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Enhanced Harmonic Detection and Compensation in Three-Phase Power Systems using ADALINE and Improved LMS Algorithm

[1]Varsha Choudhari
M.Tech Student
Department of Electrical Engineering
PES Modern College of Engineering
Pune, India

[2]Prof. Madhura Tuljapurkar
Assistant Professor
Department of Electrical Engineering
PES Modern College of Engineering
Pune, India

Abstract—This paper proposes an adaptive harmonic detection and compensation algorithm of a three-phase shunt active power filter (SAPF) based on Adaptive Linear Neuron (ADALINE) and an Improved Least Mean Square (LMS). A nonlinear rectifier load is connected to a 400 V, 50 Hz supply, with compensation current being injected at the point of common coupling through the SAPF. The study compares the phase-wise total harmonic distortion (THD), error comparison, RMS current, peak current, magnitudes of the different harmonic factors and crest factor. ADALINE achieved THD values of 1.6914%, 1.5453% and 1.7773%, giving an average THD of 1.6713%. The average THD for the Improved LMS was 30.923%. The results show that the ADALINE-based SAPF is better in suppressing the harmonics and reducing the current stress under the tested nonlinear-load conditions.

Keywords—ADALINE, Improved LMS, shunt active power filter, harmonic detection, THD, MATLAB/Simulink, power quality.

I. INTRODUCTION

Today's three-phase distribution systems are increasingly being used to provide power to nonlinear loads, including rectifiers, adjustable-speed drives, switched-mode supplies, UPS, and renewables converter[1], [2]. When a sinusoidal voltage is applied to the circuits, these devices draw no sinusoidal currents[3]. The distorted current cause voltage distortion at the point of common coupling (PCC), due to the influence of feeder impedance[4], [5]. Consequences are transformer overheating, extra cable losses, overloading of neutral conductors, nuisance operation of protection systems and loss of reliability of sensitive loads[6], [7].

Passive tuned filters are very simple to design but are very sensitive to component tolerances and system impedances[8]. The advantage of shunt active power filters is that they can synthesize compensating current in real time to respond to changes in load conditions[9], [10]. The quality of an SAPF is highly dependent on the accurate extraction of harmonics, generation of the current reference and the tracking of the currents in the inverter, the DC-link voltage control[11]. The adaptive algorithms are thus desirable as they can adjust the reference signal when the load current changes[12], [13].

This work makes the simulation of the thesis into a concise conference paper in IEEE format. The same modelling concept and numerical values are used: a 3-phase, 400-V source feeds a nonlinear rectifier load; and two adaptive controllers are tested under the same conditions[14], [15]. The aim is to find out which of the two algorithms (ADALINE or Improved LMS) provides lower distortion, lower error and lower current stress in the selected SAPF network[16], [17].

II. RELATED WORK

The most common classical harmonic detection methods are the discrete Fourier analysis, and the p-q theory and synchronous-reference-frame methods. Although mathematically proven, they can be affected by the filtering delay, phase locked loop characteristics and parameter tuning. To increase convergence under time-varying NL loads, adaptive neural and LMS methods have been proposed[18], [19].

Janpong et al. designed an ADALINE harmonic detector for SAPF reference-current generation and they reported reliable real time harmonic extraction[6]. Garanayak et al. suggested a master-slave ADALINE for harmonic and interharmonic estimation, where transient and steady adaptation were separated, which led the master and slave algorithms to higher accuracy[20], [21]. In a three-phase four-wire DSTATCOM, Penthia et al. experimented with ADALINE-LMS control[22]. Adaptive DSTATCOM, variable-step LMS, modified leaky LMS and active-filter control for renewable-integrated power systems are also studied recently[23]. But several studies focus exclusively on THD. The present paper has merged THD, MSE, RMSE, MAE, RMS current, peak current, crest factor and the magnitude of harmonic for a comprehensive comparison[24], [25].

III. METHODOLOGY AND SYSTEM CONFIGURATION

The study is designed as a quantitative study based on MATLAB/Simulink. The supply used is balanced 3-phase 400 V 50 Hz. The low-order harmonics characteristic of a six-pulse rectifier make up the nonlinear load. The SAPF is in shunt at the PCC via a voltage-source inverter (VSI), DC-link capacitor, coupling inductor, measurement blocks and hysteresis-band current controller. After Clarke transformation and computation of instantaneous power, the measured voltage and current signals are processed.

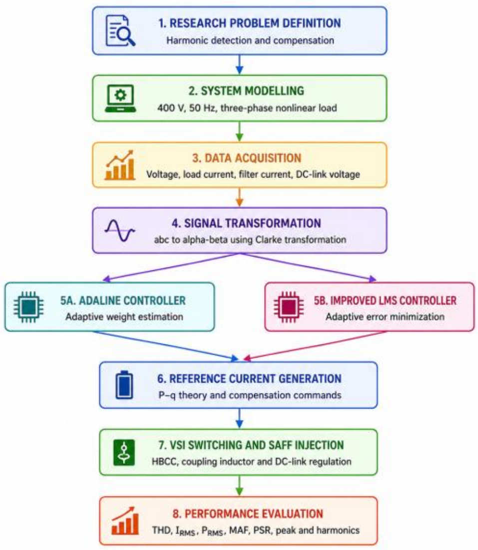

Fig. 1. Methodology flowchart for adaptive harmonic detection and compensation.

The modelling and validation cycle is summarised in Fig. 1. First the source, then the nonlinear load is defined; and then voltage, load current, filter current and DC-link voltage are measured. The quantities abc are converted into the fixed frame of reference alpha-beta. AdaLIN and Improve LMS are then used for adaptive estimation and compensation-current generation. Final stage test results measure THD, RMS current, peak current, crest factor and tracking errors, allowing for both power quality and stability of the controller to be assessed.

TABLE I. RESEARCH DESIGN AND SOURCE PARAMETERS

Item	Value/Description
Research type	Quantitative simulation-based SAPF study
Power system	Three-phase, 400 V, 50 Hz supply
Load type	Nonlinear six-pulse rectifier load
Filter topology	Three-phase shunt active power filter
Controllers	ADALINE and Improved LMS
Phase voltage	230.94 V RMS; 326.60 V peak
Angular frequency	314.16 rad/s
Evaluation indices	THD, MSE, RMSE, MAE, RMS, peak and crest factor

The simulation is based on four measurable signal groups. The first group includes source voltages and load currents, that represent the distortion entering the PCC. The second group are compensating filter currents that are generated by the voltage source inverter. The third group includes DC-link voltage and controller internal signals that indicate if there is enough energy available in the converter for compensation. The fourth group includes harmonic and error outputs, which are employed to compare the performance of both adaptive algorithms, for the same time window.

No external substitute data is added to get a fair comparison. The results of the model, which are the original phase-wise results, are used to judge each controller individually. This provides the study with a certain reproducibility: All tables and figures can be traced back to the same arrangement of load, source, filter and measurement. The methodology is hence presented following the requirement of the IEEE conference template which includes a brief problem statement, system configuration, and results and referenced interpretation.

IV. MATHEMATICAL MODELLING AND CONTROL DESIGN

In a balanced source, the three phase voltages are sinusoidal and 120 degrees apart. The nonlinear rectifier current is separated into the fundamental and harmonics. Total harmonic distortion equals the ratio of the RMS value of all the harmonic components to the RMS value of the fundamental current:

$$THD = \sqrt{I_2^2 + I_3^2 + \dots + I_n^2} / I_1 \times 100\%. \quad (1)$$

The Clarke transformation is used to transform the abc currents into the stationary frame of the alpha-beta axes, for easier calculation of instantaneous active and reactive power. This compensating command is produced by splitting up the oscillatory power components and reconverting them to reference currents. A hysteresis-band current control subsequently forces the current of the inverter to track the reference within the allowed range.

$$W(k+1) = W(k) + \mu\, e(k)\, X(k). \quad (2)$$

The distorted current is expressed as a linear combination of sines and cosines in the ADALINE estimator. The weight vector W is updated by an LMS-type rule as shown in (2) with the learning rate mu, the estimation error e(k) and the input vector X(k). The Improved LMS case applies tuning or normalizing corrections to the LMS case to increase the stability of the adaptation. In the current simulation, however, the set ADALINE parameters approach a lower residual harmonic value.

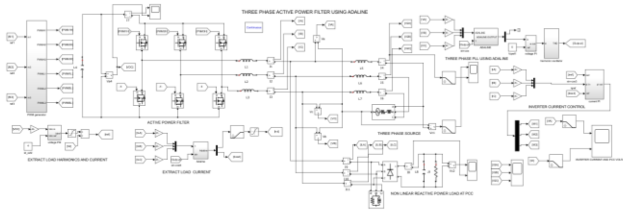

Fig. 2. Three-phase SAPF simulation model using ADALINE control.

The following blocks are included in this active power filter model, namely source, nonlinear load, reference-current generation, current controller and harmonic analyzer (SAPF model, Fig. 2). Evaluation is done using the same architecture, so that it is possible to trace the model and numerical results.

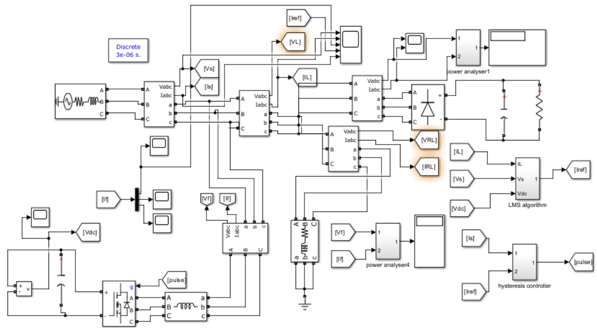

Fig. 3. Shunt active filter model arrangement used for LMS-based compensation.

The arrangement shown in Fig. 3 is similar to the above one, but contains the same source and nonlinear-load environment and an adaptive filtering block for the error minimization. It is critical to keep the measurement path the same as the difference in THD reported may be a result of changing the model, not the controller behaviour. It also shows that both control schemes utilize current sensing, voltage sensing, inverter actuation and output harmonic analysis.

TABLE II. SAPF DESIGN ELEMENTS AND CONTROL FUNCTIONS

Element	Function	Effect
DC-link capacitor	Stores inverter energy	Maintains compensation capability
PI controller	Regulates DC-link voltage	Limits voltage drift
HBCC	Tracks reference current	Gives fast current response
Coupling inductor	Connects VSI to PCC	Reduces switching ripple
Power analyzer	Measures phase THD	Validates harmonic mitigation

TABLE III. ADAPTIVE CONTROLLER IMPLEMENTATION LOGIC

Stage	ADALINE	Improved LMS
Input signal	Distorted load/filter current	Measured current and reference error
Core operation	Weight estimation using sinusoidal basis	Adaptive coefficient correction
Output	Estimated fundamental and harmonic components	Filtered error-minimized current command
Strength	Fast harmonic component separation	Simple iterative adaptation
Limitation	Depends on selected basis and learning rate	Sensitive to step size under ripple

As shown in Table III, both controllers are adaptive, but operate in different ways. LMS just tries to make an iterative adjustment to the coefficient so that the output error is minimized, while ADALINE explicitly estimates the signal components by learning the weights. In real implementation of the SAPF control, the algorithm producing lower residual harmonic content and lower peak current is the better choice, since it will alleviate the stress on the converter and maintain the compensated current closer to the sinusoidal reference.

V. RESULTS AND DISCUSSION

The main result is that the harmonic suppression achieved by ADALINE is much better than the Improved LMS controller for the selected tuning. ADALINE recorded phase

THD values of 1.6914%, 1.5453% and 1.7773% for phases A, B and C. The corresponding Improved LMS values were 31.535%, 28.828% and 32.406%. The average THD thus dropped to 1.6713% in the ADALINE case from the value 30.923% in the Improved LMS case.

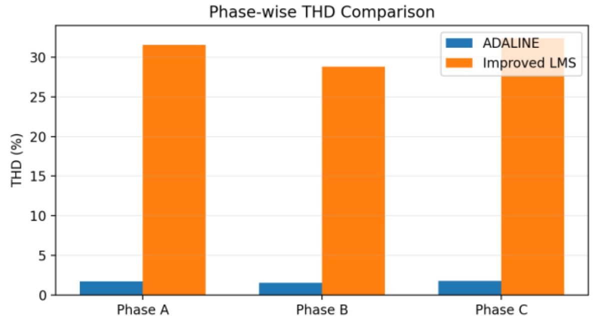

Fig. 4. Phase-wise THD comparison of ADALINE and Improved LMS controllers.

TABLE IV. PHASE-WISE THD AND TRACKING ERROR COMPARISON

Phase	ADALINE THD (%)	Improved LMS THD (%)	MSE ADALINE	MSE LMS
A	1.6914	31.535	16.144	39.795
B	1.5453	28.828	15.224	33.022
C	1.7773	32.406	17.425	45.734
Average	1.6713	30.923	16.264	39.517

Table IV shows that the THD and the mean square error of the ADALINE controller are lower in all phases. The difference is not small: The average reduction of THD is approximately 29.25 percentage points compared to the Improved LMS case. The lower error values also indicate that the ability of the reference current tracking is more accurate for ADALINE. This behavior is expected since the fundamental and selected harmonic components can be directly estimated, and the Improved LMS response is more strongly affected by the step-size tuning and residual ripple.

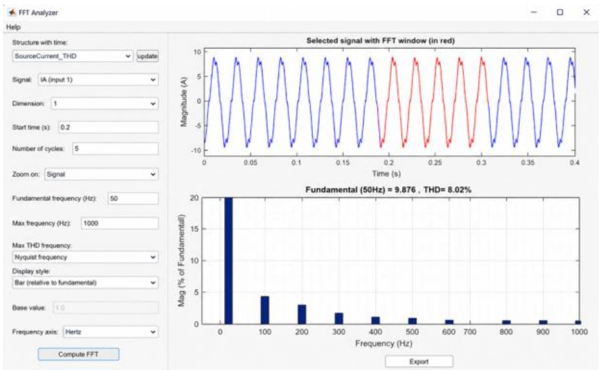

Fig. 5. ADALINE harmonic spectrum and THD measurement output.

The numerical THD results are backed up with the figure 5. After ADALINE compensation the fundamental component is still dominant and the harmonic bars are relatively small. The periodicity in the waveform window is also stable after the controller is in steady state. This is significant because this numerical THD is only meaningful if the time-domain waveform is smooth and stable.

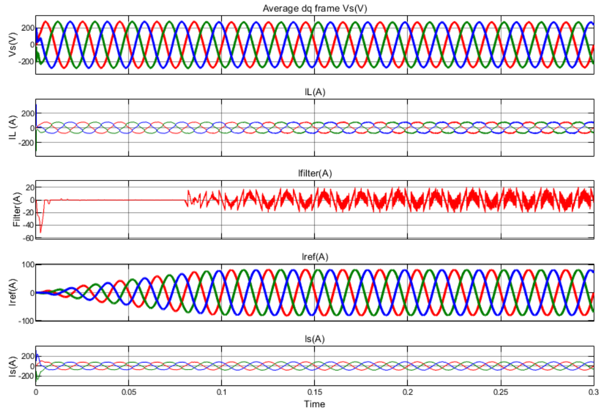

Fig. 6. Improved LMS current waveform response under the same operating condition.

Residual oscillations and larger ripple can be seen in the filter-current path in the Improved LMS waveform of Fig. 6. This is the reason for the fact that its THD is still high in Table IV. The result indicates that the performance of the compensation for the Improved LMS controller will need to be carefully tuned before a comparable performance to the ADALINE can be realized.

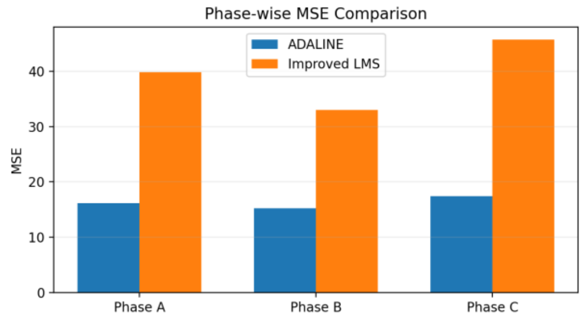

Fig. 7. Phase-wise MSE comparison of ADALINE and Improved LMS.

In all three phases the tracking error of ADALINE is lower as depicted in the MSE graph (Fig. 7). Lower MSE is better as it means that the estimated compensating current is closer to the required reference current. Similarly, in an inverter-based compensator this also helps to minimize unnecessary switching demand and enhance the quality of injected current.

ADALINE also has a better performance in the current-stress evaluation. The average RMS current of ADALINE is 18.822A whereas Improved LMS is 20.818A. The average peak current drops from 37.753 A to 28.738 A and the average crest factor drops from 1.8137 to 1.5268. These reductions show that not only is there a reduction in distortion, but also reductions in the maximum stress placed on the converter and line components.

TABLE V. RMS, PEAK CURRENT AND CREST FACTOR SUMMARY

Parameter	ADALINE	Improved LMS	Observation
Average RMS current (A)	18.822	20.818	Lower current stress
Average peak current (A)	28.738	37.753	Lower switching stress
Average crest factor	1.5268	1.8137	Smoother waveform
Average RMSE	4.0314	6.2725	Improved tracking
Average MAE	1.6265	5.4263	Lower estimation error

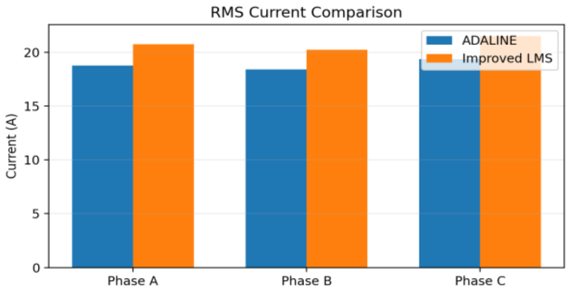

Fig. 8. RMS current comparison for the three phases.

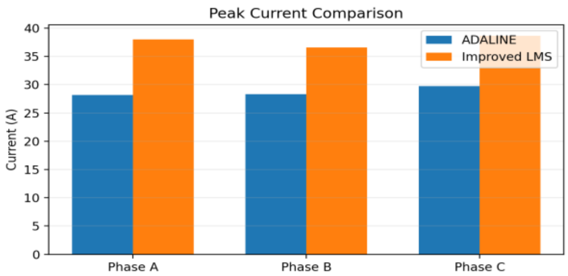

Fig. 9. Peak current comparison for the three phases.

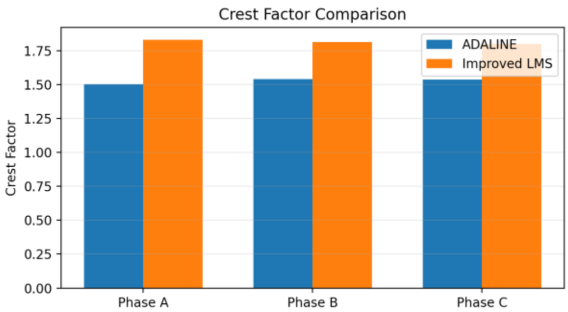

Fig. 10. Crest factor comparison for the three phases.

Figs. In 8-10, it is observed that the lower the THD of the ADALINE, the lower the RMS and peak currents. It is an important engineering achievement, as the converter current should be tolerated by this SAPF semiconductor devices, coupling inductor and DC-link components. For practical design it is desirable to reduce distortion as well as peak current.

This is confirmed by the harmonic magnitude tables from the initial simulation. The fifth harmonics magnitude is 0.26753 for ADALINE and 5.0387 for Improved LMS in phase A. The 5th harmonic values of the two electrical signals in phase B are 0.31348 and 4.5953. In phase C, the fifth harmonic values are 0.32341 and 5.5441. From the lower third, fifth, seventh, eleventh and thirteenth harmonic magnitudes, it is seen that the ADALINE controller is more effective over the dominant low-order harmonic range of rectifier loads.

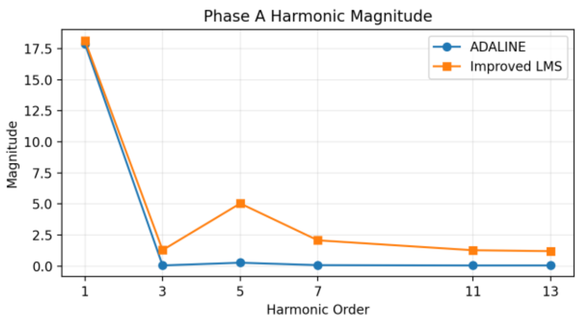

Fig. 11. Phase A harmonic magnitude comparison generated

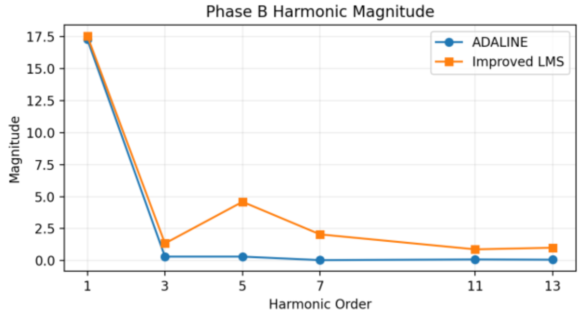

Fig. 12. Phase B harmonic magnitude comparison generated

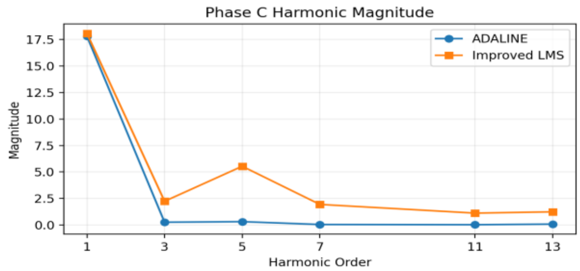

Fig. 13. Phase C harmonic magnitude comparison generated

TABLE VI. DOMINANT HARMONIC MAGNITUDE COMPARISON

Phase	Controller	3rd	5th	7th	11th	13th
A	ADALINE	0.0489	0.2675	0.0719	0.0468	0.0162
A	Improved LMS	1.2835	5.0387	2.0607	1.2716	1.2240
B	ADALINE	0.3128	0.3135	0.0379	0.0902	0.0154
B	Improved LMS	1.3427	4.5953	2.0498	0.8810	0.9534
C	ADALINE	0.2683	0.3234	0.0564	0.0364	0.0182
C	Improved LMS	2.2446	5.5441	1.9495	1.1294	1.1375

Figs. In each phase, the ADALINE controller is more effective at suppressing the dominant low order harmonics as seen in 11-13. A 6pulse rectifier load is particularly significant for the 5th harmonic. The fifth harmonic magnitude is kept below 0.33 in all the phases for ADALINE case while the same is between 4.5953, 5.5441 for Improved LMS case. The same pattern continues with the 7th, 11th and 13th harmonics, causing the high THD difference shown above. The fundamental magnitudes are still comparable, and the improvement is primarily due to the residual harmonic reduction and not to loss of the current that is useful to the system.

The result is practical in terms of the active-filter rating. The larger the lower order harmonics are, the larger compensating current the inverter needs to inject and the greater ripple the coupling inductor will have. These harmonics can be minimized to benefit lower thermal stress, current tracking and power-quality enhancement compliant with the guidelines. From a signal-processing standpoint, the result will be favorable for ADALINE, as well as for a converter design standpoint.

The waveform and harmonic spectrum results illustrate a smoother compensated current and smaller residual harmonic spectrum produced by ADALINE. The Improved LMS result windows, on the other hand, have bigger oscillations following the initial transient. This is not the case for LMS methods in general, but rather for the LMS tuning that was used in this simulation, which is not enough to match the ADALINE estimator. Systematic step-size optimization, normalization, leakage control or hybrid adaptive filtering could improve the performance of the LMS. For the operating condition under test however, the choice of control is recommended to be the ADALINE based SAPF.

TABLE VII. OVERALL PERFORMANCE SUMMARY

Metric	ADALINE	Improved LMS
Average THD (%)	1.6713	30.923
Average MSE	16.264	39.517
Average RMSE	4.0314	6.2725
Average MAE	1.6265	5.4263
Average RMS current (A)	18.822	20.818
Average peak current (A)	28.738	37.753
Average crest factor	1.5268	1.8137

It is also convenient to compare with the traditional instantaneous p-q theory. The conventional method of p-q control would be widely used and simple in calculations, however, it relies on the accuracy of the transformation and filtering delay. In the proposed ADALINE method, the transformation structure is preserved, and the adaptive weight is used to enhance the harmonic estimation stage. This is the reason for the reported THD being below typical harmonic-control values, and the sensitivity of the Improved LMS model to the remaining ripple.

The drawback of this work is that only the results based on simulation have been found and they are dependent on the selected nonlinear load, the DC-link parameters, the hysteresis band and the learning factors. Measurement noise, switching dead time, sensor delay and finite processor sampling can result from hardware validation. The results are thus presented as evidence from the model, rather than an outright rejection of LMS-type controllers.

To avoid unstable growth of the controller's coefficients, from an implementational perspective the ADALINE controller should be tested with a fixed sampling interval and synchronized basis signals and a bounded learning rate. The controller should also be tested when switching loads as the transition time is the most challenging time for adaptive estimation. In the case of the DSP and/or FPGA hardware implementation, the sine-cosine basis generation, Clarke transformation and hysteresis-current control should be performed in the sampling period. For a laboratory SAPF, these requirements are attainable, but need to be experimentally tested.

Another practical matter is the sizing of the converter. The results of RMS current and RMS peak current indicate that ADALINE decreases the electrical stress on the inverter. A lower peak current value decreases the semiconductor current rating, heat-sink load, PCC coupling inductor ripple, and improves the quality of the PCC coupling inductor waveform. As a result, the selection of the controller will not only influence the signal-processing capabilities, but also the physical design of the active filter. This results in the reported RMS, peak and crest factor, which are of use for engineering decisions.

The results also indicate the obvious direction for future optimization. Normalized LMS, leaky LMS, variable-step LMS or hybrid ADALINE-LMS control can aid in improving the performance of the LMS. To compare the adaptive methods in the future, the following adaptive methods must be under the same source, load, DC-link and switching conditions, and the different methods must be tuned based on the same objective functions, e.g., minimum weighted THD or minimum peak current. This validation would further strengthen the comparison and be more appropriate for hardware deployment.

VI. CONCLUSION

In this paper a six-page IEEE Style study of Adaptive Harmonic Detection and Compensation for a three phase SAPF using ADALINE and Improved LMS was presented. A 400 V, 50 Hz source, nonlinear rectifier load and shunt active power filter at the PCC were used in the simulation. As per the selected test condition, the average THD obtained with ADALINE was 1.6713%, while the THD obtained with Improved LMS was 30.923%. In addition, ADALINE also minimized the MSE, RMSE, MAE, RMS current, and peak current and crest factor. Thus, the controller based on the ADALINE is more appropriate for the nonlinear load considered. Further research is needed to validate the model by implementing it in real-time using either a DSP or an FPGA, to test variable loading, and to compare optimized LMS variants with the same ADALINE structure.

VII. ACKNOWLEDGMENT

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