Optimal PMU Placement for Performance Monitoring of Renewable Power Plants

Soudipan Maity
Department of Energy Science and Engineering
Indian Institute of Technology Bombay
Mumbai, India
soudipan@gmail.com

Zakir Hussain Rather
Department of Energy Science and Engineering
Indian Institute of Technology Bombay
Mumbai, India
zakir.rather@iitb.ac.in

***Abstract*—The variability and uncertainty associated with renewable energy generation significantly impact power system operation, particularly under high renewable energy (RE) penetration. Therefore, to ensure secure and stable grid operation under variable RE penetration, grid code regulations have been in place for the grid connection of generating units to power systems all over the globe. Despite these regulations, the steady-state and dynamic operations of the RE plants are mostly not monitored on a real-time or near real-time basis, and such RE plants are also not put through strict compliance checks of all the applicable regulations under operating conditions. This limitation, in turn, inherently poses a significant concern to the steady-state and dynamic stability of the grid during any contingency. In this paper, a performance monitoring strategy has been proposed that enables the utilization of Phasor Measurement Units (PMUs) to capture the time-stamped performance dynamics of RE plants operating in the grid, at a rate essential for analysing the disturbance and post-disturbance scenarios. Accordingly, an optimal PMU placement procedure has been developed for the desired system observability for effectively monitoring the RE plants.**

***Index Terms*—grid code, compliance monitoring, synchrophasor, renewable power generation, optimal PMU placement**

NOMENCLATURE

Abbreviations

RE	Renewable energy
SCADA	Supervisory Control and Data Acquisition
TSO	Transmission system operator
IEGC	Indian Electricity Grid Code
PMU	Synchrophasor Measurement Unit
LVRT	Low voltage ride through
WAMS	Wide Area Monitoring System
PCC	Point of common connection
WPP	Wind power plant
WTG	Wind turbine generator
GPS	Global Positioning System
VSG	Voltage Sag Generator
PSO	Particle Swarm Optimisation
IEC	International Electrotechnical Commission
KCL	Kirchhoff's Current Law
KVL	Kirchhoff's Voltage Law
NLDC	National Load Dispatch Centre
RLDC	Regional Load Dispatch Centre
SLDC	State Load Dispatch Centre
PGCIL	Power Grid Corporation of India Ltd.
POSOCO	Power System Operation Corporation
OPP	Optimal PMU Placement
BPSO	Binary Particle Swarm Optimization

Symbols

S	Complex power
P	Active or real power
Q	Reactive power
N_{bus}	No. of buses in the network
$Flag_{pre}$	Flag for selecting pre-installed PMUs
N_{pre}	No. of pre-installed PMUs in the network
$N_{cluster}$	No. of RE clusters in the network
N_{PMU}	Optimal no. of PMUs
N_{extra}	Extra no. of PMUs required for installation
N_{LV}	No. of observable cluster LV buses

I. INTRODUCTION

The exacerbating threat of climate change, fast increasing energy demands of developing economies, and the need to meet the long-term goal of energy security have led to a sustained push towards incorporating increasingly more renewable energy into the global energy mix. Substantial technological developments have happened in this area, particularly in the domains of wind and solar power, that are currently economical and resilient enough to be deployed in large capacities. In line with the global growth, India has also been rapidly integrating renewables into the national grid and has a current cumulative installed capacity of 78 GW with a target of installing 175 GW (100 GW solar, 60 GW wind and 15 GW other RE sources) by the year 2022.

However, the variability and uncertainty associated with the RE generation significantly impact the operation of power systems, particularly under high RE penetration. Therefore, to safeguard the system against these challenges and ensure secure and stable grid operation, TSOs have imposed several stringent measures on these RE plants through grid code regulations for preserving the steady-state and dynamic stability of the grid, for example, the IEGC applicable in Indian grid.

Some of the critical provisions present in the grid code intended for RE power plants include frequency regulation, voltage ride-through capability, active power regulations, and power factor regulation. Despite enforcing the regulations, there is generally no mechanism in place to monitor the steady-state and dynamic operations of all RE plants on a real-time basis, and check their compliance of all the prescribed grid code regulations under operating conditions. This limitation, in turn, inherently poses a significant concern to secure and stable grid operation. The traditional SCADA systems have an update rate of the measured data of around once every 4 to 6 seconds, which is highly inadequate to capture the system dynamics essential for analysing the transient performance of the RE plants and taking adequate control actions.

Low voltage ride-through (LVRT) capability is one of the critical requirements mandated in the grid regulations with regards to the integration of RE plants (solar and wind). It refers to the ability of these generating units to withstand low-voltages at PCC during fault conditions for pre-defined time duration and to support the network voltage recovery of the grid without exceeding the transient rating of the plant. Several studies are available in the literature that addresses strategies for testing the LVRT capability of wind turbine generators, particularly the Type-3 and Type-4 categories [1], [2], [3]. Although most manufacturers follow type testing for LVRT compliance, it does not guarantee the long-term compliance of the units over the due course of time, and re-evaluation of their capabilities is hardly performed.

In this paper, the primary focus has been laid on the analysis of the LVRT requirements from the RE plants during contingencies, and the study of the existing methods of LVRT testing along with the limitations associated with them. In this backdrop, an attempt has been made to bridge the gap by proposing a strategy to monitor the continuous operations of the RE plants using the network of PMUs located at various strategic and critical locations in the grid. The proposed performance monitoring strategy will enable the capture of the time-stamped dynamics at a rate essential for analysing the disturbance and post-disturbance scenarios. Correspondingly, several circumstances of the placement of PMUs on the modelled grid of the state of Gujarat in India have been developed using BPSO to aid this objective.

The rest of the paper is organised as follows. Section-II describes LVRT in detail and LVRT regulations mandated by CEA in India. Additionally, the concept of LVRT testing has been explored. Section-III discusses the synchrophasors and the use of PMUs in power systems, and the WAMS initiative undertaken in the Indian grid. Section-IV discusses the idea behind optimal PMU placement and its several methods. Section-V and VI present the techniques proposed for monitoring in the context of the Indian grid. Section-VII discusses the results obtained, and the conclusion is presented in Section-VIII.

II. Low Voltage Ride-Through

A. Background of LVRT

The disruption in the grid stability that comes with the connection of larger RE generating stations has led to much discussion on the expected transient behaviour of these plants, during contingency periods. Consequently, in conformity with the performance requisites traditionally exhibited by the conventional generators, the TSOs have enforced nearly identical requirements on the RE generators, such as active and reactive power regulation, frequency and voltage control, and ancillary services. LVRT is one such challenging requirement specified in all grid codes that are to be strictly followed by the RE generators when they are connected to the grid. When a short-circuit fault happens at any point in the system, the voltage in one or more phases (depending on the type of fault and its location) dips below the normal operating range. When RE, especially, wind power was in its nascent stage of development, the units were allowed to disconnect from the network during a fault for the sake of generator safety.

However, as the penetration level of these plants grew, abiding by the earlier regulations had often led to the cascaded disconnection of a large capacity of wind farms in the grid (blackouts) whenever a fault happened. Such occurrences reportedly took place regularly in China until recently, and are still prevalent in India in states like Tamil Nadu. Therefore, pioneering countries in wind power like Denmark and Germany were among the first to introduce strict regulations to be followed by the wind farms, which are connected to the high-voltage transmission network [4]. Other countries followed suit, and presently, the LVRT criterion forms an inherent part of almost all grid codes around the world. As discussed earlier, it states that during events of short-circuit phenomena in the system, the generating units should not only stay connected to the grid but also need to provide adequate support to the network in the form of active and reactive power injection.

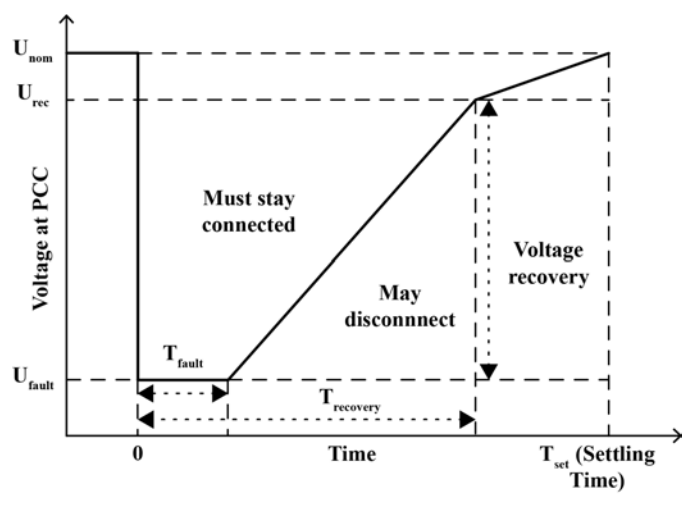

Fig. 1. Typical LVRT capability curve

LVRT requirement is usually represented by a voltage versus time characteristic (Fig. 1), which denotes the worst-case voltage recovery profile once it starts to recover from the lowest point, after the fault occurrence [5]. These requirements take into account several factors, which are listed below:

- Current and predicted penetration level of RE in future
- Strength of the grid denoted by short-circuit ratio
- Dynamic characteristic of loads in the system

- Extent and size of the power system
- Presence of reactive power compensation devices in the system (FACTS devices, synchronous condensers, etc.)

In India, CERC under the authority of CEA has mandated the LVRT capability curve, as depicted in Fig. 2 which itself has undergone several amendments since its introduction with the last one having been done in 2019 [6]. The regulations mandates that reactive power support is given first priority, while active power is given second priority during fault conditions. The active power must preferably be maintained during voltage drops, provided, an acceptable reduction in active power within the plant's design specifications takes place, and active power be restored to at least 90% of the pre-fault level within 1 second of restoration of voltage at PCC.

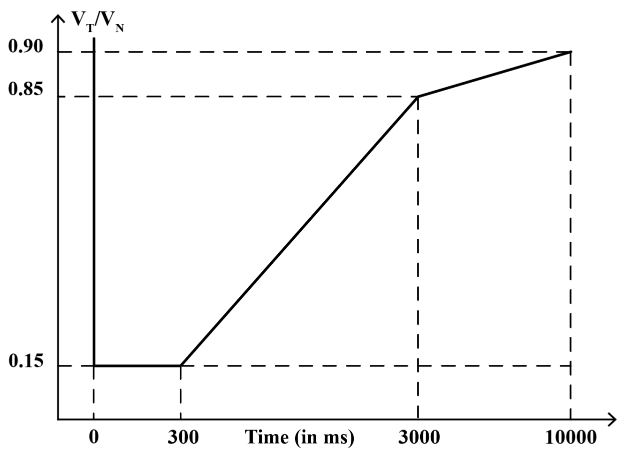

Fig. 2. LVRT capability curve mandated in India by CEA

B. LVRT Testing: Introduction and Popular Methods

The compliance with the mandated LVRT capability curve and the provision of providing grid support in the grid code must be rigorously tested for all RE generating units before connecting them to the grid and must subsequently be monitored at regular intervals, if necessary. The testing is usually performed by the manufacturers or independent certifying authorities primarily as per IEC 61400-21-1:2019 standard, which deals with "Measurement and assessment of electrical characteristics-Wind turbines". Compliance verification is always a necessity to observe the actual implications of the LVRT abilities when the generators are finally connected to the grid. Over the years, several techniques have been developed for each wind turbine type to make them comply to the LVRT requirements of the existing grid codes with decent success. Several methods have been established, both hardware and software, to undertake LVRT testing, some of which have been discussed here. Generally, in the hardware-based verifications, a grid emulator or VSG, capable of artificially simulating different types of faults in the system, is used to initiate a disturbance. The responses of the generating units are then recorded and evaluated for successive verification and validation before mass installations. In the real world, these measurements are usually carried out only for the prototypes of a particular product series since identical behaviour is expected from all the other units in the series. According to the IEC 61000-4-11:2004+AMD1:2017 standard for "Testing and Measurement Techniques for Voltage Dips and Variations", a generic three-phase voltage sag generator is supposed to exhibit the following characteristics [7]:

- Generate varying magnitudes of unbalanced and balanced voltage sags
- Regulate the extent and period of the voltage sags
- Extend the capability of programming to the recovery voltage profile

The test systems, retained in sizeable containers depending on the rating of the system being tested, are mobile devices built for easy transportation to the sites. Depending on the prevalent grid code, different depths of voltage dips are simulated on the VSGs with varying durations, and under different output power scenarios for performing LVRT certification. On the other hand, software-based LVRT testing methods involve accurate dynamic modelling of the generators in well-known power system platforms like PSS/E, DIgSILENT PowerFactory, PSCAD, etc., and simulating faults of different types on it to assess the LVRT behaviour of the units. The added advantage of software-based testing is the ability to run three-phase short circuits, the most severe kind of faults, that are practically impossible to run in VSG-based test systems. Although this kind of testing is inexpensive and less complicated, the major challenge is the appropriate validation of the dynamic models from the unit manufacturer so that it emulates the real system with utmost precision.

C. Drawbacks of Traditional LVRT Testing

Despite the conventional LVRT testing methods being tried and tested options, there are several drawbacks associated with it, as listed below.

- The cost of testing with VSGs is still on the higher side, and its use in developing countries such as India is limited.
- Generally, the testing is done by the manufacturer on the prototypes of a particular product series and therefore, it does not necessarily guarantee the long-term compliance of all the units of that series over the due course of time.
- Although LVRT capability needs to be re-evaluated after any maintenance or repair work on the generators, it can often go unattended, and malfunctioning LVRT at a large RE station can leave the grid security in a state of compromise.
- Due to limitations in cost and manual labour, it is practically impossible to perform testing of every wind or solar power plant, at various sections of a vast network, to monitor their LVRT compliance over time.

Hence, a better procedure must be formulated to perform frequent compliance-monitoring of these generating units so that the security of the network in the event of a significant disturbance is not compromised and undesired 'blackouts' can be prevented.

III. Synchrophasors and Wide Area Monitoring

A complete representation of the state of an electrical grid at any instant requires a comprehensive knowledge of the voltage, current, and apparent power at every node of the entire system. All the three quantities in an AC power system being complex notations can be represented as phasors denoted by a magnitude and a phase angle. The knowledge of any two quantities is sufficient to derive the third, based on the relation, $S = VI^* = P + jQ$ [8].

The need for a superior replacement to SCADA monitoring drove efforts to extend the concept of phasors to the estimation of real-time phasor measurements that are synchronised to an absolute time reference attributed to the worldwide availability of the GPS satellite transmissions accurate to one microsecond. This attempt led to the advent of the GPS-assisted PMU or PMU, and because of its precise functionality and high data rates (around 30 Hz), currently, PMUs are being deployed in large numbers in major power systems globally. A synchronized phasor or synchrophasor is the phasor that is calculated from measured data samples using a reference time signal identical throughout a wide geographical area. Taking the measured variable of one element as the reference and considering its phase angle as zero, the phase angles of the other elements can be calculated on the same reference and hence the corresponding synchrophasors can be obtained [9].

In modern power systems, to be able to monitor, operate, control and protect power systems in a wide geographical area, WAMS combines the functions of PMUs and conventional measurement systems with the abilities of communication systems. WAMS help TSOs to continuously analyse all the features of an extensive power network in real-time. Utilising PMUs, required information can be recorded, and critical points in the grid can be monitored to detect disturbances. It also helps in improving situational awareness of the network behaviour from the TSO's standpoint, enabling them to maximise power flow and network stability.

Generally, PMUs are placed at the most vital points in the grid which determine system security, such as,

- Conventional power plants
- Substations with line voltages $\geq$ 345/400/500 kV
- Major interconnections between large regional grids.

Internationally, numerous utilities from North America, Europe, China, and Brazil have already been reaping the benefits of having PMUs installed in their grid.

In India, the process of installation of PMUs installed in the network is still an ongoing endeavour under the active initiative of PGCIL, the central transmission utility, with several PMU pilot projects [10]. The objective of the pilot project was to gain first-hand experience of synchrophasor-based WAMS before its large-scale deployment in India. In consultation with TSOs and field experts, the ensuing PMU installations are being carried out at the following locations:

- All substations at 400 kV level and above,
- All generating stations at 220 kV and above,
- All HVDC terminals,
- Major inter-regional connections (220 kV and above)

Under this initiative, a criterion of 'N-1' redundancy is being followed, which implies that monitoring of each end of a transmission line is to be done.

IV. Optimal PMU Placement: Theory and Methods

It is widely acknowledged that it is neither economically feasible nor necessary to install PMUs at all the substations in a power system. The higher cost of PMUs and its adjoining communication infrastructure has necessitated the placement of PMUs at optimal locations for attaining intended system observability [11] [12]. Suitable methodologies are required to determine the optimal locations so that the sufficient number of PMUs necessary to make the system completely observable is minimised. In recent years, there has been significant research on the problem of finding the minimum number of PMUs to make a power system completely observable, along with determining their optimal locations. Several mathematical and heuristic techniques such as integer linear programming [13] [14] [15] [16], simulated annealing [17] [18], and genetic algorithm-based methods [19] [20] [21] have been used by researchers to achieve optimal PMU placement with varied objectives and considerations. The PSO, one such genetic algorithm-based technique, has been used successfully in numerous power system applications [22]. In [11], an improved binary particle swarm optimisation based methodology for the optimal placement of PMUs has been proposed for achieving complete observability of a power system. In this study, this optimisation technique is used to find the minimum number of PMUs required for achieving sufficient system observability for monitoring the RE plants. In general, PSO, which is motivated by behaviour of bird flocks is a population-based search method, where positions of individual and neighbouring particles help each other to adjust their status in successive iterations.

A. *Power System Observability*

A substation or a node is said to be fully observable if both the voltage and the current flows across a particular node are known [11]. Consequently, a given power network is said to be completely observable if all of its substations are observable through direct or indirect measurements. There are two methods to evaluate system observability:

1) Numerical observability
2) Topological observability

A system is regarded as numerically observable if its design matrix 'H' is well-conditioned and is of full rank. Topological observability is based on the graph theory approach, where a non-oriented graph represents the system. A power system can be considered as topologically observable if at least one spanning measurement tree in the graph is of full rank. In this paper, the approach of topological observability has been followed, which is the most implemented viewpoint in literature [11]. Since a bus can be made observable either through direct or indirect measurement, therefore fundamental concepts of circuit theory (KCL and KVL) can be effectively used to assess indirect measurements. The criteria that are used to estimate the observability of each node is as follows:

Criterion 1: For a bus selected for PMU placement, the voltage and the current phasor of all its incident branches are known.

Criterion 2: For the known voltage phasor of a bus and current phasor of a branch incident on it, voltage phasor at the other end of this branch can be evaluated.

Criterion 3: For the known voltage phasors at both ends of a branch, the current phasor of this branch can be calculated.

Criterion 4 For a zero-injection bus if current phasors of all but one incident branches are known, the current phasor of the remaining branch can be calculated using KCL.

Criterion 5: For a zero-injection bus with an unknown voltage phasor, if voltage phasor of all its adjacent buses is known then the voltage phasor of this zero-injection bus can be calculated using node voltage equations.

Criterion 6: For a set of adjacent zero-injection buses with unknown voltage phasors, if voltage phasors of all adjacent buses are known then voltage phasors of this set of adjacent zero injection buses can be obtained by node voltage analysis. Criterion 1 to 4 are termed as direct measurements, whereas 5 and 6 are known as indirect measurements. Depending on the type of application of WAMS, indirect measurements especially extension measurements (criterion 5 and 6) may or may not be considered.

B. Particle Swarm Optimization

The particle swarm algorithm optimization is an evolutionary computation technique which was first introduced in 1995 by J. Kennedy and R.C. Eberhart [23]. It is primarily a search-based method where the trajectories of a population of “particle” are continuously adjusted through a problem space on the basis of information about previous best performance of each particle and its neighbouring particles. Therefore, the direction of a particle in each swarm is determined by the particle’s history and the set of its neighbours. The position of a particle at any instant is determined by its velocity at that instant and position at the previous instant, as shown below.

$$X_i(t) = X_i(t-1) + V_i(t) \tag{1}$$

The velocity vector of a particle is updated by utilising its own experience as well as the knowledge of the performance of the other particles in its neighbourhood. The velocity update rule for a basic PSO is given below.

$$\begin{aligned} V_i(t) = V_i(t-1) + \phi_1 rand_1(pbest_i - X_i(t-1)) \\ + \phi_2 rand_2(gbest - X_i(t-1)) \end{aligned} \tag{2}$$

where, V, i, t is the velocity array, particle no. and iteration no. respectively. X is called position array. ϕ_1 and ϕ_2 are adjustable parameters termed as *individual* and *social* acceleration constants respectively. $rand_1$ and $rand_2$ are random numbers between 0 and 1. $pbest_i$ is called **historical best** which is the best position found so far by particle i, and $gbest_i$ is historical **global best** position in the entire swarm. In each iteration, the constraint conditions are assessed for each particle in a given swarm and objective function is evaluated for those particles which satisfy the constraint conditions. New position and velocity of each particle are updated, and if the position satisfies constraint condition and is better than $pbest_i$, then it should replace the existing $pbest_i$ as the new $pbest_i$. Similarly, any particle in the entire swarm that satisfies the constraints and is better than $gbest_i$, should replace $gbest_i$.

C. Binary Particle Swarm Optimization

The binary version of PSO was introduced by Kennedy and Eberhart in 1997 which extends the capabilities of the continuous-valued PSO and is able to optimize any function, continuous or discrete [24]. It was shown that BPSO successfully optimizes the test functions, and is able to converge at global optima faster than other methods. In BPSO, position of each particle X_i takes a value of either 0 or 1, and velocity V_i determines the probability to select a value as 0 or 1. At each stage of iteration, the elements of the position vector X_i are updated according to the following rule:

$$X_{ij}(t) = \begin{cases} 1, & \text{if } \rho_{ij} < s(v_{ij}) \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

where ρ_{ij} is a random number in the range $[0,1]$; $s(v_{ij})$ is the Sigmoidal function defined as,

$$s(v_{ij}) = \frac{1}{1 + exp(-v_{ij})} \tag{4}$$

D. Compliance Testing of LVRT using PMUs

The availability of synchronised phasor data from PMUs opens up new possibilities for observing and analysing RE plant operations under normal and contingency conditions. The following section discusses in detail how the availability of PMUs in the network can be utilised to test the LVRT capabilities of the plants virtually in real-time.

Case 1: The most straightforward technique is to place the PMU at PCC to monitor the current flows and voltage. However, this will primarily raise the infrastructure costs in a network with numerous RE plants, especially in remote areas.

Case 2: If the plant has one or more than one feeder emanating from its PCC, PMUs can be installed in all the substations at which the feeders are incident. Additionally, at least one of the PMUs is expected to observe the current in the plant feeder such that the voltage at the plant PCC can be calculated. The calculated current can be analysed in real-time to monitor the aggregate active and reactive current injected by the plant. It is important to note that for voltage and current calculations, the use of the nominal pi model of a medium transmission line (which considers the line capacitance) is generally used as it renders required accuracy.

As is evident from the above cases, the fundamental principle behind these depends on being able to make the voltages adjacent to the RE plant observable, after which nodal analysis can be used to calculate the current flows at the plant PCC. This approach calls for an extensive PMU placement procedure in a grid with many RE plants, which can be an expensive goal to achieve.

Case 3: However, for instances where the plant has one or more feeders emanating from its PCC, but an insufficient number of PMUs in the adjacent networks, it is not possible to calculate the current flows at PCC only by nodal analysis. In such cases, the concept of network reduction can be employed for reducing the unobservable network to its corresponding equivalent system, keeping the observable nodes as the boundaries between observable and unobservable network. Subsequently, node voltage analysis can be used to calculate the current flows.

V. Application of Network Reduction in the Context of the Indian Power System

Typically, the large-scale power systems are large and meshed in nature and involve interconnected transmission networks at different voltage levels, such as the regional power networks of India. The operation of the Indian power grid is monitored and coordinated through the NLDC, five RLDCs, 33 SLDCs, and several sub-load dispatch centers. Each control center is provided with the SCADA/EMS system, which provides necessary data visualization to the grid operators. For complementing visualization through SCADA and enhancing situational awareness of the grid operators in the control center, synchrophasor projects are presently being deployed under the initiative of POSOCO and PGCIL. The initiative started as a pilot project in the Northern Region in 2010 and has since been expanded to all the regions of the grid. In the Indian grid, PMUs are presently being employed at all generator buses at 220 kV and above, and transmission substations at 400 kV and above. However, the wind and solar power plants are generally located at 220 kV levels and below. Therefore, the PMUs located at EHV levels is unlikely to help in observing all the system dynamics at the sub-transmission levels of the network. In such a scenario, the sub-transmission network devoid of any PMUs can be reduced to its equivalent and connected to the *internal subsystem* which is equipped with PMUs at the boundary nodes, following the concept of network reduction. The unobservable network can be regarded as the *external network*, and the observable nodes as the *boundaries* between observable and unobservable system. In this work, Ward Equivalencing, which is one of the classical methods for the computation of static network equivalents, has been utilized. The Ward reduction was initially proposed by J. B. Ward in the mid-20th century [25] and has been sufficiently documented in literature [26]. In this method, the reduction of the network is performed by Gaussian elimination. The following sections investigate the prospective application of Ward reduction in monitoring the operation of RE plants.

VI. Proposed Approach for LVRT Performance Monitoring of RE Plants

A. Formation of Renewable Energy Clusters

In a typical power system such as the regional power grids of India, a large share of the wind and solar plants are connected to the 132 kV and 66 kV sub-transmission networks, with a relatively less portion connected at 220 kV. However, the PMUs are primarily located at the voltage levels of mainly 765 kV and 400 kV, and a few at 220 kV. Therefore, without additional installations of PMUs at the lower voltage levels that would significantly raise the investment costs, it is not possible to directly monitor the RE plants connected to the sub-transmission levels with the help of higher voltage PMUs. Under these circumstances, a few procedures have been proposed in this paper to bridge this gap without incurring additional investment with WAMS infrastructure at sub-transmission levels. Before these procedures can be pursued, it is essential to note that in the majority of the regional grids, the preceding level of the sub-transmission network (mainly 66 kV and below) is the 220 or 132 kV substations which house the 220/66 kV or 132/66 kV step-down transformers. Taking the above facts into consideration, the framed procedure is as follows:

- A RE plant connected at 66 kV can be connected to the geographically closest 220 or 132 kV substation's LV bus (i.e., 66 kV bus) in the modelled network either directly or via a transmission line.
- A plant connected at 132 kV grid is already linked to an adjacent 132 kV substation by default, and therefore no modification in such cases.
- When all the plants are connected to the nearby substations individually following this protocol, for simplicity, the complete set of plants connected to one main substation can be termed as a *cluster*.

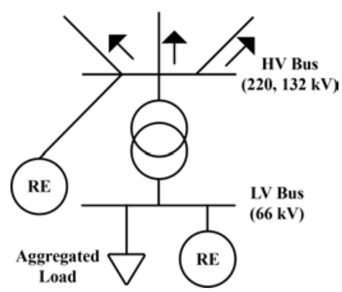

Fig. 3. Model of a renewable energy cluster

- From the standpoint of the mode of operation, a RE cluster would naturally comprise of two categories of generators, which are:
  1. *Converter-controlled plants:* All solar PV plants, and WPPs housing Type-III and Type-IV WTGs.
  2. *Converter-less plants:* WPPs with Type-I (SCIG) and Type-II (WRIG) WTGs.

  It is evident on this basis that the converter-controlled plants are capable of providing grid support during faults, whereas the converter-less plants do not provide this facility, aside from staying connected to the grid.
- Following an acceptable load aggregation method, the sub-transmission level loads are required to be aggregated to every individual 220 or 132 kV substation in a way that approximates the original system behaviour.

B. Validation of Equivalence of a RE Cluster to its Origin Configuration

A test system shown in Fig. 4 was modelled on PowerFa tory to validate the proposal that the RE plants connected at th sub-transmission network of 66 kV can indeed be connecte to the nearest 220 kV or a 132-kV substation for simulatic purpose. The system consists of 6 load buses of 66 kV in meshed network connected to two 132/66 kV substations ar three Type-III wind farms connected at 66 kV in the networ The loads are of constant impedance in nature. The substatio have a singular 132 kV bus synonymous to an infinite bus. three-phase short circuit fault was introduced at the 132-kV bus at 5 seconds for a duration of 200 milliseconds. Fig. 5 and Fig. 6 shows the dynamic characteristics (active pow reactive power, d-axis current, q-axis current, and termin voltage) for WPP-1 (50 MW) and WPP-2 with the origin configuration. The voltage profile at the 132 kV bus duri the fault duration is shown in Fig. 7.

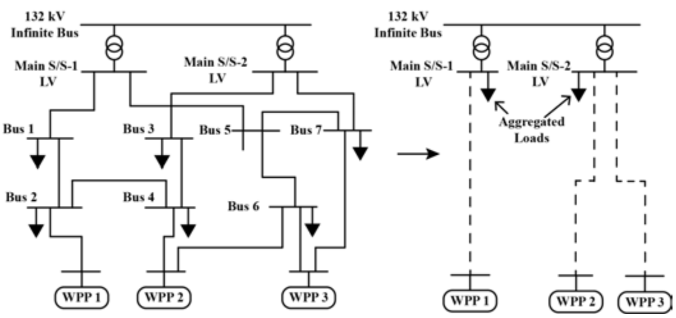

Fig. 4. Comparison of clustered configuration to the original configuratio

In Fig. 4, the clustering has been executed on the syste and WPP 1 has been connected to S/S-1 due to its proximi to it, and WPP-2 and WPP-3 to S/S-2 by the same analog The loads that have been individually allocated to the tv primary substations have been calculated by summing up t outgoing power from the corresponding substation obtain from steady-state load flow, and the power dispatch fro respective WPP clustered to that particular substation. Wi this configuration, an identical three-phase short circuit fa was introduced at the 132 kV infinite bus and the volta profile of the bus is shown in Fig. 5. The corresponding dynamic characteristics of the WPP-1 and WPP-2 is shown from Fig. 6 to Fig. 11 respectively. As is evident from the figures, the dynamic properties of the clustered system closely match the original configuration with minimal error. Therefore, this test shows that it is certainly possible to use a clustered configuration in place of the highly detailed original one for simulation purposes.

C. An Instance of an Existing Indian Transmission System

The power network of the Indian state of Gujarat was modelled in PowerFactory from the 765 kV to 220 kV voltage levels. The details of the modelled elements in the network are presented in Table I.

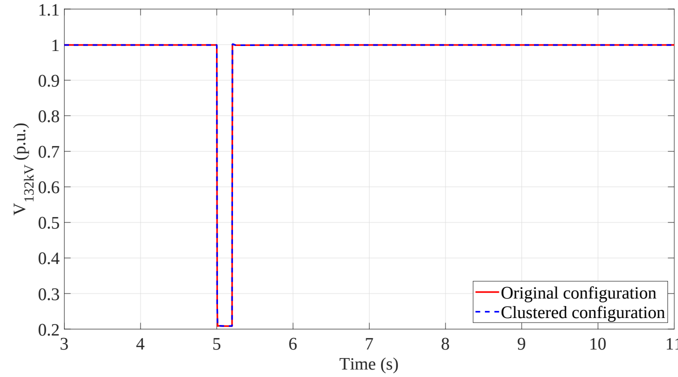

Fig. 5. Voltage at 132 kV bus in clustered and original system

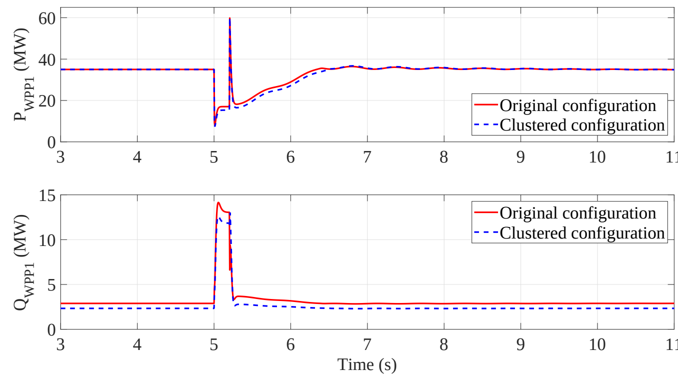

Fig. 6. Active and reactive power from WPP-1 in clustered and original system

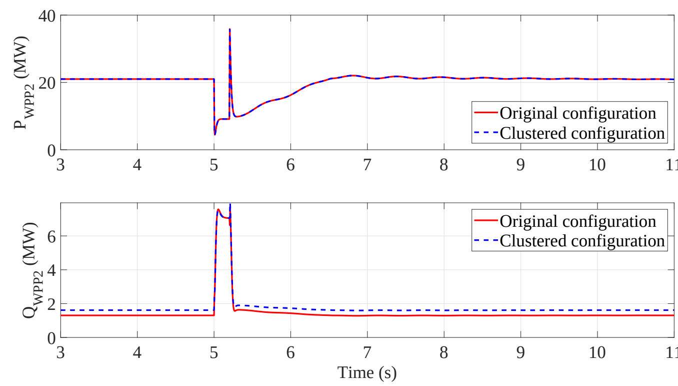

Fig. 7. Active and reactive power from WPP-2 in clustered and original system

Following the procedure described in the earlier section, the wind and solar power plants located at 132 kV and 66 kV in the network are aggregated to form 42 RE clusters spread out throughout the expanse of the grid. As is evident from the illustration of a RE cluster from Fig. 3, every cluster comprises an HV bus and an LV bus (primarily at 66 kV). Now, with the knowledge of the load connected at the LV bus and the current flowing in the HV-LV transformer, the current flow from the cluster can be calculated. From the theory of power system observability, it is understood that knowledge of the

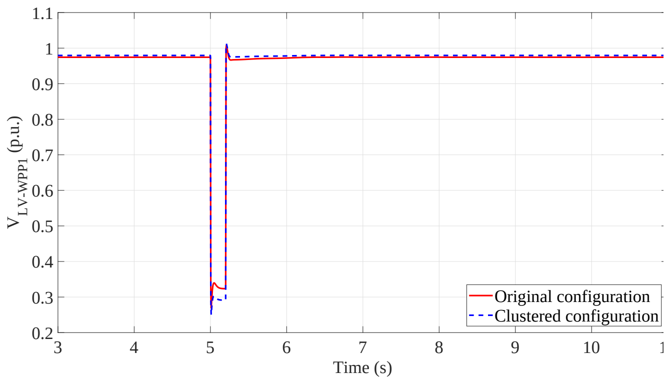

Fig. 8. WTG terminal voltage of WPP-1 in clustered and original system

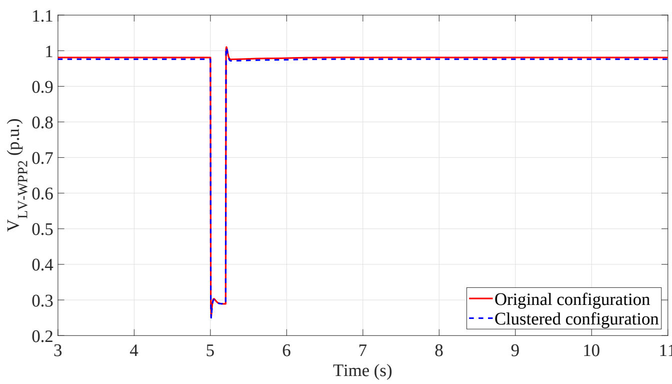

Fig. 9. WTG terminal voltage of WPP-2 in clustered and original system

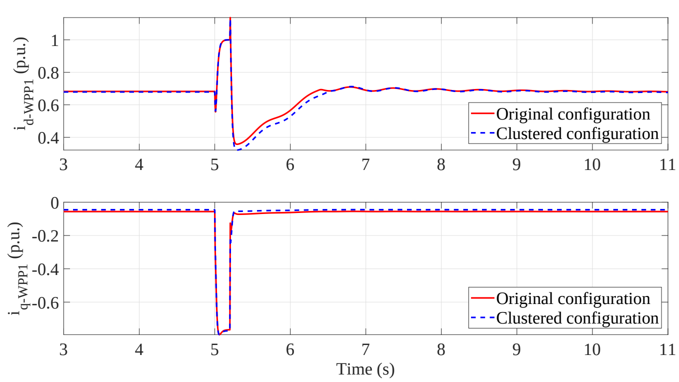

Fig. 10. Active (I_d) and reactive current (I_q) from WPP-1 in clustered and original system

transformer current is synonymous with the voltage of the LV bus being observable. Therefore, the power injected from each RE cluster can be effectively calculated if the LV bus of the same cluster is observable. However, due to restrictions related to the unavailability of efficient fiber-optic communication network and high operating cost of WAMS, PMUs cannot be incorporated at the 66 kV voltages under any circumstances. In such a situation, the methods that can be used for making the cluster LV buses observable have been proposed below.

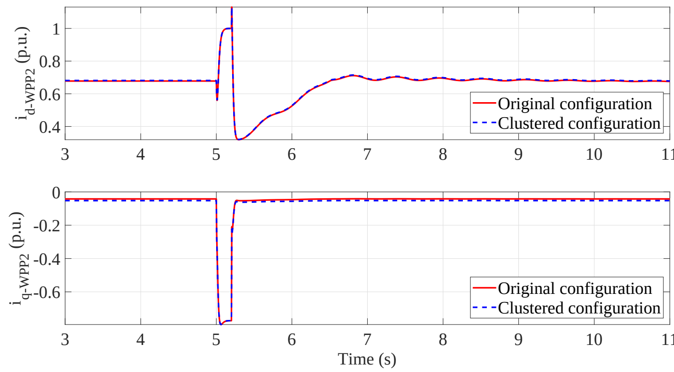

Fig. 11. Active (I_d) and reactive current (I_d) from WPP-2 in clustered and original system

TABLE I
DETAILS OF THE MODELLED GUJARAT NETWORK

Description	Quantity (Numbers)
No. of 400 kV buses	42
No. of 220 kV buses	154
No. of 132 kV buses	80
No. of synchronous generators	47
No. of Type-III wind farms	13
No. of Type-II wind farms	25
No. of Type-I wind farms	28
No. of solar PV farms	23

D. Proposed Methods for Observability of the RE clusters

i. **Without the use of network reduction:** Taking into account the constraints associated with introducing WAMS in the sub-transmission network, presently PMUs can only be incorporated in the 220 and 132 kV network to measure the current flow in all the RE clusters in the system. For achieving this objective, an optimal PMU placement problem has been formulated, which makes the low-voltage buses of the clusters observable, allowing the current flow across the HV-LV substation transformer to be traced. In the formulated problem, 292 buses in the modelled Gujarat power network are taken into consideration, and a 292×292 binary connectivity matrix is formed. Following the WAMS initiative undertaken by POSOCO, 49 buses in the system are assumed to be pre-equipped with PMUs, all of which are located from 400 to 220 kV voltages. The HV buses of the clusters are assumed to be zero-injection buses. Following the assumption of PMUs being pre-installed on some buses, two cases have been considered where the first case assumes the presence of pre-installed PMUs, and the second case ignores the condition. Accordingly, optimal PMU placement has been executed, and the results are presented in the next section.

ii. **With the use of network reduction:** It is evident from the previous procedure that the number of extra PMUs required for monitoring of the clusters with the conventional method is significantly higher. To further reduce the number of the final number of PMUs required for monitoring, an additional procedure has been proposed with the help of Ward reduction, as discussed here.

- RE clusters in the network are identified, and every cluster's HV bus is regarded as a *boundary bus*. For the case which considers pre-installed PMUs, buses at which PMUs are pre-installed (400 kV buses and 220 kV generator buses) are also considered as boundary buses. By this approach, the high voltage network (400 and 765 kV), the 220 kV generator buses, and the RE clusters form the *internal network*, whereas the remaining unobservable buses form the *external network*. Hence, the boundary buses segregate the internal area (to be reduced) from the external area (to be retained) according to this set of criteria.
- Ward reduction is executed on the internal area after defining the identified boundary buses. This generates the reduced model of the external system at a steady state at a particular pre-fault instant.
- As a result of Ward Reduction, the external network is reduced, and any generation or load located in it is aggregated on the boundary buses as AC voltage sources (or *Ward equivalents*), and impedances are introduced between the boundary buses.
- The approach to making use of Ward reduction for monitoring involves making only the cluster HV buses observable, i.e., the voltages of these buses must be known, which requires optimally placing the PMUs at particular locations that make it possible. Hence, the objective of this optimisation is the observability of the HV buses of the clusters only, notwithstanding the observability of the cluster LV buses.

VII. Results and Discussion

The results obtained from executing the optimal PMU placement using BPSO following the first method for monitoring as discussed in the preceding section is shown in Table II.

TABLE II
Optimal PMU Placement Without the Use of Network Reduction

N_{bus}	$Flag_{pre}$	N_{pre}	$N_{cluster}$	N_{PMU}	N_{extra}
292	Yes	49	42	**71**	**22**
292	No	-	42	**35**	-

In this method, with the cluster LV buses becoming observable from the obtained PMU placement, the current flows across any cluster HV bus can be effectively calculated by node voltage analysis . With the aggregated load current and the current across the HV bus known, the current and hence power injected from the RE cluster can be computed from the available data. This computed data can thereby be analysed and studied for checking the grid code compliance status of the overall RE cluster.

Following the second method of monitoring, the optimal PMU placement using BPSO is executed on the Gujarat power network which comprised of 256 buses (36 lesser buses than earlier attributed to the absence of cluster LV buses in the binary connectivity matrix) and 56 zero injection buses. The results obtained from executing the optimal PMU placement in this particular procedure are shown in Table III.

Even though the observability of the 66 kV low-voltage cluster buses does not come under the purview of optimization, still some 66 kV LV cluster buses can become observable by default in any PMU placement scenario. This is due to the configuration of the network and the cluster HV buses being considered as zero-injection buses. For these particular clusters, network reduction is not required for monitoring purpose even under this method.

TABLE III
Optimal PMU Placement with the Use of Network Reduction

N_{bus}	$Flag_{pre}$	N_{pre}	$N_{cluster}$	N_{PMU}	N_{extra}	N_{LV}
256	True	**49**	42	**67**	**18**	30
256	False	-	42	**25**	-	20

From the results shown in Table III, it can be concluded that monitoring using Ward reduction is only required to be performed on the 12 RE clusters which did not become fully observable in the followed OPP for the case where pre-installed PMUs were not considered. For the remaining 30 clusters, general node voltage analysis can be followed for current calculations. For the clusters which necessitate the use of the Ward network, the current flows from the concerned cluster HV bus to the other boundary buses in the internal network can be calculated by node voltage analysis, since the voltages of all the boundary buses are known from the obtained PMU placement. With the aggregated load current and the current flow across the cluster HV bus known, the current and hence power injected from the RE cluster can be computed from the available data by KCL. This calculated data can thereby be analysed for checking the grid code compliance status of the overall cluster.

VIII. Conclusion

The paper attempted to trace the evolution of grid code regulations concerning the renewable power plants and individually examined the details related to the LVRT criteria in them. An effort has been made to propose a new performance monitoring strategy that enables the use of PMUs to monitor the RE plants operating in the grid in real-time, at a suitable rate, which was otherwise impossible to perform with the traditional LVRT testing methods. According to the proposed technique, several optimal PMU placement procedures were performed on a test system to determine the minimum number of PMUs that would be required for the desired system observability to monitor all the RE plants in a grid.

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