

# A Deadbeat Controller Design for Single-Phase Active Power Filters Based on Forward-Backward Discretization

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**Abstract**—Nowadays, due to availability of powerful signal processors, the digital control approaches, such as deadbeat control, have received considerable attentions. The deadbeat controller offers critical advantages, such as constant switching frequency, fast dynamic response, and low settling time. Nevertheless, the parameter dependency of the deadbeat controller has always been questioned. In this regard, this paper proposes a forward-backward discretization method for a single-phase active power filter to be used for deadbeat controller design. This procedure offers high accuracy in modeling and at the same time simplicity in designing the deadbeat controller. The proposed discretization approach reduces the required two forward steps prediction down to only a step. The superiority of the developed controller is then confirmed through extensive simulations.

**Keywords**— Deadbeat controller, forward-backward discretization, shunt active power filter.

## I. INTRODUCTION

Significant growth in non-linear loads in power systems has brought several challenges, such as an increase in current harmonics. Undesirable harmonics in the power grid eventually result in distortions in the voltage waveform, rise of power losses, and interferences with communication systems [1]. A highly accepted approach for mitigating such harmonics is employing shunt active power filters (SAPF) in distribution systems. SAPFs must present a desirable performance in terms of dynamics and tracking of high-frequency components of reference waveforms. This is also crucial for the filter to coincide itself with any changes in load in such a way that the current through filter follows the reference signal without error in transient and steady-state situations. In order to reach these goals, the reference current generator and the current controller must have a fast dynamic response as possible. Accordingly, conventional control methods, i.e., proportional-integral (PI) used in inverters, are not the best choice anymore [2]–[5]. In recent years, using fast current controllers with direct digital implementation capability has always been a challenge [4].

There have been several methods in the literature to control the voltage-fed grid-connected power converters, among which current hysteresis [4], sliding mode [5], and deadbeat controllers (DBC) are the most prominent ones. The current hysteresis control method is simple and offers a very fast dynamic response, however it has a variable switching frequency [6]. Although the sliding mode controller is robust to uncertainty in modeling, it requires a high switching frequency to eliminate the system's uncertainties and disturbances effectively [5]. The predictive control also

dominates vast realms of knowledge, all of which predict the required quantities' state in one or two sampling steps ahead in order to choose the reference signal in such a way that the objective function error becomes zero in the next samples [7]. The deadbeat predictive method is one of the well-accepted approaches to control power converters due to its fast response, zero steady-state error, its digital nature, easy and direct implementation on digital processors, simple algorithm, constant switching frequency, and fast dynamic response [8]–[11]. However the performance of this technique highly depends on the accuracy of the system model.

In this paper, a DBC is proposed, which compared to the conventional deadbeat method, aims to minimize the dependency of the controller performance on the modeling accuracy and at the same time provide better control results. This control method reduces the need for a two-step forward current prediction, as reported in [9], [11], down to only a single forward step.

The rest of this paper is organized as follows. Section II illustrates the general modeling of a single-phase SAPF. Section III presents the discretization based on the forward-backward method. Section IV discusses the DBC design. Section V evaluates the simulation results and, section VI concludes the paper.

## II. MODELLING OF SAPF

The general topology of a single-phase SAPF is displayed in Fig. 1. In Fig. 2, a sample of load, source, and SAPF currents is shown. As can be seen, the load current is heavily affected by harmonics. To tackle such harmful effects, the SAPF injects a particular current equals to the load current affected by harmonics but with an inverse phase. Hence, the active power filter converts the disturbed load current into a fully sinusoidal current. Taking the mentioned concepts into account, the following equation can be written

$$i_s(t) = i_L(t) - i(t) \quad (1)$$

where  $i$  is the inverter current,  $i_L$  is the load current and  $i_s$  is the source current.

Equation (2) explains the dynamic model of the system already shown in (1).

$$L_s \frac{di}{dt} + R_s i = v_{out}(t) - v_s(t). \quad (2)$$

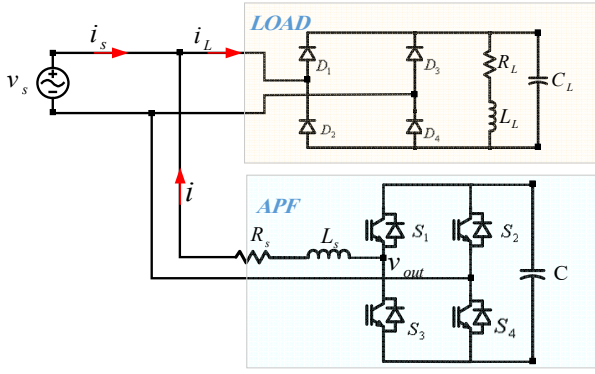


Fig. 1. SAPF.

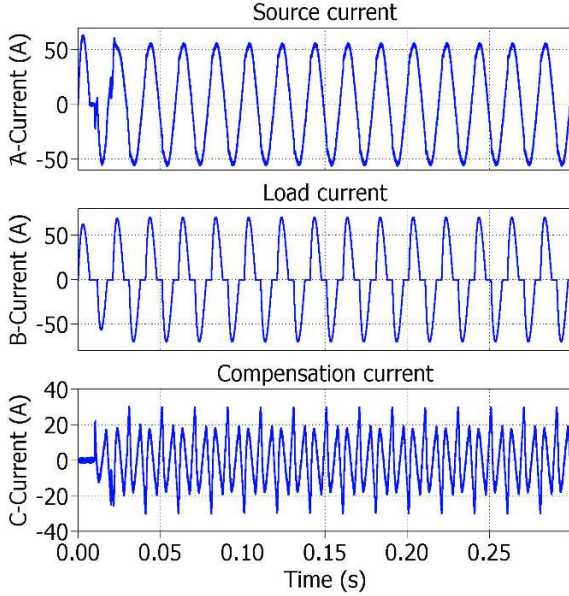


Fig. 2. Current waveforms of SAPF, which are detected by the MATLAB/Simulink based on simulation parameters listed in Table I.

In (2),  $L_s$ ,  $R_s$ ,  $v_s$ , and  $v_{out}$ , represent the filter inductance, filter resistance, source voltage, and the output voltage of the inverter, respectively. Because the value of  $R_s$  is relatively low, it can be neglected safely. So, equation (2) reduces to

$$L_s \frac{di}{dt} = v_{out}(t) - v_s(t). \quad (3)$$

### III. DISCRETIZATION OF SYSTEM BASED ON FORWARD-BACKWARD METHOD

A DBC is sensitive to uncertainties and parameter mismatches in the model. One of the main sources for these errors is the discretization. There are many discretization methods for control applications reported in literature, such as direct difference methods, indirect difference methods, bilinear transforms, binary prefixes conversions with frequency prefix, impulse response immutabilities, step response immutabilities, and matched pole-zero mapping techniques [12].

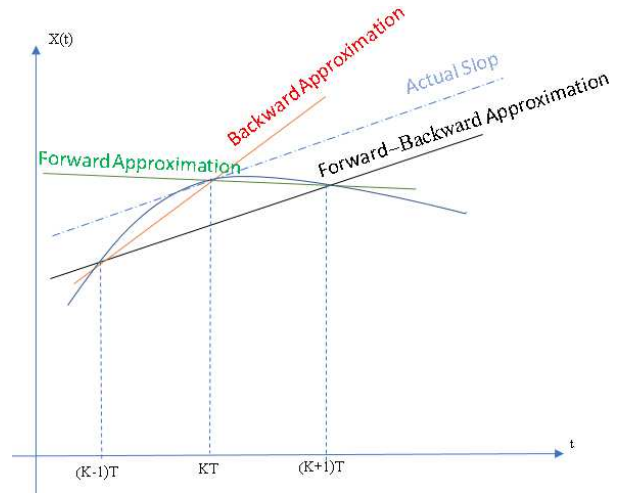


Fig. 3. Derivative approximation in four discretization approaches.

In order to develop a DBC for current control, there are three discretization approaches reported in recent papers [9]–[11]. In the following, a new method for discretization will be discussed based on the mean value theorem [13]. This method not only is accurate, but also reduces a predictive step in the implementation of the DBC. By considering the scalar system (4), one can approximate the slope of smooth scalar function  $x(t)$  at the moment  $k$ , with the slope of the linear segment of two points at  $(k+1)$  and  $(k-1)$  by equation (5). This is called Forward-Backward approximation.

$$\frac{dx}{dt} = f(x) \quad (4)$$

$$\frac{X(k+1) - X(k-1)}{2T} \approx f(k) \quad (5)$$

Figure 3 demonstrates the mentioned connector line and the tangent line to the curve. This figure implies how the forward-backward approximation offers better approximation among three competitive approximation methods. The achieved results can be redefined by using the Taylor expansion at the moments of  $(k+1)$  and  $(k-1)$  as given in (6) and (7), respectively. The difference of equations (6) and (7) results in (8), which can be replaced in (5) and the high-order terms can be also ignored.

$$X(k+1) = X(k) + T \frac{dX(k)}{dt} + \frac{1}{2!} T^2 \frac{d^2X(k)}{dt^2} + \frac{1}{3!} T^3 \frac{d^3X(k)}{dt^3} + \dots \quad (6)$$

$$X(k-1) = X(k) - T \frac{dX(k)}{dt} + \frac{1}{2!} T^2 \frac{d^2X(k)}{dt^2} - \frac{1}{3!} T^3 \frac{d^3X(k)}{dt^3} + \dots \quad (7)$$

$$2T \frac{dX(k)}{dt} = X(k+1) - X(k-1) + \frac{2}{3!} T^3 \frac{d^3X(k)}{dt^3} + \dots \quad (8)$$

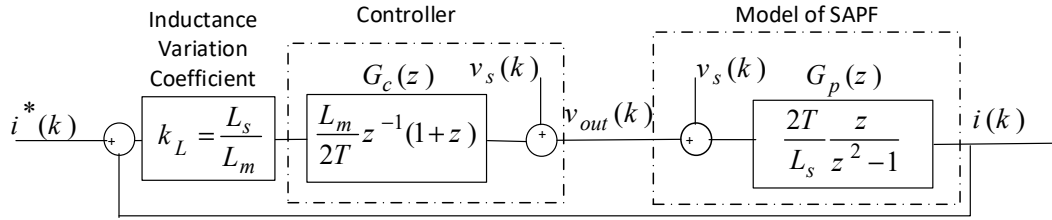


Fig. 4. Discrete model of SAPF using forward-backward method and loop control.

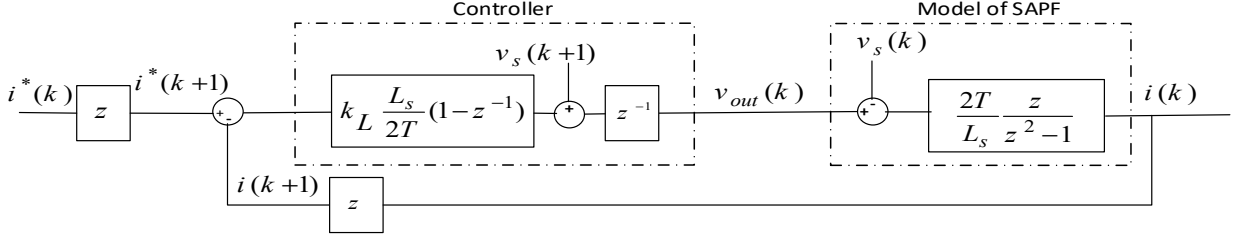


Fig. 5. DBC using forward-backward discrete model.

The system in (3) can be discretized by using (5), which results in (9) and the final transfer function given in (10).

$$i(k+1) = i(k-1) + \frac{2T}{L_s} (v_{out}(k) - v_s(k)) \quad (9)$$

$$G_p(z) = \frac{i(z)}{\Delta u(z)} = \frac{2T}{L_s} \frac{z}{z^2 - 1} \quad (10)$$

In above equations,  $T$  denotes the sampling period and  $\Delta u(z) = v_{out}(z) - v_s(z)$ . Figure 4 displays the system model along with the controller.

#### IV. DBC DESIGN

Given the system transfer function of (10), the DBC transfer function can be achieved according to the procedure developed in [12]. Accordingly, to achieve

$$\frac{i(z)}{i^*(z)} = \frac{G_c(z)G_p(z)}{1+G_c(z)G_p(z)} = \frac{1}{z}$$

is  $G_c(z)G_p(z) = \frac{1}{z-1}$  and the DBC transfer function obtains as

$$G_c(z) = \frac{L_s}{2T} (z+1)(z^{-1}). \quad (11)$$

Accordingly, the system block diagram of Fig. 4 can be modified and redrawn as shown in Fig. 5, which shows the implementation of the proposed control, in which the digital system delay is denoted by  $z^{-1}$ . Evidently, the proposed controller must predict the signals  $i(k+1)$ ,  $v_s(k+1)$ , and  $i^*(k+1)$ . It is worth mentioning that the control method presented in [11] requires two step prediction, i.e.  $i^*(k+2)$ . The value of  $i(k+1)$  can be predicted by the state observer given in (12). Also,  $v_s(k+1)$  is readily determined from (13), and  $i^*(k+1)$  is calculated by the proposed method in [11], in which  $v_s(t) = A_s \sin(\omega t) = A_s \text{Im}\{e^{j\omega t}\}$ .

TABLE I  
SIMULATION PARAMETERS

Type	Parameter	Value
Network Parameters	$v_s$	220 Volt
	$\omega$	$2\pi f$
	Grid frequency ( $f$ )	50 Hz
Filter Parameters	$L_c$	2 mH
	$V_{dc}$	400 Volt
	$T$	$5e^{-5}$
Load Parameters	$C_L$	1000 $\mu$ F
	$L_L$	50 mH
	$R_L$	5 $\Omega$

TABLE II  
HARMONIC CONTENTS OF NON-LINEAR LOAD AND SOURCE CURRENTS

Harmonic order	% in RLC load	DBC with trapezoidal discretization		DBC with forward-backward discretization	
		$k_L = 1$	$k_L = 1.05$	$k_L = 1$	$k_L = 1.05$
THD	44.7	4.3	8.37	3.24	3.06
1	55.05	54.9023	54.92	54.9409	54.90
3	18.2567	1.0212	0.92	0.1719	0.194
5	5.5730	0.4576	0.554	0.9193	0.842
7	1.6927	0.1604	0.254	0.2966	0.321
9	1.9700	0.1168	0.187	0.4117	0.375
11	1.2407	0.1353	0.138	0.303	0.326

$$\hat{i}(k+1) = \frac{2T}{L_s} \Delta u(k) + \hat{i}(k-1) + L(i(k-1) - \hat{i}(k-1)) \quad (12)$$

$$\begin{aligned} \hat{v}_s(k+1) &= A_s \text{Im}\{e^{j2\omega T} e^{j\omega(k-1)T}\} \\ &= v_s(k-1) \cos(2\omega T) + A_s \sqrt{1 - \left(\frac{v_s(k-1)}{A_s}\right)^2} \sin(2\omega T) \end{aligned} \quad (13)$$

where  $\omega$  represents the grid angular frequency.

#### V. SIMULATION RESULTS

Simulation parameters, which are done in MATLAB/Simulink are listed in Table I. In the following, the proposed method is compared to the Tustin discretization method, which is known as the superior among other conventional approaches [10]–[15] to design controllers for power electronic applications. Tustin discretization method

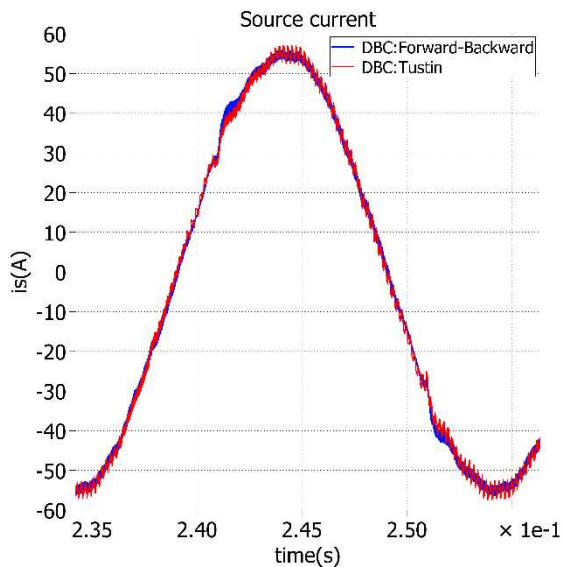


Fig. 6. Input current waveform under steady-state operation,  $k_L = 1$ .

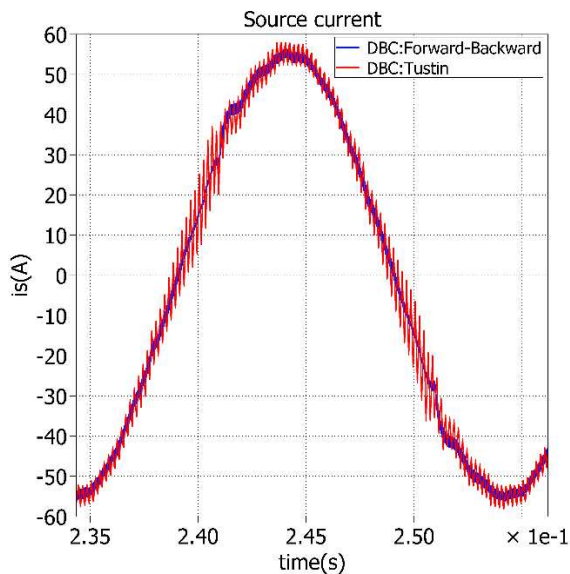


Fig. 7. Input current waveform under steady-state operation,  $k_L = 1.05$ .

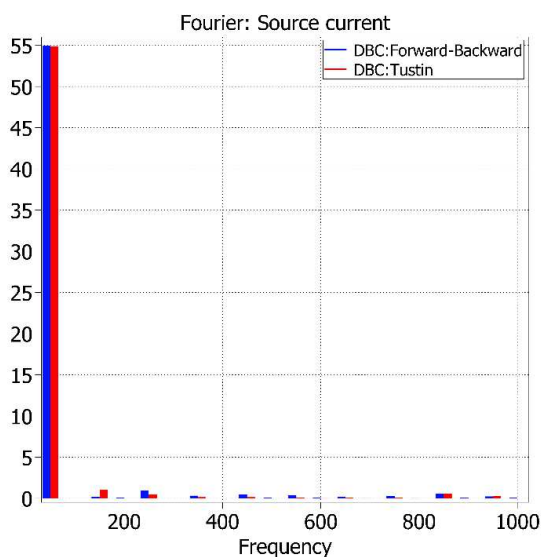


Fig. 8. Harmonics spectrum of source current,  $k_L = 1$ .

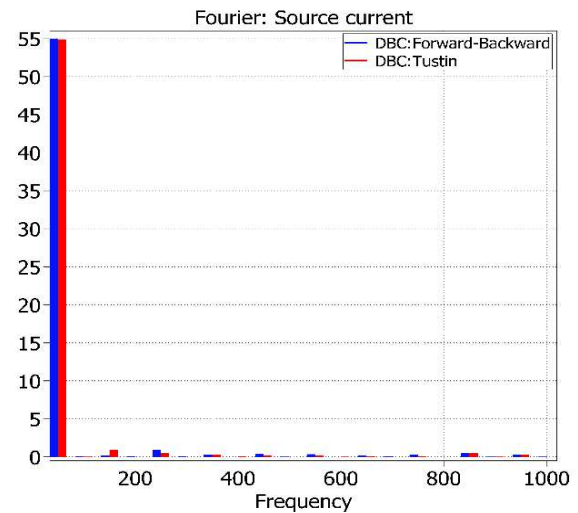


Fig. 9. Harmonics spectrum of source current,  $k_L = 1.05$  (5% mismatch).

gives system transfer function and DBC as  $G_p(z) = \frac{T}{2L_s} \frac{z+1}{z-1}$ , and  $G_c(z) = \frac{2L_s}{T} \frac{z}{z+1}$ , respectively.

Figures. 6, and 7 show the compensated source current waveform for  $k_L$  equal to 1 and 1.05 respectively. For both methods, the same PI controller is responsible for stabilizing the DC link voltage. The harmonic spectrums of the source currents are compared in Fig. 8, and 9 at the mention condition. These figures indicate the proper performance of the designed DBC with the proposed discretization method. Furthermore, Table II demonstrates the value of total harmonic distortion (THD) of the source current for both systems. The THD for the proposed technique is 3.24% compared to 4.3% with the conventional one while  $k_L = 1$ , and the load THD is 44.7%. With  $k_L = 1.05$  the THD of the Tustin based discretization DBC is increase to 8.37% while it remains at acceptable level of 3.06%, for the proposed discretization based DBC. It is worth mentioning that  $k_L$  represents the degree of mismatch in the filter inductance value.

## VI. CONCLUSION

In this paper, a novel discretization method on the basis of derivative approximation with a forward-backward approach has been proposed, which is highly advantageous for DBC design. In this discretization method, in addition to the mentioned advantage, the proposed approach decreases the needed two forward steps prediction down to only a forward step. The simulation results of the developed DBC based on the proposed discretization technique show that the THD of the compensated current is relatively reduced when compared to the conventional Tustin discretization.

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