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Taylor series expansion based repetitive controllers for power converters, subject to fractional delays

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ABSTRACT

Digital repetitive controllers are widely employed to track/reject the periodic signals with zero steady-state error. Their implementation involves the use of single or multiple digital delay elements. Practically, the delay element is implemented by the use of memory locations, where samples are held and released after a specific number of sampling periods, equivalent to the desired time delay. A problem arises when the desired time delay becomes a non-integer multiple of the sampling time. Such time delays can be accurately realized by employing a fractional delay filter

This paper presents a Taylor Series expansion based digital repetitive controller designed to implement any (integer, non-integer) delay in the control of power converters, occurring due to uncontrollable variations in the reference frequency. The T3644aylor Series expansion transforms the fractional delay filter design problem to a differentiator/sub-filter design. Finite impulse response (FIR) and infinite impulse response (IIR) fractional delay (FD) filter concepts can be applied to realize the required fractional delay. This structure provides efficient on-line tuning capabilities *i.e.* FD can easily generate any required fractional delay without redesigning the filter when the delay parameter varies. An example is demonstrated to show the effectiveness of this approach, for a single-phase power inverter feeding a passive load.

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1. Introduction

Internal model principle (IMP) based Repetitive Controllers (RC) achieve zero steady-state error tracking of any periodic signal by employing a signal generator inside the stable closed-loop system (Chen, Zhang, & Qian, 2013; Wang, Wang, Zhang, & Zhou, 2007; Zou, Zhou, Wang, & Cheng, 2014). Repetitive controllers are widely used in applications including disk drive systems, power converters and robotics motion. In these applications, periodic disturbances act upon the control system or the desired output signal is periodic. These controllers can only track or regulate signals with a known fixed frequency (Costa-Castelló, Olm, & Ramos, 2011). For those cases where the time period of the periodic reference/disturbance signal is uncertain, a robust repetitive controller structure is needed.

In many cases, the periodic reference or the disturbance varies dynamically due to the load variation or position/time dependency. Quite a number of adaptive repetitive controllers have been developed for time-varying periodic signals (Costa-Castelló et al., 2011; Steinbuch, 2002; Zou et al., 2014). These adaptive repetitive controllers either use adjustable sampling time (Cao & Ledwich, 2002) or a fractional delay (FD) filter to realize the required delay (Zou et al., 2014). Adjustable sampling time techniques adjust the sampling frequency (f_s) to obtain an integer ratio between (f_s) and the frequency of the reference signal (f).

Cao and Ledwich (2002) have proposed a method based on multi-rate control to deal with the time-varying period and non-integer samples/period caused by a fixed sampling rate (Cao & Ledwich, 2002). In this technique, only the repetitive controller experiences a variable sampling rate which is an integer multiple of the reference signal period. Interpolators are utilized to interface the repetitive controller to the rest of the system, which uses a fixed sampling rate. However, the structural changes in the control system due to the redesign of RC may result in the destabilization of the system.

Rashed, Klumpner, and Asher (2013) have proposed a similar method for three-phase grid inverters which uses the estimated grid frequency to adaptively update the RC period and resonant controller's resonant frequencies, while interpolation is used to preserve the RC rejection capability under non-integer samples per period (Rashed et al., 2013). Wang et al. (2007) proposed a fractional delay based repetitive control scheme for single-phase PWM inverters, where a fractional delay low-pass filter is introduced to approximate the internal model of the fractional-period signals. Two different

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methods are introduced to design the fractional delay (FD) low-pass filters: the Lagrange interpolation method and least square method. Chen et al. have also proposed an improved RC control scheme with a finite impulse response (FIR) filter (Chen et al., 2013). A simple zero-crossing method has been used to detect the reference period to adapt to the variable grid frequency. This method performs well in low noise environments only. Yang et al. (2014) and Zou et al. (2014) have also used finite impulse response FD filters to realize the fractional part of the required non-integer delay. Another approach is to use a higher order repetitive controller to enhance the system robustness to reference frequency variations (Steinbuch, 2002). But almost all of these techniques require the redesign of the FD filter coefficients with fractional delay variations. Among all these techniques Lagrange interpolation based FD repetitive control scheme commonly known as Fractional Order Repetitive Control (FORC) has been more frequently used in control of power converters (Nazir, Zhou, Watson, & Wood, 2015; Yang et al., 2014; Zou et al., 2014).

In this paper, a Taylor Series expansion based RC scheme is implemented. It provides a systematic approach for non-integer delay cases under a fixed sampling rate. This method designs an FD filter based on well known Taylor Series expansion, which realizes any required delay without redesigning the FD filter coefficients. Taylor Series expansion based FD filters have been widely used in signal processing and circuit theory (Abbas & Gustafsson, 2009; Abbas, Gustafsson, & Johansson, 2013; Blok, 2012; Laakso, Valimaki, Karjalinen, & Laine, 1996). Only few references have been cited here. The main contribution of this research paper is application of Taylor Series expansion based FD filter along with RC for control of power converters.

This paper is organized as follows. An overview of repetitive controllers is given in Section 2. Section 3 provides an insight to the Taylor Series expansion based RC control scheme. Section 4 presents the experimental investigation of the proposed control, and finally the conclusion is given in Section 5.

2. Overview of repetitive control

Repetitive controllers can be decomposed into three main parts; the internal model $\left(z^{-N_o}/(1-z^{-N_o})\right)$, low-pass filter $\left(Q(z)\right)$ and the compensator $\left(G_s(z)\right)$. The internal model is primary incharge of ensuring zero steady-state error, the low-pass filter enhances the system robustness while the compensator guarantees the stability of the closed-loop system (Costa-Castelló et al., 2011). Usually repetitive controllers are implemented in a plug-in fashion, as shown in Fig. 1. The conventional controller $\left(G_c(z)\right)$ stabilizes the plant $\left(G_p(z)\right)$ and provides disturbance attenuation across a broad frequency spectrum.

When the reference/disturbance period (T) and the sampling period (T_s) are both constant, the order of the repetitive controller $(N_o = T/T_s)$ is also constant. Sufficient stability criteria are given in Chen et al. (2013), Costa-Castelló et al. (2011), Yang et al. (2014), Zou et al. (2014):

- The closed-loop system without the repetitive controller $G_o(z)$ should be stable. *i.e.*

$$G_o(z) = \frac{G_c(z)G_p(z)}{1 + G_c(z)G_p(z)} \tag{1}$$

The roots of $1 + G_c(z)G_p(z)$ should be inside the unit circle.

- $\left\| z^{-N}Q(z)\left[1 - G_o(z)G_s(z)\right] \right\| \le 1$

3. Taylor series expansion based design methodology

Taylor Series expansion uses various sub-filters to approximate the required fractional delay. Assuming that $z^{-N_o} = z^{-(N_i+p)}$ where $N_i = int[N_o]$ is the integer part of N_o and $p = N_o - N_i$, $0 < p < 1$ is the fractional part. The fractional delay $z^{-p} = e^{-jwp}$ can be expressed as a polynomial in p using the Taylor Series expansion as follows (Eghbali, Johansson, Saramäki, & Method, 2013; Möller, Machiraju, Mueller, & Yagel, 1997; Vesma, Hamila, Saramäki, & Renfors, 1998):

$$e^{-jwp} = \sum_{k=0}^{\infty} \frac{(-p)^k}{k!}(jw)^k \tag{2}$$

Since the fractional part is small *i.e.* $p < 1$, the term p^{M+1} and other higher order multiples of p approaches zero when M is large.

$$e^{-jwp} \approx \sum_{k=0}^{M} \frac{(-jw)^k}{k!} p^k \tag{3}$$

where M is the order of the polynomial.

$$e^{-jwp} \approx \sum_{k=0}^{M} F_k(z)p^k \tag{4}$$

where $F_k(z) = (-jw)^k/k!$ is the scaled frequency response of *kth* order differentiator (Pei & Tseng, 2003).

The FD filter response approaches its ideal behavior as the value of M approaches infinity. According to (4) the FD filter can be implemented by $M+1$ different sub-filters $F_k(z)$ where $k = 0, 1\ldots M$ as shown in Fig. 2. This structure has been referred as a Farrow structure in Diaz-carmona and Dolecek (1996), Eghbali et al. (2013), Rajalakshmi, Gondi, and Kandaswamy (2012).

Many techniques are available in the literature to design these sub-filters (Babic, Vesma, Saramaki, & Renfors, 2002; Candan, 2007; Diaz-carmona & Dolecek, 1996; Eghbali et al., 2013; Rajalakshmi et al., 2012; Roy, 1995): IIR and FIR sub-filters can be employed (Roy, 1995; Tseng, 2002; Laakso et al., 1996). Once the $M+1$ sub-filters $(F_k(z))$ are designed and inserted into the structure of Fig. 2, only the parameter p needs to be adjusted to achieve any fractional delay. The sub-filters parameters remain unchanged even in the case of fractional delay variations.

Simplest of all, Lagrange interpolation can be used to design $F_k(z)$ in the time-domain. This method is utilized here to design $M+1$ sub-filters.

All the $M+1$ sub-filters can be expressed as N^{th} order polynomials with constant coefficients and $N \ge M$ (Farrow & Continuously, 1988). Usually $N = M$ is used. The Lagrange interpolation based sub-filters' coefficients can be calculated as follow:

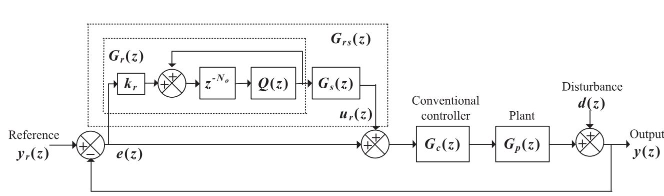

Fig. 1. General plug-in repetitive control system.

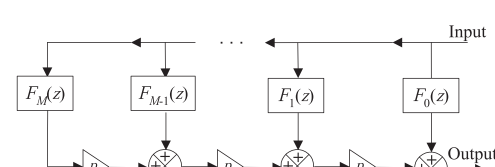

Fig. 2. Taylor Series expansion based FD filter.

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