An Optimal Sample-Data holds by using a Bi-Objective criterion: Trade-off between the Phase Delay and the Stability Robustness

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Abstract: In this paper an optimal data-holding scheme is introduced which compensates the undesirable effects of ZOH. This effect will be improved by using a simple optimal filter, therefore the optimal data-holding scheme is consist of a standard ZOH and a filter. For designing this optimal filter two type cost functions or performance measures are defined in which phase delay or robust stability are considered. In this paper, firstly an optimal filter for minimizing these two cost functions will be introduced which its coefficients is optimized by using the imperialist Competitive Algorithm (ICA) method. Secondly a bi-objective cost function is presented in which both the phase delay and robust stability are considered and then the optimal filter will be designed for minimizing this new cost function. The Simulation and Experimental Results show that efficiency of the proposed optimal filter or proposed data-holding scheme is more than that of the previous optimal filters in each cost function.

Keywords: Optimal Sample-Data Holds, Filter, Sampled Data System, ZOH, Optimization.

1. INTRODUCTION

When a continuous system is controlled by using a digital computer as a controller, a digital-to-analog converter (DAC) and a holding device must be used together with the controller. A zero-order hold (ZOH) device is commonly used as a standard holding device. It holds its output on the level of the most recent data $y(nT)$. The main inconvenience of ZOH is that it reduces the phase delay. To reduce the phase delay caused by ZOH, in (Yekutiel, 1980) the piecewise-constant higher order hold (PC-HOH) was proposed to predict the value of $y[(n+0.5)T]$ by evaluating a truncated Taylor's expansion. Then, against of the $y(nT)$, it is hold constant as a plant input or controller output in the proposed data-holding scheme. Following this idea, the Newton Extrapolation Polynomial Method (NEPM) was proposed in (Beliczynski et al., 1984). In NEPM, the Newton Extrapolation Polynomial was applied to predict the value of $y[(n+0.5)T]$. In both methods, a filter was introduced to compensate the negative phase by predicting the value of $y[(n+0.5)T]$. It is clear that by using the filter the negative phase delay caused by ZOH is compensated but the frequency response of the filter gain was not modified. Therefore it has magnitude distortion. In (Leonard, 1999), a robust stability criterion was introduced to consider the magnitude distortion of the applied filter. Then the optimal first-order phase lead filter was applied to induce the phase delay and to reduce the robust stability separately. It is called Optimal Filter Method (OFM). The robust stability criteria has considered never again.

In (Shahnazi et al., 2005a), the optimum PC-HOH was proposed in which the $y[nT+\Delta]$ is optimally predicted. To do this, the optimal value of Δ was selected between [0 T] while the phase lag of ZOH was optimally compensated. Following this idea, In (Shahnazi et al., 2005b) the NEPM was modified by optimizing the q value in prediction of the $y[(n+q)T]$ where $0 \le q < 1$. Totally, it has been shown in (Shahnazi et al., 2005a,b) that optimum NEPM and PC-HOH are more efficient methods in compensating the phase delay in comparison with the previous methods.

In each previous approach: 1- some type of expansion polynomial such as Taylor and Newton were applied to construct the optimal filter. By using those polynomials, the filter coefficients are depended together. Therefore, the obtained filter may not be optimum because its coefficients are searched in a limited area caused by this dependency. 2- The optimal filter was often designed to minimize the phase delay criteria.

In this paper, 1- a polynomial with no dependency between the coefficients is selected to construct the optimal filter. 2- A bi-objective cost function in which both the phase delay and the stability robustness are considered is defined. Then, this type of cost function and those two types of old cost functions are applied to design the optimal filter in OPC-HOH, ONEPM and proposed methods. 3- Totally, the Imperialist Competitive algorithm as a meta-heuristic method is used to optimally estimate the coefficients of the proposed filter. The results show that the proposed filter and consequently the proposed data-holding device have superior performance rather than others in each criterion.

To compensate the delay of ZOH, many methods were proposed and applied in different closed loop control structures. In (Raviv et al., 1999), Adding pole/zero pair to an existing digital controller to compensate the phase lag caused by ZOH has been proposed. In (Bibian et al., 2000), two predictive schemes based on a linear extrapolation technique are developed to compensate the sampling time delay which exists in digital control. In (Schmirgel et al., 2006), to compensate the delay and sampling time effects, Based on the Smith predictor concept, a model predictive control algorithm is implemented on the current control loop level of the cascaded drive control system. In (He et al., 2007) an algorithm is proposed and studied on the Dc-Dc converter to compensate the time delay of discretization. In (Wang et al., 2008) the ZOH discretization effect is discussed on the higher–order sliding-mode control systems. In (Nussbaumer et al. 2008), two prediction methods (i.e., a linear prediction and the smith prediction), are used to compensate time delays caused by digital control of a tree phase buck type PWM rectifier system. In (Vilcanqui et al., 2014), frequency compensation using a LMS-based Adaptive FIR filter between the controller and the reference signal is proposed to correct the amplitude and phase distortion caused by the sampling rate.

In section 2, first, the brief discussion on the problem is presented. Second, details of the old methods are presented. Finally, details of the proposed optimum filter are described. In section 3, the imperialist competitive algorithm is presented. In section 4, the proposed Bi-Objective cost function is introduced. Also, with each cost function, the proposed filter and its related results are compared with those of the other methods. In section 5, a simulation test result on an academic system and an experimental test result on the rectifier plant are presented and applied to compare the performances of aforementioned methods. In Section 6, Discussion about the obtained results is presented. Finally, the conclusions are summarized in Section 7.

2. PROBLEM DESCRIPTION

In controlling continuous systems by digital processors, the controller is usually designed continuously but applied in Z-domain for the system. Therefore a holding device is used which is usually a ZOH device. In Fig. 1 the closed loop structure of digital controlling of continuous systems is shown (Yekutiel, 1980). Therefore, the phase delay caused by holding device is mixed with the system and controller phase. In this paper, it's just been tried to compensate the phase delay effect of ZOH device. This phase delay can be seen in the ZOH transfer function:

$$ZOH(jw) = \frac{1-exp\,(-j\omega T)}{j\omega} = \frac{T\sin(0.5\omega T)}{0.5\omega T} exp(-j0.5\omega T) \quad (1)$$

The phase delay of ZOH in $\omega = 0.5,\ \omega_s = \pi/T$ will have the maximum value of -90. Therefore closed loop system's phase margin is actually less than continuous closed loop system's phase margin.

As shown in Fig. 2, a compensating filter $F(z)$ is been used for compensation of the phase delay caused by ZOH (Yekutiel, 1980). By substituting $z = exp\,(-j\omega T)$, the frequency behaviour of F(z) can be calculated and shown by F($j\omega$). Therefore:

$$H(j\omega) = \frac{1}{T}\frac{1-exp(-j\omega T)}{j\omega} F(j\omega) \quad (2)$$

In the end, the phase compensation problem is changed to phase minimization of $H(j\omega)$. The magnitude of $H(j\omega)$ changes in frequency domain due to magnitude of $F(j\omega)$. Therefore, it can be induce the gain margin and the robust stability of closed loop system. Two constraints must be considered in designing of $F(j\omega)$ in this area. First, $F(z=1)=1$ so that the negative effect of amplitude of $H(j\omega)$ to be limited (not minimized) especially in zero frequency. Second F(z) has minimum phase zeros (stable zeros) which is the necessary condition of jury's Lemma (Shahnazi et al., 2005b). So the optimization problem is a constrained problem.

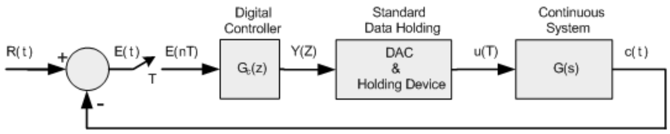

Fig. 1. A closed loop digitally controlled system (Yekutiel, 1980).

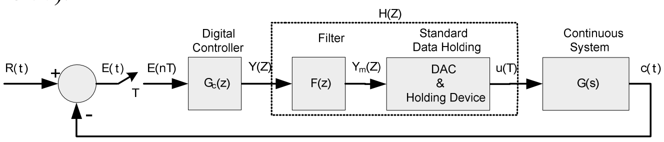

Fig. 2. The proposed closed loop digitally controlled system (Yekutiel, 1980)

Two types of cost functions or performance measures for this problem was defined as followed (Leonard, 1999):

$$J_1(X) = \int_0^{\omega_{BW}} |\Phi(\omega, X)|^2 d\omega$$
$$J_2(X) = \int_0^{\omega_{BW}} |\Phi(\omega, X)| d\omega \quad (3)$$

$$J_3(X) = \int_0^{\omega_{BW}} |1 - H(\omega, X)|^2 d\omega$$
$$J_4(X) = \int_0^{\omega_{BW}} |1 - H(\omega, X)| d\omega \quad (4)$$

In which X is an undefined vector which constructs the coefficients of $F(z)$ filter. ω_{BW} is the closed loop bandwidth of the plant which is being controlled and $\Phi(\omega, X)$ is the phase of $H(j\omega)$. The relation between ω_{BW} and the sampling frequency ω_s can be founded as follows (Pierre et al., 1995):

$$\omega_s = k.\omega_{BW} \qquad 6 \le k \le 25 \quad (5)$$

It is obvious that in cost functions J_1 and J_2, the optimal value of X is selected as to phase delay be minimized in the bandwidth, ω_{BW}. It has been shown in (Leonard, 1999), that the lesser the $|1 - H(j\omega)|$ is, the better stability robustness will be gained. Therefore J_3 and J_4 can be used for increasing the stability Robustness.

2.1 Piecewise Constant Higher-Order-Hold (PC-HOH)

In this method (Yekutiel, 1980) the output value of $y(nT+\Delta)$ was expanded as follows:

$$y(nT+\Delta) = \sum_{i=0}^{m} \frac{\Delta^i}{i!} y^{(i)}(nT) + O(\Delta^{(m+1)}) \quad (6)$$

In which $O(\Delta^{(m+1)})$ are the high order terms and $y^{(i)}$ is the ith order derivative of the $y(t)$. In this method, at first the high order terms in (6) were neglected and then by using first backward difference approximation of $y^{(i)}(nT)$, the proposed PC-HOH filter was obtained as follows.

$$F_m^{PC-HOH}(z) = \sum_{i=0}^{m} \frac{\Delta^i}{i!}\left(\frac{1-z^{-1}}{T}\right)^i \tag{7}$$

In which $\Delta = T/2$ and $F_m^{PC-HOH}(z)$ is the *m*th order PC-HOH filter that is presented in table 1.

Table 1. Filter transfer function related to PC-HOH.

	m=1	*m*=2
$F_m^{PC-HOH}(z)$	$1.5 - 0.5z^{-1}$	$1.625 - 0.75z^{-1} + 0.125z^{-2}$

2.2 Newton Extrapolation Polynomial Method (NEPM)

In this method (Beliczynski et al., 1984) the mth order Newton Polynomial was used for approximating of $y[(n+q)T]$. Finally, the NEPM filter was proposed as follows:

$$F_m^{NEPM}(z) = \sum_{i=0}^{m} B_i^m(q) z^{-i} = \sum_{i=0}^{m} (-1)^i \binom{q-1+i}{i}\binom{q+m}{m-i} z^{-i} \tag{8}$$

In which $q = 0.5$ and $F_m^{NEPM}(z)$ is the mth order NEPM filter. In table 2, the NEPM filter for different *m* is presented.

Table 2. Filter transfer function related to NEPM.

	m=1	*m*=2
$F_m^{NEPM}(z)$	$1.5 - 0.5z^{-1}$	$1.875 - 1.25z^{-1} + 0.375z^{-2}$

2.3 Optimal Filter Method (OFM)

In this method (Leonard, 1999) for compensating the phase delay, the optimal filter $F(Z)$ was proposed as follows:

$$F_1^{OFM}(z) = \frac{1+bz^{-1}}{1+b} \qquad -1 < b < 1 \tag{9}$$

In which $F_1^{OFM}(z)$ is the first-order OFM filter. Finally, the *b* was calculated to minimize the phase of $H(j\omega)$ by defining the $J_1(b)$ as follows:

$$J_1(b) = \int_0^{\omega_{BW}} |\Phi(\omega, b)|^2 d\omega \tag{10}$$

In table 3 the values of *b* and $J_1(b)$ are presented for different values of k.

Table 3. Optimal OFM filter for different *k*.

k	***b***	***J₁(b)***
k=2	-0.618	2.4551
k=4	-0.476	0.0444
k=6	-0.404	0.0030
k=8	-0.374	4.0e-4
k=10	-0.3592	8.41e-5
k=15	-0.3449	5.04e-6
k=20	-0.3398	6.49e-7

2.4 Optimum PC-HOH (OPC-HOH)

In this method (Shahnazi et al., 2005a) the optimal value of Δ in (7) was obtained for the minimum of J_1 which was defined in (3). $H(\omega,\Delta)$ and $\Phi(\omega,\Delta)$ in this method for different values of *m* are presented in (11) and (12).

$$\begin{cases} H(\omega,\Delta)_{m=1} = (1/T)\, ZOH(\mathrm{j}\omega \mathrm{T})\left(1 + \Delta\dfrac{1-\exp(-\mathrm{j}\omega\mathrm{T})}{T}\right) \\ \Phi(\omega,\Delta)_{m=1} = -0.5\omega\mathrm{T} + \mathrm{Arctan}\left(\dfrac{\Delta\sin(\omega\mathrm{T})}{\mathrm{T}+\Delta(1-\cos(\omega\mathrm{T}))}\right) \end{cases} \tag{11}$$

$$\begin{cases} H(\omega,\Delta)_{m=2} = (1/T)\, ZOH(\mathrm{j}\omega \mathrm{T})\left(1 + \Delta\dfrac{1-\exp(-\mathrm{j}\omega\mathrm{T})}{T} + \dfrac{\Delta^2}{2!}\left(\dfrac{1-\exp(-\mathrm{j}\omega\mathrm{T})}{T}\right)^2\right) \\ \Phi(\omega,\Delta)_{m=2} = -0.5\omega\mathrm{T} + \mathrm{Arctan}\left(\dfrac{\Delta\mathrm{T}\sin(\omega\mathrm{T}) + \Delta^2\sin(\omega\mathrm{T}) - (\Delta^2/2)\sin(2\omega\mathrm{T})}{\mathrm{T}^2 + \Delta\mathrm{T}(1-\cos(\omega\mathrm{T})) - \Delta^2\cos(\omega\mathrm{T}) + (\Delta^2/2)(1+\cos(2\omega\mathrm{T}))}\right) \end{cases} \tag{12}$$

2.5 Optimum NEPM (ONEPM)

In this method (Shahnazi et al., 2005b) by defining the optimal value of q in the (8) for the minimum value of J_1 which was defined in (3), the Optimum NEPM (ONPEM) was proposed. $H(\omega,q)$ and $\Phi(\omega,q)$ are presented for *m*=1, 2 in (13) and (14).

$$\begin{cases} H(\omega,q)_{m=1} = (1/T)\, ZOH(\mathrm{j}\omega \mathrm{T})\left(q+1-q.\exp(-\mathrm{j}\omega\mathrm{T})\right) \\ \Phi(\omega,\Delta)_{m=1} = -0.5\omega\mathrm{T} + \mathrm{Arctan}\left(\dfrac{\mathrm{q}.\sin(\omega\mathrm{T})}{q+1-q.\cos(\omega\mathrm{T})}\right) \end{cases} \tag{13}$$

$$\begin{cases} H(\omega,\Delta)_{m=2} = (1/T)\, ZOH(\mathrm{j}\omega \mathrm{T})\left(\dfrac{(\mathrm{q}+2)(\mathrm{q}+1)}{2} - q(\mathrm{q}+1)\exp(-\mathrm{j}\omega\mathrm{T}) + \dfrac{q(\mathrm{q}+1)}{2}\exp(-\mathrm{j}2\omega T)\right) \\ \Phi(\omega,\Delta)_{m=2} = -0.5\omega\mathrm{T} + \mathrm{Arctan}\left(\dfrac{\mathrm{q}(\mathrm{q}+2)\sin(\omega\mathrm{T}) - 0.5\mathrm{q}.(\mathrm{q}+1)\sin(2\omega\mathrm{T})}{0.5(\mathrm{q}+2)(\mathrm{q}+1) - \mathrm{q}(\mathrm{q}+2)\cos(\omega\mathrm{T}) + 0.5\mathrm{q}(\mathrm{q}+1)\cos(2\omega\mathrm{T})}\right) \end{cases} \tag{14}$$

2.6 The proposed Optimal Filter

In this method a compensating filter of mth order which minimizes one cost function is assumed as:

$$F_m^{Proposed}(z) = \sum_{i=0}^{m} \alpha_i z^{-i} \tag{15}$$

$F_m^{Proposed}(z)$ is the optimal proposed filter of mth order and α_i is the *i*th coefficient of filter. In addition to $F(1) = 1$ condition, the stability of the compensator zeros is also the necessary condition. Therefore the optimal selection problem of the proposed compensator filter is a constrained optimization problem which can be defined as follows:

$$\begin{aligned} &Minimize_{X=[\alpha_0\cdots\alpha_m]}(J(X)) \\ &such\ that \begin{cases} \sum_{i=0}^{m} \alpha_i = 1 \\ Max|roots([\alpha_0 \cdots \alpha_m])| < 1 \end{cases} \end{aligned} \tag{16}$$

Which $J(X)$ is one cost function. The above constrained problem can be changed to an unconstrained problem by defining the two positive coefficients β_1 and β_2 as follows:

$$Minimize_{X=[\alpha_0 \cdots \alpha_m]}(J(X)+\beta_1(|1-\sum_{i=0}^{m}\alpha_i|) +\beta_2 sign(Max(|roots([\alpha_0 \cdots \alpha_m])|)\geq 1)) \tag{17}$$

If the two constraints are hold, the cost function of (16) and (17) would be equal. In this paper, by optimizing the (17) using the ICA method, the proposed filter shown in (15) is obtained.

3. IMPERIALIST COMPETITIVE ALGORITHM

The ICA as a multi-agent optimization algorithm simulates the social political process of imperialism and imperialistic competition (Atashpaz-Gargari et al. 2007). Like other evolutionary optimization algorithm, the ICA starts with an initial population. Population individuals called country. There are two types of countries; some of the best countries are selected to be the ''imperialist'' states and the remaining countries form the ''colonies'' of these imperialists (The country power is inversely proportional to its cost). Then, these countries are divided among the imperialists based on their ''power''. Each imperialist together with its colonies forms an ''empire''. The main processes of ICA include Assimilation and Revolution inside each empire, Imperialistic competition among all empires and Elimination of powerless empires. Under assimilation policy, the colonies move toward their relevant imperialist in each empire. Under Revolution policy, some colonies of each empire move suddenly to other positions that are randomly selected. Under imperialistic competition the weak empire will miss its weak colonies and consequently its power will gradually decrease. Under the competition policy, one of the more powerful empires possesses the weakest colonies of the weakest empire. Finally, the weakest empire that has no colony will be eliminated and its imperialist will participate in imperialist competition like a weak colony. Therefore, under Elimination policy, all countries converge to one empire and then the algorithm is finished. The total power of an empire depends on both the power of the imperialist country and its colonies power. This fact is modelled by defining the total power of an empire as the power of the imperialist country plus a percentage of the mean of its colonies power. The flowchart of the ICA (Atashpaz-Gargari et al. 2007) is shown in Fig. 3.

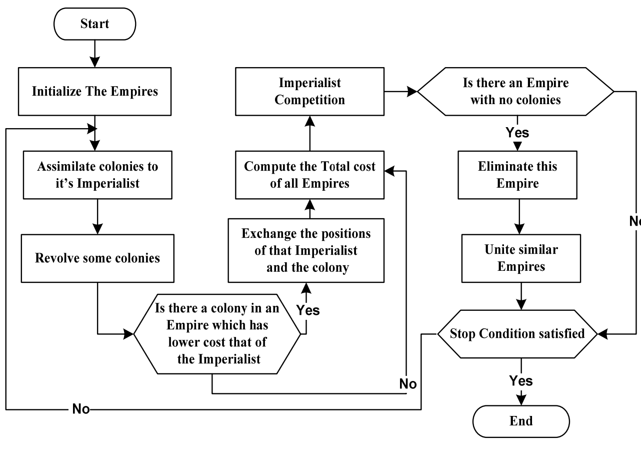

Fig. 3. Flowchart of the imperialist competitive algorithm.

3.1 Original ICA

The normalized power (cost) of an imperialist is defined as:

$$\boldsymbol{C_l = f_{cost}^{(imp,l)} - max_i(f_{cost}^{(imp,l)})} \tag{18}$$

Where $f_{cost}^{(imp,l)}$ is the power (cost) of the lth imperialist and C_l is its normalized power. By using the normalized power of imperialists, the colonies number of lth empire (NC_l) is obtained as follows:

$$\boldsymbol{NC_l = Round\left(\left|\frac{C_l}{\sum_{i=1}^{N_{imp}} C_i}\right| . N_{col}\right)} \tag{19}$$

Where N_{col} is the colonies number of all empires and N_{imp} is the number of imperialist. Then, for each empire, its colonies are randomly selected according to its NC_l. The total cost of lth empire (TC_l) is obtained by the (20) and is introduced as follows:

$$\boldsymbol{TC_l = f_{cost}^{(imp,l)} + \xi . \frac{\sum_{i=1}^{NC_l} f_{cost}^{(col,i)}}{NC_l}} \tag{20}$$

Where ξ is a value between 0 and 1. The normalized total cost of lth empire (NTC_l) is introduced as follows:

$$\boldsymbol{NTC_l = TC_l - max_l(TC_l)} \tag{21}$$

Using the normalized total cost of empires, the possession probability of lth empire is obtained from the below equation.

$$\boldsymbol{P_l = \left|\frac{NTC_l}{\sum_{i=1}^{N_{imp}} NTC_i}\right|} \tag{22}$$

The empire with bigger possession probability is more likely to win the imperialistic competition.

The Assimilation policy in original ICA is defined by moving the colony toward relevant imperialist as follows:

$$\boldsymbol{\{x\}_{new} = \{x\}_{old} + U(0, \bar{\beta} \times d) \times \{V_1\}} \tag{23}$$

Where $\{x\}_{new}$ and $\{x\}_{old}$ are new and previous location of the colony respectively. $\bar{\beta}$ is a parameter greater than 1 and d is the distance between the colony and its relevant imperialist. $U(0, \bar{\beta} \times d)$ is a random scalar value that is uniformly distributed between *0* and $\bar{\beta} \times d$. $\{V_1\}$ is a unity vector that shows the direction between the colony's previous location and its relevant imperialist location.

3.2 Design the optimal filter by using the ICA

The ICA is extensively used to solve different optimization problems such as other meta-heuristic optimization methods. In this paper, the ICA is used to design the proposed m-order filter. As initial population, 100 countries have been chosen randomly while the position of each country is defined by the filter coefficients. The related cost function with each country was obtained by (17). Then from these countries, $N_{imp} = 10$ countries with best position (i.e. with least cost function values) have been chosen as the imperialists. To form the empires, the colony of each imperialist must be selected. The colonies number of the lth imperialist ($\boldsymbol{NC_l}$) is obtained by using (19) and then the colonies of each empire are chosen randomly to construct the empire.

Totally, with $\xi = 0.1$ and $\bar{\beta} = 2$, the colonies under Revolution and Assimilation and Imperialistic Competitive policies are being moved until reaching a better and new position with less cost function value. This process will be repeated 200 times (iteration number) and after that the position of the best imperialist (i.e. a filter with the least cost function value) is considered as the final result of the ICA optimization algorithm. It will be checked in each iteration whether there is an empire without colonies and if so the elimination policy will be applied. Therefore the algorithm will stop whether after the iteration number or converging to one empire.

4. DESIGNING OPTIMAL FILTER

In this section three types of cost functions: 1- phase delay reduction, 2- Robust stability increment, and 3- phase delay reduction and robust stability increment simultaneously, are to be considered. For each of these functions, OPC-HOH, ONEPM filters and the optimal proposed filter will be designed and compared to each other. The coefficients of the optimal proposed filter will be optimized by using ICA method. The first and second cost functions have been studied previously and many works are presented based on them. The third cost function will first be introduced and then the optimal filters will be designed and compared with each other based on this new defined cost function. The main contributions of this paper are presenting a new structure for the ZOH compensator optimal filter and introducing a new cost function for designing this ZOH compensator optimal filter.

4.1 Minimizing the phase delay

In order to design an optimal filter for reducing the phase delay caused by ZOH the following cost function is considered:

$$J_1(X) = \int_0^{\omega_{BW}} |\Phi(\omega, X)|^2 d\omega \qquad X = [\alpha_0 \cdots \alpha_m] \tag{24}$$

The optimal proposed filter is obtained by substituting $J_1(X)$ as $J(X)$ in (16) and (17) for different values of m and k. The obtained results for $\omega_s = 10$ are presented in tables 6-9. In table 4 the optimal values of Δ and q for different values of k and m in OPC-HOH and ONEPM methods are presented. These results show that with a fixed value of m and by increasing the value of k, the values of Δ and q are converging to definite values. In table 5 and 6 the value of cost function J_1 for different values of k and m in ONEPM, OPC-HOH and proposed method are presented. The obtained results for m=1 and each value of k show that all obtained filters are the same. These results also show that the proposed method has the most and the OPC-HOH has the least phase delay compensation for m=2 and k<6. The proposed method has the most (i.e. smallest J_1) and the ONEPM has the least (i.e. biggest J_1) phase delay compensation for m=2 and for $k \geq 6$. In table 7 the obtained optimal digital filters by using these three mentioned methods are presented for k=6 and different values of m.

Table 4. Parameters of optimum PC-HOH and NEPM for different *k* and *m*.

J_1	m=1		m=2	
	q	Δ	q	Δ
k=2	1	0.6283	0.6632	0.6269
k=4	0.9098	0.5717	0.4475	0.4103
k=6	0.6767	0.4252	0.4210	0.3500
k=8	0.5969	0.3751	0.4340	0.3323
k=10	0.5611	0.3526	0.4488	0.3250
k=15	0.5267	0.3309	0.4722	0.3186
k=20	0.5149	0.3235	0.4832	0.3166

Table 5. Cost function of optimum NEPM and PC-HOH and proposed Method for different k and m=1.

J_1	m=1		
	$J_1^{OPC-HOH}$	J_1^{ONEPM}	$J_1^{Proposed}$
k=2	2.5397	2.5397	2.5397
k=4	0.0450	0.0450	0.0450
k=6	0.0030	0.0030	0.0030
k=8	4.12e-4	4.12e-4	4.12e-4
k=10	8.71e-5	8.71e-5	8.71e-5
k=15	5.13e-6	5.13e-6	5.13e-6
k=20	6.86e-7	6.86e-7	6.86e-7

Table 6. Cost function of optimum NEPM and PC-HOH and proposed method for different *k* and *m*=2.

J_1	**m=2**		
	$J_1^{OPC-HOH}$	J_1^{ONEPM}	$J_1^{Proposed}$
k=2	2.0278	1.9300	1.7630
k=4	0.0133	0.0037	0.0028
k=6	4.96e-4	2.32e-4	3.05e-5
k=8	4.94e-5	1.24e-4	1.23e-6
k=10	8.64e-6	4.76e-5	1.03e-7
k=15	4.04e-7	5.00e-6	1.17e-9
k=20	4.91e-8	8.20e-7	5.3e-10

Table 7. Optimal digital filter transfer function of different method by minimizing J_1 (m=1, 2).

Method	m=1	m=2
OPC-HOH	$1.6767 - 0.6767Z^{-1}$	$1.7122 - 0.8673Z^{-1} + 0.1551Z^{-2}$
ONPEM	$1.6767 - 0.6767Z^{-1}$	$1.7201 - 1.0192Z^{-1} + 0.2991Z^{-2}$
Proposed	$1.6767 - 0.6767Z^{-1}$	$1.7188 - 0.9635Z^{-1} + 0.2447Z^{-2}$

4.2 Maximizing the robustness stability

In order to design the optimal filter with the purpose of maximizing the robustness stability in presence of ZOH, the following cost function is considered:

$$J_3(X) = \int_0^{\omega_{BW}} |1 - H(\omega, X)|^2 d\omega \qquad X = [\alpha_0 \cdots \alpha_m] \tag{25}$$

By assuming the above cost function $J_3(X)$ as $J(X)$ in (16) and (17) for different values of k and m, the optimal filter is obtained. The obtained results for $\omega_s = 10$ are presented in tables 8-11. In table 8 the optimal values of Δ and q for different values of k and m in OPC-HOH and ONEPM methods are presented. These results show that with a fixed value of m and by increasing the value of k, the values of Δ and q are converging to definite values. In table 9 and 10 the value of cost function J_3 for different values of k and m in ONEPM, OPC-HOH and proposed method are presented.

Table 8. Parameters of optimum PC-HOH and NEPM for different *k* and *m*.

J_3	m=1		m=2	
	q	Δ	Q	Δ
k=2	0.0644	0.0405	0.0787	0.0494
k=4	0.3791	0.2382	0.3248	0.2577
k=6	0.4456	0.2800	0.3928	0.2921
k=8	0.4693	0.2949	0.4265	0.3017
k=10	0.4803	0.3018	0.4467	0.3072
k=15	0.4912	0.3087	0.4722	0.3112
k=20	0.4951	0.3111	0.4833	0.3126

Table 9. Cost function of optimum NEPM and PC-HOH and proposed method for different *k* and *m*=1.

J_3	m=1		
	$J_3^{OPC-HOH}$	J_3^{ONEPM}	$J_3^{Proposed}$
k=2	2.9468	2.9468	2.9468
k=4	0.2421	0.2421	0.2421
k=6	0.0384	0.0384	0.0384
k=8	0.0097	0.0097	0.0097
k=10	0.0033	0.0033	0.0033
k=15	4.45e-4	4.45e-4	4.45e-4
k=20	1.07e-4	1.07e-4	1.07e-4

Table 10. Cost function of optimum NEPM and PC-HOH and proposed method for different *k* and *m*=2.

J_3	m=2		
	$J_3^{OPC-HOH}$	J_3^{ONEPM}	$J_3^{Proposed}$
k=2	2.9386	2.8471	2.4239
k=4	0.1754	0.0915	0.0449
k=6	0.0216	0.0053	0.0029
k=8	0.0048	5.69e-4	4.02e-4
k=10	0.0015	9.67e-5	8.57e-5
k=15	1.87e-4	5.55e-6	5.09e-7
k=20	4.36e-5	1.21e-6	6.83e-7

Table 11. Optimum digital filter transfer function of different method by minimizing J_3 (*m*=1, 2).

Method	m=1	m=2
OPC-HOH	$1.4457 - 0.4457Z^{-1}$	$1.5730 - 0.6810Z^{-1} + 0.1081Z^{-2}$
ONPEM	$1.4457 - 0.4457Z^{-1}$	$1.6663 - 0.9399Z^{-1} + 0.2735Z^{-2}$
Proposed	$1.4457 - 0.4457Z^{-1}$	$1.6938 - 1.0495Z^{-1} + 0.3556Z^{-2}$

The obtained results for m=1 and each value of k show that all obtained filters are the same. These results also show that the proposed method has the most (i.e. smallest J_3) and the OPC-HOH has the least (i.e. biggest J_3) robustness stability. In table 11 the obtained optimal digital filters by using these three mentioned methods are presented for k=6 and m=1, 2.

4.3 Bi-Objective Criterion: trade-off between the phase delay and the robustness stability

There are many methods for designing a multi objective cost function which could be used here. The Weighted Sum Approach (Miettinen, 1999) is the simplest one. By using this method the cost function J_5 for a trade-off between phase delay reduction and robustness stability increment defined as follows:

$$J_5(X) = \int_0^{\omega_{BW}} (\lambda|\Phi(\omega,X)|^2 + \gamma|1-\Phi(\omega,X)|^2)d\omega$$
$$J_6(X) = \int_0^{\omega_{BW}} (\lambda|\Phi(\omega,X)| + \gamma|1-\Phi(\omega,X)|)d\omega \qquad (26)$$
$$X = [\alpha_0 \cdots \alpha_m]$$

γ and λ are the weighing parameters where $\lambda + \gamma = 1$. Considering the different values of J_1 and J_3 for different values of k (tables 14-18), the values of γ and λ are selected in such a way that the effects of both purposes in the cost function would be approximately the same. The considered variations of γ in accordance with k is presented in table 12. By assuming the above cost function as $J(X)$ in (16) and (17) for different values of k and m, the optimal filter is obtained by using ICA Method. In table 13 the optimal values of Δ and q for different values of k and m in OPC-HOH and ONEPM methods are presented.

Table 12. Amount of γ weight for different *k* (*m*=1, 2).

γ	m=1	m=2
k=2	0.4621	0.4211
k=4	0.1567	0.0587
k=6	0.0725	0.0104
k=8	0.0407	0.0031
k=10	0.0257	0.0012
k=15	0.0114	0.0023
k=20	0.0064	0.0008

Table 13. Parameters of optimum PC-HOH and NEPM for different *k* and *m*.

J_5	m=1		m=2	
	Q	Δ	q	Δ
k=2	0.2615	0.1643	0.1977	0.1820
k=4	0.6530	0.4103	0.4304	0.3865
k=6	0.6378	0.4007	0.4206	0.3491
k=8	0.5879	0.3694	0.4340	0.3321
k=10	0.5581	0.3507	0.4488	0.3250
k=15	0.5262	0.3306	0.4722	0.3186
k=20	0.5148	0.3235	0.4832	0.3166

In table 14 and 15 the value of cost function J_5 for different values of k and m in ONEPM, OPC-HOH and Proposed method are presented. The obtained results for m=1 and each value of k show that all obtained filters are the same. These results also show that the proposed method has the most and the OPC-HOH has the least phase delay compensation for m=2 and k<6. The proposed method has the most (i.e. smallest J_5) and the ONEPM has the least (i.e. biggest J_5)

phase delay compensation for m=2 and for $k \geq 6$. In table 16 the obtained optimal digital filters by using these three mentioned methods are presented for *k*=6 and *m*=1, 2.

Table 14. Cost function of optimum NEPM and PC-HOH and proposed method for different *k* and *m*=1.

J_5	m=1		
	$J_5^{OPC-HOH}$	J_5^{ONEPM}	$J_5^{Proposed}$
k=2	3.2170	3.2170	3.2170
k=4	0.1170	0.1170	0.1170
k=6	0.0073	0.0073	0.0073
k=8	9.40e-4	9.40e-4	9.40e-4
k=10	1.90e-4	1.90e-4	1.90e-4
k=15	1.07e-5	1.07e-5	1.07e-5
k=20	1.40e-6	1.40e-6	1.40e-6

Table 15. Cost function of optimum NEPM and PC-HOH and proposed method for different *k* and *m*=2.

J_5	*m*=2		
	$J_5^{OPC-HOH}$	J_5^{ONEPM}	$J_5^{Proposed}$
k=2	3.0981	2.8926	2.3450
k=4	0.0311	0.0124	0.0082
k=6	7.89e-4	2.94e-4	1.49e-4
k=8	6.58e-5	1.26e-4	9.37e-6
k=10	1.06e-5	4.76e-5	1.15e-6
k=15	8.45e-7	5.00e-6	2.55e-7
k=20	8.33e-8	8.2e-7	2.21e-8

Table 16. Optimum digital filter transfer function of different method by minimizing J_5 (*m*=1, 2).

method	*m*=1	*m*=2
OPC-HOH	$1.6701 - 0.6701Z^{-1}$	$1.7100 - 0.8643Z^{-1} + 0.1544Z^{-2}$
ONPEM	$1.6378 - 0.6378Z^{-1}$	$1.7194 - 1.0181Z^{-1} + 0.2988Z^{-2}$
Proposed	$1.6378 - 0.6378Z^{-1}$	$1.7181 - 0.9723Z^{-1} + 0.2543Z^{-2}$

5. PERFORMANCE EVALUATION

In this section for performance evaluation of the designed filters, the results of a simulation test and an implementation test are presented. An academic system was considered in the simulation section. The optimal compensating filter was designed and the obtained results in the frequency domain were analysed. In the implementation section, the output voltage and input current control system of a rectifier was considered. The optimal filter based on the sampling time of this system and with the purpose of minimizing J5 was designed and the obtained experimental test results in the time domain were compared with each other.

5.1 Simulation test

In Fig. 4 the compensation with a led/lag for a double-integer plant is shown so that the efficiencies of the obtained optimal filters with this structure be compared. In doing so, the continuous controller by using bilinear transform $\left[s \to \frac{2}{T}(z-1)/(z+1)\right]$ is substituted with its digital version. The sampling time is selected in such a way that $\omega_s = 10\ r/s$. Therefore for *k*=6 the bandwidth ω_{BW} will be equal to 1.6. Finally the digital controller is obtained as $G(z) = \frac{1.9(z-0.794)}{z+0.078}$. In tables 17-21 the results of continuous and digital controller for *k*=6, *m*=1, 2 and cost functions J_1, J_3 and J_5 are presented. In table 18, the first order filters results are shown for J_1, J_3 and J_5. These results show that the phase margin of J_5 is alike with that of J_1 and the gain margin of J_5 is approximately alike with that of J_3. Therefore the obtained results from cost function J_5 are a trade-off between those of the cost functions J_1 and J_3 as so expected.

In table 19, the two order filters results are presented for J_1. These results show that the gain margin, phase margin, closed loop bandwidth and step overshoot of the proposed filter are approximately better than those of the other methods. The other results are approximately the same. In table 20, the two order filters results are presented for J_3. These results show that the phase margin and closed loop bandwidth of the proposed filter is better than those of the others. But the gain margin and step overshoot of the proposed method is not better than those of the others. In table 21, the two order filters results are presented for J_5. These results show that the gain margin, phase margin, closed loop bandwidth and step overshoot of the proposed filter are approximately better than those of the others. The other results are approximately the same.

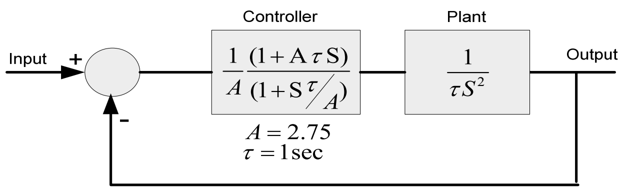

Fig. 4. Plant and continuous controller (Yekutiel, F. 1980).

In Fig.5 to Fig.7 the frequency response of two order filters are presented for k=6 and cost functions J_1, J_3 and J_5. In Fig. 5 the phase and amplitude of the obtained filters with the purpose of reducing phase delay for *k*=6 are shown. These results show that the proposed method has a good phase delay compensation in ωT=[0 1]. Therefore, the obtained filter by using ICA method has compensated the caused phase delay in low and middle frequencies. Comparing the magnitude diagram of the filters in frequency domain shows that the proposed filter has the best performance in robustness stability.

Table 17. Closed loop performance comparison.

System	Continuous	Digital + ZOH
Phase Margin [deg]	50.0338	36.5924
Gain Margin [db]	∞	9.09
Open Loop BW(0db) [r/Sec]	1	1.0275
Closed Loop BW (0db) [r/Sec]	1.2372	1.7695
Closed Loop Peak-Freq [db]/ [r/Sec]	2.586 - 0.630	4.108 - 0.931
Step Over Shoot %	28.03	46.11

In Fig. 6 the phase and magnitude diagrams of the obtained filters with the purpose of increasing robustness stability for k=6 are shown. The magnitude diagram of the filter obtained by using ICA (proposed filter) shows the better performance of this filter in ωT=[0 1]. In contrary its phase diagram shows a weak performance in compensating the phase delay in comparison with the two other methods in ωT=[0 1].

Table 18. Closed loop performance comparison (m=1).

Cost Function	J_1	J_3	J_5
System (Digital + ZOH + Filter)	Optimum Filter	Optimum Filter	Optimum Filter
Phase Margin [deg]	53.5813	49.4363	53.4927
Gain Margin [db]	6.0719	6.1079	6.1079
Open Loop BW(0db) [r/Sec]	1.2970	1.2930	1.2930
Closed Loop BW (0db) [r/Sec]	2.9970	2.9853	2.9853
Closed Loop Peak-Freq [db]/ [r/Sec]	2.236 - 2.419	2.347 - 0.620	2.182 - 2.408
Step Over Shoot %	31.7775	29.4543	31.56

Table 19. Closed loop performance comparison (m=2).

Cost Function	J_1		
System (Digital + ZOH + Filter)	OPC-HOH Filter	ONEPM Filter	Proposed Filter
Phase Margin [deg]	55.5926	55.0355	55.4879
Gain Margin [db]	6.2983	6.3142	6.3290
Open Loop BW(0db) [r/Sec]	1.1746	1.0696	1.1070
Closed Loop BW (0db) [r/Sec]	1.7783	2.5756	2.3931
Closed Loop Peak-Freq [db]/ [r/Sec]	2.121 - 0.5538	2.344 - 0.5770	2.252 - 0.5678
Step Over Shoot %	27.1016	27.7338	25.8756

Table 20. Closed loop performance comparison (m=2).

Cost Function	J_3		
System (Digital + ZOH + Filter)	OPC-HOH Filter	ONEPM Filter	Proposed Filter
Phase Margin [deg]	52.2441	53.7054	53.4657
Gain Margin [db]	7.0884	6.6668	6.4405
Open Loop BW(0db) [r/Sec]	1.1392	1.0641	1.0243
Closed Loop BW (0db) [r/Sec]	2.5682	1.2689	3.1419
Closed Loop Peak-Freq [db]/ [r/Sec]	2.299 - 0.5927	2.407 - 0.5901	2.507 - 0.5954
Step Over Shoot %	24.1909	27.1324	29.7440

Table 21. Closed loop performance comparison (m=2).

Cost Function	J_5		
System (Digital + ZOH + Filter)	OPC-HOH Filter	ONEPM Filter	Proposed Filter
Phase Margin [deg]	55.5362	55.0134	55.3943
Gain Margin [db]	6.3111	6.3190	6.3349
Open Loop BW(0db) [r/Sec]	1.1740	1.0695	1.0998
Closed Loop BW (0db) [r/Sec]	1.6046	2.5774	2.4345
Closed Loop Peak-Freq [db]/ [r/Sec]	2.124 - 0.5544	2.345 - 0.5773	2.270 - 0.5698
Step Over Shoot %	27.0619	27.7264	26.2133

In Fig. 7 the phase and magnitude diagrams of obtained filters with the purpose of minimizing J_5 are presented for k=6. These results show that the proposed method has a good trade-off between phase delay compensation and stability robustness in ωT=[0 1]. Thus, the proposed filter has a better performance in achieving the desired purpose in the medium and low frequencies.

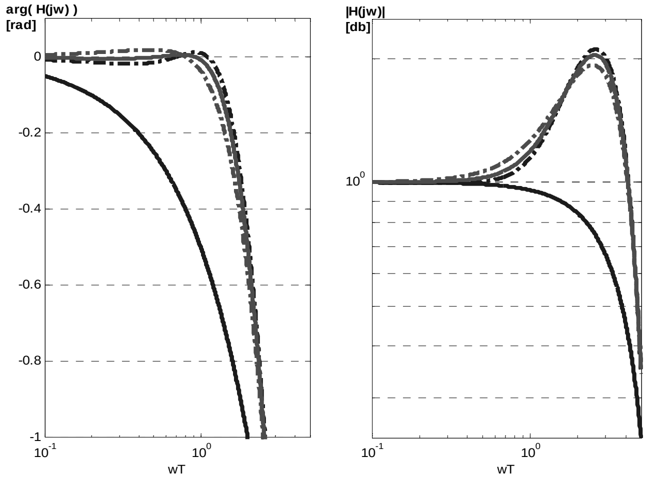

Fig. 5. Angle and magnitude of the Filters by minimizing J_1 (m=2): ZOH is blue (line), ONEPM filter is blue (dash-dot), proposed filer is red (line) and OPC-HOH filter is red (dash-dot).

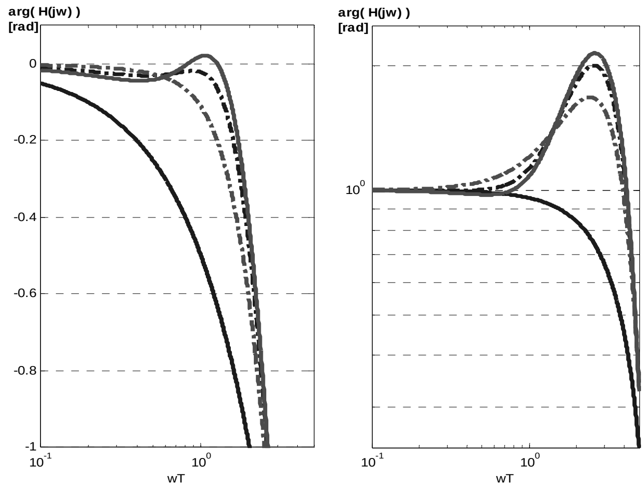

Fig. 6. Angle and magnitude of the filters by minimizing J_3 (m=2): ZOH is blue (line), ONEPM filter is blue (dash-dot), proposed filer is red (line) and OPC-HOH filter is red (dash-dot).

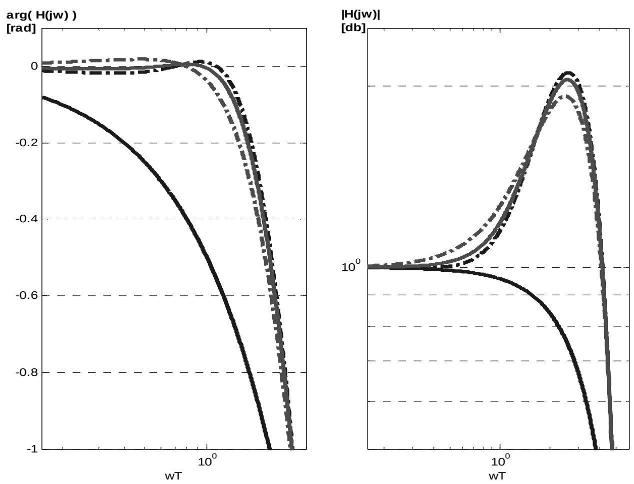

Fig. 7. Angle and magnitude of the filters by minimizing J_5 (m=2).): ZOH is blue (line), ONEPM filter is blue (dash-dot), proposed filer is red (line) and OPC-HOH filter is red (dash-dot).

5.2. Experimental test

In this section, the optimum filters effect on a digitally controlled rectifier is discussed in time domain. The full-bridge rectifier and associated control system scheme is shown in Fig.8. The controller includes a voltage controller that regulates the output DC voltage and a current controller which suppresses the input current harmonics and ensures the unity power factor operation of the rectifier. The controller design has been fully investigated in the literature (Singh et al., 2003), (Kanaan et al., 2009) and (Vahedi et al., 2015).

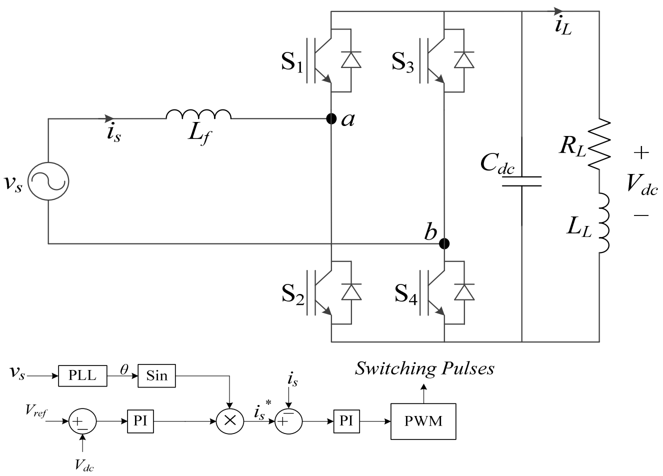

Fig.8. Full-Bridge Rectifier and PI Control System Scheme.

The input AC voltage is 25V peak and output DC voltage is regulated at 30V and after a step change at 50V. Line inductor (L_f) is 2.5mH. Output capacitor (C_{dc}) is 1mF and the RL load consists of 37Ω and 10mH. The illustrated controller has been implemented on a dSpace 1103 DSP real-time controller to generate and send required pulses to the rectifier switches.

The filters in table 22 are the results of optimizing the cost function J_5 with $T_s = 200\ \mu Sec$ which its calculation process has been mentioned in the previous sections. The magnitude and phase of these filters are also shown in Fig. 9. These results show that the performance of the proposed filter in ωT=[0 1] is better than the other methods.

Table 22: Optimum digital filter transfer function of different methods by minimizing J_5 ($T_s = 200\ \mu Sec$).

method	m=2
OPC-HOH	$1.7031 - 0.8550Z^{-1} + 0.1519Z^{-2}$
ONPEM	$1.7170 - 1.0147Z^{-1} + 0.2976Z^{-2}$
Proposed	$1.7182 - 0.9724Z^{-1} + 0.2543Z^{-2}$

For performance evaluation of the compensating filters in time domain, the closed loop system step response with continuous controller was compared to the closed loop system step response with discontinuous controller (with compensating filter). It is obvious that the lesser difference between these two step responses shows the better performance of the designed filter.

The obtained results of the experimental test are shown in Fig. 10 to Fig.13. In Fig. 10 the output voltage (blue) and input current (red) responses under continuous (Analog) closed loop control are shown. In Fig. 11 to Fig.13 the practical test results by discontinuous control with the compensating filters of the table 22 and $T_s = 200\ \mu Sec$ are shown. In Fig. 11 the digital control results with the proposed filter is presented. In Fig. 12 and Fig.13 the digital control results with *OPC-HOH* filter and ONPEM filter are shown respectively. The applied Parallel PI controllers' coefficients are presented in table 23. These coefficients are obtained by try and error.

As one appropriate criterion, the integral of time-weighted absolute error (ITAE) criteria can be used to compare two step responses in the time domain. It is obvious that in this criterion the errors in longer time have more importance. In other words, the errors in low frequencies have higher weights.

$$ITAE = \int_0^\infty t.\,|e(t)|\ dt$$

Where e(t) is the difference between the step response obtained by applying the optimal filters and that of obtained by using continuous controller. The value of ITAE for the results obtained from applying filters of table 22 is presented in table 24. This result shows that the step response obtained by applying proposed filter is more alike (less ITAE) with the system continuous step response. In other words the compensation of the error caused by discretization is especially better in low and medium frequencies.

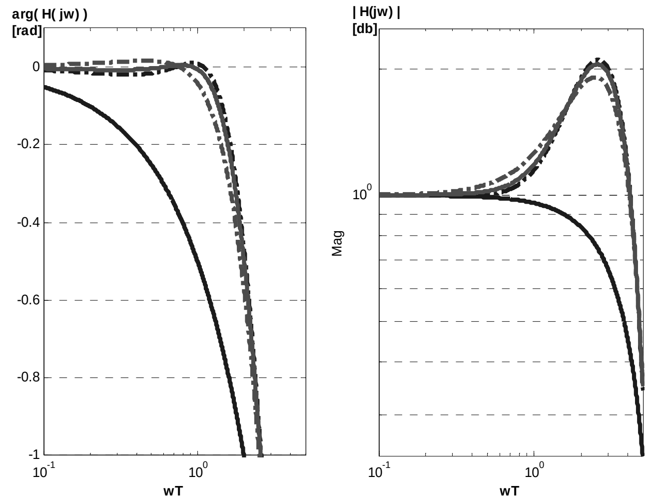

Fig. 9. Angle and magnitude of the Filters by minimizing J_5 (m=2): ZOH is blue (line), ONEPM filter is blue (dash-dot), proposed filer is red (line) and OPC-HOH filter is red (dash-dot).

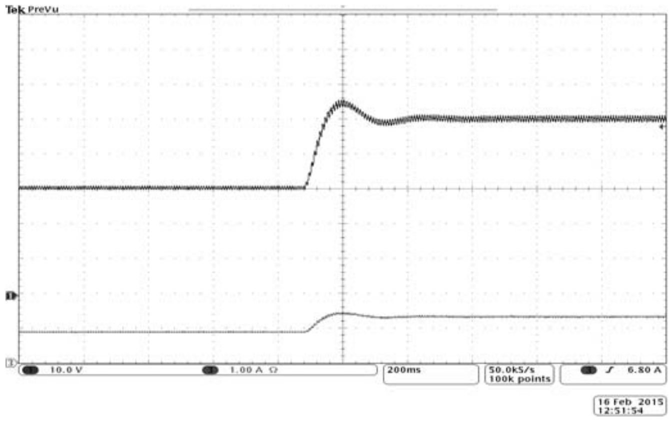

Fig. 10. Output voltage (blue) and Input current (red) step response of analog closed loop controlled rectifier system.

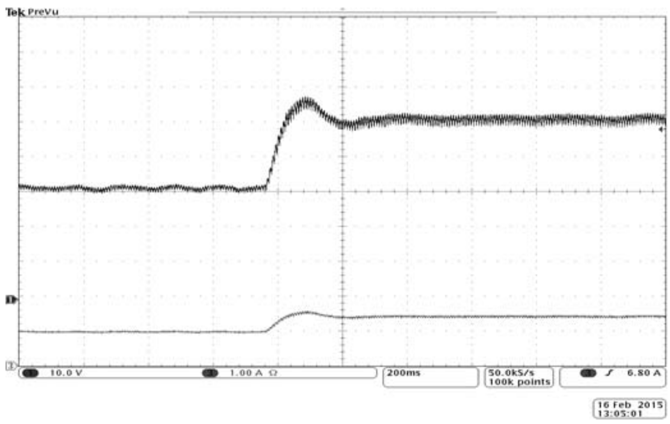

Fig. 11. Output voltage (blue) and input current (red) step response of closed loop controlled rectifier system (Digital control together with the proposed filter).

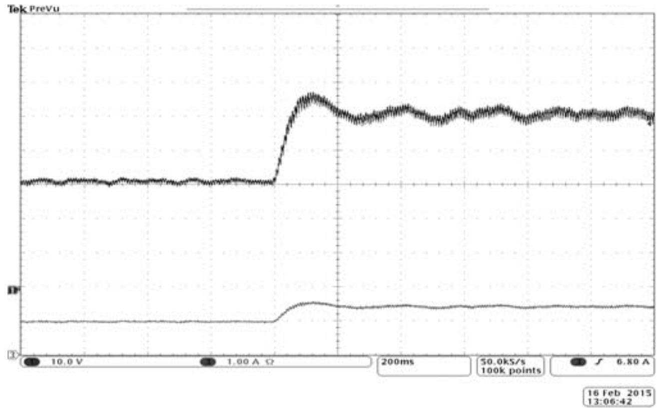

Fig. 12. Output Voltage (blue) and input current (red) step response of closed loop controlled rectifier system (Digital control together with the OPC-HOH filter).

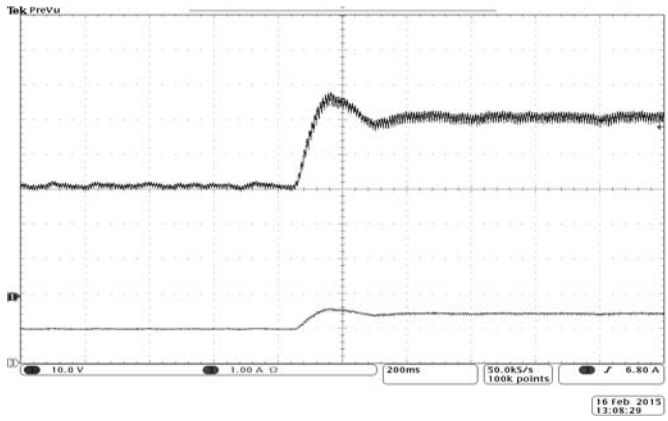

Fig. 13. Output voltage (blue) and input current (red) step response of closed loop controlled rectifier system (Digital control together with the ONPEM optimum filter).

Table 23: applied digital parallel PI controller.

T_s: Sampling Time	PI_{inner}	PI_{outer}
$\mathrm{PI(z)} = \mathrm{P} + \mathrm{I}\dfrac{\mathrm{T_s}}{\mathrm{z}-1}$	P = 10 I = 0.01	P = 0.001 I = 10

Table 24: ITAE criterion of voltage step response under experimental test.

Criteria	OPC-HOH Filter	ONPEM Filter	Proposed Filter
ITAE	0.1997	0.3398	0.1876

6. DISCUSSION

In the previous methods because of applying famous polynomial like Newton Extrapolation Polynomial the problem of selecting a filter became an one-variable problem. For example in OPC-HOH method the unknown variable is the Δ parameter and in ONPEM the unknown variable is the q parameter. By defining this parameter, every coefficients of filter of nth order is defined. Two major advantages of applying these methods are: first; the stability of zeroes of obtained filter is assured and second; the DC gain of the obtained filter is always equal to 1. In the proposed method, the number of unknown variables of problem is equal to $m+1$, where m is the order of the filter. In other words, the filter's parameters are the unknown coefficients of the problem. For stability guaranteeing and obtaining the DC gain equal to 1, the cost function is modified as (17). Therefore it can be said that in designing the filter of m-order by applying the proposed method, there are more degrees of freedom compared to previous methods and it would be natural that better results be obtained.

In simulation test section, the frequency responses of closed loop system by applying different filters (J_1, J_3 and J_5) were compared with each other. The frequency response of obtained filters are also drawn and analysed. The results of the closed loop frequency response analysis have shown that the filters performance in low and middle frequencies is absolutely better. In the experimental test section, the results obtained by applying filters for reducing J_5 on a rectifier output voltage and input current control system in time domain were analysed. The output voltage response of the closed loop system by applying these filters and for $T_s = 200\ \mu Sec$ is compared with the closed loop system response by using continuous control. This comparison has shown that the closed loop system response by applying the proposed filter together with discrete controller is the most similar response to that of the closed loop system with the continuous controller.

6. CONCLUSIONS

In this paper the ICA optimization method is been used for designing a filter which is used for compensating the undesirable effect of ZOH device. Three cost functions have been considered in this study: 1.for reducing the phase delay 2.for increasing the robustness stability and 3.for reducing the phase delay and increasing the robustness stability at the same time. The simulation and experimental results show that the proposed optimal filter, compared with other methods, has a better performance in the low and medium frequency domain with any of these three cost functions.

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