QFT APPROACH TO ROBUST CONTROL OF DC-DC BUCK CONVERTER

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Abstract— **This work addresses the disturbance attenuation problem of DC-DC buck converter system with uncertainties using the well-known robust PID controller. Quantitative Feedback Theory (QFT) approach is used to synthesize the robust PID controller by means of loop-shaping technique. The advantages of proposed design are (i) explicit inclusion of disturbance dynamics by means of the o/p impedance transfer function and audio susceptibility transfer function in the design stage itself, (ii) easy and simple controller design method to accommodate the uncertainty in the converter system transfer function, (iii) point by point frequency design method facilitates the tradeoffs between different conflicting requirements. Extensive Simulation have been carried out on the buck converter subjected to a variation in the load resistance and in source voltage.**

Keywords— DC-DC Buck Converter, Quantitative Feedback Theory (QFT), Disturbance rejection problem, robust control, loop shaping.

I. INTRODUCTION

The electrical energy demand abnormally increasing due to the changes in industry such as electric vehicles etc., So here Power converters plays a vital role in order to compatible with source and load. Out of the Power Converters DC-DC converters are essential in most of the power stages. The applications of DC-DC buck converters are DC motor drives, Aerospace, Automotive industry Adapters of HVDC transmission, medical appliances, instrumentation etc.. [1],[2].

In most of the cases the converter operate either in voltage mode control (VMC) or current mode control (CMC) [3] based on the inductor current. The current mode control of buck converter using QFT is discussed in [2] along with LQR-PI controller. The addition of inner current loop increases the hardware complexity and more tuning is required in LQR-PI controller. Further, the converter operates in two modes namely continuous conduction mode (CCM) and discontinuous conduction mode (DCM) if the inductor current greater than zero the converter operates in CCM otherwise it operates in DCM [4]. If the converter operates in DCM the performance of the converter deteriorating. The traditional approach uses two loop CMC approach for controlling the terminal voltage of DC-DC converters wherein external-loop regulates the voltage and an internal-loop is responsible for the current. Despite the converter parameter uncertainty and disturbances, the regulation of output voltage is an important requirement to meet the satisfactory operation of connected loads and devices. In CMC operation, the inductor current achieves the specified current regulation [5]. Due to the presence of parametric uncertainties and external disturbances like input voltage variation, load resistance variation, the output voltage/current regulation may not be satisfactory [5]. Sliding mode controls applied to regulate the voltage and current with in the specified limits as in [6]. Adaptive back stepping control achieves the desired voltage regulation by using current sensor less control technique with an integration of finite time current observer in [7]. An adaptive energy based controller is designed to regulate the voltage under the class of nonlinear loads in [8].

The organization of paper is as follows: Section II describes the QFT scheme to DC-DC buck converter and Section III explains the QFT controller design and its validation. Section IV discusses the simulation study applied to DC-DC buck converter using MATLAB/Simulink followed by the conclusion in Section V.

II. QUANTITATIVE FEEDBACK THEORY (QFT) TO DC-DC BUCK CONVERTER

In DC-DC converters to maintain the specified limits of the output voltage regulation is a challenging task when the converter suffers with parametric uncertainties and external disturbances such as input voltage variation and load resistance variation. This enforces the need for the robust controller. Among many robust techniques, QFT based robust controller is preferred in this work due to it simple and elegant way of designing the controller by means of loop shaping ideas (transparent tool) [9]. The main stage of QFT is to synthesis a feedback controller by means of the nominal loop-shaping approach (graphical). The so-called QFT bounds conveys the conversion of the robust performance and stability requirements into a set of bound on the nominal open loop transfer function. QFT is preferred due to the resulting controller structure is of low order. The fundamental idea of nominal loop-shaping is to have sufficient (large) gain at low frequency and less gain at high frequency so as to avoid the noise problem. This is possible by appending the controller to the plant with the combination of the poles (real/complex) and zero (real/complex). To achieve the regulation task of buck DC-DC converter by the QFT approach, the closed loop specifications [10] are considered as follows:

1. Robust stability margin:

$$\left|\frac{G(j\omega)C(j\omega)}{1+G(j\omega)C(j\omega)}\right| \leq W_s \qquad (1)$$

2. Output Sensitivity (robust output disturbance rejection):

$$\left|\frac{1}{1+G(j\omega)C(j\omega)}\right| \leq W_d(\omega) \qquad (2)$$

3. Input Sensitivity (robust input disturbance rejection):

$$\left|\frac{G(j\omega)}{1+G(j\omega)C(j\omega)}\right| \leq W_{di}(\omega) \qquad (3)$$

4. Robust Tracking:

$$T_L(\omega) \leq \left|F(j\omega)\frac{G(j\omega)C(j\omega)}{1+G(j\omega)C(j\omega)}\right| \leq T_U(\omega) \quad (4)$$

The control requirement, eq(1), gives the relation between the M-circle magnitude and the stability margin. The specification for stability margin, Ws represent the required phase and gain margin.The sensitivity (output disturbance rejection) specification given in eq(2) is denoted as Wd. The aim is to fulfill the required specifications over the desired frequency range.

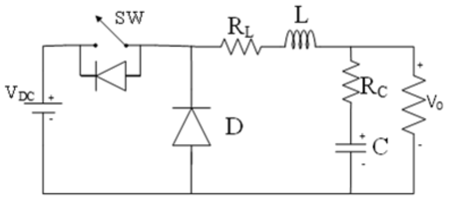


FIGURE 1. (A) BUCK CONVERTER MODEL

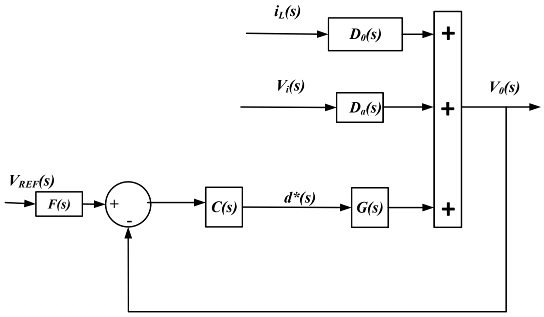


FIGURE 1. (B) ITS FEEDBACK CONTROL FOR DISTURBANCE REJECTION PROBLEM [3]

TABLE-I PARAMETERS FOR DC-DC BUCK CONVERTER

1.	Input Voltage (Vin)	24 V
2.	Output Voltage (V0)	12 V
3.	Duty Ratio (D)	0.5
4.	Switching Frequency (Fsw)	100KHz
5.	Inductor (L)	300µH
6.	Inductor Resistance (RL)	16.3mΩ
7.	Capacitor (C)	220 µF
8.	Capacitor Resistance (Rc)	0.305 Ω
9.	Load Resistance (R)	12 Ω

The nominal buck converter transfer function [2] is given as

- $G_0(s) = \frac{V_0(s)}{d^*(s)} = \frac{23795(s+1.4910^4)}{s^2+1415s+1.48\times10^7}$ (5)

By the considering the uncertainty of around 30%,the uncertain transfer function becomes

- $G(s) = \frac{V_0(s)}{d^*(s)} = \frac{[1.62e04,3.03e04]s+[2.41e08,4.52e08]}{s^2+[1.14e03,3.88e03]s+[1.22e07,1.50e07]}$ (6)

The chosen design frequency set Ω = [0.1, 1, 5, 10, 25, 50, 100, 390, 500, 1000, 3900, 10000, 15000, 25000, 35000, 39000].

Design Specifications:

1.Robust Stability Margin: $\left|\frac{C(j\omega)G(j\omega)}{1+G(j\omega)C(j\omega)}\right| \leq 1.2$ (7)

Here, W_s =1.2 corresponds to thegain margin(GM) ≥ 5dB and phase margin(PM) ≥60^0.

2.Load current disturbance rejection problem:

$$\left|\frac{D_0(j\omega)}{1+G(j\omega)C(j\omega)}\right| \leq \frac{s}{s+75} \quad (8)$$

Where in the load current disturbance transfer function is

$$D_0(s) = \frac{V_0(s)}{i_L(s)} = \frac{-0.29744\times(s+1.49\times10^4)(s+54.33)}{s^2+1415s+1.48\times10^7}$$

3.Source voltage disturbance rejection problem:

$$\left|\frac{D_a(j\omega)}{1+C(j\omega)G(j\omega)}\right| \leq \frac{s}{s+75} \quad (9)$$

Here, the source voltage disturbance dynamics is given as

$$D_a(s) = \frac{V_0(s)}{V_i(s)} = \frac{495.73\times(s+1.49\times10^4)}{s^2+1415s+1.48\times10^7}$$

4. Robust Tracking problem

The upper and lower tracking limits are chosen as follows

$$T_U(s) = \frac{1.01*\left(\frac{s}{10}+1\right)}{\left(\frac{s^2}{244.14}+\frac{1.6s}{15.625}+1\right)} \quad (10)$$

$$T_L(s) = \frac{0.99}{\left(\frac{s^2}{100}+\frac{2s}{10}+1\right)} \quad (11)$$

III. Loop shaping approach to QFT controller as well as pre-filter design and its validation

The job of the controller is to achieve quick recovery to the steady state output voltage, despite the external changes in the source voltage and load current. The loop shaping method is used to shape the loop transmission function in order to satisfy the QFT bounds at each design frequency. This can be achieved by means of placing the loop transmission function above the open performance bounds (disturbance rejection specifications (7-8)) and outside the stability margin bounds (6) at their respective frequencies as shown in figure (2). The designed robust controller [11] is as follows.

$$G(s) = \frac{0.027777(s+2062)(s+1910)}{s(s+7079)} \quad (12)$$

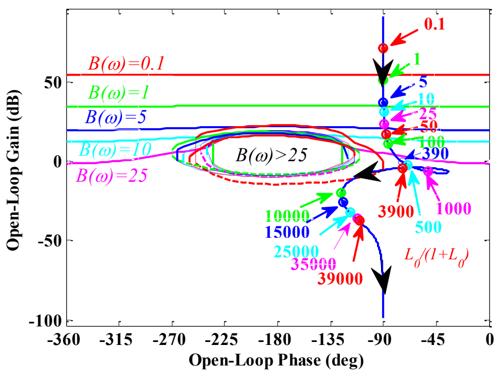


Figure 2. Loop shaping for Uncertain DC-DC Buck converter system.

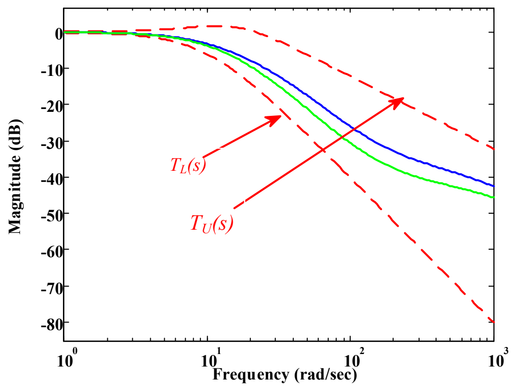
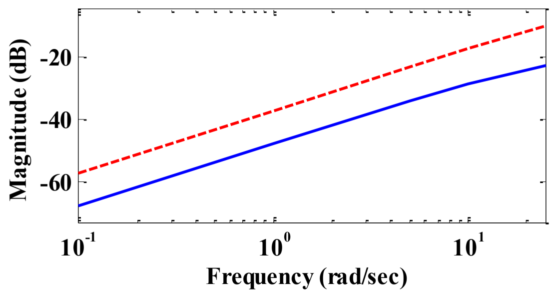


Figure 3. Pre-filter Shaping for Uncertain DC-DC Buck converter system.

The job of the pre-filter is to achieve desired transient response with in the specified tracking bounds irrespective of the source and load changes. By using IDE (Interactive Design Environment) adjust the poles and zeros in order to achieve desired response with in the tracking limits. The designed pre-filter (Refer figure 3) is as follows.

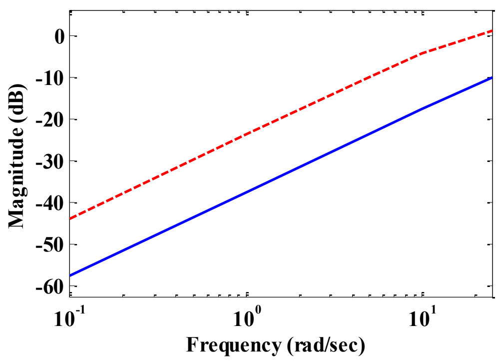
$$F(s) = \frac{25}{s+25} \tag{13}$$

The frequency domain validation of the system with the designed controller (equ.12) and pre-filter (equ.13) is shown in figure 4 for the disturbance rejection and tracking specifications.



(a)

Figure 4a: Frequency domain validation (Worst cases) for load current disturbance problem



(b)

Figure 4b: Frequency domain validation (Worst cases) for source voltage disturbance problem

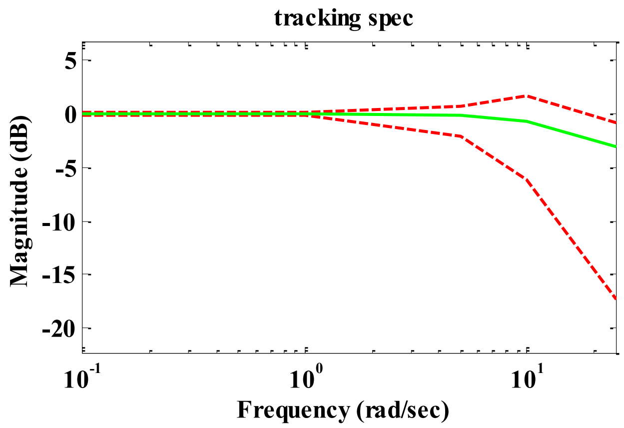


Figure 4c: Frequency domain validation (Worst cases) for tracking problem.

IV. SIMULATION RESULTS AND DISCUSSION

To validate the performance of obtained controller, extensive simulations are carried out using the MATLAB/SIMULINK.

(a) Variation (step) in the input voltage from 24 to 28V.

(b) Variation (step) in the load resistance from 12Ω to 60Ω

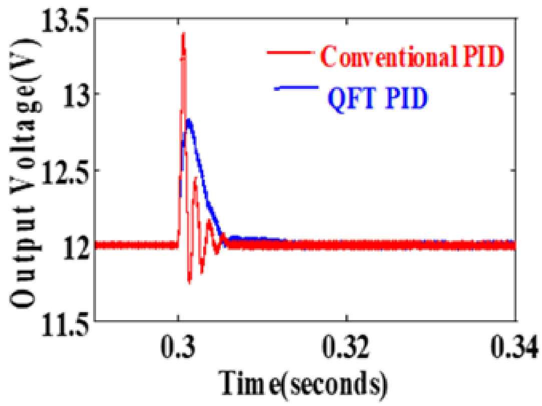
(c) Simultaneous variation in the input voltage (24 to 28V) and in load resistance (12Ω to 60Ω).

For comparison purpose, the conventional PID controller tuned using Ziegler-Nichols method is given as follows

$$K_p = 0.027363, K_i = 69.2812, K_d = 2.6662 \times 10^{-6}, \\ T_f = 1.8431 \times 10^{-6}.$$

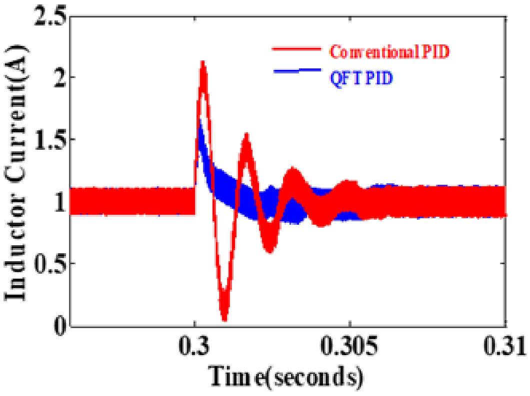
Scenario (a):

To access the regulator performance of the buck converter the source voltage changed from 24V to 28V at time period t=0.3sec. The proposed QFT controller is able to minimize the output voltage deviation quickly as shown in Fig. 5(a) and returns to the steady state within 0.01sec (i.e., 0.31sec). The corresponding inductor current comparison plot is shown in Fig. 5(b).



(a)

Figure. 5: Step change in input voltage from 24V to 28 V (a) Output Voltage (Vo) response

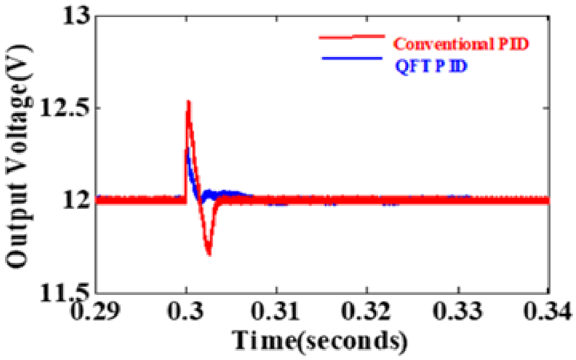


(b)

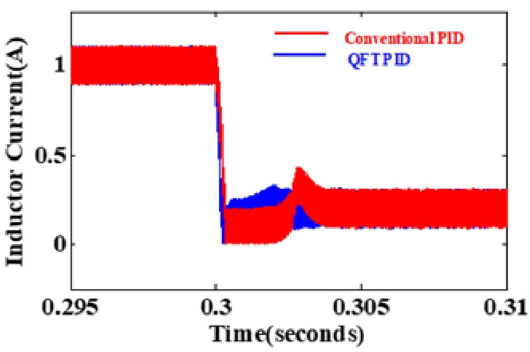
Figure. 5: Step change in input voltage from 24V to 28 V (b) Inductor Current (A) response

Scenario (b):

To observe the performance of the controller, the load resistance is changed from 12Ω to 60Ω at time period t = 0.3sec. The proposed design is able to reduce the deviation of output voltage as shown in Fig. 6(a) and returns to the steady state within 0.007sec (i.e., 0.307sec) with the corresponding inductor current comparison in Fig. 6(b).



(a)



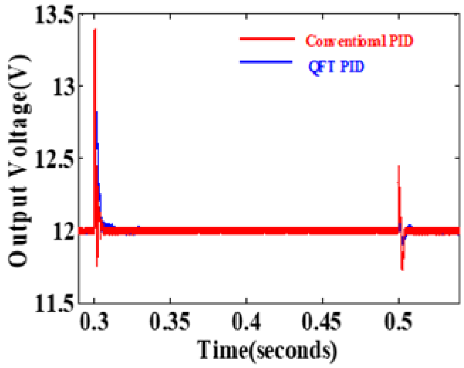
(b)

Figure. 6 Step change in load resistance from 12Ω to 60Ω

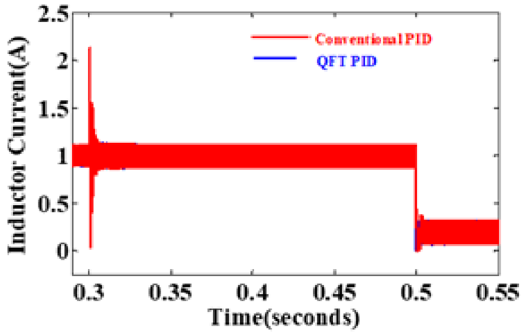
(a) Output Voltage (Vo) , (b) Inductor Current (A).

Scenario (c):

Further to illustrate the performance of the controller under simultaneous disturbance, the input voltage changes from 24 to 28V at time period t=0.3sec and load resistance changes from 12Ω to 60Ω at time period t=0.5sec.The proposed design is able to reduce the deviation of output voltage as shown in fig. 7(a) and reaches the steady state quickly with less inductor current as in fig. 7(b).



(a)



(b)

Figure.7: Simultaneous variation scenario

(a) Output Voltage (V) (b) Inductor Current (A)

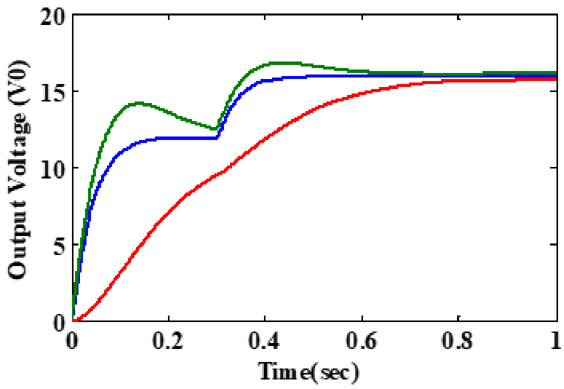


Figure. 8: Robust tracking performance

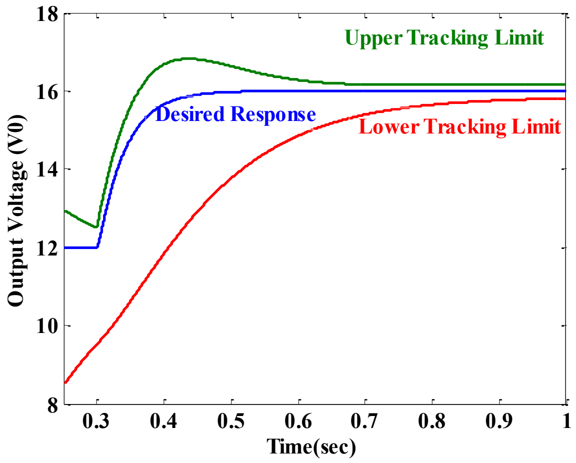


Figure. 9: Robust tracking performance while changing V_{REF} from 12V to 16V.

To observe the performance of the pre-filter, the reference voltage is changed from 12V to 16V at time period t = 0.3sec($3*10^5 \mu sec$). The proposed QFT design is able to keep the desired response with in the specified tracking limits as shown in Fig. 8 and reaches the new steady state within 0.1sec (i.e., 0.4sec) shown in zoomed Fig.9.

V. CONCLUSION

In this work, QFT PID controller is designed for regulatory problem of DC-DC Buck type converter with the external disturbance models. The loop-shaped design enhanced the performance of rejecting the disturbances (input and load).By the design of pre-filter it enhances the robust tracking performance. Future scope will be on experimental implementation of QFT-PID scheme for the DC-DC buck converter.

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