TIE-LINE MODELLING IN INTERCONNECTED SYNCHROPHASOR NETWORK FOR MONITORING GRID OBSERVABILITY, CYBER INTRUSION AND RELIABILITY

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Abstract:

The incorporation of a tie-line between two areas may be beneficial in two ways. First, the reserve capacity of the assisting area support to the assisted area, and second, the number of Phasor Measurement Unit (PMU) requirements will become smaller for complete observability of the interconnected grid. The objective function is formulated to integrate the observability and reliability analysis for the two interconnected synchrophasor networks. The effect of Zero Injection Bus (ZIB) is included in the observability constraints to reduce the number of PMUs deployed in the system. The number of optimal PMU deployments will be greater for two interconnected systems in comparison with a single area. Therefore, interconnected systems become more vulnerable to cyber risk. The paper discusses the cumulative analysis of system observability and reliability during an anomaly situation that occurs with a PMU device due to a cyber-attack. The reliability indices Interconnected System Load Interruption Probability (ISLIP) and Interconnected System Demand Not Supplied (ISDNS) are evaluated when an anomaly occurs with optimally deployed PMU in the network by including and excluding the effect of ZIB. By doing so, the most reliable location for PMU deployment can be obtained for both the area. Reliability Test System (RTS)-24 bus is used for each area to modify the test system by incorporating tie-lines between them.

1 Introduction

Monitoring the reliability of power systems is becoming an increasingly adaptive field with the advancement of synchrophasor interconnected grid systems. Therefore, research is conducted to obtain reliable scenarios of the interconnected grid by observing the cyber intrusion with measuring devices. The introduction has three points: Aim and Motivation, Background and Contribution to present the research carried out for the paper.

1.1 Aim and motivation

The interconnected synchrophasor network is beneficial for improving reliability and reducing the number of PMU requirements for complete observability of the grid network. Due to the incorporation of tie-line between two areas of interconnection, the observability of the network can be achieved with a lower number of PMUs. Therefore, the network becomes less vulnerable to cyber-attack. It may offer a more reliable network when an anomaly occurs with PMU devices. The interconnected system is widely used for exchanging the reserve capacity of one area to another area [1]. Therefore, the risk level can be reduced for the interconnected system by transferring reserve capacity from one area to another through tie-line. If the number of tie-lines between two areas is increased, the transfer capability of the tie-lines also increases, which causes more capacity to be transferred to the assisted area. This will result in a more reliable interconnected network [2]. The number of

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PMU requirements will be reduced by adding the tie-line or including the effect of ZIB. Cyber-attacks occur on measuring devices such as PMUs, which affect the system's reliability and observability. Therefore, the modelling of interconnected systems becomes a more focused field for analysis of reliability, cyber intrusion, and observability [3]. The incorporation of tie-line is advantageous to improve system reliability and, simultaneously, reduce the number of PMU requirements for complete observation of the interconnected grid. The motivation of this paper's analysis is to study the cumulative effect of observability, cyber intrusion, and reliability by adding the tie-line in several step sizes [4]. The power network's effectiveness and long-term sustainability have been enhanced by the integration of smart infrastructures that enable two-way communication via information and communication technology (ICT). Network failures, cyber–physical interrelations, and cyber intrusions are all disadvantages of technologies like dynamic thermal rating (DTR) systems and system integrity protection strategies (SIPS). These drawbacks lead to the network's decreased reliability. This study presents a DTR and SIPS system that integrates wide-area monitoring functions utilising PMUs, as well as the impact of ICT disruptions on network reliability [5]. The transfer of synchrophasor data between geographically separated PMUs and phasor data concentrators (PDCs) can be made easier with wireless communications. Moreover, modern communication systems may cause PMU channels to experience random access delays and interruptions, resulting in missing synchrophasor data frames at the PDC's output. A novel method for assessing and improving the reliability of synchrophasor data is presented [6]. The two-state reliability model, which has been additionally superimposed with the generation models of renewable sources, was used to assess the adequacy of independent systems with integrated generating sources. The IEEE-RTS has been used to model demand, common reliability indices, and system availability margins [7].

1.2 Backgrounds

Initially, a pilot project initiative has been started by Power System Operation Corporation (POSOCO) with the objective of deploying the measurement devices in the Northern Region (NR) of India. The objective of this project was focusing on the real-time observation of the operating grid. India has five regions with power grids serving the corresponding regional grids, namely the northern, eastern, southern, western, and north-east regions [8, 9]. All the regional grids were operating individually until the 1990s, but with the time changes, the interconnection between the grids was formed to make a central grid operating at a single frequency. In December 2013, one of the remaining (southern) grids was connected to the central grid (formed by the interconnection of the remaining four regional grids) by deploying the synchrophasor measurements devices in the overall system to form one nation, one grid, and one frequency [10]. The pilot project initiative was extended to install the PMU devices in all the specified regions to get real-time observation of the interconnected grid [11]. Figure 1 shows the geographical distribution of PMU devices deployed by a pilot project on the Indian power grid.

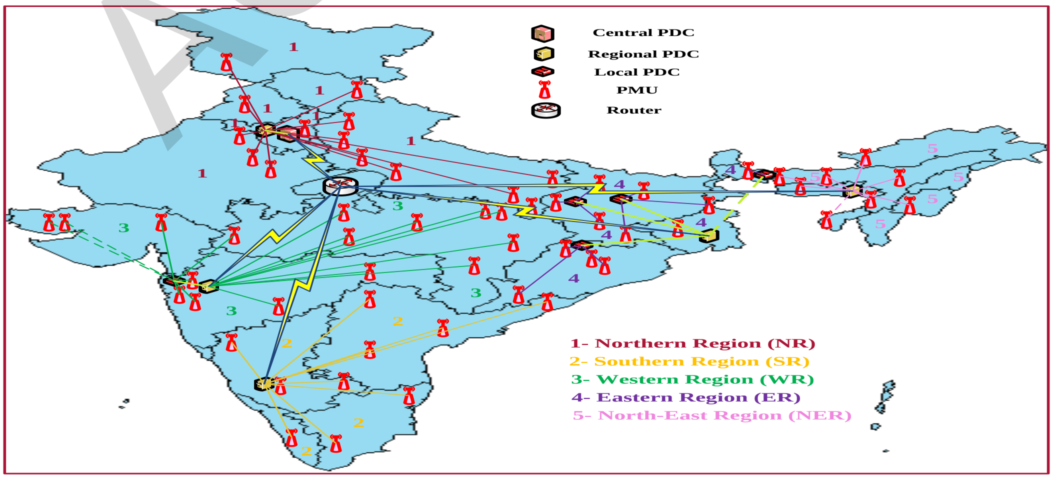

Figure 1: Geographical deployment of PMUs across different region of Indian power grid.

For multi-area interconnected power systems, monitoring the revolutionary frequency regulation paradigm, and reliability are major studies for large power networks. To address design restrictions imposed by conventional supervisory control and data acquisition (SCADA) systems, the suggested technique takes advantage of PMUs to improve monitoring. A unique measurement-based controller that integrates primary and secondary regulation is presented to accomplish this. First, utilising dynamic data acquisition and the synchronised measurements of PMUs, unique centralised corrective measures are established [12]. Several research studies on the interconnected power system reliability have been conducted in the past to determine the reliable status of the assisted area. The optimal allocation of PMU devices is also explained in several research papers [13-15]. This paper includes the gap research of combining the two areas with tie-line and deploying the PMU devices in interconnected networks to form a synchrophasor network. In this way, the effective deployment of PMU devices is reduced and the system is protected from highly vulnerable cyber risks. The paper goes into detail the impact of incorporating a tie-line between two regional areas on the reliability, observability, and cyber risk of an interconnected synchrophasor grid. Table 1 provides a taxonomy of several research papers analysing the effects of the interconnected grid, synchrophasor network observability, cyber risk with PMU devices, and power system reliability.

Table 1: Taxonomy of various research contributing to specified research area.

Research area	**Contributions to research study**	**References**
Interconnected smart grid network	• A review of energy management in interconnected multi-microgrids is discussed, along with schedule optimization.	[16]
	• Computing the composite system reliability assessment of interconnected networks based on contingency, energy balance study of various zones, taking into account consumer demand, generation and transmission capability.	[17]
	• A hybrid algorithm to enumerate the transmission and generation states of an interconnected system to evaluate the composite system's reliability. It has been tested for assessing the reliability of the Unified Egyptian Power System.	[18]
	• Hypothesized cyber-attack impact on interconnected grid network for mid and long term.	[19]
Synchrophasor Grid observability/ Cyber risk	• Modelling of zero injection bus is presented to optimize the number of PMU in the network for full observability. The set for the bus is created to observe the objective.	[20]
	• A novel linear framework is modelled for observability of network considering the effect of adjacent zero injection bus.	[21]
	• Self-healing PMU network exploiting dynamic and programmable configuration in software to achieve resiliency against the cyber intrusion.	[22]
	• A strategic PMU deployment method is elaborating the reduction in cyber vulnerability of power network subjected to cyber-attack.	[23]
Power grid reliability	• A novel coalitional based cyber insurance design is discusses the estimation of insurance by considering the reliability analysis of power system and cyber risk modelling.	[24]
	• A review on power system reliability is specified by integrating the impact of information and communication technology.	[25]
	• The minimal cut set approach is discussed to evaluate the reliability of composite power system. The test is performed on IEEE RTS-96 system.	[26]
	• Universal generating function reliability model is discussing the impact of different components on power system reliability.	[27]

1.3 Contribution

The paper integrates the cumulative study of observability and reliability for two areas of interconnected synchrophasor networks with the inclusion and exclusion of ZIB characteristics. The Reliability Test System (RTS) is used for both the area and interconnection by incorporating four tie-lines between them. The paper's contribution is classified into two subsections of the study as follows:

- **Interconnected synchrophasor grid observability:** The observability terms are used for measuring devices such as the PMU to measure real-time grid data. The PMU will measure the real time data of each bus connected to it. The interconnected synchrophasor network may reduce the required number of PMUs due to the incorporation of tie-lines between them. Interconnected system observability is obtained by deploying the optimal number of PMUs on the test system buses by including and excluding the effect of ZIB. The objective function is modelled with several constraints to achieve the observability of the grid network. The requirements for the number of PMU and their installation position are obtained by incorporating additional tie-lines to improve the reliability of the interconnected system. As a result, increasing the number of tie-lines may reduce the number of PMUs required in the network for complete observability. The effect of a cyber-attack that occurs with PMU devices is also discussed. To maintain the complete observability of the network, the backup PMU is deployed in the synchrophasor grid.
- **Interconnected synchrophasor grid reliability:** The reliability of an interconnected synchrophasor network is discussed with several indices such as ISLIP and ISDNS to compute the reliability of the network during anomalies. The interconnected system becomes more reliable due to the exchange of power from one area to another. Therefore, the reliability of the synchrophasor network is modelled for the assisted and assisting areas by including the state probability of the tie-line and PMU. The most reliable bus for deploying the PMU is obtained when an anomaly occurs with several optimally allocated PMUs in the network. The reliability indices result in the most reliable PMU deployed bus in the network during a cyber-attack by excluding and including the characteristics of ZIB.

The whole paper is systemized as follows: Section 2 explains the methodology for modelling the objective function and its constraints for analysing the observability and reliability of interconnected grid networks. Section 3 gives brief details about the case study. The test system consists of two-area interconnection of the RTS 24-bus system by incorporating tie-lines between them. Section 4 discusses the results and simulation part of the paper, which includes the observability and reliability analysis of interconnected systems during anomaly events with PMU devices with and without considering the effect of ZIB. Section 5 shows the concluding remarks of the whole paper contribution, followed by references.

2 Methodology

The inclusion of tie-lines between two areas of interconnection is more favourable for improving grid reliability and observability. The assisting area reduces the risk level of the assisted area by exchanging the reserve power between them. The characteristics of the area might change according to the peak load demand of the individual area. This means an area might be an assisting area or assisted area by observing the peak load demand and reserve capacity of the corresponding area. Therefore, reliability becomes a more important issue when two or more areas are interconnected. This paper presents a model for the combined effect of observability and reliability for interconnected synchrophasor networks. The objective function is to determine the optimal number of PMUs installed across the system buses to fulfil the complete observability of the network, along with the optimization of load interruption in the interconnected grid [28, 29]. Equation (1) is a mathematical objective function used to calculate the complete observability and reliability of the RTS-24 bus synchrophasor network's two-area interconnection. The objective function is subjected to several equality and inequality constraints for observability and reliability. The observability constraints are shown in equation (2), which results in the complete observation of the interconnected network. By including the ZIB in the system, the number of PMUs required for the network can be reduced. Equation (3) is a mathematical formulation to considering the effect of ZIB on the network. Equation (4) represents the state of a PMU installation at a particular bus. Equation (5) is a mathematical formulation to obtain the entities of the connectivity matrix.

Equation (6) is a mathematical model to obtain the entities of the connectivity matrix resulting from tie-line interconnection. The result is that the entity is zero if there is no interconnection of tie-line between a bus from area-1 and another bus from area-2; otherwise, entities will be one. The reliability constraints are formulated as shown in equation (7-10). The power flow constraints result in the optimum solution for load interruption during load flow analysis[30]. The optimum value of load interruption is used to evaluate the reliability parameter of the interconnected synchrophasor network.

$$Min \quad \sum_{b=1}^{Nb} Pm_b + \sum_{b=1}^{Nb} LI_b \tag{1}$$

Interconnected network observability constraint is subjected to-

$$O_b \geq 1 \quad \forall b \in B$$

$$O_b = \sum_{i=1}^{Nb} a_{bi} * Pm_i + \sum_{i=1}^{Nb} a_{bi} * y_{bi} + \sum_{i=1}^{Nb} t_{bi} * y_{bi} \quad \forall b \in B \tag{2}$$

$$\sum_{b=1}^{Nb} y_{bi} = \begin{cases} 1, & If \;\; bus \;\; i \;\; is \;\; ZIB \\ 0, & otherwise \end{cases} \tag{3}$$

Where,

$$Pm_b = \begin{cases} 1, & If \; a \; PMU \; is \; installed \;\; at \;\; bus\, b \\ 0, & Otherwise \end{cases} \tag{4}$$

$$a_{bi} = \begin{cases} 1, & If \; b = i \\ 1, & If \; bus\, b \;\; and \; bus \; i \;\; are \;\; connected \\ 0, & Otherwise \end{cases} \tag{5}$$

$$t_{bi} = \begin{cases} 1, & If \; b = i \\ 1, & If \;\; bus\, b \;\; and \; bus \;\; i \;\; are \;\; connected \;\; through\, tie-line \\ 0, & Otherwise \end{cases} \tag{6}$$

Power flow constraints for obtaining load interruption is subjected to-

$$\delta_b^{\min} \leq \delta_b \leq \delta_b^{\max} \qquad \forall b \in B$$

$$P_{gc}^{\min} \leq P_{gc} \leq P_{gc}^{\max} \qquad \forall gc \in GC$$

$$-LF_{tr}^{\min} * \xi_{tr} \leq LF_{tr} \leq LF_{tr}^{\max} * \xi_{tr} \qquad \forall tr \in TR$$

$$0 \leq LI_b \leq LD_b$$

$$\sum_{b \in B} CM_{b,gc} * P_{gc} - \sum_{tr \in TR} IM_{b,tr} * LF_{tr} = LD_b - LI_b \qquad \forall b \in B \tag{7}$$

$$\sum_{b \in B} IM_{b,tr} * B_{tr} * \delta_b - LF_{tr} + \left(1 - \xi_{tr}\right) * \Omega \geq 0 \tag{8}$$

$$\sum_{b\in B} IM_{b,tr} * B_{tr} * \delta_b - LF_{tr} - (1-\xi_{tr}) * \Omega \le 0 \tag{9}$$

$$\sum_{tr\in TR} (1-\xi_{tr}) \le \lambda^{\max} \tag{10}$$

$$\xi_{tr} \in \{0,1\} \qquad tr \in TR$$

2.1 Synchrophasor interconnected network observability by incorporating tie-line and considering the effect of ZIB

The voltage phasor of a bus and the current phasor of a transmission line connected to this bus are correctly measured by a PMU installed on this particular bus. The PMU installed on a specified bus can measure all the states of the bus directly, and it can also measure the other bus states connected to this specified bus indirectly. The states of a particular bus are specified by the voltage magnitude and angle phasor of the bus. An interconnected synchrophasor network is said to be fully observable if all the states of the network are known or measured by PMU directly or indirectly. By incorporating the effect of ZIB into the network, the number of PMU requirements may be reduced because a ZIB is indirectly observable by applying Kirchhoff's Current Law (KCL) to the bus [20]. If the voltage on all the buses connected to ZIB is known, then the unknown voltage on ZIB is obtained by applying KCL at the ZIB node. Figure 2 shows the effect of tie-line and ZIB in the interconnected grid to obtain the topological observability of the network. The following concluding remarks can be pointed out from the observation by incorporating tie-line and ZIB into the network:

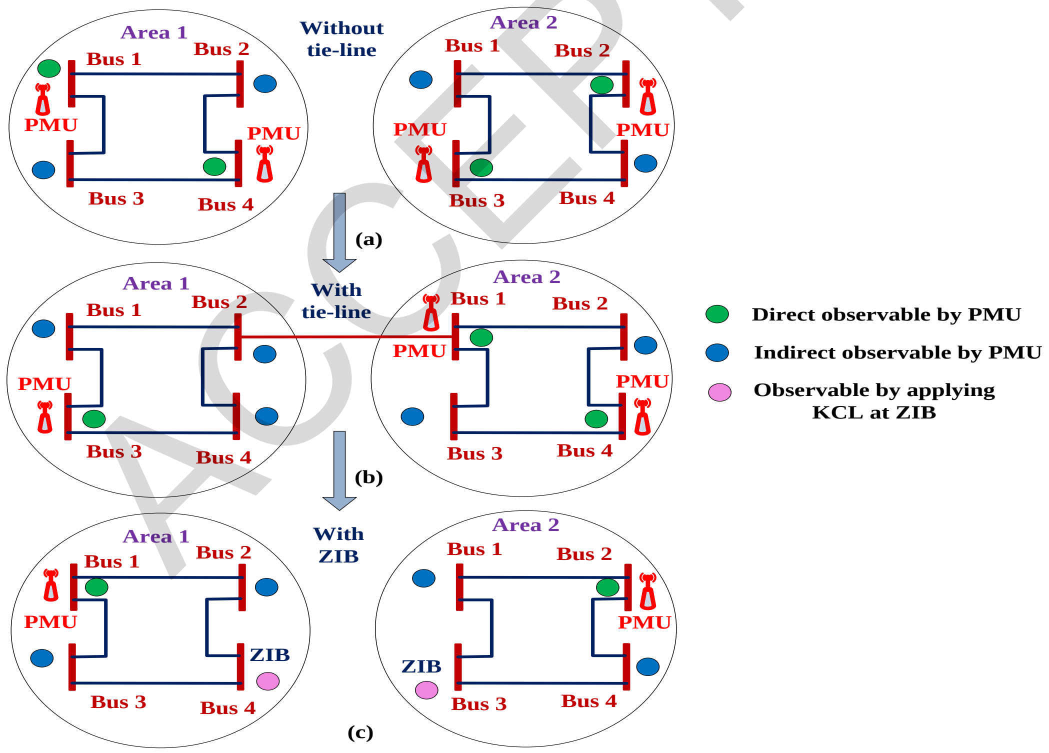

Figure 2: Effect of tie-line and ZIB in interconnected system for topological observability of synchrophasor power grid using PMUs.

i. From Figure 2(a), area-1 and area-2 are independent, and there is no interconnection between these two areas. There is no ZIB in either of the areas. Now, four PMU are required to obtain the complete observability of both areas. Suppose in area-1, a PMU is placed at bus-1, then it can directly measure the bus-1 states and indirectly measure the bus-2 and bus-3 states because of its interconnection with bus-1. Now, one extra PMU is required to measure the states of bus-4 for complete observability of area-1. Similarly, two PMUs are required to measure all the states of area-2 for complete observation. Therefore, four PMUs are required to complete the observability of both areas.

ii. From Figure 2(b), a tie-line is incorporated between bus-2 of area-1 and bus-1 of area-2. By doing so, the number of PMU requirements is now three to complete the observability of both areas. By placing one PMU at bus-3 in area-1, it can measure the states of buses 3, 1, and 4 directly or indirectly. Bus-2 of area-1 is indirectly observable from the PMU deployed at bus-1 of area-2 due to tie-line interconnection. Now, area-2 is observable by deploying PMU at bus-1 and bus-4. The two areas are observable by three PMU by incorporating a tie-line between the two areas of interconnection. Therefore, the conclusion is that the number of PMU requirements can be reduced by incorporating the tie-line between two areas of interconnection.

iii. From Figure 2(c), the bus-4 of area-1 and the bus-3 of area-2 are taken as ZIB. If a PMU is placed on bus-1 in area-1, it can observe buses 1, 2, and 3 directly or indirectly. As bus-4 is ZIB, the state of bus-4 can be measured by applying KCL at ZIB, as the voltage of all the other connected buses is measured or known. Therefore, only one PMU is required to complete the observability of area-1. Similarly, one PMU is also required to complete the observability of area-2. By doing so, both the areas are observable by deploying two PMU. This will conclude that by including the effect of ZIB in the network, the number of PMU can be reduced.

2.2 Reliability parameter formulation for interconnected synchrophasor grid during anomaly occurs with PMU devices due to cyber-attack

The interconnected system is advantageous in many aspects, such as improving reliability and observability of the grid network. The incorporation of tie-lines between two areas of interconnection is mainly used for the transfer of reserved capacity from one area to another. By doing so, the system's risk level can be reduced by observing the same loading pattern in the assisted area [31]. To obtain the equivalent assisting capacity states for the assisted area, the assisting area and tie-line individual probability are convolved to each other. The inclusion of cyber-attacks into the system may lead to unhealthy operation of the PMU. Therefore, the reliability of the synchrophasor grid is formulated for such anomalous conditions. The reliability parameters Interconnected System Load Interruption Probability (ISLIP) and Interconnected System Demand Not Supplied (ISDNS) are evaluated to identify the most affected PMU or to identify the most reliable buses to place the PMU during a cyber-attack [32]. The PMU and tie-line states probability model is for obtaining the reliability of the network during such abnormalities. Equation (11-12) represents the mathematical formula for evaluation of reliability indices during anomaly situations.

$$ISLIP_T^{Cy} = \left(\sum_{LI \neq 0} \Pr_i^{IA} \, \Theta \, \Pr_i^{CTA} \right) * \left(\sum_{EPR \neq 0} \Pr_{st}^{pmu} + \sum_{NTO \neq 0} \Pr_{st}^{Tie} \right) \tag{11}$$

$$ISDNS_T^{Cy} = \left(\sum_{\substack{b \in B \\ c \in C}} LI_b * (\Pr_i^{IA} \, \Theta \, \Pr_i^{CTA}) * SR_{tr} \right) * \left(\sum_{p \in P} \Pr_{st}^{pmu} * EPR_n + \sum_{te \in TE} \Pr_{st}^{Tie} * NTO \right) \tag{12}$$

2.3 Impact of cyber-attack in modelling of synchrophasor smart grid network

The synchrophasor measurements system's technological advancement is incorporating cyber security research for its healthy operation. There are several cyber-attacks, such as Distributed Denial of Service (DDoS) and Man-in-The-Middle (MITM) attacks, which can modify the operating data of PMU or damage the PMU operations. Therefore, a novel approach to deploying backup PMU is discussed to maintain the observability and reliability of the interconnected synchrophasor network [33]. The backup allocation of PMU is based on the abnormality characteristics of optimally deployed PMU by including and excluding the effect of ZIB. If a PMU is subjected to cyber threats, then the alternative backup PMU gives real-time data from the respective grid to the energy management control room for healthy operation [34]. The states for PMU are divided into two parts, such as healthy and unhealthy states to model the objective function and its constraints [35].

Equation (13-16) represents the healthy and unhealthy states of the PMU device to integrate the cyber-attack model into the synchrophasor network. Equation (17) formulate the state probability of PMU. FOR_p is forced outage rate or unavailability rate for p^{th} healthy PMU and FOR_q is forced outage rate or unavailability rate for q^{th} unhealthy PMU. S_p is state of p^{th} PMU. np is the number of PMUs in the system. Figure 3 illustrates the flow chart for analysing the observability and reliability of two interconnected systems by integrating the cyber-attack and ZIB characteristics. The flow chart of the whole paper is divided into three layers, i.e., observability, reliability, and cyber layer, to model the objective of the analysis.

$$S_p = \begin{cases} 1, & If\ \ PMU\ \ p\ is\ in\ \ healthy\ \ condition \\ 0, & If\ \ anomaly\ exist\ \ with\ PMU\ \ p\ during\ cyber-attack \end{cases} \tag{13}$$

$$S = \{S_1, S_2, ..., S_{np}\} = \{S_H^{pmu}, S_{UH}^{pmu}\} \tag{14}$$

$$S_H^{pmu} = \{j : S_j = 1 \mid S\} \tag{15}$$

$$S_{UH}^{pmu} = \{j : S_j = 0 \mid S\} \tag{16}$$

$$\Pr_{st}^{pmu} = \prod_{p\in H}\prod_{q\in UH}(1 - FOR_p) * (FOR_q) \quad \forall\ p \in S_H^{pmu}\ , q \in S_{UH}^{pmu} \tag{17}$$

Similarly, tie-line states can be defined as shown in equation (18-21) and the state probability of tie-line healthy and unhealthy states can be represented as shown in equation (22). S_t is set of tie-line and nt is total number of tie-line for interconnected system.

$$S_t = \begin{cases} 1, & If\ \ tie-line\ t\ is\ in\ \ healthy\ \ condition \\ 0, & Contrarily \end{cases} \tag{18}$$

$$S = \{S_1, S_2, ..., S_{nt}\} = \{S_H^{Tie}, S_{UH}^{Tie}\} \tag{19}$$

$$S_H^{Tie} = \{j : S_j = 1 \mid S\} \tag{20}$$

$$S_{UH}^{Tie} = \{j : S_j = 0 \mid S\} \tag{21}$$

$$\Pr_{st}^{Tie} = \prod_{p\in H}\prod_{q\in UH}(1 - FOR_p) * (FOR_q) \quad \forall\ p \in S_H^{Tie}\ , q \in S_{UH}^{Tie} \tag{22}$$

The objective function is modified by including the states of PMU and tie-line to implement the behaviour of network observability and reliability during anomaly conditions. The constraints are also updated with the inclusion of the state characteristics of the PMU device and tie-line. The mathematical formulation of the objective function and constraints can be represented as shown in equation (23-24) to model the cyber-attack inclusion in the grid network.

$$Min \quad \sum_{b=1}^{Nb} Pm_b * S_p + \sum_{b=1}^{Nb} LI_b \tag{23}$$

The interconnected network observability constraint is altered when a PMU device experiences an anomaly as a result of a cyber-attack and by integrating tie-line states.

$$O_b \geq 1 \quad \forall b \in B$$

$$O_b = \sum_{i=1}^{Nb} a_{bi} * Pm_i * S_p + \sum_{i=1}^{Nb} a_{bi} * y_{bi} + \sum_{i=1}^{Nb} t_{bi} * y_{bi} * S_t \quad \forall b \in B \tag{24}$$

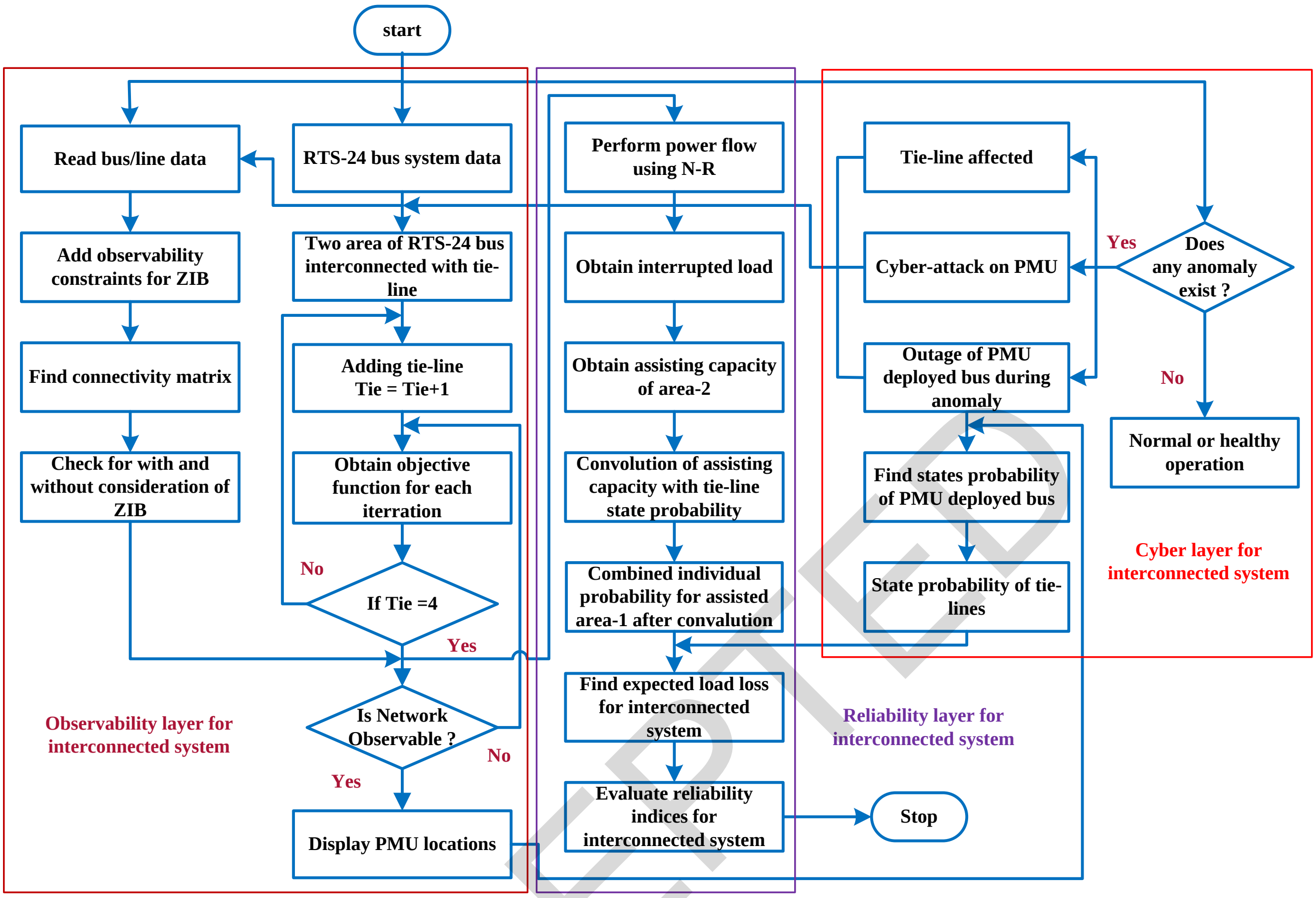

Figure 3: Flow chart representation for reliability and observability analysis of interconnected power grid during anomaly occurs with PMU.

3 Test System Description

The conventional RTS-24 bus is used for both areas to create an interconnected network by incorporating tie-lines between them [36]. The interconnected system is modified into a synchrophasor network by installing the PMU on the network buses. The paper's objective is to integrate the combined study of interconnected network observability and reliability by including and excluding the effect of ZIB. With the growing field of synchrophasor measurements technology, the cyber risk of the grid is gaining more focus to maintain the network's healthy operation. The two-area interconnection of the RTS-24 bus is incorporated with four tie-lines to transfer the reserve capacity of area-2 to area-1. By doing so, the risk level of the assisted area-1 can be reduced, and it may help to improve the reliability of the interconnected network. The placement of each tie-line between two areas is obtained by finding the optimal number of PMU requirements in the network for complete observability. Figure 4 illustrates the test system of two area interconnections of the RTS-24 bus by incorporating the tie-line between them optimally. The bus data, line data, generating unit data, availability or unavailability data, and many more are taken from the standard RTS-24 bus conventional system. The data related to PMU and tie-line is shown in Table 2. The interconnected system consists of eight ZIBs located on buses 11, 12, 17, and 24 in area-1 and 35, 36, 41, and 48 in area-2. Due to two-area interconnection, the number of PMUs deployed for the whole interconnected network will be greater. Therefore, cyber intrusion into the network will affect the observability of the grid. The paper discusses cyber-attack modelling to prevent the network from being in an unwanted situation. The backup PMU deployment can make the system healthy during any abnormalities that occur with PMU devices. Therefore, the test system is simulated to obtain the most reliable bus for PMU installation. The reliability index ISLIP and ISDNS is evaluated to conclude the reliability performance of the interconnected grid network during anomaly situations.

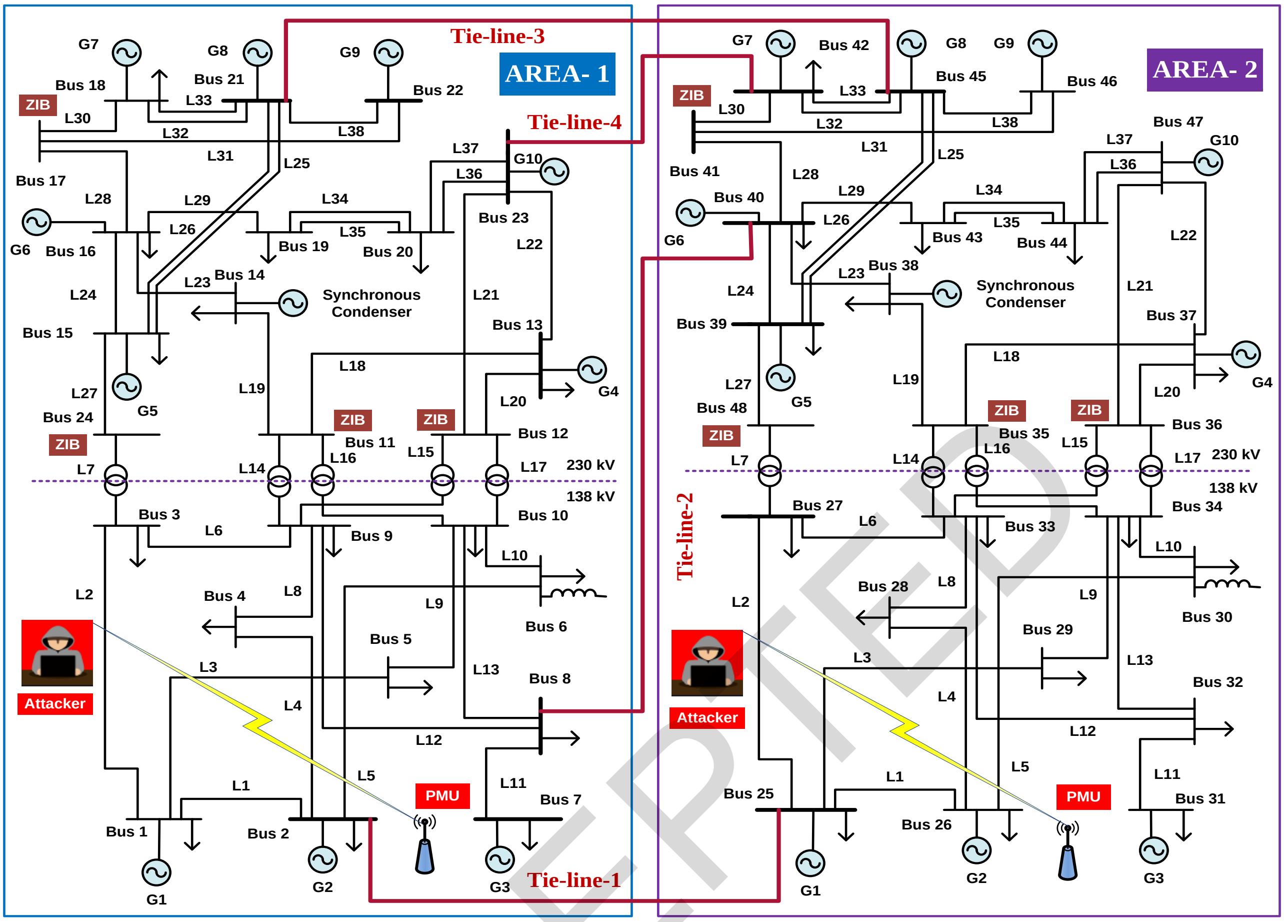

Figure 4: Test system illustration for two area interconnection of RTS-24 bus synchrophasor system with tie-line.

Table 2: Input simulation data of PMUs availability and tie-line outage rate for reliability and observability analysis of interconnected synchrophasor grid.

Bus Number	**Bus 1, Bus 25**	**Bus 2, Bus 26**	**Bus 3, Bus 27**	**Bus 4, Bus 28**	**Bus 5, Bus 29**	**Bus 6, Bus 30**	**Bus 7, Bus 31**	**Bus 8, Bus 32**
PMU availability rate	0.99152	0.99845	0.91602	0.95710	0.98209	0.93519	0.96311	0.99221
Bus Number	**Bus 9, Bus 33**	**Bus10, Bus 34**	**Bus 11, Bus 35**	**Bus 12, Bus 36**	**Bus 13, Bus 37**	**Bus 14, Bus 38**	**Bus 15, Bus 39**	**Bus 16, Bus 40**
PMU availability rate	0.97416	0.96330	0.99101	0.98731	0.97501	0.96284	0.95877	0.97389
Bus Number	**Bus17, Bus 41**	**Bus 18, Bus 42**	**Bus 19, Bus 43**	**Bus 20, Bus 44**	**Bus 21, Bus 45**	**Bus 22, Bus 46**	**Bus 23, Bus 47**	**Bus 24, Bus 48**
PMU availability rate	0.94617	0.97650	0.93509	0.91934	0.95441	0.99336	0.96705	0.98210

Tie-line connection	**Number of tie-line**	**Capacity of tie-line (in MW)**	**Failure rate (failure/year)**	**Repair rate (repair/day)**	**Forced outage rate (FOR)**
Area-1 to Area-2	4	20	4	1	0.010840108

4 Simulation Results and Discussion

In this section, simulation modelling is discussed for analysing the interconnected synchrophasor grid observability and reliability with the inclusion of cyber threats. The incorporation of tie-lines between the two areas could result in a more adequate power grid to improve the reliability of the network. The assisting area's reserve capacity is transferred to the assisted area through the tie-line. Access-supporting capacity may lead to improved reliability of the assisted area by observing the unchanged loading pattern or peak load demand in the system. Power grid observability can be achieved by deploying the optimal number of PMU across the bus for complete observation of the interconnected synchrophasor network. The tie-line incorporation may result in a reduced number of optimal PMU locations for complete observability of the interconnected smart grid. The synchrophasor network is always subjected to several cyber threats across the measuring instruments and communication channels. Therefore, the backup allocation of measuring devices is modelled for different PMU deployed buses for complete observation of two area interconnections during anomalies that occur with PMU. The following subsection discusses the objective simulation model for incorporating tie-line between two interconnected RTS-24 bus synchrophasor grids for complete observability and reliability with cyber intrusion.

4.1 Optimal PMU deployment in two interconnected RTS-24 bus synchrophasor network by step increasing of tie-line without consideration of ZIB

By excluding the characteristics of ZIB, a new PMU device is required to measure the ZIB voltage in real time, because if the bus is not a ZIB, then the voltage of the particular bus can not be evaluated by using KCL. For the single area RTS-24 bus system, the optimum number of PMU required is seven without considering the effect of ZIB. The optimum allocation of PMU devices is observed at buses 2, 3, 8, 10, 16, 21, and 23 for network complete observation without considering the effect of ZIB. Therefore, the best choice for placing the tie-line one end into area-1 is similar to the previous case, i.e., including the effect of ZIB. Now, the best placement of tie-line second end into area-2 can be observed with the simulation results without affecting the observable characteristics. The optimum allocation of PMU devices across the interconnected system by considering the effect of ZIB. The best position for placing the individual tie-line is selected for each step size. The best result of one step size is that it fixes the corresponding tie-line position. Now, the new tie-line position can be obtained in the second step size by fixing tie-line-1 between the specified buses as obtained in the first step. The best position is obtained by placing the tie-line-1 between bus-2 of area-1 and bus-31 of area-2.

By doing so, the optimum number of PMU required for complete observation is equal to 13, which is less for other bus connections. Therefore, the tie-line-1 position is fixed between buses 2 and 31 during the exclusion of ZIB from the network. Similarly, the best position for placing the tie-line-2 between two areas of interconnection is obtained between buses 8 and 40. The optimum solution for placing tie-line-3 between these two areas is fixed between buses 21 and 45. Now, the final step size for tie-line-4, the best position is specified between bus-23 and bus-27. Therefore, after incorporating all four tie-lines into the interconnected system, the best optimum allocation for PMU devices is obtained at buses 2, 3, 8, 10, 16, 21, and 23 for area-1 and 26, 27, 34, 40, 45, and 47 for area-2. The number of PMU devices required is seven for area-1 and six for area-2 for complete observation of the interconnected system during the exclusion of the characteristics of ZIB. Figure 5 illustrates the optimal deployment of PMU in the two-area interconnection of the RTS-24 bus system with the incorporation of four tie-lines by excluding the ZIB characteristics from the network. Tie-line 2, 3 and 4 can be observed with both end PMU directly and tie-line-1 is observable with one end PMU directly. As from observation, adding tie-line-1 to the network between bus-2 and bus-31 reduces the number of PMU requirements, i.e., equals to 13. Further, after placing the four tie-lines between interconnected systems, the best solution for the optimum number of PMU is also equal to 14. The colours are as follows: PMU deployed bus (green), ZIB (red), Line with one end PMU bus (blue), Line with two end PMU bus (green), Line without PMU bus (red).

Therefore, the question arises, should we go for four tie-line interconnection if the same results are achieved through incorporating one tie-line? The answer is that, as the paper is discussing the combined behaviour of network observability and reliability, four tie-line models are used for reliability analysis, because all these tie-lines are used for transferring assisting capacity from area-2 to area-1. If the focus of the paper is to observe the network completely with PMU, then one tie-line connected between bus-2 and bus-31 is sufficient for complete observability of the synchrophasor network.

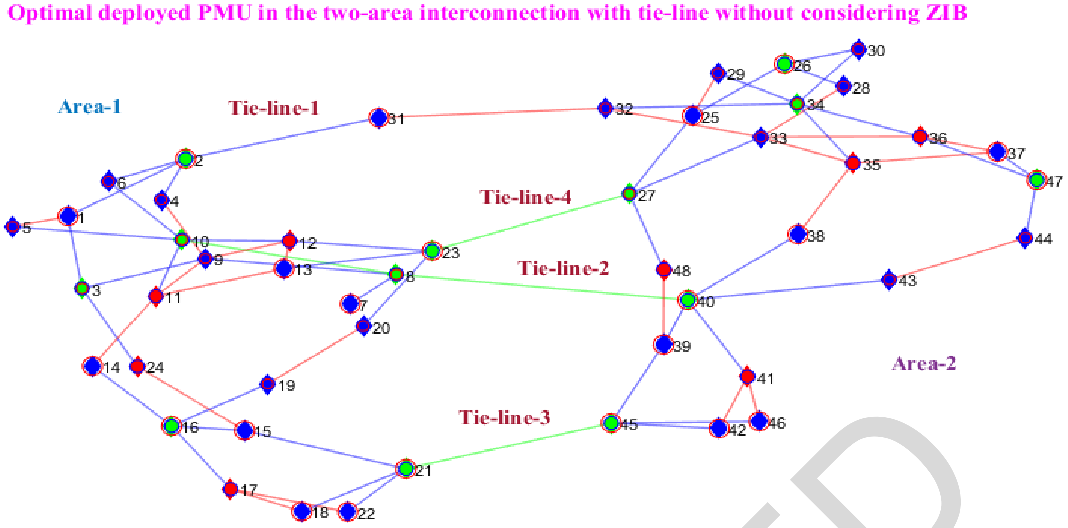

Figure 5: PMU deployment in interconnected system without considering the effect of ZIB.

4.2 Backup PMU allocation and identification of affected tie-line incorporated between two interconnected area during anomaly due to cyber-attack by including the effect of ZIB

The growing field of synchrophasor technology across the power grid makes the system smarter by collecting real-time data from the network through measuring devices such as PMU. Therefore, the communication channels between the control centre and the measuring device are subjected to several cyber threats. The backup PMU installation across the interconnected system may lead to a more reliable synchrophasor network when anomalies occur with PMU devices. The paper models such a backup PMU deployment in the system, which may lead to proper observation of the grid during the anomaly condition with PMU. By doing so, the network reliability can be improved without any loss of data from PMU in real time. The extra PMU required for the system during the cyber-attack at the existing optimally deployed PMU bus and identifies the affected tie-line in such an abnormal condition by including the characteristics of ZIB. The optimal allocation of PMU buses is obtained for buses 1, 2, 8, 16, 21, and 23 of area-1 and 25, 26, 32, 40, and 47 of area-2 by considering the effect of ZIB. Therefore, backup PMU installation is obtained for all these PMU buses if any anomaly occurs in the system.

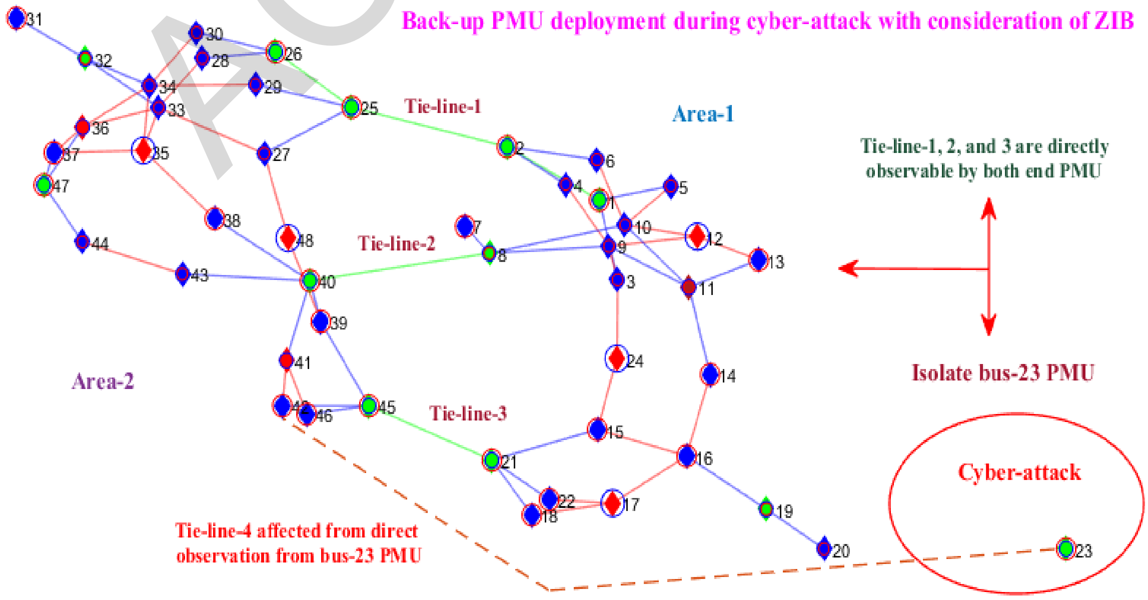

Figure 6:Backup modelling of PMUs deployment during anomaly with PMU located at bus 23 by considering ZIB.

If a PMU allocated bus is affected during a cyber intrusion, then it will isolate itself from the observation of the network. Therefore, the network observability is now evaluated by considering the fact that there is no PMU installed on the affected bus. The results obtained in such a case are used to identify the bus that requires extra PMU for complete observation. If a cyber-attack occurs on PMU that is deployed on bus 21, the extra PMU required to back-up such anomalies is allocated to buses 17, 34, and 39. Therefore, during the failure of bus-21 PMU, the network's complete observability can be achieved through PMU allocation to buses 1, 2, 8, 16, 17, and 23 for area-1 and buses 26, 32, 34, 39, 40, and 47 for area-2. The backup PMU installed at buses 17, 34, and 39 will now provide the measuring data to the control centre to maintain the network observability and reliability. During the failure of bus-21 PMU, tie-line-3 is affected by direct observation by the PMU, while tie-line-2 is observable directly by both ends of the PMU. Similarly, if a cyber-attack or any abnormality occurs with PMU deployed at bus-23, then backup PMU locations can be obtained at buses 11, 19, and 45 for complete observability of the grid network. During such a situation, tie-line-4 is affected with direct observation from either end of the PMU, and the other three, namely, tie-lines 1, 2, and 3, are directly observable from both ends of the PMU. Therefore, backup PMU installation in the synchrophasor network leads to a more observable and reliable grid during a cyber intrusion. Figure 6 illustrates the backup PMU allocation in the interconnected grid of the RTS-24 bus system during a cyber-attack that occurs on PMU deployed at bus-23 by including the ZIB characteristics.

4.3 Reliability indices mapping for interconnected system by incorporating tie-line between area-1 and area-2 during anomaly with PMU bus by considering the effect of ZIB

The reliability of the power system network is a focus area with growing synchrophasor technology in power grids across the world. Therefore, as the synchrophasor network is more vulnerable to cyber threats, it is necessary to maintain the observability and reliability of the power grid during such anomalies. The interconnected system plays a key role in supporting the reserve capacity of one area (assisting area) to the other connected area (assisted area). This may lead to improving the reliability of the assisted area by observing the same peak load demand. Here, reliability modelling for two interconnected areas is mapped while considering cyber intrusion in the synchrophasor network. The reliability indices ISLIP and ISDNS are evaluated during cyber-attacks that occur with optimally deployed PMU in the interconnected synchrophasor network. The optimal allocation for PMU placement is obtained at bus 1, 2, 8, 16, 21, and 23 for area-1 and bus 25, 26, 32, 40, and 47 for area-2 by considering the effect of ZIB. Therefore, reliability indices are evaluated for the cyber-attack that occurs on individual PMU for this scenario. Figure 7 illustrates the mapping of reliability parameter ISLIP for two interconnected systems during a cyber-attack that occurs at an optimally deployed PMU bus by considering the characteristics of ZIB. A cyber-attack occurs with PMU deployed buses 1, 2, 8, and 16 are resulting the most reliable PMU deployed zones during anomalies for area-1.

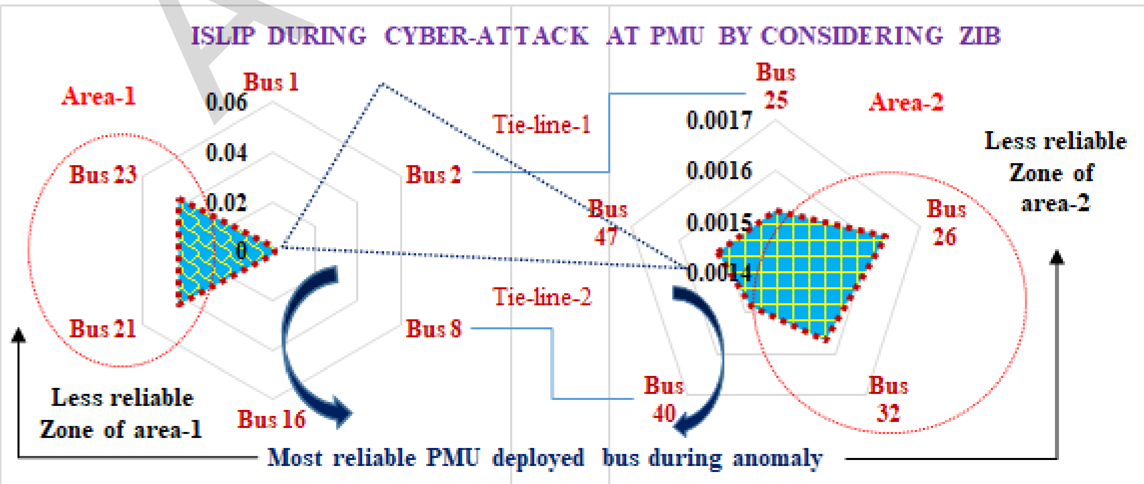

Figure 7: Interconnected system reliability parameter ISLIP mapping for area-1 and area-2 during anomaly with PMU bus by considering the effect of ZIB.

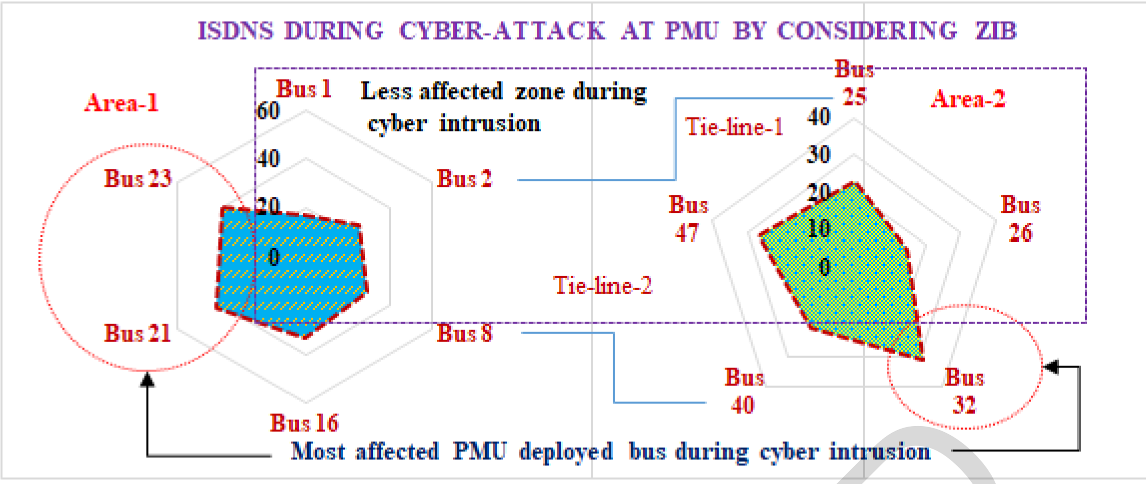

Figure 8: Interconnected system reliability parameter ISDNS mapping for area-1 and area-2 due to cyber-attack at PMU bus by considering the effect of ZIB.

A cyber-attack occurred with PMU allocated to bus-21, and bus-23 affected the reliability of the network strongly in comparison with other bus PMU for area-1. The system reliability will be better with the minimum value of reliability indices such as ISLIP and ISDNS. The reliability index ISLIP get reduce by 10%, 5.37%, and 17.26% during anomalies that occurred with PMU deployed at bus 2, 8, and 16 respectively, by observing that a cyber-attack occurred on PMU deployed at bus-1. Therefore, all these PMU deployed buses result in the most reliable zone for area-1 during an anomaly. Similarly, the reliability analysis for area-2 is obtained during cyber intrusion. The reliability index ISLIP get reduced by 2.51% and 0.01% during cyber-attacks that occurred on PMU deployed buses 40 and 47, respectively, by observing that cyber-attacks occurred on PMU deployed on bus 25 of area-2. The reliability index ISLIP increased by 6.93% and 2.98% during cyber-attacks that occurred on PMU deployed buses 26, and 32, respectively, by observing with cyber-attack occurred on PMU deployed on bus-25 in area-2. Therefore, the most reliable zone for area-2 is obtained when anomalies occur with buses 25, 40, and 47, and similarly, anomalies occur with PMU deployed on buses 26 and 32, which results in the least reliable zone for area-2. Similarly, Figure 8 illustrates the mapping of reliability index ISDNS between two area interconnections to find the most reliable PMU allocated bus in the system during a cyber-attack by considering the characteristics of ZIB. If $ISDNS_k$ represents the reliability index during cyber-attack occurs at bus k then the reliability index can be written in descending order for both the interconnected area.

Reliability index ISDNS for area-1 during anomaly with PMU by considering the effect ZIB,

$$ISDNS_{21} > ISDNS_{23} > ISDNS_{16} > ISDNS_{8} > ISDNS_{2} > ISDNS_{1}$$

Reliability index ISDNS for area-2 during anomaly with PMU by considering the effect ZIB,

$$ISDNS_{32} > ISDNS_{47} > ISDNS_{25} > ISDNS_{40} > ISDNS_{26}$$

4.4 Reliability indices mapping for interconnected system by incorporating tie-line between area-1 and area-2 during anomaly with PMU bus without considering the effect of ZIB

The number of PMU requirements would be higher if we excluded the effect of ZIB. The synchrophasor network is highly affected during cyber intrusion by the number of PMUs in the grid. Therefore, reliability may be affected highly during a cyber-attack that occurs with PMU by excluding the characteristics of ZIB. The optimal number of PMU requirements for complete observation of the network is 13 without considering the effect of ZIB. PMU is installed at bus 2, 3, 8, 10, 16, 21, and 23 of area-1 and bus 26, 27, 34, 40, 45, and 47 of area-2 for grid observability by excluding the characteristics of ZIB. The reliability parameter ISLIP is reduced by 93.3%, 93.27%, 93.53%, 94.09%, 93.39%, and 93.88% during cyber-attack occurs with PMU deployed at bus 3, 8, 10, 16, 21, and 23 respectively with respect to observing the cyber-attack at bus-2 of area-

1. Therefore, reliability is most affected during anomaly exist with bus-2 PMU of area-1 and less affected with other PMU installed on buses in area-1. The most reliable zone exists with PMU deployed on buses 2, 3, 8, 10, 16, 21, and 23 in area-1. Similarly, the reliable zone for PMU deployment in area-2 is determined in order to analyse cyber threat effects on the synchrophasor network. The reliability index ISLIP decreased by 15.15%, 0.84%, 12.3%, 2.87%, and 15.17% during the anomaly occurs with PMU allocated to buses 27, 34, 40, 45, and 47, respectively, with respect to observing the anomaly that existed with PMU deployed at bus-26 in area-2. Therefore, cyber-attacks occur with PMU deployed on buses 26, 34, and 45 offering less reliable zones for reliability, and on the other hand, anomalies occur with PMU allocated to buses 27, 40, and 47 offering the most reliable zones for PMU deployment. The overall interconnected system reliability is highly affected when a cyber-attack occurs with PMU deployed on bus-2 in comparison with other bus PMUs in area-1 and area-2. Figure 9 shows the mapping of the reliability index ISLIP for interconnected systems of area-1 and area-2 during anomaly, with optimally deployed PMU in the network by excluding the effect of ZIB. Similarly, Figure 10 illustrates the mapping of the reliability index ISDNS for two area interconnections during abnormalities that exist with optimally deployed PMU in the network by excluding the characteristics of ZIB.

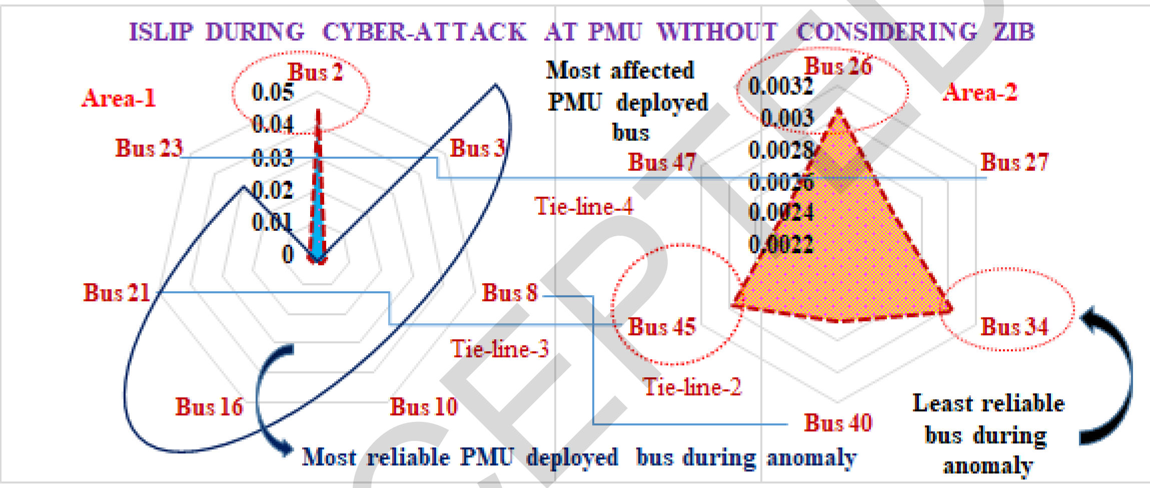

Figure 9: Interconnected system reliability parameter ISLIP mapping for area-1 and area-2 during anomaly with PMU bus without considering the effect of ZIB.

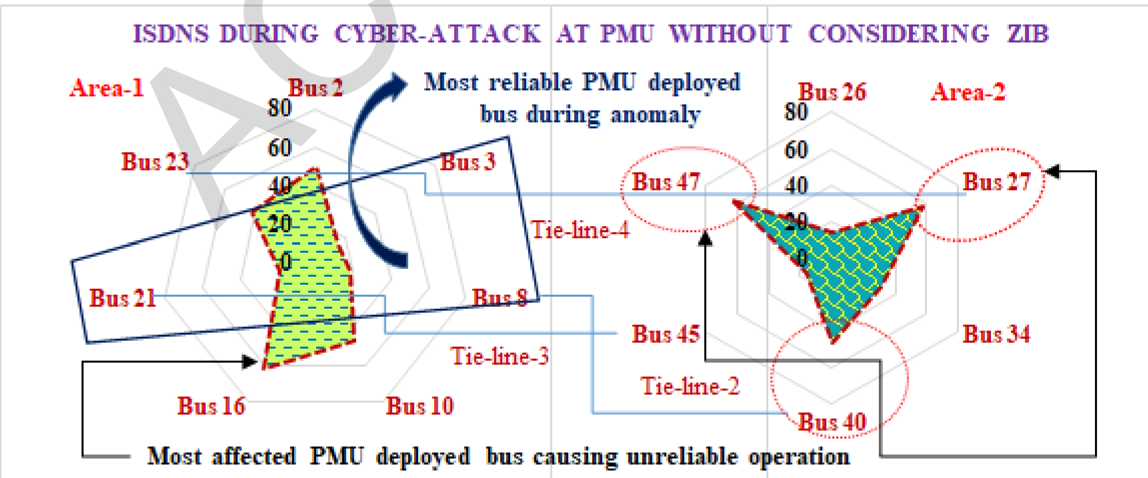

Figure 10: Interconnected system reliability parameter ISDNS mapping for area-1 and area-2 due to cyber-attack at PMU bus without considering the effect of ZIB.

Reliability index ISLIP for area-1 during anomaly with PMU by excluding the effect ZIB,

$$ISLIP_2 > ISLIP_8 > ISLIP_3 > ISLIP_{21} > ISLIP_{10} > ISLIP_{23} > ISLIP_{16}$$

Reliability index ISLIP for area-2 during anomaly with PMU by excluding the effect ZIB,

$$ISLIP_{26} > ISLIP_{34} > ISLIP_{45} > ISLIP_{40} > ISLIP_{27} > ISLIP_{47}$$

5 Conclusion

By incorporating tie-lines between them, the paper simulates the cumulative effect of observability and reliability for two-area interconnection. The interconnected system is modelled for four tie-lines and the connectivity of all the tie-lines is obtained based on the optimal solution of PMU deployment. The best interconnection of tie-lines is used to transmit the reserve capacity of assisting area-2 to the assisted area-1. The backup PMU deployment is used to allocate the alternative PMU for each affected PMU during a cyber-attack. By doing so, the most reliable PMU-allocated bus is obtained for both areas. Backup PMU requirement is minimum during cyber-attack occurs with PMU deployed at bus 3, 8, 21, 26, and 45. The reliability parameters ISLIP and ISDNS are obtained to conclude the reliability performance of the interconnected grid during anomaly conditions. With the inclusion of ZIB, ISDNS is reduced by 36.2% and 12.4% during anomaly events with PMU deployed at bus 26, and 40, respectively, by observing that a cyber-attack occurs on PMU deployed at bus-25 for area-2. By excluding the effect of ZIB, the reliability parameter ISDNS is reduced by 69.40%, 63.85%, 8.22%, 62.58%, and 14.73% during cyber-attacks that occur with PMU installed at bus 3, 8, 10, 21, and 23, respectively, with respect to observing the anomaly that exists with PMU deployed at bus-2 of area-1. Similarly, reliability parameters ISDNS is increased by 22.35% during an anomaly that happens with PMU installed at bus 16 with respect to observing the anomaly that exists with PMU deployed at bus-2 in area-1. Therefore, cyber-attacks exist with buses 3, 8, and 21 offering the most reliable zone for PMU placement in area-1 and other PMUs deployed on buses 2, 10, 16, and 23, offering less reliable zones for PMU placement during cyber intrusion. The overall concluding remarks of the paper are that with the incorporation of tie-line between two interconnected systems, reliability can be improved by reducing the risk level, and the number of PMU deployments can also be reduced by incorporating tie-line and observing ZIB characteristics. Apart from that, the most reliable PMU location is also obtained for both the areas during cyber intrusion.

Nomenclature

Index and Sets

b	Interconnected network bus index
gc	Interconnected network generator unit index
tr	Transmission line index for interconnected grid
te	Tie-line index for interconnected grid
c	Synchrophasor network contingency index
p	Indexing for deployed PMU in synchrophasor grid
B	Set of interconnected grid bus
GC	Set of interconnected grid generator unit
TR	Set of transmission lines in synchrophasor network
TE	Set of tie-lines in synchrophasor network
C	Set of contingency in test system
P	Set of installed PMU in the grid

Variables and parameters

Nb	Number of bus in interconnected grid system
LI_b	Load interruption in interconnected network at bus b
O_b	Complete observability index of bus b by including tie-line
a_{bi}	Bus connectivity matrix element for b^{th} row and i_{th} column

y_{bi}	An auxiliary variable assign for ZIB
t_{bi}	Tie-line connectivity matrix element of b^{th} row and i_{th} column
δ_b	Angular separation of voltage at bus b
P_{gc}	Capacity of active power generation for generator unit gc
LF_{tr}	Capacity limit of power flow through transmission line tr
ξ_{tr}	Variable assign for line contingency as binary digit
LD_b	Load demand for interconnected grid at bus b
$CM_{b,gc}$	Connection node matrix for interconnected network, which entities gives 1 if bus deployed with generating unit contrarily 0
$IM_{b,tr}$	Incidence node matrix for interconnected network, entities gives 1 if bus are sending bus for transmission line, -1 if it is receiving bus and 0 if there is no connection between transmission line tr and bus b
B_{tr}	Susceptance of transmission line tr
Ω	Large number for balancing the power flow constraints
$\lambda^{\max}$	Extreme number of allowable line switching for interconnected network
EPR_n	Number of extra PMU required for backup observation
NTO	Number of tie-line outage
$\Pr_i^{IA}$	Individual probability of an area of interconnected system obtain from capacity outage table for corresponding area
$\Pr_i^{CTA}$	Individual probability for combination of tie-line and assisting area obtain by convolution
$\Pr_{st}^{pmu}$	State probability of PMU for interconnected system
$\Pr_{st}^{Tie}$	State probability of tie-line for two area interconnection
Θ	Convolution between two individual state probability
SR_{tr}	Switching rate of transmission line tr
$ISLIP_T^{Cy}$	Interconnected system load interruption probability index during cyber-attack occurs with PMU devices
$ISDNS_T^{Cy}$	Interconnected system demand not supplied index during cyber-attack occurs with PMU devices
S_H^{pmu}	Set of healthy PMU
S_{UH}^{pmu}	Set of unhealthy PMU
S_H^{Tie}	Set of healthy tie-line for interconnected network
S_{UH}^{Tie}	Set of unhealthy tie-line for interconnected network

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