

Three-Phase Reference Current Generator Employing with Kalman Filter for Shunt Active Power Filter

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Abstract – This paper presents a new technique of reference current generator based on Kalman filter (KF) estimator for three-phase shunt active power filter (APF). The stationary reference frame ($d-q$ algorithm) is used to transform the load currents into DC component. The harmonics of load currents are extracted and the three-phase reference currents are generated using KF estimator. The work is simulated using Matlab/Simulink platform. To validate the simulation results, an experimental test-rig have been perform using real-time control dSPACE DS1104. In addition, hysteresis current control was used to generate the switching signal for the correction of the harmonics in the system. The non-linear load were constructed with three-phase rectifier which connected in series with inductor and parallel with resistor and capacitor. The results shows that the new technique of shunt APF embedded with KF is proven to eliminate the harmonics created by the non-linear load with some improvement on the total harmonics distortion (THD).

Keywords: Active power filter, Harmonics, Kalman filter estimator, Non-linear load

1. Introduction

Harmonics interference in power system become increasingly critical due to the wide application of power electronic equipment of non-linear load and harmonics contamination that affects the power quality of the system. Various methods have been proposed to solve these problems. One of the method is by using passive filter which connected in parallel with non-linear loads (NLL) resulting in the improvements of the power factor [1], harmonic suppression [2] and exhibit lower impedance at a tuned harmonics frequency [3]. This approach is popular due to its simplicity, reliability, efficiency and low cost [4], but at the expense of providing incomplete solutions particularly when compensating random frequency variations in the current, tuning and parallel resonant problems. In recent years, various active power filters (APF) configuration with their respective control strategies have been proposed and have been recognized as a viable solution to the problem created by harmonics [5-7]. Amongst the technique that have been developed are the extraction and the estimation approach. Instantaneous reactive power theory ($p-q$ theory), modified $p-q$ theory [8-10], $p-q-r$ theory [11, 12], vectorial theory [13] and $d-q$ theory [7, 14, 15] are the techniques that fall into the

extraction technique. In many cases, $d-q$ algorithm have been widely used to eliminated the harmonics due to its simplicity of control design relative to the rest [6].

On the other hand, estimation approach is used to estimate harmonics of frequency component present in the signal and measurement or estimation of the amplitude and phases of those frequencies [16]. These approach can be divided into two classes, non-parametric and parametric methods. The non-parametric methods are based on transformation of the given time-series data sequence. During the estimation process, this methods are not capable of incorporating with any available information about the system. Frequency domain approach using Fourier transform is the most commonly used for spectrum analysis in this harmonics estimation [16]. In addition, parametric methods use an appropriate model to represent the signal and then estimate the parameters of the model from the available data points. Estimated parameter are applied to the selected model to determine harmonics contents in the signal. This parametric methods offer higher resolution and better accuracy compared to the non-parametric methods [16]. KF estimator is one of the methods that fall into the parametric method category which have been widely studied and used for different applications [16-23]. In active power filter, KF is used to estimate and track the current harmonics of the grid which reported in [24-26]. In this technique, it is assume that the frequency of the grid are constant and its only detect the harmonics in the system. Furthermore, the DC NLL have been used by many researchers to generate the distorted current waveform [5, 27-31]. Generally, the NLL is constructed using combination of resistor, inductor and

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capacitor (RLC). The inductor is connected in series with parallel resistor and capacitor. This non-linear loads created various problems to the system which can eliminated using shunt APF.

Generally, the d - q algorithm using Butterworth low-pass filter used to filter out the unwanted DC component to ensure the correct reference currents are been generated in the system. Fail to obtain the corrected reference current will reduce the overall performance of the active power filter (APF). However, time delay introduce when applying the low-pass filter will contribute to the phase shift in harmonics and high transient current [32-34]. Therefore, this paper proposed a new technique of the current reference generator embedded with KF estimator for shunt APF system. This technique reduce the time delay thus produced improvement of the overall total harmonics distortion (THD) in the system.

2. Shunt Active Power Filter

The typical connection of the three-phase shunt active power filter (APF) is shown in Fig. 1.

The inverter act as voltage source which capable of blocking harmonics current that flow from the non-linear load. The APF system is the feedback system that monitor the supply current, I_{sa} , I_{sb} , and I_{sc} . The corrective signals for generating compensation current, $I_{inj(abc)}$ are required for injection into the supply system which are done at the harmonics detection using d - q algorithm. In this reference current generation, harmonics from the loads current are extracted/estimated to generate the reference signal which are then subtracted with the non-linear load current to produce the corrected signal. Then, the corrective PWM are generated and injected to the system through the voltage source inverter. The magnitude of the compensated current must be in a correct amplitude with respect to the load. The magnitude of the compensated current must match with the power drawn from the supply and capable

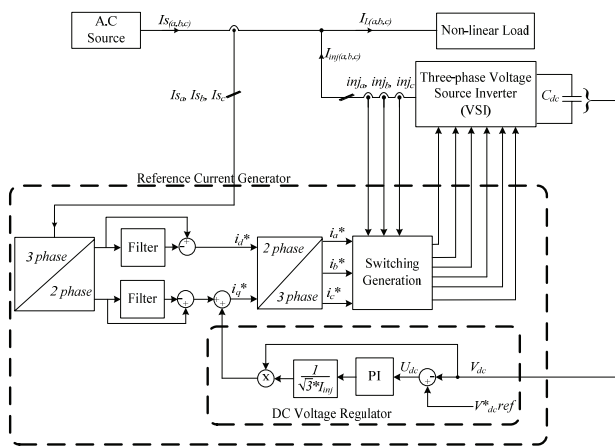


Fig. 1. Shunt active power filter configuration

Table 1. System parameters

Parameter	Notation	Values
Source Voltage	V_s	120 Vrms
Source frequency	f	50 Hz
DC link capacitor	C_{dc}	2200 μ F
Line Inductor	L_{in}	3 mH
Load Capacitor	C_L	2200 μ F
Load Resistance	R_L	100 Ω

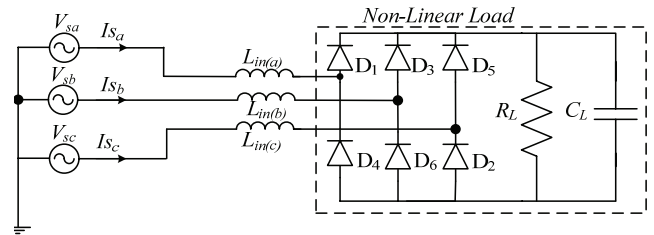


Fig. 2. Non-Linear Load

in matching the load power together with the losses in the compensator. Therefore, DC voltage regulator is used to provide the magnitude of the desired current which correspond to the amplitude of the fundamental component of the load plus the losses. The simulation and experimental studies on KF estimator for three-phase reference current generation are carried out using the system parameters as mentioned in Table 1.

2.1 Non-linear load

The non-linear load consists of three-phase bridge rectifier connected to the voltage supply by means of linear inductor (L_{in}) feeding resistor and capacitor load as shown in Fig. 2. The pulsating current waveform being drawn from supply line current are obtain in this circuit.

2.2 Kalman filter based reference current generator

In this new technique, the KF use a form of feedback control in which the filter estimates the process at any time and then obtains feedback in the form of noisy measurement. As such, equations of the KF is implemented in two steps; time update and measurement update equations. The time update also known as predictor equation is responsible for projecting forward (in time) the current state and error covariance estimate to obtain the estimation in the next time step. While the measurement update equation also called corrector equations are responsible for the feedback such as for incorporating a new measurement into the estimator to further improve the estimation. Therefore the estimation resembles the combination of predictor-corrector algorithm which used in the system. Originally KF was designed for linear systems based which define as;

$$\begin{aligned} x_k &= Ax_{k-1} + Bu_{k-1} + w_{k-1} \\ z_k &= Hx_k + v_k \end{aligned} \quad (1)$$

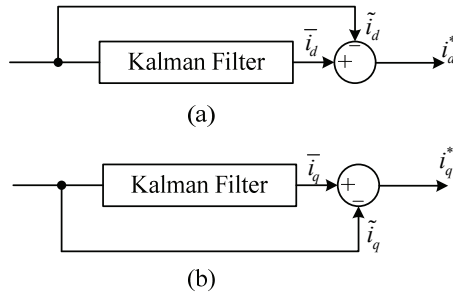


Fig. 3. Kalman Filter harmonics estimation: (a) d-axis component; (b) q-axis component

where;

- x_k = state of system
- z_k = measurement state
- u_{k-1} = control input of system
- A = matrix of previous state to current state
- B = matrix of control input to current state
- H = matrix of measurement state to system
- w_{k-1} = system error
- v_k = measurement error

In order to separate the harmonics from the fundamental of the load currents, it is enough to separate the direct term of the state system and measurement state from the original equation. Fig. 3 shows the principle of this extraction filter.

Based on Eq. (1), the estimation states of dynamic system can be obtain from the noisy measurement. Since there is no plant to control, therefore the input signal (u_{k-1}) and system error (w_{k-1}) can be neglected. Therefore, it can be written as;

$$\begin{aligned} i_{d(k)} &= A i_{d(k-1)} \\ \tilde{i}_{d(k)} &= H i_{d(k)} + v_k \end{aligned} \quad (2)$$

By exploiting the Eq. (2), the time update (predicator) and measurement update (corrector) are show in Eq. (3) and (4).

Time update equation;

$$\begin{aligned} \hat{i}_{d(k)}^- &= A \hat{i}_{d(k-1)} \\ P_k^- &= A P_{k-1} A^T + Q \end{aligned} \quad (3)$$

Measurement update equation;

$$\begin{aligned} \hat{i}_{d(k)} &= \hat{i}_{d(k)}^- + K_k (i_{d(k)} - H \hat{i}_{d(k)}^-) \\ K_k &= \frac{P_k^- H^T}{H P_k^- H^T + R} \\ P_k &= (I - K_k H) P_k^- \end{aligned} \quad (4)$$

where;

- $i_{d(k)}$ = measurement of DC current
- $\hat{i}_{d(k)}$ = estimation DC reference current
- $\hat{i}_{d(k)}^-$ = predicted state of DC reference current
- P_k = estimation error covariance
- P_k^- = predicted error covariance

- K_k = Kalman Gain
- I = Identity matrix

The time update equation and measurement update equation were calculated continuously for each time step. The measurement error, “ R ” could be specified offline, prior to the operation of the filter (refer Table 2). While measurement of system error covariance, “ Q ”, is difficult to determine due to inability to directly observe the estimating process. Therefore to determine the optimum value of Q , a study have been conducted by looking at the THD using different values of Q which represented in Fig. 4. From the graph, the optimum value of Q to reduce the THD is $1e-8$. Other parameters are shown in Table 2, while the cycle of the time update and the measurement update equation was shown in Fig. 5.

Table 2. Parameter of KF estimator

Variables	Initial Condition
Estimated current state, $\hat{i}_{d(k-1)}$	0.5 (initial)
Estimated error covariance, P_{k-1}	1 (initial)
State transition matrix	$A = [1]$
Measurement matrix	$H = [1]$
Measurement noise covariance, R	4

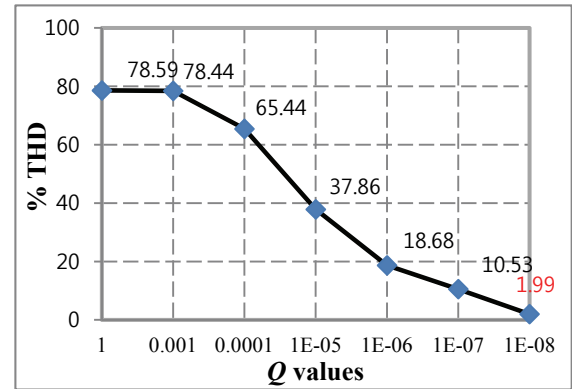


Fig. 4. Graph THD versus Q values.

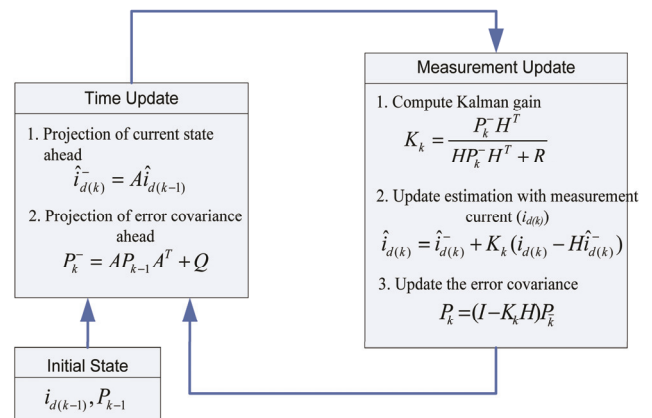
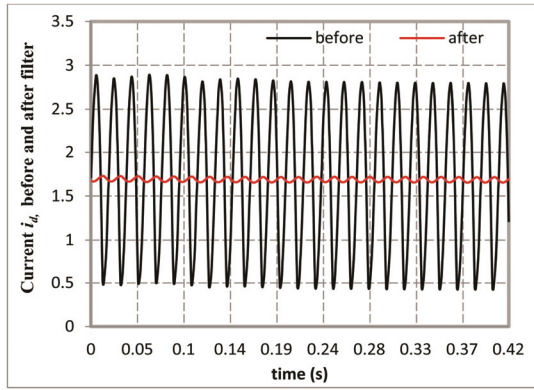
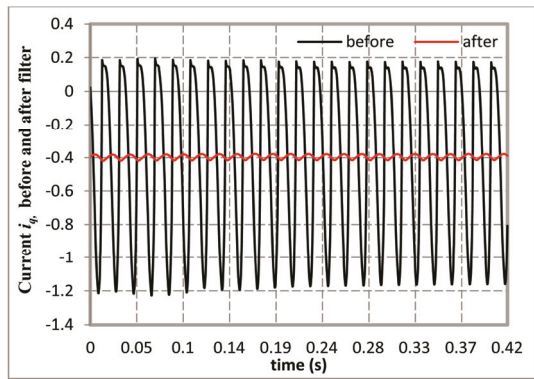


Fig. 5. Cycle of Discrete Kalman filter


 Fig. 6. Current at d -axis (i_d)

 Fig. 7. Current at q -axis (i_q)

Initial state of “ $i_{d(k-1)}$ ” and “ P_{k-1} ” were set at 1 before the operation. After the process started, the filter would continuously update the value according to the input state and measurement value. The same parameters of KF estimator were also used for q -axis. Fig. 6 and Fig. 7 shows the DC current waveform before and after KF estimator was implemented for d -axis and q -axis. From the, it is observed that after the KF was implemented, only the fundamental current is obtained (red line).

2.3 Three-phase reference current generation employing Kalman filter estimator

This unit is design to generate the required current reference that is used to compensate the undesirable load currents components. In this case, the load currents are measured and transform into d - q coordinates (rotating reference frame with fundamental frequency) using Park transformations. The equations to transform a - b - c coordinate into α - β -0 coordinate is presented in Eq. (5).

$$\begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (5)$$

By employing Park transformation, the α - β -0 coordinate

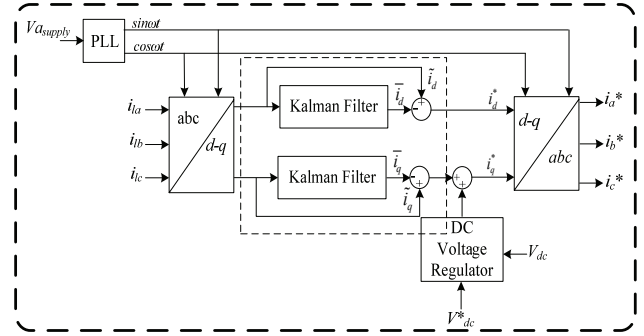


Fig. 8. New technique of three-phase reference current generator employing Kalman filter estimator

is transform into d - q coordinate as shown in Eq. (5)

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (6)$$

where; $\theta = \tan^{-1} \left(\frac{i_\beta}{i_\alpha} \right)$

The phase angle, θ in d - q frame is the same with fundamental frequency which makes the DC fundamental current component (i_d , i_q) and harmonics AC component (i_d , i_q) arise due to harmonics at the load [6]. Conventionally, low-pass filter are used to determine the DC component. However, phase shift in harmonics and high transient response are commonly obtained in the system before the system achieved its steady state. Therefore, KF estimator are used to overcome the problem from the low-pass filter hence help to improve the overall performance of the THD. In order to stabilize the voltage on the DC side of the VSI, the measurement voltage, V_{dc} measure must follow the reference voltage, $V_{dc} \text{ ref}$. Therefore, PI-improved voltage regulator loop is designed by integrating a suitable PI controller. Fig. 8 shows the techniques to determine the harmonics component in the system.

2.4 DC voltage regulator

The DC voltage regulator is controlled with a traditional PI controller. In the block diagram show in Fig. 8, the DC voltage V_{dc} is measured and then compared with a constant reference value V_{dc}^* . The error is process by a PI controller with two gains; K_p and K_i . Both gain are calculated and tuned accordingly to the dynamic response which the values of both gain are set to 4 for K_p and 91 for K_i .

3. Experimental Setup

The new structure of the three-phase reference current generation employing KF estimator as shown in Fig. 1, whereas Fig. 9 shown the experimental test rig. The experiment uses 75A insulated bipolar transistor (IGBT)

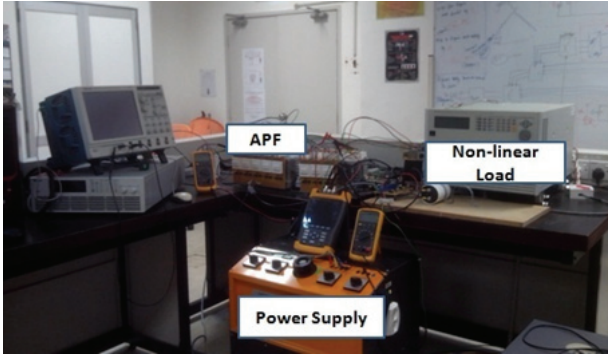


Fig. 9. Experimental test rig

(semikron SKM 75GB123D), IGBT driver dual module (SKHI22AR) DC link capacitor (2200 μ F, 450VDC), current sensor circuit (LEM HY-10P), voltage sensor (LV25-P), three-phase high switching inductor (3mH). The shunt APF is connected to a line voltage at 50Hz and 120V (rms line-line). The shunt APF control is implemented on a dSPACE 1104 DSP controller to generate the switching pattern. the non-linear load used in the studies are three-phase load inductor, three phase power bridge rectifier module (SKD62/08), current sensor circuit (LEM HY-10P), DC capacitor (1100 μ F, 400V) and three-phase resistor load). The voltage supply is set to 120Vrms and the sampling time is set at 100 μ s for dSPACE. The tests are conducted to evaluate the performance of the APF when having variation of load.

4. Simulation and Experimental Results

The simulation and experimental results of the proposed three-phase reference current generation employing KF estimator for three-phase shunt APF are presented. The work is simulated and implemented using Matlab/simulink and dSPACE.

4.1 Non-linear load

The results for the APF before and after compensation are by simulated using Matlab/simulink while Fluke Power Quality Analyzer capture the results for the experimental. Fig. 10 (a) and (b) shows the supply current waveform before the compensation for simulation and experimental result thus, the harmonics spectrum of both simulation and experimental are shown in Fig. 11 respectively.

From the harmonic spectrum results, the total harmonics distortion (THD) can be determine by using the formula as define as;

$$\%THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_h^2}}{I_f} \quad (7)$$

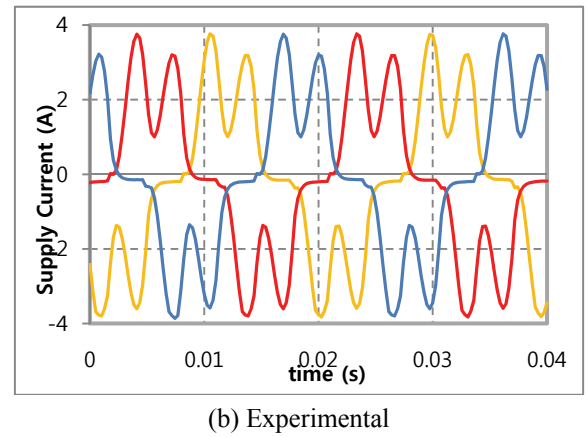
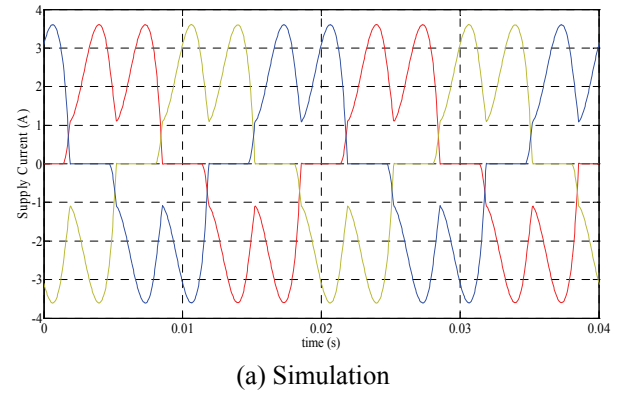


Fig. 10. Simulation and experimental result without shunt APF

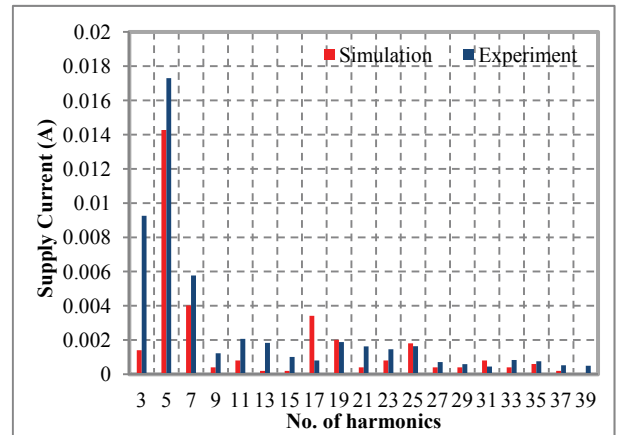


Fig. 11. Harmonic spectrum before the compensation

where;

- I_h : harmonics component
- I_f : fundamental component
- n : harmonics number; 2, 3, 4, etc.

Therefore, the THD of the line current obtain by the simulation is 56.14% while the experimental obtain about 47.26%. There are slightly different between the simulation and experimental results because the simulation is simulated

at ideal condition.

4.2 Kalman filter estimator result versus low-pass filter

Commonly, when applying $d-q$ algorithm a Butterworth low-pass filter is used to filter out the unwanted DC component to ensure the correct reference currents are been generated in the system. Fail to obtain the correct reference current will reduce the overall performance of the active power filter (APF). However, when applying the low-pass filter, there are time delay which contribute to the phase shift in harmonics and high transient current. Fig. 12 shows the shunt APF when applying Butterworth low-pass filter. From the waveform, it clearly shows that the waveform

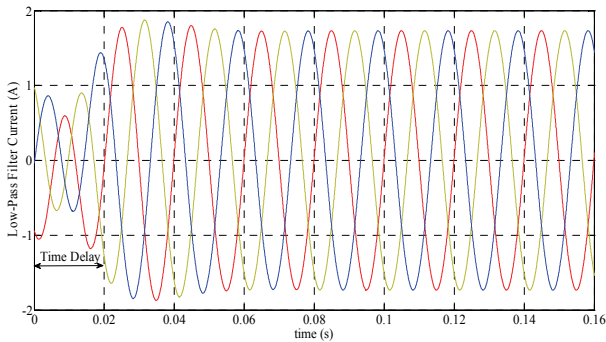


Fig. 12. Simulation Butterworth low-pass filter

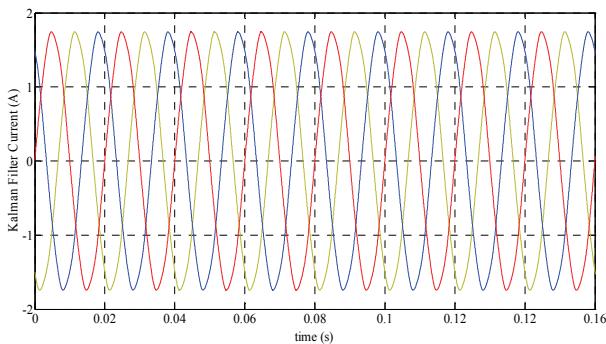


Fig. 13. Simulation Kalman filter

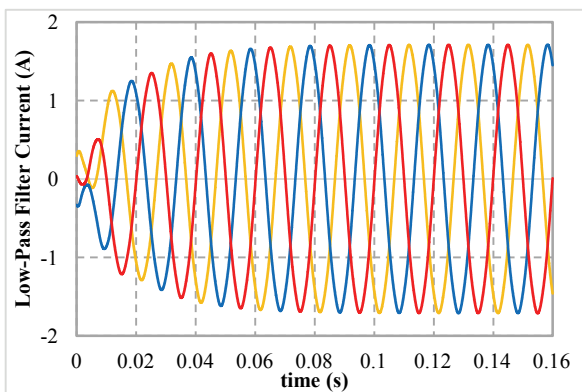


Fig. 14. Experimental Butterworth low-pass filter

having almost 0.02s delay with 43.36% of THD. On the other hands, there is no time delay when applying the shunt APF using KF estimator which is shown in Fig. 13. Therefore, the THD produce by the KF estimator is better compared to low-pass filter which about 0.77%. On the other hand, the experimental results for low-pass and KF is shown in Fig. 14 and Fig. 15 respectively.

4.3 Three-phase shunt active power filter

In this shunt active power filter feeding a non-linear load, the results between Butterworth low-pass filter and KF estimator are compared between simulation and experimental

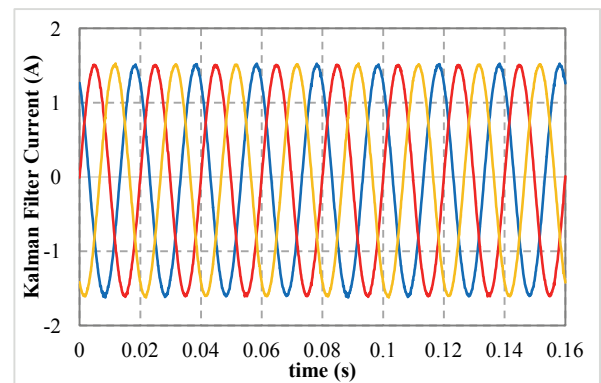
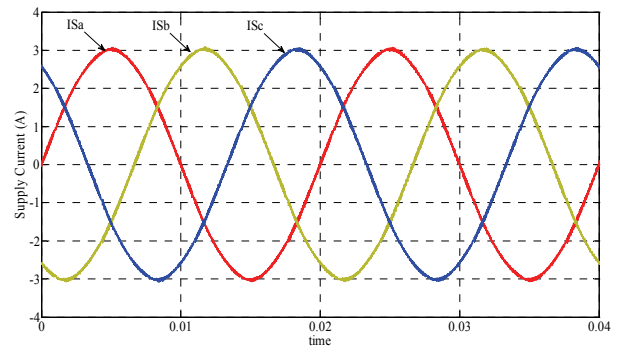
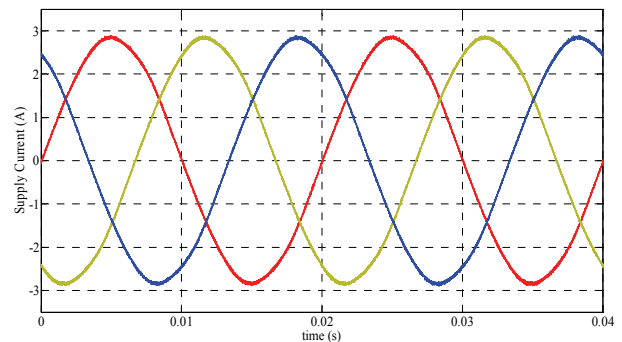


Fig. 15. Experimental Kalman filter



(a) Low-pass filter



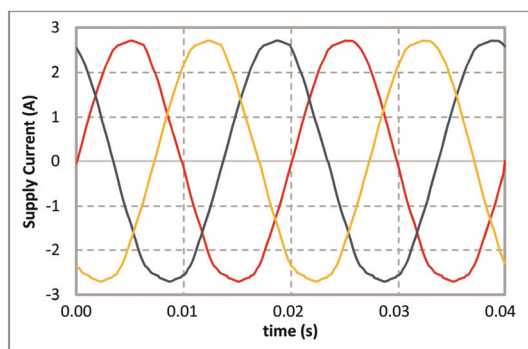
(b) Kalman filter

Fig. 16. Simulation result for shunt APF (a) low-pass filter, (b) Kalman filter

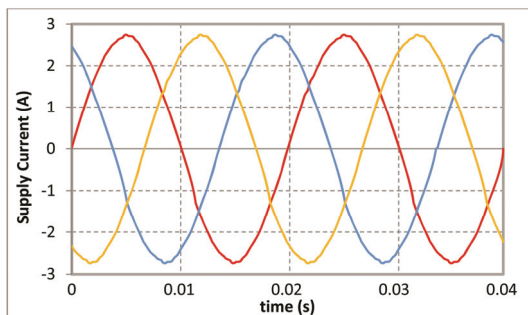
are shown in Fig. 16 and Fig. 17 respectively.

From the results obtain, it can be concluded that almost the same waveform were produced for both simulation and experimental approach. Furthermore, the harmonics spectrum form the experimental are shown in Fig. 18.

It is clearly shown that all the harmonics component were reduce when applying both low-pass filter and KF. In addition, the fundamental current for both techniques were found almost identical between simulation and experimental. The THD results obtain shows that the new techniques shunt APF abide the regulation of IEEE 519-1992 standard. Table 3 and Table 4 shows the THD after simulation and experimental results respectively.



(a) Low-pass filter



(b) Kalman Filter

Fig. 17. Experimental results for shunt APF: (a) low-pass filter; (b) Kalman filter

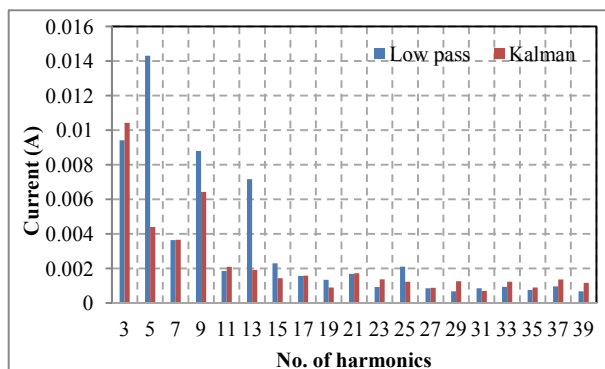


Fig. 18. Harmonics spectrum

Table 3. Simulation results

Types of reference current generation	THD before	THD after
Low-pass filter	55.88%	2.09%
Kalman filter estimator		1.99%

Table 4. Experimental results

Types of reference current generation	THD before	THD after
Low-pass filter	47.27%	2.30%
Kalman filter estimator		2.18%

From the observation, the shunt APF using KF estimator technique produce about 0.1% better THD compared to low-pass filter either in simulation and experimental. About THD of improvement from simulation and experimental are produce by using KF.

5. Operation with Three-Phase Induction Motor Speed Drive

A 1.5 kW, 380 V variable speed induction motor (IM) drive is connected in parallel to the APF and the three-phase supply voltages. The motor is operated as a non-linear load and starts to accelerate from standstill at time, $t = 0.06s$ until it reached the required reference speed which is set at 1400 RPM. The supply current when the motor start to accelerate without shunt APF is shown in Fig. 19 while Fig. 20 shows the supply current waveform when applying shunt APF. The THD of the supply currents is measured at steady state condition ($t=0.28s$) using Fluke Power Quality Analyser. The THD without shunt APF obtained from the supply current is 168.39%, while the THD reduced to 2.38% and 2.80% when shunt APF employing KF and low-pass filter. Furthermore, in Fig. 21 until Fig. 23 shows the harmonic spectrum with or without shunt APF for both KF and low-pass filter. It can conclude that from the results, the shunt APF employing KF based-estimator produced lower THD compared to low-pass filter for an induction motor drive application.

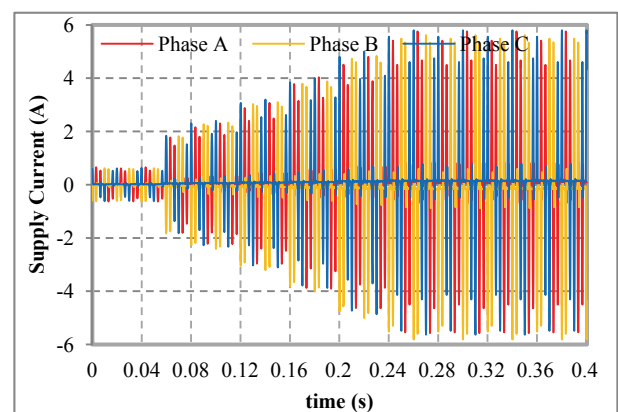


Fig. 19. Supply current waveform without shunt APF

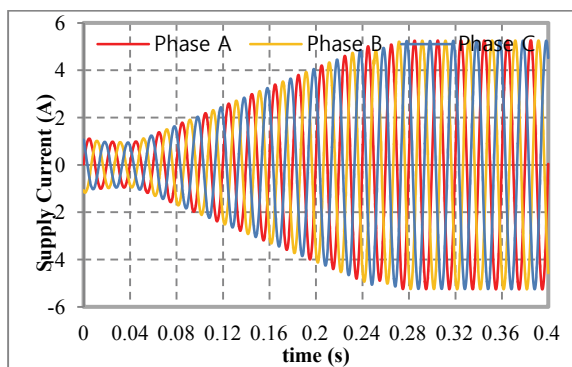


Fig. 20. Supply current when applying shunt APF with Kalman filter estimator

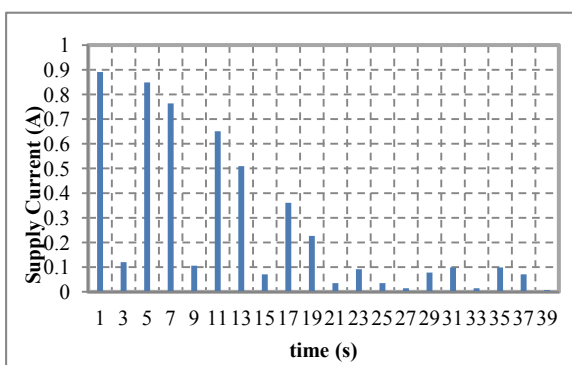


Fig. 21. Harmonic spectrum without shunt APF

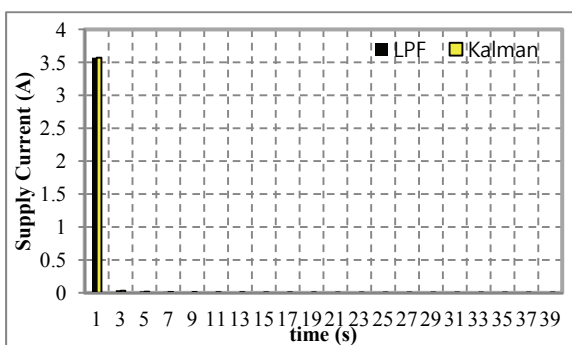


Fig. 22. Harmonics spectrum after applying shunt APF

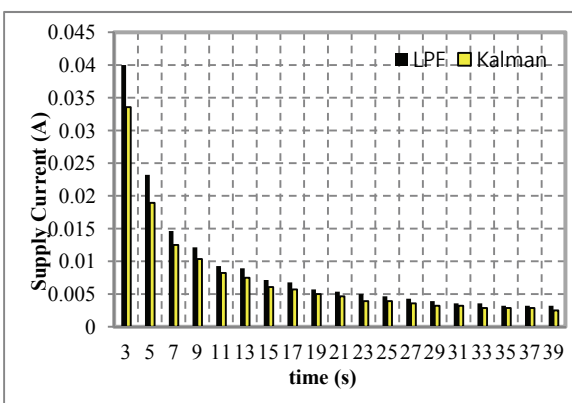


Fig. 23. Harmonics spectrum without fundamental

Table 5. THD of supply current before and after applying shunt APF

Reference current generation	THD before	THD after
Low-pass filter	168.39%	2.80%
Kalman Filter estimator		2.38%

The overall total harmonic distortion with or without shunt APF is showed tabulated in Table 5 which shows that the KF estimator produce lower THD compared to low-pass filter for three-phase induction motor.

6. Conclusion

This paper proposed a new techniques of current reference generator by employing KF estimator for shunt APF technique. The simulation and hardware results have validated the proposed technique in generating the three-phase reference current towards reducing the THD. For the three-phase rectifier connected with RC load, the performance of the proposed technique is comparable with those based on the low-pass filter reference current generation. The THD of the source current from the experimental result after the compensation is 2.18% which is less than 5% of the harmonics limit imposed by the IEEE 519 standard. In addition, almost 0.1% THD improvement was obtain by the proposed techniques compared to low-pass filter. Thus, the comparison of different reference current grid generation for shunt APF is also presented. The performance of KF estimator reference current generation was also studied for induction motor variable speed drive. In induction motor almost 0.42% improvement of THD was gather when applying KF estimator compared to low-pass filter.

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