al., (2013), the state-space averaging technique is being used for modelling of the DC-DC boost converter as a time invariant system by using a set of differential equations that can signify the system working during *on* and *off* states.

The state space averaging techniques have been used in modelling the system in the sliding model controller (Li, Lu, & Shen, 2015)(J. Zhang et al., 2016)(Prasanna & Rathore, 2014). In addition, in order to develop the modelling, state space also has been used to derive the small- signal model (J. Zhang, Dorrell, Li, & Area, 2016)(Prasanna & Rathore, 2014)(Mane & Jain, 2015). Another DC-DC converter that used the state space averaging for modelling the system is the deadbeat controller, which is used averaging to model their double boost converter by Veerachary, (2014).

Antsaklis, (2001) and Branic, (1995) found that the state space techniques are applicable in modelling the hybrid system that exists from continuous controls and discrete phenomena. Through this literature, the state space averaging is one of the best modelling techniques that can handle the hybrid behaviour of the DC-DC converter and be used in variety types of DC-DC converter controllers.

2.2.3 Power Losses

The operation of DC-DC converter involved semiconductor devices. These devices present few losses such as conduction losses, switching losses, OFF-state losses and gate losses (BasemAlamri, 2014). Nevertheless, OFF-state losses and gate losses are normally neglected due to the very small value. The number of switching of the system gives significant effect to the conduction losses and switching losses. Every switch operates by turn *on* and *off* in order to supply the current to the circuit. The switching state's operations are illustrated in Figure 2.4. At the *on* state, the voltage value that flows through the circuit is zero. Thus, by using the formula of $p = vi$, the power associated is zero, in which the zero current flows through the circuit during the *off* state. However, practically, the power loss on the semiconductors devices occurs when the transition of the switches.



(a) *on* state (b) *off* state

Figure 2.4 Switching states semiconductors devices.
Sources : Leslie Wright., (2015)

The theory of Leslie Wright, (2015) provides a useful account of how to measure the power losses on power semiconductor devices. Figure 2.5 shows the power losses signal flow on power semiconductor devices. At the *on*-state, the voltage drop occurs and it associated with the power losses of the switches (W. Hart Danial, 2010). Furthermore, switching losses occur when the device is transitioning states (turning-*on* and turning *off*). Subsequently, the number of switching associated with the power losses of the converter due to the amount of switching transition is shown in Figure 2.5.

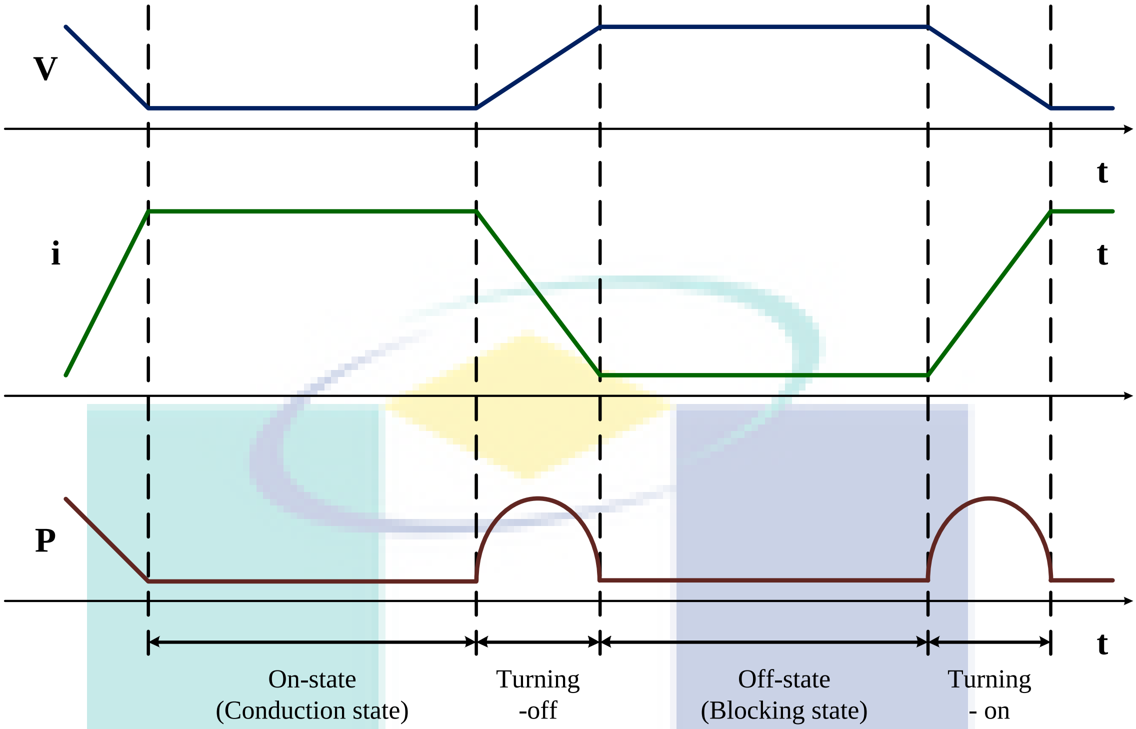


Figure 2.5 Power losses on power semiconductor devices.

Sources : Leslie Wright., (2015)

The total power losses on semiconductor devices are obtained by the equation 2.1. Thus, the higher number of switching has significantly contributed to high power losses.

$$P_T = P_{c(on)} + P_{off} + P_{b(off)} + P_{on} \tag{2.1}$$

Where;

P_T = Total power loss on a power semiconductor device

$P_{c(on)}$ = Conduction losses during *on* state

P_{off} = Turning off loses

$P_{b(off)}$ = Blocking mode during *off* state

P_{on} = Turning on losses

Recently, there are the studied that show on the reducing the power losses of DC-DC converter. One of the methods is by using Zero Voltage Switching (ZVS). In Dong et al., (2016), the ZVS schemes is being used apart of reducing switching components. In order to reduce the number of switches, the (ZVS) operation is retained for one switch. Similarly, Sabahi et al., (2014) also used the ZVS for a bidirectional DC-DC converter with interesting features in terms of low switching losses, bidirectional power flow and less number of the switching device.

Besides, the Zero Current Switching (ZCS) also is one of the methods in order to reduce power losses. The reducing power losses can be achieved by decreasing the switching losses. Thus, less number of switching will reduce the switching losses. In (Kumar, Bhajana, & Drabek, 2016) and (Ko, Lee, & Liu, 2011), both researchers used the ZCS as power losses reducing method. The ZCS interleaved bidirectional buck-boost DC-DC converter is proposed for energy storage applications (Kumar, Bhajana, & Drabek, 2016). In addition, the ZCS for bidirectional DC-DC converter structure has been proposed to reduce current ripple, switching loss and significantly increase the converter efficiency and power density (Ko, Lee, & Liu, 2011). In Yang, Liao, & Cheng, (2011), both of ZCS and ZVS are being combined and added with Synchronous Rectification (SR) for reducing the switching and conduction losses.

Furthermore, the switching losses are being considered for the battery charging applications. In details, a new battery charging high-frequency power converter module has been developed for Plug-in hybrid electric vehicles (PHEV) systems. In this previous study, the three-phase semi-controlled rectification topology is used in order to decreases the switching and conduction losses (Amin & Mohammed, 2011). Besides, in Babu at al., (2011), synchronous buck converter based PV energy system for portable applications; especially low power device applications such as charging mobile phone batteries is studied. The soft switching technique to reduce the switching losses has been implemented.

The hybrid buck–boost feedforward (HBBFF) technique is integrated into this converter to achieve fast line response. This control topology minimizes the switching and conduction losses at the same time even when four switches are used. Similarly, in (Lee, Park, Kwon, & Kwon, 2015), hybrid control scheme are implemented in the hybrid-type full-bridge DC-DC converter. This control scheme converter operates as a phase-shift full-bridge series-resonant converter under a normal input range that provides high efficiency by applying soft switching on all switches and rectifier diodes and reducing conduction losses. It can be seen that, most of these control scheme are using soft switching method to reduce the switching and conduction losses, which one of the techniques for reducing the switching and conduction losses. However, these studies have only paid attention to the losses, whereas our study also focuses on the considerations of DC-DC buck parameters by recalculating at each of prediction horizons.

2.3 Model Predictive Control

There is considerable interest in an advanced control method for a DC-DC converter with the existence of hybrid behaviour (Rodriguez & Cortes, 2016)(Lachichi et al. 2005). The DC-DC converter characteristic consists of a finite number of switching and continuous times of output voltage. There are the studies of investigating the controller for DC-DC converter using Model Predictive Control (MPC). The MPC has been established in control for processing oil distillation (Forbes et al., 2015) and automation industry for automotive control including engine, transmission, emissions, mechatronics actuators, steering, suspensions, energy management and thermal management (Hrovat et al., 2012).

The basic structure of MPC is shown in Figure 2.6. In optimizing the control signal, a model of the process is used by the MPC to predict the future evolution of the process. Same as DC-DC converter, the mathematical model of the DC-DC converter is derived to formulate the MPC such as in Karamanakos, Geyer, & Manias, (2014). One of the advantages of MPC, the nonlinear behaviour of DC-DC converters is being captured by the hybrid modelling techniques (Vlad et al., 2012).

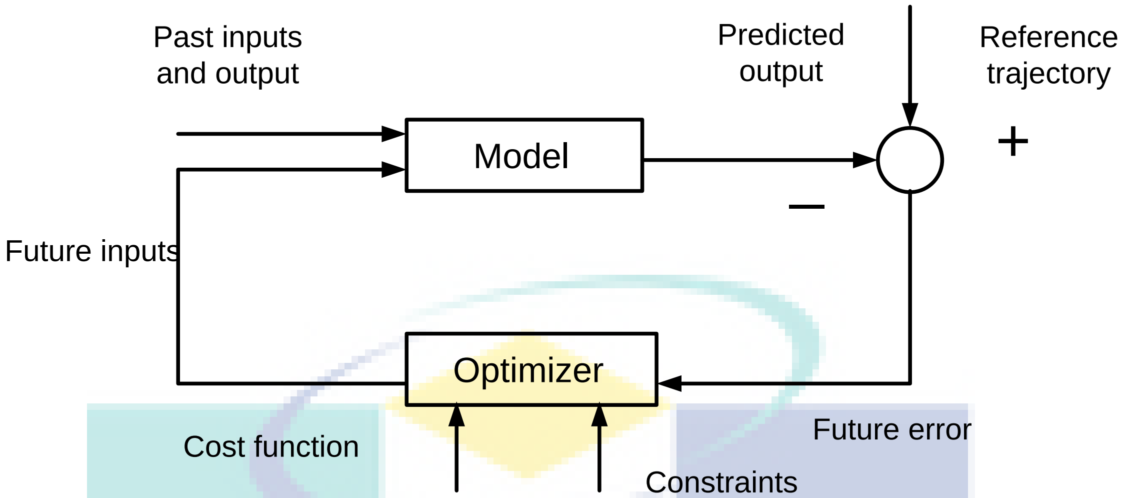


Figure 2.6 Basic structure of MPC

Sources : E.F. Camacho and C.Bordons (2003)

Furthermore, the state space equation is widely used to model the DC-DC converter. The state space averaging equation measured all the parameter constraints at each switching mode. Consequently, the control objectives are formulated for a DC-DC converter by interpreting an applicable objective function and by using the desired constraints. The control signal attains by reducing the objective function (Al-hosani, Malinin, & I. Utkin, 2009).

Meanwhile, Figure 2.7 shows the MPC process that contains the prediction horizons and sampling time. Significantly, the control evolution has been operated at each sampling time over a finite prediction horizon, l by on-line or off-line optimizations, which referring to the objective functions. Correspondingly, the objective function is reduced to the best sequence of the control input that includes all constraints and discrete-time model. This process called *receding horizon policy*. In this process, model uncertainties and disturbances could be considered as an element of the sequence of control inputs. Then, at the next sampling time, the optimization problem is repeated with updated measurements or estimations (Karamanakos et al., 2014). This has shown that the MPC required an extensive algorithm for optimizing the control signal.

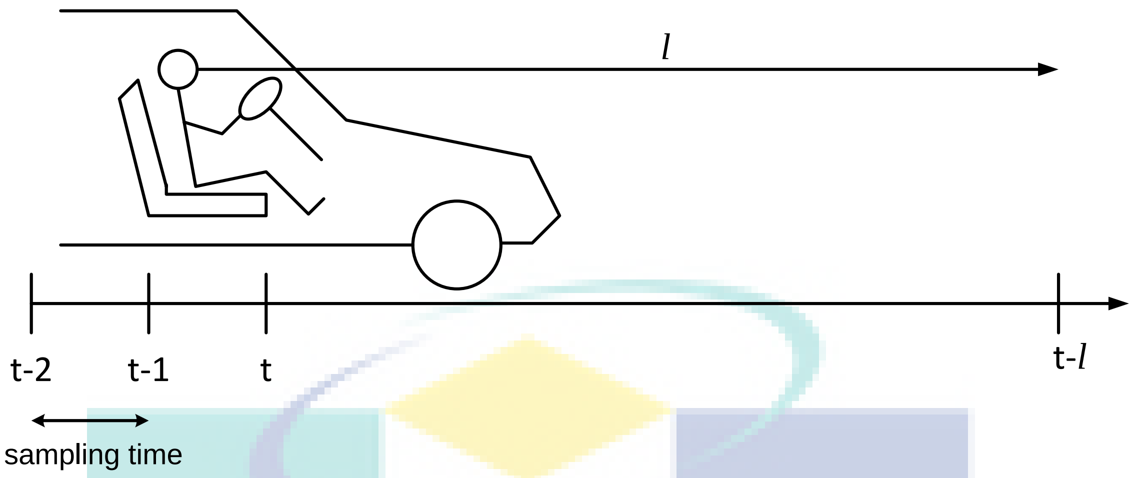


Figure 2.7 MPC analogy.
Sources : E.F. Camacho and C.Bordons (2003)

It is known that the DC-DC converters require high switching characteristics, which is difficult to control using extensive controller algorithm without advanced microprocessor assistance. Since the microprocessor/microcontroller has been further improved in processing speed, the MPC also has started introduced in power electronic applications. For DC-DC converters, some papers such as Mariethoz, Herceg, & Kvasnica, (2008), Vlad et al., (2012), Y. Wang, Member, Xuan, Yu, & Kim, (2013), Karamanakos et al., (2011) and Bououden et al., (2014) had applied MPC in buck and boost converters.

In literature, the MPC approaches use algorithms that based on the recursive computational. The drawback of recursive computation is difficult to implement on-line. Previously, the discrete-time MPC method is introduced by Molla-ahmadian et al., (2012) and Xie et al., (2012). The proposed method is completed based on a discrete-time piecewise affine (PWA) model of the converter. Furthermore, another researcher Xie et al., (2012) and Karamanakos, Geyer, & Manias., (2014) proposed the MPC schemes implemented an off-line computation, which developed by changes of duty ratio and the reducing the 1-norm of output voltage error. Unfortunately, the limitations of these approaches are needs depend on the lookup table which significant with the complexity of computation of multi-parametric programming.

In addition, the paper from Kuntal et al., (2014) and Kazmierkowski et al., (2002) have documented the MPC scheme based on an input constrained infinite set. By using MPC method, the procedure begins with solving the unconstrained optimization.

Then it continues with searching the ideal input value in the finite set by using the nearest neighbor vector using the polyhedral partition. Nevertheless, these approaches may not be appropriate in many situations due to the mathematical solution is difficult in practical implementation.

Recently, the study to simplify the MPC controller algorithm has put an extensive issue in MPC approach. As in DC-DC converters, the promising controllers are still extensive developed due to the DC-DC converters are widely used in most applications. In terms of control beneficial, the controller algorithms are useful to explore since the DC-DC converters in nature produce hybrid behaviour. Thus, to obtain good controller with simple implementation is essential in DC-DC converters. Hence, several schemes have been proposed using MPC approach in DC-DC converters. One of the MPC schemes with the hybrid problem is presented in Geyer, Papafotiou, & Morari., (2008). The formulation for solving a constrained optimal control problem is made based on the hybrid model of the converter. For achieving this, the explicit state-feedback control law is derived offline. It can be applied in a lookup table and easily stored. The method used is approximately equal to the study by Shen et al., (2013), which solving the optimal control problem offline to create the lookup table.

Furthermore, there are many others research that implements MPC in the DC-DC Buck converter. Yan et al., (2015) found the buck converter is modelled as sampled data based on switched affine system to describe the closed- loop dynamics. Online state prediction is introduced such that the switching signal is computed one period before its implementation. While for the switching law, it was designed offline.

Moreover, the long prediction horizon of MPC is one of MPC controller strategy that has been implemented in the systems in order to get the best-predicted values. Ayad et al., (2015) develop a new MPC strategy to control both sides of a quasi-Z- source inverter (qZSI) based on the inductor and the output currents. In their systems the long prediction horizons are implemented. In Geyer, Oikonomou, & Kieferndorf, (2014), a longer prediction horizon enhance stability and plant execution. Yet, the computational complexity relying on the type of the optimization problem rises together with the length of the prediction horizon and the number of manipulated variables. Nonetheless, since the long prediction horizon is used, the complexity of the algorithm is the main problem encountered, which is a trade-off with the good performance and controller complexity burden (Karamanakos, Geyer, & Kennel (2014)). In addition, the long prediction horizon needs to use dynamic programming which required toolbox and existence algorithms.

Ayad et al., (2015) and Karamanakos et al., (2015) have developed the branch-and-bound technique for MPC strategy to minimizing the computational algorithm burden for long prediction horizon. Meanwhile, the offline estimation of an infinite prediction horizon function based on approximate dynamic programming is stated in Stellato, Geyer, & Goulart, (2016). Nevertheless, the computational complexity grows exponentially with the length of the prediction horizon and still consider as a complex algorithm. Beside of that, even some improvement of minimizing complexity on the MPC algorithm have been proposed, but the switching number of switched device is not taking into account for reducing the conduction losses. This perhaps one of the issues could be further investigate for enhancing the controller performance and efficiency..

2.4 PID Controller

Proportional Integral Derivatives (PID) is one of the famous controllers that widely been used in many applications including power electronics. Due to the simplicity of the controller design, the PID is often used in controlling DC-DC converters as shown in Figure 2.8. This is including the modified PID controller and combination with another control method such as sliding mode and fuzzy logic control for enhancing the DC-DC converter performances.

In Al-hosani et al., (2009), the combination of sliding mode and PID controller is carried out to control a DC-DC buck converter. Furthermore, the combination of PID controller with fuzzy logic control is proposed to improve the transient response performance for load variation conditions (Vindhya & Reddy, 2013). By implementing this method, it exhibits that satisfactory voltage regulation without having complicated mathematical models for the DC-DC buck (Kabir, Ieee, & Mahbub, 2012) are presented. Figure 2.8 shows the block diagram of PID controlled buck converter.

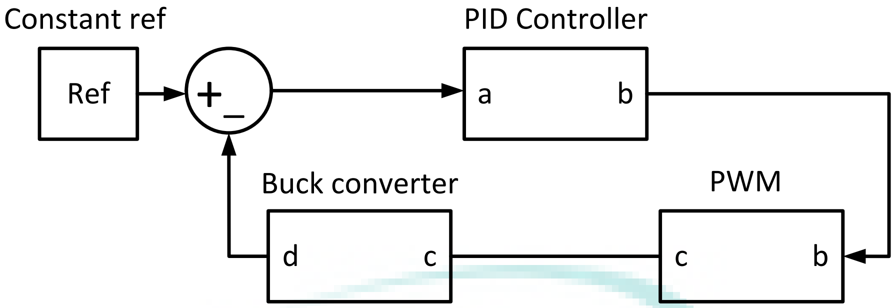


Figure 2.8 Block diagram of PID controlled Buck Converter.
Source: Kabir et al., (2012)

Other than that, Tomita et al., (2013), Arthika & Priya, (2015) and (Abbas et al., 2014) have shown that the implementation of modified PID controller could improve the transient response and the margin of stability. Hence, converter performance can be improved accordingly.

Although the PID and improvement of PID controllers have shown the acceptable result, the transient response of the output voltage DC-DC converter could be further improved due to the limitation of PID controller. This is due to the PID is classified as linear controller and need to re-tune the gains if the operating points of the system are varied. Thus, the more promising controller could be proposed in order to improve converter performance and robustness.

2.5 Kalman Filter

Despite the demand for consistent operation of power electronic applications in various industries, several problems have not been completely issued yet, for instance robustness to load parameter variations and ease of controller design and tuning. Several recent studies investigating the load parameter variations have been carried out to tackle the load variations difficulties (Zakipour & Salimi, 2015)(Rigatos et al., 2015)(Q. Zhang et al., 2014) and (Kurucs, 2015).

Generally, a number of authors have studied the parameter estimation of the load. One of the methods is online parameter tuning method for power converter with predictive control-mode. This scheme generates upon adding an additional current sampling between two pulse width modulated output (Chang at al., 2009). Likewise, in 2014, another interesting approached to this issue has been proposed by Al-Hosani &

Utkin, (2012). Their proposed method is based on the sliding mode by tune the convergence rate with linear operators such as time delay. Furthermore, another latest solution is described in (Alonge et al., 2015), which practice Hammerstein approach to deals with parameter uncertainty and load variations. However, the limitation with this approached is in that it applied complex numerical simulation.

Furthermore, in generating the proposed scheme of the estimator of the load variation, the nonlinearities of the DC-DC converter should be considered. Most of the approaches need to deal with the nonlinear difficulties of DC-DC converter. Recently, the State Observer-Based, Luenberger state observer and Extended Kalman filter (EKF) are the can approach to handle the nonlinearities. Up to now, (Renaudineau et al., 2015) have analyzed the accuracy and precision of all these control methods. Commonly, the state observer-based dedicated to an online estimation of the model parameters. Nevertheless, the EKF need to linearized the DC-DC converter by using composite mathematical schemes (Joukov et al., 2015).

Moreover, a great and increasing body of literature has investigated the parameter estimation scheme using Kalman Filter (KF). In Missailidis et al., (2014), the proposed approached of KF is performed by estimated the transfer function parameters of a DC–DC converter based on KF algorithms. In Izadian et al., (2010), the KF is generated by using outstanding indicator based on a time-averaging model. In order to estimate the conditions of dynamics system, the recursive computations of KF are used. In KF strategy, the estimation step is improved by using two steps, which consists of the prediction and the corrections. Briefly, the *dynamics model* is used in predicting the state. Then, it will be corrected at the second step by using the *observation model*, which reducing the covariance error (Kleinbauer, 2004).

For many years, when it comes to controlling noise systems, KF has been thought of as an effective component. Generally, smoothing noisy data and producing estimates of parameters of interest has been done by KF. Many achievements of smoothing signal for typical applications of KF such as laptop trackpads, phase locked loops in radio equipment and global positioning system receivers. In terms of theoretical standpoint, the KF is an algorithm authorizing accurate assumption for both linear and nonlinear dynamical systems (Faragher, 2012). In numerous applications, the load uncertainty will affect the output voltage error (Izadian & Khayyer, 2010)(Al-sheikh & Hoblos, 2015) and (Aoune et al., 2016). Thus, in order to eliminate the error and estimates the load changes, the KF is one of the best approaches.

In Figure 2.9, show the combination of MPC and KF for estimating the parameter value during the load variations (Karamanakos et al., 2014). This approach overcomes the load variation by adding the additional external loop. The current reference will be adjusted by the additional loop to eliminate output voltage error. Nonetheless, this approach still proposed an extensive mathematical derivation and recursive algorithm for MPC controller. Hence, in this thesis, the KF will be further investigated to use with MPC for controlling the DC-DC converter.

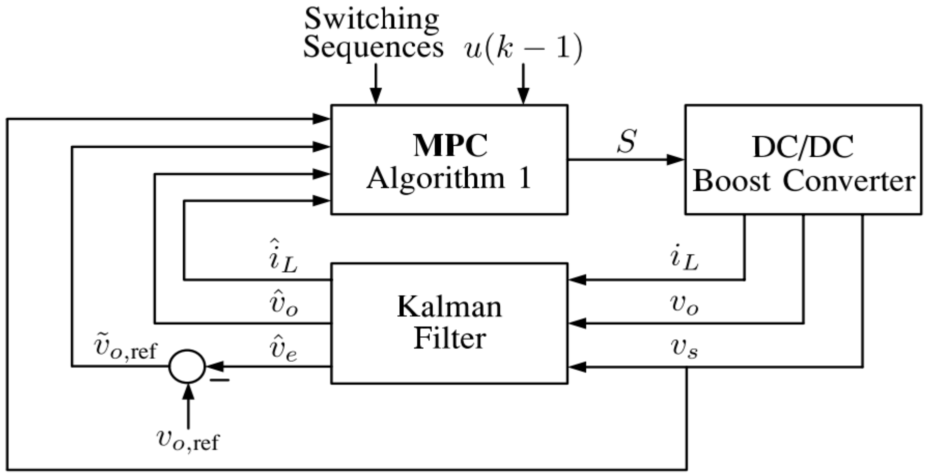


Figure 2.9 Control diagram of proposed MPC-KF strategy.
Sources : Karamanakos et al., (2014)

2.6 Summary

This chapter describes the characteristics of DC-DC converter, MPC schemes, PID controllers and load variation method. Through this literature review, it can be concluded that there are many researchers are trying to improve the performance of the DC-DC converters using MPC controller. Nevertheless, these methods cope with the complex algorithm and deal with dynamics programming. The proposed short prediction horizons using an analytical MPC algorithm have more benefits regarding light computational and reducing the number of switching of the switches. Then, KF is the best approaches in identifying and smoothing the signal during the load changes due complex mathematical for other approaches to linearized the DC-DC converter.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the proposed method of controlling the DC-DC buck converter using Model Predictive Control (MPC). The first step explores the DC-DC buck converter behaviour. The mathematical modeling of a DC-DC buck converter is presented by considering the nature hybrid behaviour of the converter by using the state space averaging techniques. The state-space averaging technique consists of two circuit operation, which is *on* and *off* of the switching state conditions. Then, the MPC strategy is presented. The MPC strategy and control algorithm have been developed to improve the efficiency of DC-DC buck converters by using search tree optimization techniques. Lastly, a design methodology for solving the load variation problem of MPC by using the Kalman Filter (KF) with MPC is presented for tackling the load changes in the DC-DC converter.

3.2 Mathematical Model of DC-DC Buck Converter

The state space averaging techniques was being used to represent the model of DC-DC buck converter. The DC-DC buck converter diagram is illustrated in Figure 3.1. It consists of inductor *L*, which carry and supply energy depend on the operational mode of the converter and it is connected in series with the additional internal resistor r_L. Besides, to ensure constant output voltage in steady-state operation of the converter, the filter capacitor *C* and additional capacitors resistor r_c are connected in parallel with the load resistor, *R*. In addition, two power semiconductors were included (i.e., the controllable switch *S* and diode, *D*). In this project, the buck converter is modelled by using the same technique that was been used in previous researcher Al-sheikh & Hoblos, (2015), Modabbernia & Group, (2013), Alonge et al., (2015), Karamanakos et al., (2013) and Zakipour & Salimi, (2015), i.e., using the state-space averaging technique. Besides, the effectiveness of steady state averaging techniques for various controller also being proved in Nizami & Mahanta, (2015). In this technique, the dynamics of the buck converter system is defined by direct application of voltage law (KVL) and Kirchhoff's current (KCL) for the present circuit topologies and switching state.

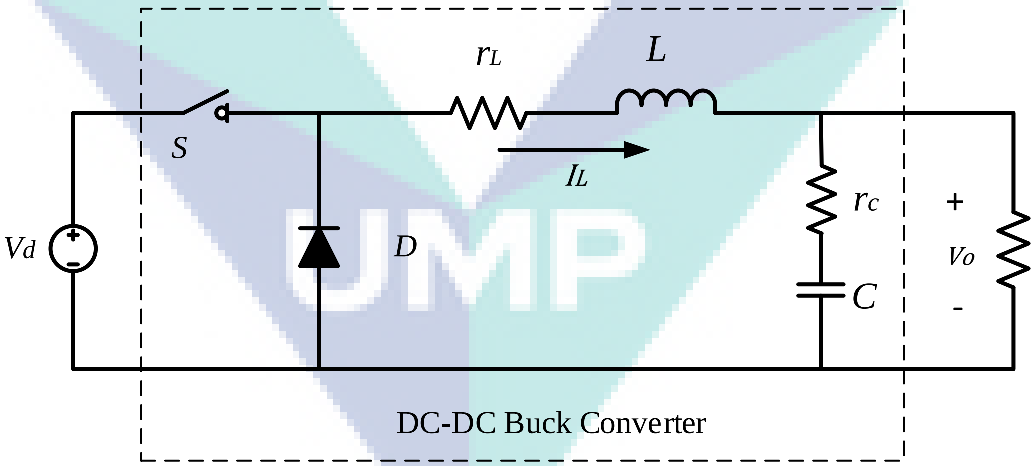


Figure 3.1 General model of DC-DC buck converter

3.2.1 Mathematical Modelling

Generally, the main purpose of the state-space averaging is to estimate the switching converter as a continuous linear system (A. Simon and O. Alejandro, 2005). In state space modeling, output and state equations are employed using a set of first order differential equations which are organized in term of state variables. The DC-DC buck converter physically topographies two operations based on switching modes *on* and *off*. Figure 3.2 and Figure 3.3 show the equivalent circuit of DC-DC buck converter when the switches are turned *on* and *off*, respectively.

First, to calculate how much energy is stored in a capacitor, we start by looking at the basic relationship between voltage and current in a capacitor, where;

$$i_c(t) = C\frac{dV_c}{dt}(t) \tag{3.1}$$

While the voltage through inductors is;

$$V_L(t) = L\frac{dI_L}{dt}(t) \tag{3.2}$$

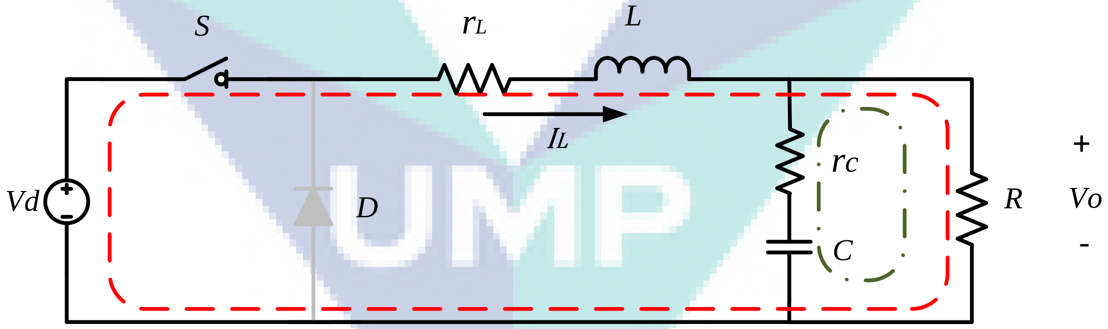


Figure 3.2 Mode 1 (switch *on*)

At mode 1 (switch *on*), the first order equation when the switch *S* is turned *on* can be determined (refer to Figure 3.2). The KVL around the outer loop of red dash line is applied to produce the first order differential Equation of 3.3 and 3.4 as follows;

$$V_d = (r_L + r_C)I_L + L\frac{dI_L}{dt} + V_C \tag{3.3}$$

$$\frac{dI_L}{dt} = -I_L \frac{(r_L + r_C)}{L} - \frac{V_C}{L} + \frac{V_d}{L} \tag{3.4}$$

Where V_C is the voltage across the output capacitor, and I_L is the current through the inductor. In order to complete the KCL of the switch *on* mode, the voltage divider was derived such that;

$$V_0 = V_c \frac{R}{R + r_c} \tag{3.5}$$

And the inductor current I_L from KCL as follows;

$$I_L = C \frac{dV_C}{dt} + \frac{V_o}{R} \tag{3.6}$$

By substitute Equation (3.5 to Equation (3.6, yields;

$$\frac{dV_c}{dt} = \frac{I_L}{C} - \frac{V_C}{C(R + r_c)} \tag{3.7}$$

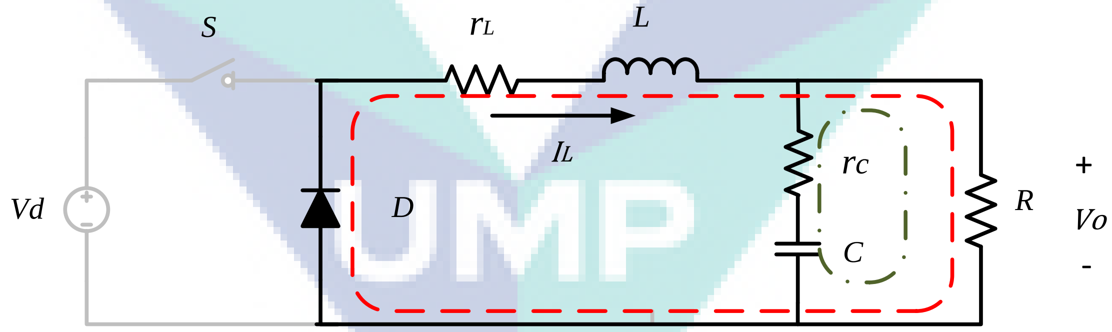


Figure 3.3 Mode 2 (switch *off*)

Then, for mode 2 (switch *off*), the KVL is obtained as in Equation 3.8 and 3.9 (Refer To Figure 3.3).

$$I_L(r_L + r_c) + L\frac{dI_L}{dt} + V_c = 0 \tag{3.8}$$

$$\frac{dI_L}{dt} = -\frac{I_L(r_L + r_c)}{L} - \frac{V_c}{L} \tag{3.9}$$

It is also observed that the KCL is same as Equation 3.7 for mode 2, which is identical to mode 1. Then, taking up the inductor current I_L and capacitor voltage V_c as state variables, the variable structure of the converter's model (from Equations 3.4, 3.7 and 3.10) can be obtained as follows;

$$\begin{bmatrix} \frac{dI_L}{dt} \\ \frac{dV_C}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{r_L + r_C}{L} & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{C(R+r_C)} \end{bmatrix} \begin{bmatrix} I_L \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_d \tag{3.10}$$

It is then can be simplified to affine continuous-time state-space structure for each switching mode as follows;

$$\dot{x}(t) = A_1 x(t) + B_1 v_d \tag{3.11}$$

$$\dot{x}(t) = A_2 x(t) + B_2 v_d \tag{3.12}$$

Where;

$$A_1 = A_2 = \begin{bmatrix} \frac{-(r_L + r_C)}{L} & \frac{-1}{L} \\ \frac{1}{C} & \frac{1}{C(R+r_C)} \end{bmatrix} \tag{3.13}$$

$$B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \tag{3.14}$$

$$B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{3.15}$$

In this case, A_1 and A_2 represent for *on* and *off* mode respectively, and $x = [I_L, V_C]^T$ and v_d is the input. For both modes (mode 1 and 2), the switch is alternately turned *on* and *off*; hence the switching characteristic can be assumed as a binary control Ω, such that $\Omega \in (1, 0)$. Therefore the output voltage at the load R can be represented as

$$y = v_0 = \Omega x, \tag{3.16}$$

Where, x is the affine continuous-time state-space.

3.3 Proposed Model Predictive Control (MPC) in DC-DC Converter

Figure 3.4 shows the MPC strategy for a predicted output that to be optimized for the measured output at each sampling time. Since the predicted output is calculated based on the sampling time, the updated value of output will be considered at each sampling time until it meets the reference trajectory, and thus would increase the control efficacy. In this MPC strategy, the modes are finite that able to predict the state trajectories on-line. Hence, the optimal sequence of switching mode could be solved over a certain prediction horizon. In addition, the aim of proposed MPC is to obtain a straightforward objective function so as the optimization could be performed in short prediction horizon. The closed loop of MPC is shown in Figure 3.5.

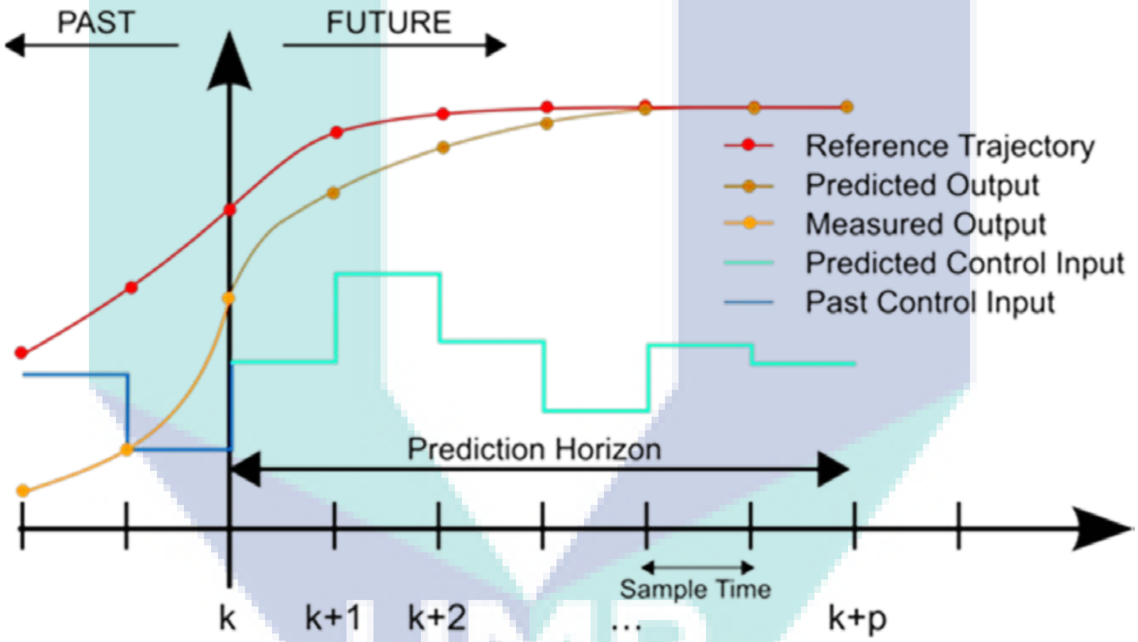


Figure 3.4 MPC strategy

Sources : E.F. Camacho And C.Bordons (2003)

For PI/PID controller (or linear controllers), the pulse width modulation (PWM) is usually used for adjusting the control signals of duty ratio to the switch device. However, for MPC the idea is to optimize the constrained *on* and *off* such that bound in {1, 0} of a binary number. Therefore, the objective function for MPC needs to be minimized so that the constrained is optimized. The new formulation is carried out so as the analytical solution for optimization problem can be performed. The search tree optimization is adapted due to it is easier to implement in the algorithm.

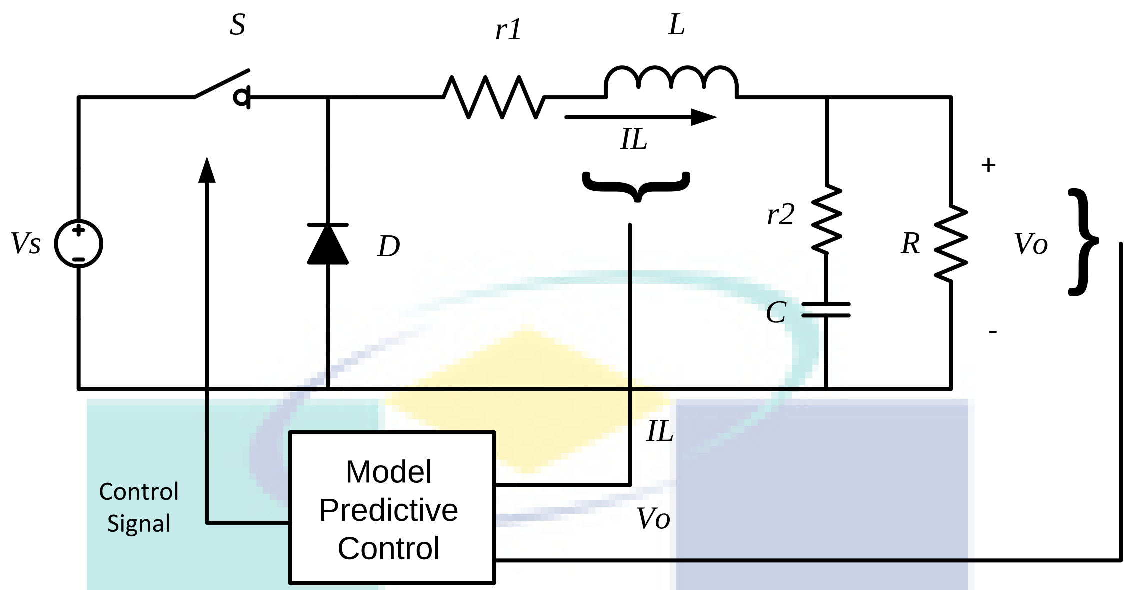


Figure 3.5 Closed loop system with MPC.

3.3.1 Hybrid Analysis

In many systems, the model of the state could be in the form of continuous *x* and discrete state q. The combination of both states is called the hybrid automata. The continuous state $x \in X$, where $X \subseteq R^n$ is being continuous state-space. Meanwhile $q \in Q$, where $q = \{q_1, \cdots, q_n\}$ is discrete state of finite set. This phenomenon is then used in formulating the MPC objective function.

3.3.2 Computation of Control Objective

In this section, the MPC formulation is presented. To make the equation easier to read, let index $\rho = 1$ represent the *on* mode and $\rho = 2$ represent the *off* mode. Then the modeling of the converter in affine continuous-time such as;

$$\dot{x}(t) = A_\rho x(t) + B_\rho u \tag{3.17}$$

$$y(t) = V_o(t) = \Omega x(t) \tag{3.18}$$

In this case, let consider that voltage supply, $u = v_d$ is a fixed and all A_p are stable. Instantly, the result of $x(t)$ in $t \in (t_0, t)$ with initial state $x(t_0)$ could be calculated as;

$$x(t) = e^{A_\rho(t-t_0)}x(t_0) - \left(I - e^{A\rho(t-t_0)}\right)A_\rho^{-1}B_\rho u \\ = e^{A_\rho(t-t_0)}\left(x(t_0) + A_\rho^{-1}Bu\right) - A_\rho^{-1}B_\rho u \tag{3.19}$$

Where I is the identity matrix and then the output is such;

$$y(t) = \Omega e^{A_\rho(t-t_0)}\left(x(t_0) + A_\rho^{-1}Bu\right) - \Omega A_\rho^{-1}B_\rho u \tag{3.20}$$

In order to track the reference of output voltage, the square area of the tracking error *e(t)* is considered for objective function formulation that will be minimized through finite prediction horizon as follows;

$$e(t) = y(t) - v_r \tag{3.21}$$

Where v_r is a reference and tracking error *e(t)* over finite prediction horizon can be derived such as;

$$J(t_1, t_0) = \int_{t_0}^{t_1} e^2(t)dt = \int_{t_0}^{t_1} (y(t) - v_r)^2 dt \tag{3.22}$$

To fulfill the ultimate purpose of the converter that is to track the reference voltage v_r, the tracking error only deals with the voltage. However, the state x is measured for inductor current I_L and capacitor voltage V_c such that $x = [I_L, V_C]^T$. Then, from Equation 3.21, the vector of ξ and scalar of η are form such as follows;

$$\xi_\rho = x(t_0) + A_\rho^{-1}Bu, \quad \eta_\rho = -\Omega A_\rho^{-1}B_\rho u - v_r \tag{3.23}$$

Substitute vector ξ and scalar η into Equation 3.22 and expanding the tracking error to $e^2(t)$ get as in Equation 3.24;

$$e^2(t) = \eta_\rho^2 + \xi_\rho^T e^{A_\rho^{-1}(t-t_0)}\Omega^T \Omega e^{A_\rho(t-t_0)}\xi_\rho + 2\eta_\rho \Omega e^{A_\rho(t-t_0)}\xi_\rho \tag{3.24}$$

For the tracking error over finite prediction horizon, the index $J_\rho\,(t_1, t_0)$ can be derived as follows;

$$J_{\rho}(t_1,t_0)=(t_1-t_0)\eta_{\rho}^2+\xi_{\rho}^T\int\int_{t_0}^{t_1}e^{A_{\rho}^T(t-t_0)}\Omega^T\Omega e^{A_{\rho}(t-t_0)}dt\xi_{\rho}+2\eta_{\rho}\Omega\int\int_{t_0}^{t_1}e^{A_{\rho}(t-t_0)}dt\xi_{\rho} \tag{3.25}$$

Afterward, in order to indicate the state is in mode ρ, a subscript is added to the index function. It shown later the Lyapunov equation is obtained such in Equation 3.25. Therefore, it can be employed to determine the observability grammian to satisfying stability of the controller. Hence, for A_{ρ} is stable, then, it exists the matrix $X_{\rho}>0$ to satisfy as follows;

$$A_{\rho}^T X_{\rho}+X_{\rho}A_{\rho}+Q=0 \tag{3.26}$$

The observability grammian holds in Equation 3.27 such as;

$$\begin{aligned}Q_p(t_1-t_0)&:=\int_{t_0}^{t_1}e^{A_{\rho}^T(t-t_0)}\Omega^T\Omega e^{A_{\rho}(t-t_0)}dt\\&=\int_0^{t_1-t_0}d\left(e^{A_p^T t}X_{\rho}e^{A_p t}\right)\\&=X_{\rho}-e^{A_{\rho}^T(t_1-t_0)}X_{\rho}e^{A_{\rho}(t_1-t_0)}\end{aligned} \tag{3.27}$$

Then, Equation 3.28 can be rewritten for objective function MPC after substitute $Q_p(t_1-t_0)$ as stated below;

$$J_{\rho}(t_1-t_0)=(t_1-t_0)\eta_{\rho}^2+\xi_{\rho}Q_{\rho}(t_1-t_0)\xi_{\rho}+2\eta_{\rho}\Omega A_{\rho}^{-1}\left(e^{A_{\rho}(t_1-t_0)}-I\right)\xi_{\rho} \tag{3.28}$$

In this proposed control, the vector ξ_p is calculated on-line. Meanwhile, the other is computed off-line. This can increase the computational time of the on-line computation. Therefore, due to the existing discrete nature of DC-DC converter, on-line implementation is important. In addition, the on-line implementation is essential to reduce the computational effort of the controller due to the finite number of switching states of power converters.

3.3.3 Model Predictive Control Algorithm

The minimization of the objective function of the MPC uses the search tree optimization method. The illustration of the search tree for prediction horizon $l \leq 3$ is shown in Figure 3.6. Since the MPC is computed at each sampling instant, for the long prediction horizon will increase the computational algorithm burden. Thus, in this MPC algorithm, the aim is to find the short prediction horizon in minimizing the objective function of the MPC. It is noted that, when using long prediction horizon, more precise control output would be obtained. However, complexity and controller cost higher are the shortcomings of long prediction horizon (Karamanakos et al.,2016) and (Geyer et al., 2014). Another advantage of short prediction horizon is an analytical optimization computation could be performed. In this thesis, the short prediction horizon ($l \leq 3$) is being proposed.

The control problem is to calculate the sequences of switching modes so that the output voltage tracks the reference trajectory v_r as good as possible. It involves by minimizing the objective function along a finite prediction horizon, l. Henceforth, the equivalent switching sequences are assigned by $\sigma = [\sigma(1),...,\sigma(1)]$, where $\sigma(k) \in \{1, 2\}$. Due to the effect of unpredicted disturbance, each of sampling instant is recalculating consecutively to obtain an optimizing sequence. Furthermore, the changes of repeated optimal switching mode depend on the disturbance effect.

For optimizing step, first $Q_\rho(T)$ $CA_\rho^{-1}(e^{A\rho T} - I)$ are computed off-line for all $\rho \in P$. Secondly, the state at $t = t_0$ is being sampled and vector ζ_ρ and scalar η_ρ are estimated for all $\rho \in P$. Third, the predicted state is computed at all switching instants from $t_0 + T$ up to $t_0 + lT$ for all switching sequence σ. Then, the control objective $J_{\sigma(k)}(t_0 + kT, t_0 + (k+1)T)$ is calculated for all switching sequence σ and $k \in \{1,...,l\}$. Lastly, the switching sequence, such that $I_\sigma(t_0 + lT, t_0) = J_{\sigma(1)}(t_0 + T, t_0). + ... + J_{\sigma(l)}(t_0 + lT, t_0 + (l-1)T)$ is searched through the tree sequence.

The search tree equation for the case of three prediction horizon length (l=3) is illustrated in Figure 3.6. The fundamental switching period is set as the sampling period

T, where $t_0 - t_1$ is one sampling instant. The first branch at the t_0 that labeled as 1 and 2 indicated the switching state of *on* and *off*. Next, at the second prediction horizons, $t_0 - 2T$, two branches develop another two switching state for $\rho \in (1, 2)$. Then, the same procedure is used in the further prediction horizon. As a result, the control objective is to find the best switching state for constrained duty ratio required using search three optimizations. It depends on how long the prediction horizon is used, for example, $l = 1, 2$ or 3 $(t_0 - t_1, t_1 - t_2, t_2 - t_3)$. If $l = 3$, the possible switching states are eight candidates that bound from *a* to *h*. The value of the index for each branch is listed below;

$$\begin{aligned}
&a. J_1(t_0+T,t_0)+J_1(t_0+2T,t_0+T)+J_1(t_0+3T,t_0+2T)\\
&b. J_1(t_0+T,t_0)+J_1(t_0+2T,t_0+T)+J_2(t_0+3T,t_0+2T)\\
&c. J_1(t_0+T,t_0)+J_2(t_0+2T,t_0+T)+J_1(t_0+3T,t_0+2T)\\
&d. J_1(t_0+T,t_0)+J_2(t_0+2T,t_0+T)+J_2(t_0+3T,t_0+2T)\\
&e. J_2(t_0+T,t_0)+J_1(t_0+2T,t_0+T)+J_1(t_0+3T,t_0+2T)\\
&f. J_2(t_0+T,t_0)+J_1(t_0+2T,t_0+T)+J_2(t_0+3T,t_0+2T)\\
&g. J_2(t_0+T,t_0)+J_2(t_0+2T,t_0+T)+J_1(t_0+3T,t_0+2T)\\
&h. J_2(t_0+T,t_0)+J_2(t_0+2T,t_0+T)+J_1(t_0+3T,t_0+2T)
\end{aligned} \tag{3.29}$$

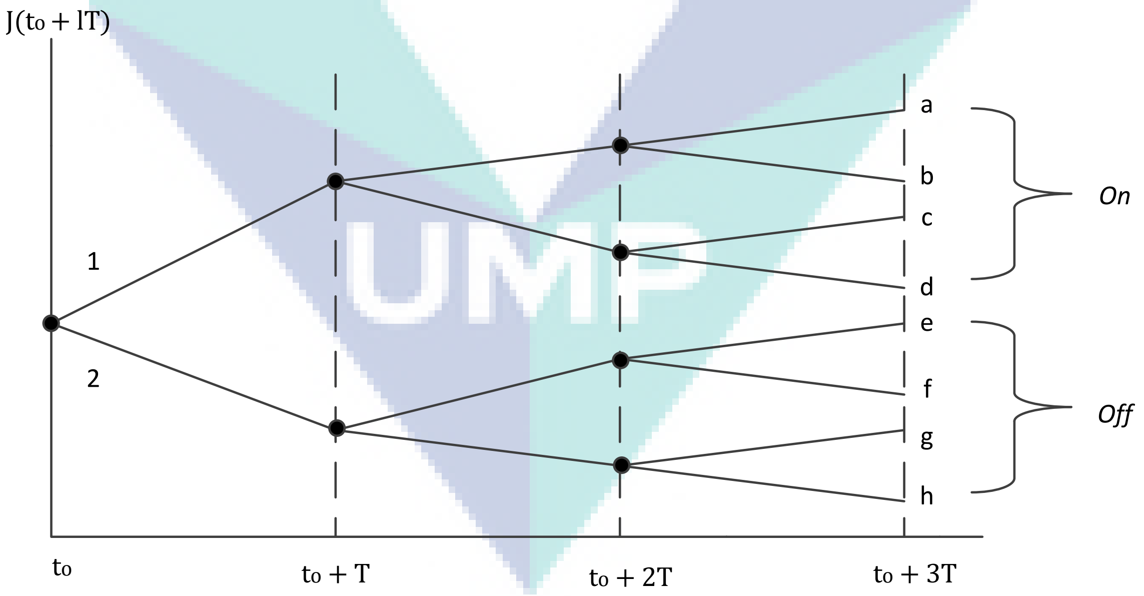


Figure 3.6 Illustration of the search tree for prediction horizon $l \leq 3$.

While, the search tree for long prediction horizon, l = 5 is illustrated in Figure 3.7. The index value for each branch for the search tree equation intended for long prediction horizon is listed below;

$$
\begin{aligned}
&1. J_1(t_0+T,t_0)+J_1(t_0+2T,t_0+T)+J_1(t_0+3T,t_0+2T)+J_1(t_0+4T,\\
&t_0+3T)+J_1(t_0+5T,t_0+4T)\\
&2. J_1(t_0+T,t_0)+J_1(t_0+2T,t_0+T)+J_1(t_0+3T,t_0+2T)+J_1(t_0+4T,\\
&t_0+3T)+J_2(t_0+5T,t_0+4T)\\
&3. J_1(t_0+T,t_0)+J_1(t_0+2T,t_0+T)+J_1(t_0+3T,t_0+2T)+J_2(t_0+4T,\\
&t_0+3T)+J_1(t_0+5T,t_0+4T)\\
&.\\
&.\\
&.\\
&32. J_2(t_0+T,t_0)+J_2(t_0+2T,t_0+T)+J_2(t_0+3T,t_0+2T)+J_2(t_0+4T,\\
&t_0+3T)+J_2(t_0+5T,t_0+4T)
\end{aligned}
\tag{3.30}
$$

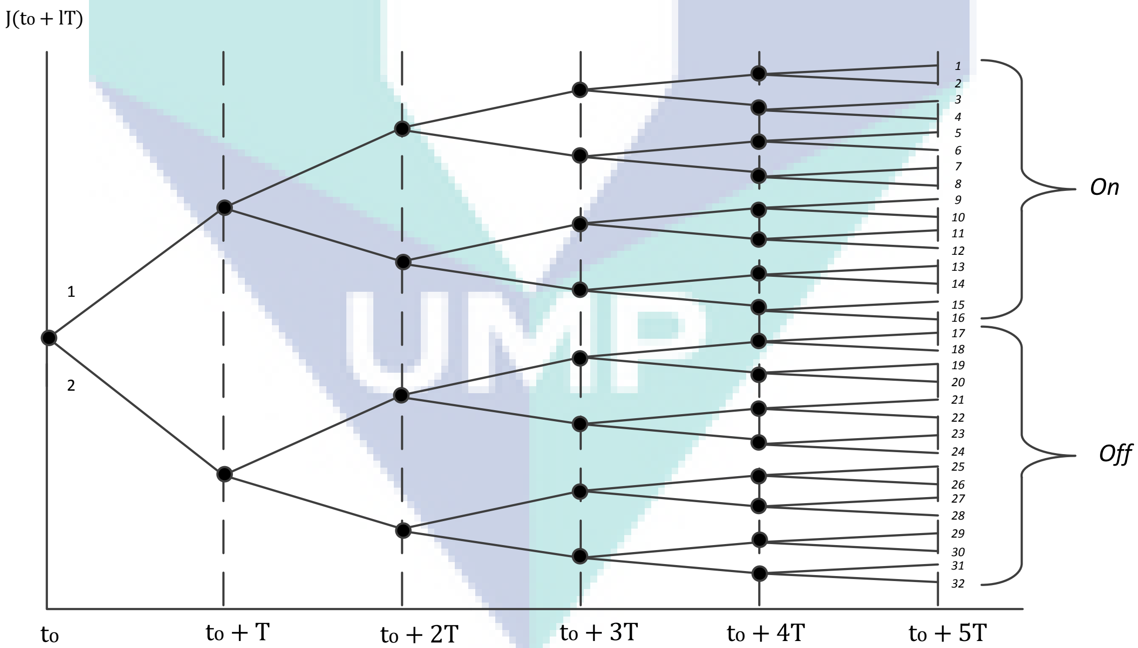


Figure 3.7 Illustration of the search tree for prediction horizon $l \leq 3$.

3.4 Simulation Circuit and Controller Using Matlab

In this research project, the simulation using MATLAB/Simulink is being used to verify the effectiveness of the proposed controller. It includes MPC approach and PI controller approach.

3.4.1 Model Predictive Control (MPC)

The topology of the buck converter is shown in Figure 3.1. This circuit topology has generated using MATLAB Simulink together with all the parameters. The circuit parameter of the step-down DC-DC converter was shown in Table 3.1.

Table 3.1 Buck converter parameter

Parameter	Value
L	15.91mH
C	94µF
$\mathbf{r_c}$	0.001Ω
$\mathbf{r_l}$	0.517Ω
R	4Ω
$\mathbf{v_d}$	24V

Figure 3.8 below shows the block diagram of buck converter by using the MPC. The block diagram consists of MATLAB function block and others parameter block of the buck converter. The simulation being conducted on discrete simulation with the sample time 5µs. The square area of the tracking error *e(t)* from Equation 3.21 has generated by a comparison of the output voltage with reference to the actual voltage output.

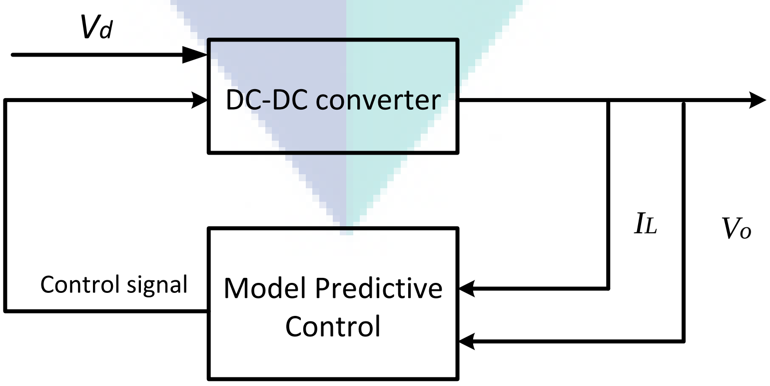


Figure 3.8 Buck converter Block Diagram using MPC.

3.4.2 PI Controller

In order to examine the performance of MPC. The MPC results are being compared with PI controller. Thus, the parameters of the PI controller are shown in Table 3.2 that consists of Kp and Ki. The best parameters of PI controller were chosen based on the trial and error method, which is one of the tuning methods that had been used by previous researchers. By using this method, the best value of PI gains were chosen in order to reach the optimal performance of PI (Nahapetian, 2008).

In PI Controller, P represents Proportional will shorten the rise time. P responsible in tracking the voltage reference, v_r. There is always a steady state error in proportional control. The error will decrease with increasing gain. Then, I stand for integral to reduce the settling time and the overshoot value. The steady state error disappears when integral action is used.

For the switching frequency of PI Controller, 200kHz is being used. Both methods used same value of switching frequency.

Table 3.2 Parameter of PI controller.

Parameter	Value
Switching frequency	200kHz
Kp	100
Ki	20

Figure 3.9 shows the block diagram of PI controller. It consists of a PI block diagram. The PI controller will detect the error that generated from the comparison of actual output and the setpoint output. Then, the gains are autotuned to the best PI parameter’s value in order to produce the desired output voltage. Meanwhile Figure 3.10 illustrated the block diagram of implementing PI controller in the DC-DC converter, which is consists of pulse width modulation (PWM) generator for controlling the switched device.

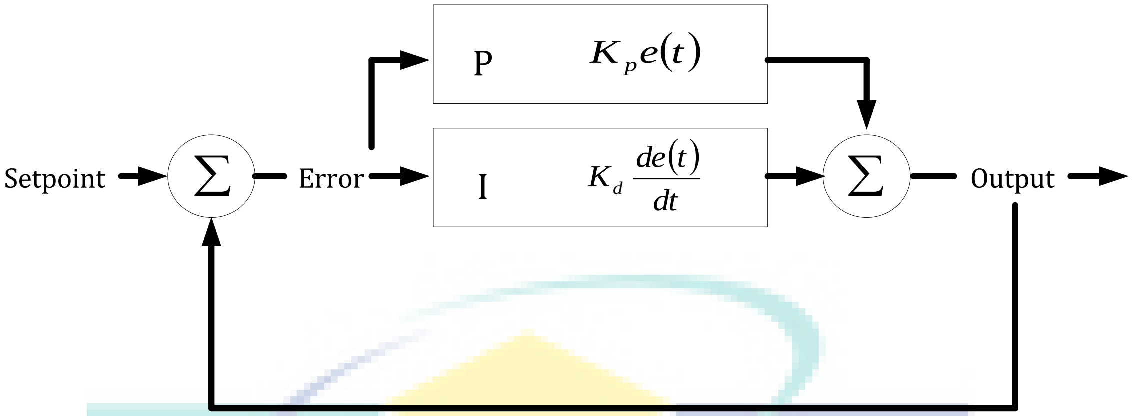


Figure 3.9 PI controller Block Diagram

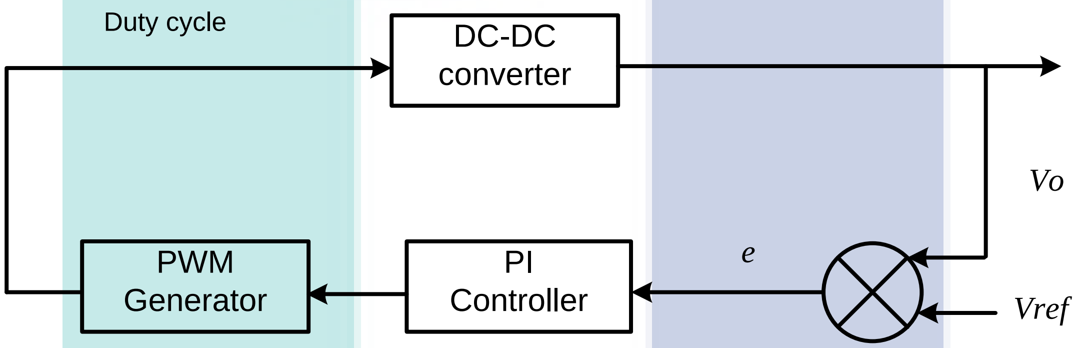


Figure 3.10 PI controller in DC-DC converter

3.4.3 Step Response of Control System

In order to calculate the effectiveness of MPC and PI controller, the typical step response of a control system is by using the second order underdamped response specification that shows in Figure 3.11 is being used. In any response, the performance of the systems is measured using the rise time, settling time, overshoot and peak time. The rise time, *tr* is the time required for the waveform to go from 0.1 of the final value to 0.9 of the final value. While, the peak time, *tp* is the time required to reach the first, or maximum peak. Furthermore, percent overshoot, *OS* is the amount that waveform overshoots the steady-state or final value at the peak time expressed as a percentage of the steady-state value. Next, Settling time, *ts* is the time required for the transient's damped oscillation to reach and stay within ±2% of the steady-state value.

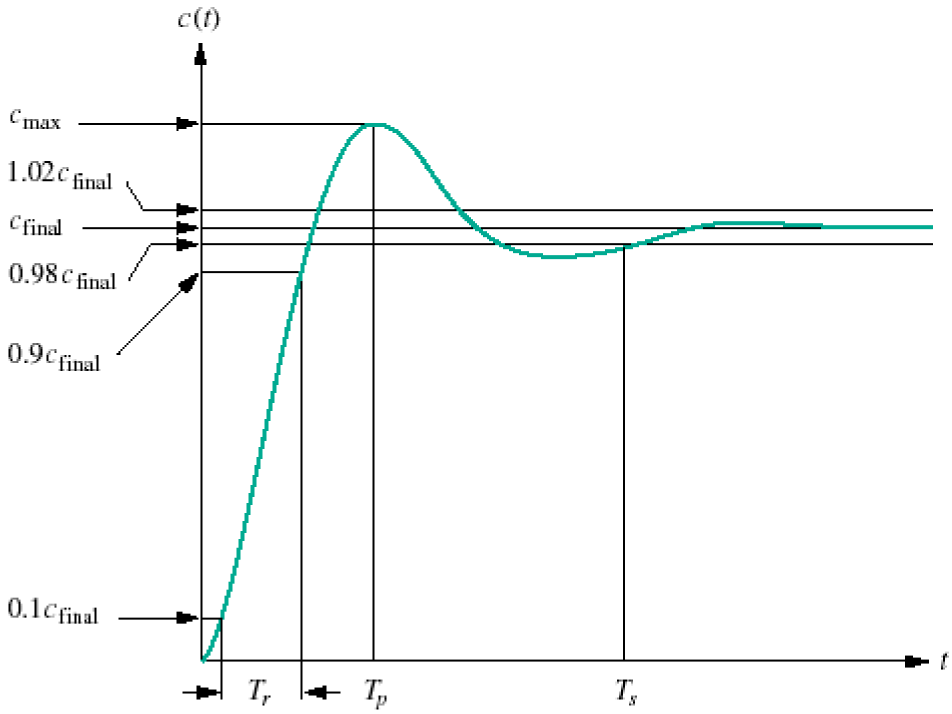


Figure 3.11 Second order underdamped response specifications.

Sources : Nise (2011)

3.5 Load Variation

The proposed objective of controlling the DC-DC converter is to track the desired output voltage. However, since the model of the converter is used; the output voltage will degrade when load *R* is changed that may affect the robustness of the converter. Previously, in most studies, the load has been assumed as unknown and fluctuating (may effect from the heating variation).

Load parameter *R* is required in the MPC formulation to track the voltage reference. Thus, in order to address the unknown loads (load variations) and remove the output voltage degradation in the occurrence of load variations, an additional external loop is included. The additional external loop method is one of the more practical ways of in improving the DC-DC converter performance during load variations. It is done by tracking the parameter value of load changes into the steady state formulation.

In this thesis, in order to track the new load resistor during the load changes, Equation 3.31 is used. Figure 3.12 shows the additional loop of using a simple *R* calculation that use to track the load resistor value. Hence, Equation 3.31 will be used to track the value of load variance for state space formulation

$$R = \frac{v_e}{i_e} \tag{3.31}$$

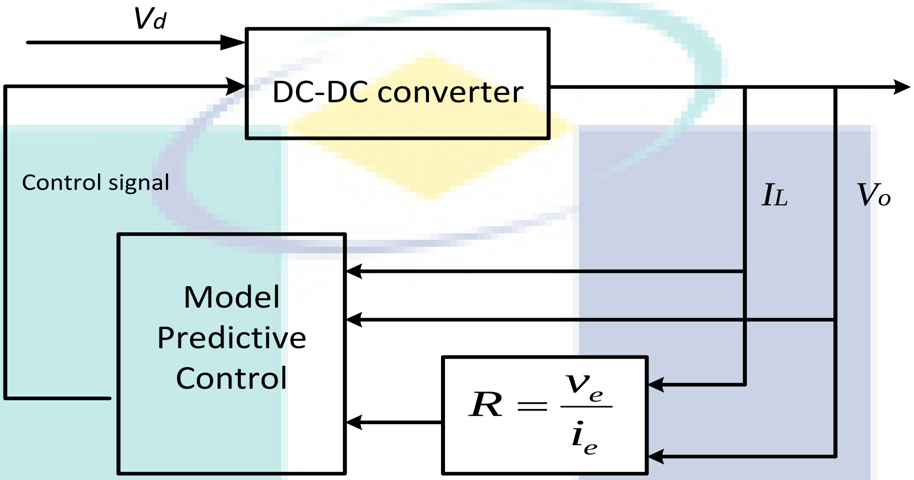


Figure 3.12 Block Diagram of Buck converter using a modification of MPC.

The results show that a modification of MPC can track the load changes. However, it is achieved that steady state error occurs after the load changes. Therefore, another method is introduced in solving this problem, which is by using Kalman Filter (KF). KF is one of the most well-known tools for assessing parameter estimation (Izadian & Khayyer, 2010),(Missailidis et al., 2014) and (Karamanakos, Geyer, & Manias, 2014).

The KF is proposed to use in the external loop for solving the load variations. This will form the so-called controller MPC-KF. It is done by connecting the external loop with the current and voltage references, which will offer a zero steady-state output error. In addition, as to eliminate the steady state error between both references, this loop will regulate the current and voltage reference. Further, two integrated disturbances states, i.e., $i_{.e.,}$ and v_e, are presented to represent the new signal of the output voltage, v_o and inductor current, i_l after being filtered by KF.

Moreover, KF basically uses a group of mathematical equation and iterations in order to come out with the filtered signal of v_o and i_l. Subsequently, these will offer an efficient computational means to evaluate the behavior of the DC-DC converter.

The first step in developing the MPC-KF is by building a model. In this thesis, the equation model is stated as Equation 3.32 and 3.33. This model is widely used for most of the system and also being used at Al-sheikh & Hoblos, (2015), Aoune et al., (2016), Kurucs, (2015) and Zakipour & Salimi, (2015).

$$x_k = Ax_{k-1} + Bu_k + w_{k-1} \tag{3.32}$$

$$z_k = Hx_k + v_k \tag{3.33}$$

Thus, the linear stochastic equation is being used in order to evaluate the signal value, x_k. Furthermore, the existence of x_k relies on the combination of its previous value plus a proses noise and control signal x_k. Meanwhile, the measurement value z_k is significance from the linear combination of the signal value and measurement noise.

The next step continued with iteration process. In KF, the iteration process involving two distinct sets of the equation which consists of *Time update* and *Measurement update*. Both of this equation represent *prediction* and *correction* phase, respectively. Figure 3.13 illustrates the KF process.

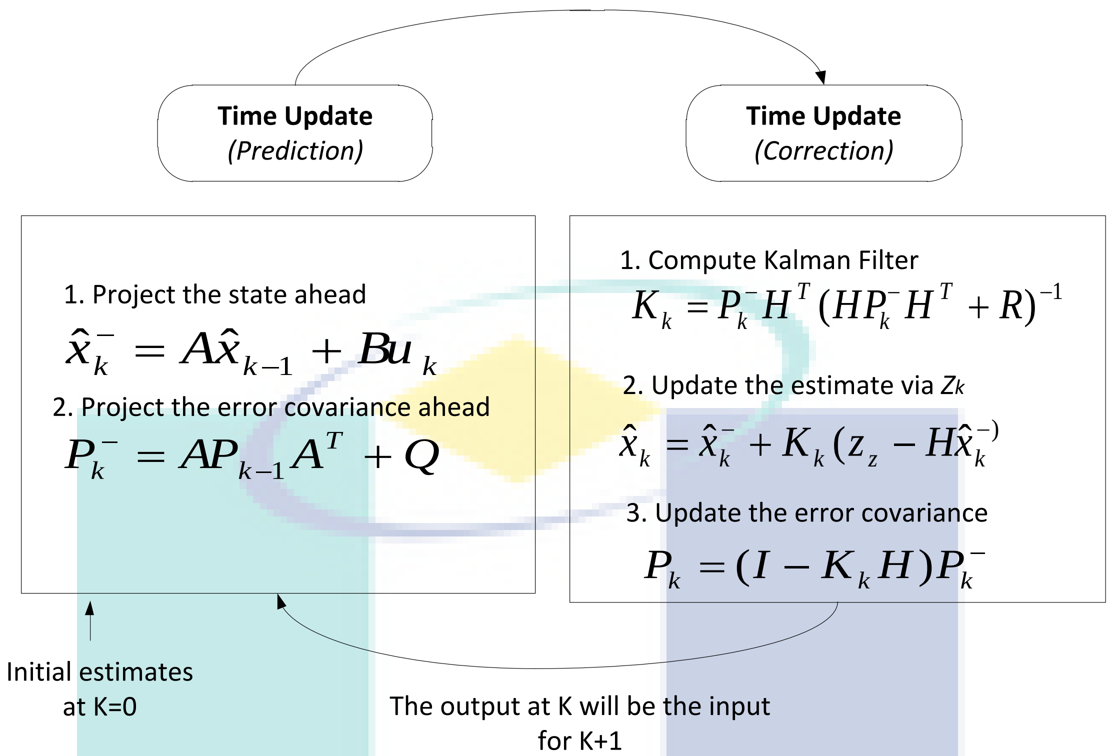


Figure 3.13 Kalman filter equations and iterations

Sources : Aoune et al., (2016).

For the purpose of getting a more accurate approximation, Equation 3.33 is used to estimate the current state of the system. Where each of the parameters representing the Kalman gain, K_k prior estimation $\hat{X}_k^-$ and prior error covariance, P_k^-. Both of the prior value being used in *Measurement update* equations. The estimation and the covariance value updated at each iteration. Additionally, in order to get the accurate value of, $i_{.e.,}$ and v_e, the decision of the gain vector selection should be made essentially accurate. In Figure 3.14, the proposed control diagram of the proposed MPC-KF strategy is illustrated;

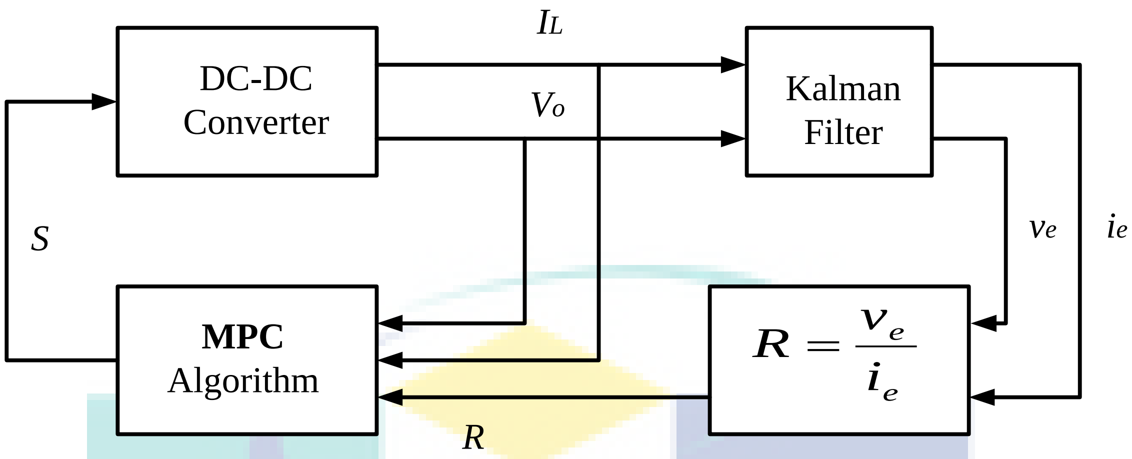


Figure 3.14 Control diagram of the proposed MPC-KF strategy.

3.6 Summary

Summarize from this chapter is the development of MPC algorithm that has been proposed to control the DC-DC buck converter is discussed. The new MPC in short prediction horizon is introduced. The formulation of the MPC algorithm by considering the hybrid behavior of DC-DC converter based on analytically optimization is described. For the load changes problem, the KF is introduced to solve the problem. It is the load identification and smoothing signals. The implementation of KF is done by connecting the external loop with the current and voltage references.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

In this chapter, the effectiveness of the proposed MPC method for DC-DC buck converter is properly checked by means of a simulation study that carried out in the MATLAB/Simulink. For verifying the effectiveness of proposed controller, the comparative performances are made by PI controller. The simulation results are presented to demonstrate the performance of the proposed controller under several conditions. Specifically, the first case examined the transient response of the output voltage that consists of maximum overshoot, delay time, settling time and also the number of switching sequences for MPC for prediction horizon, $l=1$ until $l=6$. In this case, the best prediction horizon will be determined and be used for the next analysis. While in the second case focussed on the analysis of proposing the additional Kalman filter (KF). Then, the next case devoted to simulation testing on varying the reference voltage in order to see the effectiveness of MPC-KF for reference changes. Lastly, the analysis focussed on the load variations for some condition of load changes.

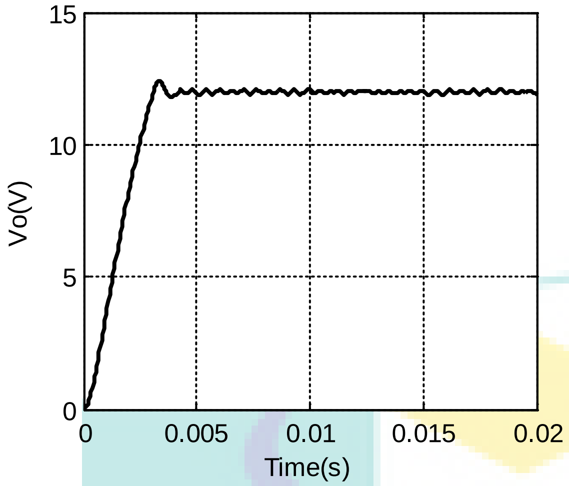
4.2 Prediction Horizon Test

The first cases investigate the performance a few prediction horizon length, which consists of six prediction horizon. The output voltage signal, inductor current and the switching signal for $l = 1$ until $l = 6$ are shown in Figure 4.1(*a-f*). Through the output voltage signal, $l = 1$ produce the worst transient response compared to others.

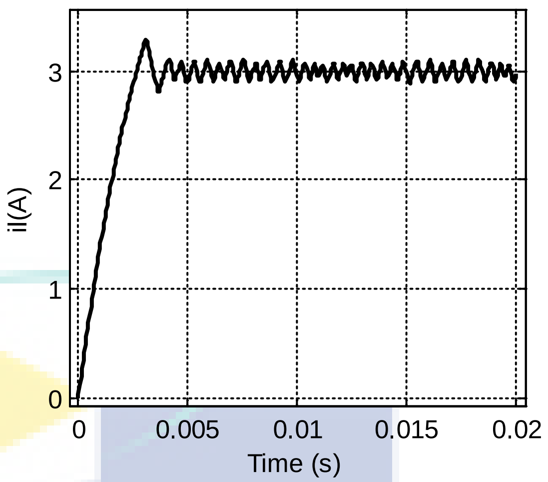
The transient response performance improved following the increments of the number of prediction horizon. It can be seen from the data in Table 4.1 that the best performance of prediction horizons was observed at $l=3$. Moreover, $l=3$ has the best overshoot value with shorter rise time. However, for $l > 3$, no significant improvement for the transient response was observed. A possible explanation for this might be that the proposed controller predicted the output at $l = 3$ for best trajectory, which is the voltage reference. This result was found to be closed agreement with the study that reported by Geyer et al., (2014), which the use of longer horizons carries less performance benefit. Therefore, in order to reduce the computational burden, $l=3$ is selected for MPC-KF controller.

Table 4.1 Transient response of output voltage for $l = 1$ until $l = 6$

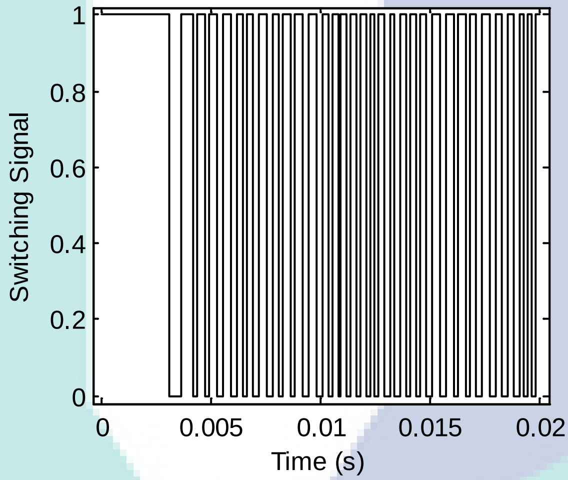
No. of predictions horizon, l	**Delay time, t_d (s)**	**Peak time, t_p (s)**	**Max overshoot (%)**	**Settling time, t_s (s)**	**Rise time, t_r (s)**
1	0.0150	0.00332	3.17	0.0042	0.0022
2	0.0015	0.00330	2.08	0.0031	0.0023
3	0.0015	0.00325	0.83	0.0030	0.0023
4	0.0015	0.00325	0	0.0029	0.0023
5	0.0015	0.00325	0	0.0028	0.0023
6	0.0015	0.00325	0	0.0028	0.0023



(i)

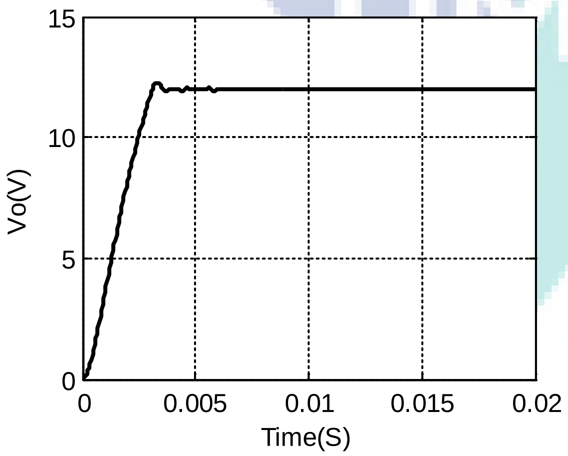


(iii)

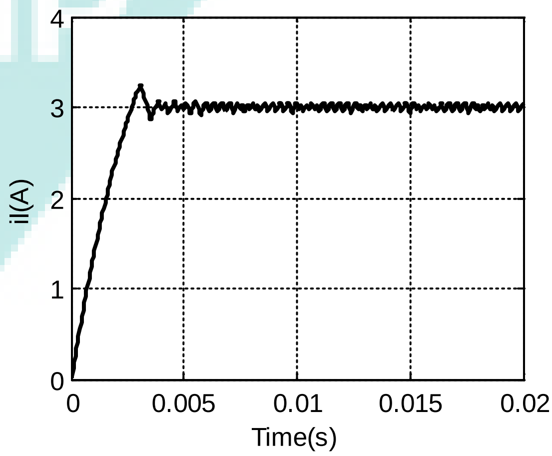


(iii)

(a) Prediction horizon, *l*=1

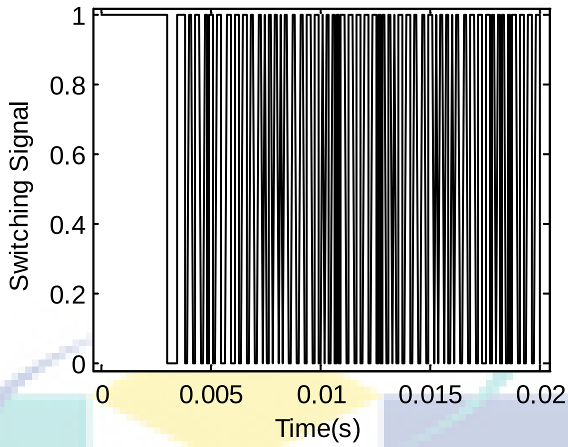


(i)



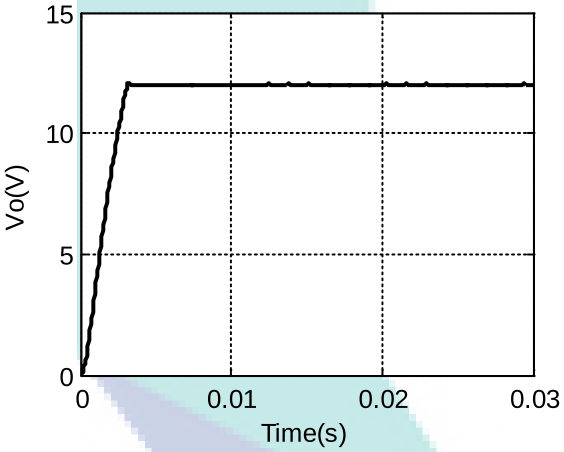
(ii)

Figure 4.1 Continued

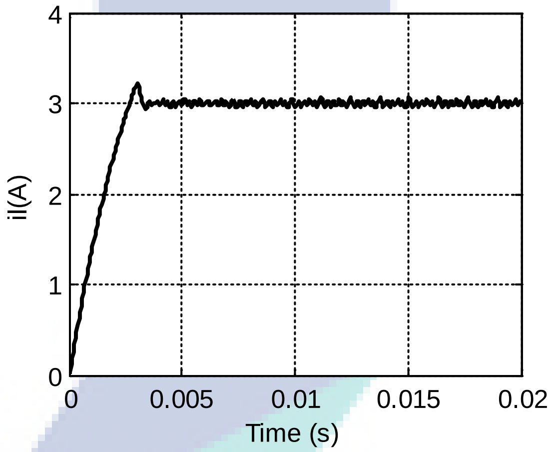


(iii)

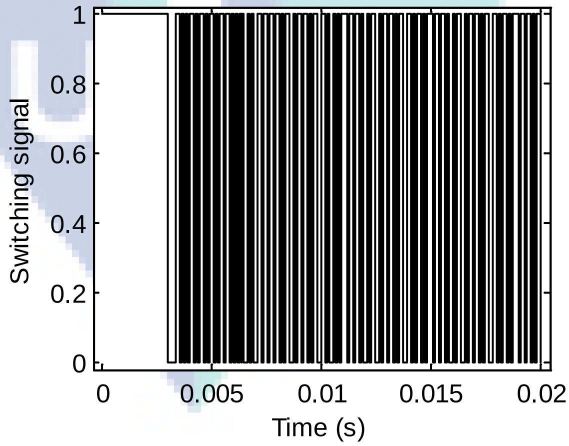
(b) Prediction horizon, *l*=2



(i)



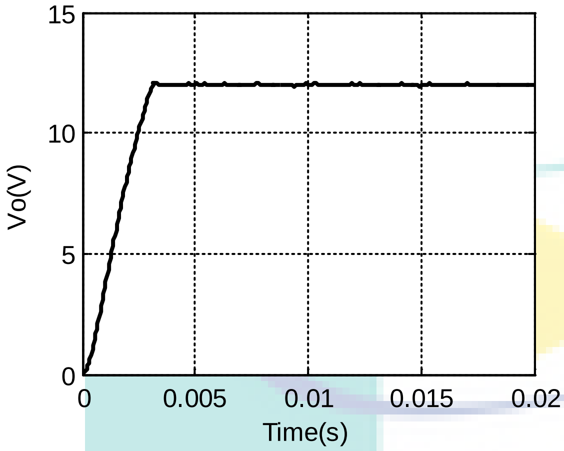
(ii)



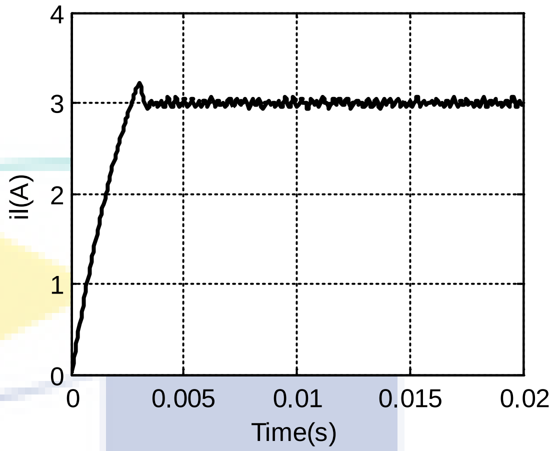
(iii)

(c) Prediction horizon, *l*=3

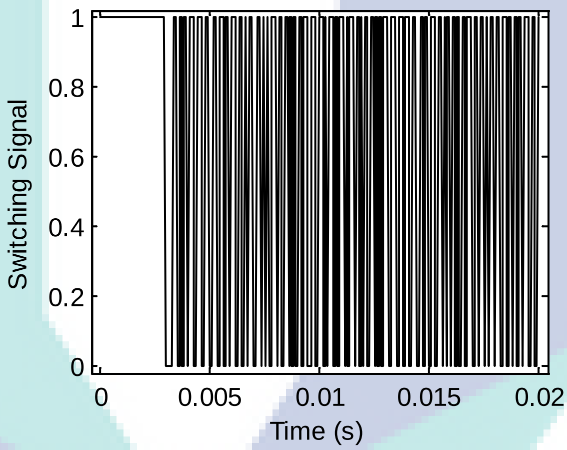
Figure 4.1 Continued



(i)

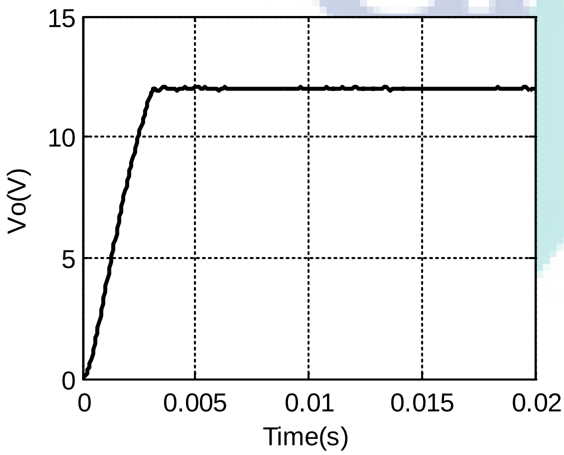


(ii)

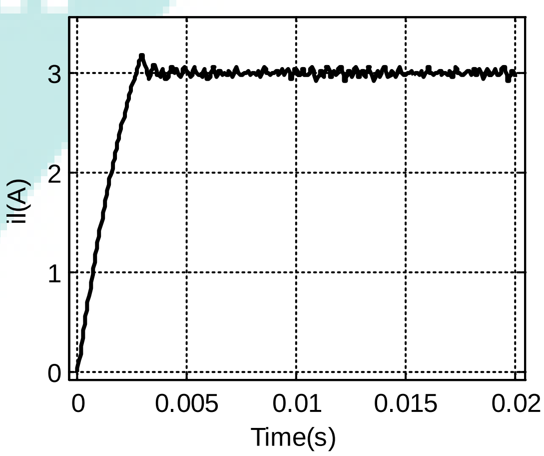


(iii)

(d) Prediction horizon, *l*=4

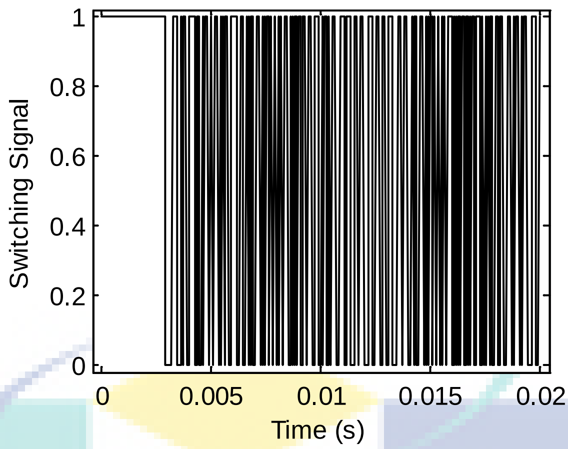


(i)



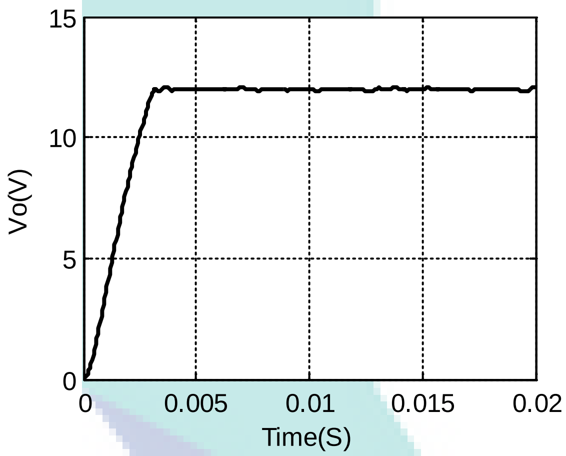
(ii)

Figure 4.1 Continued

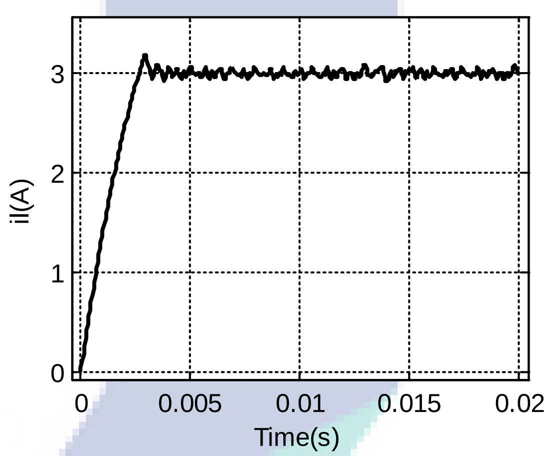


(iii)

(e) Prediction horizon, *l*=5

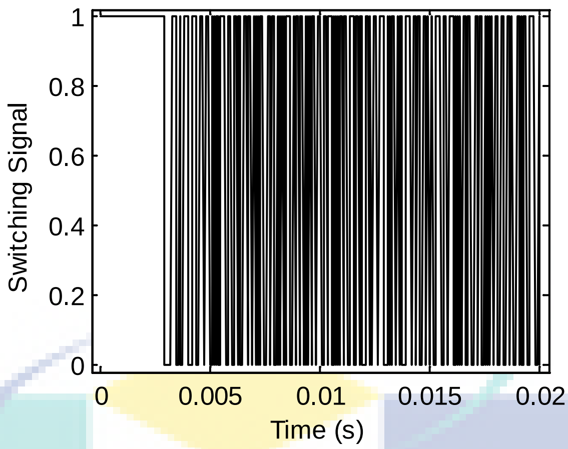


(i)



(ii)

Figure 4.1 Continued



(iii)

(f) Prediction horizon, *l*=6

Figure 4.1 Simulation result for prediction horizon $l = 1$ until $l = 6$: i) output voltage, ii) inductor current, iii) switching sequence signal.

Figure 4.2 shows the graph of switching sequence signal numbers for $l = 1$until $l = 6$. A number of switching sequence for $l=1$ is 64, which is the lowest switching sequence. Followed by $l=2$, which is 111. Next, for $l \geq 3$ can be referred in Figure 4.2. The analysis and simulation indicate that the number of switching sequences were increasing proportionally together with the number of prediction horizons, *l*. In term of transient response and tracking performances, l = 3 is sufficient prediction horizon to best track the reference signal. Thus, the longer prediction horizon is omitted to use since $l > 3$ produce a greater number of switching sequences. The lower numbers of switching sequences have a better performance due to the smaller switching losses. These results have the same agreement with Yang et al., (2011), which claims that the increased switching losses result in lower efficiency of the circuit and the needs of a large heat sink. Significantly, the number of switching sequence will affect a number of losses due to the conduction losses. The conduction losses are semiconductor device losses. It occurs when the switch of the power device turns *on* and *off* frequently. The onwards investigation and comparison with PI controller will be proceeded by using the prediction horizon $l=3$.

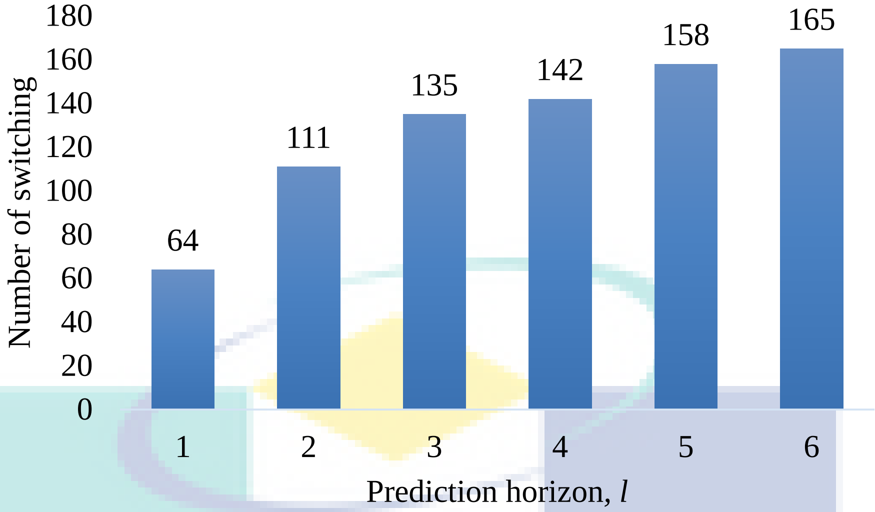
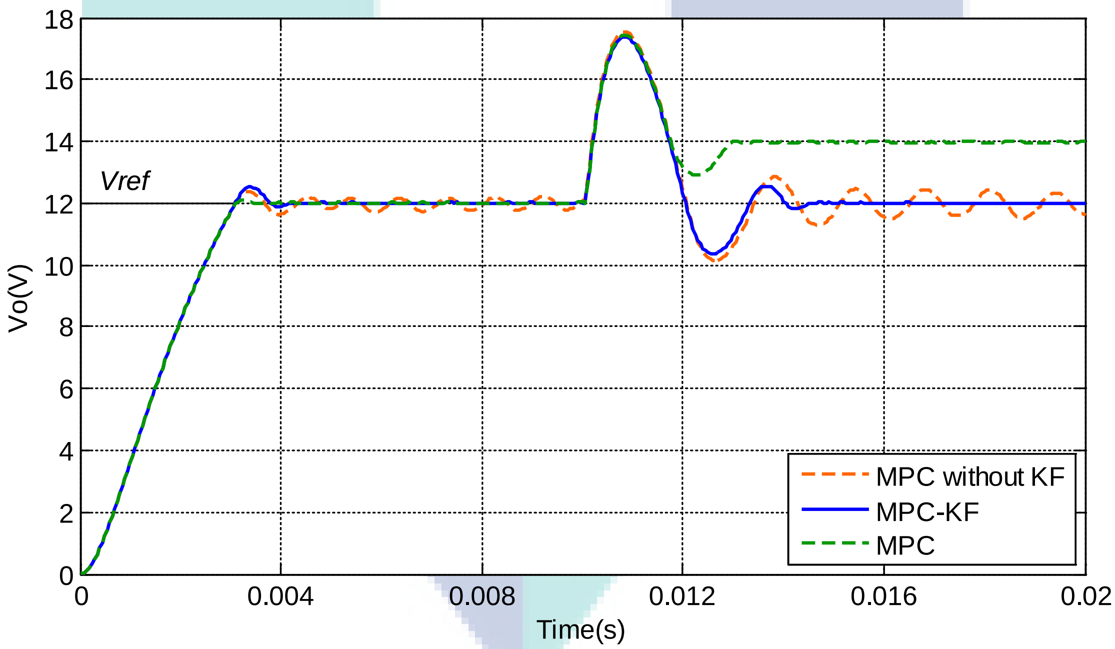


Figure 4.2 Number of switching sequences for each prediction horizon.

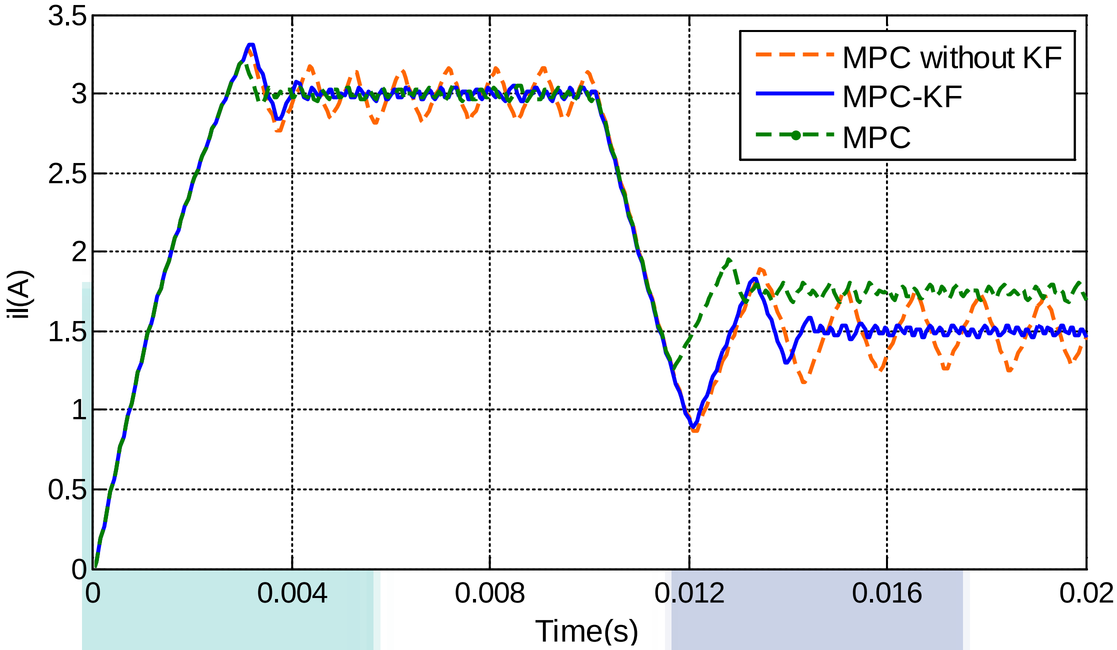
4.3 Comparison between MPC, MPC without KF and MPC-KF

The second analysis is to show the effectiveness of proposed KF with MPC in rectifying the load variations. The sequence comparison is carried out for MPC, MPC without KF (using simple *R* calculation) and MPC-KF. In clarifying the analysis, the *R* is changed by increase the nominal value *R*=4Ω to *R*=8Ω.

During the load changes at t=0.01s, the output voltage should track the reference after fluctuation (refer to Figure 4.3 (a)). However, the MPC does not track the output voltage after the load change due to the changes *R* is not updated in converter model. For MPC,the output voltage is increased to 14V from 12V. Nonetheless, for updated *R* that employ simple calculation to converter model, the steady-state error and voltage ripple are increasing (refer to Figure 4.3 (a)). Therefore, the KF is proposed for load *R* estimation. It is shown that the MPC-KF produce a promising tracking of the output voltage. Furthermore, MPC-KF achieved almost zero steady state error. Figure 4.3 (b) shows the inductor current waveform for the converter.



(a)



(b)

Figure 4.3 Load changes result; a) Output voltage, b) Inductor current for MPC without KF (orange), MPC-KF (blue) and MPC (green).

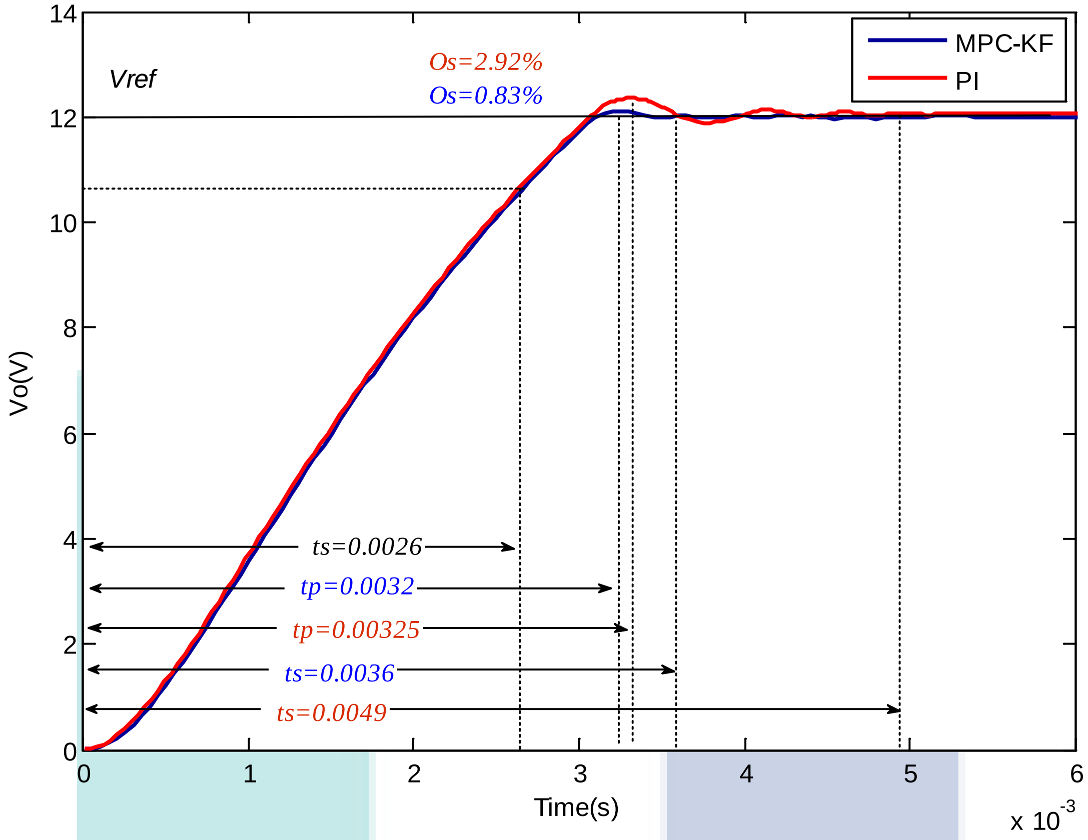
4.4 Comparison MPC-KF with PI Controller

The start-up scenario for the proposed controller with PI controller is presented. Table 4.2 shows the transient response performance of output voltage for both controllers. The simulation result for proposed controller and PI controller are shown in Figure 4.4 and Figure 4.5, respectively. As seen from the Table 4.2, both controllers have slightly same result in terms of peak time, settling time and rise time. However, it is observed that the overshoot percentage of PI controller is higher than MPC-KF. Furthermore, the MPC-KF controller quickly tracks the reference v_r.

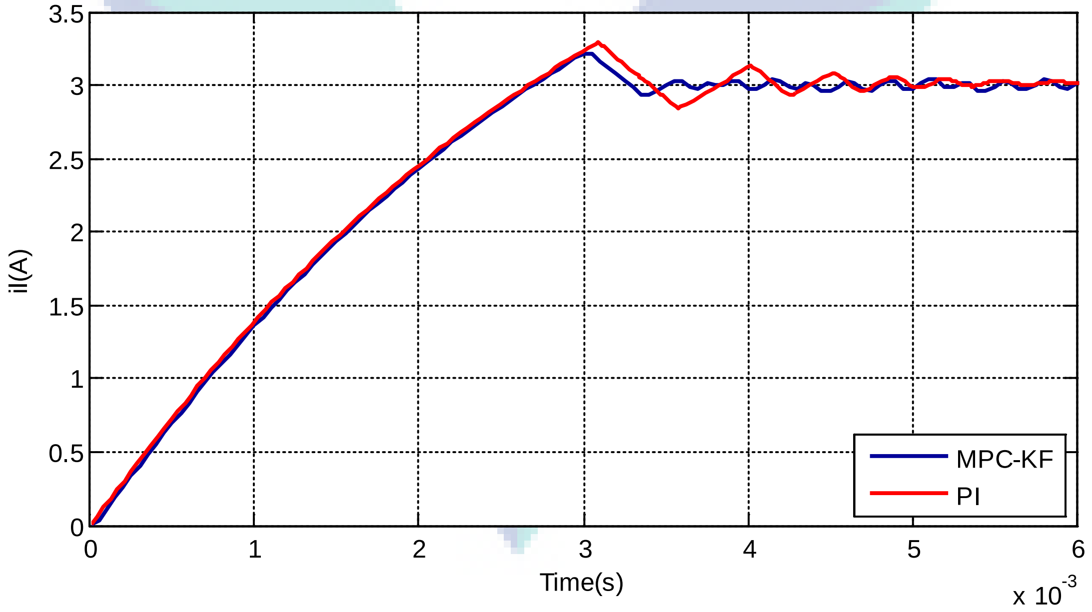
In terms of switching sequence numbers, it is observed that there are huge differences between both controllers. MPC-KF controller recorded a lower number of switching states compared to PI controller.

Table 4.2 Transient response of output voltage for MPC-KF and PI controller.

Controller	MPC	PI controller
Peak time, *tp* (*s*)	0.0032	0.0033
Max overshoot (%)	0.83	2.92
Settling time, *ts* (*s*)	0.0036	0.0049
Rise time, *tr* (*s*)	0.0026	0.0026
No. of switching	25	805

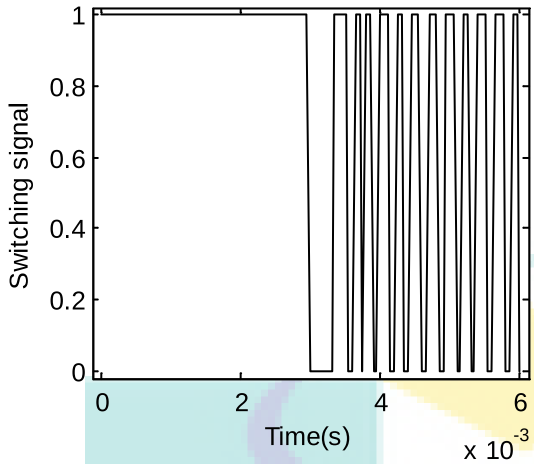


(a)

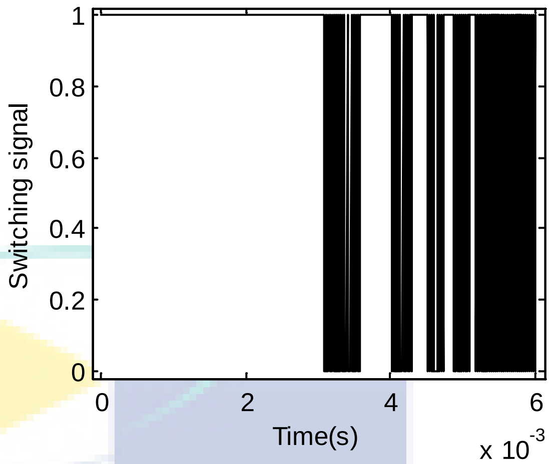


(b)

Figure 4.4 Step down converter result for 24V to 12V; a) Output voltage, b) Inductor current for MPC (blue) and PI (red).



(a)



(b)

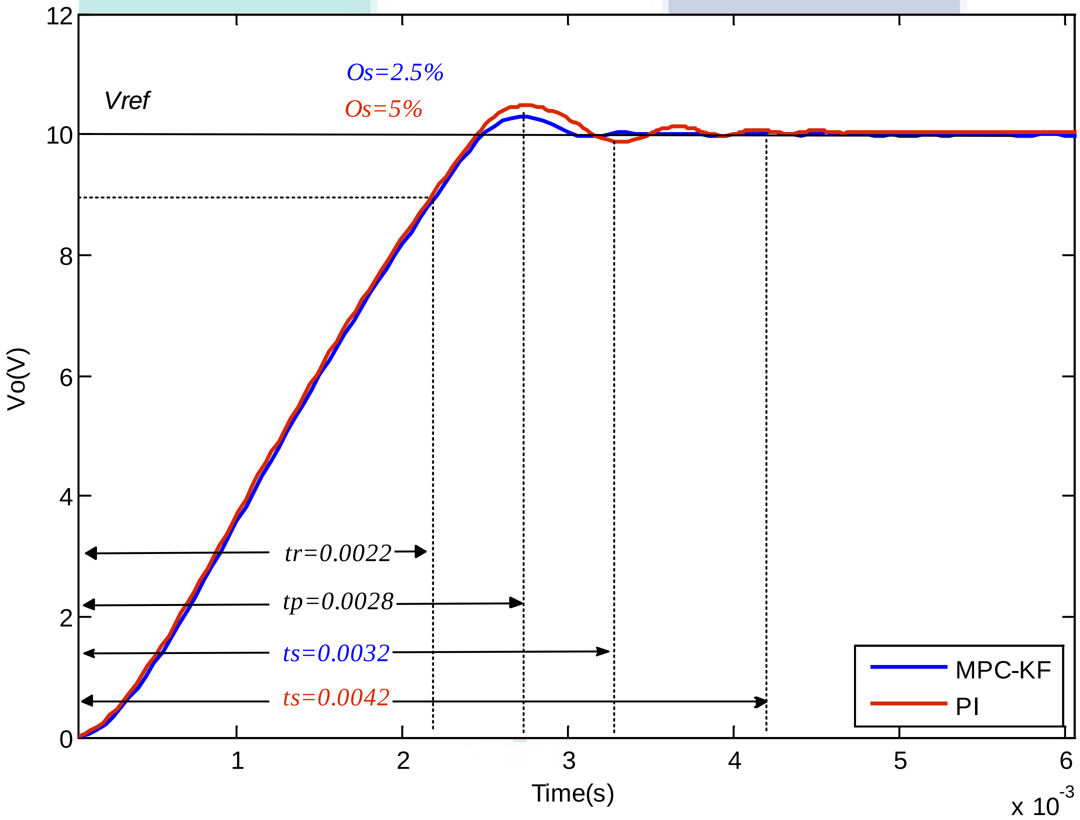
Figure 4.5 Step down converter result 24V to 12V switching sequence signal; a) MPC and b)PI controller.

4.5 Variation of Voltage Reference

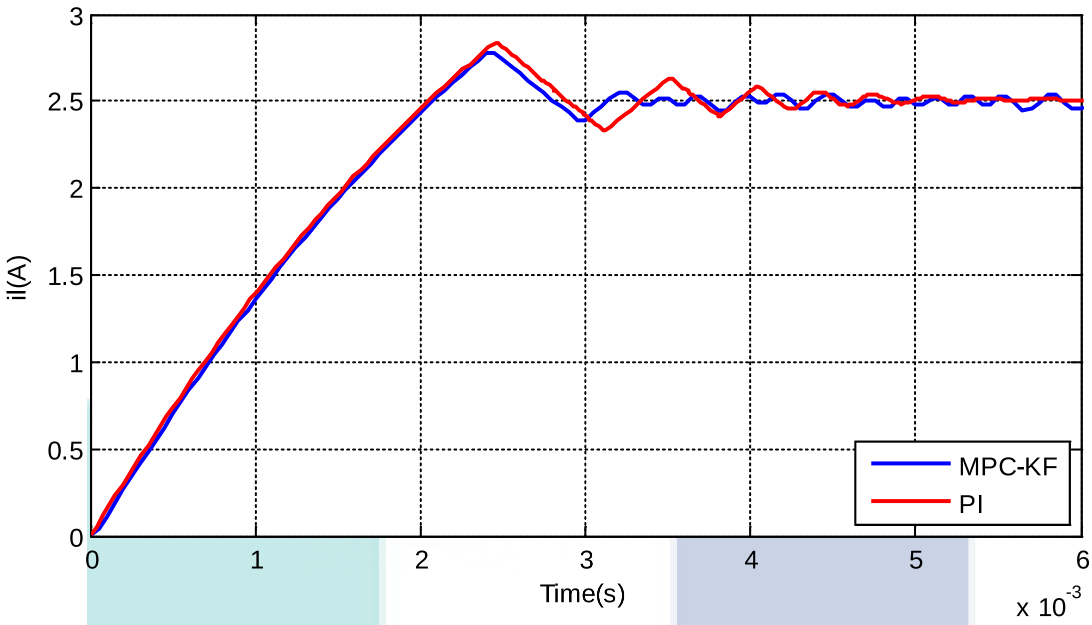
In this analysis, the change in reference voltage is observed. Table 4.3 shows the transient response performance for both controllers. Figure 4.6 shows the voltage output signal of MPC-KF for prediction horizon, $l=3$. The new v_r has decreased 20% from the initial value (nominal value). At time t ≈ 0.0032s the output voltage tracks the new voltage reference from $v_r = 24V$ to $v_r = 10V$. The transient response for output voltages of both controllers is shown in Table 4.3. The overshoot value of PI controller is higher than a proposed controller.

Table 4.3 Transient response at v_r=10V

Controller	MPC	PI
Peak time, *tp* (*s*)	0.0028	0.0028
Max overshoot (%)	2.5%	5%
Settling time, *ts* (*s*)	0.0032	0.0042
Rise time, *tr* (*s*)	0.0022	0.0022



(a)



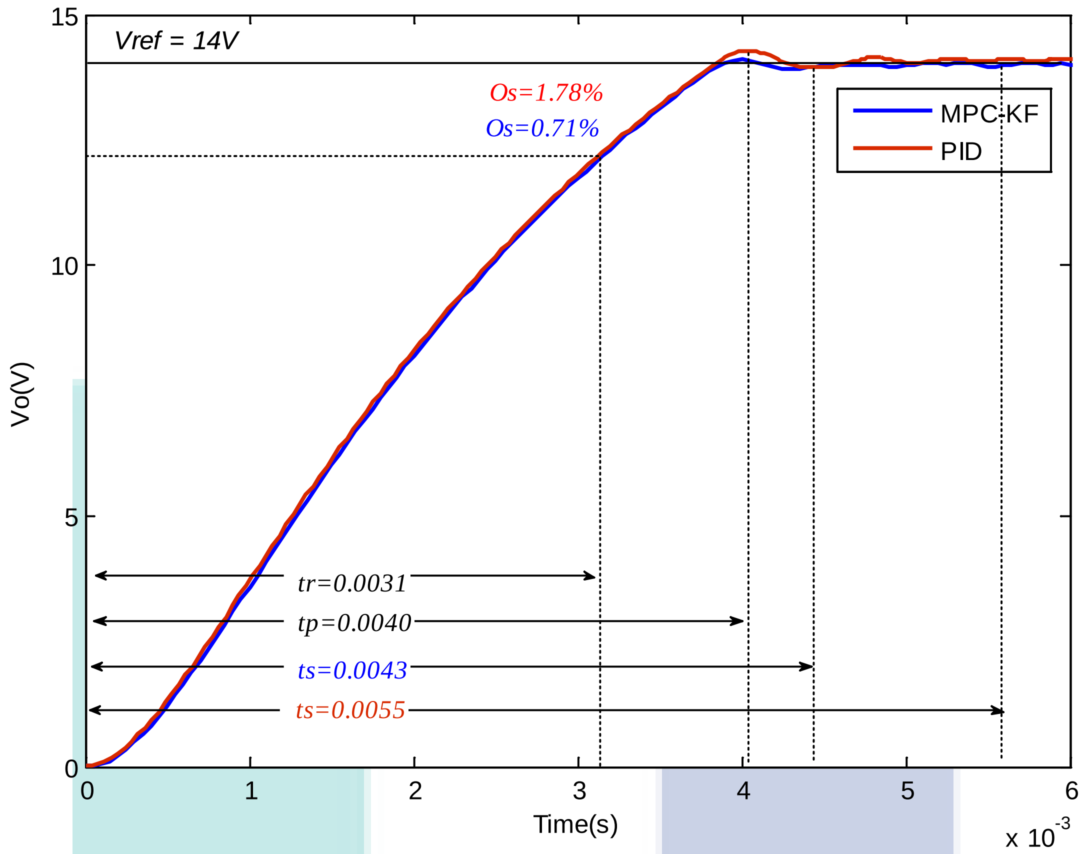
(b)

Figure 4.6 Step down converter result for 24V to 10V; a) Output voltage, b) Inductor current for MPC (blue) and PI controller (red).

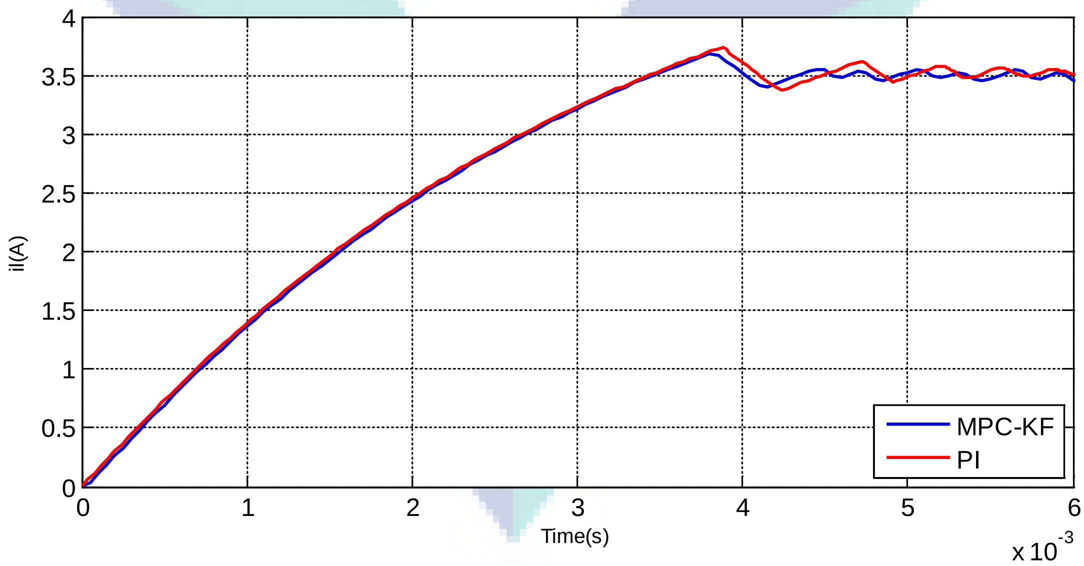
Next, the reference is increased from its nominal value, v_r=12V to v_r=14V. Table 4.4 shows the transient response performance for both controllers for v_r=14V. From the table, it shows that both controllers perform an excellent behavior during the transient, reaching the new output voltage. As seen in both figures, at t ≈ 0.004s, the output voltage for both controllers track the new reference value without any noticeable overshoot. Furthermore, it is observed that the start-up behaviors are under normal conditions. Comparably, it takes longer rise time compared to previous, which is v_r=10V.

Table 4.4 Transient response at v_r=14V

	MPC	**PI**
Peak time, *tp* (*s*)	0.0040	0.0040
Max overshoot (%)	0.71%	1.78%
Settling time, *ts* (*s*)	0.0043	0.0055
Rise time, *tr* (*s*)	0.0031	0.0031



(a)



(b)

Figure 4.7 Step down converter result for 24V to 14V; a) Output voltage, b) Inductor current for MPC (blue) and PI (red).

4.6 Load Changes Comparison.

For MPC, the load changes are affecting the tracking response. Thus, the MPC-KF controller is proposed. However, for PI/PID controller, there is no big issue with the load changes since the output error is used as the input control signal.

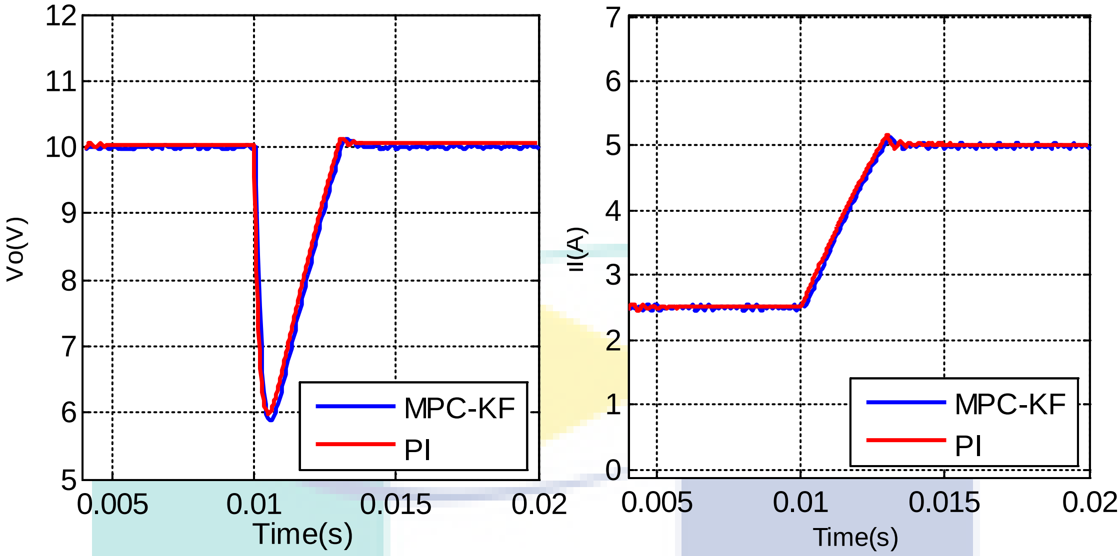
For the last analysis, the transient response is observed for the load changes at a certain period during steady-state. Both controllers' output responses are being compared in order to verify the effectiveness of the proposed controller. It is shown that the results for proposed controller (MPC-KF controller) are comparable with the PI controller. There are three voltage references being used which are v_r=10V, v_r=12V and v_r=14V for this analysis. All reference voltages are tested using three conditions of the load resistance, which have decreased to 50% (2Ω), increase to 50% (6Ω) and increase to 100% (8Ω) from its nominal value, 4Ω.

4.6.1 Analysis of v_r=10v

Three conditions of load resistance are being used for v_r=10V. All results are compared with PI controller.

4.6.1.1 Load Resistance Decrease by 50%

The load resistor R is decreased to 2Ω at 0.01s. As shown in Figure 4.8, the KF quickly track the voltage accordingly. There are no significant differences between both controllers in terms of the output voltage and inductor current. From the figure, it is observed that output voltage of MPC-KF reaches its reference at 0.013s. This results supported by Andrea et al., (2009) which stated that the steady state error are eliminates by the integration of KF. Yet, for the PI controller, the results shows that there is a small overshoot occurs before its reaches the reference. However, after the load changes the v_o obtained by PI controller is 10.05V which is 0.05V higher than the v_r.



(a) (b)

Figure 4.8 Step down converter result for 24V to 10V using 2Ω; a) Output voltage, b) Inductor current for MPC (blue) and PI (red).

4.6.1.2 Load Resistance Increase by 50%

The load resistance R is increased to 6Ω at t ≈ 1.0ms. The results are presented in Figure 4.9. In terms of transient response, the result of MPC-KF is better than the PI controller based on the overshoot signal waveform. Furthermore, for MPC-KF, the output voltage tracks the reference as good as possible when compared to PI controllers. In terms of settling time, MPC-KF reaches at t = 0.01255s while PI controller t = 0.0165s which is higher than the MPC-KF. Both controllers successfully achieve the voltage output with reference v_r=10V. The results obtained for MPC-KF is v_o=10V while for the PI controller v_o=10.02V

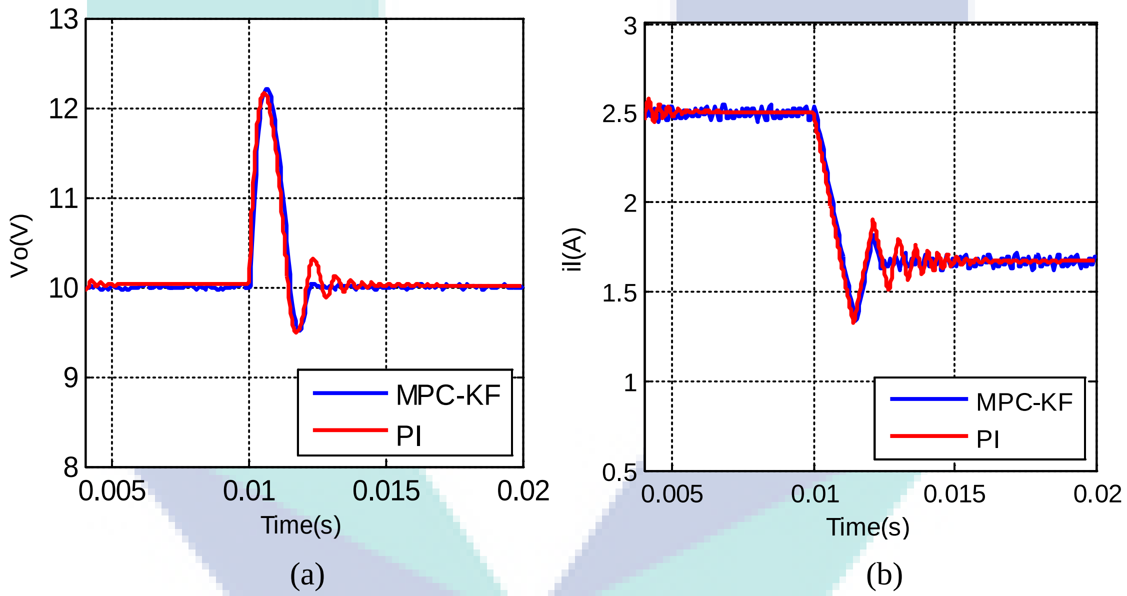
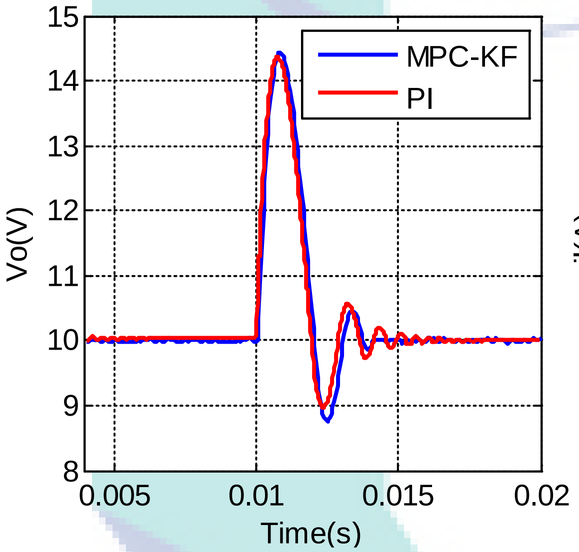


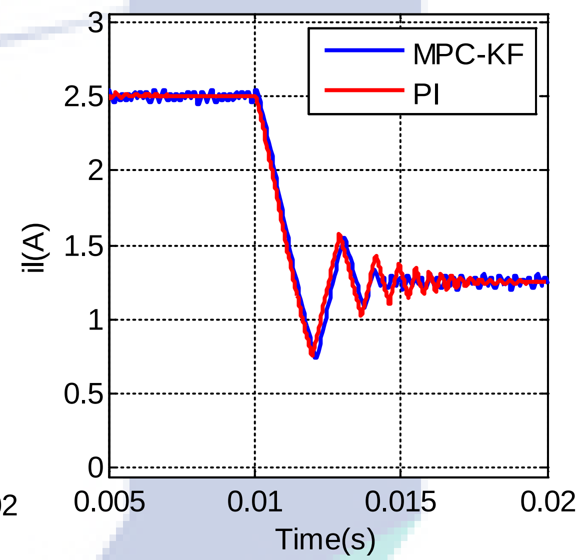
Figure 4.9 Step down converter result for 24V to 10V using 6Ω; a) Output voltage, b) Inductor current for MPC (blue) and PI (red).

4.6.1.3 Load Resistance Increase by 100%

The load resistance R is increased to R = 8Ω at t ≈ 1.0ms. Comparing both controllers in term of overshoot signal, MPC-KF has better performance than PI controller. During the load changing, the MPC-KF is comparable with PI controller. However, as seen in Figure 4.10, MPC-KF produce faster settling time than PI controller, which is at t=0.0142s and t=0.018s respectively. Nonetheless, after the load changes, both controllers track the voltage output with reference as good as possible.



(a)



(b)

Figure 4.10 Step down converter result for 24V to 10V using 8Ω; a) Output voltage, b) Inductor current for MPC (blue) and PI (red).

4.6.2 Analysis of v_r=12v

Next, the effectiveness of MPC-KF to the load variation when v_r=12V is presented. In this section, the *R* is changed same in section 4.5.1 for both controllers. The comparison performances are then performed thoroughly.

4.6.2.1 Load Resistance Decrease by 50%

The load resistance *R* is changed to R = 2Ω at t ≈ 1.0ms. Figure 4.11 shows the simulation results for both controllers. According to the results, both controllers achieve the desired voltage references after the existence of load variation. Nevertheless, PI controller achieved v_o = 12.1V, which is 0.1V higher than the nominal voltage reference v_r=12V. Furthermore, as can be seen in the figure, there are undershoot in both output voltage during the transient. This result significantly shows that both controllers are successfully reaching its reference. In terms of settling time, it is observed that only slight differences between MPC-KF and PI controller, which is at t=0.0152s and t=0.0156s, respectively.

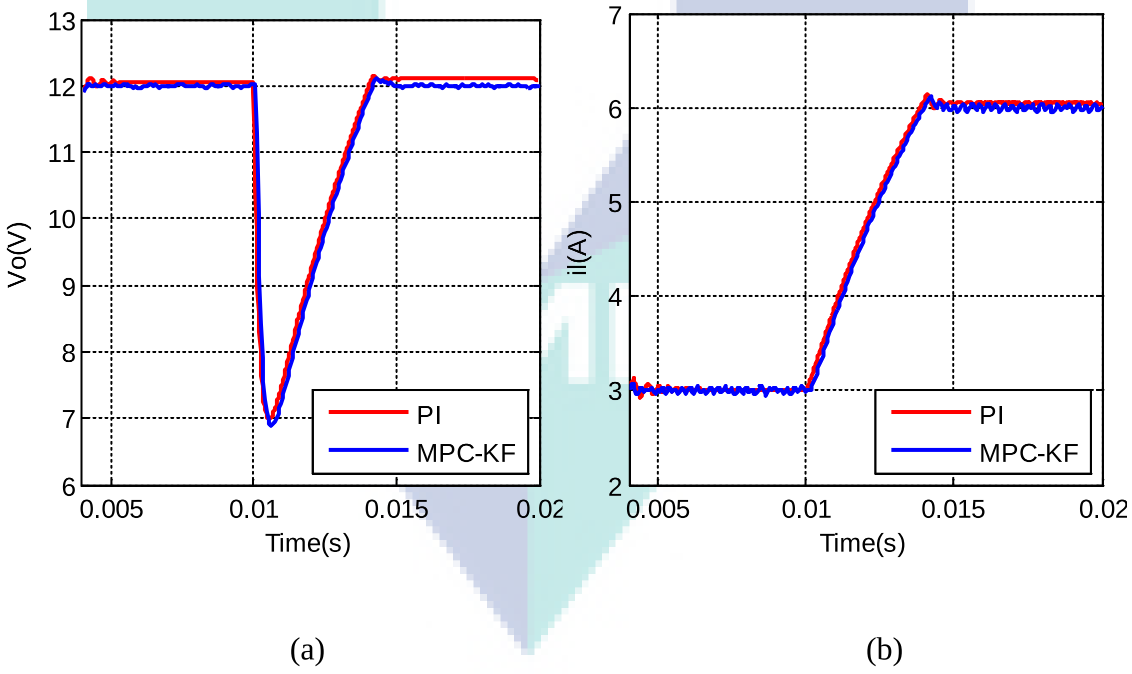
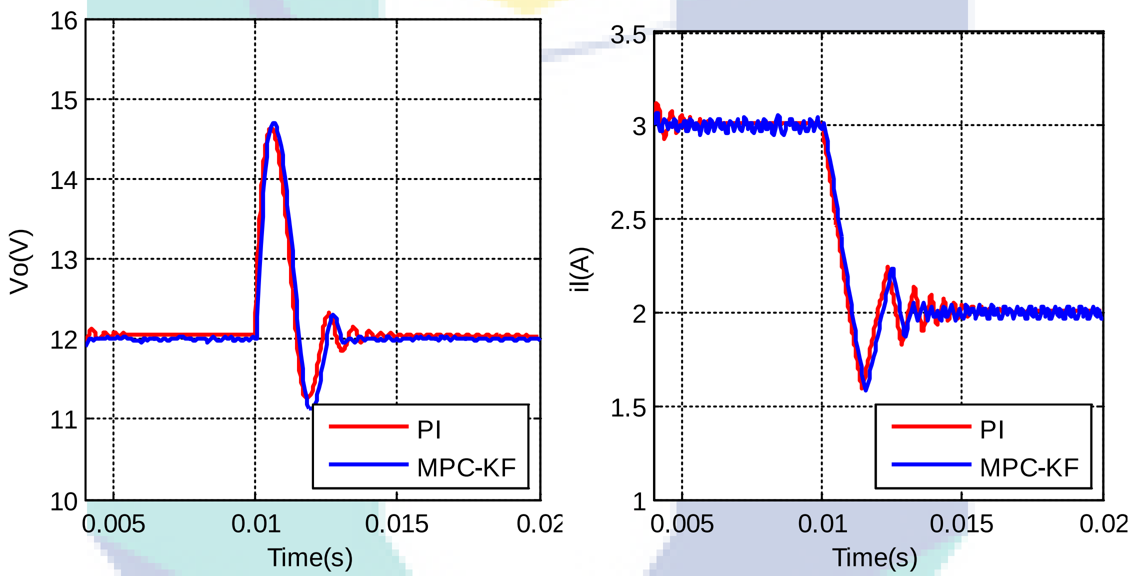


Figure 4.11 Step down converter result for 24V to 12V using 2Ω; a) Output voltage, b) Inductor current for MPC (blue) and PI (red).

4.6.2.2 Load Resistance Increase 50%

Next, same as previous analysis, the resistance load R is increased to R = 6Ω at t = 0.01s. As shown in Figure 4.12(a), MPC-KF tracks the output voltage comparable with PI controller. The transient response of MPC-KF is better than PI controller. The overshoot is comparable with PI controller, but the settling time is longer for PI controller, i.e., at t=0.0155s for MPC-KF and at t=0.016s for PI controller. Nonetheless, for the PI controller, the v_o settle at 12.05V which is slightly higher than the v_r=12V.

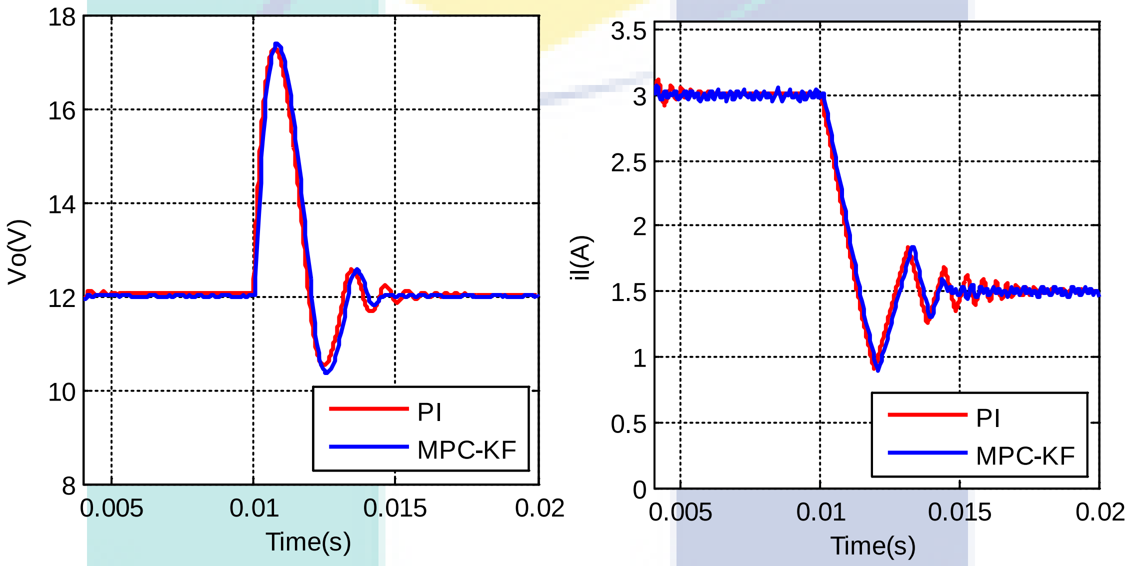


(a) (b)

Figure 4.12 Step down converter result for 24V to 12V using 6Ω; a) Output voltage, b) Inductor current for MPC (blue) and PI (red).

4.6.2.3 Load Resistance Increase by 100%

For R= 8Ω, it can be seen the result as in Figure 4.13. It is observed that MPC-KF accurately track the reference compared with PI controller, which the MPC-KF achieved v_o=12V and PI controller achieved v_o=12.03V. For the settling time, MPC-KF recorded t=0.016s while the PI controller recorded t=0.019s. There is no significant difference between both controllers.



(a) (b)

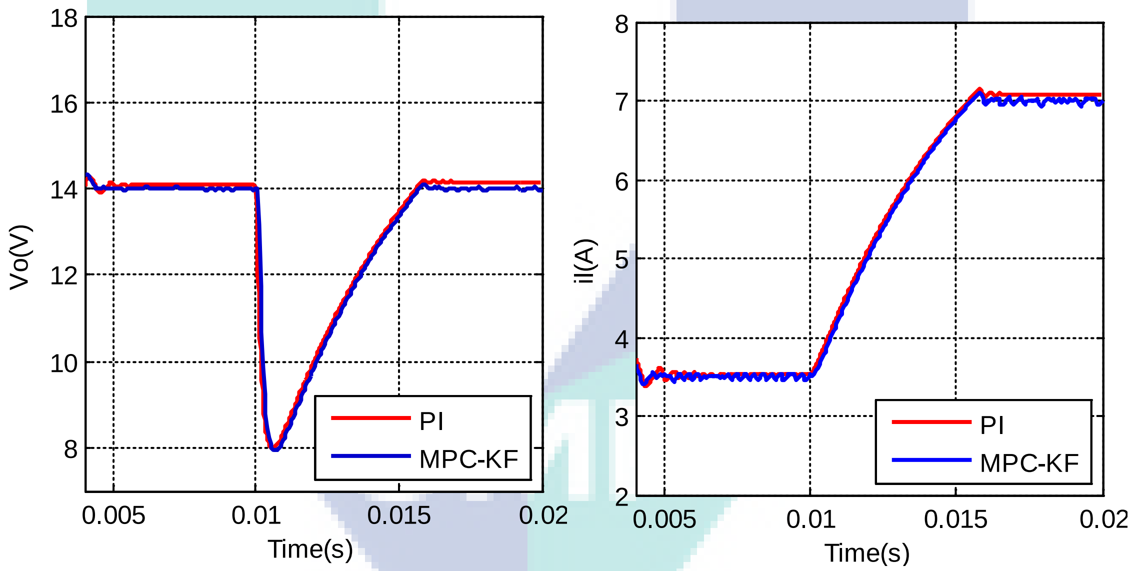
Figure 4.13 Step down converter result for 24V to 12V using 8Ω; a) Output voltage, b) Inductor current for MPC (blue) and PI (red).

4.6.3 Analysis of v_r=14v

Last, the effectiveness of MPC-KF to the load variation when v_r=14V is presented. In this section, the R is changed same in section 4.6.1 for both controllers. The comparison performances are then performed thoroughly.

4.6.3.1 Load Resistance Decrease by 50%

The R is dropped to R = 2Ω that occurs at t=0.01s. There is no noticeable overshoot occurs for both controllers. Besides, a slight difference for steady state error is observed for PI controller. The MPC-KF positively tracks the voltage to the voltage reference. For the settling time value, as can be seen from the Figure 4.14, the MPC-KF and PI controller reach at t=0.016s and t=0.0165s respectively. Yet, PID controller has not reached the actual voltage reference, which is higher than the voltage reference, v_o=14.06V.

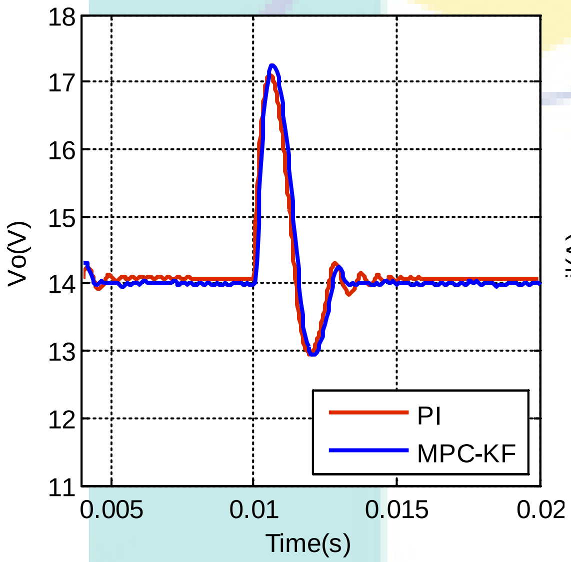


(a) (b)

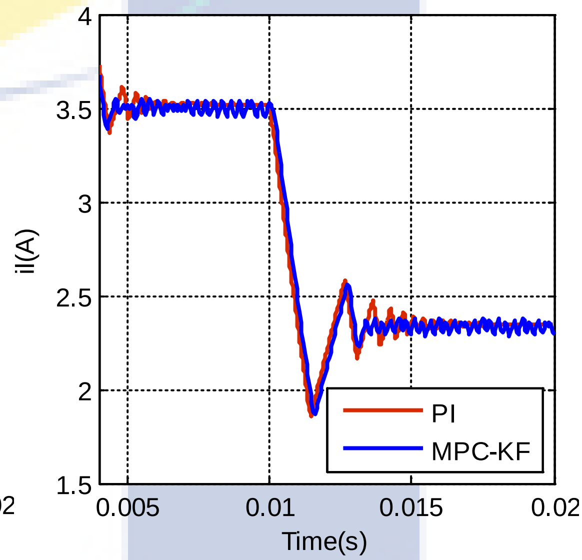
Figure 4.14 Step down converter result for 24V to 14V using 2Ω; a) Output voltage, b) Inductor current for MPC (blue) and PI (red).

4.6.3.2 Load Resistance Increase by 50%

Then, for R = 6Ω, the MPC-KF controller exhibit a favorable performance, which reach the reference voltage with comparable overshoot with PI controller. The MPC-KF achieved the sampling time at t=0.0145s and PI controller at t=0.017s, respectively. Moreover, in terms of output voltage after the load changes, PI controller has a higher voltage output v_o=14.07V which is 0.07V higher than the reference



(a)



(b)

Figure 4.15 Step down converter result for 24V to 14V using 6Ω; a) Output voltage, b) Inductor current for MPC (blue) and PI (red).

4.6.3.3 Load Resistance Increase by 100%

Lastly, the R is changed to R= 8Ω. As shown in the Figure 4.16, the MPC-KF rapidly regulates the voltage reference accordingly, resulting in a zero steady state error in the output voltage. From the figure 4.24, it shows that the MPC-KF successfully achieved the desired output voltage v_o=14V, while PI controller achieved v_o=14.05V which is higher than the voltage reference $v_{r=}$14V. Moreover, for the settling time, MPC-KF reaches the sampling time at t=0.015s whereas PID controller at t=0.018s.

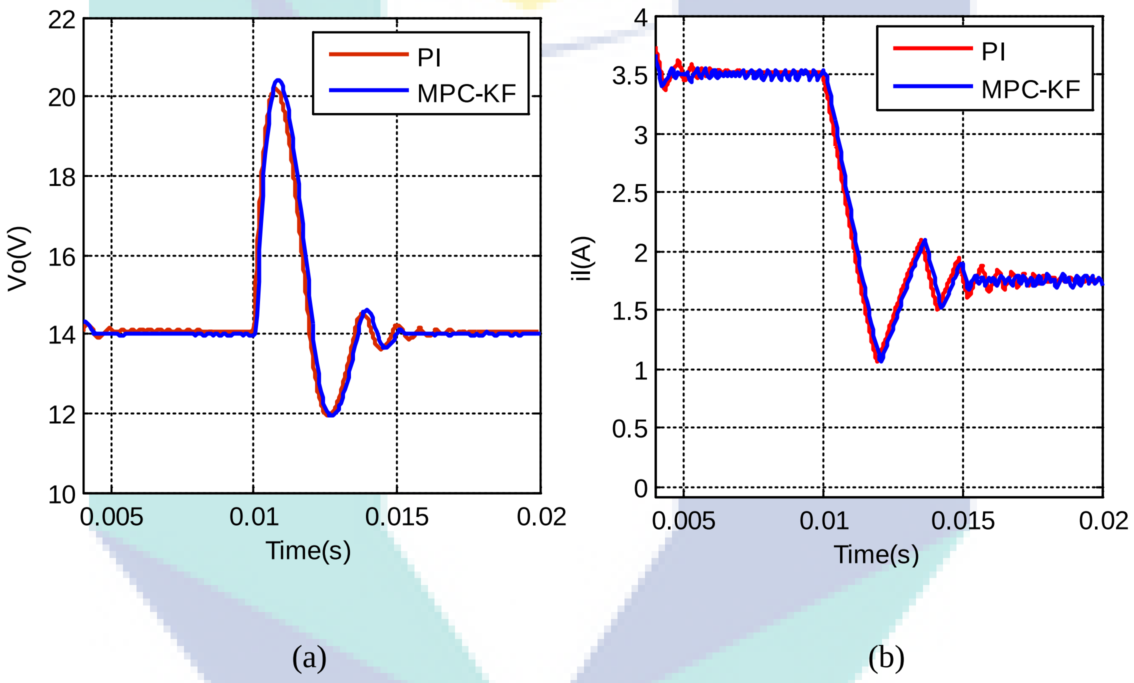


Figure 4.16 Step down converter result for 24V to 14V using 8Ω; a) Output voltage, b) Inductor current for MPC (blue) and PI (red).

4.7 Summary

In this chapter, simulation results for numerous prediction horizons are demonstrated in order to see the best prediction horizon to be used. Based on the analysis, the implementation of MPC-KF in DC-DC converter enable the use of short prediction horizons *l=3*, since it experienced lowest computational burden compared with *l>3*. Furthermore, in term of switching sequences, *l=3* have the best number of switching sequence with good performance, , which is 135.

Then, the effectiveness of MPC-KF is observed for variation references of the output voltage. The simulation results show that MPC-KF still can successfully work in these two conditions in terms of transient response and tracking to reference voltage. The analysis proceeded with the variation of load changes. It observed that, the MPC-KF had solved the load changes problem by tracking the reference that comparable with PI controller. It is proved by the transient response performance generated by MPC-KF and PI controller. In terms of overshoot value, MPC-KF recorded 0.83%, while PI controller has 2.92%, which is higher that MPC-KF. Besides, MPC-KF also has lower value of setting time which is 0.0036s while PI controller 0.0049s. Furthermore, MPC-KF also generate smaller value of switching number compared to PI controller, which is 25 and 805. These results of this study indicates that MPC-KF have better performance than PI controller.

CHAPTER 5

CONCLUSION

5.1 Conclusion

The enhancement performance for DC-DC buck converter in term of transient response has been presented in this thesis using the proposed MPC-KF controller. The MPC has been successfully implemented in short prediction horizon thus can make an optimization algorithm of the objective function is performed in analytical, which is using search tree optimization. Some comparisons with a very popular controller (i.e., PI controller) have been made. It is shown that the transient response during the start-up scenario performs better for the proposed MPC-KF than PI controller. The comparison analysis has been tabled.

With the problem of load changes for implementing MPC, the simple Kalman filter (KF) has been proposed. It is shown that the proposed MPC-KF is comparable with PI controller for any load changes. This has proof that the proposed MPC-KF is comparable in robustness with the PI controller and could be further investigated for advanced load identification methods.

In term of converter modelling, the state-space equation techniques are used based on the characteristics of the switching state, i.e., *on* and *off*. Then, the computational of the objective function is formulated based on minimizing the squared area of the tracking error over the prediction horizon. The minimizing of the objective function is optimized through the search tree optimization techniques for each sampling instant. In reducing the complexity of the algorithm, the short prediction horizon $l=3$ has been used. Then, the load variation technique is proposed using the additional loop of KF that associated with MPC. The objectives have been achieved and presented the results in Chapter 4.

5.2 Future Work and Recommendation

1) This thesis is to develop a new control method for a DC-DC converter in order to improve DC-DC converter performance. This improvement has been achieved with the proposed method of short prediction horizon of MPC $l=3$ that described in Chapter 3. All these control schemes have so far been tested for DC-DC buck converter as controller solution to tackle the hybrid nature of DC-DC buck converter. Further research could be employed the MPC as a new control method for others DC-DC converters such as boost, buck-boost, Sepic and Cuk converters.

2) The MPC scheme in this thesis used the search tree optimization in order to minimize the error and tracking the best reference value. During the search tree optimization, the optimizing of error is done by recalculated the error at each of the following sampling instant of the prediction horizons. However, the increment of prediction horizon significance with complex computation that made the controller cost higher. Thus, since the long prediction horizon could give more precise in MPC control objective, the further research should be developed for long prediction horizon with less computational burden in the optimization algorithm.

3) In this thesis, the verification method is being tested using a simulation study using MATLAB Simulink. A few analyses have been done to verify the performance of proposed controller. The further research should continue with the experimental study of the proposed controller.

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