

Improving the Active Power Filter Performance with a Prediction Based Reference Generation

M. Routimo, M. Salo and H. Tuusa

Abstract—In this paper a current reference generation method for a voltage source shunt active power filter is examined. The proposed method improves the harmonic filtering by compensating the delays in the system. In stationary operating point of the load the method uses measurement data sampled in previous periods to generate a reference prediction. Since in transient state of the load the prediction no longer holds true, a computational control delay compensation algorithm is used in the reference generation instead of the prediction in this situation. Changing the algorithm according to the operating point guarantees effective harmonic compensation in all operating points. In this paper the system performance is examined with an active filter simulation model.

Index terms—digital control, control delay, current reference generation, shunt active power filter

I. INTRODUCTION

IN recent years active power filters (APFs) have been widely studied and several methods to control them have been proposed, e.g. [1] – [4]. In harmonic filtering the active filter current reference generation plays an important role: if the reference is poor, a good filtering result cannot be achieved. A common problem in voltage source shunt active filters (Fig. 1) is their ability to filter only low order harmonics effectively. This is mainly caused by performing the digital control algorithm and sampling the measurement signals, which cause a delay. Because of this, the control is always late and the active filter cannot react fast enough to rapid changes in the load current. As a result the filtering of higher order harmonics is difficult but the compensation of lower order harmonics also deteriorates.

Methods to improve the active filter performance with prediction based current reference generation methods have been presented in the literature, e.g. [5] – [6]. In [5] the prediction is based on the measurements of dc link variables of the individual load. The method is very effective for harmonic filtering. However, with multiple loads the number of measurements is increased. In addition the system uses an artificial neural network in the reference generation, thus a lot of computing is needed. In [6] the active filter current reference is predicted based on the data sampled in the previous fundamental periods. The method is very effective with constant load, but if the load changes, the system performance deteriorates.

This paper presents a simple method to effectively compensate all the harmonics up to 2 kHz both in stationary

and transient states of the load. The method is based on the change of the reference generation algorithm according to the operating point. In the stationary state the reference generation is based on the prediction while in the transient state a computational control delay compensation method is used instead. The theory behind the proposed method is presented and it is applied to the control system of the voltage source shunt active power filter. The performance of the proposed method is examined with an active filter simulation model and the results are compared with other reference generation methods.

II. CURRENT REFERENCE GENERATION

In this section the active filter current reference generation methods for the control system based on the load current feedforward connection are examined. The control system is based on [7] and it is implemented in the synchronously rotating reference frame, which is tied to the supply voltage vector. The basic idea in reference generation for this kind of control system is to extract the harmonics from the measured load currents. They are taken negative to the active filter harmonic reference. In the reference frame the fundamental current component can be seen as a dc component and as a consequence the harmonics can be extracted with a high pass filter.

A. A Conventional Method

In a conventional method the harmonics are extracted with a high pass filter. In [7] the high pass filter is based on a fourth order Butterworth low pass filter, and in [8] and [9] to keep the extraction algorithm simple high pass filtering is realised utilizing the forward Euler discretized first order low pass filter. A block diagram of the system is illustrated in Fig. 2, where i_{id} is the measured load current real axis current component, i_{id0} a fundamental current component

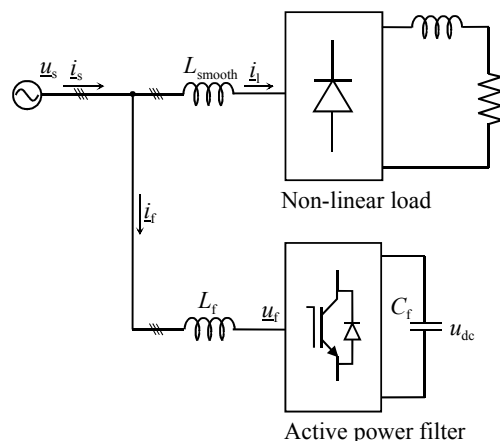


Fig. 1. Configuration of the voltage source shunt APF.

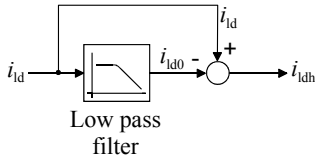


Fig. 2. Block diagram of the high pass filter.

and i_{ldh} the harmonics. Since the aim is also to compensate the reactive power, the load current quadrature component is not high pass filtered.

The main problem in the conventional method is that because the control system is implemented digitally, delays occur. Even if the high pass filter would perform perfectly, not all the harmonics could be filtered because of the delays. The high pass filter time constant is about 8 ms in [8] and [9]. That is, in the case of step change in the fundamental load current component it takes about 19 ms for the high pass filter to remove 90 % of the new dc value. In addition, the system cannot completely compensate the unbalance of the load currents (100 Hz component in the synchronous reference frame), because of the phase shift caused by the filter. This could be solved by choosing a bigger time constant, but this would lead to even longer response time.

B. Control Delay Compensation

A computational control delay compensation method is presented in [8] and [10]. The method improves the performance of the conventional method. The first step in the method is to extract the harmonics, for example, based on the conventional method and after that the current reference given by the high pass filter is modified so that the delay will be compensated.

In the method the active filter current reference is modified based on the knowledge of the filter current behaviour in a case of step change in the current reference. The reference is corrected so that the filter current behaves as desired. The algorithm can be written in discrete form as

$$\underline{i}_{fh}^{*s}(k+1) = -\frac{\tau_c}{T_s} \left(\underline{i}_{lh}^s(k) - \underline{i}_{lh}^s(k-1) \right) - \underline{i}_{lh}^s(k), \quad (1)$$

where \underline{i}_{fh}^{*s} is an active filter harmonic current reference, \underline{i}_{lh}^s load current harmonics in synchronous reference frame, τ_c is a compensation time constant, T_s sampling interval and k a discrete time instant. The system performs well both in stationary and transient state of the load and sinusoidal supply currents are achieved. A drawback of the method is that the high order harmonics increase.

C. Prediction

Symmetrical three-phase loads connected to sinusoidal mains cause harmonics of the order

$$n = 6p \pm 1, p \in [1, 2, 3, \dots]. \quad (2)$$

In the synchronous reference frame, which is tied to the supply voltage vector, they are seen as the supply frequency multiples of the orders

$$n^s = 6p. \quad (3)$$

That is, when the load operates in stationary state and the system is examined in the synchronous reference frame, the load current frequency can be seen as a dc quantity with a ripple caused by the harmonics. The period of the ripple is

$$T_r = 1/(n_{\min}^s f_s), \quad (4)$$

where n_{\min}^s is the lowest order harmonic in the synchronous reference frame and f_s the supply voltage frequency. According to this the load current behaviour at the next sampling instant could be predicted based on the load current sampled in the last period T_r .

Unbalanced load currents can be divided into positive and negative sequence components. In the synchronous reference frame the positive sequence current can be seen as a dc component and the negative as a harmonic with a frequency of $2f_s$. To also observe the unbalance of the phase currents, the prediction should be done on the basis of the load current measured time $T_u = 1/2f_s$ ago. Since the period T_u is a multiple of T_r , both the harmonics and unbalance can be predicted using the data collected during last T_u .

The delay caused by sampling the measurement signals and performing the control algorithm can be approximated to be about $1.5T_s$, where T_s is the sampling interval. Since in the discrete time system only multiples of the sampling interval can be handled, the delay is rounded to $2T_s$. Let us assume that we have stored m samples of the load current performance in a table during the last period T_u . According to the discussion above, we can now predict the load current performance at the next sampling instant $t(k+1)$ and compensate the control delay by using the data measured at time instant $t(k-(m-2))$. This yields the active filter current reference equations:

$$\underline{i}_{rdh}^*(k+1) = \underline{i}_{ld0}(k) - \underline{i}_{ld}(k-(m-2)) \quad (5)$$

$$\underline{i}_{rdq}^*(k+1) = -\underline{i}_{ldq}(k-(m-2)), \quad (6)$$

where k denotes a discrete time instant, m the number of samples in one period T_u and \underline{i}_{ld0} the fundamental load current component in the synchronous reference frame. The prediction made based on the data sampled in the previous period applies to the operating point where the load is in stationary state. If the load changes problems occur, since the prediction is no longer valid.

D. The Proposed Method

A solution for the drawback in the prediction method is to use the prediction in stationary operating point and a more robust reference generation algorithm under the transient state operation. As was discussed, the computational control delay compensation method also performs well in transient state operation. That is why we choose to use the method in the transient state. Although a drawback of the method is that the high order harmonics increase, this is not a problem since we will use the CDC method for only a while, that is during the transient state of the load. The prediction is used to generate the reference in the stationary operating point.

Since the two algorithms are used in the current reference generation, the control system has to know whether the load is in transient state or not. This can be done comparing the measured load current to the value that is measured one period ago. In the stationary state we have

$$\underline{i}_l^s(k) - \underline{i}_l^s(k-m) = 0. \quad (7)$$

In any case, because of the inaccuracies in the system (e.g. measuring noise), the new and the old current do not necessarily have exactly the same values. In the implementation of the system the condition of the transient becomes

$$\left| \underline{\hat{i}}_1^s(k) - \underline{\hat{i}}_1^s(k-m) \right| > \underline{e}_{\max}, \quad (8)$$

where \underline{e}_{\max} defines the accepted maximum error between the new and the old values.

1) Floating Average

To make the reference prediction we have stored measurement data of the load currents in the memory. Thus the fundamental load current component can be determined calculating the average of the samples of the load current. To compensate the reactive power, only the load current d axis component is high pass filtered. The floating average algorithm is then

$$\begin{aligned} i_{ld0}(k) &= \frac{1}{m} \sum_{k-(m-1)}^k i_{ld}(k) \\ &= \frac{1}{m} i_{ld, \text{sum}}(k) \\ &= \frac{1}{m} [i_{ld, \text{sum}}(k-1) - i_{ld}(k-m) + i_{ld}(k)] \end{aligned} \quad (9)$$

If the dc component is calculated as an average of the m samples collected during the time period $T_u = 1/2f_s$ (10 ms with $f_s = 50$ Hz), this kind of low pass filter completely damps all the frequencies that in the synchronous reference frame are multiples of $2f_s$. This holds true with half wave symmetrical load currents. If this cannot be assumed, the measurement data collected during the whole fundamental period has to be used. In the case of step change in the fundamental load current component, the new dc value will be removed after m samples. As a conclusion, with a high pass filter based on the floating average all the harmonics in the load current, including that caused by an unbalanced load, can be extracted without any damping in magnitude or phase shift.

III. CONTROL SYSTEM

The proposed current reference generation method is used in the control of a voltage source shunt active power filter. The control system is introduced in Fig. 3. Subscripts s, l and f refer to supply, load and active filter variables respectively, h to harmonics and 0 to fundamental frequency quantities in synchronous reference frame. Underlined variables refer to space vectors, the superscript s to a space vector in synchronously rotating reference frame, * to reference value and subscripts d and q to real and quadrature components respectively.

The system is based on the load current feedforward connection. The measured load current $\underline{\hat{i}}_l$ is first transformed to the synchronous reference frame with a block "3 → 2". The reference frame angle θ_s is determined with a phase locked loop (PLL) by observing the supply voltage \underline{u}_s . The current reference to compensate the harmonics is generated with the block "Reference Generation". The content of the block is presented in Fig. 4. In the figure block "Average" calculates the floating average according to Equation (9) and the block "Table" gives the load current values sampled $m - 2$ time instants ago. The current reference $\underline{\hat{i}}_{fh}^{*s}(k+1)$ is calculated using Equations (5) and (6) and another reference candidate using the control delay compensation method presented in Equation (1). The error signal $\underline{e}(k)$ is calculated to find out if the load operates in transient state. A switch in

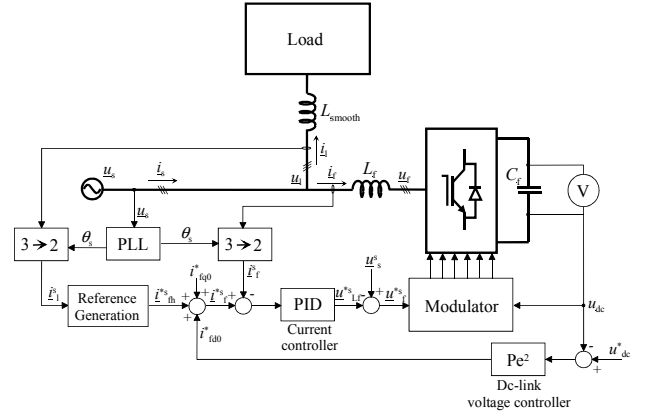


Fig. 3. Control system block diagram.

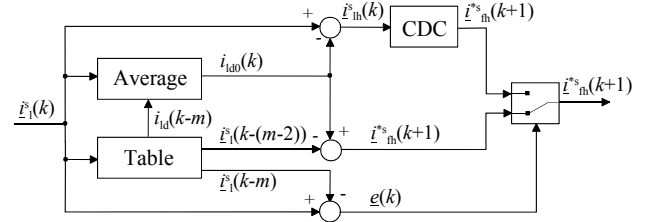


Fig. 4. Block diagram of the reference generation.

the figure uses this information to decide which one of the two reference candidates is used in the active filter current control.

The APF dc link voltage is controlled with a fundamental frequency d axis current reference component \underline{i}_{fd0}^* . This is a dc quantity in a synchronously rotating reference frame and it is added to the harmonic reference $\underline{\hat{i}}_{fh}^*$. The reactive power can be controlled with a fundamental frequency q axis reference \underline{i}_{fq0}^* . A PID controller is used in closed-loop control of the filter currents $\underline{\hat{i}}_f$. Finally the active filter voltage reference \underline{u}_f^* is produced by subtracting the filter inductor voltage reference \underline{u}_{Lf}^* from the supply voltage \underline{u}_s^* .

IV. SIMULATION RESULTS

The performance of the proposed current reference generation method was examined through simulations. The simulation model was made using Matlab / Simulink. The modelled voltage source shunt active power filter was designed to compensate harmonics caused by a nonlinear load of 5 kVA nominal power. The simulation model parameters are shown in Table I.

A. Stationary State Operation

First an active filter performance was examined in stationary state operation. A three-phase diode rectifier with an RL load was used as a harmonic producing load. The load resistance was 64 Ω and the inductance 10 mH. A phase-a load current waveform is presented in Fig. 5a.

In simulations three different methods to control the active filter were used. Figure 5b presents a phase-a supply current, when a method based on [7] has been used. Glitches can be seen in the supply current waveform at time instants when the load current changes suddenly. They are caused by the delays and the active filter system dynamics. The harmonic content of the waveforms in Fig. 5 is presented in Table II.

The computational control delay compensation method

(CDC) improves the active filter performance [8]. The filtering result can be seen in Fig. 5c. The glitches have now been reduced and the harmonic distortion calculated up to 2 kHz (THD_{2 kHz}) has been halved. Although the filtering performance with the low order harmonics has been improved, the high order harmonics have been increased. This can be seen in Table II, where the THD calculated up to 20 kHz remains almost constant regardless of whether the conventional or the CDC method is used.

TABLE I
ACTIVE FILTER PARAMETERS

Supply phase voltage U_s	230 V
Supply frequency f_s	50 Hz
Filter inductor L_f	5 mH
Filter inductor resistance R_f	0.3 Ω
Dc link capacitor C_f	1.1 mF
Smoothing inductor L_{smooth}	2.3 mH
Switching frequency f_{sw}	10 kHz
Sample time T_s	50 μ s
Samples stored in memory m	200
Compensation time constant τ_c	$2T_s$
Maximum accepted d axis error e_{dmax}	1.5 A
Maximum accepted q axis error e_{qmax}	2.0 A

TABLE II
HARMONIC CURRENT COMPONENTS

n	RL Load $i_{la(n)}/i_{la(1)}$ [%]	Shunt APF $i_{sa(n)}/i_{la(n)}$ [%]	Shunt APF with CDC $i_{sa(n)}/i_{la(n)}$ [%]	Proposed Method $i_{sa(n)}/i_{la(n)}$ [%]
5	21.7	11.9	1.0	1.7
7	11.1	16.5	8.0	2.8
11	7.6	26.3	7.5	3.4
13	5.6	28.5	12.4	3.9
17	3.8	40.0	20.7	3.7
19	3.2	43.1	25.5	4.0
23	2.0	55.6	42.1	4.2
25	1.8	59.9	47.5	3.9
29	1.1	75.0	74.4	7.4
31	1.0	80.2	81.6	5.7
35	0.7	104.0	121.6	13.4
37	0.6	108.4	132.6	10.9
THD _{2 kHz}	26.8	5.0	2.7	0.7
THD _{20 kHz}	26.8	7.8	7.1	4.6

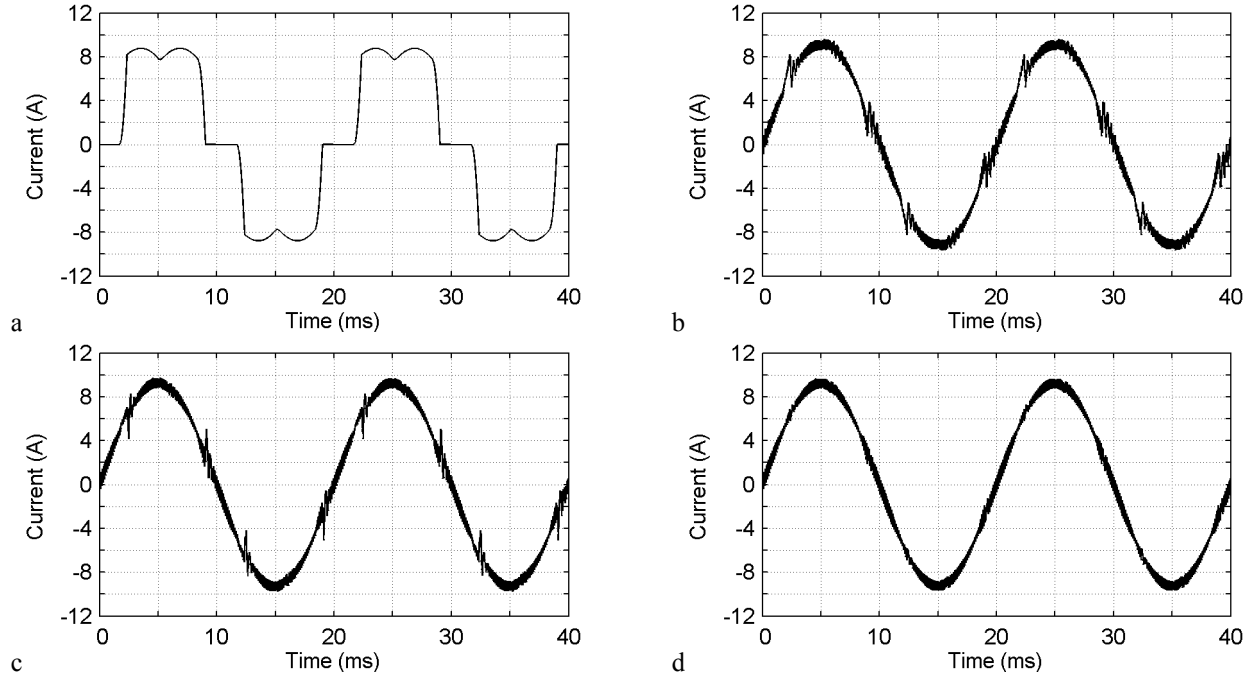


Fig. 5. Simulated phase-a current waveforms in stationary state operation. a) Load current. b) Supply current with a conventional method. c) Supply current with computational control delay compensation method. d) Supply current with the proposed reference generation method.

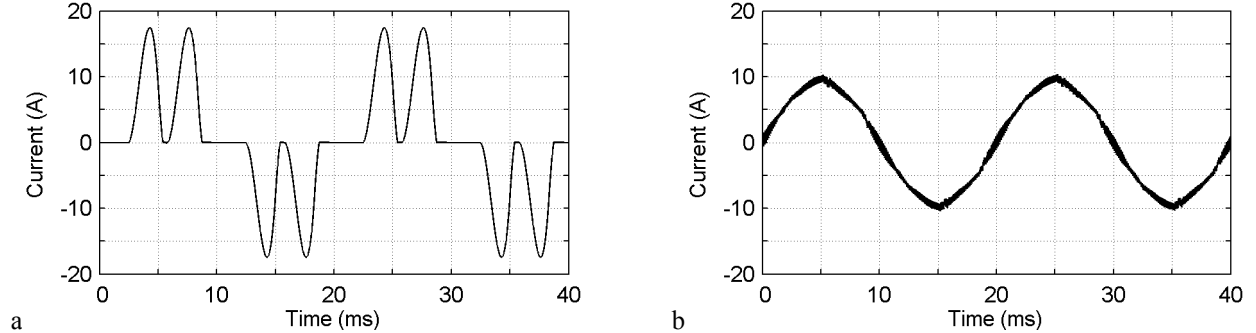


Fig. 6. Simulated phase-a current waveforms, when a diode rectifier supplies an RC load. a) The load current. b) The supply current with the proposed method.

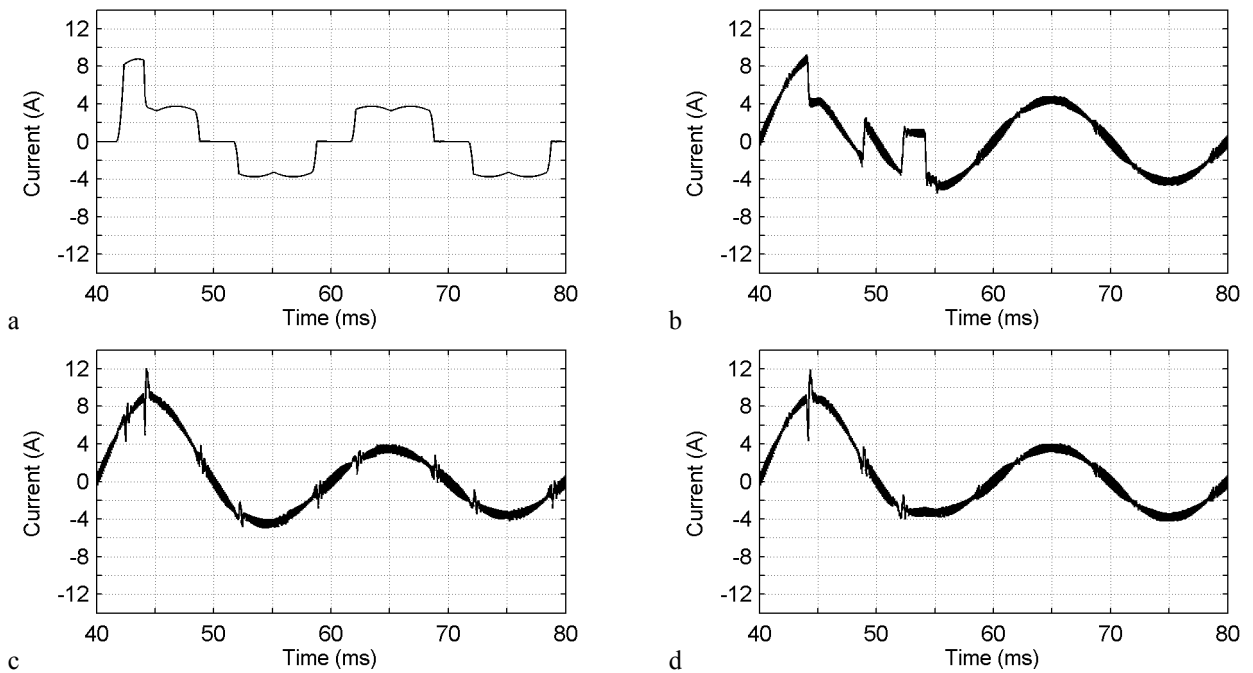


Fig. 7. Simulated phase-a current waveforms in transient state. a) The load current. b) The current reference is generated using a pure prediction. c) The control delay compensation method is used. d) The proposed method is used.

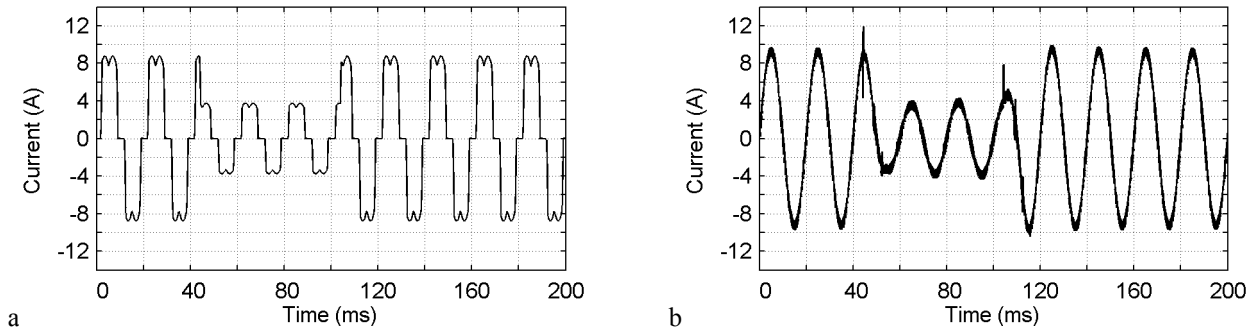


Fig. 8. Simulated phase-a current waveforms of transient state operation when the proposed method is used. a) Load current. b) Supply current.

When the proposed prediction based current reference generation has been used, the resulting supply current waveform can be seen in Fig. 5d and the harmonic content of that in Table II. Thanks to the prediction, effects of control delays have been completely compensated and all the harmonics up to 2 kHz have been effectively filtered. Figure 6 demonstrates that harmonics of RC type load have also been effectively reduced.

B. Transient State Operation

As was discussed previously, a purely prediction based reference generation causes problems if the load changes. Figures 7a and b illustrate this situation. It can be seen that since the load changes at time instant 44 ms, the prediction no longer holds true. This results in a highly distorted supply current. Figure 7c demonstrates that the computational control delay compensation method also performs well in the transient state operation and the supply current is also kept sinusoidal at this operating point. Thus the proposed current reference generation method combines these two methods: in stationary state operation the reference is generated using the prediction and in transient state using the CDC method. The result is shown in Fig. 7d. It can be seen in the figure that the supply current is kept sinusoidal in both of the operating points. If the load

changes stepwise, the new operating point is found in 10 ms, as can be seen. The CDC method is in use during this time interval. Figures 8a and b demonstrate the proposed method performance in the case of two changes in the load. It can be seen that the method performs very well.

V. CONCLUSIONS

An active power filter current reference generation method was examined in this paper. In stationary harmonic compensation condition the method predicted the current reference on the basis of the data collected during the previous period. When the load changed and the prediction was not valid, the computational control delay compensation method was used. Both the algorithms were simple and no complicated computation was needed.

The performance of the proposed current reference generation method was examined with simulation model and the results were compared to other methods. Both the stationary and transient state operations were examined. The results showed that with the proposed method sinusoidal supply currents with a low harmonic distortion were achieved both in stationary and transient state operation.

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