Transmission Line Back-up Protection with Unreliable PMU Data

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Abstract—Phasor Measurement Units have been widely used for transmission line back-up protection due to its speed and accuracy. Most of the methods completely rely on the accuracy of the PMU measurements for faulted line identification. However, PMU data may consist of measurement noise and missing data at some instances which may eventually lead to relay maloperation for many algorithms. The proposed scheme deals with the identification of faulted line using difference in estimated voltage phasor at a bus connected to a faulted line, which is derived from cubature kalman filtering (CKF) based dynamic state estimation. The scheme is tested on a New-England 39-bus system for several faulted conditions with the effect of missing data and measurement noise on the proposed scheme with measurement data from fewer PMUs.

Keywords—phasor measurement unit; dynamic state estimation; faulted line identification; cubature kalman filtering

I. INTRODUCTION

Wide-area protection has become quite feasible due to development of information and communication technologies in last few decades. Wide area measurement systems (WAMs) consists of phasor measurement units (PMUs) which delivers synchronized phasors time-tagged with GPS clock [1]. Due to its speed and accuracy, various back-up protection schemes have been proposed in literature that require PMU information for identifying the faulted line [2]. Paper [3] identifies the faulted bus using minimum bus voltage information and faulted line using current angle difference between faulted bus and adjacent buses. In [4], the faulted line is identified by first identifying the faulted bus, the faulted line is found by calculating the phase angle between voltage and current at that bus. A PAPSII based method is proposed in [5] to identify the fault and tested for various stressed conditions. Similarly, a method based on voltage at a non-PMU bus calculated using the phasors from the adjacent PMU buses to calculate the faulted line is proposed in [6].

All the above mentioned methods rely completely on the accuracy of the PMU data. However, PMU data may be corrupted with certain non-uniform noise which when received by phasor data concentrator (PDC) may lead to an incorrect results when applied to power system applications. Moreover, sometimes the data from PMUs to PDCs may be missing at some instant of time. This may lead to incorrect relay operation when applied to any protection scheme based on PMU information. To eliminate these issues, a dynamic state estimator (DSE) is needed to fetch the phasor for power system applications. Earlier, the estimation was done through SCADA measurements received from RTUs (Remote Terminal Units) [7]. However, the data are non-linear and have a refresh rate of 1-5 s which is unsuitable for protection applications because the tripping decision has to be taken within few milliseconds. To alleviate this issue, the data is fetched using PMUs which reports the data to the phasor data concentrator (PDC) at the rate of 50/60 frames/second of a 50/60 Hz system. Therefore, PMU measurements should be integrated with dynamic state estimator to provide accurate phasors in case of missing data and measurement errors. Since, the usage of PMUs at all the buses is uneconomical, it is advisable to use the PMUs at fewer buses to achieve full observability.

Different DSE schemes utilizing Kalman Filters have been proposed in literature earlier. Extended Kalman Filter (EKF) utilizes first order approximation of Taylor series expansion to achieve the required estimates [8]. However, it is unable to deal with the non-linearity present in the measurements. Unscented Kalman Filter (UKF) has better accuracy, however, it is unsuitable for larger power systems [9]. The CKF based static estimator poses a better accuracy and efficiency with larger power systems than the other two methods [10].

The proposed scheme deals with enhancing the back-up protection scheme for faulted line identification by integrating the protection algorithm with Cubature Kalman Filtering (CKF) based dynamic state estimator with fewer PMU placements to mitigate the relay maloperation arising due to device inaccuracies. The faulted line identification is based on change in voltage phasor at a bus measured through adjacent buses due to topological change in case of fault. Section II deals with the basic knowledge of CKF based DSE and its incorporation into the proposed wide-area back-up protection scheme. Section III shows the simulation results for several fault conditions as well as for measurement loss and missing data cases using the proposed scheme for a New-England 39-bus system and section IV concludes the paper.
II. PROPOSED SCHEME

A. Cubature Kalman Filterbased DSE

CKF based dynamic state estimation is used to provide voltage phasor estimates from the PMU buses to be utilized in the back-up protection scheme. It takes the measurement vector from PMU buses as input at a particular instant and delivers the required estimates before the arrival of data set at the next instant. For this, PMUs are placed at few locations using the following rules for proposed scheme maintaining the system observability:

1. A bus with three or more connected branches should be a PMU bus and the buses attached to it should be non-PMU buses.

2. A bus connected to only two branches should be a PMU bus.

Various sets of PMU placement locations are achieved using these two rules. Out of these, the set with minimum PMUs is considered for a system. The PMU measurements are fed onto the state estimator to get the required voltage phasors to be utilized for the proposed scheme.

A non-linear system states and measurements can be expressed as [11]:

\[
\begin{align*}
    x_k &= f(x_{k-1}) + w_{k-1} \quad (1) \\
    z_k &= h(x_k) + v_k \quad (2) \\
    w_{k-1} &= N(0,Q_{k-1}) \quad (3) \\
    v_k &= N(0,R_k) \quad (4)
\end{align*}
\]

where, \( x_k \) and \( z_k \) are the state and measurement vectors respectively at \( k \)th instant with \( f(.) \) and \( h(.) \) as state and measurement transition function respectively. \( w_{k-1} \) and \( v_k \) are the gaussian process noise with zero mean and \( Q_{k-1} \) covariance and gaussian measurement noise with zero mean and \( R_k \) covariance respectively.

Holt's two parameter linear exponential technique is utilized to calculate state transition matrix which is used to forecast the states from one time step to the next time step [12]. The time update steps and measurement update steps are carried out in each iteration to obtain the state estimates at an instant before the arrival of next measurement sets.

The state vector comprises of voltage magnitude (\( V_z \)) and voltage angle (\( \delta_z \)). The measurement vector comprises of voltage magnitude (\( V_{mk} \)), voltage angle (\( \delta_{mk} \)), real power injection (\( P_{mk} \)), reactive power injection (\( Q_{mk} \)), real power flow (\( P_{ijmk} \)) and reactive power flow (\( Q_{ijmk} \)) which are calculated using phasors at PMU buses and measured phasors at non-PMU buses. Thus, the parameters for \( k \)th instant is expressed as,

\[
\begin{align*}
    x_k &= [V_z | \delta_z] \\
    z_k &= [V_{mk} | P_{mk} | Q_{mk} | P_{ijmk} | Q_{ijmk} | \delta_{mk}]
\end{align*}
\]

B. Faulted Line Identification

The faulted line identification is carried out by calculating the voltage phasors at the non-PMU buses and some of the monitored PMU buses using the phasors at the PMU buses. It is based on the difference in voltage phasor at a bus from its actual value when calculated via its adjacent PMU bus for a faulted line. This occurs due to change in network topology after fault. First of all, the voltage phasors at the non-PMU buses and some of the PMU buses are calculated through the adjacent PMU buses which are placed according to the rules specified in the previous section.

Let 'c' from Fig. 1 be a non-PMU bus with its phasors calculated via two adjacent PMU buses 'a' and 'b'.

\[
\begin{align*}
    \bar{V}_{mc,a} &= \bar{V}_a - I_{ac}Z_{ac} + \bar{V}_a Z_{ac} \frac{Y_{aa}}{2} \quad (7) \\
    \bar{I}_{mea,a} &= \bar{V}_{mea,a} Y_{cc} + \frac{(\bar{V}_{mea,a} - \bar{V}_a)}{Z_{ac}} \quad (8) \\
    \bar{I}_{mc.b} &= \bar{V}_b - I_{bc}Z_{bc} + \bar{V}_b Z_{bc} \frac{Y_{bb}}{2} \quad (9) \\
    \bar{I}_{mcb,b} &= \bar{V}_{mcb,b} Y_{cc} + \frac{(\bar{V}_{mcb,b} - \bar{V}_c)}{Z_{bc}} \quad (10)
\end{align*}
\]

where, \( \bar{V}_{mc,a}, \bar{V}_{mea,a}, \bar{I}_{mea,a}, \bar{I}_{mcb,b} \) are the voltage and current phasors at bus-c calculated using phasors at buses a and b. Similarly, for two the adjacent PMU buses, one of the bus has a data of its own as well as the data calculated via phasors at its adjacent bus. Thus, the state estimator receives the measurement vector as the data from the PMU buses and
the calculated data for non-PMU and some monitored PMU-buses. A monitored bus connected through \( n \) number of branches will have \( n \) number of phasors to be fed onto the estimator to obtain the required voltage phasors for faulted line identification (FLI).

For two adjacent PMU buses of a line a-b, the index for FLI is defined as,

\[
\Delta V_a = |\vec{V}_{a,a} - \vec{V}_{a,b}| \tag{11}
\]

where, \( \vec{V}_{a,a} \) and \( \vec{V}_{a,b} \) are the estimated voltage phasors at bus-a measured from its own PMU and calculated through PMU at bus-b respectively.

Similarly, for a non-PMU bus connected with \( n \) number of PMU buses, the index at bus-a is defined as,

\[
\Delta V_a = |\vec{V}_{a,i} - \vec{V}_{a,j}| \quad \forall i, j = b, c, ... n \text{ and } i \neq j \tag{12}
\]

For a no faulted line, the index should be negligible. However, for the faulted line the index should be higher for the faulted bus. The buses which violates the proposed index is used to identify the faulted line.

The identifying the faulted line, the bus with maximum value of index is selected. The faulted line for that bus is detected if

\[
\Delta V > h \tag{13}
\]

where, \( h \) is the threshold for determining the faulted line. and is equal to 500 times the maximum pre-fault value of index calculated by taking its average for three consecutive cycles (which is in the range of \( 10^{-2} \) to \( 10^{-5} \) for the present study. The buses which are involved in the index exceeding the threshold is used to find the faulted line.

III. RESULTS AND DISCUSSIONS

The proposed scheme is studied on a New-England 39-bus system as shown in Fig.2. The PMUs are placed according to the rules specified in section II.(A) taking into consideration the minimum PMU requirement as shown in Fig.1. as bolded buses. The PMUs reports data to the Phasor Data Concentrator (PDC) at the rate of 60 frames/second for the studied system. All the non-PMU buses and one of the PMU bus for two adjacent PMU buses are monitored to find the faulted line. Several faulted condition along with the effect of communication failure and measurement error from the PMU buses are analyzed to study the performance of the proposed scheme.

A. CKF based State Estimation on 39-bus system

The CKF based state estimation is performed and the simulation results for the same is illustrated for different test cases at bus-23.

A missing data from PMU may arise while communication failure for data from PMU to PDC. For simulating this condition, the measurement from bus-23 is reduced to zero for a time period of 1.2-1.5s. The results in Fig. 3(a) shows that the estimator fetches the data for the missing period using pseudo-measurements at the previous instant.

A measurement error in PMU can lead to inefficient power system applications. To study the performance of estimator for measurement noise in PMU, a noise of zero mean and 2% standard deviation is entered into measurement data at bus-23. The results in Fig. 3(b) shows that the estimator nearly nullifies the measurement error from PMU.

Since, the present analysis deals with the detection of faulty line, the state estimation performance for the faulted situation should be checked. A three-phase fault of fault resistance 1 \( \Omega \) is created at the middle of line 23-24. Fig.3(c) shows the measured and estimated voltage magnitude and angle which has an accuracy of order of \( 10^{-2} \) and \( 10^{-3} \) respectively. Hence, the simulation results shows the effectiveness of CKF based state estimator for different cases.
B. Faulted line identification

The scheme is tested for different fault types to identify the faulted line. For each case, the buses with maximum value of index is selected and the results shown in the figures are corresponding to the lines connected to those buses.

1) Symmetrical fault - A three-phase fault of fault resistance 1 \( \Omega \) is created at the middle of line 1-39. Since, bus-39 consists of only two connecting branches, PMU is placed at this bus. For studying line 1-39, PMU is also placed at bus-1 and 9. The voltage at all the other chosen buses for identifying the faulted bus shows the similar value through all the connected branches. Now, for line 1-39, the voltage at bus-39 is calculated via PMU at bus-1 and 9. Fig. 4(a) shows that the index crosses the threshold as soon as fault occurs, the index involving bus 1 and 39 crosses the threshold indicating line 1-39 as the faulted line.

2) Far-end and near-end faults- For simulating a far-end fault at line 8-5, a line-to-ground fault of fault resistance 300 \( \Omega \) is initiated at 80% from bus-8. Bus-8 is connected to three PMU buses 5, 6 and 7. From Fig 4 (b), it is clear that the index calculated using PMU information at these buses shows that the index involving bus-5 crosses the threshold which suggests that line 8-5 is the faulted line. Similarly to simulate a near-end fault, a bolted three phase fault is initiated at 20% from bus-23 at line 23-24. The maximum of index involves bus-23 and 24 and it crosses the threshold indicating line 23-24 as the faulted line as shown in Fig.4(c).

From above cases, it can be seen that the maximum time at which the index reaches its maximum value for faulted line is around 40-50 milliseconds. Adding the delays associated with data processing, transducers, multiplexing and communication which can reach up to 200 ms and the delay of 100 ms which is intentionally added to avoid relay operation for switching or delay in estimation, the total time for relay operation can reach up to 400 ms [13]-[14]. A back-up protection can be designed to operate after 1000-1500 ms, hence, the proposed scheme has the ability to detect faulted line well within the standard time for back-up protection.

C. Performance for measurement noise

It may be possible that PMU data consists of some communication or measurement error. This leads to a noisy signal received at the PDC end. To simulate a measurement error from PMU, a 2% error is introduced in the measurement data. The index \( \Delta V \) observed at bus-2 in Fig 5 are calculated using PMU data at bus-1, 3 and 25. To compare the result for given case without state estimation, the index is calculated directly using PMUs. From Fig. 5(a), it is observed that for case without estimation, the index is highly fluctuating whereas for proposed case the index is within the range of 10^{-4}. Hence, for the case without estimation it becomes difficult to set the threshold for faulted case. To prove this, a three-phase fault of fault resistance 10 \( \Omega \) is created between line 1-2. The results for both the non-estimated case and proposed case is shown in Fig.5(c) and (d) respectively. Since, there is very less difference in the index for pre-fault and post-fault case without estimation, it is very difficult to set the threshold. However, for the proposed case, the threshold can be easily set using the index values for pre-fault case.

D. Performance for measurement loss

As discussed previously, there may be a communication link failure between PMU and PDC leading to missing data at some instant. This data when utilized for protection algorithm may result in relay maloperation. To study the performance of the proposed scheme for missing data, the phasor information for bus-3 is reduced to zero from 1.5-2 s. Fig.6 shows that the index almost remains same during missing data preventing it to detect any fault. This happens as the data from bus-3 before measurement loss is taken as a pseudo-measurement to predict states to estimate its phasor in case of missing data.
IV. Conclusion

The proposed method is used to address the issues related to PMU inaccuracies for transmission line protection algorithm. The algorithm for faulted line identification is based on the change in topology for faulted line. The scheme works effectively for various fault condition. The cases with missing data and measurement error from PMUs have also been tested and verified to determine the effectiveness of the proposed scheme. The usage of dynamic state estimator in conjunction with protection scheme can be studied further for future analysis.

References


