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Modelling and Control of a Chopper using Feedback and Feedforward Control Schemes

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Abstract: *Designing two degree of freedom controller to control the boost chopper system is challenging. A new feedforward combined with feedback controller design is proposed. Increasing the efficiency of the DC-DC converters can be achieved by decreasing the distortion and noise for both input and output stages in the system. A linearization mathematical model analysis for boost chopper is presented. Both the input voltage with multiple steps and the duty cycle of PWM which control the switching circuit were applied to study the behaviour of the system. In this study, the simulation results show that the disturbance rejection and input tracking were improved for different cases and situations. Also, the results show that the proposed method can be adapted by redesigning the feedforward controller to recover the impact of the boost parameter changes.*

Keywords:*Modelling, Chopper, Feedback controller, Feedforward controller.*

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I. Introduction

Nowadays DC-DC converters are widely used in industry, all types of DC-DC converters such as: buck, boost, and buck-boost are applied to improve the transformation of power in power systems. Applying these converters to design power systems such as: hybrid vehicles, lighting systems, computer chargers, power supplies, and DC motor drives become very essential. This can make the power systems design easier, more efficient, lower cost, weight, and size see [1, 2, 3, 4].

One of the biggest problems in power systems is the ripple voltage with higher frequency components which can be generated from reference and input voltages jumps during the process of transforming the power, so each DC-DC converter has a lowpass filter in the output stage to decrease the impact of this phenomenon in the system. Using lowpass filter in the design of these converters doesn't cancel the ripple hundred percent.

In this paper we introduce an adaptive control strategy that can improve reference tracking and disturbance rejection that comes from voltage jumps in both input and reference voltages. We use two-degree of freedom controller, the feedback and the feedforward. The feedback controller alone has the ability in improving the state trajectory response, but it can't solve the problem of disturbing caused by the input voltage, so we need another controller that can help in improving the response by cancelling the disturbance caused by the input voltage. This is a control strategy that used in control theory, but in this paper the new thing is that when the parameters of the boost model changes then the feedforward with its original parameters may not improve the response, then adaptive control can be used to overcome the changes happened in the response caused by the changing of the model parameters.

In some cases, using only one feedforward for the input voltage is not enough to insure higher efficiency of the system, so in these cases we combined both feedforward designs (i.e. use feedforward block after reference voltage and other one after input voltage). This will be helpful in improving our system.

In this paper the second section introduces the boost model analysis, we derive the nonlinear analysis equations, and then the linearization equations are derived. The third section shows the feedback and feedforward controllers design. In this section we introduce also the adaptive feedforward controller, after that the simulation results for each corresponding case are placed in this section using Matlab software. Finally, some concluding remarks that summarize our paper are introduced.

II. Dc-Dc Boost Chopper Model Analysis

Figure 1 below shows the boost chopper step up converter circuit diagram. According to on/off ($q = 1$ and $q = 0$) switching Pulse Width Modulation (PWM)signal the state differential equations and output equation of the circuit can be derived see [5, 6].

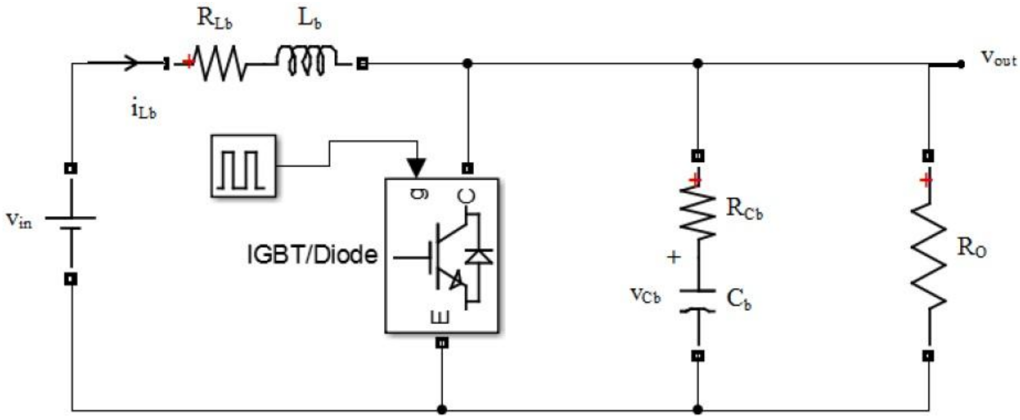

Fig. 1. Boost chopper step up circuit diagram

Assume the PWM is on (q = 1) then the systemequations will be:

$$\frac{di_{Lb}}{dt} = \frac{1}{L_b}\{v_{in} - i_{Lb}R_{Lb}\}$$
$$\frac{dv_{Cb}}{dt} = \frac{-v_{Cb}}{C_b(R_O+R_{Cb})},\ v_{out} = v_{Cb}\left[1+\frac{R_{Cb}}{R_O+R_{Cb}}\right]$$

then, the state space representation of the abovesystem equations is as follows:

$$\dot{x} = A_1x + B_1u$$
$$y = C_1x + D_1u$$

With

$$x = \begin{bmatrix} i_{Lb} \\ v_{Cb} \end{bmatrix}, u = v_{in} \text{ and}$$
$$A_1 = \begin{bmatrix} \frac{-R_{Lb}}{L_b} & 0 \\ 0 & \frac{R_{Cb}}{R_O + R_{Cb}} \end{bmatrix}$$
$$B_1 = \begin{bmatrix} \frac{1}{L_b} \\ 0 \end{bmatrix},\ C_1 = \begin{bmatrix} 0 & 1+\frac{R_{Cb}}{R_O+R_{Cb}} \end{bmatrix}, D_1 = 0$$

Assume the PWM is off (q = 0) then the systemequations will be:

$$\frac{di_{Lb}}{dt} = \frac{1}{L_b}\left\{v_{in} - \left[i_{Lb}R_{Lb} + v_{Cb} + R_{Cb}\frac{R_O i_{Lb} - v_{Cb}}{R_O + R_{Cb}}\right]\right\}$$
$$\frac{dv_{Cb}}{dt} = \frac{1}{C_b}\frac{R_O i_{Lb} - v_{Cb}}{R_O + R_{Cb}}$$
$$v_{out} = v_{Cb} + R_{Cb}\frac{R_O i_{Lb} - v_{Cb}}{R_O + R_{Cb}}$$

then, the state space representation of the abovesystem equations is as follows:

$$\dot{x} = A_2x + B_2u$$
$$y = C_2x + D_2u$$
$$A_2 = \begin{bmatrix} \frac{-1}{L_b}\left\{R_{Lb} + \frac{R_{Cb}R_O}{R_O + R_{Cb}}\right\} & \frac{-1}{L_b}\left\{1 - \frac{R_{Cb}}{R_O + R_{Cb}}\right\} \\ \frac{R_O}{C_b(R_O + R_{Cb})} & \frac{-1}{C_b(R_O + R_{Cb})} \end{bmatrix}$$
$$B_2 = \begin{bmatrix} \frac{1}{L_b} \end{bmatrix},\ C_2 = \begin{bmatrix} \frac{R_{Cb}R_O}{R_O+R_{Cb}} & 1-\frac{R_{Cb}}{R_O+R_{Cb}} \end{bmatrix}, D_2 = 0$$

Now: the boost model after combining both state spaceand output equations for both on/off (q = 1 with duty cycle d and q = 0 with duty cycle 1 - d) (PWM) signalswill be:

$$\dot{x} = d(A_1x + B_1u) + (1-d)(A_2x + B_2u) = F(d,x,u)y = d(C_1x + D_1u) + (1-d)(C_2x + D_2u)$$

According to the system discussed above we have two nonlinear differential equations with two nonlinear inputs (disturbance input voltage u and duty cycle control d). So, the easiest way to control this system is to linearize the model around such point (such as equilibrium point), then apply the standard control strategies to design the controller.

Using linearization, the model of boost converter will be:Inorder to do that let us define the following:
Nominal values point of $(d,x,u) is (\bar{d},\bar{x},\bar{u})$The perturbations$\tilde{d} = d - \bar{d}, \tilde{x} = x - \bar{x}, \tilde{u} = u - \bar{u}$
Find the equilibrium points of the function $F(d,x,u) at (\bar{d},\bar{x},\bar{u})$

$$F(\bar{d},\bar{x},\bar{u}) = \bar{d}(A_1\bar{x} + B_1\bar{u}) + (1-\bar{d})(A_2\bar{x} + B_2\bar{u}) = 0 \text{solve for } \bar{x} = \begin{bmatrix}\bar{I}_{Lb}\\ \bar{V}_{Cb}\end{bmatrix} at(\bar{d},\bar{x},\bar{u})$$

Then the linearization model will be

$$\dot{\tilde{x}} = A\tilde{x} + B_1\tilde{d} + B_2\tilde{u}$$
$$\tilde{y} = y - \bar{y} = C\tilde{x} + \widetilde{D}_1\tilde{d} + \widetilde{D}_2\tilde{d}$$

$$A = \frac{\delta F}{\delta x}\downarrow_{(\bar{d},\bar{x},\bar{u})} = \begin{bmatrix} \frac{-1}{L_b}\left\{R_{Lb} + \bar{d}\frac{R_{Cb}R_O}{R_O + R_{Cb}}\right\} & \frac{\bar{d}}{L_b}\left\{\frac{R_{Cb}}{R_O + R_{Cb}} - 1\right\} \\ \frac{R_O\bar{d}}{C_b(R_O + R_{Cb})} & \frac{-1}{C_b(R_O + R_{Cb})} \end{bmatrix}$$

$$B_1 = \frac{\delta F}{\delta d}\downarrow_{(\bar{d},\bar{x},\bar{u})} = \begin{bmatrix} \frac{1}{L_b}\left\{\bar{V}_{Cb} + R_{Cb}\frac{(R_O\bar{I}_{Lb} - \bar{V}_{Cb})}{R_O + R_{Cb}}\right\} \\ \frac{R_O\bar{I}_{Lb}}{C_b(R_O + R_{Cb})} \end{bmatrix}$$

$$B_2 = \frac{\delta F}{\delta u}\downarrow_{(\bar{d},\bar{x},\bar{u})} = \begin{bmatrix}\frac{1}{L_b}\\ 0\end{bmatrix} C = \begin{bmatrix}\bar{d}\frac{R_{Cb}R_O}{R_O + R_{Cb}} & 1 - \frac{R_{Cb}}{R_O + R_{Cb}}\end{bmatrix} \widetilde{D}_1 = \begin{bmatrix}\bar{I}_{Lb}\frac{R_{Cb}R_O}{R_O + R_{Cb}}\end{bmatrix}, \widetilde{D}_2 = [0]$$

From the above linearization system, let us define thetransfer function with respect to $\tilde{d}$ as P1(s) and the
transfer function with respect to $\tilde{u}$ as P_2(s). Where:

$$P_1 = \frac{\tilde{y}(s)}{\tilde{d}(s)} = C(sI - A)^{-1}B_1 + \widetilde{D}_1$$
$$P_2 = \frac{\tilde{y}(s)}{\tilde{u}(s)} = C(sI - A)^{-1}B_2 + \widetilde{D}_2$$

III. Feedforward And Feedback Controller Design

In this section we will discuss the impact of feedbackcontroller alone and after adding the feedforward to the system. The block diagrams that represent our whole system with both feedforward and feedback controllers are shown in Figures 2 and 3 below [10,11,12].

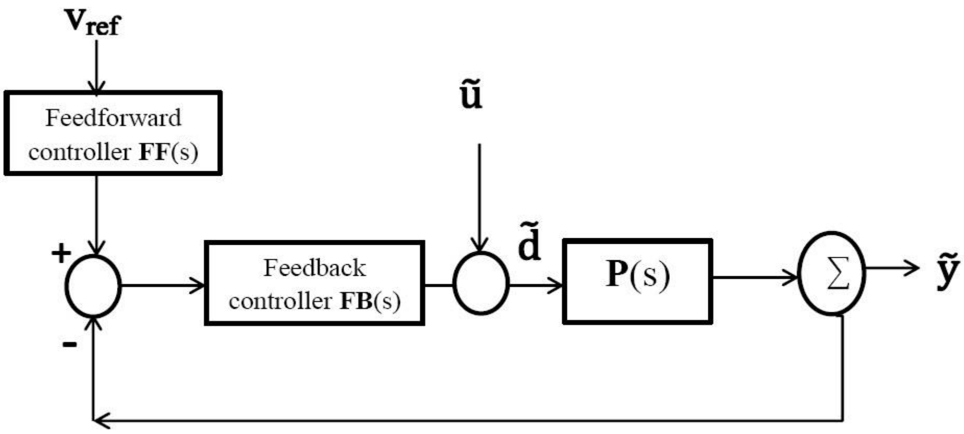

Fig. 2. Boost Chopper System with Both Feedback and Feedforward Controllers design 1

From Figure 2 the output equation with feedforward controller is:

$$Y(s) = \frac{P(s)FB(s)FF(s)}{1 + P(s)FB(s)} V_{vef}(s) + \frac{P(s)}{1 + P(s)FB(s)} \widetilde{U}(s)$$

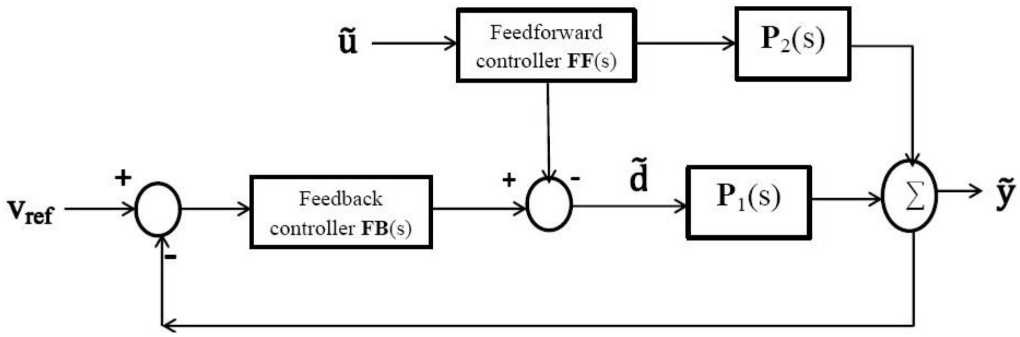

Fig. 3. Boost Chopper System with Both Feedback and Feedforward Controllers design 2

From Figure 3 the output equation without feedforwardcontroller is:

$$Y(s) = \frac{P_1(s)FB(s)}{1 + P_1(s)FB(s)} V_{vef}(s) + \frac{P_2(s)}{1 + P_1(s)FB(s)} \widetilde{U}(s)$$

and the output equation with feedforward controller is:

$$Y(s) = \frac{P_1(s)FB(s)}{1 + P_1(s)FB(s)} V_{vef}(s) + \frac{P_2(s) - P_1(s)FF(s)}{1 + P_1(s)FB(s)} \widetilde{U}(s)$$

A. PI Feedback Controller Design

In practice controllers are nowadays almost exclusively implemented digitally. Digital controllers are far more convenient to implement on microprocessors than continuous-time controllers. Also they are easily implemented using difference equations, i.e. simple computer software. The continuous-time PID controller can be written in the form [7]

$$C(s) = K_c \left[1 + \frac{1}{\tau_1 s} + \tau DS\right]$$

Where τ_I is the integration time constant or 'reset time', τ_D is the derivative time constant. The Discretetime PID controller with sampling rate $T_s$can be written in the form

$$C(z) = K_c \left[1 + \frac{T_s}{\tau_{1D}} \frac{\mathcal{Z} + 1}{z - 1} + \frac{\tau_{DD}}{T_s} \frac{z - 1}{z + 1}\right]$$

where the digital integral and derivative time constants are $\tau_{1D} = 2\tau_I$, $\tau_{DD} = 2\tau_D$In this paper we use PI controller for our system with the following transfer function:

$$C(z) = K_c \frac{z - 0.9882}{z - 1}$$

B. Feedforward Controller Design

In this part a feedforward controller design is introduced. This controller can be designed in two different ways according to its position in the block diagram, so in the literature you can find that this controller can be used after the reference voltage as in Figure 2 or after the input voltage as in Figure 3 or both cases. Each case has its own design for the feedforward controller. The design in Figure 2 can be first order with transfer function

$$FF(s) = \frac{K_f}{s/f_{s1} + 1}$$

In this design to achieve better tracking for the reference input voltage, we can change the frequency f_{s1} for fixed value of $K_f = 1$ [8]. This design is simple, has two parameters to control K_f and f_{s1}, and improve the tracking of the reference voltage, but it can't solve the problem of disturbance that comes from input voltage (i.e. jumps in input voltage). The second design which shown in Figure 2 is proposed for better tracking and disturbance rejection. In this case the feedforward controller is designed such that its transfer function $F(s) = \frac{P_2(s)}{P_1(s)}$. This design can solve both voltage jumping problems, the problem of jumping caused by reference voltage and the problem of disturbance which comes from the jumps in the input voltage. In order to see the impact of feedforward design on the output performance, we do the following examples that are simulated using MatLab 2012.

Example 1: Suppose that the boost chopper system is simulated over the time interval [0, 0.1] second with the sampling period$T = 50\mu sec$. The input voltage is a periodic step function with amplitudes 40 $*$ [0.67, 0.69, 0.64, 0.62] V. The boost chopper specification values are as follows: $L_b = 3mH, R_{Lb} = 0.1\ ohm, C_b = 200\mu F, R_{Cb} = 0.1\ ohm, R_O = 7.2\ ohm$, The duty cycle d = $\frac{2}{3}$.

Figure 4 shows the open-loop output of the boost chopper system for both continuous and discrete models. You can see that the discretization model is sufficiently accurate for system control.

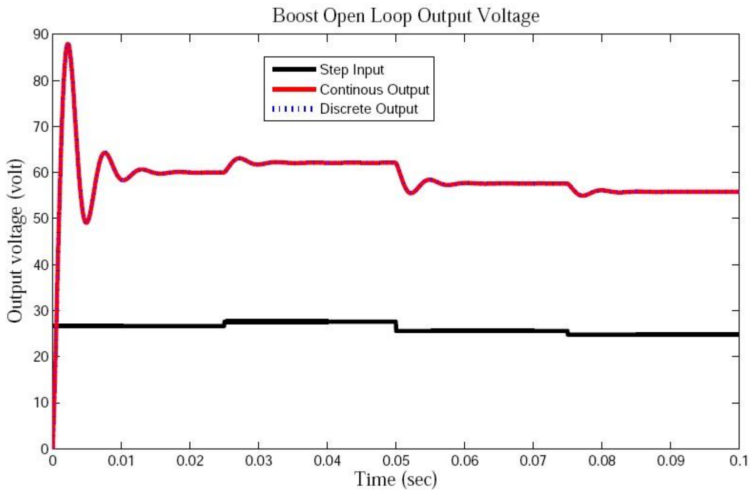

Fig. 4. Continuous-time and discrete-time open loop response of the boost chopper converter

Example 2: In this example the whole system shown in Figure 2 is simulated for feedback controller only and for both feedback and feedforward using the samespecifications of the boost chopper in Example 1 with $V_{ref} = 20\ V$.

Figure 5 shows the output voltage of the system in Figure 2 with and without feedforward.

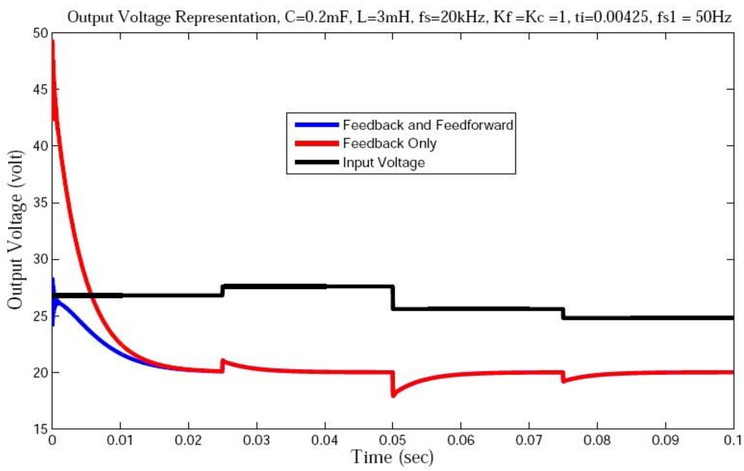

Fig. 5. Voltage responseof the system design 1

Based on Figure 5, the feedforward design 1 can solvethe problem for the first jump in reference voltage, butfor other input jumps this design failed to cancel theeffect of the input disturbance.

Example 3: In this example the system shown inFigure 3 is simulated for feedback controller only and for both feedback and feedforward using the samespecifications of the boost chopper in Example 1 with$V_{ref} = 20\ V$. The feedforward is designed here such that$FF(s) = \frac{P_2(s)}{P_1(s)}$, where

$$P_1(s) = \frac{1.233s^2 + 6{:}304 * 10^4 s + 6{:}961 * 10^7}{s^2 + 740.2s + 7.584 * 10^5}$$

$$P_2(s) = \frac{21.92s + 1.096 * 10^6}{s^2 + 40.2s + 7.584 * 10^5}$$

Figure 6 shows the output voltage of the system inFigure 3 with and without feedforward.

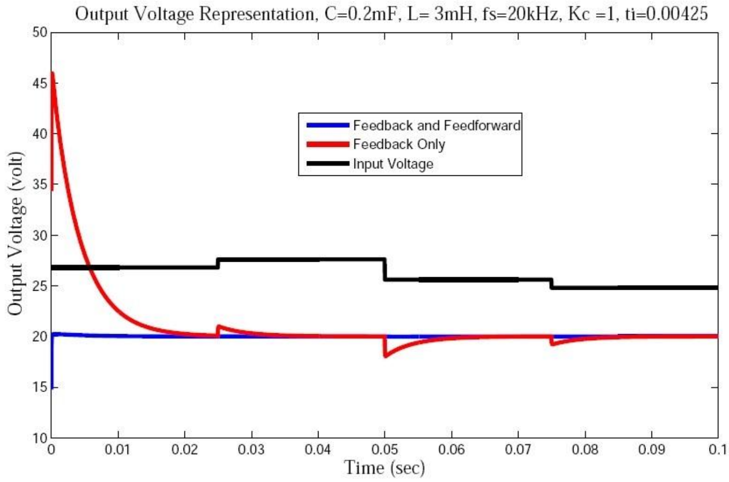

Fig. 6. Voltage responseof the system design 2

Figure 6 shows that the output voltage of the boostchopper converter is improved in tracking and disturbance rejection such that the multiple jumps in theinput doesn't affect the output now. In this design it is obvious that the location of $FF(s)$ is very importantin improving the output voltage against the disturbances that come from the reference and the input voltages. Another thing you should notice that one of the zero's of $P_1(s)$ equals the zero of $P_2(s)$, so the feedforwardresultant transfer function has zero/pole cancelation. Then, the resultant transfer function of $FF(s)$ is a firstorder which can be written as

$$FF(s) = \frac{kfb}{s - \lambda_1} = \frac{0.1}{s + 1129}$$

where λ_1 is the non cancelation zero of $P_1(s)$.

Example 4: In this example the system in Figure 3is simulated for different values of $\acute{C}$s,$\acute{L}$s, and $\acute{R}_O$ s. we use the same specifications as in Example 3 overtime interval (0,0.01) sec. We use the same design ofthe feedforward that used in Example 3 and the outputis simulated for different values of the boost chopperparameters C,L and R_O. Figures 7,8,and 9 below showhow the output change according to the change in boostchopper parameters, this is because as soon as thefeedforward parameters are fixed, then the output voltage still good but with higher overshoot which reaches up to10 percent of its maximum.

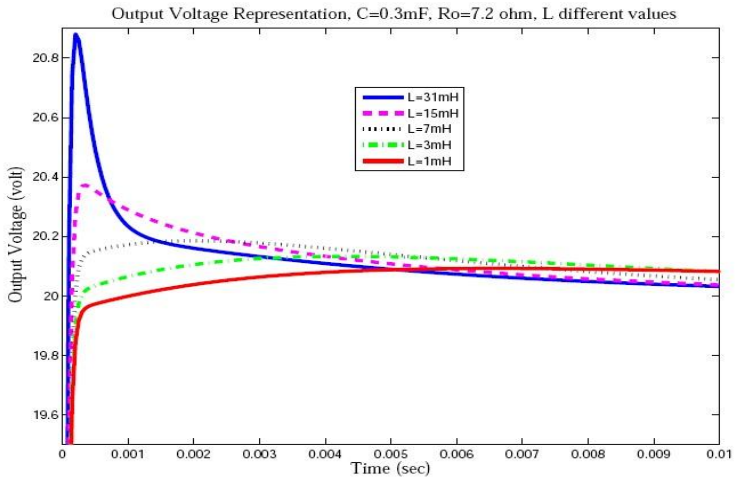

Fig. 7. Voltage response for different inductance values L_b

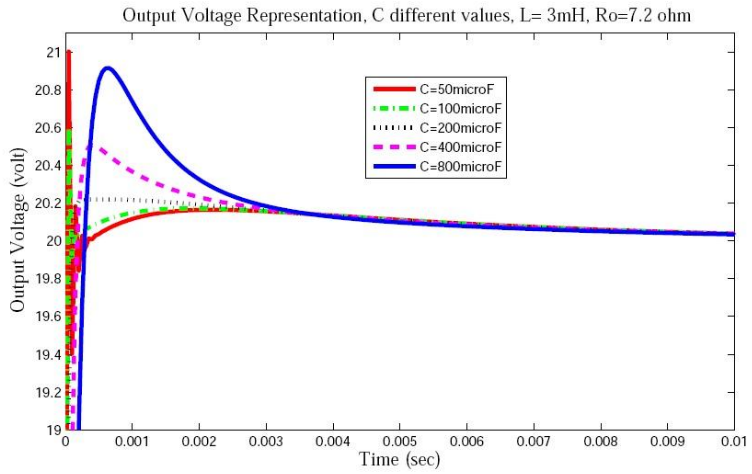

Fig. 8. Voltage responsefor different capacitance values C_b

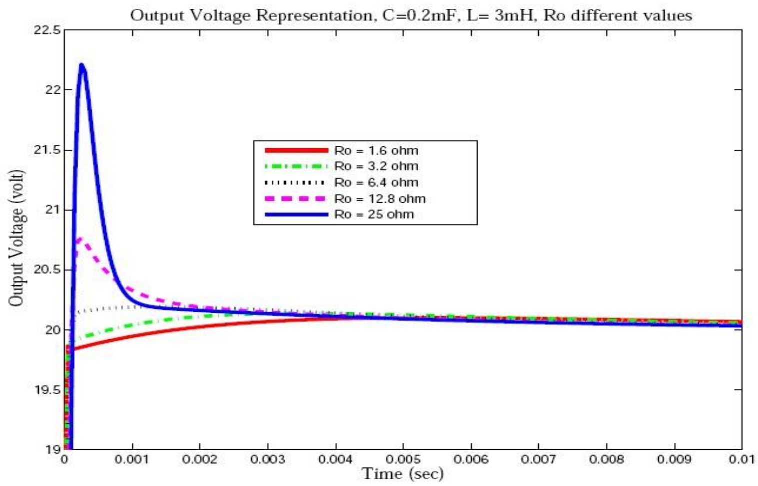

Fig. 9. Voltage responsefor different load resistance values R_O

C. Adaptive Feedforward Control

Adaptive feedforward controller is a feedforward controller that can be updated such that the response maintain the same according to any changes in the modelparameters. The controller type is not change but theparameters of the controller are changed. It is very usefulin control design to keep the response in the wantedbehavior, like tracking and disturbance rejection of bothreference and input voltages in our design. In order to understand how this characteristic in controllerdesign is helpful in our design let us take the following examples.

Example 5: In this example the specifications of theboost chopper which are used in Example 1 are the same,but now we use L_b = 31 mH the worst case responseof the inductance values that are shown in Figure 7, inthis example we update the value ofλ_1 according to newvalue of L_b = 31 mH, this means that the new designis

$$FF(s) = \frac{0.1}{s + 109.3}$$

Figure 10 shows the response before and after thefeedforward updated.

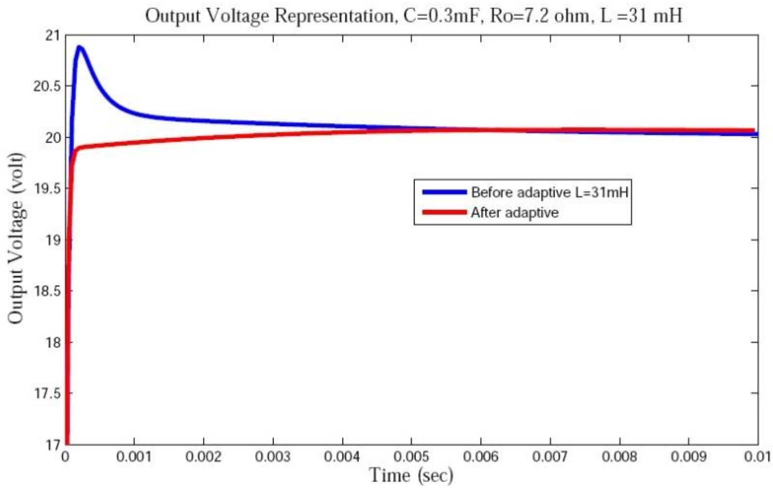

Fig. 10. Voltage responsebefore and after adaptive control of the system after changing inductance parameter

Example 6: In this example the specifications of theboost chopper which are used in Example 1 are the same,but now we use C_b = 0.8 mF the worst case responseof the inductance values that are shown in Figure 8, inthis example we find that λ_1 = -1129 according tonew value of C_b = 0.8 mF (i.e. doesn't change), so thecapacitor change has no impact on the pole location of $FF(s)$. In this case we combined the feedforward thatused in Figure 2 and the feedforward that used in Figure3 together. Usingf_{S1} = 400 Hz for the first one and theλ_1 = -1129 for the second one. Figure 11 shows the response before and after thefeedforward updated.

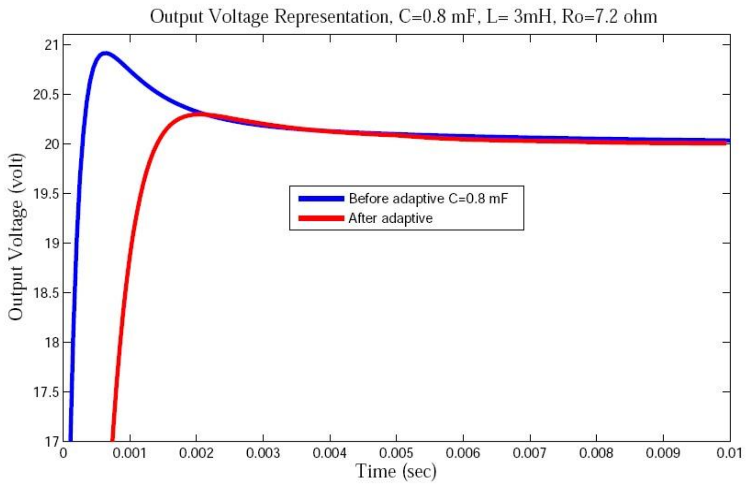

Fig. 11. Voltage responsebefore and after adaptive control of the system after changing capacitance parameter

Example 7: In this example the specifications of theboost chopper which are used in Example 1 are the same,but now we useR_O = 25 ohm the worst case response ofthe load resistance values that are shown in Figure 9, inthis example we find that λ_1 = -3767 according to newvalue of R_O = 25 ohm. In this case we combined thefeedforward that used in Figure 2 and the feedforwardthat used in Figure 3 together. using f_{s1} = 600 Hz forthe first one and the λ_1 = -3767 for the second one toget better and faster response.Figure 12 shows the response before and after thefeedforward updated.

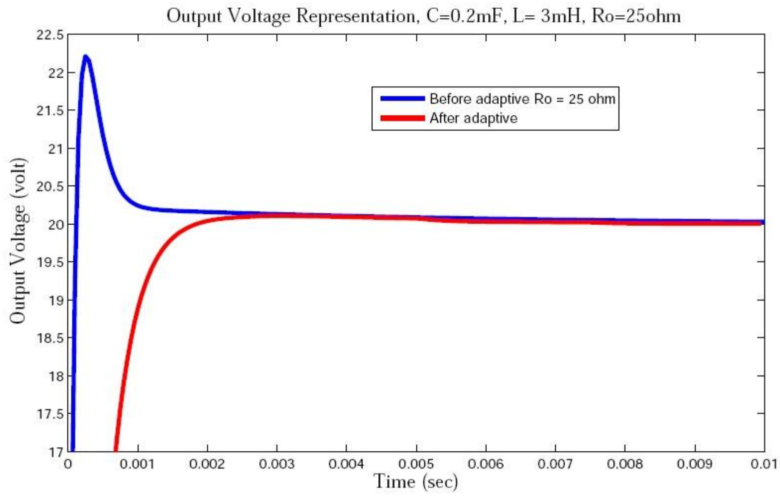

Fig. 12. Voltage responsebefore and after adaptive control of the system after changing resistance parameter

From Figures 10, 11, and 12 It can be seen that in10 one degree of freedom for feedforward design solvethe problem of disturbance and overshoots properly. Butin the Figures 11 and 12 you should add another filter(feedforward controller), so the feedforward becomestwo-degree of freedom, then the noise amplification canbe reduced by adding a filter. The resultant feedforwardnow will be

$$FF(s) = \frac{kfb}{s-\lambda_1} * \frac{kf}{s/f_{s1}+1}$$

This can be adapted by updated the values of λ_1,$f_{s1}$and tune the constants kfb, kf

IV. Conclusion

This research introduces an adaptive feedforward controller with feedback controller strategy to improve the performance of boost chopper system. The simulationresults show that the two-degree-of-freedom design results in much improved performance in disturbancerejection from the input power sources and trackingresponses when the voltage references change quickly.When converter parameters change, an adaptive schemefor revising the feedforward controller is shown to benecessary and can restore desired system performance.The economic benefits of feedforward control can comefrom lower operating costs and/or increased salabilityof the product due to its more consistent quality. Feedforward control is always used along with feedbackcontrol because a feedback control system is required totrack the referance changes and to suppress unmeasureddisturbances that are always present in any real process.

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