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Fractional Order PI Controller Design for Non-Monotonic Phase Systems

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Abstract: In this paper, a fractional order proportional-integral (FOPI) controller is proposed for controlling the non-monotonic decreasing phase DC-buck regulator system. The parameters of FOPI controller are optimized by Nelder's-Mead (NM) method. The FOPI controller provides fast closed-loop performance as well as improves the robust properties of the system in time and frequency domain. The controller preserves the monotonic phase between the desired bandwidth and improves the characteristic performance of the system. The proposed method is validated by comparing the time domain as well as frequency domain characteristics with the integer order proportional-integral (IOPI) controllers tuned using various techniques.

Keyword: Fractional Order PI controller, non-monotonic phase system, DC-buck regulator, Nelder's-Mead optimizer.

1. INTRODUCTION

Feedback control system maintains a prescribed relationship between the reference input and the desired output. The difference between the input-output relationships of the system is noted as error of the system and minimized using controller. In frequency response compensation of a continuous (or discrete) linear time invariant (LTI) system is done by applying a negative feedback control system. In classical control design the phase margin of a closed-loop system having monotonically decreasing phase inside the bandwidth is the distance between the open-loop phase at the gain crossover frequency and the stability limit of -180°. However, the system having a left half-plane zero located near the dominant-poles (i.e minimum-phase system) shows non-monotonic phase behaviour inside the bandwidth (Caio F.de Paula et al. 2012). For a closed loop system to be stable the phase margin must be positive. In addition, the phase margin of a closed-loop system estimate the robustness and informs how much the open-loop system phase may vary while the closed-loop system remains stable (S. Skogestad and I. Postlethwaite 2005).

DC-buck regulator taken in this paper also shows the non-monotonic phase behaviour inside the bandwidth. Hence a controller is needed for non-monotonic system to get the wider bandwidth, faster time response and more sensitive to noise and parameter variations.

Since few decades, the fractional order controllers are being the part of the control application due to having extra degree of freedom. The integral and the derivative term of the fractional order controller are in fractions ($PI^{\lambda}D^{\mu}$) (I. Pan and S. Das 2012; Shantanu Das 2008; G. Q. Zeng et al. 2015; H. Shayeghi et al. 2015; I. Podlubny 1999a, b). These fractional terms increases the complexity of the controller but more powerful than the conventional integer order controllers and supple design methods to satisfy the controlled system specifications. In I. Podlubny (1999) two additional tuning knobs given which are able to make balance between settling time and maximum overshoot of the system.

In the last few years, fractional order control strategies have been successfully applied to many systems like controlling of smart wheel via internet with variable delay (Inés Tejado et al. 2015), Automatic voltage regulator system (H. Remezanian et al. 2013) and many other (D.Y. Xue et al. 2006; S. Das 2012; G. Q. Zeng et al. 2015; Guo-Qiang Zeng et al. 2015). The FOPI controller is designed for DC-buck regulator system in this work. The optimization of the FOPI parameters can be done by any optimization algorithm like Genetic Algorithm, Particle Swarm Optimization etc. In this paper Nelder-Mead algorithm has been used for this purpose (Nelder, John A. and R. Mead (1965). Before applying in the closed-loop system the fractional order terms of the FOPI controller are approximated into integer order using Oustaloup's approximation algorithm within a frequency range of $\omega \in (10^{+3} - 10^{+8})$ rad/sec (A. Oustaloup, 1991; A. Oustaloup, 1981).

The detailed organization of this paper is as follows: in Section 2 the circuit diagram of DC-buck regulator and its non- monotonically decreasing phase behaviour is addressed. Section 3 explains detailed study of FOPID controller design. Section 4 shows the results and comparative study of FOPI and other conventional IOPI techniques. Finally, the conclusion followed by the references.

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2. DC-BUCK REGULATOR SYSTEM

The DC-buck regulator is the most commonly used dc-dc converter topology and have a very large application area like in power management and microprocessor voltage regulator applications (Caio F.de Paula, and Luís H. C. Ferreira, 2012). This is very popular because of its smaller size and efficiency compared to the linear regulators. In this paper the design of controller is made on the simplest dc-dc converter circuit i.e. the DC-buck regulator circuit.

The DC-buck regulator system is a combination of the power stage (i.e a LC low-pass filter) and a pulse-width modulation (PWM)-based controller (International Rectifier, 2002). The circuit diagram of DC-buck converter with voltage controller is given in Fig. 1.

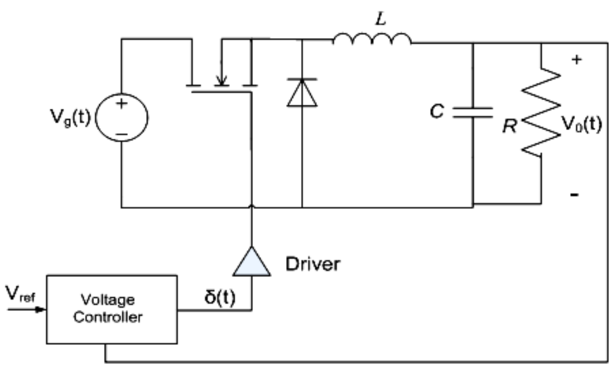

Fig. 1. The DC-Buck Converter with a voltage controller

The transfer function of DC-buck regulator system can be written as ratio of the output (regulated voltage) to the input (PWM modulator input voltage) as:

$$G = \frac{V_{in}(1+sR_C C)}{V_{OSC}LCs^2+s\left(R_C C+\frac{L}{R}\right)+1} \tag{1}$$

where C is output capacitance, L is output Inductance, R is load resistance, R_C is the output capacitor intrinsic resistance, V_{in} the power stage input voltage and V_{OSC} is the PWM oscillator reference voltage.

For a typical application of DC-buck regulator taken in International Rectifier, (2002) with $R_C = 40\,m\Omega$, the transfer function is given as:

$$G = \frac{4(1+1.2\times10^{-5}}{3\times10^{-9}s^2+3.6\times10^{-5}s+1} \tag{2}$$

The Bode plot of the DC-buck regulator is shown in Fig. 2, where the non-monotonic phase behaviour close to the undammed frequency can be seen in the phase plot. The closed-loop step response without any controller is also shown in Fig. 3, which shows that the system is under-damped. Hence a controller is needed to compensate the non-monotonic phase actions of the system.

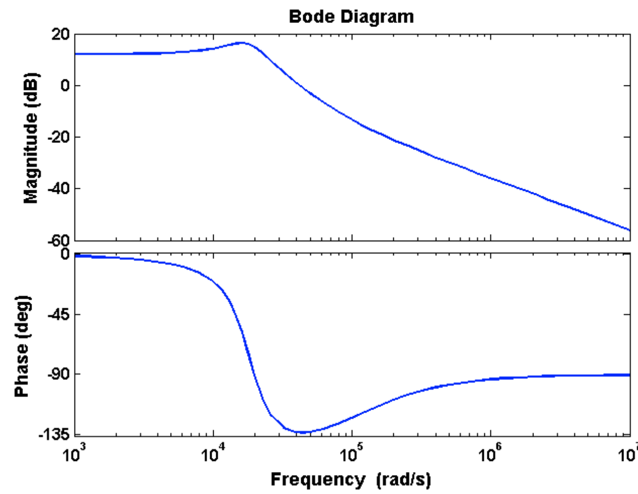

Fig. 2. Bode plot of DC-buck regulator system

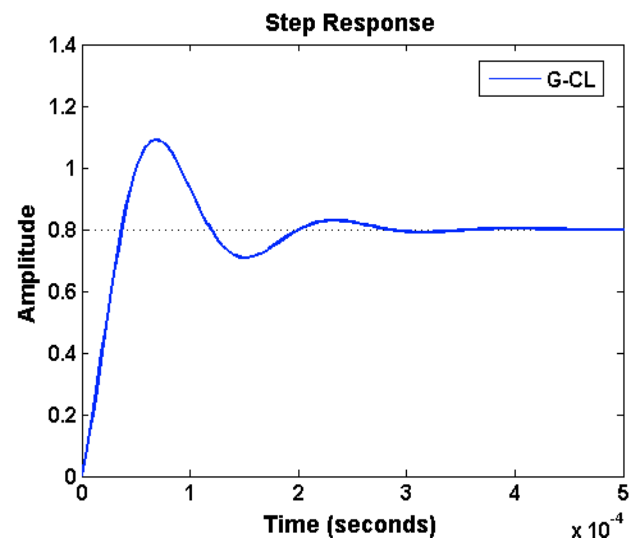

Fig.3. Step response of closed-loop DC-buck regulator

3. FRACTIONAL ORDER PID CONTROLLER

FOPID is presented in generalized form of IOPID controller and represented as $PI^{\lambda}D^{\mu}$ (I. Podlubny, 1999). The FOPID controller is very powerful and provides flexible control design approach. The transfer function for the FOPID controller is given as:

$$C_{FOPID}(s) = K_P + \frac{K_I}{s^{\lambda}} + Ds^{\mu} \tag{3}$$

where for λ and μ are the fractional power of integral and differential control respectively.

For FOPI controller the transfer function will be:

$$C_{FOPI}(s) = K_P + \frac{K_I}{s^{\lambda}} \tag{4}$$

Theses FOPI controller variables ($K_P, K_I,$ and λ) are optimized by using Nelder-Mead algorithm (Nelder, John A. and R. Mead, 1965).