CHAPTER 8

AN ON-LINE ADAPTIVE CURRENT HARMONIC ELIMINATION OF A VSI DRIVE USING RECURSIVE LEAST SQUARE ALGORITHM

8.1 INTRODUCTION

The elimination of LOH is an important issue in many applications where low switching-frequency PWM patterns are preferred. Even though many online modulation techniques have been extensively studied, online current harmonic elimination methods are the straightforward ways to improve the performance especially in applications such as drives as mentioned in Chapter 7. The merits of SHEPWM includes (i) There is a reduction in switching frequency of about 50% when compared to conventional NSPWM strategies and hence lowering the switching losses, and (ii) As the quality of the output voltage and current is improved, the ripple in the DC link is small. Hence the size of the DC link filter is reduced. A systematic and sequential approach to overcome difficulty of solving the SHE transcendental equations through polynomial mapping and followed by reduction. A way for conjuring up a notch filter action for the selected frequencies through weights amendment using LMS algorithm has been detailed in Chapter 7 and it is a successful SCHE scheme.
8.2 PROBLEM IDENTIFICATION

Harmonics in the front end rectifier of three-phase VSI based drive prevents the power system pollution. The harmonic elimination scheme must work evenly well for different loading conditions of the motor, any PWM strategies employed in VSI, DC link voltage of both constant and fluctuating cases etc. Hence the scheme must be an on-line self adaptive one. A successful amendment of LMS based adaptive filtering algorithm for the SCHE is reported. Among the adaptive algorithms, the LMS algorithm is the most popular one. However, the LMS algorithm suffers from slow and data dependent convergence behaviour and its variant, the RLS algorithm exhibits a better balance between simplicity and performance. To improve the ability of on-line input current harmonic elimination scheme, the RLS algorithm is used instead of LMS.

8.3 ADAPTIVE ALGORITHM FOR SELECTIVE HARMONIC ELIMINATION

RLS based adaptive filters have wide applications in channel equalization, voice and modems, digital mobile radio, beam forming, and speech and image processing. Traditionally, LMS is the more commonly used algorithm in adaptive filtering applications. A limitation of the LMS algorithm is that it does not make full use of the information available to it. Consequently, it has a much slower convergence rate. The convergence of the LMS algorithm is also very sensitive to the eigen value spread of the correlation matrix of the input data. The convergence of the RLS algorithm is an order of magnitude faster than the LMS algorithm, but its computational complexity is an order of magnitude higher than LMS. As the earlier restriction on RLS algorithm viz. high speed computational platform is overcome by the recent developments in digital technology. The RLS algorithm has almost practically replaced the LMS algorithm. This
performance enhanced properties of RLS algorithm is due to the fact that in contrast to the LMS algorithm, the RLS algorithm uses information from all past input samples (and not only from the current tap-input samples) to estimate the (inverse of the) autocorrelation matrix of the input vector. To decrease the influence of input samples from the far past, a weighting factor for the influence of each sample is used.

**8.3.1 Recursive Least Squares Algorithm (RLS)**

Least-squares algorithms aim at the minimization of the sum of the squares of the difference between the desired signal and the model filter output. When new samples of the incoming signals are received at every iteration, the solution for the least-squares problem can be computed in recursive form resulting in the RLS algorithms. Figure 8.1 shows the application of RLS algorithm in power converter based systems.

![Figure 8.1 RLS algorithm in power converters](image)

The task of eliminating an undesirable harmonic component from a signal in DSP can be done by the ASHE algorithm or filter. The filter, shown in the following Figure 8.2 consists of a combiner, a RLS algorithm, and a summing point. It operates as follows.
(i) The reference signal either using one component or with two orthogonal components cosine and sine ($X_a$ and $X_b$) having the frequency $\omega_o = 2\pi f_o$ is to be eliminated from input signal $D_k$. $T$ is a sampling period and $K$ is a discrete time index.

(ii) The reference input ($X_a$ and $X_b$) is multiplied with corresponding weights ($W_a$ and $W_b$). The weighted sine and cosine components of reference signal are combined / added together to match amplitude and phase angle of interfering sinusoid in the primary input $D_k$. Adaptation process adjusts weights to exactly match amplitude and phase of the interference.

(iii) The signal $Y_k$ created by a combiner, is subtracted from the primary input $d_k$ (signal to be filtered) and eliminated from the output of the filter $e_k$.

Figure 8.2 Structure of single frequency ASHE cancelling filter
8.3.2 Formulation of RLS Algorithm

The objective here is to choose the coefficients of the adaptive filter such that the output signal $Y(k)$ during the period of observation will match the desired signal as closely as possible in the least-square sense. The minimization process requires the information of the input signal available so far. Also the objective function to minimize is deterministic. The input signal information vector at a given instant $k$ is

$$X(k) = [x(k) x(k-1).....x(k-n)]^T$$  \hspace{1cm} (8.1)

Where, 'n' is the order of the filter. The deterministic objective function is given by

$$\varepsilon^2 (i) = \lambda^{k-i} \varepsilon^2(i)$$  \hspace{1cm} (8.2)

Where, $i = 0$ to $k$.

$$\varepsilon(i) = d(i) - X^T (i) w(k)$$  \hspace{1cm} (8.3)

$$w(k) = \begin{bmatrix} w_o(k) & w_1(k) & .... & w_n(k) \end{bmatrix}^T$$  \hspace{1cm} (8.4)

where $w(k)$ is the adaptive filter coefficient vector. The coefficients $w_i(k)$, for $i= 0,1, \ldots, n$, are adapted aiming at the minimization of objective function. $\varepsilon(i)$ is the posteriori output error at instant $i$. The parameter $A$ is an exponential weighting factor since the information of the distant past has an increasingly negligible effect on the coefficient updating. Each error consists of the difference between the desired signal and the filter output, using the most recent coefficients $w(k)$. By differentiating Equation (8.3) with respect to $w(k)$ and equating it to zero it is possible to find the optimal vector $w(k)$ that minimizes the least-squares.
\[ w(k) = \left[ \lambda^{k-i} x(i)x^T(i) \right]^{-1} \lambda^{k-i} x(i)d(i) = R_D(k)^{-1} P_D(k) \]  

(8.5)

Where, \( R_D(k) \) and \( P_D(k) \) are called the deterministic correlation matrix of the input signal and the deterministic cross-correlation vector between the input and desired signals respectively. The Figure 8.3 shows the procedure of RLS algorithm. The complete system of implementation is shown in Figure 8.4. To enable more clarity in results discussion, the waveform measuring points are marked as stages 1 to 12.

Figure 8.3 Step by step procedure of RLS algorithm
8.4 RESULTS OF SIMULATION STUDY

The three phase VSI fed drive is simulated with uncompensated dead time without and with ASHE algorithms. Figure 8.5 to Figure 8.16 show the various signals/waveforms in the implementation of RLS algorithm based SCHE for induction motor drive respectively from stage 1 to stage 12. The harmonic spectrum of the source current is shown in Figure 8.17.
Figure 8.5 Stage 1 (output waveforms)

Figure 8.6 Stage 2 (abc to dq - stationary)
Figure 8.7 Stage 3 (dq-stationary to dq-rotationary)

Figure 8.8 Stage 4 (weight of RLS fundamental)
Figure 8.9 Stage 5 (Weight of RLS 5\textsuperscript{th} harmonics)

Figure 8.10 Stage 6 (Weight of RLS of 7\textsuperscript{th} harmonics)
Figure 8.11 Stage 7 (Output of MF SHE block)

Figure 8.12 Stage 8 (System corrected d & q current component in synchronously rotating frame)
Figure 8.13 Stage 9 (dq- rotationary to dq- stationary)

Figure 8.14 Stage 10 (Selected harmonics cancelled reference (d & q components) in stationary frame)
Figure 8.15 Stage 11 (dq - stationary to abc)

Figure 8.16 Stage 12 (PWM)
The Table 8.1 compares triumph of RLS based scheme with the LMS based one. The results confirm the superiority of the RLS based scheme. The LMS algorithm brought the specific harmonic components below 5% while the RLS could eliminate them completely. Both the adaptive algorithms additionally minimize THD; their deductions are 34% and 94% respectively in LMS and RLS algorithms.

Table 8.1 Performance comparison of ASHE schemes

<table>
<thead>
<tr>
<th>Harmonic order</th>
<th>Without ASHE</th>
<th>LMS based ASHE</th>
<th>RLS based ASHE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>39.59</td>
<td>3.81</td>
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<td>7</td>
<td>15.23</td>
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<tr>
<td>11</td>
<td>7.97</td>
<td>2.28</td>
<td>0.56</td>
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<tr>
<td>THD</td>
<td>87.75</td>
<td>57.84</td>
<td>5.70</td>
</tr>
</tbody>
</table>

Figure 8.17 Source current and spectrum with RLS-ASHE
8.5 SUMMARY

An algorithm to generate unconstrained PWM patterns to successfully eliminate selected source current harmonics in VSI fed drives is formulated. The adaptive filtering of SCHE based on RLS is successfully implemented in MATLAB/Simulink software package. The RLS method eliminates the dominant harmonics in line current and it requires only the knowledge of the frequency of the particular harmonic to be eliminated. The algorithm also reduces the THD up to 5%.