Situation Projection Based on Multi-time-scale Recursive Dynamic State Estimation

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Abstract. In order to solve the problem of lacking of situation awareness in smart distribution network, this paper proposed a real-time situation projection method for distribution network based on multi-time-scale dynamic state estimation. Based on hybrid measurement including micro PMU, a multi-time-scale recursive dynamic state estimation was realized through recursive transformation between state projection and pseudo measurement. A pseudo measurement Correction algorithm is implemented in the proposed state estimation loop to increase the estimation accuracy. Utilizing the historic states data calculated from the proposed state-measurement recursive dynamic state estimation, a novel real-time situation projection method is proposed in this paper. With the modelling of partitioned multivariate time series analysis, the proposed situation projection method is achieved by predicting the situation indexes for the distribution network operator in real time. Simulation validates the feasibility of the proposed method to improve the situation awareness level in the distribution network.

1. Introduction
Since the 21st century, large-scale power outages occur frequently due to the lack of sufficient perception of real-time status or future trends in complex power systems [1][2]. In order to improving the perception of the potential risk and spatiotemporal correlations for operators, situation awareness technology is proposed to be applied in power system [3]. Situation awareness application technology in power system inherits the traditional definition of situational awareness. Conventional situation awareness divides its framework into three levels [4]: situation perception, situation comprehension, situation projection. Situation awareness technology in power transmission system, also known as wide area situation awareness in power system, caused attention first and massive research related is carried out in recent years [5][6]. However, the research on situation awareness in distribution level, especially related key technologies of power distribution system situation awareness, has just started at present.

The basic architecture and key method for reaching high level situation perception of power distribution network are summarized in [7]. Literature [7] pointed out the future aspects of situation awareness research in power distribution system. But the key method summarized in [7] are preliminary designed without thorough study. The application of state estimation is widely used in distribution level situation awareness research. In literature [8], a method of situation information calculation was proposed with the combination of datamining and distribution network modelling. Literature [9] established an effective situation assessment system on the basis of state estimation and analytic hierarchy process. With cost reduction and performance improvement, Phasor Measurement Units (PMU) predominantly applied in power transmission systems has been installed gradually in distribution systems. PMUs is a kind of measurement with high accuracy measurements greatly improve the calculation accuracy of state estimation [10][11]. Thus some researches is studied on situation awareness with PMUs-based state
estimation. Literature [12] proposed a state estimation strategy based on hybrid multi-sampling-period measurements to solve problems induced by asynchronous measurements.

In order to improve the projection capability of situation awareness system in distribution network, a real-time situation projection method based on multi-time-scale state estimation is proposed in this paper. The main contribution of this paper are as follows:

1) A novel state-measurement recursive transformation mechanism with pseudo measurement correction is implemented into the state estimator to improve the performance of fast transformation between state predictions and multi-time-scale hybrid measurements.

2) Based on the proposed Multi-time-scale recursive dynamic state estimation (MRDSE) and partitioned multivariate time series analysis, a novel real-time situation projection method is proposed to predict the situation index of the distribution network.

The rest of the papers is organized as follows. Section 2 introduces the model of multi-time-scale recursive dynamic state estimator. Section 3 describes the situation projection method for distribution network based on historic state estimation. Simulation is conducted in section 4 and section 5 is conclusion.

2. Multi-time-scale Recursive Dynamic State Estimation

Two key challenges should be solved when applying hybrid measurements in state estimation: 1) The measurements received from SCADA and AMI lack the phase angle information. These measurements cannot be linear transformed into equivalent measurement in Cartesian coordinate system. 2) The sampling rate of SCADA measurement and AMI measurement is much slower than the sampling rate of μPMU measurement. To calculate phasor information, the state estimation equation has to iterate repeatedly which is not appropriate for dynamic state estimation.

In order to provide pseudo measurement for state estimation only with real-time μPMU measurement, a state-measurement recursive transformation method is proposed in this paper. By calculate the measurement estimation $H(\hat{x}_{k+1|k})$, the estimated states can be transform into predicted states and the predicted states can be equivalent transformed into pseudo measurement as shown in Fig 1. At the next μPMUs sampling time, the pseudo measurement will be utilized to calculate the optimal estimation of the states $\tilde{x}_{k+1|k+1}$. The loop of this state-measurement recursive transformation are described into formula as follows:

$$z_{\text{pse}, k+1} = HF\hat{x}_{k+1|k}$$

(1)

$$z_{\text{eq}, k+1} = T(z_{\text{pse}, k+1}, z_{k+1})$$

(2)

$$\hat{x}_{k+1|k+1} = \hat{x}_{k+1|k} + K_{k+1}(z_{\text{eq}, k+1} - HF\hat{x}_{k+1|k})$$

(3)

Where $z_{\text{pse}, k+1}$ is the pseudo measurement of time $k+1$, $z_{\text{eq}, k+1}$ is the equivalent measurement for state estimation at time $k+1$. $T(\bullet)$ in (2) is a piecewise merging function which combines the pseudo measurement with the real-time measurement at $k+1$. When only the PMU measurement upgrades, the pseudo measurement of μPMUs is replaced by corresponding real-time measurement. Similarly, the pseudo measurements of SCADA would be corrected by real-time SCADA measurements. Take the
amplitude SCADA measurement of one branch in distribution network $|I|$ for example. $I_{pse,r}$ and $I_{pse,i}$ are respectively the real part and imaginary part of corresponding pseudo measurement. The correction formula is as follows:

$$
\begin{align*}
I_{eq,r} &= I_{pse,r} \frac{|I|}{\sqrt{I_{pse,r}^2 + I_{pse,i}^2}} \\
I_{eq,i} &= I_{pse,i} \frac{|I|}{\sqrt{I_{pse,r}^2 + I_{pse,i}^2}}
\end{align*}
$$

(4)

AMI pseudo measurements should also be corrected when the node power injection upgrades. Take the power injection of node $I$, $P_i$ and $Q_i$, as example. The corresponding pseudo measurement are injection current $I_{eq,r}'$ and $I_{eq,i}'$. The correction formula is as follows:

$$
\begin{align*}
I_{eq,r}' &= \frac{P_i e_{i,k+1} + Q_i f_{i,k+1}}{e_{i,k+1}^2 + f_{i,k+1}^2} \\
I_{eq,i}' &= \frac{P_i f_{i,k+1} - Q_i e_{i,k+1}}{e_{i,k+1}^2 + f_{i,k+1}^2}
\end{align*}
$$

(5)

where $e_{i,k+1}^l$ and $f_{i,k+1}^l$ are the voltage phasor of node $i$ in Cartesian coordinate system. Fig 2 demonstrates the state-measurement recursive transformation with pseudo measurement correction.

The whole loop of the multi-time-scale recursive dynamic state estimation can be divided into 4 steps: Step1) calculate the state prediction of time $k+1$ at time $k$. Step2) conduct the state-measurement recursive transformation to obtain the pseudo measurement of time $k+1$. Step3) calculate the equivalent measurement via the measurement correction. Step4) estimate the optimal estimation through kalman filter.

3. Situation Projection Method Based on Multi-time-scale Recursive Dynamic State Estimation

The operator of the distribution power system conducts the state estimation in real time and restore the estimation result as historic states. Based on multivariate time series analysis (MTSA) method, a situation projection method is proposed in this paper. MTSA has a good performance on analysing stationary timing information with white noise. The historic estimation data within tens of seconds is exactly a smooth model with white noise appropriate for MTSA analysis. The spatiotemporal correlation model of the historic state can be described as below:

$$
\begin{align*}
u_1 &= \alpha_{10} + \alpha_{11} x_1 + \alpha_{12} x_2 + \cdots + \alpha_{1m} x_m + \varepsilon_1 \\
u_2 &= \alpha_{20} + \alpha_{21} x_1 + \alpha_{22} x_2 + \cdots + \alpha_{2m} x_m + \varepsilon_2 \\
\cdots \\
u_l &= \alpha_{lo} + \alpha_{li} x_1 + \alpha_{lj} x_2 + \cdots + \alpha_{lm} x_m + \varepsilon_l
\end{align*}
$$

(6)

where $u_l$ is the state prediction at future time $l$. $x_m$ is the historic state in past time $m$. $\alpha_{lm}$ is the independent coefficient. $\varepsilon_l$ represents the model errors. Define $U = [u_1, u_2, \ldots, u_l]$ and $X = [x_1, x_2, x_3, \ldots, x_m]$. (6) can be equivalent as $U = AX + \varepsilon$.

Historic state vector $x_m$ represents the states of every node in the distribution network. The size of $X$ and $A$ could be so large that overfitting or underfitting may occur. The correlation between the historic state vectors is stronger when the electrical distance of the nodes become shorter. Thus, distribution power system with numerous nodes have to be partitioned into several subnetworks. $U = [U_1, U_2, U_3, \ldots, U_r]$, $X = [X_1, X_2, X_3, \ldots, X_r]$. $r$ is the total amount of subnetworks. The independent coefficient matrix turns into diagonal block matrix that $A = [A_1; A_2; A_3; \ldots; A_r]$. The majority of the elements in diagonal block matrix $A$ is zero. The sparsity of $A$ decreases the computational complexity of MTSA and the state prediction of the distribution network is able to calculated in real time.
After obtaining the state prediction, the future situation of the distribution network can be projected by utilizing the situation index assessment formula [9]. Situation index can be classified into 3 categories: economic situation index, reliability situation index and safety situation index. The safety of the distribution network is more urgent to perceive than the other two situations. Thus short-time-scale prediction of safety index by the proposed situation method brings valuable information to the distribution network operator. In this paper, the safety situation projection is taken as an example to describe the proposed situation prediction method.

There are 5 indexes to assess the safety situation of the distribution network: qualified voltage rate, heavy-load rate of distribution transformers, overload rate of distribution transformers, heavy load-rate of distribution wirings and overload rate of distribution wirings. The qualified voltage rate is the ratio of nodes with qualified voltage to all nodes in distribution network. Generally, if the voltage deviation rate of the node is over 10%, it can be assumed as unqualified voltage. The voltage deviation rate is calculated as follows:

$$r_i = \left| \frac{V_{R,i} - V_i}{V_{R,i}} \right| \times 100\%$$  \hspace{1cm} (7)

where $V_{R,i}$ is the operating voltage rating of node $i$. $V_i$ is the actual operating voltage of node $i$. Similarly, the overload rate or the heavy load rate of transformers/wirings is respectively the ratio of overload or heavy-load transformers/wirings to all transformers/wirings in the distribution network. With the state prediction to predict the voltage phasor of every node in the distribution network, the branch currents and the injection currents can be also predicted by utilizing the admittance matrix. The load condition of the transformer/wiring is then respectively obtained by multiplying the node voltage and injection/branch current.

Figure 3. procedure of real-time situation projection method based on multi-time-scale recursive dynamic state estimation.

There are mainly 3 step in the procedure of the proposed situation projection method as shown in Fig 3:

1. Upgrade the state information via the multi-time-scale recursive dynamic state estimation in the operation centre of the distribution network. The historic state for a certain time period is stored after every state estimation.

2. Predict the future state based on the partitioned multivariate time series analysis model. Calculate the future branch currents and injection currents.

3. Calculate the future situation index to perceive the projection of the distribution network situation.

4. Simulation Analysis

A 8 nodes regional distribution network model of a community in a city in eastern china is constructed on Matlab to verify the feasibility of the proposed situation projection method. The topology is shown in Fig. 4. The voltage level of the distribution network is 10kV. The network has two feeders and a tie line. The tie line turns off in normal operation and the topology of the regional distribution network is radial.

The hybrid measurement data is modelled by add measurement errors to the power flow result of the distribution power system. The standard deviation of $\mu$PMU measurement errors is 0.002 p.u. The SCADA system measures power with 0.02 p.u standard deviation and current/voltage with 0.01 p.u standard deviation. A 300s load disturbance was simulated based on the regional distribution network model and the experiment of the proposed state estimation method was conducted in real time. The estimation result of three important nodes is demonstrated in Fig. 5.
As illustrated in Fig. 5, the node voltages remain steady due to the constant load condition before 50s. The load of node A2 and B3 increased continuously after 50s causing voltage fall of every node in the distribution network except the substation bus node. The conventional state estimation method [13] and a multi-time-scale estimation method proposed in [12] is also simulated for comparative analysis as demonstrated in table 1. From table 1, it can be seen that the proposed multi-time-scale recursive dynamic state estimation method shortened the upgrade cycle and increase the estimation accuracy. Take the estimated states before 250s as historic states. Then the states after 250s is predicted by establishing MTSA model. The prediction accuracy is illustrated in table 2. The deviation between the prediction states and estimated states after 250s is less than the allowable error for state estimation which verifies the validity of the proposed situation projection method.

### Table 1. Performance comparison with the proposed multi-time-scale recursive state estimation method and other two conventional methods.

| estimation method                        | average calculation time / ms | update cycle / s | estimation accuracy (amplitude) / p.u |
|-----------------------------------------|-----------------------------|-----------------|-------------------------------------|
| proposed multi-time-scale recursive     | 7.04                        | 1               | 0.00083                             |
| conventional multi-time-scale state     | 20                          | 10              | 0.00106                             |
| estimation                            | 104                         | 900             | 0.00078                             |

### Table 2. the deviation between the predicted states based on MTSA model and estimated states.

| node | deviation at 260s | deviation at 270s | deviation at 280s | deviation at 290s |
|------|------------------|-------------------|-------------------|------------------|
| A1   | 0.0037           | 0.0042            | 0.0045            | 0.0069           |
| A2   | 0.0047           | 0.0051            | 0.0058            | 0.0083           |
| B1   | 0.0021           | 0.0033            | 0.0037            | 0.0045           |
| B2   | 0.0023           | 0.0034            | 0.0035            | 0.0043           |
| C1   | 0.0101           | 0.0117            | 0.0140            | 0.0197           |

### 5. Conclusion

Situation awareness is necessary for the construction of smart grid. However, the perception of the distribution network situation is in its infancy nowadays. For improving the situation awareness level of the distribution power system, a novel situation projection method is proposed in this paper based on a novel dynamic state estimation algorithm with a recursive state-estimation transformation loop. By utilizing hybrid measurements (μPMU measurements, SCADA measurements and AMI measurements), the novel multi-time-scale recursive state estimation provides optimal estimated states for the operator.
of the distribution network in real time. The upgrade cycle is shortened to 1s and the massive measurements collected from μPMUs is utilized efficiently. The operator stores the result of state estimation as historic states. MTSA model is established for state prediction by analysing the spatiotemporal correlation between the historic states. Based on the prediction of states, the situation projection is realized by calculate the situation indexes. Simulation conducted on Matlab confirms the calculation capability of the proposed state estimation method and the feasibility of the proposed situation projection method.

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