INTRODUCTION

- This research presents a novel algorithm to find optimal sets of Phasor Measurement Units (PMUs) in power systems using measurement sensitivity analysis aiming for fault detection without multi-estimation.
- Synchronized Phasor Measurement Units (PMUs) roles in power systems operation, control, and protection are prominent and constantly developing.
- The proposed algorithm generalizes the impediment method in fault detection through optimizing PMU utilization in order to detect a fault with desired precision in interconnected power systems.
- A normal observable system is when voltage phasors for all the system buses are available, while fault observable is a system during fault where voltage phasors of all buses and current phasors at any end of all lines are determinable. Normal observability in power system is defined as knowing the voltage phasors of all the buses.
- While many PMU placement approaches are proposed to solve normal observability (under normal operating condition) for power systems, there are a very limited number of related studies that target fault observability.
- Though the available approaches take advantage of various algorithms to impose observability constraints, the important issue of measurement precision and its impact on OPP and fault location is considered in very few literatures.

Methodology

- Problem Statement
  - When a fault occurs in the system, according to the location and impedance of the fault all voltages and currents of the network change including at PMU location buses.
  - The problem rises when more than one fault (with possibly different impedances and locations) cause the same change in the voltages and currents at PMUs which is called multi-estimation.
  - What is the PMUs optimal location set to avoid multi estimation, and to use measured voltage and current changes at the PMU locations to uniquely identify a fault, i.e. resulting in a fault observable system?
  - Develop a fault locator by utilizing obtained optimal PMU sets via artificial neural networks (ANNs).

- Definitions
  - Fault: A fault is identified by value $F = (D, D_r, R_f)$ where $D = 1, 2, ..., L$ is the line number where fault occurs with $L$ being the total number of lines in the power system, and $D_r = 0, 1$ is the normalized distance of the fault with respect to one of the line ends buses ($D = \text{length} (\text{m})$ from Fig. 1), and $R_f \in R_F = [0, R_{Max}]$ is the fault resistance.
  - Observant bus: Bus $h \in \{1, 2, ..., N\}$, with $N$ being the total number of power system buses, where a measurement device capable of measuring the bus voltage and currents (of the lines connected to that bus) is installed, is an observant bus.
  - Observant set: A set $H \in \{1, 2, ..., N\}$ of observant buses is called an observant set.
  - Multi-estimation: Multi-estimation is a condition where different faults cause similar measured values in an observant set.

- Power System Measurement Sensitivity Analysis
  - The approach presented in this paper is built upon the classical fault analysis.
  - Figure 1a illustrates the faulty network with known impedance matrix $Z_u$, voltages, and currents. Also, the figure depicts the four steps which are developed to modify $Z_u$ and obtain $Z_4$. Explicit form of $Z_4$ is needed to develop the indices as explained next, similarly for $y_4$.

D. Fault locator with unique function mapping using ANN

Assume $H$ is OPP solution for IEEE 7-bus test system is the observant set $H = \{2, 3\}$, and multi-estimation set $S(h, F)$. Fault location plane $D \leq D_{Max}$ is represented by $\Delta Z_{bus}$, then the voltage sensitivity indices are defined as derivatives of fault distance $D$ and impedance $R_f$ with respect to $\Delta Z_{bus}$ as:

$$\frac{\Delta V_k}{\Delta Z_{bus}} = z_{2k}$$

where $Z_{2k}(p) = \emptyset$, $Z_{2k}(p, 0) = \emptyset$, and the system Thévenin impedance seen from imaginary bus $p$, and $V_{pref}$ is the prefault voltage at the point of fault in the system. With the assumption of linear voltage drop along the transmission lines between buses and by ignoring line capacitances to avoid complexity, $V_{pref}$ can be calculated as:

$$V_{pref} = V_i + (1 - D) \times (V_i - V_p)$$

A. Voltage Sensitivity Indices

If deviation from the voltage’s normal value at observant bus $h$ due to fault $F = (D, D_r, R_f)$ is represented by $\Delta V_{h}$, then the voltage sensitivity indices are defined as derivatives of fault distance $D$ and impedance $R_f$ with respect to $\Delta V_{h}$ as:

$$\frac{\Delta V_{h}}{\Delta D} = \frac{\Delta V_{h}}{\Delta R_f} = \frac{\Delta V_{h}}{\Delta Y_{l1}}$$

B. Current Sensitivity Indices

An installed PMU on any grid bus measures the phasor of the bus voltage as well as those of the currents of all the connected lines.

In a similar manner to voltage sensitivity indices, current sensitivity indices can be defined for each line connected between observant bus and an adjacent bus. These indices are defined as:

$$\frac{\Delta I_{l}}{\Delta D} = \frac{\Delta I_{l}}{\Delta R_f} = \frac{\Delta I_{l}}{\Delta Y_{l1}}$$

The number of current sensitivity indices derived for each observant bus $h$ in $R$ is equal to the number of lines connected to bus $h$. Since $\Delta V_{h}$ and $\Delta I_{l}$ are available for any observant bus $h$ within the network, line current changes can be expressed as:

$$\Delta I_{l} = \frac{\Delta I_{l}}{\Delta D} \times Y_{l1}$$

where $Y_{l1}$ is the impedance of line bus, $Z_{2k}(p) = \emptyset$, and $V_{pref}$ is the (h, u) admittance matrix that corresponds to $Z_4$ according to Figs. 1 and 2.

C. Sensitivity Requirements, an example on IEEE 7-Bus

In the proposed methodology, fault is analyzed by $\text{TP}$ as “target precision for $D$” and $\text{TP}^2$ as “target precision for $R_f$.” Fault location range is $0 \leq D \leq 1$ on a power line and, thus, for a given $\text{TP} = 1$, fault can be detected to be on one of equally-spaced points on any power line, similarly for $R_f$. Subsequently, the desired upper limits for sensitivity indices introduced in (3) and (4) can be calculated as:

$$\frac{\Delta V_{h}}{\Delta D} \leq \text{TP}$$

where $\text{TP}$ is total vector errors in voltage and current measurements, respectively. In this section $\text{TP} = 0.1$ and $\text{TP} = 0.05$ are the desired resolutions in the fault detection algorithm. That is, the final upper limit resulting used PMU sets from the proposed algorithm should not have errors more than 1% and 5% from fault’s actual $D$ and $R_f$. Therefore, one has sensitivity requirements $\epsilon_{\text{TP}} = 10$, $\epsilon_{\text{TP}} = 50$, $\epsilon_{\text{TP}} = 10$, and $\epsilon_{\text{TP}} = 50$. Sensitivity requirement $\frac{\Delta I_{l}}{\Delta D} \leq \epsilon_{\text{TP}} = 10$ for Bus 4 and all system is illustrated in Fig. 4 and 5, respectively.

RESULTS

- The IEEE 7-bus, 14-bus and 30-bus benchmarks are used as the case studies.
- Various Target Precisions and measurement accuracies are considered and results are provided for IEEE 7-bus in Table I.
- Some OPP sets are used for ANF training and fault locator application. The percentage of correct fault detection is also provided in results.

Table I IEEE 7-bus OPP and ANN results for various target precisions and different measurements accuracies

<table>
<thead>
<tr>
<th>IEEE 7-bus OPP (System 14 bus)</th>
<th>ANN</th>
<th>Percentage estimation accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{TP}^2 = 0.1, \text{TP} = 0.05$</td>
<td>OPP (final tested)</td>
<td>$96.3 %$</td>
</tr>
<tr>
<td>$\text{TP} = 0.05$</td>
<td>OPP (final tested)</td>
<td>$96.3 %$</td>
</tr>
</tbody>
</table>

CONCLUSIONS

- A new sensitivity analyses is derive and corresponding indices are provided.
- The required number of the PMUs for fault observability is significantly reduced compared to the past works.
- The proposed algorithm is capable to reach a fault detection target precision for $D$ and $R_f$ when considering available voltage and current measurement accuracies.
- ANN is utilized to estimate the unique function mapping available between OPP set measurements and fault criteria ($D, R_f$).
- High percentage of correct fault detection is yielded in random fault data sets which were not used in ANN training process.