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Optimal Placement of PMUs in Smart Grid for Voltage Stability Monitoring using AMPSO and PSAT

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ABSTRACT- Efficient energy use is critical for a growing nation like India. The smart grid (SG) idea enables the creation of a highly dependable electricity system that optimizes existing resources. The Indian electricity grid as it now exists needs fundamental modifications to satisfy increasing demand and to make the system more intelligent and dependable. Since the past several decades, power system stability has been seen as a significant challenge to power system researchers and utilities. With a not many strategically placed Phasor Measurement Units (PMUs), it may be feasible to observe the power system stability of the network. This article suggests an optimum location for PMUs, considering the effect of power system stability-related serious situations. The disturbances have been prioritized according to their voltage stability boundary (the gap among the stand case working and nose points). Changes in the voltage stability tolerance due to shifting load conditions were also considered in the crucial contingency determination. PMUs were inserted in the system based on Adaptive Mutated Particle Swarm Optimization (AMPSO) findings for the intact system and crucial contingency scenarios on the basis of voltage stability. The effectiveness of the suggested PMUs placement strategy was determined by examining nose curves produced with PMUs data and pseudo-observations under increasing demands to nose curves calculated offline using continuation power flow data. Using the software tool Power-System Analysis Toolbox (PSAT), case studies were conducted on a conventional IEEE14 bus system and a realistic 246 bus Indian Power Grid system.

Keywords: Optimal PMUs placement, Voltage stability, Contingencies, Adaptive Mutated Particle Swarm Optimization, Observability.

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1. INTRODUCTION

Reliable electric power is a prerequisite for every country's growth. Around 75% of India's electrical energy is produced by thermal power plants, which significantly affects the environment and contributes to global warming [1, 2]. Additionally, decreasing fossil fuel reserves will be unable to meet the growing need for electricity in the near future. By integrating the idea of the smart grid (SG), it is possible to improve resource usage and incorporate alternative energy resources (solar, wind, etc.) into the power network [2, 3]. The observability requirement ensures the utilization of current, power, and voltage flow data for all buses in the smart grid. With the development of phasor technology, researchers have emphasized its use in monitoring and controlling power system stability. Phasor readings made using Phasor Measurement Units (PMUs) may be used to address a variety of power system network problems [4]. PMU technology has a long history of monitoring, regulating, and safeguarding power systems [5].

Cost and other constraints prohibit the majority of utilities from deploying PMUs on all network buses. Thus, the optimum position for PMUs may be determined by considering a variety of factors such as network transient stability, vulnerability, observability, and voltage stability. The method based on network observability may use either topological or numerical observability [6]. Numerical observability methods use a gain matrix for jacobian measurement that represents the measurement set and system setup. Several techniques that take numerical observability into account include those that use simulated annealing [7], Tabu search [8], and Genetic Algorithm [9]. The location of PMUs using numerical observability has been studied in light of dynamic susceptibility [10], transitory stability [11], consistency [12], and estimation of state [13]. A semi definite programming method based on arithmetical observability has been explored for the optimum placement of PMUs, taking into account the presence of zero-injections, conventional measurements, and the effect of the PMU ports limit [14].

Arithmetic observability-based techniques are loaded costly due to the massive matrix operations required, and in the event of bulk power system networks, the measured matrices may become ill-conditioned. Methods based on topographical observability take graph theoretic features of power system networks into account. The location of PMUs only considered on topological considerations [15-17] may be insufficient to monitor the system's health. Thus, in addition to topological relations, system characteristics should be addressed while optimizing PMU placement. System features should take transient stability, vulnerability, voltage stability, and the effect of decisive contingencies into account. The optimal location of PMUs has been studied in terms of geometrical observability under voltage stability based serious situations [18]. However, the suggested PMU placement strategy is not successful in estimating the voltage stability boundary under disturbed conditions. A binary integer linear program-based method has been proposed for identifying necessary buses based on their voltage level, connection to other buses, transient significance, and voltage stability [19]. However, the effect of essential contingencies has been overlooked while determining the optimum placement for PMUs. The optimal site of PMUs has been suggested using binary-integer linear programming, taking into account the generator and load bus's susceptibility to disturbances [20]. However, susceptible PQ bus numbers identified using Thevinen's equivalent circuit, which are inaccurate at the nose point. The optimal location of PMUs has been suggested [21], utilizing a binary imperialistic competition algorithm that considers the effect of contingencies. It has been suggested to optimize the number of substations for installing PMUs by integrating transformer taps and contradiction in measuring decisive components [22]. The methods offered in [21] and [22] for the locations of PMUs do not reflect on the bus's stability vulnerability.

The optimum location of PMUs has been studied in this work, considering the effect of voltage stability-related vital contingencies. The positions of PMUs were determined using the findings of the Adaptive Mutated Particle Swarm Optimization algorithm in both the intact and critical contingency scenarios. Along with network observability, the suggested PMU placement method can efficiently estimate the voltage stability boundary with necessary disturbances at various load variations. There have been case studies undertaken on conventional IEEE14 bus-system and Indian Power Grid system with 246 buses [23].

2. VOLTAGE STABILITY BASED ON CONTINGENCY RANKING

PMU location should also take disturbances into account since a base case observable system may become un-observable in the event of a contingency. PMUs were placed in this study with the effect of voltage stability-related critical contingencies in mind. Because PMU placement is an offline approach, it is essential to choose necessary contingencies correctly, even if the contingency ranking method is computationally intensive. As a result, significant contingencies have been determined in this study on the basis of voltage stability boundary (gap among the intact case working point and peak load-ability tip). As shown in *figure 1*, a contingency with a smaller voltage stability margin (VSM) has been deemed quite serious, where incident-*j* is probably quite serious compared to incident-*i*.

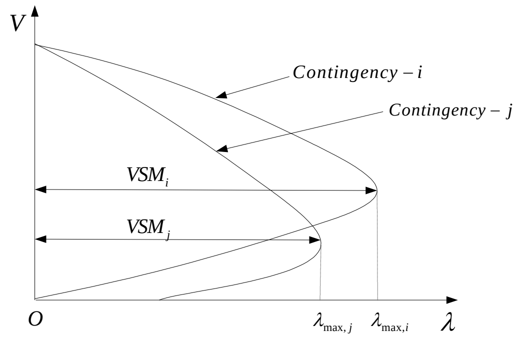

Figure 1: Rankings of Contingency using voltage-stability margin

Significant coincidences might vary in response to variations in the system's operational circumstances. To assess the effect of changing operating circumstances on the recognition of essential contingencies, the VSM was calculated under contingencies by altering the actual and inductive power loads on buses are as follows:

$$P_{D_i} = P_{D_{ib}}(1 + \lambda) \quad (1)$$
$$Q_{D_i} = kQ_{D_{ib}}(1 + \lambda) \quad (2)$$

Where,
P_{D_i} = Real power demand at bus i
Q_{D_i}= Reactive power demand at bus i
$P_{D_{ib}}$=Real power demand at bus i at the base case operating point
$Q_{D_{ib}}$=Reactive power demand at bus i at the base case operating point
λ = System loading factor common to all the buses
k = A multiplier used to change Q_{Di}/P_{Di} ratio to consider different patterns of load in augment

The multiplier k has been set at 0.2, 0.5, 1.0, and 1.2 in the current study to account for wide changes in the Q_{Di}/P_{Di} ratio. For the values of k studied, nose curves (-V curves) were produced for all single line outage instances, and voltage stability margin was derived under contingencies for k = 0.2, 0.5, 1.0, and 1.2, respectively. The lowest voltage stability margin among the margins estimated for different values of k examined in this study was used to identify critical situations.

3. OPTIMAL PHASOR MEASURMENT UNIT PLACEMENT

The prime goal of the PMU site challenge is to deploy the fewest possible PMU's in order to obtain comprehensive system visibility at the lowest possible cost. With a 'mm' bus system, the PMU Problem is defined as

$$ff(pp) = min \sum_{ii=1}^{mm} ww_{ii} * pp_{ii} \quad (3)$$

Constraints were imposed on them as

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$$GG(pp) \geq bb \quad (4)$$

Where the binary variable 'pp' is a PMU vector with the following definitions for its entries

$$pp_{ii} = \begin{cases} 0, if\, a\ PMU\ not\ placed\ at\ ii^{th}\ bus \\ 1, else \end{cases} \quad (5)$$

Where ii=1, 2….mm are positioned bus, ‘ww_{ii}’ is the value of sited PMU at i^{th} bus

‘bb’ is unit array of span ‘mm’

$$bb = [11111.....1]^T \quad (6)$$

The observability restraint vector function has an entry. If the relevant buses can be observed with regard to the defined measurement set, GG (pp) is non-zero; otherwise, it is zero. The vector-constraint function ensures that all system nodes are fully visible. It is important to calculate a response, that is, a minimum set of pp_i, in order to satisfy the restriction. The binary connectivity matrix (AAA) of the power system is considered as input to generate the restraint vector function. It reflects a power system's bus connection information, which may be extracted from the line element data of the underlying electrical system.

The *mm-nn*th value of matrix *AAA* relates to bus *mm*, and bus *nn* has the following definition.

$$AAA_{mm,nn} = \begin{cases} 1, if\, mm = nn \\ 1, if\, bus'nn' is\ linked\ to\ bus\ 'mm' \\ 0, else \end{cases} \quad (7)$$

Let us take IEEE 5 bus network as model represented in *figure 2.*

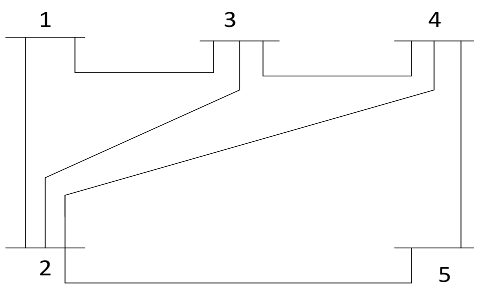

Figure 2: IEEE-5 bus test network

Binary-connection matrices (*AAA*) for IEEE 5 bus test network is

$$AAA = \begin{pmatrix} 11010 \\ 11111 \\ 11101 \\ 01111 \\ 01011 \end{pmatrix} \quad (8)$$

For the network considered in *figure 2*, the restraint array task for the IEEE-5 bus the following equation was used to implement the test network to attain full observability

$$GG(pp) = [G11\ G12\ G13\ G14\ G15]^T = AAA * PP$$
(9)

Where for buses

$$\left.\begin{aligned} &Bus-1:\ pp_5 + pp_1 + pp_2 \geq 1 \\ &Bus-2:\ pp_5 + pp_4 + pp_2 + pp_3 + pp_1 \geq 1 \\ &Bus-3:\ pp_4 + pp_2 + pp_3 \geq 1 \\ &Bus-4:\ pp_9 + pp_7 + pp_4 + pp_5 + pp_3 + pp_2 \geq 1 \\ &Bus-5:\ pp_5 + pp_2 + pp_4 + pp_1 \geq 1 \end{aligned}\right\} \quad (10)$$

In *equation (10)* ‘+’ works as ‘OR’ logical operator. It is true to state from *equation (10)* that, to make bus-2 observable in the considered test system, at least 1 PMU must be placed at one of the buses (5,4,3, 2 or 1), if *eq. (10)* is true. The considered network in *Figure 2* is then entirely observable.

4. ADAPTIVE MUTATED PARTICLE SWARM OPTIMIZATION

The standard PSO algorithm simulates birds' foraging behavior by requiring individuals to collaborate to find the optimum solution. A bird represents each optimization issue in search space called a particle in this method; each particle assesses its current location using the fitness function and has a directional speed to determine its search route. Kennedy and Eberhart devised the binary PSO (BPSO) algorithm to work in a binary search area [23]. Thus, the location vector y in BPSO for every particle may take only the logical value 1 or 0 and is updated using the S-shaped sigmoid function. A significant issue in this application of BPSO is early convergence; this issue arises due to an excessive loss of population variability. This article presents a V-shaped sigmoid function and a mutation method for solving the OPP concern to address these issues. While mutation is often associated with increasing particle diversity, the mutation approach in this thesis aims to enhance the algorithm's local search to assist particles in escaping from local optimal while enhancing the p-best of the relevant solutions. The mutation approach is intended to use the search area created by the p-best to discover the improved ones, where the benchmark unimodal and multimodal functions favour the V shaped sigmoid function over the S shaped sigmoid function. The following equation is used to update the value of velocity V.

$$V_{ij}^{t+1} = K[V_{ij}^t + C_1 * R_1 * (Pbest_{ij}^t - x_{ij}^t) + C_2 * R_2 * (Gbest_{ij}^t - x_{ij}^t)] \quad (11)$$

To solve this problem, a V-shaped sigmoid function was utilised, and its definition is as follows: (24)

$$sig(V_{ij}^{t+1}) = 2 * \left|\frac{1}{1+e^{-V_{ij}^{t+1}}} - \frac{1}{2}\right| \quad (12)$$

Following that, the position vectors y are updated as follows using the probability values derived from (12):

$$x_{ij}^{t+1} = \sim x_{ij}^t, if\, rand < sig(V_{ij}^{t+1}) \quad (13)$$

This work employed a single element mutation operator (SMO) in addition to the aforementioned techniques to avert pre-mature convergence and stagnation. A random considered bit from the result collection is chosen and inverted using the SMO concept.

5. VOLTAGE STABILITY ASSESSMENT USING PMUs

The suggested PMU placement strategy was evaluated for its effectiveness in estimating the voltage stability margin of essential buses in the presence of contingencies. Critical buses are those that are most vulnerable to the system's voltage instability. It is vital to identify necessary buses because they need immediate control action to maintain the voltage stability. Critical buses were determined in this study using the sensitivity factor of voltage magnitude (V_i) to loading (λ) i.e., $dV_i/d\lambda$. The maximum negative $dV_i/d\lambda$ value bus has been deemed the mainly dangerous. Changes in the operational scenario affect critical buses. As a result, $dV_i/d\lambda$ sensitivity for all buses have been estimated for the intact system case and voltage-stability using severe contingency models considering a maximum load rise (k = 0.2, 1.0, 0.5, and 1.2, correspondingly). For most load patterns and significant outages evaluated, the sensitivity $dV_i/d\lambda$ was determined at a position near to the nose point. The most crucial buses in the system were those with the collection of buses with the highest negative $dV_i/d\lambda$ values for the system intact case and crucial contingency cases based on voltage stability under various load rise patterns. Using the results of pseudo measurements and PMU measurements, all critical buses nose curves were derived in different operational circumstances. To evaluate the suggested PMU placement algorithm's accuracy in assessing voltage stability, nose curves for these buses were also produced under various operating circumstances using continuous power flow method. The nose-curves produced applying the suggested technique was contrasted to those estimated off-line using the continuing power flow method [26].

6. CASE STUDIES

Case- A: The proposed method for locating PMUs to find VSM was validated using the PSAT software on a conventional IEEE14 bus system and a realistic 246 bus Indian Power-Grid system. The following table summarizes the findings from two systems:

Case-B: IEEE14 bus system [27] contains two generators (on buses 1, 2), three synchronous capacitors (on buses 8, 6, and 3), and twenty transmission-lines, including three transformers. At bus number 7, this system has zero injection.

The Power System Analysis Toolbox (PSAT) program produced nose curves (V-λ curves) for the normal case and one line outage scenarios for k = 1.2, 1.0, 0.5, and 0.2, correspondingly. The contingency ranking was performed using the VSM (the close among the nose point operating condition and normal case) calculated for the various values of k examined in this study. *Table 1* illustrates the most severe five scenarios due to the VSM for k = 0.5, 0.2, 1.2, and 1.0, correspondingly. *Table 1* lists the most rigorous three contingencies identified in [18] using the voltage-stability criteria. As shown in *table 1*, the most rigorous three contingencies produced using the suggested method are not dependent on load sample, but the severity scale in order varies when k = 1.2. However, depending on the pattern of load rise, contingencies with ranks 4 and 5. Five of the most critical situations identified using the suggested methodology also corresponds to the key contingencies [18]. Based on the voltage stability criteria, line outages 1-2, 2-3, 5-6, 2-4, 7-9, 2-5, and 6-13 were deemed the most significant contingencies for Taking into account the broad trend of load rise (viz. = 0.2, 0.5, 1.0, and 1.2, correspondingly).

Table 1: IEEE14-Bus System Critical Contingencies

R	Critical circumstances for various K values, also in [18]								
	***K* = 0.2**		***K* = 0.5**		***K*= 1.0**		***K*= 1.2**		**[18]**
	S.L.O.	VSM	S.L.O.	VSM	S.L.O.	VSM	S.L.O.	VSM	S.L.O.
1	1-2	1.343	1-2	1.340	1-2	1.335	1-2	1.333	1-2
2	2-3	2.280	2-3	2.270	2-3	2.250	5-6	2.212	2-3
3	5-6	2.551	5-6	2.453	5-6	2.271	2-3	2.242	5-6
4	2-4	3.366	2-4	3.340	7-9	2.865	7-9	2.702	2-4
5	2-5	3.537	7-9	3.348	6-13	3.203	6-13	3.052	2-5

R = Ranking, S.L.O. =Single Line Outage, VSM = Voltage Stability Margin

For both the intact system and voltage-stability critical contingency-based scenarios, the Adaptive Mutated Particle Swarm Optimization method was used. The locations of candidate PMU's for the intact system and voltage-stability based essential unforeseen event scenarios were determined using the findings and are listed in *table 2*. *Table 2* additionally includes candidate sites for PMU deployment based on the PMU locations found for many critical contingency scenarios.

As shown in *table 2*, adaptive mutated particle swarm optimization results provide bus locations 2, 5, 4, 6, and 9 as PMU position sites considering on an arrangement of PMU placement sites determined for various severe unforeseen event situations. As a result, these sites were chosen as the best locations for phasor measuring units. This involves the addition of five PMUs to the system.

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Table 2: IEEE14 Bus System PMU Locations

S.C	Placements of PMU	S.O.I.
Base Case	2, 6, 9	14
1-2	4, 5, 6, 9	19
2-3	4, 5, 6, 9	19
5-6	2, 6, 9	14
2-4	2, 6, 9	13
7-9	4, 5, 6, 9	17
2-5	2, 6, 9	13
6-13	2, 6, 9	13
Z	2, 4, 5, 6, 9	24

S.C. = Severity case, S.O.I. = Sum of observability-index
Z = PMU placement acquired for combined all S.C.

The SOI has also been computed for the PMU sites under normal operating conditions and during critical contingency conditions based on voltage stability. For serious contingency situations, the SOI has been computed for the group of PMU sites. *Table 2* shows the Total Observability Index for various conditions. As shown in *table 2*, combining PMU sites for all severe disturbed situations outcomes in a SOI of 24, much more than value obtained in base case. This guarantees system observability in the event of a few PMU's being lost due to contingencies.

The set of severe buses was found by calculating the susceptibility factor level of voltage to loading ($dVi/d\lambda$) for all load-buses at a position near the edge position for the base case system and circumstances that are critical in the event of voltage stability with k = 0.5, 0.2 1.2, and 1.0. For k = 0.5, 0.2, 1.2, and 1.0, the most vulnerable buses (those among the significant *-ve* sensitive ratings) are 4, 9, 5, 13, 10, and 14, which were initially considered to be the system most vital buses as shown in *table 3*.

PSAT software was used to generate nose curves (V-λ curves) for serious buses utilizing a mix of PMU data and for k = 0.5, 0.2, 1.0, and 1.2, respectively, pseudo-observations for the intact network scenario and based on voltage-stability important incident situations. Additionally, the PSAT software is an offline continuous power flow technique produced nose curves for essential buses for the studied instances. The nose curve of crucial bus four during line outage 3-2 with k = 1.0 was acquired using PMUs and pseudo measurements. The nose curve produced using the offline continuous power flow technique without using PMUs data is presented in *figure 2*. This demonstrates that the nose curves of essential bus's determined using ideally located PMU data and pseudo-observations agree with those calculated using the off-line cpf technique.

Table 3: IEEE 14 Bus System Maximum Severe Buses with Contingencies

S.L.O.	*K* = 0.2	*K* = 0.5	*K* = 1.0	*K* = 1.2
	Bus No.	Bus No.	Bus No.	Bus No.
Base Case	5	5	5	5
1-2	5	5	5	5
2-3	4	4	4	4
5-6	9	9	10	10
2-4	5	5	5	5
7-9	9	9	9	9
2-5	5	5	5	5
6-13	14	13	13	13

S.L.O = Single Line-outage

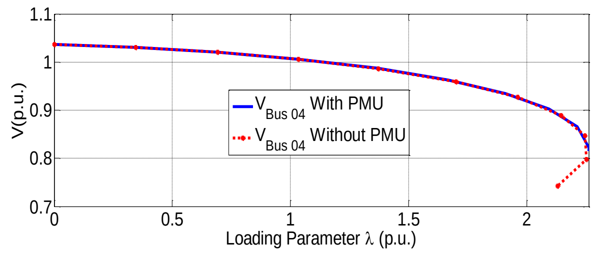

Figure 3: Nose curve with line outage 3-2 of severe bus 4 considering k = 1.0 (IEEE14 Bus network)

Case- C: Indian-246 Bus-System

India's 246 buses Indian Power-Grid [28] is comprised of 36 transformers and 42 generators. It operates fifteen zero injection buses under the following routes: 63, 81, 75, 103, 102, 107, 104, 122, 180, 155, 210, 226, 241, 237, and 244.

The Power System Analysis Toolbox (PSAT) program produced nose-curves (V-λ curves) for the network normal case and combined one line-outage scenario for k = 1.2, 0.2, 1.2, and 0.5, correspondingly. For the values of k examined in this study, contingency ranking was performed using the VSM (the close between the nose case operating point and the base point). *Table 4* lists the ten most critical situations based on VSM for k = 0.5, 0.2, 1.2, and 1.0, correspondingly. Based on the voltage stability criteria, line outages 156-158, 40-41, 173-174, 166-173, 181-158, 219-77, 160-164, 168-171, 106-123, 158-160, and 165-171 were judged to be the most important situations. The crucial situations found in [18] are 105-245, 75-91, 116-229, 166-173, 188-190, and 121-122, where only one severe contingency (line-outage 173-166) corresponds to the severe circumstances produced using the suggested method. This demonstrates that important perturbations depend on the correctness of the perturbation grade technique and the system's operational circumstances. Thus, while planning PMU deployment, an offline technique, appropriate attention should be paid to the approach's precision. While identifying key contingencies, it is also necessary to evaluate the network's operational circumstances, such as changes in load patterns.

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Table 4: 246 Bus System Most Severe Buses with Contingencies

R	Critical circumstances for various K values, also in [18]							
	K = 0.2		*K* = 0.5		*K* = 1.0		*K* = 1.2	
	S.L.O.	VSM	S.L.O.	VSM	S.L.O.	VSM	S.L.O.	VSM
1	156-158	0.19	40-41	0.92	156-158	0.34	156-158	0.39
2	40-41	0.75	173-174	1.25	173-174	1.05	173-174	0.99
3	166-173	1.10	165-174	1.39	40-41	1.08	165-174	1.09
4	173-174	1.39	181-158	1.50	165-174	1.16	40-41	1.10
5	165-174	1.55	219-77	1.51	181-158	1.29	181-158	1.22
6	219-77	1.63	160-164	1.53	160-164	1.31	160-164	1.23
7	181-158	1.64	168-171	1.59	168-171	1.36	168-171	1.29
8	160-164	1.68	106-123	1.61	219-77	1.37	219-77	1.35
9	106-123	1.73	158-160	1.67	165-171	1.47	158-160	1.36
10	168-171	1.75	158-34	1.73	106-123	1.48	165-171	1.38

The Adaptive Mutated Particle Swarm Optimization technique was used to determine potential sites for the location of PMU's in the network base and voltage-stability based key perturbed situations. *Table 5* contains candidate sites for PMUs in the intact system and a few voltages stability-based essential contingency situations. *Table 5* additionally includes candidate sites for PMU placement based on the PMU locations acquired for all critical contingency scenarios.

As shown in *table 5*, the findings generate 97 PMU sites due to the combination of PMU locations acquired for various critical contingency situations. As a result, these buses were chosen as the best places for phasor measuring units.

The SOI has also been computed for the PMU sites under normal operating conditions and during critical contingency conditions based on voltage stability. For serious contingency situations, the SOI has been computed for the group of PMU sites. *Table 2* shows the Total Observability Index for various conditions. As shown in *table 2*, combining PMU sites for all severe disturbed situations outcomes in a SOI of 419, much more than value obtained in base case. This guarantees system observability in the event of a few PMU's being lost due to contingencies.

The set of severe buses was found by calculating the susceptibility factor level of voltage to loading (dVi/dλ) for all load buses at a position near the edge position for the base case system and circumstances that are critical in the event of voltage stability with k = 0.5, 0.2 1.2, and 1.0. For k = 0.5, 0.2, 1.2, and 1.0, the most vulnerable buses (those among the significant *-ve* sensitive ratings) are 156, 164, 173, 171 and 174, which were initially taken into account to be the system mainly vital buses represented in *table 6*.

PSAT software was used to generate nose curves (V-λ curves) for serious buses utilizing a mix of PMU data and for k = 0.5, 0.2, 1.0, and 1.2, respectively, pseudo-observations for the intact network scenario and based on voltage-stability important eventuality situations. Additionally, PSAT software is an offline continuous power flow technique produced nose curves for essential buses for the studied instances. The nose curves during line outage171-168 of crucial bus 171 considering k = 0.5 was acquired using PMUs and pseudo measurements. The nose curve produced using the offline continuous power flow technique without using PMUs data is presented in *figure 3*. This demonstrates that the nose curves of essential bus's determined using ideally located PMU data and pseudo-observations agree with those calculated using the off-line continuation power-flow technique.

Table 5: PMU Placement for 246-Bus Network

S.C.	PMU Placement	S.O.I
Base case	6, 21, 24, 23, 33, 40, 34, 48, 45, 54, 57, 55, 60, 62, 61, 65, 70, 74, 73, 75, 80, 79, 84, 83, 93, 98, 95, 101, 100, 109, 106, 117, 121, 126, 125, 128, 129, 132, 131, 134, 141, 140, 142, 147, 158, 157, 160, 168, 163, 173, 181, 185, 183, 187, 191, 190, 199, 194, 201, 207, 203, 216, 225, 219, 235, 234, 245, 243	311
156-158	6, 7, 23, 34, 40, 42, 45, 48, 54, 55, 57, 60, 61, 62, 65, 68, 70, 73, 75, 78, 80, 83, 93, 94, 95, 98, 100, 101, 106, 117, 121, 125, 126, 128, 129, 131, 132, 134, 140, 141, 142, 153, 157, 160, 167, 168, 169, 174, 181, 183, 185, 187, 190, 191, 194, 199, 201, 202, 203, 206, 217, 219, 234, 235, 239, 243	298
166-173	6, 18, 23, 24, 33, 34, 40, 45, 48, 54, 55, 57, 60, 61, 62, 65, 68, 70, 73, 74, 75, 78, 80, 83, 88, 93, 95, 98, 100, 101, 106, 117, 121, 125, 126, 128, 129, 131, 132, 134, 141, 142, 144, 147, 157, 158, 160, 167, 168, 169, 174, 181, 185, 187,	307

	190, 191, 194, 199, 201, 203, 207, 216, 219, 225, 234, 235, 243, 245	
Z	6, 7, 8, 10, 14, 18, 21, 22, 23, 24, 32, 33, 34, 40, 42, 45, 48, 54, 55, 57, 60, 61, 62, 65, 68, 70, 73, 74, 75, 78, 79, 80, 83, 84, 88, 93, 94, 95, 96, 98, 100, 101, 106, 108, 109, 116, 117, 119, 121, 125, 126, 128, 129, 131, 132, 134, 140, 141, 142, 144, 147, 153, 157, 158, 160, 163, 165, 166, 167, 168, 169, 170, 173, 174, 181, 183, 185, 187, 190, 191, 193, 194, 199, 201, 202, 203, 206, 207, 216, 217, 219, 225, 234, 235, 239, 243, 245	419

Table 6: List of Severe Serious Buse's Under Disturbances For 246-Bus Network

S.L.O.	*K* = 0.2	*K* = 0.5	S.L.O.	*K* = 1.0	*K* = 1.2
	Bus No.	Bus No.	.	Bus No.	Bus No.
Base Case	156	156	Base Case	156	174
156-158	174	174	156-158	174	174
40-41	156	174	40-41	174	174
166-173	173	173	181-158	156	156
160-164	164	164	160-164	164	164
168-171	171	171	168-171	171	171

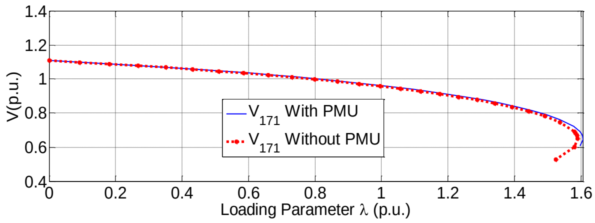

Figure 4: Nose-curve under line-outage 171-168 at essential bus 171 considering k = 0.5 (246-bus network)

7. CONCLUSION

This article makes recommendations for the optimum location of phasor measuring devices for monitoring the power system stability under varying operating circumstances. PMU's have been installed based on the findings of the system base case and important contingency scenarios based on power system stability. The critical contingencies were chosen for different load patterns based on the least Voltage Stability Margin (the space between the nose point and the base case operating point). The nose curves calculated under various operating circumstances using ideally positioned PMU observations closely match the nose curves derived from offline continuing power flow measurements. The simulation results on an IEEE14 bus system and a real-world 246 bus Indian Power-Grid system in India demonstrate the efficacy of the suggested method for calculating the VSM under perturbations at various load variations.

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