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Comparative Study of Short Prediction MPC-KF with PI Controller for DC-DC Buck Converter

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***Abstract*— In nature, the DC-DC converter deals with high switching phenomenon that contributes to the higher conduction losses. Its operation conventionally associated with PI/PID controller in order to meet the desired output. To increase the DC-DC converter performance, an advanced controller has been proposed. However, it is deals with complex algorithm that made the controller cost higher. In this paper, the short prediction horizon of MPC using search tree optimization that generates low switching phenomenon is proposed. The optimal problem is being solve using on-line to reduce the computational effort. The kalman filter is then used for load estimation. This control approach for DC-DC converter has produced the promising output transient performance when compared with conventional PI controller while also minimizing the switching losses phenomenon.**

***Index Terms*—DC-DC converter, PI/PID control, Model Predictive Control (MPC), Kalman Filter (KF)**

then return back to complexity of MPC control index optimization problem, which is the converter constraints is included.

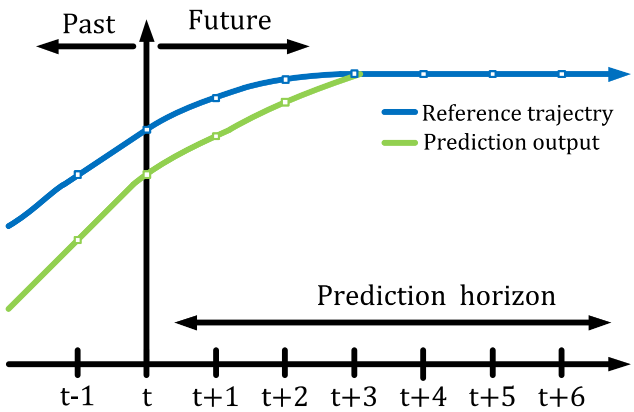


Fig. 1. MPC strategy

In this paper, a new technique of MPC is proposed. To solve the optimization problem, the short prediction horizon ($l \leq 3$) is proposed. The proposed scheme is done by fundamental revising the new control index of MPC used in DC-DC converters. Constraint optimization is solved directly using analytic solution in order to achieve the objective of high efficiency DC-DC converters with simple controller. This paper is structured as follows. In section II, the state space averaging model by considering the hybrid of the buck converter is provided6. Section III devoted to MPC algorithm formulation. Result and discussion presented in section IV. Finally, conclusion presented in V.

II. Modelling of Buck Converter

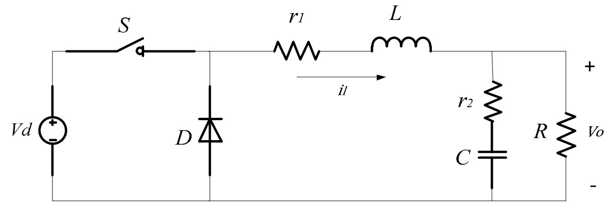
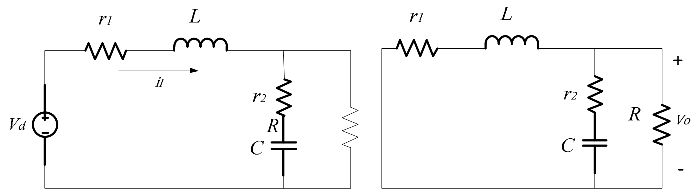


Fig. 2. Topology of the DC-DC buck converter

The DC-DC buck converter illustrated in Figure 2 is a converter that reduces the dc input voltage, v_s to a higher desired dc output voltage, v_o. The buck converter consists of two power semiconductors consists of the controllable switch *S*, and the diode, *D*. The inductor *L* with the internal resistor r_1 is used to supply and deliver energy depending on the operational mode of the converter, while the filter capacitor *C* and capacitors resistor r_2 are connected in parallel with the load resistor *R* so as to assure constant output voltage during steady-state operation of the converter.

In state space averaging model of DC-DC converter, the dynamics of the buck converter system is described by direct application of voltage law (KVL) and Kirchhoff's current (KCL) for the existent circuit topologies and switching state.



(a) Switch *On* (b) Switch *Off*

Fig. 3. Switching modes of buck converter

Fig. 3 shows the circuit condition in the buck converter when the position is switch *on* and *off*. To easy the dynamics of buck converter, let the switch *on* signify by *p*=1 while *p*=2 signify switch *off*. The of state space equation represented in the form of (1) and (2):

$$\dot{x}(t) = A_{on}x(t) + B_{on}v_s$$

$$\dot{x}(t) = A_{off}x(t) + B_{off}v_s \quad (1)$$

Where;

$$B_{on} = \begin{bmatrix} \frac{1}{L} \\ \frac{Rr_c}{L(R+r_c)} \end{bmatrix}, \; B_{off} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (2)$$

In addition, the output voltage, V_o through the load *R* is known by;

$$y = v_o = Cx \, , \; C = [0,1] \quad (3)$$

The states generate between two modes according the switching operation. Suitable switching control and constant input signal will track the best reference output.

III. MPC Algorithm

Continuous time state space equation of converter is shown in (1) and (2). To produce the output *x*(*t*), let consider that voltage supply, $u = vs$ is a constant and all *Ap* parameter are steady. Thus, the result *x*(*t*) in $t \in (t0, t)$ with initial state *x*(*t*0). Instantly, the output is calculated as;

$$y(t) = Ce^{A_p(t-t_0)}\left(x(t_0) + A_p^{-1}Bu\right) - CA_p^{-1}B_p u \quad (4)$$

In consideration of the implement the tracking of the reference output voltage v_r, the squared region of the tracking error *e*(*t*) is being minimize over a finite prediction horizon;

$$e(t) = y(t) - v_r \quad (5)$$

Thus, MPC objective function can be derived as;

$$J(t_1, t_0) = \int_{t_0}^{t_1} e^2(t)dt = \int_{t_0}^{t_1} \left(y(t) - v_r\right)^2 dt \quad (6)$$

Then, the optimization of the objective function is performed. In this case, the search tree optimization for prediction horizon is implemented as illustrated at Fig. 4. The fundamental of switching period is fixed as sampling period, *T*. The control difficulty is to compute the sequence of switching modes to make sure that the output voltage v_r traces the reference accordingly, by using the minimization of the index function (6) over a finite prediction horizon, *l*. Each consecutive sampling instant are recalculating due to the effect of disruption cannot be predicted is the method of optimizing the sequence. Recalculating of each consecutive sampling instant is the method of optimizing sequence. It is done due to the effect of disruption cannot be expected. Consecutive of optimal switching mode will change based on the influence of disturbance.

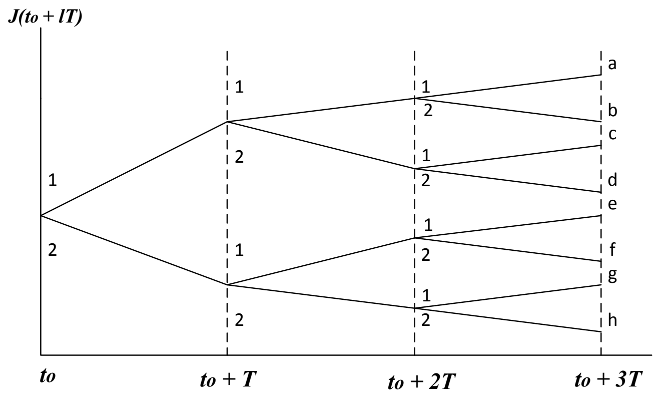


Fig. 4. Diagram of search tree for prediction horizon l=3

A. Load Uncertainty

In most applications, the load has been assumed to be unknown and varying. However, through simulation, in this proposed MPC it is noticed that when the load changes, the output has deviated to certain value due to the model mismatch and therefore produce large steady-state error. Essentially, the parameter of the load is required in this proposed MPC. Thus, the new external loop should be added to remove the output voltage error in the existence of load uncertainties. It is done by tracking the parameter value of load changes into the steady state formulation as mention in (3). To achieve this, the external loop of Kalman Filter (KF) is proposed. It is connected at current and voltage output to allows a zero steady-state output error. The additional loop will remove the steady state error by tuning the current and voltage between both references. In addition, two disturbance states, i_e and v_e are introduced in order to model the of load variations. A set of mathematical equation (8)-(10) of KF is used to generate the filtered signal of output voltage and inductor current. These will come out an effective computational method to estimate the behavior of the DC-DC converter.

$$x_k = Ax_{k-1}$$
$$z_k = Hx_k + v_k \tag{7}$$

Eqn. (7) define the noisy linear system.

$$x_k^- = A\hat{x}_{k-1}$$
$$P_k^- = A\hat{P}_{k-1}A^t + Q \tag{8}$$

The estimated state, $\hat{x}_{k-1}$, is used to predict the current state at time *K*, x_k^-, as shown in Eqn. (8).

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1}$$
$$\hat{x}_k = x_k^- + K_k(z_k - Hx_k^-) \tag{9}$$
$$\hat{P} = (I - K_k H)P_k^-$$

For more accurate approximation, Eqn (9) is used to estimate the current state of the system. Where, gain vector and the error covariance matrix represented as *K* and *P*. the gain vector is chosen wisely due to the accuracy of i_e and v_e are depends on it.

$$R = \frac{v_e}{i_e} \tag{10}$$

Hence, (10) will be used to track the value of load variance for state space formulation (2). In Fig. 5 the control diagram of proposed control strategy including both loops is illustrated.

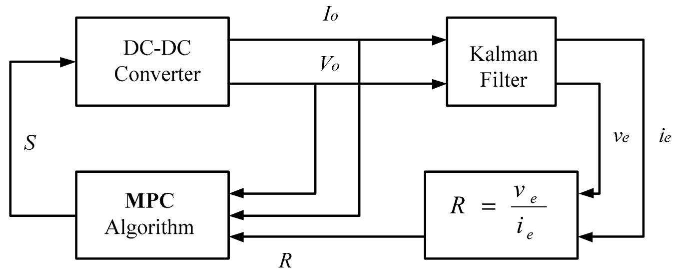


Fig. 5. Control diagram of the proposed MPC strategy.

IV. Result and Discussion

The aim of this part is to observe the simulation results in order to clarify the efficiency of the MPC-KF controller by using MATLAB/Simulink. To shows the effectiveness of MPC-KF, the comparisons with PI-PWM controller of DC-DC converter are made. The PI-PWM controller is being compared fairly because both controller using the same switching frequency. The simulation results are shown to demonstrate the performance of the proposed controller under several conditions. For the first case, the frequent of switching signal is presented. While for the second case, the transient responses of the start-up scenario and load changes are analysed. The circuit parameter of step-down DC-DC converter is shown in Table 1. Meanwhile, the parameters of PI-PWM controller are shown in Table 2.

TABLE 1 BUCK CONVERTER PARAMETER

PARAMETER	VALUE
L	15.91[mH]
C	94[μF]
r_c	0.001[Ω]
r_l	0.5179[Ω]
R	4[Ω]
V_{dc}	24 [V]

TABLE 2 PARAMETER OF PID-PWM CONTROLLER

PARAMETERS	VALUE
Switching frequency	200[kHz]
Kp	100
Ki	20
Kd	0

A. Switching sequence

The first case is devoted to the investigation of switching number. The switching signal illustrated in Fig 6. for PI-PWM controller and Fig. 7 (a-c) for MPC-KF. The number of switching for every simulation that consists of PI-PWM controller and numerous prediction horizon of MPC-KF are recorded in Table 1. As the results, the switching number of conventional PI-PWM controller produce higher values when compared with proposed MPC-KF. For the proposed MPC-KF, the analysis and simulation indicates that number of switching was increasing proportional to the number of prediction horizons. In that case, the conduction switching losses decreasing corresponding with the number of switching signal.

TABLE 1 SWITCHING NUMBER OF CONVENTIONAL PID-PWM CONTROLLER AND PROPOSED MPC.

Controller	Number of Switching
PWM-PID	3220
***l*=1**	64
***l*=2**	111
***l*=3**	135

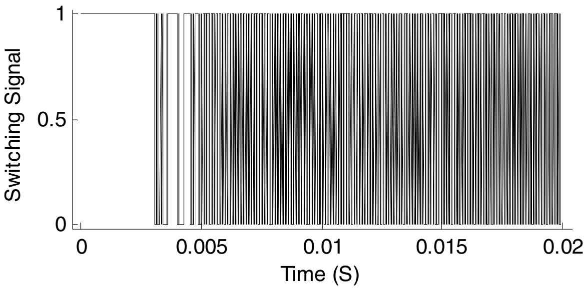
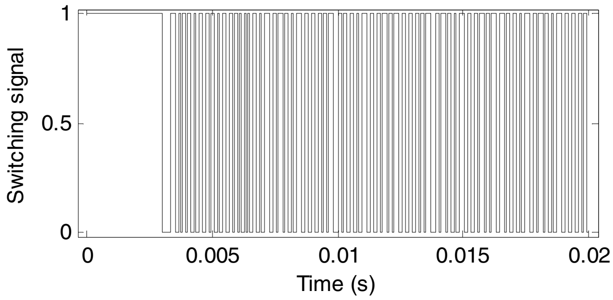
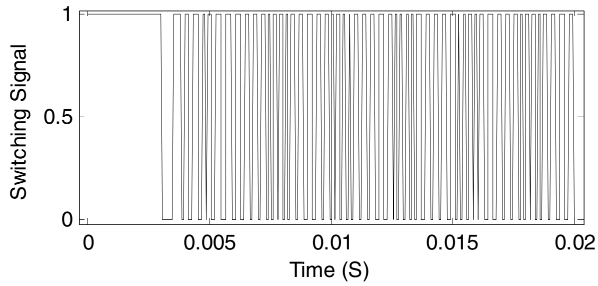


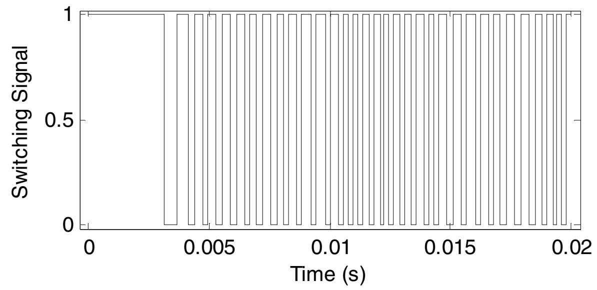
Fig. 6. Switching signal of PI-PWM controller



(a) Switching signal of proposed MPC-KF (l=1)



(b) Switching signal of proposed MPC=KF (l=2)



(c) Switching signal of proposed MPC-KF (l=3)

Fig. 7. Switching Sequence of proposed MPC-KF based on prediction horizon l

B. Dynamics Response

The second case is examined the transient response of PI-PWM controller and MPC-KF of buck DC-DC converter. The results are illustrated in Fig. for PI-PWM controller and Fig. 9(a-c) for the proposed MPC-KF. It is observed that MPC-KF has better dynamics response than PI-PWM controller. Compared to the PI-PWM controller, the results show the graph has no obvious overshoot for the proposed MPC-KF. The overall transient responses values are summarized at Table 2. It has been found that the overshoot value of MPC-KF decreasing proportionally with the number of prediction horizons. Subsequently indicates that proposed MPC-KF provides better results compared to the PI-PWM controller.

TABLE 2 COMPARISON BETWEEN PI-PWM AND MPC-KF

	PID Controller	MPC		
		***l*=1**	***l*=2**	***l*=3**
Delay time (t_d)	0.0016	0.015	0.0015	0.0015

Rise time (t_r)	0.0030	0.0022	0.0023	0.0023
Peak time (t_p)	0.00375	0.0034	0.0033	0.0033
Max overshoot (%)	2.50	3.17	2.08	1.25
Settling time (t_s)	0.00325	0.0042	0.0031	0.0030

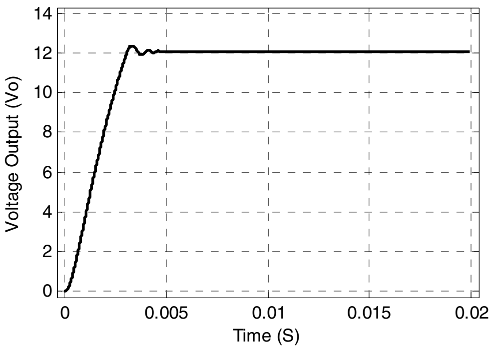
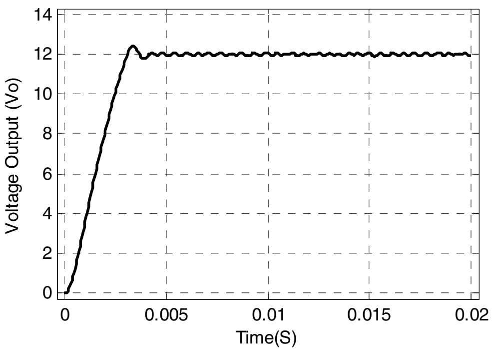
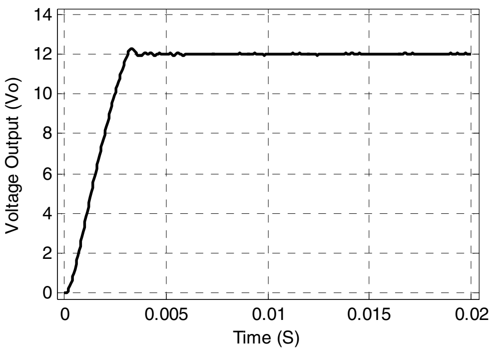


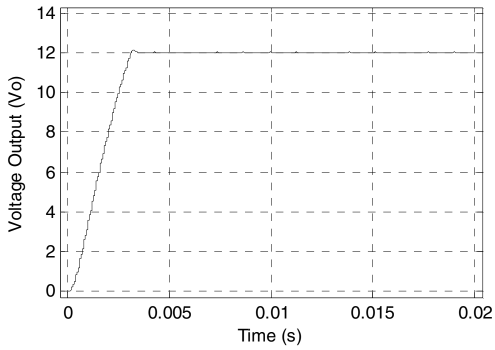
Fig. 8. PI-PWM controller output voltage signal



(a) Proposed MPC-KF (*l*=1)



(b) Proposed MPC-KF (*l*=2)



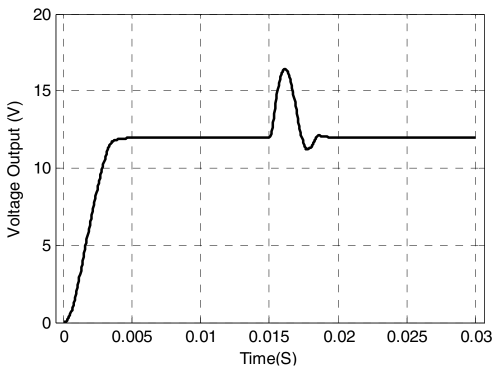
(c) Proposed MPC-KF (*l*=3)

Fig. 9. Voltage output of MPC-KF based on various prediction horizon *l*

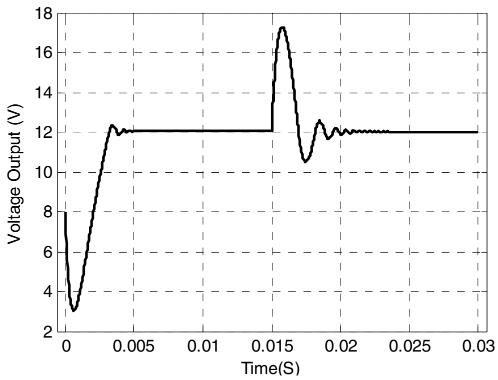
C. Load Step Change

The last case to be examined is the step variation of the load resistance R during the steady state operation using MPC-KF and PI-PWM controller. For MPC-KF, prediction horizon, l=3 is chosen. At t ≈ 1.5ms the load resistance is being increase to 100% from its nominal value of R=4Ω to R=8Ω. In Fig. 10 and 11, the simulation results of output voltage and current response are depicted respectively. In Fig. 10(a) the KF adjusts voltage output references of the proposed MPC. It is shows that there are no overshoot and the output voltage accurately follows its reference compared to PI-PWM controller.

While for the inductor current, I_L the KF eliminates the ripple that contributed zero steady state error. However, when PI-PWM controller is used, the longer settling time and the current response is weakly dampened, indicating that the tuning of the PI-PWM controller is fairly aggressive.

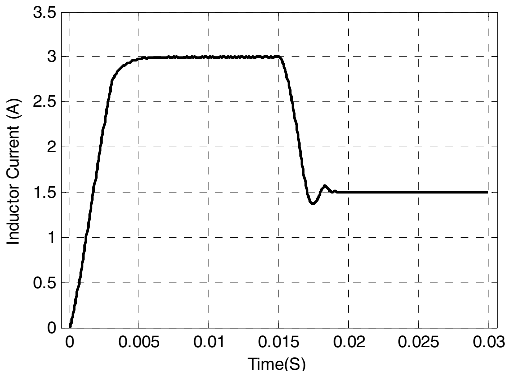


(a)

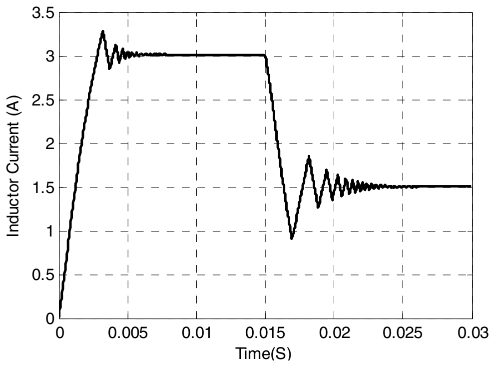


(b)

Fig. 10. Output voltage for step variation of load resistance (a) MPC-KF, *l*=3. (b) PI-PWM controller



(a)



(b)

Fig. 11. Inductor Current for step variation of load resistance (a) MPC, *l*=3. (b) PI-PWM controller

V. CONCLUSION

In this paper, the simple short prediction Model Predictive Control (MPC) that combined with Kalman Filter (KF) is being used and compared with the conventional PI-PWM controller. In MPC-KF, the desired output voltage has been regulated by using the tree search optimization of prediction horizon.

From the work that been carried out, MPC-KF come out with low switching number compared to the PI-PWM controller. Low switching number could be reducing the switching losses of the buck DC-DC converter. Furthermore, it is observed that the transient response of the buck DC-DC converter gives the better response in terms of maximum overshoot, delay time, settling time and steady state error when compared to PI controller. Same goes also to when the load changes are analysed.

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