Optimal PMU Placement for LVRT Monitoring of Renewable Power Plants

Soudipan Maity

Zakir H. Rather

Indian Institute of Technology, Bombay
Mumbai, 400076

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Outline

- Low Voltage Ride-Through (LVRT)
- LVRT Testing
- Introduction to WAMS and WAMS Initiative in India
- Optimal PMU Placement: Theory and Methods
- LVRT Compliance Monitoring of RE Plants using PMUs
- Proposed Approach for LVRT Monitoring
- Results and Discussion
Low Voltage Ride-Through (LVRT)

- Primary focus of this work is on the compliance monitoring of the LVRT criteria

**Definition of LVRT**

- Generators should withstand low voltages at PCC during fault conditions for a pre-defined duration
- Support the network voltage recovery of grid without exceeding the transient rating of the plant

Represented by a voltage vs time curve → Worst-case voltage recovery profile, once it starts to recover from the dip, after the fault occurrence [1]

**Grid support schemes:**

- **Active power priority**: Supply active power in proportion to retained voltage at PCC
- **Reactive power priority**: Maximize reactive current during LVRT

![LVRT curve mandated by CEA (2019)](image)
## LVRT Testing: Importance and Popular Techniques

<table>
<thead>
<tr>
<th>Why is LVRT testing necessary?</th>
<th>▪ To ensure RE plant complies with LVRT regulation in place</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC 61400-21-1:2019</td>
<td>▪ Wind energy generation systems - Part 21-1: Measurement and assessment of electrical characteristics - Wind turbines</td>
</tr>
</tbody>
</table>
| **Hardware Based Techniques** | ▪ **Voltage Sag Generators (VSG)** to simulate voltage sags with specified depth and duration, with a voltage recovery profile [3]  
▪ **Types of VSGs**: Shunt impedance-based, transformer-based and fully-controlled converter-based |
| **Software Based Techniques**  | ▪ Accurate dynamic modeling of generators  
▪ Ability to run balanced and unbalanced faults  
▪ Requires appropriate model validation from manufacturer |
Limitations in Performing LVRT Monitoring

- Higher cost and limited use of VSG-based testing in developing countries
- Testing done only once on the type of a generator series
- Re-testing not executed on units that underwent maintenance work
- Difficulty in monitoring LVRT performance of plants in a real network, and whether they are complying with prescribed LVRT criteria or not

Solution?
## Solution: Phasor Measurement Unit (PMU)

### Phasor

**AC waveform rendition:**
\[ x(t) = X_m \cos(\omega t + \varphi) \]

**Phasor rendition:**
\[ \bar{X} = X_m \angle \varphi \]
- \( \bar{X} \) = RMS value of \( x(t) \)
- \( \varphi \) = phase angle

### Synchrophasor

- **Synchronized Phasor** \([4]\) → Phasors calculated from data samples using a reference time signal from GPS, identical over a wide area
- A particular measured variable is taken as reference.

### Sample Rate

Around 25-50 samples per second

### WAMS

- PMUs + Wide-band communication + Phasor Data Concentrators
- Helps to continuously monitor and analyze the system in real-time

### Location of PMUs

Large power plants, transmission substations, and major grid interconnections

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**Fig.: Signals in time domain and phasor form**

- **Re**
- **Im**
- **x_m**
- **t**
- **\( \theta \)**
# WAMS Initiative in the Indian Network

## Pilot Project
Installation of PMUs at 9 substations and a PDC in the Northern grid

## Subsequent Proposal for PMU Installation (PGCIL, 2012)**

**Unified Real-time Dynamic State Measurements (URTDSM)**
- Substations at 400kV level and above in the State & Central grids,
- All generating stations at 220kV level and above,
- HVDC terminals,
- Important inter-regional and inter-national connection points,
- PDCs at all SLDCs, RLDCs and NLDC with visualization tools

## Phases of URTDSM Implementation

**Phase-1**: 1186 PMUs at locations with existing communication system + 27 Nodal PDCs at strategic sub-stations + 25 Master PDCs at SLDCs + 5 Super PDCs at RLDCs + 2 PDC at Main & Backup NLDC
- Broad estimated cost: **INR 169.82 Cr**

**Phase-2**: 483 PMUs + Fiber Optic based communication systems.
- Broad estimated cost (including communication): **INR 185.57 Cr**

**‘Unified real time dynamic state measurement,’** Power Grid Corporation of India Ltd., 2012
# Current Status of URTDSM Deployment

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Regional Grid</th>
<th>No. of PMUs Proposed in URTDSM</th>
<th>No. of PMUs Installed**</th>
<th>Date of Reporting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Northern</td>
<td>458</td>
<td>401</td>
<td>July 2019</td>
</tr>
<tr>
<td>2.</td>
<td>Eastern</td>
<td>307</td>
<td>275</td>
<td>June 2019</td>
</tr>
<tr>
<td>3.</td>
<td>Western</td>
<td>483</td>
<td>531</td>
<td>Aug. 2019</td>
</tr>
<tr>
<td>4.</td>
<td>Southern</td>
<td>335</td>
<td>255</td>
<td>Oct. 2018</td>
</tr>
<tr>
<td>5.</td>
<td>North-eastern</td>
<td>86</td>
<td>45</td>
<td>Nov. 2018</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>1669</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The total number of PMUs that are in actual operation are not depicted here.

**‘WAMS Availability Reports’ and multiple ‘Minutes of Meeting’ of Regional Load Dispatch Centres and Regional Power Committees of the N-S-E-W-NE regional electricity grids**
Optimal PMU Placement: Theory And Methods

A bus/node is **fully observable** if voltage and current flows across it are known \[^5\].

| Background | • Higher cost of PMUs and the adjoining communication systems  
• Neither feasible, nor necessary to install PMUs at all buses  
• Need to place PMUs at **optimal locations** for desired observability |
|---|---|
| Suitable methods | Several mathematical and heuristic techniques to achieve optimal PMU placement with varied objectives and considerations such as:  
• Integer linear programming  
• Simulated annealing  
• Genetic algorithms  
• Metaheuristics (e.g., **Particle Swarm Optimization**) |
| Basic PSO | • Evolutionary computation method developed by J. Kennedy and R.C. Eberhart (1995)  
• Search-based method where the trajectories of a population of ‘particles’ are adjusted through a problem space based on previous best performance of each particle and its neighboring particles. |
# Binary Particle Swarm Optimization (BPSO)

## Backdrop
- Introduced by Kennedy and Eberhart in 1997 \[^6\]
- Extends the capabilities of the continuous-valued PSO and is able to optimize any function, continuous or discrete
- Proven to converge at global optima faster than other methods

## Method
- Position of each particle takes a value of either 0 or 1.
- Velocity determines the probability to select a value as 0 or 1, using the Sigmoidal function.

**Note:** BPSO \[^7\][^8\] is used in this work to find the minimum number of PMUs for achieving the desired system observability.
Compliance Monitoring of LVRT of RE Plants using PMUs

**Prospective solutions**
- Place PMU at plant PCC → **Costly**
- RE plants having PMU enabled adjacent substations, if not, at their own terminal
- All the adjacent buses and plant terminal should be observable
- Extensive PMU placements required → **Costly**

**Possible scenario**
- Plant terminal and/or adjacent nodes of the PCC not observable
- Not possible to calculate the current flows from the plant

**Proposal**
1. **Clustering** several wind and solar power plants, and connecting them to a HV node that is more likely to be observable by PMUs
2. **Clustering & network reduction** to reduce the unobservable network to its reduced equivalent, and subsequent use of node voltage analysis to calculate the cluster currents
### Challenges of RE Monitoring in the Indian Electricity Grid

| Available Voltage Levels | **Transmission** (AC, L-L voltages): 132 kV, 220 kV, 400 kV, 765 kV  
|**Sub-transmission** (AC, L-L voltages): 110 kV, 66 kV, 33 kV |
|-------------------------|---|
| Grid Connection of RE Plants | **Large-scale renewable power plants** (wind and solar) are connected primarily to 220 kV, 132 kV, and 66 kV grids. |
| PMU Locations | **Generator buses at 220 kV and above**  
|**Transmission substations at 400 kV and above** |
| Challenge | **220 and 400 kV level PMUs unlikely to monitor plant dynamics at sub-transmission levels**  
|**Requirement of an effective strategy to monitor the RE plants without placing PMUs at sub-transmission network** |
Equivalence of a RE Cluster to its Original Layout

- Test system modelled to validate the proposal for formation of clusters.
- An initial steady state power flow is performed.
- **Load aggregation:** Load at a 132 kV cluster = Outgoing power from that substation LV bus + Total dispatch of WPPs assumed to be clustered to that bus

Fig.: Comparison of clustered configuration to the original configuration
Equivalence of a RE Cluster to its Original Layout

Responses of WPP-2 following active power priority scheme is shown:

- 3-phase fault introduced at the 132 kV infinite bus to check the transient response in both configurations
- Dynamic properties of clustered system closely match that of original configuration’s with minimal error.
- Use of clustered configuration instead of highly detailed original one is valid.
Case Study- Gujarat Grid

Power network of the Indian state of Gujarat was modelled from 765 kV to 132 kV

Fig.: Gujarat electricity grid
### Proposed Methods for Observability of the RE clusters

<table>
<thead>
<tr>
<th>Method 1: Normal clustering</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OPP objective:</strong> Make the cluster LV buses observable, allowing the current flow across HV-LV transformer to be traced</td>
</tr>
<tr>
<td>No. of buses considered in the Gujarat network: <strong>292</strong></td>
</tr>
<tr>
<td>No. of buses (400 &amp; 220 kV) assumed to be pre-equipped with PMUs (sourced from the URTDSM report): <strong>49</strong></td>
</tr>
<tr>
<td>Cluster HV buses are considered as zero-injection buses</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Method 2: With the use of network reduction (after performing OPP)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OPP objective:</strong> Observability of cluster HV buses only (ignoring the observability of cluster LV buses)</td>
</tr>
<tr>
<td>Cluster HV buses + Pre-equipped PMU buses → <strong>Boundary buses</strong></td>
</tr>
<tr>
<td><strong>Internal network:</strong> 765 &amp; 400 kV network + 220 kV generator buses + RE clusters</td>
</tr>
<tr>
<td><strong>External network:</strong> Remaining unobservable system.</td>
</tr>
<tr>
<td><strong>Ward reduction</strong> executed on the network</td>
</tr>
<tr>
<td>Internal network intact → Introduction of Ward equivalents and impedances between boundaries</td>
</tr>
</tbody>
</table>
## Results and Discussion

Total no. of RE clusters in the Gujarat electricity grid (as per the model) : **42**

<table>
<thead>
<tr>
<th>Method used</th>
<th>No. of buses considered</th>
<th>Pre-equipped PMUs considered (Yes/No)</th>
<th>Total no. of PMUs</th>
<th>No. of extra PMUs required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method-1 (Without reduction)</td>
<td>292</td>
<td>Yes</td>
<td>71</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>292</td>
<td>No</td>
<td>32</td>
<td>N/A</td>
</tr>
<tr>
<td>Method-2 (With reduction)</td>
<td>292</td>
<td>Yes</td>
<td>68</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>292</td>
<td>No</td>
<td>25</td>
<td>N/A</td>
</tr>
</tbody>
</table>

- Full observability (both current and voltage measurable) of some clusters happen after OPP in Method-2 due to the particular network layout and PMU placements.
Conclusion

- Studied the evolution of grid codes and RE specific regulations in the code
- Challenging to perform on-site testing of all operational RE plants with the traditional methods
- Proposed a strategy using PMUs for monitoring the operational RE plants in real-time or near real-time basis
- Performed optimal PMU placement to find out the minimum number of PMUs required for monitoring all the RE clusters in the grid
- Proposed strategy is currently under further development by the authors to perform actual LVRT monitoring in the modelled system
References


THANK YOU
Proposed Approach: Formation of RE Clusters

**Procedure**

Directly connect a 66 kV RE plant to geographically closest 220 or 132 kV substation’s LV bus

132 kV RE plant already linked to an adjacent 132 kV substation

Complete set of plants connected to one main substation termed as a ‘cluster’

**Categories based on mode of operation:**

i. **Converter-controlled** (grid support capable) : Solar PV plants + WPPs with Type-III and Type-IV WTGs

ii. **Converter-less** (grid support incapable) : WPPs with Type-I + Type-II WTGs

**Load aggregation**

- Sub-transmission level loads aggregated to every individual 220 or 132 kV substation
- Should approximate original system dynamics with high accuracy

**Fig.: Model of an RE cluster**
Rationale Behind the Proposed Strategy

Total complex power injected from a cluster is calculated

Composition of the installed capacity of WTGs of Type-1, Type-2 and Type-3 varieties, and Solar PV in the cluster is determined

Current and hence the power from the Type-1 and Type-2 WTGs is estimated using a suitable method

\[
\text{Power from converter-controlled (CC) section of the cluster} = (\text{Total power from RE cluster} - \text{Total power injected from Type-1 & Type-2 WTGs} - \text{Aggregated load})
\]

**LVRT Requirement from CC section**: Follow the P- or Q-priority grid support scheme as mandated in the grid code during any contingency

Check pre-fault power of CC section → Calculate power during LVRT in ideal case → Compare with the monitored data to obtain the LVRT compliance status of the cluster