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A Review on the Importance of Kalman Filter Technique in Power System

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Abstract

Because electrical power system parameters are frequently mixed with noise, AC distribution systems have recently encountered high harmonic pollution. The perfect AC power system should have a constant frequency at a certain voltage, but due to connected nonlinear loads, non-sinusoidal active source injection into the grid, and other factors, both the current and voltage waveforms are significantly distorted today. As a result, other system-connected equipment has been impacted. This has raised system losses. If these impacts cannot be completely eliminated, then it is necessary to mitigate them, which is why the Kalman filter was proposed. In the area of electrical power discipline, especially in harmonic estimation, it has been very helpful. It has also found use in power system dynamics, optimal motor control and operation, relay operation and protection, and precise forecasting of short- and medium-term electrical demand. In this essay, the importance of the Kalman filter methodical approach, which is used in electrical power systems, is highlighted.

Keywords: *AC distribution system Electrical Power System; Electrical Load; Harmonic Estimation. Kalman Filter*

1. Introduction

In electrical power systems, power signals get perturbed from pure sinusoidal waveform due to presence of harmonics. Reason behind the existence of such harmonics rich signals is mainly because of the increasing demand of non-linear loads comprises of power electronics based devices, high power industrial loads, etc. which results in deterioration of power quality. Therefore, it is indeed an essential task to estimate harmonics with accuracy to take corrective actions for power quality improvement. There are several non-parametric methods of harmonic estimation which includes methods used on Discrete Fourier Transform (DFT), Fast Fourier Transform (FFT), Least Mean Square (LMS), Recursive Least Square (RLS) and other Recursive algorithms. Kalman filter (KF), reportedly, is a simple and strong candidate for estimation of harmonic parameters of a power signal corrupted with measurement noise and is given preference as it is free from the shortcomings of the other methods. Therefore, the present workers have focused on Kalman filter based harmonics estimation. However, Kalman Filter has a restricted application when non-linearity is introduced in the measurement equation. In such situations the non-linear estimation is carried out by nonlinear variants of Kalman. Filters out of which Extended Kalman Filters (EKF) is the most popular. In the paper, Robust Extended Kalman Filters (REKF) is presented for tracking time-varying harmonic components. But as the degree of non-linearity in the signal increases, the performance of EKF deteriorates due to linearization of significant nonlinearities. As an alternative, UKF has been used, where the harmonic estimation in microgrid is done and UKF outperforms EKF. Still, for high dimension nonlinear signal, the accuracy of UKF deteriorates.

CKF is, therefore, introduced based on spherical cubature rule, as an alternative to UKF which leads to nominal computational effort and linearization problem is also taken care of, as CKF is based on non-linear model.

The CKF is free from tuning parameters like UKF and has comparable estimation accuracy of UKF. Several other filters such as Local Ensemble Transform based Kalman filter (LETKF) is used which compared to Ensemble Kalman Filter (En-KF) reported, revealing that LET-KF outperforms En-KF in terms of accuracy and computational efficiency. In a linear system, the best estimation for a non-adaptive filter is possible only when the measurement and process noise co-variances i.e., Q and R are known a priori. In practice an arbitrary choice of noise covariance due to the lack of knowledge leads to the divergence of the estimates. For satisfactory performance of Kalman filter proper tuning of Kalman filter is essential. Improper tuning of noise covariances severely degrades the performance of the filter and may cause divergence. Therefore, large number of cases needs to be undertaken for offline tuning of KF. Adaptive Kalman filters can avoid this by online tuning/ adaptation of the noise covariance. Early works on KF report on auto tuning of noise covariance by online adaptation using the parameter estimation methods, viz., Maximum

Likelihood Estimation (MLE), Maximum a Posterior (MAP) respectively. The performance Kalman filter incorporated with the adaptation algorithms for harmonics estimation has been explored in this paper. For static harmonics estimation (where amplitude of harmonics remains constant) usually the system dynamics is hardly affected by system noise and therefore the noise covariance should be of lower value. If the relative difference between the true noise covariance and the noise covariance initialized for the filter is high then the estimation accuracy for non-adaptive KF degrades significantly. AKF can adapt online the inaccurate initial choice of noise covariance and ensure satisfactory estimation result. During the dynamic harmonics estimation where the amplitude of harmonics are time varying the system dynamics is modeled as random walk model with time varying noise covariance. In such situations the use of AKF is highly recommended. When along with harmonics the fundamental frequency needs to be estimated the measurement equation becomes nonlinear and AKF cannot be employed. For such joint estimation problem adaptive Extended Kalman filter (AEKF) and its successors may be employed. In this work along with AEKF, adaptive Cubature Kalman filter (ACKF) and adaptive Cubature Quadrature Kalman filter (ACQKF) have been employed and their relative performance has been carried out. A few works have been reported in literature where adaptive Kalman filters or their nonlinear variants are employed in power system harmonics estimation. A self-tuning Kalman filter algorithm is applied for harmonic estimation where the harmonic parameters are time varying. The adaptation was performed on the basis of an intuitive adaptation algorithm. In the value of process noise covariance is switched between different values on the basis of a hypothesis framed on t-statistics. Hybrid Genetic Algorithm and Adaptive Particle Swarm Optimization based Unscented Kalman Filter (UKF) is developed to estimate the power system harmonic components. The hybrid Genetic Algorithm and Adaptive Particle Swarm Optimization algorithm is used to estimate the process and measurement noise covariance matrices by minimizing the Root Mean Square Error (RMSE) of the UKF. Here, the approach of standard parameter estimation methods has not been explored.

2. Literature Review

S. H. Hosseini and K. Mohammadi [13] Kalman filter-based algorithm is developed and implemented for measuring time-varying harmonics. The efficiency of the proposed algorithm has been successfully tested in off-line mode by various computer simulations. Based on this algorithm, a prototype harmonic analyzer has been designed, fabricated and used for on-line harmonic monitoring and assessment studies. To assess the severity of time-varying harmonics, cumulative time indices that are computed in real-time using the output of the analyzer are proposed. In addition, new cumulative time curves for total harmonic distortion and individual harmonic distortions are presented. In addition, an auto-synchronization algorithm is proposed to accompany the Kalman filter algorithm in order to eliminate the errors occurred due to the variations in the incoming signal frequency.

Pravir Yadav and Aritro Dey [14] investigated the efficacy of adaptive Kalman filers for power system harmonics estimation. Significant increment of non-linear loads is responsible for the presence of harmonics in power signals which deteriorates the power quality. Towards the improvement of power quality, estimation of the harmonic components is an essential task, which has been proposed to be carried out by adaptive Kalman filter and its nonlinear variants. The paper investigates the suitability of adaptation algorithms for harmonics estimation and recommends an appropriate choice of adaptation algorithm. In addition to this, this paper presents a scheme of joint estimation of fundamental frequency along with the harmonic parameters using the nonlinear variants of Adaptive Kalman filter. From the relative performance comparison of adaptive nonlinear filters during harmonics estimation adaptive Cubature Quadrature Kalman filter is recommended for power system harmonics estimation for its performance accuracy, numerical stability and reasonable computation cost.

Matilde de Apráiz, Ramón I. Diego and Julio Barros [15] proposed the application of a non-linear Extended Kalman Filter (EKF) for accurate instantaneous dynamic phasor estimation. An EKF-based algorithm is proposed to better adapt to the dynamic measurement requirements and to provide real-time tracking of the fundamental harmonic components and power system frequencies. This method is evaluated using dynamic compliance tests defined in the IEEE C37.118.1-2011 synchrophasor measurement standard, providing promising results in phasor and frequency estimation, compliant with the accuracy required in the case of off-nominal frequency, amplitude and phase angle modulations, frequency ramps, and step changes in magnitude and phase angle. An important additional feature of the method is its capability for real-time detection of transient disturbances in voltage or current waveforms using the residual of the filter, which enables flagging of the estimation for suitable processing.

Kumar et al [16] considers the adoption of optimization techniques for distributed generation planning in radial distribution systems from different power system performance viewpoints; it considers the use of different DG types, distribution models, DG variables, and mathematical formulations; and it considers the participation of different countries in the stated DG placement and sizing problem. Moreover, the summary of the literature review and critical analysis of this article helps the researchers and engineers to explore the research gap and to find the future recommendations for the robust optimal planning of the DGs working with various objectives and algorithms. The paper considers the adoption of uncertainties on the load and generation side, the introduction of DGs with energy storage backups, and the testing of DG placement and sizing on large and complex distribution networks.

Eslami et al. [17] addressed based on the permissible current limits recommended by IEEE 519 Standard, with a determination of whether or not injected harmonics are within these limits. If limits are violated, the extent of the violations are characterized to provide information about harmonic current levels in the power system and facilitate remedial actions if necessary. A novel feature extraction method is proposed, whereby each set of harmonic measurements in a power system are transformed into a unique RGB image. Harmonic State Estimation (HSE) is discretized as a classification problem. Classifiers based on deep learning have been developed to subsequently locate and characterize harmonic sources. The approach has been demonstrated effectively both on the IEEE 14-bus system and on a real transmission network where harmonics have been measured. A comparative study indicates that the proposed technique outperforms state-of-the-art techniques for HSE, including Bayesian Learning (BL), Singular Value Decomposition (SVD) and hybrid Genetic Algorithm Least Square (GALS) method in terms of accuracy and limited number of monitors.

K. Dhinesh kumar, and C. Subramani [18] 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.

Vathsal and Pasam [19] The ever increasing improvement of the semiconductor industry on the one hand and the rising power Electronics applications on the other hand have changed this scenario for ever, paving the way to the very fruitful area of digital control and signal processing applied on power systems and power electronics. This new area has been applying successfully all the knowledge gathered to improve processes like power quality monitoring, power systems protection, power conditioning and synchronization of distributed generators(among others). The most used digital techniques have been digital filtering, discrete Fourier Transforms, phase locked loop tracking methods and more recently, the Kalman Filtering. This paper presents a concise survey of applications of KF to power system and power Electronics giving emphasis on the topic of signal's fundamental component identification, which has a key role in most of them.

3. Kalman Filter

The Fast Fourier Transform (FFT) is the most frequently used for harmonic analysis as its computational efficiency is really appreciable. By transforming the measured signal from time domain to frequency domain, it can precisely track the harmonic components. However, since the harmonic level and the fundamental frequency in the power system usually time varying, the direct application of FFT for spectral analysis may lead to inaccuracies due to the leakage and picket-fence effects . Thus we go for the Kalman Filter. The Kalman filter is a recursive and optimal estimator suitable for systems described in state variables. The prime objective of Kalman filter (KF) is to obtain an optimal estimation of state variables which may be corrupted with noise. It achieves this by minimizing the square of the expected error between the values of the actual system measurements and estimated system states. Kalman Filter (KF) is used in power systems to estimate the amplitudes and phase angles of harmonics from their sampled voltage or current data. The reduction of these harmonics in a system ensures a good system quality.

3.1 Kalman Filter Algorithm

For implementing the Kalman Filter, a mathematical model for the system under consideration should be in the following state form:

$X_{k+1} = \emptyset_k x_k + wk$ (1)

And the measurement (observation) of this system is assumed to occur at discrete points of time in accordance with the relation:

$Z_k = H_k x_k + Vk$ (2)

Where,

Zk= measurement of current samples

Hk= measurement matrix

xk= state to be determined

Vk= noise covariance vector

wk= measurement error to be minimised

Let be known covariance of a white sequence. Assuming that we have a prior estimate, and its error covariance matrix; then the general recursive filter equations are as follows:

(a) Compute the Kalman Filter gain, Kk as

$K_k = P_k - (HP_k - Ht + R)^{-1}$ (3)
(b) The error covariance is computed for updating
$Pk = (1 - KkH)Pk$ (4)
(c) Update the estimate with the measurement
(d) Project ahead the error covariance and the estimate

4. KF on Power Electronics and Power Systems-State of the Art

A concise description of different applications of the KF in power electrons and power systems areas is summarized in next sections. Even if some of them have been proposed more than 20 years ago, especially those based on off-line processing, the applications are quite limited if compared with other digital techniques applied in such areas. Probably, it happened because of the computational complexity of the KF for on-line applications that could not have solve off-line (for example, when the model's matrices change in not a priori known pattern). Nevertheless, considering the ever increasing capacity of digital processor's technology, this line has been broken down and new KF applications have emerged, including on-line approaches. Most of them are based on the identification of the fundamental 60Hz Components (x1) of phase voltages and/or currents (amplitude, phase and frequency) or even based on the fundamental positive sequence components.

A. Lord forecasting and modal estimation

One of the first applications of the KF in the power system area had been to forecast the total load demanded by a multi-node system. Temporal load data, collected by the various agents in the power system administration, are used in order to predict load conditions, and the KF is frequently a fundamental part of the algorithm. Normally, the collected data are hourly based, and the prediction algorithm must yield short-term results, that would be useful in scheduling the actual system in order to supply the daily demand, and medium and long-term results, what would be useful in, for example, expansion planning and annual maintenance scheduling. Load forecasting has been gaining more importance as long as the electricity market becomes deregulated and the power sources become more and more distributed in the interconnected grid. In this kind of application, there is not much difference from the forecasting of economic data, as presented in (Clements & Hendry, 1998). There is a temporal series of power consumption and several periodicities and trends can be detected. The most evident is the daily periodicity on weekdays, which assumes the peak value around the beginning of the night. On Sundays and holydays, however, the pattern consumption tends to be less correlated. This pattern also reveals a weekly and monthly periodicity, and a yearly periodicity can obviously be assumed. Trends are always present in this kind of data, and the most important is the rising consumption that can be observed in the series. It is also important to mention the parameter dependence variations coming from the climate (mostly temperature). In tropical countries, the load is expected to be higher in summer, by the use of air conditioning systems, for example. On the technical side, it is always possible to associate to a temporal series a model like (1), where y(k) is the series itself. The states, on the other hand, could be the periodic components (in a Fourier series sense) or even non-periodic, and the matrices could be determined in order to generate those components (obviously time-invariant in this case). Disturbances and noise covariance should be adequately selected. The KF would act in order to estimate those components, which would be the states and could represent trends and seasonal behavior. The matrices could even be time-varying, if the process is known to be more complex. In a similar away, other interesting application is the modal estimation of the power system. Based on power system`s measurements under normal conditions and defining a stochastic model relating different disturbance inputs (e.g., load changes), the KF is adjusted to estimate the outputs produced by the disturbances. Then, by monitoring the difference between the measured output and the estimated output, one can recognize if there is any change in the model parameters.

B. Protection and digital relaying

Other key application of KF in power systems is to detect fault conditions and to control protection devices, a task normally done by digital relays. Based on information coming from voltages and currents, decisions must be taken in order to detect and protect the power system from more severe faults and maintain its stable operation. The discrete signals coming from several sensors do contain valuable information, but it is necessary to extract it from input disturbances, what means that it is necessary to identify the signals Of course, this information is in the transient condition and depending on the kind, frequency of occurrence and location of the fault, the effects produced in the 60 Hz components (and other frequencies), are of very particular type, allowing gathering valuable information in order to control a protective device or to plan a repair as soon as possible.

C. Analysis and control of electrical machinery

Considering the digital control or analysis of induction motors, the KF has been applied in some different ways, e.g., to estimate the rotor time constant in PWM motor drives to estimate the air gap flux in order to implement a direct flux control strategy or also to identify the rotor resistance in order to propose adaptive vector control schemes. In addition, KF has been also applied in order to reduce or avoid the use of additional sensors in the motor controlling or monitoring, considering the so called sensor less applications. It is interesting to mention that these applications use the KF as part of an automatic closed loop control system, that is, in the same way as its first applications he information from the estimates was used by people in decision making processes or open-loop applications.

D. Power conditioners control and synchronization

The requirement of synchronization of several electronic devices (such as active rectifiers, active power filters, uninterruptible power suppliers, dynamic voltage restorers, distributed generators, etc.) has been motivating the development of different algorithms to detect the amplitude, frequency and phase angle of the power grid fundamental voltage, as it will be demonstrated in the following: In the matter of power conditioning, several closed-loop control schemes have been applied in order to control the voltages and currents waveforms, frequency, and amplitudes of an electrical load or point of common coupling (PCC). Many control laws can be used in order to guarantee the voltage/current to track the references, and to compensate for disturbances, running from classically inspired techniques to those including a KF in the control loop. An active rectifier, e.g., should drain a sinusoidal current from the supply system, which should be in-phase with the fundamental component of the grid voltage, even if this one is distorted. This will ensure a high power factor for the resulting active rectifier. In case of three-phase devices, it is also desired to ensure equal phase currents, it means that the three phase rectifier will act as resistive balanced load. An active power filter, either in series or parallel to the loads, should ensure, e.g., that voltages and/or currents (depending of the configuration) are sinusoidal, balanced, symmetrical and with constant magnitude. It is possibly based on the identification of the disturbing signals, which will become the references for the control scheme in order to be injected in or filtered out of the power system. In this case, the KF should be responsible for the detection of the ideal signals (fundamental positive sequence components x+1) and by the difference with the original voltages or currents, the deteriorated signals (harmonic distortions, voltage sags and swells, low power factor, unbalances, etc.) could be identified ($x_d = x - x_{1+}$). In the matter of distributed generation, the control of different power sources (AC or DC) have been carried out by means of electronic power converters and usually, it depends on some synchronized signal, in order to ensure that the generated voltages have the same frequency and phase angle of the main power grid. Again, in this case, the required information could be achieved by means of the KF.

E. Revenue metering and power quality monitoring

The continuously increasing demand for electronic equipment's and power converter applications has been the most important cause of power quality deterioration phenomena, including voltage and current distortions and imbalances. The impacts of such disturbing effects can be directly related to power losses, insulation stress, over voltages, power oscillations or even malfunction and damage on sensitive loads. Among a number of different areas related to this question, during the last decades intensive research has been directed to the directed to the definition of power quality indices and revenue metering techniques, suitable for monitoring nonlinear and unbalanced systems.

Considering the power quality monitoring, important indices have been defined to estimate the amount harmonic distortion or unbalances on the measured voltage (v) and current (i) or also how these distortions affect other indicators, such as, e.g., the power factor (PF). Once more, the KF can be applied in order to identify the fundamental components (v1, i1) and the positive sequence components (v_1+, i_1+), which could be used to the calculation of the mentioned indices. Thus, indices such as, the voltage Total Harmonic Distortion. n the matter of revenue metering, considering for example the IEEE STD 1459-2000, which brings the definition of several power quantities related to fundamental components, positive sequence components, harmonic components, among others, the KF application could be responsible for the calculation of e.g., the Fundamental Active Power (P_1), the Fundamental Equivalent Apparent Power (S_{e1}), the Fundamental Power Factor (FP_1), the Fundamental Positive Sequence Power Factor (FP_{1+}).

The KF has also been applied to the development of expert systems focused on the analysis, classification and possible cause`s identification of short term power quality disturbances, such as; voltage sags, swells and interruptions.

5. Conclusion

Although the Kalman filter theory has been around for more than 50 years, its importance for electricity systems cannot be overstated. Additionally, it has been extensively used in robotic engineering for location estimation and telecommunication for satellite position. In terms of manufacturing, it has a wide range of applications. The characteristics of the Kalman filter and its extension form in the area of application and related aspects of electric power networks are reviewed in this paper. Although Kalman filter has flaws and shortcomings that must be acknowledged, combining it with other intelligent algorithms has emerged as the direction of growth going forward.

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