Testing and Validation of a Dynamic Estimator of States in OPAL-RT Real Time Simulator

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***Abstract*—The paper presents an adaptive Kalman filter based linear dynamic estimator of power system states, and validates its performance in a real-time simulation environment. OPAL-RT ePHASORsim is used as the real time environment, and procedure of developing the dynamic test case is discussed in detail. The estimator is based on measurements available from phasor measurement units (PMUs). On OPAL-RT platform, it is validated that the execution of the estimator can be completed before the arrival of each complete set of PMU measurements. The performance of the proposed method is also compared with extended Kalman filter based estimator on New England 39 bus test system under various disturbances such as three phase fault, sudden load changes, and load outage.**

***Index Terms*—Adaptive Kalman filter, measurement uncertainty, OPAL-RT, real-time simulation, synchrophasor measurements.**

I. Introduction

Nowadays, real-time monitoring is prerequisite for appropriate operation and control of power systems. The awareness of the real-time operating condition of the system might have averted or abated the extent of the power system blackouts [1], [2]. The measurement devices are placed at the distinct locations of the system, and facilitate the regular surveillance over the operating conditions of the power system. These measurements are telemetered to the control centre, where the state estimator estimates the states of the system. Bus voltage magnitudes and phase angles are generally considered as the system states [3].

Usually, weighted least squares (WLS) type of algorithms are deployed in the control centres, to estimate the states from the set of measurements collected over a time-window. The use of dynamic estimator of states (DES), utilizing Kalman filter type of algorithms [4], has not been much admired with the supervisory control and data acquisition (SCADA) based measurements because of slow refresh rate of the measurements. With the advancement of the technology, the advent of phasor measurement units (PMUs) made it possible to get the measurements at every few milliseconds [5]. This reinvigorated the research enthusiasm in DES [6]- [7]. A DES based on PMU measurements, can update the states of system at the sub-second rate. A PMU provides synchronized bus voltage phasors, line current phasors, system frequency, and the rate of change of system frequency. These measurements are comparatively much more accurate than the conventional SCADA measurements. In the PMUs, measurement reporting rate is usually up to 50 (for 50 Hz system) or 60 (for 60 Hz system) times per second, that is much higher than the reporting rate of conventional SCADA measurements (typically few seconds).

Exclusively PMU measurements based state estimator becomes linear, because of linear measurement-state relationship and can be executed at the faster rate. In this paper, an Extended Kalman Filter (EKF) based linear DES has been applied for the estimation of states, considering PMU measurements only. Usually, the measurement error variance is taken as fixed, as pre-specified by the manufacturers. Instead of taking it fixed, a new adaptive method has been discussed, in which the measurement error variance is time varying and depends on the difference between actual and last estimated measurements [6]. This adaptive scheme to assign measurement weight is found to result in better accuracy in the estimated states.

The system is assumed to be completely observable with minimal number of PMUs. In order to fully utilize the high refresh rate of the PMU measurements, it is important that the DES completes its execution before the arrival of the next set of PMU measurements. The main motivation of this paper is to execute the DES in a real-time simulation environment, and validate that the execution is completed before the next PMU data set arrives.

The real-time simulator from OPAL-RT technologies provides a platform for simulating the dynamics of power systems in real-time [8]. In RT-LAB environment, ePHASORsim is a tool that provides Microsoft Excel based interface for network data [9]. ePHASORsim is particularly suitable for simulating a large power system in real-time. The real-time phasor measurements obtained from ePHASORsim are used by the DES to estimate the states. It is validated that the execution of DES is completed within 10ms and 40ms for PMU refresh rate of 100 and 25 frames per second, respectively.

The paper is organized as follows. Section II gives the basics of the linear state estimation problem formulation. The implementation of the EKF and the adaptive Kalman filter (AKF) is given in Section III and IV, respectively. Section V presents overview of RT-LAB and ePHASORsim. In Section VI, step-by-step procedure is given for developing a system dynamic model in RT-LAB ePHASORsim platform.

Simulation and results are demonstrated in Section VII.

II. Linear State Estimator

The formulation of the linear state estimation problem is presented here in brief. System states and measurements may be taken either in rectangular or in polar form. In this work, both are taken in rectangular form. Let the the state vector, $\mathbf{x}$, consist of the real part, $\mathbf{v}_{real}$, and the imaginary part, $\mathbf{v}_{imag}$, of the bus voltages. The measurement vector, $\mathbf{z}$, consists of real and imaginary parts of the available voltage and current phasors collected from PMUs. The relationship between system states and measurements is given by [10],

$$\begin{bmatrix} \mathbf{v}_{real}^m \\ \mathbf{i}_{real}^m \\ \mathbf{v}_{imag}^m \\ \mathbf{i}_{imag}^m \end{bmatrix} = \begin{bmatrix} \mathbf{C} & \mathbf{0} \\ \mathbf{H}_1 & -\mathbf{H}_2 \\ \mathbf{0} & \mathbf{C} \\ \mathbf{H}_2 & \mathbf{H}_1 \end{bmatrix} \begin{bmatrix} \mathbf{v}_{real} \\ \mathbf{v}_{imag} \end{bmatrix} \tag{1}$$

Or, in compact form,

$$\mathbf{z} = \mathbf{H}\mathbf{x} \tag{2}$$

where $\mathbf{v}_{real}^m$, $\mathbf{v}_{imag}^m$, $\mathbf{i}_{real}^m$, and $\mathbf{i}_{imag}^m$ are PMU voltage and current measurements. In (1), matrix $\mathbf{C}$ is the voltage incidence matrix, $\mathbf{0}$ is a null matrix having the same dimension as $\mathbf{C}$, and $\mathbf{H}_1 = real(\mathbf{YA} + \mathbf{Y}_S)$, $\mathbf{H}_2 = imag(\mathbf{YA} + \mathbf{Y}_S)$. The matrices $\mathbf{C}$, $\mathbf{A}$, $\mathbf{Y}$, and $\mathbf{Y}_s$ are defined as follows:

- Voltage incidence matrix, $\mathbf{C}$: PMU voltage phasors are in fact direct measurements of the system states. The dimension of this matrix is $m \times n$, where m and n are the number of buses where PMUs are placed and the total number of buses, respectively. If the kth voltage measurement is located at the ith bus, then in the kth row of this matrix, the (k, i)th element will be one, and other elements will be zero.
- Current incidence matrix, $\mathbf{A}$: This matrix represents the location of the current measurements. The dimension of this matrix is $l \times n$, where l is the number of current phasors measured by the PMUs. If current flow between the ith and the jth bus is the kth current measurement, then the (k, i)th element of this matrix will be 1, (k, j)th element will be -1, and other elements in the kth row will be zero.
- Series admittance matrix, $\mathbf{Y}$: This matrix is $l \times l$ diagonal matrix, and each diagonal element represents the series admittance of line where current measurement is available.
- Shunt admittance matrix, $\mathbf{Y}_S$: This matrix is also having dimension $l \times n$. If current flow between the ith and the jth bus is the kth current measurement, then the (k, i)th element of this matrix will be the shunt admittance of the side of the line where PMU is placed. All other elements in the kth row will be zero.

III. Extended Kalman Filter based Linear State Estimator

In this work, the EKF has been used for estimation of states. In the EKF, system states are estimated in two steps: prediction using last estimated state, and correction using current available measurement set. At the instant k, the predicted states, $\widehat{\mathbf{x}}$, are given by,

$$\widehat{\mathbf{x}}^k = \mathbf{F}\mathbf{x}^{k-1} + \mathbf{q}^{k-1} \tag{3}$$

where $\mathbf{F}$ is the state transition matrix. Here we have considered that the model perfectly matches real system, so matrix $\mathbf{F}$ is assumed to be constant and unity matrix. Additional term, $\mathbf{q}$, represents Gaussian noise (added to the actual states) having zero mean and uncorrelated error covariance matrix, $\mathbf{Q}$. The Gaussian noise, $\mathbf{r}$, added to measurement set also has zero mean and uncorrelated error covariance matrix, $\mathbf{R}$.

The covariance matrix, $\widehat{\mathbf{P}}^k$, at the prediction stage is calculated using,

$$\widehat{\mathbf{P}}^k = \mathbf{F}\mathbf{P}^{k-1}\mathbf{F}^T + \mathbf{Q} \tag{4}$$

As soon as the next measurement set $\mathbf{z}^k$ arrives, the system states and covariance matrix are updated using,

$$\mathbf{x}^k = \widehat{\mathbf{x}}^k + \mathbf{K}^k[\mathbf{z}^k - \mathbf{H}\widehat{\mathbf{x}}^k] \tag{5}$$

$$\mathbf{P}^k = \widehat{\mathbf{P}}^k - \mathbf{K}^k\mathbf{H}[\mathbf{K}^k]^T \tag{6}$$

where $\mathbf{K}^k$ is the Kalman filter gain, and computed as,

$$\mathbf{K}^k = \widehat{\mathbf{P}}^k\mathbf{H}^T(\mathbf{H}\mathbf{P}\mathbf{H}^T + \mathbf{R})^{-1} \tag{7}$$

As PMU measurements are linearly related to the system states, and depend only on network topology, there is no need to evaluate jacobian matrix in each step. This makes the estimation non-iterative and fast. In above equations, iteration indices of $\mathbf{H}$, $\mathbf{R}$, $\mathbf{Q}$, and $\mathbf{F}$ have been dropped as these are assumed constants in this formulation.

IV. Adaptive Kalman Filter based Linear State Estimator

To improve the performance of the estimator, time varying measurement uncertainty has been included in Kalman filter, instead of keeping it always fixed as in EKF. An exponential term involving the measurement residual (i.e. the difference between actual and last estimated measurement) has been included in measurement error covariance, that make the process of tracking more accurate by updating the error variance at each step. If any raw measurement is having a large deviation from its actual value, exponential residual vector will reduce the effect of that measurement.

The Kalman filter is now adaptive to measurement residual vector. In (7), the measurement error covariance $\mathbf{R}$ is replaced by $\mathbf{R}\mathbf{M}^k$, where $\mathbf{M}^k$ is a diagonal matrix, and its elements are defined by,

$$\mathbf{M}^k(i, i) = exp(|[\mathbf{z}^k](i) - [\mathbf{H}\widehat{\mathbf{x}}^k](i)|) \tag{8}$$

where $i = 1, 2, \ldots$ is the index of the measurements, $[.](i)$ is the ith element of the vector, $[.]$.

The exponential residual vector is arranged diagonally to reflect its effect in corresponding measurement error variance. It ensures that, with the increase in measurement residual, the measurement uncertainty increases, and hence the associated weight factor reduces. This increases the robustness of the estimation process. In case of any bad data, it automatically reduces the weight, and avoids performance degradation.

V. OPAL-RT Real Time Environment

The state estimator described in the preceding section is tested and validated in OPAL-RT real-time simulator for power systems [8]. The RT-LAB platform in OPAL-RT offers ePHASORsim package, which is particularly suitable for simulating large power systems in real-time. In this section, a brief information about RT-LAB and ePHASORsim is provided, with the intention to make the new users familiar with the model development and validation process.

A. RT-LAB

RT-LAB is a simulation platform where the user can build mathematical model of dynamic systems in MATLAB/SIMULINK environment in real-time. It allows the user to separate models in subsystems for enabling parallel processing on target and standard PCs or hosts. In RT-LAB, the XHP (extreme High Performance) mode of execution enables the simulation in real-time, i.e., computation is completed within the pre-assigned time-step, without any overrun. In Fig. 1, t_s and t_e are the simulation time step (predefined) and execution time (time taken for estimation), respectively. In Fig. 1(a), $t_{e1} < t_s$, i.e., estimation process completes within the time step chosen, and this represents a real-time estimation process. In Fig. 1(b), $t_{e1} > t_s$, i.e., the estimation process is not completed before the starting of next time step, and overrun occurs. This represents a non-real-time estimation process, and a number of overruns are reported at the time of online execution of the model at the target.

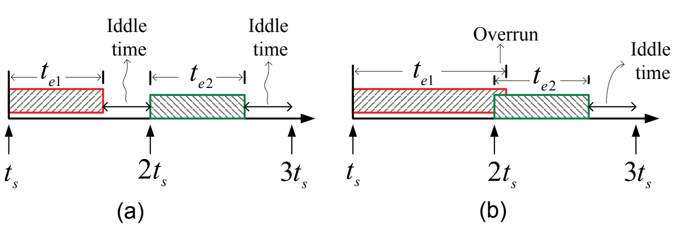

Fig. 1. Time diagram:(a) without overrun (b) with overrun

B. ePHASORsim

ePHASORsim is basically a MATLAB/SIMULINK S-function masked as 'Solver' block in RT-LAB library. The network data, input, output pins, all the components, their required parameters and initial values are defined on micro-soft excel sheets. To develop a practical large scale (in the range of 20,000 buses) dynamic system, use of single excel workbook is convenient. The network data can also be imported form PSS/E load flow case files and dynamic data files.

Input data parameters may be modified in run time by sending any single or multiple control commands, such as line fault at specific location on line, symmetrical and unsymmetrical faults on buses, outage of loads, tap position switching, and load change at various buses. These control sequence are defined in input pins of the solver. Output pins are used to define the signals that are to be monitored or captured.

VI. Implementation

This section describes the step-by-step procedure to build the dynamic model of a power system, and to run it in real-time environment.

A. Development of model

1) Defining network data: Network and dynamic data (i.e., bus data, line data, load data, transformer, machine, exciter data etc.) of the test power system and input-output pins are entered in an excel workbook.

2) Inclusion of Solver block: The 'solver' block form ePHASORsim's Phasor library is added to simulink model, and the excel workbook is called for the required network and dynamic data. The solver will read data and it will create *.opal file containing all details of the network and control sequences as well.

3) Creating subsystems: After successful inclusion of the solver block, three subsystems (identified as SM, SS, and SC, i.e., master, slave, and console subsystems, respectively) are created to enable execution in parallel processing, as shown in Fig. 2.

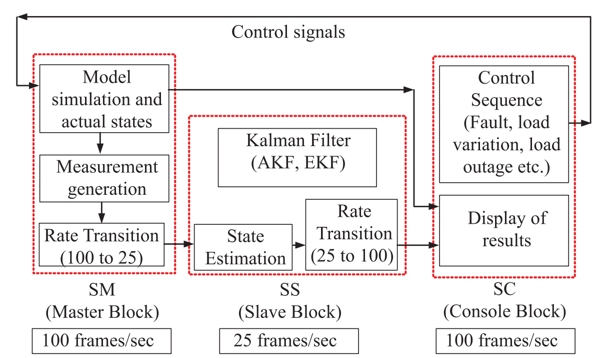

Fig. 2. Block Diagram

- *Master subsystem:* The solver is included in the master subsystem. Output pins defined in excel workbook provide the actual states, i.e., bus voltage magnitude and angles. Real and imaginary part of bus voltage phasors and line flow currents are generated according to PMUs location. A *rate transition* block is used to generate the PMU measurements at the desired refresh rate (e.g., 25 or 100 frames per second). This is needed because the time step of simulation is usually much smaller than the PMU data intervals.
- *Slave subsystem:* Using the slave subsystem, model elements are distributed across different cores. This enables parallel processing and makes the execution much

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faster. EKF and AKF algorithms are used as embedded MATLAB functions for estimation of states. The DES is executed at each arrival of the complete PMU data set. To compare the estimated states with the actual states at same rate, a rate transition block involving interpolation is used again.

- *Console subsystem:* The signals that are needed to be monitored in real time are kept in console subsystem along with control sequences that are needed to be applied at run-time. All the signals, coming from master and slave subsystem, are passed through OpComm block, that simulate the behavior of the real-time communication link, while transferring the data from master to console or console to master block. The type of control sequences (such as type of fault, load outage, load variation) are defined in the input pins of the solver, and the instant (event time) of applying these controls with changed parameters (pre- and post- event values) are specified in the console.

B. Compilation

All the supporting files and test case simulink model are imported in RT-LAB and the model is compiled. Compilation converts each components of the model to executable C++ codes.

C. Loading in target system

After successful compilation, the model is loaded to the available target system. Model initialization and synchronization is done by target and communication links, and run-time console become active.

D. Execution in real-time

Model execution starts the simulation, and the generated signals can be seen in active console. We can store the results in OpWriteFile block of RT-LAB, for further analysis of the output streams.

VII. Simulation and Results

Dynamic model of the New England 39 bus test system [11] is developed in this work by entering all the input data in an excel workbook. Simulation have been carried out by choosing different time-steps, and it was found that the solver performs well (without any over-run) for time-step size above 1.5ms. Therefore, the maximum refresh rate of measurements, for which the DES may be tested in real-time in OPAL-RT is about 660 frames per second. Usually, the phasor measurements are are available from PMU at the rate of 5, 10, 25, 50, or 100 frames per second, for 50 Hz system. In this paper, the proposed DES is tested for PMU measurement rates of 25 and 100 times per second. Simulation have been done for 15s duration, and different control sequences have been applied to generate measurements under different disturbances. PMUs are considered to be available at the buses 2, 6, 10, 11, 14, 17, 19, 20, 22, 23, 25, and 29 of the 39 bus test system, which ensures complete observability of the system [12]. To obtain the PMU measurements from the actual simulated system, the refresh rate is kept 100 frames per second. Using rate-transition, the refresh rate have been decreased to 25 frames per second and the system states have been estimated via EKF and AKF at each 40 ms interval.

To simulate and capture a real power system's response under various operating conditions, OpWriteFile block of RT-LAB has been used. Three successive disturbances have been applied on the test system, as described below.

- At time 2s, a three phase fault is applied on bus 30 for 12 cycles (i.e. 0.12sec).
- At 9s, a sudden load change (reduction by 20 %) is applied on bus 7, and restored to 100% at 10.5s.
- At 13.5s, load outage is applied at bus 16.

Fig. 3 shows the actual and estimated voltage magnitudes using AKF and EKF at different refresh rates, at bus 13. Fig. 4 shows the actual and estimated voltage angles at bus 13. Some portions of the figures have been enlarged to better view the instance where disturbances were applied.

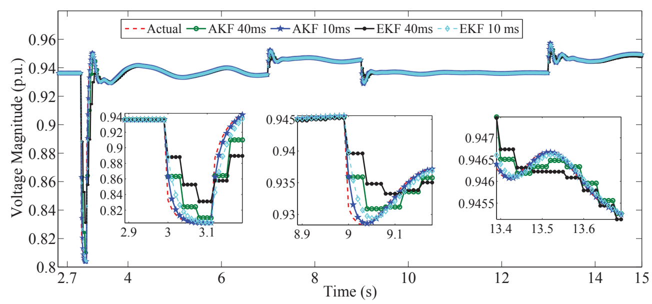

Fig. 3. Voltage magnitude at bus 13

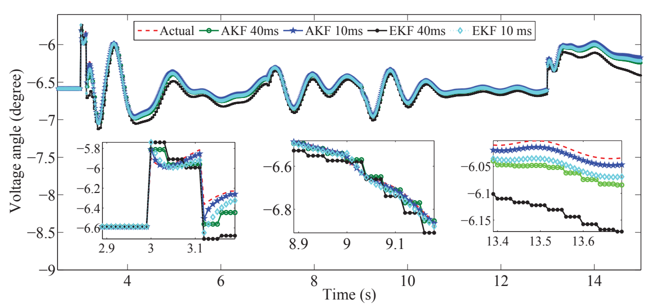

Fig. 4. Voltage angle at bus 13

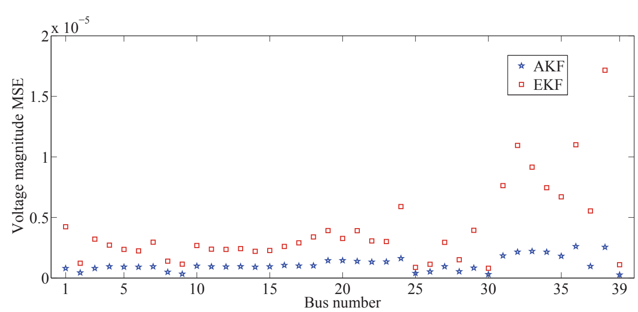

Fig. 5. MSE in voltage magnitude at the refresh rate of 25 frames per second

The performance of EKF and AKF have been compared using mean squared error (MSE), and is computed as,

$$MSE(\widehat{x}^k) = \frac{1}{N}\sum_{k=1}^{N}(\widehat{x}_{est}^k - \widehat{x}_{true}^k)^2 \tag{9}$$

Fig. 5 and Fig. 6 show the MSEs of voltage magnitude and angle using EKF and AKF at refresh rate of 25 frames per sec (at each 40ms), respectively, at different buses of the test system. Fig. 7 and Fig. 8 show the MSE of voltage magnitude and angle, respectively, using EKF and AKF at 100 frames per sec (at each 10ms) refresh rate of the measurements, at different buses of the test system.

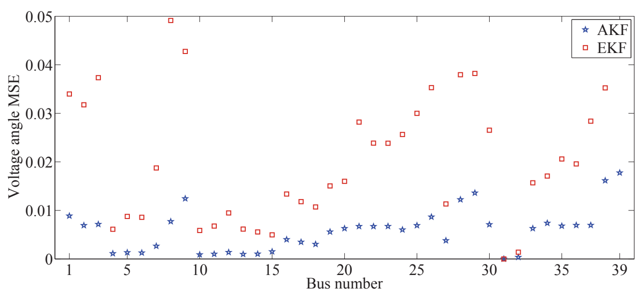

Fig. 6. MSE of voltage angle at refresh rate of 25 frames per second

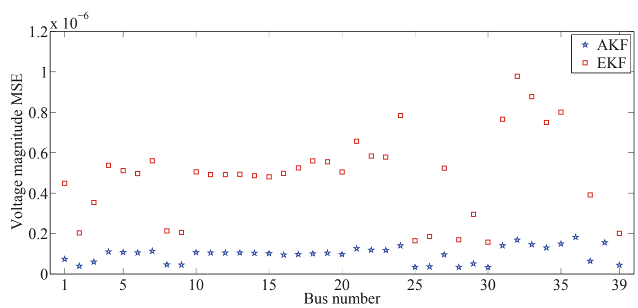

Fig. 7. MSE of voltage magnitude at refresh rate of 100 frames per second

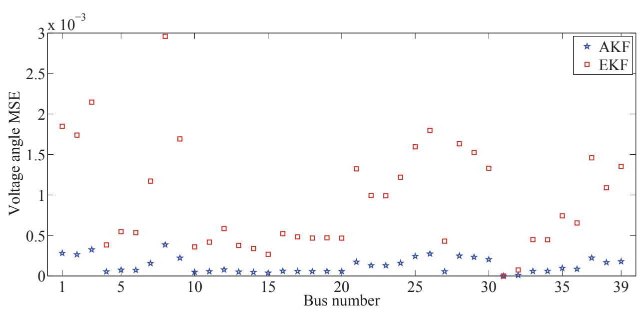

Fig. 8. MSE of voltage angle at refresh rate of 100 frames per second

TABLE I
EXECUTION TIME FOR EKF AND AKF

EKF		AKF	
Minimum	Maximum	Minimum	Maximum
1.4 ms	2.3 ms	1.8 ms	3.3 ms

The EKF and AKF both have estimated the states without any overrun. The average execution time of EKF and AKF based LSE for normal operating condition and for disturbed condition is shown in Table I. Although the execution time of AKF is slightly more than the EKF, the accuracy of AKF is higher. In both the methods, accuracy increases with the refresh rate of measurements.

VIII. Conclusion

The paper develops an adaptive Kalman filter (AKF) based dynamic estimator of states (DES) for power systems, and validates its real-time applicability with the help of a real-time simulator. The AKF based DES achieves higher accuracy, compared to the existing methods such as the EKF, by implementing a systematic way of assigning measurement weights depending on the measurement residuals. The ePHASORsim solver in RT-LAB platform of the OPAL-RT real-time simulator is used to validate the performance of the estimator. The model-building and validation process in OPAL-RT is described with significant details. Test results on New England 39 bus system demonstrates the effectiveness of the proposed method and also validates that the DES may be executed in real-time, i.e., the states are estimated before the arrival of next set of measurements.

IX. Acknowledgement

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