Front. Energy 2013, 7(4): 413–428
DOI 10.1007/s11708-013-0274-6

RESEARCH ARTICLE

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Optimal redundant placement of PMUs in Indian power grid — northern, eastern and north-eastern regions

Abstract Effective utilization of renewable energy sources and efficient management of electric energy are essential for any developing countries like India. This can be envisioned through the implementation of concepts of smart grid (SG). One of the key requisites for SG implementation is that the grid should be completely observable. Renovation of conventional Indian power grid to a SG necessitates incorporation of the phasor measurement units (PMUs) in the present power grid measurement and monitoring system. Since the cost of PMU is high and any bus containing a PMU makes the neighboring connected buses observable, optimal placement of PMUs is very important for complete observability of the grid. This paper proposes optimal redundant geographical locations in the northern, eastern and north-eastern regions of Indian power grid for PMU placement. The PMUs installed in these geographical locations will make the grid completely observable and maintain the observability under the conditions of failure of some PMUs or branch outages. Integer linear programming has been used for finding the optimal PMU locations. The results proposed in this paper can be a stepping stone for revamping the Indian power grid to a SG ensuring complete observability during different contingency conditions.

Keywords phasor measurement unit (PMU), smart grid (SG), Indian power grid, northern region Indian power grid (NRIPG), eastern region Indian power grid (ERIPG), north-eastern region Indian power grid (NERIPG), redundancy, integer linear programing (ILP)

Received February 14, 2013; accepted May 12, 2013

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1 Introduction

The soaring demand for electrical energy in the modern society has the ramification of the excessive consumption of fossil fuels in traditional power generating units. One of the consequences of this increased dependence on diminishing fossil fuels is the increased global warming, which is hazardous to every living being on the earth planet. This is the main driving force behind the development of an eco-friendly, efficient and intelligent power system like smart grid (SG).

The ever increasing population of India has made the demand for electrical energy to rise each and every year. Currently in India, the major portion of electrical energy is generated using fossil fuels. Approximately 10%–20% of the power generated is wasted though transmission losses [1]. So the concept of SG is of great significance in India. The government of India has initiated various programs for the implementation of SG. As a major step, India smart grid task force (ISGTF) and India smart grid forum (ISGF) have been developed, with a mission to coordinate the various activities related to SG across the country and to accelerate the development of SG[1]. Compared to the traditional power system, SG offers real time bidirectional communication, extensive customer interaction, real time remote power system monitoring, centralized and distributed power generation, comprehensive power flow control, smart metering, pro-active real time fault detection, and self-healing [2]. For the real time power flow control and fault detection, values of voltage, current and power flow of each and every bus in the power grid should be instantaneously available for analysis. In other words,

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[1] An initiative of Ministry of Power, Govt. of India. India Smart Grid Forum, Available: http://indiasmartgrid.org

the power grid should be completely observable.

The present Indian power grid monitoring system consists of remote terminal units (RTUs), state estimators, and supervisory control and data acquisition unit (SCADA) [2]. RTUs are installed at various buses in the power grid, which measure and send the RMS values of voltage and current at that bus to the state estimators placed in the main control center (MCC). The state estimator calculates the phase angle and power flow values using the power system model and then transmits the calculated values to the SCADA. State estimators are inherently slow and introduce some time delay which ranges from a few seconds to a few minutes. So this type of monitoring system is insufficient for the implementation of the SG [2–5]. A more accurate and real time monitoring can be achieved by replacing the RTUs by phasor measurement units (PMUs) [6]. The PMUs installed in a bus measure and send the phasor values (both magnitude and phase angle) of voltages at that bus and currents through all the branches connected to that bus to the state estimator [5]. The measured values are synchronized using Global Positioning Satellite (GPS) for the synchronous operation of all PMUs connected to the power grid. Direct measurement of phase angles and the synchronous operation of all PMUs lead to a better and faster state estimation.

One of the important features of PMUs is that, the PMU installed in a bus facilitates the estimation of the voltage phasors of all neighboring connected buses. Thus it is redundant to place PMUs at all the buses in the network for its complete observability. Therefore, finding the minimum number of PMUs and their locations in the network are of immense research interest across the globe.

Phadke et al. [6] introduced an algorithm for measuring the phase angle and frequency of AC signals using Discrete Fourier Transform (DFT), which was the edifice for computations related to PMU. After that many researchers attempted to apply PMUs in various areas including computer networks, telecommunication networks, power system networks etc. Nuqui et al. [7] proposed optimal placement of PMUs in a power grid using the spanning tree method. The method was proved to be very effective, but it took a long time for larger power grids. Gou [8] proposed an alternative approach for finding optimal PMU locations in a power grid using integer linear programing (ILP). The proposed method was faster than the spanning tree method. But the paper analyzed only standard IEEE bus systems and no practical networks were studied. The optimal PMU placement algorithm which made the power system completely observable even in the case of single branch outage was proposed by Abur et al. [9]. But the paper investigated only IEEE standard buses but did not study practical networks.

This paper studied the optimal PMU placement problem incorporating redundancy for the Northern Region Indian Power Grid (NRIPG), Eastern Region Indian Power Grid (ERIPG) and North-eastern Region Indian Power Grid (NERIPG). The concept of depth of redundancy is defined. The geographical locations of the PMUs in the above mentioned regions for their complete observability without redundancy and with depth of one redundancy are being proposed.

2 Power system monitoring using PMU

2.1 PMUs

PMUs are the microcontroller based digital device that measure the phasor values of voltages and currents with respect to a time reference provided by the GPS [6,10]. A phasor is a complex quantity that represents both magnitude and phase angle of a sinusoidal waveform. A sinusoidal waveform and its phasor representation are shown in Fig. 1.

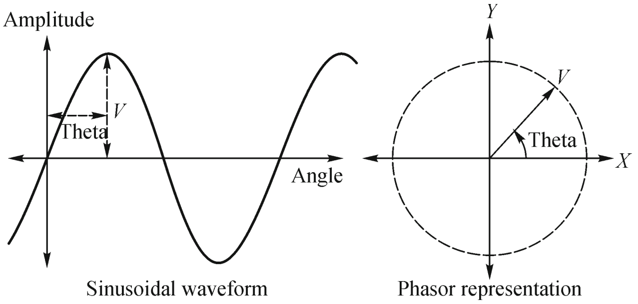

Fig. 1 A sinusoidal wave and its phasor representation

All the PMUs installed across the power grid measure the phasor values based on the same time reference set by the GPS. Such phasors are called synchronized phasors. The principle of the operation of PMUs can be clearly understood from the functional block diagram given in Fig. 2. It is seen evidently from Fig. 2 that the analog signals of voltage and current from potential transformer and current transformer respectively are filtered through anti-aliasing filters to restrict the bandwidth of the signals to approximately satisfy the sampling theorem. The filtered

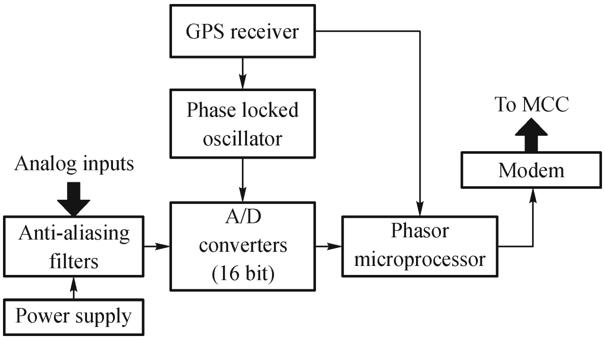

Fig. 2 Functional block diagram of PMU

signals are then converted to digital using analog to digital converters (A/D converters). The phase locked loop maintains the synchronization of the sampling with reference signals from the GPS. These digital signals are then fed to the phasor microprocessor, which computes the phasor values by using DFT [6].

2.2 Observability of SG

A SG is envisioned as highly interconnected network between electricity generation units and end consumers, which incorporates sophisticated sensing and monitoring, information technology and communication to provide highly reliable and efficient electric supply to consumers [11,12]. The monitoring system consists of PMUs (used as measurement devices), state estimator and SCADA based control system. For the proper operation of smart grids, the power system network should be completely observable. A power system network is said to be completely observable if the voltage, current and power flow values at each and every bus can be obtained through the monitoring system [13–19]. A typical SG network comprising of a PMU based monitoring system is depicted in Fig. 3.

Since the PMUs installed in a bus can measure the phasor values of the current passing through all the branches connected to that bus, the voltage phasors of all the neighboring buses connected can be estimated using Ohm's law. Based on this principle, the network in Fig. 3 requires only two PMUs (buses 2 and 6) for the complete observability of the seven buses. Buses 2 and 6 are called directly observable buses while the others are called indirectly observable buses.

2.3 Redundancy of PMU placement

Since the power grid monitoring system plays a vital role in the operation of the SG, it is important that every bus in the system should be observable even in case of branch outages or loss of functioning of PMUs [10]. One way to achieve this goal is that each bus should be observable by

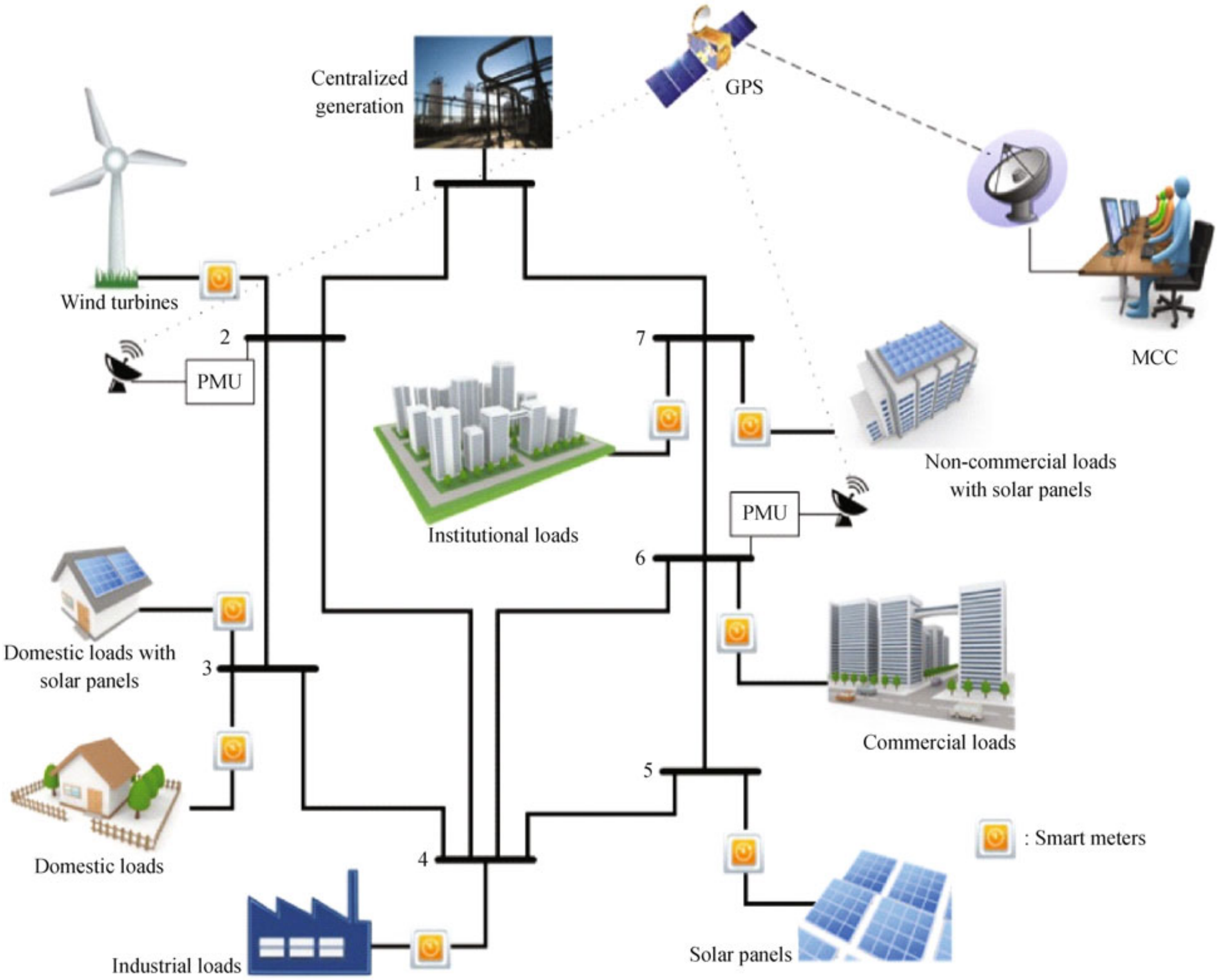

Fig. 3 A typical SG with a PMU based monitoring system

more than one PMU. It is observed from Fig. 3 that all the buses are observable by only one PMU except bus 4 which is observable by two PMUs. So even if one PMU is lost or one branch outage happens, bus 4 is still observable by the other PMUs. If the PMUs are placed at buses 1, 2, 4 and 6, every bus in the system will be observable by at least 2 PMUs. This is defined as depth of one-redundancy. If every bus in the system is observable by at least 3 PMUs, it is defined as depth of two-redundancy. As the depth of redundancy increases, the number of PMUs also will increase.

This paper proposes optimal PMU locations with their geographical names in the Northern, Eastern and North-eastern regions of Indian power grid for their complete observability with and without depth of one-redundancy.

3 Optimal redundant PMU placement using ILP

The optimization of PMU locations with any depth of redundancy can be achieved using ILP. ILP is a mathematical optimization method for attaining the optimal outcome from a given mathematical objective function, subject to the given linear inequality constraints [8,20]. For brevity, only salient features of the ILP are given in this section. It is assumed here that there is no constraint for the PMU on the number of measuring channels and communication systems [15,16].

The optimization of PMU locations in a given power system network starts with crafting the incident matrix $\boldsymbol{T}_{\mathrm{PMU}}$, in such a way that its entries are defined as

$$t_{ij} = \begin{cases} 1 & \text{if } i = j, \\ 1 & \text{if } i \text{ and } j \text{ are connected,} \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

The second stage of optimization is the development of the objective function. For "N" bus network, if the PMUs are placed in all the buses, the cost of installation will be "x_k" where $k \in \mathbf{N}$. So the overall cost minimization can be chosen as the objective function for optimal placement and it takes the form of

$$\min \sum_{k=1}^{N} x_k. \tag{2}$$

Subject to the constraint that

$$\boldsymbol{T}_{\mathrm{PMU}}\boldsymbol{X} \geqslant \boldsymbol{b}_{\mathrm{PMU}},$$

$$\boldsymbol{X} = [x_1, x_2, \ldots, x_N]^{\mathrm{T}} \quad x_i \in \{0, 1\}, \tag{3}$$

$$\boldsymbol{b}_{\mathrm{PMU}} = [1, 1, \ldots, 1]^{\mathrm{T}}_{Nx_1}, \tag{4}$$

where x_i is called the ith PMU placement variable.

If it is defined that $\boldsymbol{Y} = \boldsymbol{T}_{\mathrm{PMU}}\boldsymbol{X}$, the ith element of $\boldsymbol{Y}$, given by y_i indicates the number of times the bus "i" is observable by the PMUs. For the depth of one-redundancy in the case of complete observability, the matrix "b_{PMU}" in the constraints of the ILP problem has to be modified as Eq. (5)

$$\boldsymbol{b}_{\mathrm{PMU}} = [2, 2, \ldots, 2]^{\mathrm{T}}_{Nx_1}. \tag{5}$$

Similarly, for the depth of two-redundancy, the matrix "b_{PMU}" takes the form of Eq. (6)

$$\boldsymbol{b}_{\mathrm{PMU}} = [3, 3, \ldots, 3]^{\mathrm{T}}_{Nx_1}. \tag{6}$$

4 Indian power grid: an overview

Indian power grid has been divided into five regions, viz, northern region power grid, southern region power grid, eastern region power grid, western region power grid and north eastern region power grid [21]. This paper only studies the power grid of northern, eastern, and north-eastern regions.

Northern region Indian power grid (NRIPG) covers the largest geographical area (30.7% of the country's area) amongst the five regions and constitutes of seven states (Punjab, Haryana, Jammu and Kashmir, Himachal Pradesh, Uttaranchal, Uttar Pradesh, Rajasthan) and 2 union territories (Delhi, Chandigarh) [22,23]. NRIPG consists of 104 buses of ultra-high voltage (UHV, 765 kV), extra high voltage (EHV, 400 kV), and high voltage (HV, 220 kV) transmission lines. The single line diagram of the NRIPG is illustrated in Fig. 4. The geographical names of the buses in the single line diagram are given in Table 1. Since all these regions are interconnected, the common buses are shown in both regional grids.

Eastern region Indian power grid (ERIPG) consists of five states, namely, Bihar, Jharkhand, Orissa, Sikkim and West Bengal. ERIPG is the only region having connectivity with all other regions of the country and having international connection with Nepal and Bhutan. It consists of 90 buses of UHV, EHV, and HV transmission lines. The single line diagram of NRIPG is demonstrated in Fig. 5. The geographical names of the buses in the single line diagram are presented in Table 2.

North eastern region indian power grid (NERIPG) constitutes seven states, namely, Arunachal Pradesh, Assam, Meghalaya, Manipur, Mizoram, Nagaland, and Tripura. NERIPG consists of 14 buses of extra high voltage (EHV), and high voltage (HV) transmission lines. The single line diagram of NRIPG is displayed in Fig. 6. The geographical names of the buses in the single line diagram are tabulated in Table 3.

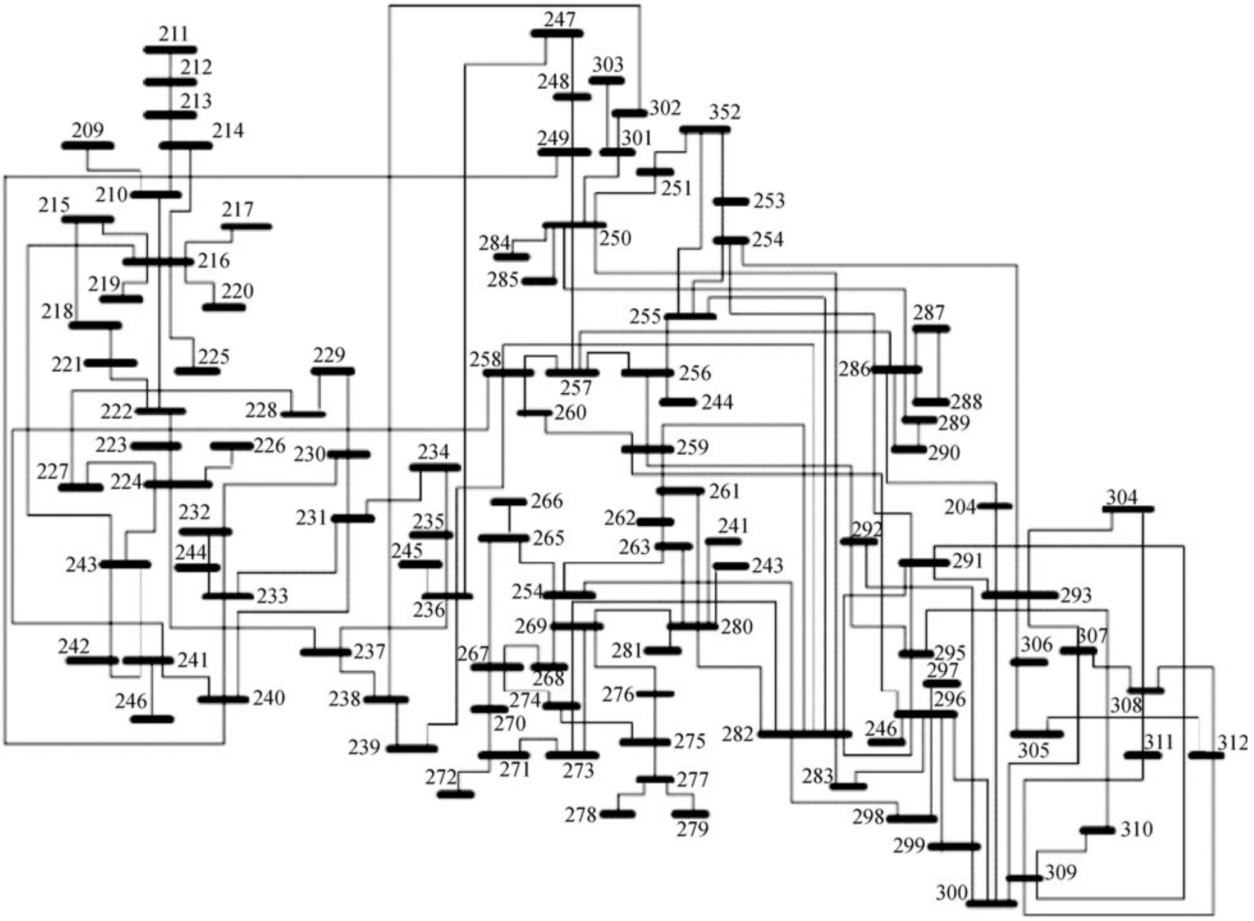

Fig. 4 Single line diagram of NRIPG

5 Results and discussion

The optimal redundant locations for PMU placement in IEEE-14 bus system and geographical locations of PMUs in the above mentioned regions are found out using ILP methodology. PMU locations for complete observability with and without depth of one-redundancy have been proposed for these regions.

5.1 IEEE standard bus system

The IEEE-14 bus system is considered in this paper as a standard case study. The single line diagram of standard IEEE-14 bus system is exhibited in Fig. 7. The buses opted for PMU placement, which result in depth of one-redundancy are bus 2, bus 4, bus 5, bus 6, bus 7, bus 8, bus 9, bus 11 and bus 13.

5.2 Regional power grids

5.2.1 NRIPG

Table 4 displays the optimal PMU locations in NRIPG for its complete observability and the complete observability with depth of one-redundancy. For better visualization of the PMU placement, the locations given in Table 4 are marked in the single line diagram of ERIPG and shown in Figs. 8 and 9, respectively.

The above results show that NRIPG requires only 27 PMUs for its complete observability and 65 PMUs for complete observability with depth of one-redundancy. The 65 PMUs in the above mentioned locations can ensure that the grid will be completely observable in the case of PMU failure or single branch outages in NRIPG.

5.2.2 ERIPG

Table 5 shows the optimal PMU locations in ERIPG for the complete observability and complete observability with depth of one redundancy. For better understanding, the locations given in Table 5 are marked in the single line diagram of ERIPG and shown in Figs. 10 and 11, respectively.

From the above results it is seen that ERIPG requires only 26 PMUs for its complete observability and 62 PMUs for its complete observability even under PMU failure or

Table 1 Bus details for NRIPG

No.	Bus name	No.	Bus name	No.	Bus name
209	Uri	244	Malerk'L	279	Udaipur
210	Wagoora	245	K.Wangtoo	280	Bhiwadi
211	Amargarh	246	Bhiwani	281	Kotputli
212	Kishenganga	247	Dehradun	282	Agra
213	Alistong	248	Saharanpur	283	Auraiya
214	Wampoh	249	Baghpat	284	Tehri
215	Salal	250	Merrut	285	Koteshwar
216	Kishenpur	251	Muzaffar Ngr	286	Bareilly
217	Dulhasti	252	Rishikesh	287	Pithorgarh
218	Jammu	253	Kashipur	288	Bhauliganga
219	Samba	254	Muradabad	289	Tanakpur
220	Udhampur	255	Murad Nagar	290	Kitchcha
221	Hiranagar	256	Dadri	291	Unnao
222	Sarna	257	Jhatikra	292	Mainpuri
223	Dasuya	258	Bawana	293	Lucknow
224	Jalandhar	259	Ballabgarh	294	Shahjahanpur
225	Chamera	260	Bamnauli	295	Panki
226	Hamirpur	261	Gurgaon	296	Kanpur
227	Amritsar	262	Manesar	297	Unchahap
228	Pooling Point	263	Neemrana	298	Fatehpur
229	Parbati	264	Sikar	299	Allahabad
230	Koldam	265	Ratangarh	300	Rihand
231	Nallagarh	266	Suratgarh	301	Bulandshahr
232	Ludhiana	267	Merta	302	Hapur
233	Patiala	268	Jaipur RSEB	303	Orai
234	N.Jhakri	269	Jaipur	304	Gorakhpur
235	Panchkulan	270	Jodhpur	305	Balia
236	Abdullapur	271	Kankroli	306	Sohawal
237	Kurukshethra	272	Bhinmal	307	Sultanpur
238	New Hissar	273	RAPP-C	308	Azamgarh
239	Sonepat	274	Kota	309	Anpara
240	Kaithal	275	Anta	310	Obra
241	Hissar	276	Dausa	311	Varanasi
242	Fatehbad	277	RAPP-B	312	Mau
243	Moga	278	Chittorg'h		

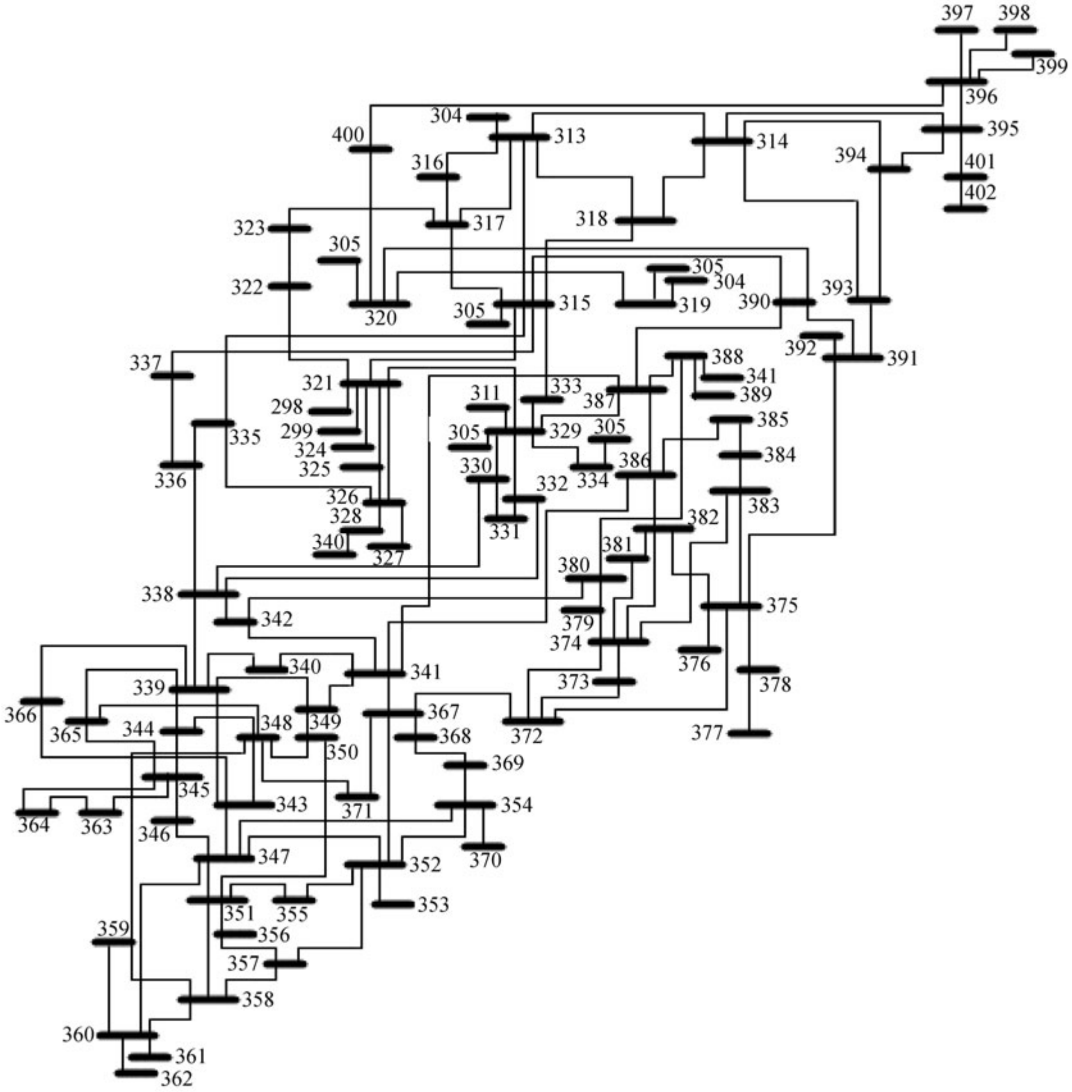

Fig. 5 Single line diagram of ERIPG

single branch outage in ERIPG with depth of one redundancy.

5.2.3 NERIPG

Table 6 presents the optimal locations in NERIPG for complete observability and complete observability with depth of one redundancy. For the better visualization, the locations portrayed in Table 6 are marked in the single line diagram of NERIPG and shown in Figs. 12(a) and 12(b), respectively.

From the above results, it is seen that NERIPG requires only 5 PMUs for its complete observability and 14 PMUs for its complete observability under the contingency of PMU failure or single branch outage in NERIPG with depth of one redundancy.

6 Inter-regional power grids

Inter-regional power grids play an important role in developing the power grid to function as a highly reliable and more efficient network. Inter-regional power grids mainly bring three benefits to the country. First, the demand for additional power generation capacity can be reduced. Next, generating stations can be placed further away from congested areas like cities. Finally, reliability of the supply can be improved with reduced chances for blackouts [24].

In this paper, various regional power grids explained in the previous sections are combined to form inter-regional power grids. NRIPG and ERIPG are combined to form the Northern and Eastern region Indian power grid (NRER-IPG), ERIPG and NERIPG are combined to form the

Table 2 Bus details for ERIPG

No.	Bus name	No.	Bus name	No.	Bus name
313	Muzaffarpur	343	Talcher STPS	373	Howrah
314	Purnea	344	Tarkeera	374	Arambag
315	BHRSHRF	345	Brajrajnagr	375	Jeerat
316	Hazipur	346	IB Valley	376	Subhasgram
317	Fatwa	347	Mera Mundli	377	LKPUR
318	Begusarai	348	Rengali	378	KASBA
319	Barh	349	Joda	379	Bisnupur
320	Patna	350	Talcher TPS	380	Santaldih
321	Sasaram	351	BHNJNGR	381	Purulia
322	Arrah	352	Chandaka	382	Bidhannagar
323	Khagaul	353	Bhubaneswar	383	Bakreswar
324	DLTNGNJ	354	Duburi	384	Gokarna
325	Karamnasa	355	Nayagarh	385	Sagardighi
326	Dehri	356	Aska	386	Durgapur
327	Nabi NGR	357	Chhatrapur	387	Maithon
328	Garwa	358	Theruvelli	388	Bokaro
329	Gaya	359	Indravati	389	Majia
330	Jharkhand PL	360	Jeypore	390	Kahalgaon
331	Ranchi	361	U.Kolab	391	Farraka
332	NKSTPP	362	Balimela	392	Lalmatia
333	Koderma	363	Hirakud	393	Malda
334	Tilaiyya	364	Bolangir	394	Dalkhola
335	Bogaya	365	Tarkera	395	Siliguri
336	Patratu	366	SNDRGRH	396	Melli
337	Tenughat	367	Baripada	397	Rangit
338	Ranchi	368	Balasore	398	Gangtok
339	Rourkela	369	Bhadrak	399	Rangpo
340	Chaibasa	370	Paradeep	400	Kishanganj
341	Jamshedpur	371	Keonjhar	401	Birpara
342	Chandil	372	Kolaghat	402	Alipurduar

Table 3 Geographical names of buses in NERIPG

No.	Bus name	No.	Bus name	No.	Bus name
403	Bongaigaon	408	Ranganadi	413	Silchar
404	BTPS	409	Subansiri	414	Imphal
405	Balipara	410	Misa	415	Melriat
406	Khupi	411	Kathalguri	416	Pallatana
407	B. Chariali	412	Mariani		

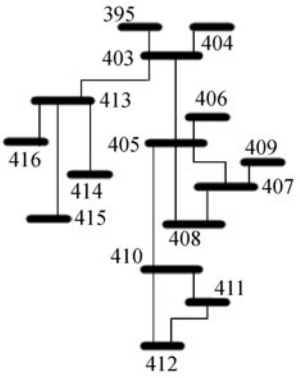

Fig. 6 Single line diagram of NERIPG

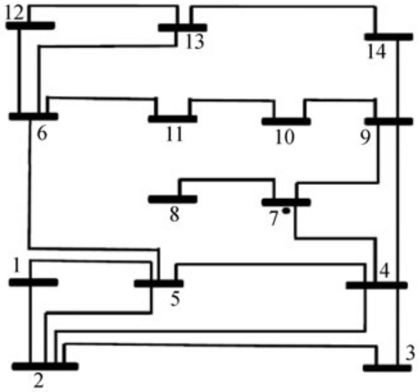

Fig. 7 Standard IEEE-14 bus system

Table 4 Optimal PMU locations in NRIPG

Sl	Cases	PMU locations
1	Complete observability	210, 212, 216, 221, 224, 228, 231, 236, 238, 243, 244, 249, 250, 252, 259, 263, 265, 269, 271, 277,280, 286, 293, 296, 301, 309, 312
2	Complete observability with depth of one redundancy	209, 210, 211, 212, 214, 216, 217, 218, 219, 220, 221, 223, 224, 225, 226, 228, 229, 231, 233, 235, 236, 239, 241, 243, 244, 245, 248, 249, 250, 252, 253, 259, 260, 262, 263, 265, 266, 267, 269, 271, 272, 276, 277, 278, 279, 280, 281, 282, 284, 285, 286, 288, 290, 293, 296, 297, 299, 301, 302, 303, 306, 308, 309, 310, 312

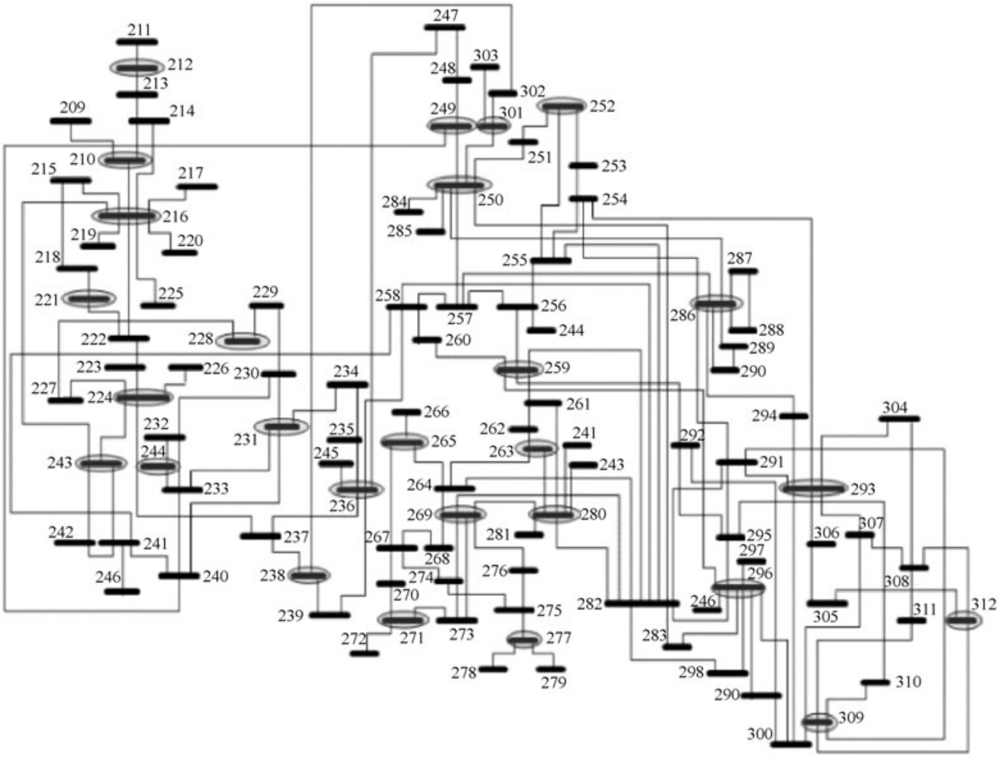

Fig. 8 Optimal PMU locations for complete observability of NRIPG

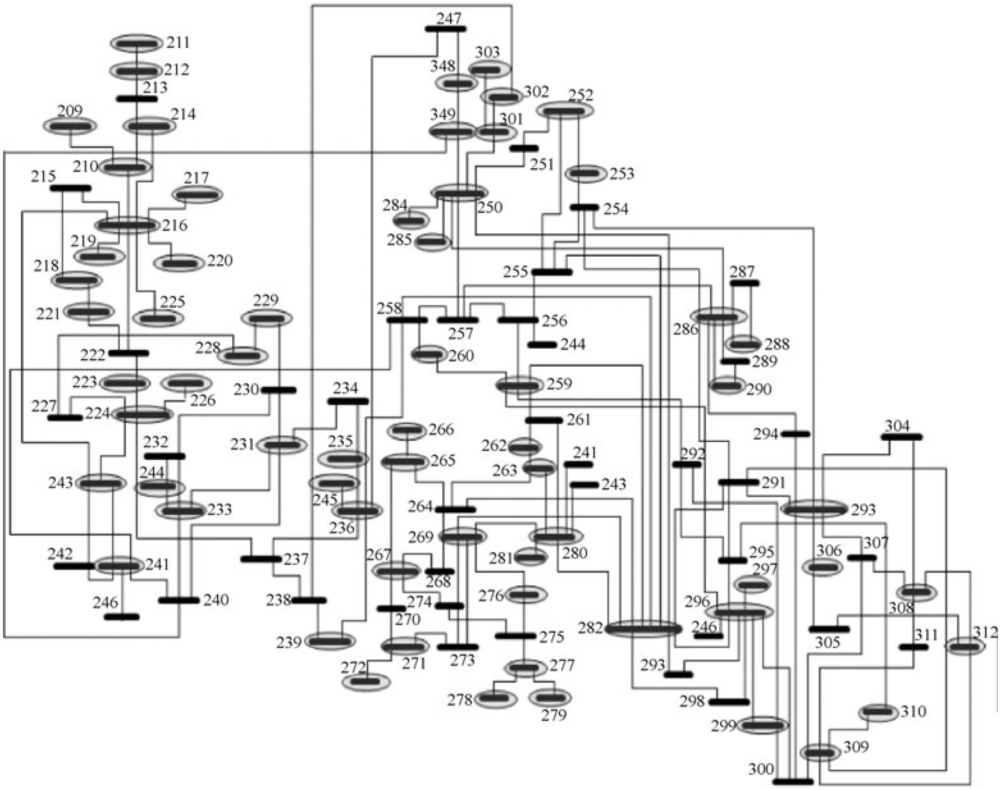

Fig. 9 Optimal PMU locations for complete observability with depth of one redundancy of NRIPG

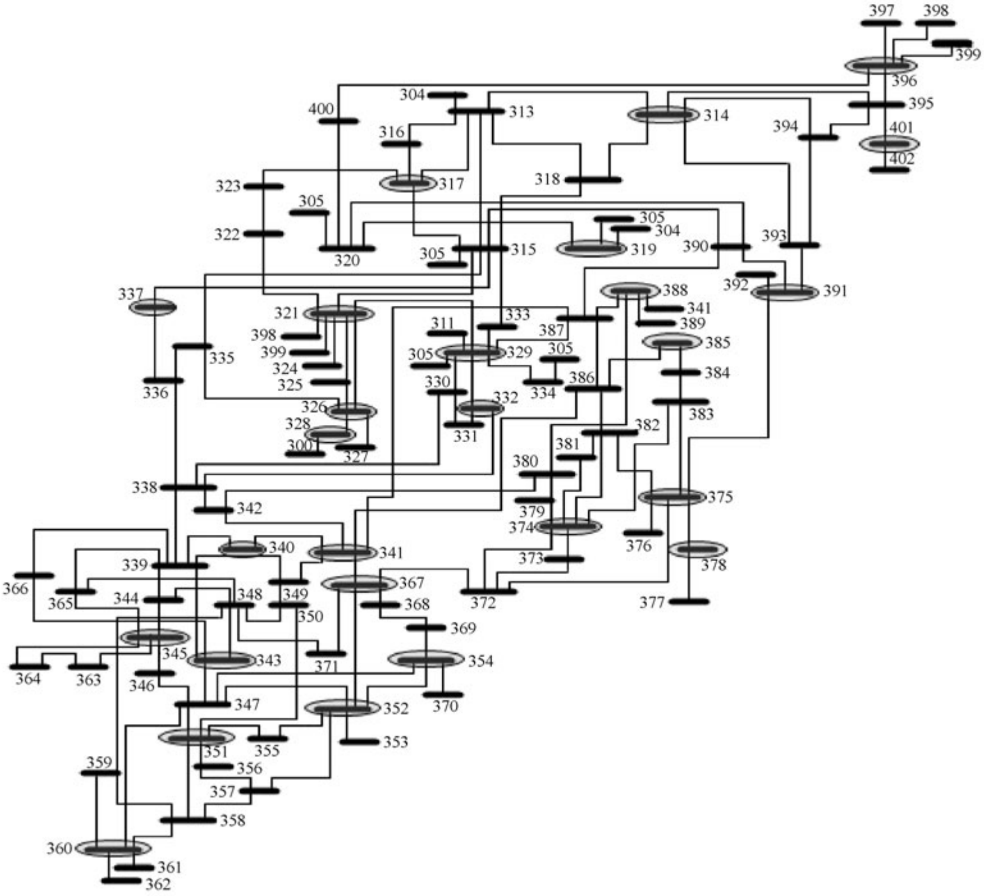

Fig. 10 Optimal PMU locations for complete observability of ERIPG

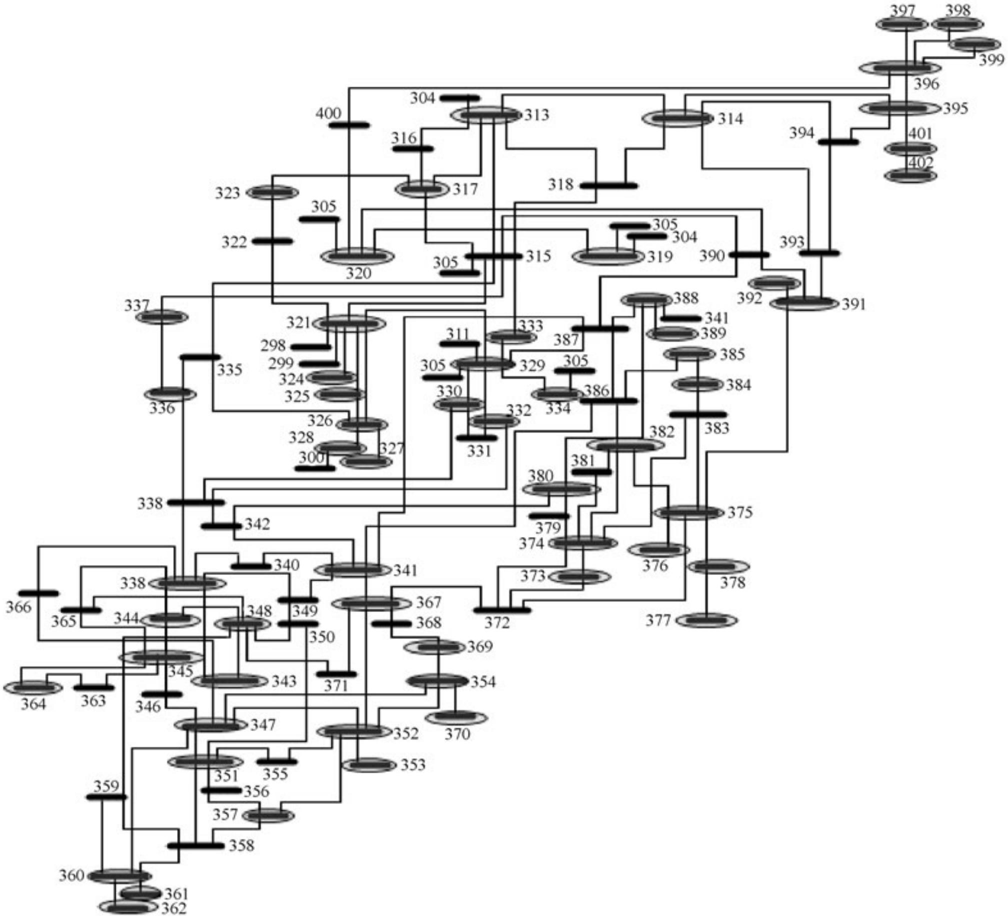

Fig. 11 Optimal PMU locations for complete observability with depth of one redundancy of ERIPG

Table 5 Optimal PMU locations in ERIPG

Sl	Cases	PMU locations
1	Complete observability	314, 317, 319, 321, 326, 328, 329, 332, 337, 340, 341, 343, 345, 351, 352, 354, 360, 367, 374, 375, 378, 385, 388, 391,396, 401
2	Complete observability with redundancy	313, 314, 317, 319, 320, 321, 323, 324, 325, 326, 327, 328, 329, 330, 332, 333, 334, 336, 337, 339, 341, 343, 344, 345, 347, 348, 351, 352, 353, 354, 357, 360, 361, 362, 364, 367, 369, 370, 373, 374,375, 376, 377, 378, 380, 382, 384, 385, 388, 389, 391, 392, 395, 396, 397, 398, 399, 401, 402, 405,406, 407

Table 6 Optimal PMU locations in NERIPG

Sl	Cases	PMU locations
1	Complete observability	403, 405, 407, 410, 413
2	Complete observability with redundancy	403, 404, 405, 406, 407, 408, 409, 411, 412, 413, 414, 415, 416, 416

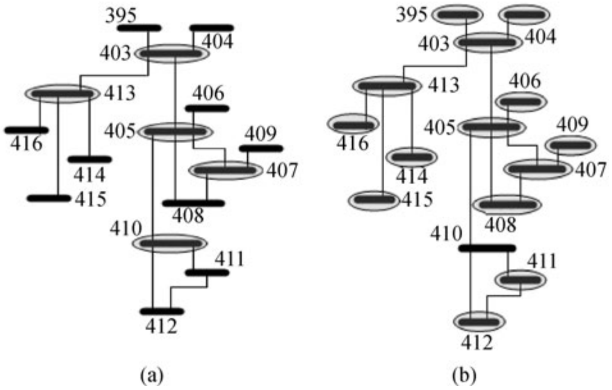

Fig. 12 Optimal PMU locations for NERIPG
(a) Complete observability; (b) complete observability with depth of one redundancy

Table 7 Number of PMUs for various inter regional power grids

Sl	Test system	Total number of buses	Complete observability	Complete observability with redundancy
1	NRERIPG	194	42	119
2	ERNERIPG	104	28	74
3	NRNERIPG	128	32	79
4	NRERNERIPG	208	56	135

Eastern and North-eastern region Indian power grid (ERNERIPG), and NRIPG and NERIPG are combined to form the Northern and North-eastern region Indian power grid (NRNERIPG). The total number of buses and required number of PMUs are given in Table 7.

The power grid of the three regions is combined to form the Northern region Eastern region North-eastern region Indian power grid (NRERNERIPG). The optimal PMU locations for complete observability and the complete observability with depth of one-redundancy are marked in Figs. 13 and 14, respectively and corresponding bus numbers are given in Table 8. For higher depths of redundancy, the number of PMUs required will increase and may exceed the total number of buses in the system. So in this paper, only up to depth of one-redundancy has been considered.

7 Savings after optimal PMU placement

In normal PMU placement, the PMUs have to be installed in all the buses in the grid. In optimal PMU placement, the PMUs are placed in selected buses so that with minimum number of PMUs, the grid will be observable. Figure 15 shows the total number of buses and the number of PMUs required for the complete observability with and without depth of one-redundancy for various regional power grids. Figure 16 depicts those for the inter-regional power grids. Considering the case of NRIPG, only 27 PMUs are required for the complete observability of 104 buses in the grid. However, in normal PMU placement, as many as 104 PMUs have to be installed. If per unit cost of PMU is assumed to be USD 30,000, the total PMU cost for normal PMU placement will amount to USD 3.12 million. However, with optimal PMU placement, the total PMU cost is reduced to USD 0.81 million. So the cost savings after optimal PMU placement is USD 2.31 million or 74% of the total PMU cost in normal PMU placement. The total PMU cost for optimal placement with depth of one-redundancy is USD 1.95 million and the savings in the PMU cost is 37.5% of the total PMU cost in normal placement. The total PMU cost for normal PMU placement, optimal PMU placement and optimal PMU placement with depth of one-redundancy are given in Table 9. Figure 17 illustrates the percentage savings in the total PMU cost with optimal PMU placement with and without depth of one-redundancy for various grids discussed in previous sections.

8 Conclusions

The vital requirement of SG is that it should be completely observable, which can be achieved through incorporation of PMUs in the existing power grid. In this paper, the optimal geographical locations of PMUs are proposed for the complete observability of the NRIPG, ERIPG and NERIPG of the Indian power grid. The PMUs installed in the proposed locations not only make the grid completely observable, but also maintain the observability under

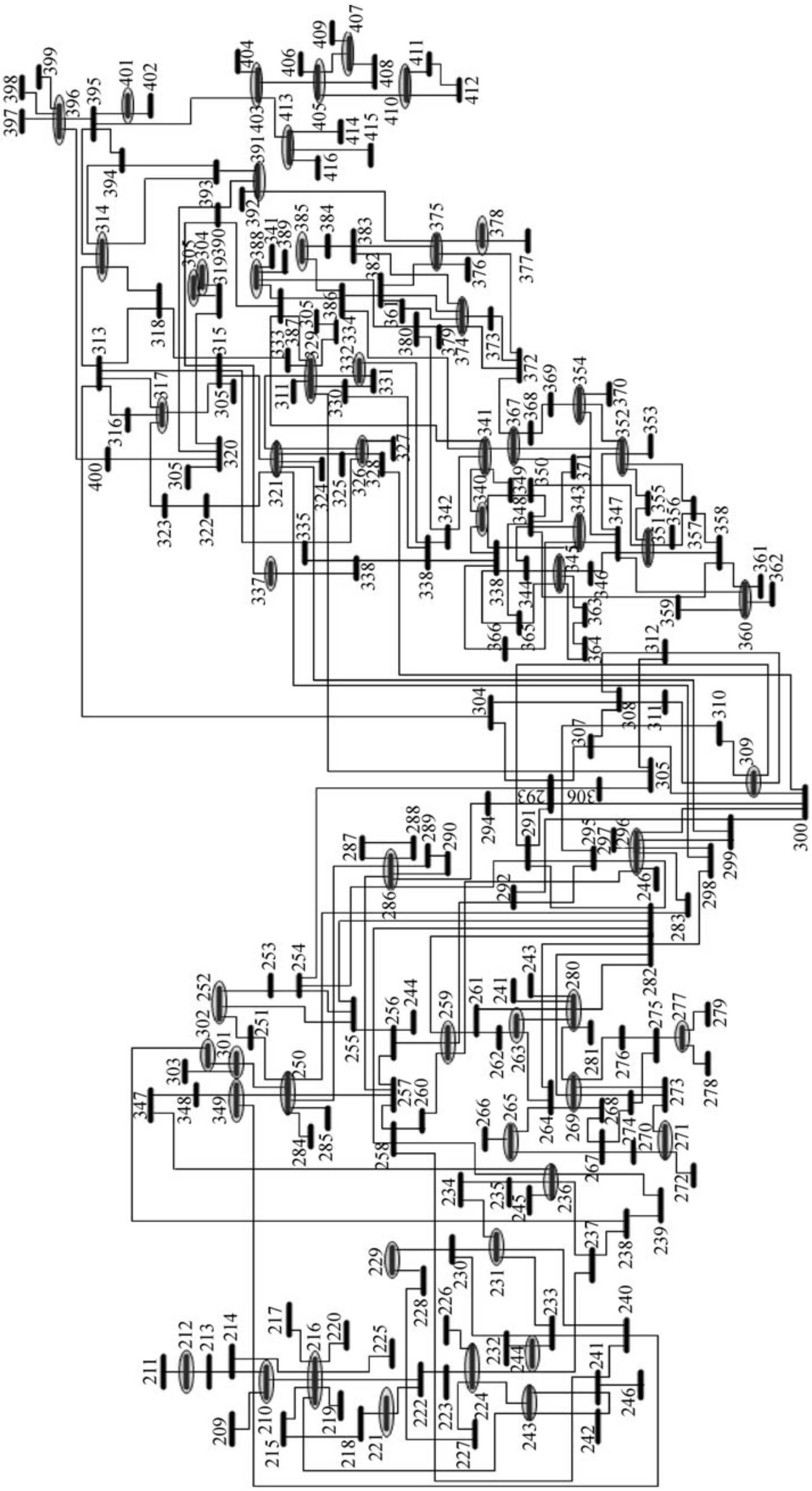

Fig. 13 Optimal PMU locations for complete observability of NRERNERIPG

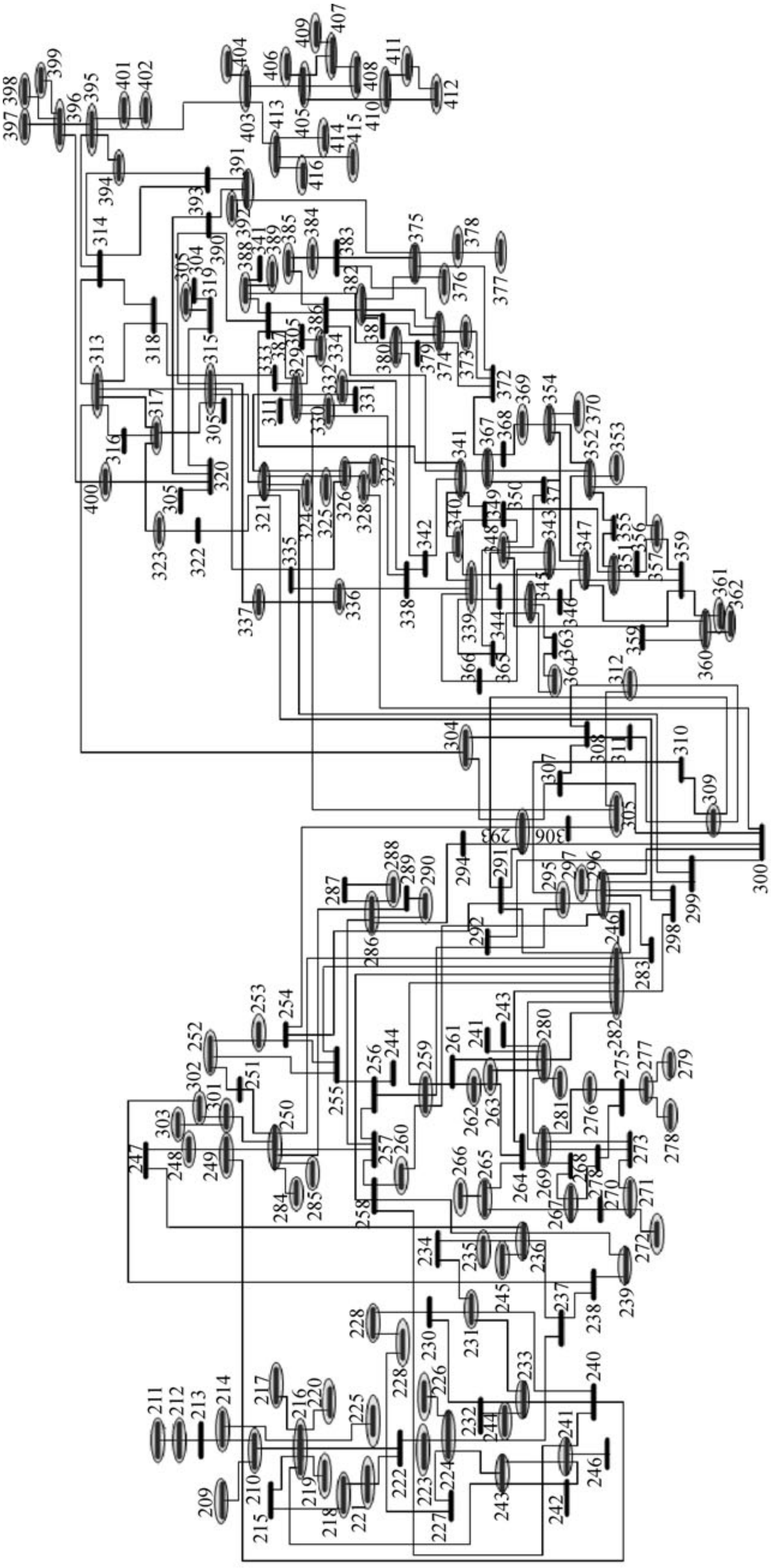

Fig. 14 Optimal PMU locations for complete observability with depth of one redundancy of NRERNERIPG

Table 8 Optimal PMU locations in NRERNERIPG

Sl	Cases	PMU locations
1	Complete observability	210, 212, 216, 221, 224, 229, 231, 236, 243, 244,249,250, 252, 259, 263, 265, 269, 271, 277, 280,286, 296, 301, 302, 304, 305, 309, 314, 317, 321, 326, 329, 332, 337, 340, 341, 343, 345, 351, 352, 354, 360, 367, 374, 375, 378, 385, 388, 391, 396, 401, 403, 405, 407, 410, 413
2	Complete observability with redundancy	209, 210, 211, 212, 214, 216, 217, 218, 219, 220, 221, 223, 224, 225, 226, 228, 229, 231, 233, 235, 236, 239, 241, 243, 244, 245, 248, 249, 250, 252, 253, 259, 260, 262, 263, 265, 266, 267, 269, 271, 272, 276, 277, 278, 279, 280, 281, 282, 284, 285, 286, 288, 290, 293, 295, 296, 297, 301, 302, 303, 304, 305, 309, 312, 313, 315, 317, 321, 323, 324, 325, 326, 327, 328, 329, 330, 332, 334, 336, 337,339, 340, 341, 343, 345, 347, 348, 351, 352, 353, 354, 357, 360, 361, 362, 364, 367, 369, 370, 373, 374, 375, 376, 377, 378, 380, 382, 384, 385, 388, 389, 391, 392, 394, 395, 396, 397, 398, 399, 400,401, 402, 403, 404, 405, 406, 407, 408, 409, 411, 412, 413, 414, 415, 416

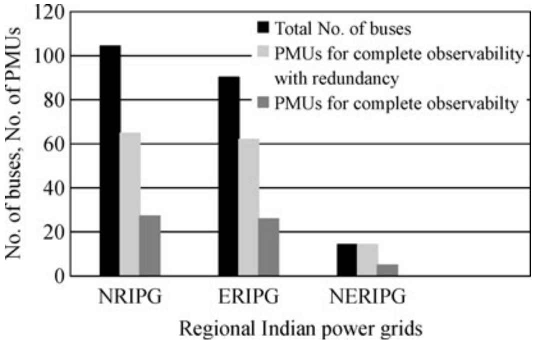

Fig. 15 Number of PMUs in various regional power grids

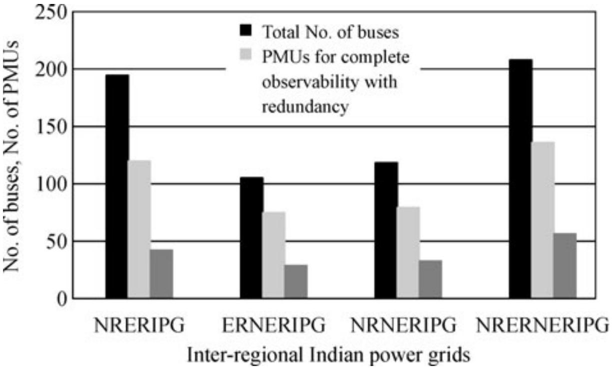

Fig. 16 Number of PMUs in various inter-regional power grids

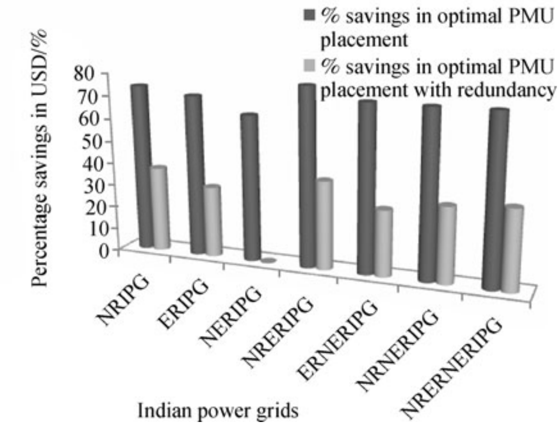

Fig. 17 Percentage savings after optimal PMU placement in various power grids

contingencies like PMU failures or branch outages. The contingency considered in this paper is single PMU failure or single branch outage. But the method can be extended to any number of contingencies, if the cost of additional PMUs is financially acceptable. From the results it has been seen that 73% of the total PMU cost can be saved by optimal PMU placement for the complete observability of combined NRIPG, ERIPG and NERIPG compared to the cost for PMU placement in each bus. Similarly 35% can be saved with optimal placement for complete observability with depth of one-redundancy.

Table 9 Total PMU cost for various Indian power grids Unit: 10^6 USD

Sl	Test system	Normal PMU placement	Optimal placement	Optimal placement with depth of one-redundancy
1	NRIPG	3.12	0.81	1.95
2	ERIPG	2.7	0.78	1.86
3	NERIPG	0.42	0.15	0.42
4	NRERIPG	5.82	1.26	3.57
5	ERNERIPG	3.12	0.84	2.22
6	NRNERIPG	3.54	0.96	2.37
7	NRERNERIPG	6.24	1.68	4.05

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