Kalman Filter Algorithm for Mitigation of Power System Harmonics

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ABSTRACT

The maiden application of a variant of Kalman Filter (KF) algorithms known as Local Ensemble Transform Kalman Filter (LET-KF) are used for mitigation and estimation power system harmonics are proposed in this paper. The proposed algorithm is applied for estimating the harmonic parameters of power signal containing harmonics, sub-harmonics and inter-harmonics in presence of random noise. The KF group of algorithms are tested and applied for both stationary as well as dynamic signal containing harmonics. The proposed LET-KF algorithm is compared with conventional KF based algorithms like KF, Ensemble Kalman Filter (En-KF) algorithms for harmonic estimation with the random noise values 0.001, 0.05 and 0.1. Among these three noises, 0.01 random noise results will give better than other two noises. Because the phase deviation and amplitude deviation less in 0.01 random noise. The proposed algorithm gives the better results to improve the efficiency and accuracy in terms of simplicity and computational features. Hence there are less multiplicative operations, which reduce the rounding errors. It is also less expensive as it reduces the requirement of storing large matrices, such as the Kalman gain matrix used in other KF based methods.

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1. INTRODUCTION

For the development of effective Power Quality (PQ) monitoring techniques, greater efforts are made by the researchers towards the development of less-complex and more efficient techniques for detection, classification, identification of power quality distribution. Another key and challenging problem reported recently by the researches related to power quality is the estimation of harmonics parameters for fundamental, inter-harmonics and sub-harmonics components of voltage and currents signals. Accurate and estimation of harmonics from distorted voltage signals is an important issue for checking and analysis of power quality problems. Harmonics components are distorted periodic waveform, whose frequencies that are integral multiples of the fundamental frequency. In power electronic base loads and power system network use of nonlinear loads has cause much more harmonic pollution, which a lot of deteriorates the power quality. With estimated parameters, such as amplitude and phases, correct compensation system can be designed for improving the poor quality performances [1]. Many recursive algorithms are also proposed to solve harmonic estimation problems but each of them has several limitations in terms of accuracy and convergence. The Least Mean Square (LMS) algorithms have the drawbacks for their poor convergence in addition to being failure in case of signal drifting and changing conditions. RLM algorithms involve more

complicated mathematical operations and require much computational resources. The accuracy is also limited for RLS, LMS class of algorithms [2], [3].

Another extensively used algorithm is the KF, which is known for its simplicity, linearity and robustness. The Kalman Filter algorithm is capable enough to estimate harmonic parameters in presence of noise and other non-linearity's present in harmonic signal [4-6].However, the main limitation is that it requires prior information of the statistics of the harmonic signal and the initialization of the state matrix in an accurate and faster way is the main challenge [7-10].

The variant KF called EnKF is proposed for accurate estimation of amplitude and phase of the harmonic components of distorted power system signal. The propose method used sample covariance in Kalman gain instead of state covariance to avoid the singularity problem and computational feasibility for high-dimensional system [20]. But the prominent limitation of the most EnKF-based systems is perhaps the resource limited ensemble size [21-23]. This is true eve for medium-size systems, with the model state vector size of the order of just tens of thousands, not to mention the large-scale applications [11-14].

The main ojectives of the proposed work in this paper are.

a. Maiden application of Local Ensemble Transform Kalman Filter Algorithm for estimating amplitudes and phases of the fundamental, sub-harmonics, inter-harmonics in presence Random noise I power system signal.

b. To estimate the comparative performance of KF, EnKF and proposed LET-KF algorithms to find the best harmonic estimator.

c. To test the accuracy and time of convergence for harmonic signal estimation with the propose LET-KF algorithm.

d. To estimate the performance of the proposed LET-KF algorithm for accurately estimating harmonic signal parameters on real time data obtained from a real time industrial data setup for harmonic estimation.

2. KF ALGORITHM

Several variants of KF algorithms, which are applied for harmonic estimation problems, are discussed in this section. The detail procedure of the LET-KF algorithm for Harmonic Estimation is also reported in this part.

2.1. Kalman Filter

In this algorithm X is the vector of unknown parameter taken and updates the weights as KF algorithm is applied in Equation (1). The KF is discussed in this section is referred from [9], [18].

$$G(k) = P(k/k - 1)H(k)^T(H(k)P\left(k/k - 1\right)H(k)^T + Q)^{-1} \tag{1}$$

Where k is the Kalman gain, H is the observation matrix, Q is the noise covariance of the signal. P=SI is covariance matrix, where S is the large number and I is the square identity matrix.

The covariance matrix is related with Kalman gain as give in the following estimation.

$$P(k/k - 1) = P(k/k - 1) - G(k)H(k)P(k/k - 1) \tag{2}$$

Here the updated estimated state vector is related with earlier state vector as follows

$$\hat{X}(k/k) = \hat{X}(k/k - 1) + G(k)(y(k) - H(k)\hat{X}(k/k - 1)) \tag{3}$$

After updating the weight vector, amplitude, phases of the fundamental and n^{th} harmonic parameters are found out using the above equations.

2.2. Ensemble Kalman Filter (En-KF)

The En-KF method is a Monte Carlo approximation method of the Kalman Filter, which let alone evolving the covariance matrix of the Probability Density Function (PDF) of the state vector, X. In this case, the distribution is represented by a sample, which is called an ensemble.

$$X = [x_1, x_2, \dots x_N] \tag{4}$$

Where X is a $n \times N$ matrix, whose columns are the ensemble members, and it is called the prior distribution. As every En-KF step ties ensemble members together so they are not independent. Signal data y (t) is arranged as $m \times N$ matrix.

So the vector of unknown parameter/Ensemble as in Equation (5) and Equation (6)

$$X(k) = [X_1(k) X_1(k) \ldots X_{2N-1}(k) X_{2N} \ldots X_{2N+2}(k)]^T \qquad (5)$$

$$X(k) = [A_1 \cos(\phi_1) A_1 \sin(\phi_1) \ldots A_n \cos(\phi_n) A_n \sin(\phi_n)]$$
$$A_{dc} A_{dc} \alpha_{dc}]^T \qquad (6)$$

The ensemble mean and covariance are

$$E(X) = \frac{1}{Q} = \sum_{k=1}^{Q} X(k) \qquad (7)$$

$$C = \frac{GG^T}{Q-1} \qquad (8)$$

$$G = X - E(X) \qquad (9)$$

The updated the ensemble is given then

$$\hat{X} = X + CH^T(HCH^T + R)^{-1}(y - HX) \qquad (10)$$

Columns of X represents a sample from the prior probability distribution and columns of $\hat{X}$ will form a sample posterior probability distribution. The En-KF is now obtained by replacing the state covariance P in Kalman gain matrix $K = PH^T(HPH^T + R)^{-1}$ by the sample covariance, C computed from the ensemble members. R is a covariance matrix, which is a ways positive semi definite and usually positive definite, so the inverse of the above exists. Using Equation (7) to Equation (9)) obtain the amplitudes, phases of the fundamental and n[th] harmonics parameters.

2.3. Background theory of LET-KF algorithm

The background theory discussed in this section about LET-KF is taken from [21-23]. The main features of LET-KF method are well known for its more efficiency and accuracy and also less multiplicative operations that reduce rounding errors. This method is very less expanse, because of the reduction of storage of large matrices that include Kalman gain matrix (k_e).To describe the proposed LET-KF algorithm, consider the ensemble size to be N and represented by the local forecasted ensemble members by $x_i^f, i = 1,2, \ldots \ldots, N$, each of which length n.

$$x_i^f = [x_1^f, x_2^f, \ldots \ldots, x_N^f] \qquad (11)$$

The forecasted ensemble mean is given by

$$\overline{x^f} = \frac{1}{N} \sum_{i=1}^{N} x_i^f \qquad (12)$$

$n * N$ Forecasted ensemble matrix is also defined by

$$x^f = \frac{1}{\sqrt{N-1}} (x_1^f, x_2^f \ldots \ldots x_N^f) \qquad (13)$$

Whereas the forecasted ensemble perturbation matrix is defined by

$$X'^f = \frac{1}{\sqrt{N-1}} (x_1^f - \overline{x^f}, x_2^f - \overline{x^f}, \ldots \ldots, x_N^f - \widehat{x^f} \qquad (14)$$

The Eigen value decomposition is used on a matrix of measured, real data, the inverse may be less valid when all Eigen values are used unmodified. This is because as Eigen values become relatively small. Their contribution to the inverse is very large. Those near Zero or at the noise of the measurement system will have undue influence and could hamper solutions using the inverse. Eigen value decomposition with

avoid the problems, the scaled and forecasted observation ensemble of the perturbation matrix can be introduced as y_i^f which can be replaced by

$$y_i^f = h(x_i^f) \tag{15}$$

Linear observation operator h = H is considered then the mean of this ensemble is and the $\overline{y^f} = H\overline{x^f}$ ensemble perturbations are replaced by

$$y_i^f = H(x_i^f) - \overline{H(x^f)} = H(x_i^f) - H(\overline{x^f}) = H(x_i^f - \bar{x}^f) \tag{16}$$

After, updating the vector of unknown parameters using the LET-KF algorithm, amplitudes and phases of the fundamental and nth harmonic parameters can be computed using the following expression (14) to (16):

$$v_n = \sqrt{X_{2N}'^{f2} + X_{2N+2}'^{f2N}} \tag{17}$$

$$\phi_n = \tan^{-1}\frac{X_{2N}'^f}{X_{2N-1}'^{f2N}} \tag{18}$$

$$v_{dc} = X_{2N+1}'^f \tag{19}$$

$$\alpha_{dc} = \left(\frac{X_{2N+2}'^f}{X_{2N+1}'^f}\right) \tag{20}$$

3.   LET-KF ALGORITHM FOR HARMONIC ESTIMATION
The step wise algorithm of LET-KF for harmonics estimation given as:
   a. Initialize Amplitude, Phase and Frequency of fundamental and Harmonic components and forecasted ensemble vector (Local Members of the Ensemble).
   b. Generate the power signal containing fundamental conditions as-one period of the signal samples at 2.5 KHz rate and also conform to 200-ms winding in practice.
   c. Discrete and Model the signal in parametric from using Equation (11).
   d. Initialize the number of unknown parameters/ensembles and specify error covariance matrix(R).
   e. Evaluation estimation error using Equations (13)-(14).
   f. Calculate the forecasted ensemble mean and forecasted ensemble matrix and forecasted ensemble perturbation matrix of ensemble using Equation (15)
   g. Obtain the estimation forecasted ensemble vector using Equation (16).
   h. If final iteration is not reached, got to step-5.
   i. Estimate amplitude and phase of fundamental and harmonic components and dc decaying components using Equation (17) to Equation (20) from final estimate of the forecasted ensemble vector.

4.   SIMULATION RESULTS AND DISCUSSION
4.1. Stationary Signal Corrupted with Random Noise
To evaluate the performance of the proposed LET-KF algorithm for estimating the harmonics amplitudes and phases for harmonic, sub-harmonics and inter harmonics, a discrete signal having a fundamental frequency of $f_1 = 50\ H$, third harmonic frequency $f_3 = 150\ Hz$, fifth harmonic frequency $f_5 = 250\ Hz$, seventh harmonic frequency $f_7 = 350\ Hz$ and eleventh harmonics frequency $f_{11} = 550\ Hz$ is generated using MATLAB. The stationary power signal consisting of 1st, 3rd, 5th, 7th, 11th order of harmonics is given in Equation (17). This type of signal is typically present in industrial load comprising of power electronic devices and arc furnaces.

$$x_t = 1.5\sin(2\pi f_1 t + 80^0) + 0.5\sin(2\pi f_3 t + 60^0) + 0.2\sin(2\pi f_5 t + 45^0) + 0.15\sin(2\pi f_7 t + 36^0) + 0.1\sin(2\pi f_{11} t + 30^0) + \mu_n \tag{21}$$

Figure 1, Figure 2 and Figure 3 represents the amplitude and phase estimation plot of the harmonic signal containing fundamental harmonic with different random noise i.e. is 0.01 random, 0.05 random, 0.1 random. 0.01 Random value produced the less noise and also produced better efficiency, accuracy to the 0.05, and 0.1 random noises. This three random noises used then comparison between the sub – harmonics, fundamental, Inter – harmonics, dynamic harmonics, 3rd, 5th, 7th, 11th harmonics.
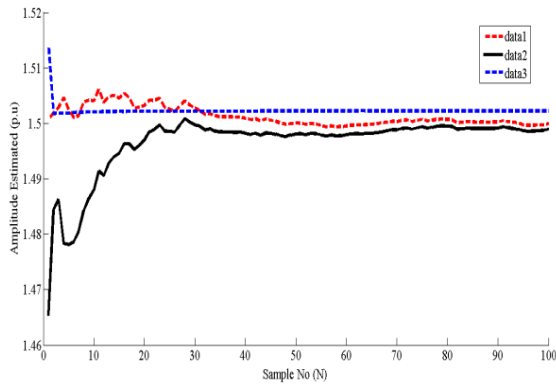

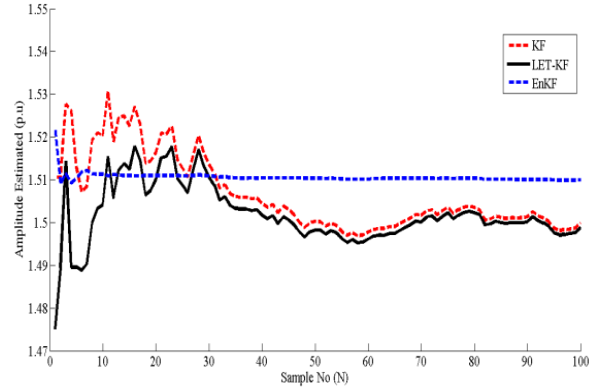Figure 1. Fundamental Harmonic signal
(Random: 0.01)

Figure 2. Fundamental Harmonic signal
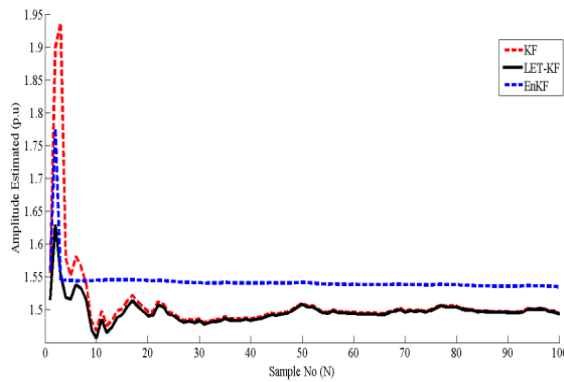(Random: 0.05)
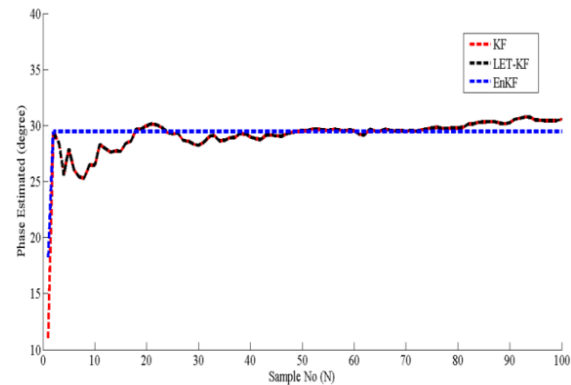

Figure 3. Fundamental Harmonic signal
(Random: 0.1)

Figure 4. Eleventh Harmonic signal (Random: 0.01)

Random noises 0.01, 0.05 and 0.1 are used in eleventh harmonics and the coreesponding response has shown in Figure 4, Figure 5 and Figure 6. Sub and inter harmonic graphs shows actual verses estimated values of signal using four different algorithms. In case of LET-KF algorithm, actual verses estimated signals almost match with each other with little deviation. To study the performance of the proposed LET-KF algorithm for sub harmonics signals, a signal as given by (34) is created in MATLAB. The proposed LET-KF algorithm is applied and then amplitude and phase are estimated. Figure 7 represents the amplitude of estimation plot along with actual signal of the sub harmonic signal in presence with Random noise obtained with LET-KF algorithm. It is found that the estimation error achieved with the proposed algorithm for the sub harmonic signal is very much reduced and almost matches with the actual signal. Figure 8 represents the amplitude estimation plot along with actual signal containing inter harmonics using LET-KF algorithm at 130 Hz frequency. The estimation signal obtained with the proposed LET-KF almost matches with the actual inter harmonic signal.

Table 1, Table 2 and Table 3 shows the comparative performance of KF, EnKF and proposed LET-KF algorithm for estimating harmonic parameters for fundamental, third, fifth, seventh and eleventh order harmonics along with sub and inter harmonics corresponding to the random noises 0.01, 0.05 and 0.1. The estimated values obtained with all three algorithms for each of amplitude and phase is reported with their

computational time as well. It is evident from the Table 1, Table 2 and Table 3 that the performance of proposed LET-KF algorithm is better than any of the other two algorithms in terms of accuracy.
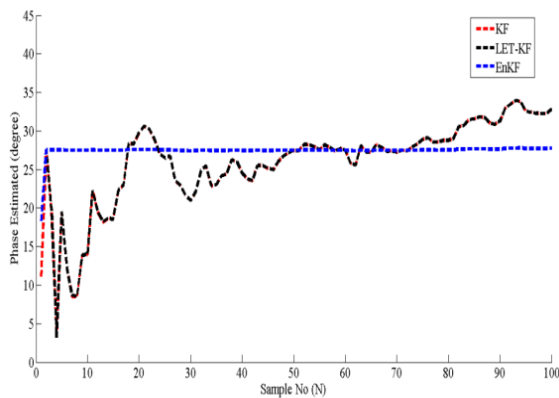

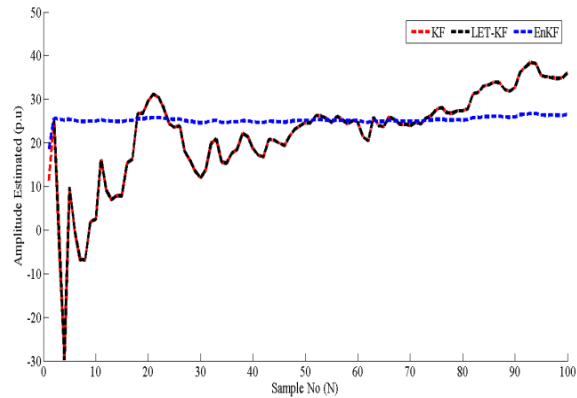
Figure 5. Eleventh Harmonic signal (Random: 0.05)   Figure 6. Eleventh Harmonic signal (Random: 0.1)
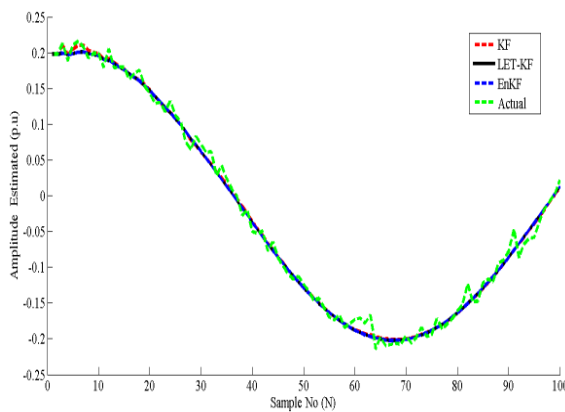

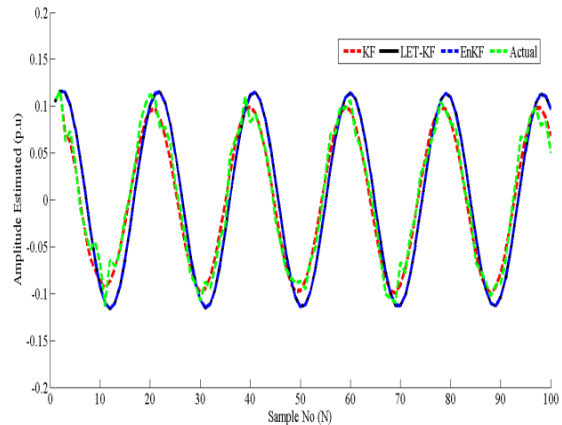Figure 7. Sub Harmonic signal   Figure 8. Inter-1 Harmonic signal

4.2. Dynamic Signal

Dynamic signal are time dependent signals whose parameters such as amplitude, phase and frequency varies with respect to time. The proposed LET-KF algorithm is evaluated for dynamic signal using Equation (22). The amplitude, phase and frequency are estimated by the algorithm one by one and performance is evaluated. The dynamic performance is investigated for three different frequencies, such as 1Hz, 3Hz, and 6Hz and different amplitudes.

$$y(t)=\{1.5+a_1(t)\}\sin(\omega_0 t+80^0)+\{0.5+a_3(t)\}\sin(3\omega_0 t+60^0)+\{0.2+a_5(t)\}\sin(5\omega_0 t+45^0)+\mu_n \qquad (22)$$

Where,

$a_1 = 0.15 \sin 2\pi f_1 t + 0.05 \sin 2\pi f_5 t,$
$a_3 = 0.05 \sin 2\pi f_3 t +0.002 \sin 2\pi f_5 t,$
$a_5 = 0.025 \sin 2\pi f_1 t+0.005 \sin 2\pi f_5 t$
$f_1 = 1.0$ Hz, $f_2 = 3.0$ Hz, $f_3 = 6.0$ Hz.

The LET_KF algorithm has applied for obtaining the performance of dynamic signal and the results are shown in Figure 9, Figure 10 and Figure 11. It can be observed that actual verses estimated signal almost match with each other with little deviation in case of LET-KF algorithm.
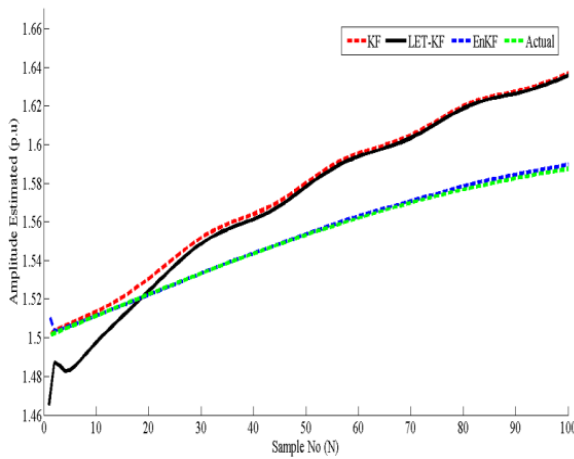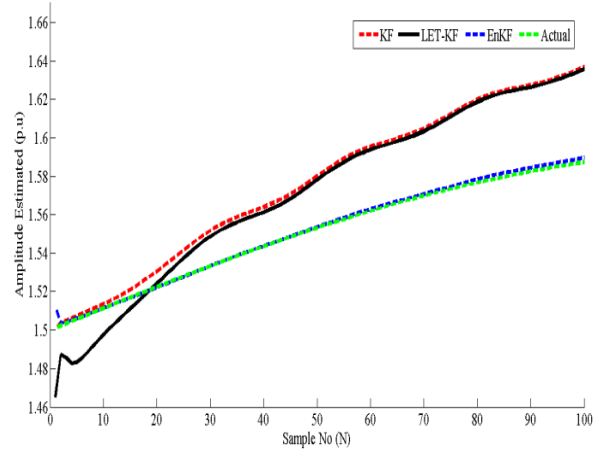
Figure 9. Dynamic Harmonic signal (Random: 0.01)

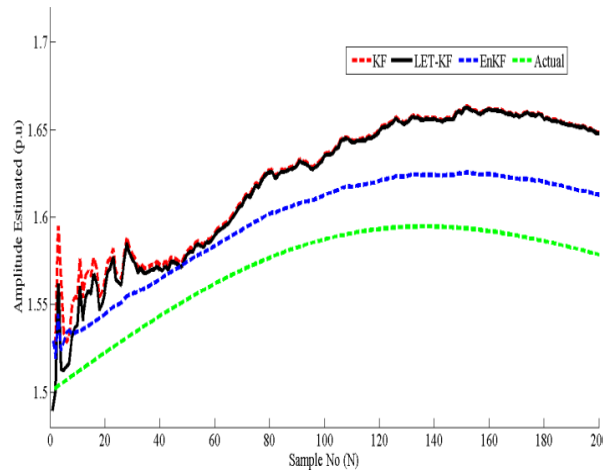
Figure 10. Dynamic Harmonic Signal
(Random: 0.05)

Figure 11. Dynamic Harmonic Signal (Random: 0.1)

Table 1.Performance of KF, En-KF and proposed LET-KF algorithm for harmonic parameter estimation
including sub and inter harmonics, with 0.01 random values

Algorithm	Parameters	Sub	Fund	3rd	Inter-1	Inter-2	5th	7th	11th
	Frequency	20	50	150	130	180	250	350	550
Actual	Amp (V)	0.2	1.5	0.5	0.1	0.15	0.2	0.15	0.1
	Phase(deg)	75	80	60	65	10	45	36	30
	Amp (V)	0.2020	1.500	0.5010	0.0999	0.1525	0.2029	0.1483	0.0989
	Error (%)	-0.003	-0.001	-0.0003	0.00115	0.002	-0.0028	0.001659	0.0029
KF	Phase	74.8035	79.9	59.70	64.375	8.5899	44.799	35.5325	30.5384
	Error (%)	0.9	-0.11	0.2	0.9845	1.4101	0.062	0.4675	-0.5384
	Amp (V)	0.2071	1.5023	0.5108	0.1021	0.1490	0.2021	0.1524	0.1023
	Error (%)	-0.01	-0.002	-0.001	-0.0133	-0.0015	-0.0023	-0.00238	-0.0023
En-KF	Phase	73.101	80.25	60.57	67.4502	11.4627	45.57	36.5251	29.47
	Error (%)	7.4	-0.1	-0.7	15.771	-1.4627	-0.8	-0.5251	0.5263
	Amp (V)	0.2019	1.4990	0.5007	0.0999	0.1524	0.2027	0.1483	0.0988
	Error (%)	-0.004	0.00105	-0.002	0.001212	-0.0013	-0.0027	0.001749	0.001161
LET-KF	Phase	74.7910	79.7	59.65	64.3731	8.5962	44.792	35.5344	3.5412
	Error (%)	0.5	0.2	0.3	0.9888	1.4038	0.062	0.4656	-0.5412

Table 2. Performance of KF, En-KF and proposed LET-KF algorithm for harmonic Parameters estimation including sub and inter harmonics with 0.05 random values

Algorithm	Parameters	Sub	Fund	3rd	Inter-1	Inter-2	5th	7th	11th
	Frequency	20	50	150	130	180	250	350	550
Actual	Amp (V)	0.2	1.5	0.5	0.1	0.15	0.2	0.15	0.1
	Phase(deg)	75	80	60	65	10	45	36	30
	Amp (V)	0.2045	1.4998	0.5051	0.0997	0.1635	0.2143	0.1418	0.0946
	Error (%)	-0.012	0.0001	-0.00503	0.00030	-0.0135	-0.01423	0.00819	0.0055
KF	Phase	75.5545	79.825	60.8927	61.8788	3.4093	44.93	33.5543	32.8157
	Error (%)	-0.55	-0.056	-0.360	3.119	8.0	0.06882	2.447	-2.8150
	Amp (V)	0.2121	1.5100	0.5100	0.1107	0.1592	0.2107	0.1606	0.1105
	Error (%)	-0.0045	-0.0011	-0.0097	-0.0107	-0.004	-0.01	-0.012	-0.012
En-KF	Phase	75.2547	77.79	60.1679	67.0259	12.1409	48.2	37.4381	27.7478
	Error (%)	0.25	0.17	-1.0	-2.0259	-5.0	-3.6	-0.0106	2.5
	Amp (V)	0.2044	1.4998	0.5048	0.0996	0.1634	0.2142	0.1417	0.0945
	Error (%)	-0.0044	0.0012	-0.00473	0.00036	-0.0132	0.01404	0.0084	0.0057
LET-KF	Phase	75.5417	79.803	60.1708	61.8750	3.4159	44.93	33.5566	32.8180
	Error (%)	-0.539	-0.05	-0.354	3.125	7.96	0.06874	0.00827	-2.8173

Table 3. Performance of KF, EnKF, and proposed LET-KF algorithm for harmonic Parameters estimation including sub and inter harmonics with 0.1 random values

Algorithm	Parameters	Sub	Fund	3rd	Inter-1	Inter-2	5th	7th	11th
	Frequency	20	50	150	130	180	250	350	550
Actual	Amp (V)	0.2	1.5	0.5	0.1	0.15	0.2	0.15	0.1
	Phase(deg)	75	80	60	65	10	45	36	30
	Amp (V)	0.2091	1.4995	0.1502	0.00997	0.1789	0.2286	0.1339	0.0894
	Error (%)	-0.009	0.7	-0.0010	-0.0003	-0.0274	-0.0285	0.0162	0.0105
KF	Phase	76.0847	79.492	60.336	58.7477	-2.1141	44.871	30.8145	35.964
	Error (%)	-0.28	0.060	-0.335	6.2524	12.12	0.129	5.1869	-5.964
	Amp (V)	0.2236	0.15156	0.5186	0.1188	0.1771	0.2218	0.1659	0.1163
	Error (%)	-0.024	-0.018	-0.018	-0.0187	-0.027	-0.021	-0.017	-0.016
En-KF	Phase	75.2819	79.6	60.625	6307706	9.6295	46.56	36.2209	26.539
	Error (%)	0.1	0.58	-0.62	1.1	-0.37	-1.52	-0.1	3.8
	Amp (V)	0.2089	1.4985	0.05098	0.0996	0.1787	0.2285	0.1338	0.0894
	Error (%)	-0.0087	1.9	-0.0097	-0.0004	-0.0272	-0.028	0.01623	0.0106
LET-KF	Phase	76.0719	79.937	60.332	58.7444	-2.1075	44.8711	30.8172	35.965
	Error (%)	-0.26	0.071	-0.337	6.2554	12.13	0.12891	5.182	-5.966

6. CONCLUSION

A new variant of KF and LET-KF is applied for the first time for the estimation of amplitude and phase of a time varying fundamental signal, its harmonics, sub harmonics and inter harmonics corrupt with random noise. The harmonic parameters are estimated using the proposed LET-KF and other two variants of Kalman Filter, i.e. KF and En-KFalgorithms, for evaluating their comparative performance with the random noise values 0.001, 0.05 and 0.1. Among these three noises, 0.01 random noise results will give better than other two noises. Because the phase deviation and amplitude deviation less in 0.01 random noise. The performance results obtained with all the three algorithms reveals that the proposed LET-KF algorithm is the best amongst all the three algorithms in terms of accuracy in estimating harmonic, sub-harmonic, inter harmonics. It is also less expensive, as it does not require the storing of large Kalman gain matrices like in the other KF based methods.

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