

Identification of Substation Configurations in Modern Power Systems using Artificial Intelligence

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Abstract—Power system transmission network topology is utilized in energy management system applications. Substation configurations are fundamental to transmission network topology processing. Modern power systems consisting of renewable energy sources require reliable and fast network topology processing due to the variable nature of wind and solar power plants. Currently used transmission network topology processing, which is based on the relay signals communicated through SCADA is not highly reliable or highly accurate. Substation configuration identification (SCI) for different substation arrangements including main and transfer bus arrangement (MTBA), ring bus arrangement (RBA), and single bus arrangement (SBA) is investigated. Synchrophasor measurement based SCI for functional arrangements (FA) using artificial intelligence (AI) approaches is proposed in this paper. This method improves monitoring FA. Typical results for MTBA, RBA and SBA substation configuration identification is presented. A modified two-area four-machine power system model with two grid connected solar PV plants consisting of MTBA, RBA and SBA is simulated on real-time digital simulator. AI based SCI is shown to accurately identify all possible FAs for the three substation arrangements under any operating condition.

Index Terms—Substation Configurations, Artificial Intelligence, Phasor Measurement Units, Transmission Network Topology

I. INTRODUCTION

Power system is a large, geographically distributed single circuit that supply power to the consumers from the generation stations. Modern power system is highly dynamic due to the nature of renewable energy sources (RES), distributed energy resources, etc. Thus, modern power system control requires high resolution real-time system monitoring and processing capability. The control center is responsible for the reliable and secure power system operation. Thus, control center requires the knowledge of each and every component's connectivity to the transmission network. Power system transmission network topology processing (TNTP) is used in the control center to understand the power system transmission network component

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connectivity. TNTP defines the node-breaker model (NBM) based on status of breakers located in substations [1]. The NBM is converted to a dynamic bus-branch model (BBM) to be used in the energy management system (EMS) applications. Substation Bus sections or branches with very low or zero impedance are eliminated under this conversion to facilitate efficient numerical calculations [2].

BBM derived by the TNTP is used by EMS online applications including state estimation [2], [3], [4], power flow [5]. At the same time, reliable BBM is important for energy market application such as locational marginal pricing [6], security constrained optimal dispatch and optimized renewable integration, unit commitment [7]. Power system planning division uses TNTP to conduct contingency analysis and stability analysis [2], where online BBM can be used to decrease the gap between planning simulation results and the practical results [2].

Currently, TNTP uses the relay signals collected by the remote terminal units in the substation about breaker status, which communicated to the control center via SCADA to derive the power system TNTP [2]. Thus, the substation configuration is the fundamental for TNTP. The existing TNTP is not precise [8]. At the same time, breaker malfunction or false data injection by a man-in-the-middle attack [9] can easily compromised the derived TNTP in the control center. Which cause erroneous in results obtained by the applications based on TNTP. There has been numerous research focus on this problem. As described in [10], graph methods can be integrated to derive the changes in the TNTP. As proposed in [11], novel wireless sensor network can be establish to identify the branch status, which can be used to derive the TNTP. Thus, an improved TNTP or an validation for the existing TNTP is required. This can be done either communicating the breaker status through a secure communication channel or data-driven TNTP based on the measurements communicated through a secure communication channel respectively. Although implemented PMUs has the capability of integrating the digital relay signals of breakers status to it's data frame [12], implementing such infrastructure in the existing synchrophasor network will be expensive. Thus, a

redundant TNTP that use the measurements communicated through secure communication channel with only addition of computational nodes to the system without modification to the infrastructure is ideal.

To enhance the situational awareness of the power system, Phasor Measurement Units (PMUs) are introduced [13] in the substations to enable high resolution real-time measurements. PMUs measure phasor quantities at a higher rate. Typically, 30Hz reporting frequency is used. This data set is a representation of the power system state, which open possibilities to investigate the system online and implement TNTP based solely on the measurements. Although there are proposed methods to improve the TNTP by introducing measurement based TNTP [14]- [15] most of this are lacking in-depth investigation of substation configurations. The substation configuration identification is studied in [16], [17], which are still rely on the breaker signals, which is again depends on the existing method of TNTP. This study is an effort to investigate the different substation configurations. Substation configuration identification (SCI) is the first level of TNTP.

High voltage substations are established in critical locations of the power system transmission network to enable control of power flow and monitoring of system states to supply power securely. Connectivity of power system critical components such as generators, transmission lines, transformers, loads, etc. can be controlled in the substations by operating the breakers accordingly. Power system measurement instrumentation such as PMUs are deployed in the substations to monitor branch current, bus-section voltage, power flow and frequency. There are several substation arrangements [18]. In this study, three such substation arrangements are considered. They are main and transfer bus arrangement (MTBA), ring bus arrangement(RBA) and single bus arrangement (SBA) as shown in Fig. 1. Selection of the particular substation arrangement to extend in the power system transmission network is based on the type of connections, level of required reliability and the expenditure capability. Furthermore explanation on selected three substation arrangement types are explained in section II.

The demand side power requirement is becoming complex. The utility grid requires modernization to be compatible with complex demand requirement. TNTP is one application that will come under this modernization [19]. The future power grid will have higher number of switching operations and frequent topology changes. This is driven by the rapid integration of renewable source based generation which is intermittent and the accumulation of commercial micro-grids, which islanding will be a standard frequent operation. Artificial intelligence (AI) algorithms can be used to establish a real-time TNTP [15]. Furthermore, AI techniques can be used to provide enhanced situational awareness with PMU data [20], [21]. In this study, AI based SCI for MTBA, RBA and SBA is proposed. Use of data-driven AI based approach is new to SCI. The authors considered this approach due to following considerations,

- Future power system transmission network is expected to handle more frequent topology changes. Thus, more

intelligent AI based approach is preferred.

- The proposed AI based approach is scalable to handle substation expansions with growing power system complexity.
- Operation and management of modern power systems will be more dependent on real-time complex data and thus, AI based approaches are more robust for substation configuration identification.

The SCI is based on either knowledge based logical decision making (LDM) or neural network (NN). An LDM or NN based SCI for each substation type is selected based on complexity of the arrangement and efficiency of the algorithm.

SCI is tested using PMU data from a real-time simulation of MTBA, RBA and SBA. Section II, elaborates on the substation configurations. Section III, explains the AI based SCI methodology. In section IV, results of all possible substation configurations for the MTBA, SBA and RBA is presented. Section V concludes the study by elaborating on the findings and future directions of the study.

II. SUBSTATION CONFIGURATION

A substation consists of branches, bus-sections, protection equipment (relays), measurement instruments (PMUs) and switching equipment (Breakers, Isolators). Each of these equipment is required in the power system control. TNTP is defined based on the status of each breaker established in all substations. The breaker status is identified using the relays and the relay signals are communicated to the control center, which is eventually used to establish the TNTP. The substation configurations can be analyzed as follows,

- 1) Component Arrangement (CA).
- 2) Functional Arrangement (FA).

CA explains the physical connectivity of each branch and bus-section of the substation. CA is the NBM in the substation context. Each breaker status is used to define the CA of the substation. FA is explained by the fundamental electrical circuit nodal analysis theorems. FA is the BBM in the substation context. The FAs are a subset of the CAs.

Since the power system TNTP is highly dependent on the reliable relay signal communication, an fail-safe redundancy or a validation is recommended. Use of synchrophasor network measurements to establish an intelligent data-driven BBM is ideal to overcome this issue. A novel BBM can be defined by integrating all substation FAs. This novel BBM can be used as a replacement or to validate the current BBM, which is derived using TNTP based on relay signals communicated to the control center [2]. Thus, extension of the proposed FA for SCI in this study can be used to improve the reliability of the existing BBM of the network and the EMS applications. The remaining subsections describe the MTBA, RBA and SBA arrangements and elaborate on FAs.

A. Main and Transfer Bus Arrangement (MTBA)

The MTBA substation arrangement design to connect all the branches in between main bus and transfer bus. At any

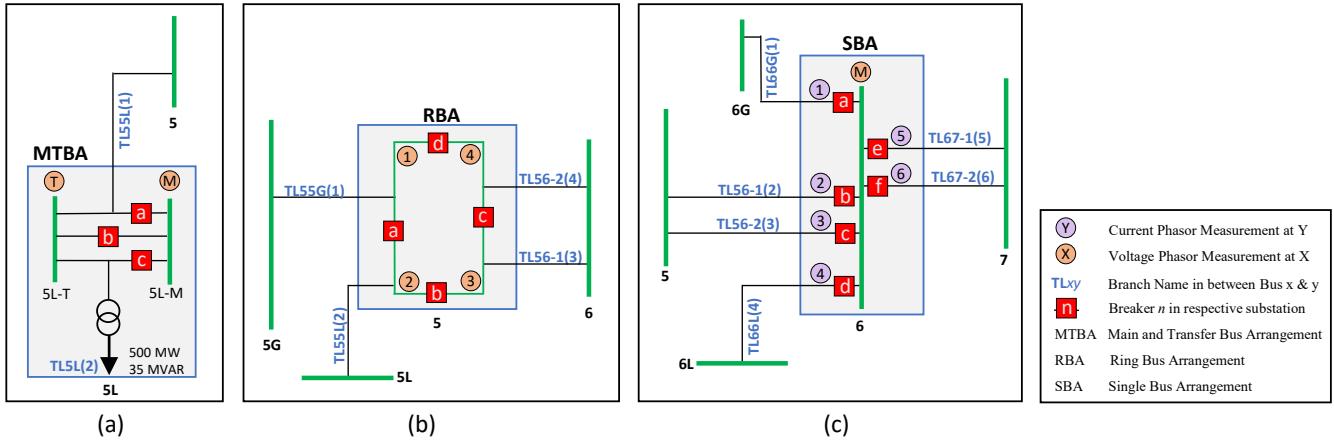


Fig. 1. Substation Circuit Arrangements: a) Main and Transfer Bus Arrangement (MTBA), b) Ring Bus Arrangement (RBA) and c) Single Bus Arrangement (SBA).

point of active operation the main bus can be taken out of service and the substation operation can be continued without interruptions using only the transfer bus. Although the transfer bus is typically used in a main bus maintenance, it can be used as a redundancy for the main bus in the substation under emergency operation. PMUs are installed to measure the bus voltages. MTBA can have 2^n (where n = number of breakers in the substation) CAs and only two FAs. A load transfer substation of MTBA with two branches is shown in the Fig. 1 (a).

B. Ring Bus Arrangement (RBA)

The RBA consists of bus-sections connected through circuit breakers. RBA is a reliable bus arrangement. Any single breaker malfunction does not affect the substation operation. Combination of multiple circuit breakers operations are used to disconnect and reconnect high voltage power system components such as generators, transmission lines, transformers, etc. to the substation and change the power routing pattern. The common practice by the utilities to measure each current through connected branches and the voltages of the bus sections at the connected node of the ring bus arranged substation. Thus, current phasor measurements of each branch connecting to the RBA substation and voltage phasor measurements of each bus section is available at the substation and the control center. RBA have 2^n (where n = number of bus sections or breakers in the substation) CAs and $(2^n - n - 1)$ FAs. The RBA test case of this study, is a four-node RBA substation with PMU measurement points is shown in the Fig. 1 (b). An example of CAs and FAs of a four-node RBA is shown in Fig. 2.

C. Single Bus Arrangement (SBA)

The SBA is the fundamental substation arrangement. Reliability is very low due to lack of redundancy under breaker failure or bus fault. All the branches are directly connected to a single bus through circuit breakers. PMUs are installed to measure all branch currents and the bus voltage. Thus,

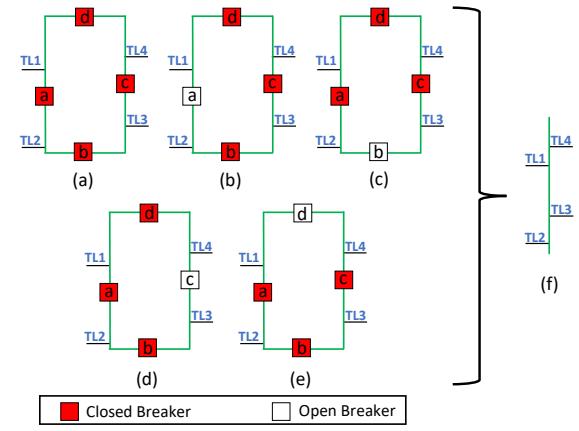


Fig. 2. Four-node RBA. Functional arrangement of the component arrangements in (a) - (e) is shown in (f).

both branch currents and the bus voltage is available at the control center. SBA is a special case, where each FA, and corresponding CA is unique. SBA have 2^n (where n = number of breakers or branches in the substation) CAs and FAs. In this study, SBA substation test case has 6 branches connected as shown in Fig. 1 (c).

III. AI BASED SUBSTATION CONFIGURATION IDENTIFICATION

In this study, two AI based algorithms are considered to identify the functional arrangements to derive substation configuration, namely, logical decision making (LDM) and neural network (NN). For each type of substation arrangement, either LDM or NN is selected considering the complexity of the problem and the arrangement based on the computation efficiency. Proposed MTBA, SBA and RBA SCIs are expected to be reliable, intelligent and easy to implement. The SCI can be developed using knowledge based LDM algorithm that follows the flow diagrams shown in Figs. 4, 6 and 8 or using NNs that are trained offline and use at any substation similarly

arranged, despite of the powers system state. Training data set generation for NN approach can be done based on the simple logical algorithm that follows the highlighted section that is shown in Figs. 4, 6 and 8. Thus, the proposed SCI development is only requires basic substation information such as substation type, number of branches. Thus, NN based SCIs can be implemented and trained offline with a generic binary training data set and used in the field. The proposed SCI approach can be summarized as shown in Fig. 3.

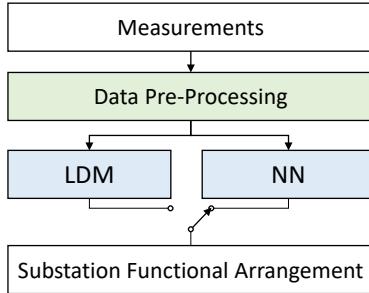


Fig. 3. Procedure of the proposed substation configuration identification approach.

A. Main and Transfer Bus Arrangement (MTBA)

MTBA substation with two branches is considered as the test case, which is shown in the Fig. 1 (a). The PMUs are in place to measure main and transfer bus voltages as shown in orange circles in the Fig. 1 (a). The two possible FAs of any MTBA substation can be inferred by using the main and transfer bus voltages. The intelligent decision procedure is shown in the Fig. 4 flow diagram. A LDM algorithm that checks equality of main and transfer bus voltages can be developed by following the flow diagram shown Fig. 4 or a single binary neuron can be trained using the pre-generated training data by following the flow diagram shown in Fig. 4 as shown in Fig. 5 to identify the FA. The NN is for MTBA is a single binary neuron. This is a simple linear separable problem. Therefore a NN is not needed. Although for comparison of LDM vs NN purpose, a single neuron NN is developed.

B. Ring Bus Arrangement (RBA)

RBA substation with four-nodes is considered as the test case, which is shown in the Fig. 1 (b). The PMUs are in place to measure each bus-section voltages as shown in orange circles in the Fig. 1 (b). Each FA of the RBA substation can be inferred based on the circuit nodal analysis using only voltage phasor measurements of the bus sections. In the substation each bus section voltage phasor is compared with neighbor bus section voltage to identify the nodal connectivity which is separated by the breaker. Bus-section voltage measurements are considered as the inputs in the RBA to identify FAs as shown in the Fig. 6 flow diagram.

X and Y are consecutive nodes in the RBA. The quantities shown are PMU measurements. For RBA substation arrangement an LDM can be setup by following the procedure shown

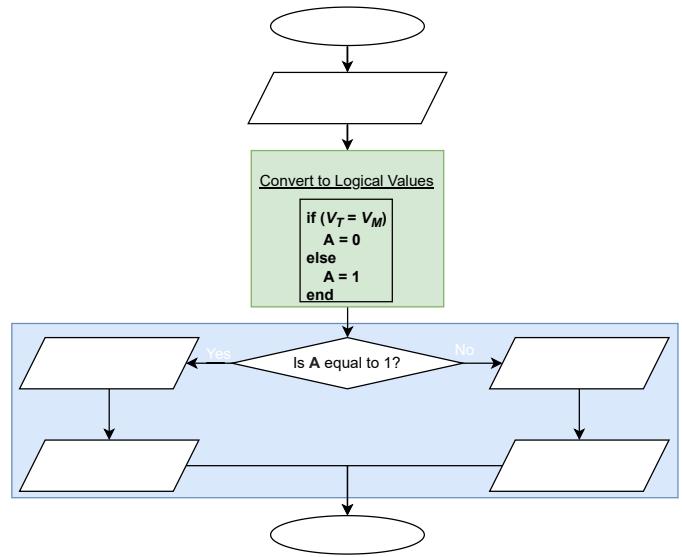


Fig. 4. A flow diagram for substation configuration identification of functional arrangement of MTBA type substation.

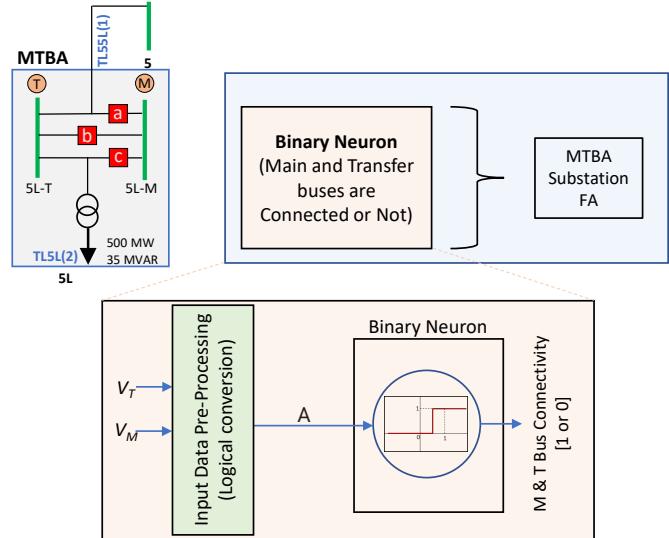


Fig. 5. The single binary neuron structure based substation configuration identification developed for MTBA substation shown in Fig. 1 (a).

in the Fig. 6 or a feed forward multilayer perceptron (MLP) neural network can be trained as shown in Fig. 7 using the generic pre-generated training data as shown in TABLE I which was derived by following the flow diagram shown in Fig. 6 to get the FAs. LDM or MLP can be selected based on the computation efficiency. Furthermore, for RBA, a single LDM or MLP is tasked with identifying the connectivity of two consecutive bus-sections (nodes). Since the approach identifying the FA of the substation, all single breaker operations are considered similar to the FA shown in Fig. 2. (f). Each LDM or MLP takes in the two consecutive bus section voltage phasor measurements and compare them and converts into logical values in pre-processing. The binary outputs of the pre-

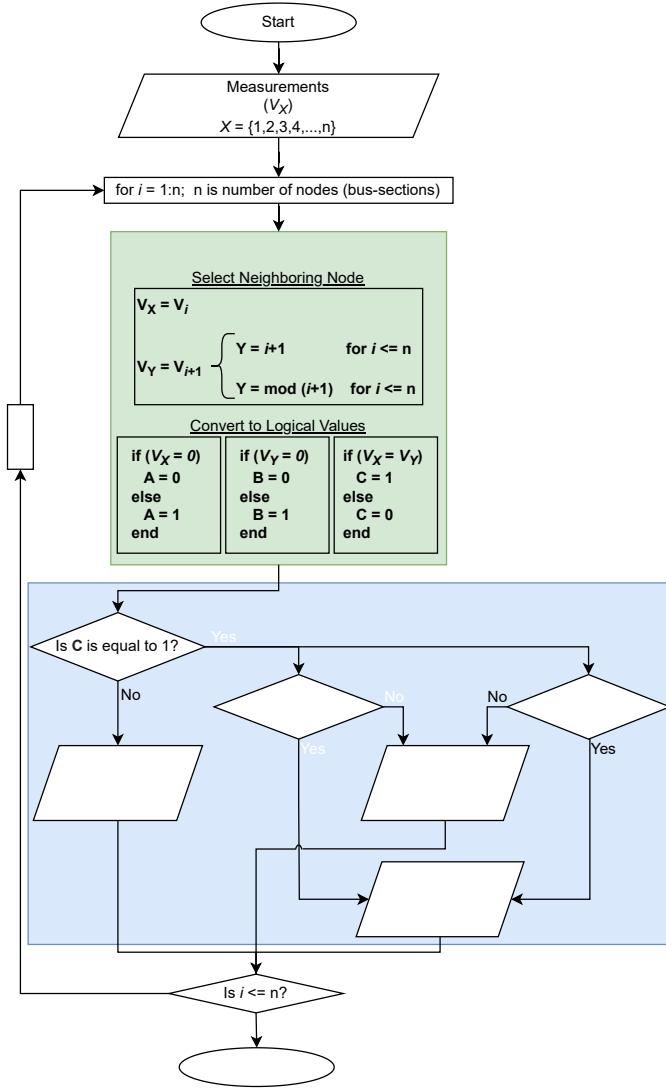


Fig. 6. A flow diagram for substation configuration identification of functional arrangement of RBA type substation.

processing is used as the inputs to the LDM or MLP training data generation. The output is the connectivity in between the respective two bus-sections. All node connectivity statuses combined together to get the FA of the RBA substation as shown in Fig. 7. Equation (1) shows the MLP that derive the connection between X and Y bus-sections (nodes) of RBA.

TABLE I
TRAINING DATASET OF MLP FOR X AND Y NODE CONNECTIVITY OF RBA SUBSTATION.

Inputs			Output
C	A	B	Node X and Y Connection Status
1	1	1	1
1	0	0	0
0	1	1	0
0	1	0	0
0	0	1	0
0	0	0	0

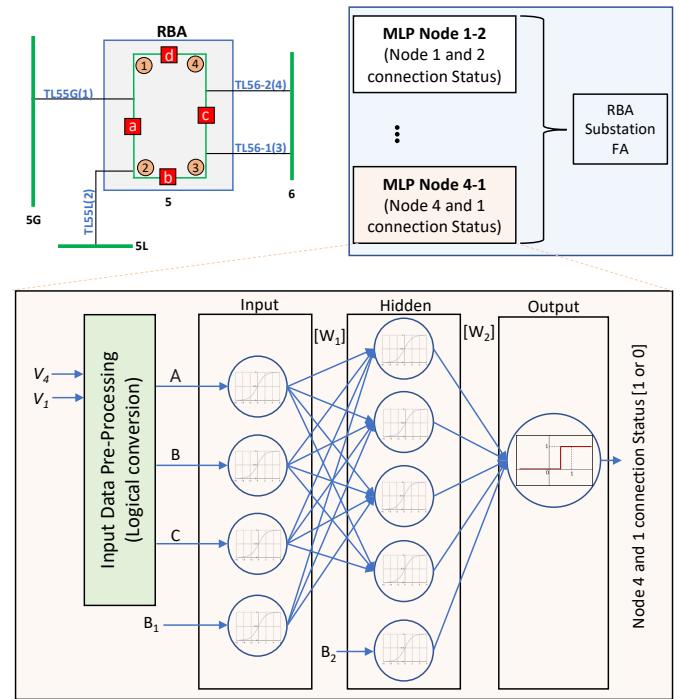


Fig. 7. The neural network structure of the MLP based substation configuration identification developed for a four-node RBA substation shown in Fig. 1 (b).

$$Y_{X,Y} = f(A, B, C, B_1, [W_1], B_2, [W_2]) \quad (1)$$

C. Single Bus Arrangement (SBA)

SBA substation with six branches considered as the test case, which is shown in Fig. 1 (c). Branch current phasor measurements (circled in purple) and bus voltage phasor measurements (circled in orange) are in place as shown in Fig. 1 (c). All FA configurations of the SBA can be derived considering circuit nodal analysis using branch currents and the bus voltage. In the SBA substation, each branch current availability is considered to identify the branch connectivity to the bus which is connected through the breaker. It is important to defined the branch current availability rule based on the system expert knowledge about the current measurements for a no-load line vs disconnected branch. Combining the branch connection status with the bus voltage to identify the single bus isolation to confirm the substation is in service or not will be used to derive the Fa for the SBA. The SBA SCI method identify FAs as shown in Fig. 8 flow diagram.

For SBA substation arrangement, an LDM can be setup by following the procedure shown in the Fig. 8 or a MLPs can be trained as shown in Fig. 9 using the generic pre-generated training data as shown in TABLE II by following the flow diagram shown in Fig. 8 to identify FAs. Furthermore for SBA, each branch is considered by a single LDM or MLP, which takes bus voltage phasor and branch current phasor as input to identify the branch status and eventually derive the FAs.

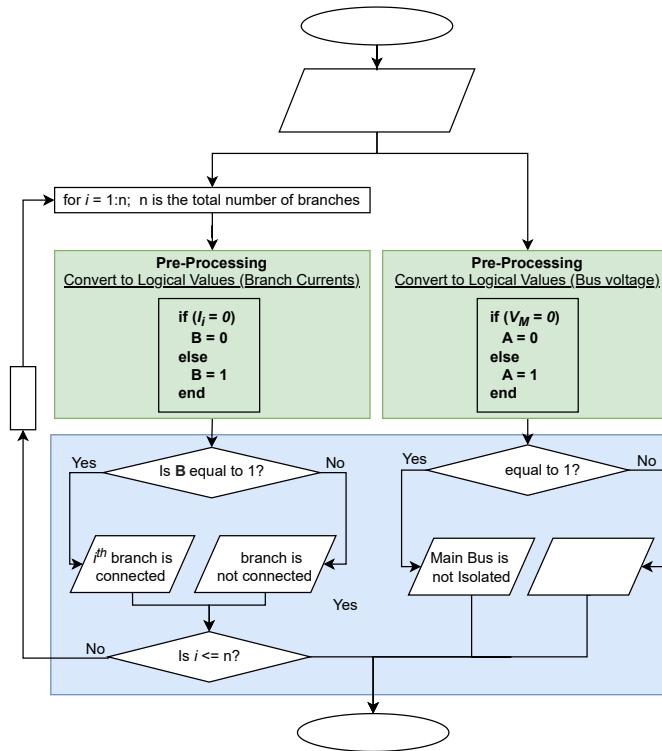


Fig. 8. A flow diagram for substation configuration identification of functional arrangement of SBA type substation.

as explained by the Fig. 9. MLP module use to identify the connectivity of i^{th} branch of SBA can be summarized into (2).

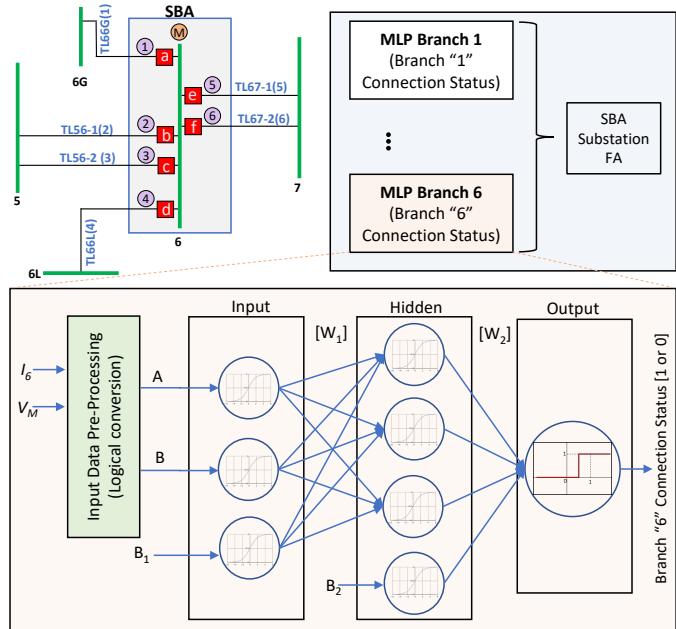


Fig. 9. The neural network structure of the MLP based substation configuration identification developed for six branch SBA substation shown in Fig. 1 (c).

TABLE II
TRAINING DATASET OF MLP FOR BRANCH i CONNECTIVITY OF SBA SUBSTATION.

Inputs		Output
B	A	Branch i Connection Status
1	1	1
0	1	0
0	0	0

$$Y_i = f(A, B, B_1, [W_1], B_2, [W_2]) \quad (2)$$

IV. RESULTS & DISCUSSION

A modified two-area four-machine power system model is shown in Fig. 10. The model consists of four conventional power plants at substation 5G, 6G, 10G and 11G and two RES based grid connected solar power plants at substation 12 and 13 instead of single generators in the original model [22]. The loads are distributed through load distributions substations 5L, 6L, 7L, 9L, 10L and 11L. Substation 5L is configured as MTBA, substation 6 configured as SBA and substation 5 is configured as RBA as shown in Fig. 1. The simulation of the power system is carried out on the real-time digital simulator (RTDS). All measurements are obtained using PMUs.

MTBA, RBA and SBA substation arrangements are simulated on the RTDS simulator. The simulation PMU measurements is used to test the LDM and NN based SCIs proposed in section III. The SCI methods are developed in MATLAB. All possible substation FAs derived from the SCIs are cross-checked with the actual substation FAs in the test cases including unstable power system operation caused by some substation configurations, due to exceeding the (n-1) contingency level. Under all these operating conditions, substation configurations are checked. The SCI accuracy is not affected by the state of the power system. The TABLE III shows the SCI accuracy for the MTBA, RBA and SBA substation types. Computation time for LDM and NN for all three substation types estimated for single PMU frame processing is shown in TABLE IV. The timing values are in the TABLE IV are based on the same computational platform (The testing platform is a consist of Intel Xeon(R) Gold 3.3GHz with 63.7GB RAM). The computational timing is not a stable metric to estimate the computational efficiency, since it is based on the computational platform. Thus, a time ratio index is introduced. The time ratio index is the ratio between the LDM computation time and the NN computation time, which normalize the dependency on the computational platform. Based on the time ratio index, it is identified that for MTBA substation arrangement efficiency is close in both LDM and NN and for RBA and SBA substation types NN is efficient.

The FAs for MTBA are shown in Fig. 11. There are two FAs. (i) case connects both Main and Transfer bus together and the (ii) case separate main and transfer bus and connect all the branches to the transfer bus, which isolate the main bus from the system.

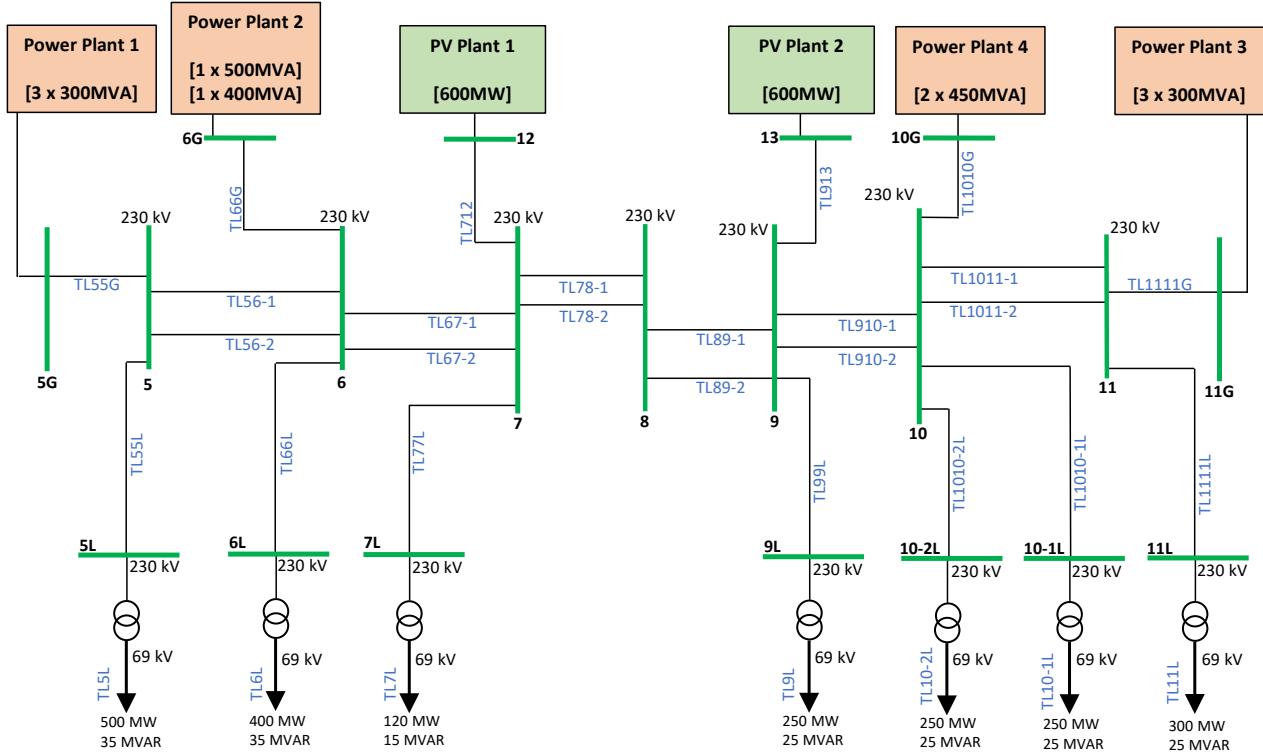


Fig. 10. Test Case: Modified Two-Area Four-Machine Power System with renewable energy sources.

TABLE III
SUBSTATION CONFIGURATION IDENTIFICATION ACCURACY OF THE LDM AND NN APPROACHES FOR THE TEST CASES MTBA, RBA AND SBA SUBSTATIONS SHOWN IN FIG. 1.

Substation Type	Substation ID	Number of Breaker	CAs	FAs	SCI Accuracy
MTBA	5L	3	8	2	100%
RBA	5	4	16	11	100%
SBA	6	6	64	64	100%

TABLE IV
COMPUTATION PERFORMANCE OF THE LDM AND NN APPROACHES FOR THE TEST CASES MTBA, RBA AND SBA SUBSTATIONS SHOWN IN FIG. 1

Substation Type	Substation ID	Computation Time (us)		Time Ration Index ($t(\text{LDM})/t(\text{NN})$)
		LDM	NN	
MTBA	5L	27.98	26.73	1.04
RBA	5	77.35	51.56	1.50
SBA	6	130.45	84.67	1.54

The FAs for RBA substation are shown in Fig. 12. There are total of twelve FAs possible for a four-node RBA substation. Which can be described under five categories as shown in Fig. 12. (i) category shows all branches are connected together through the RBA substation. This scenario can be occurred under five different CAs as shown, where all four breakers are closed or in any single breaker opened cases, which result in the same FA. (ii) category shows a single branch is disconnected from the substation. There are four possible CAs and respective four FAs in four-node RBA substation. Any two consecutive breakers can be opened to disconnect a single

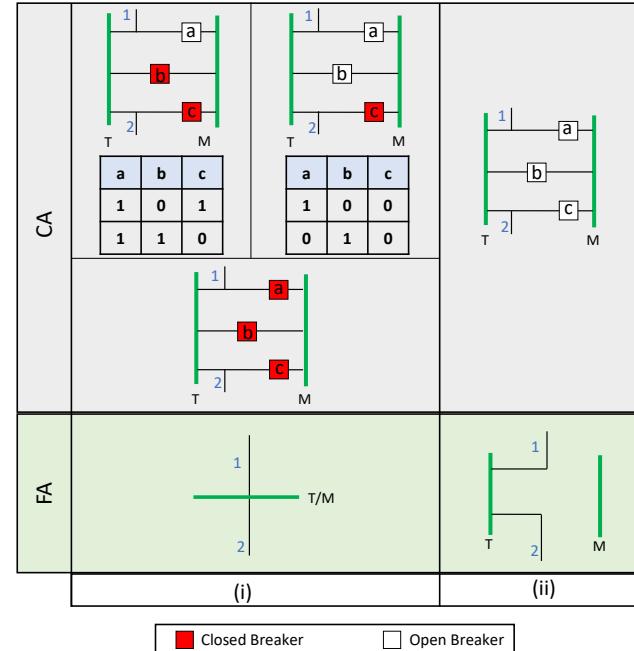


Fig. 11. Identified functional arrangements using proposed substation configuration identification approaches for the MTBA substation shown in Fig. 1 (a).

branch from the RBA substation. This characteristic of the RBA substation improve the substation reliability, where single

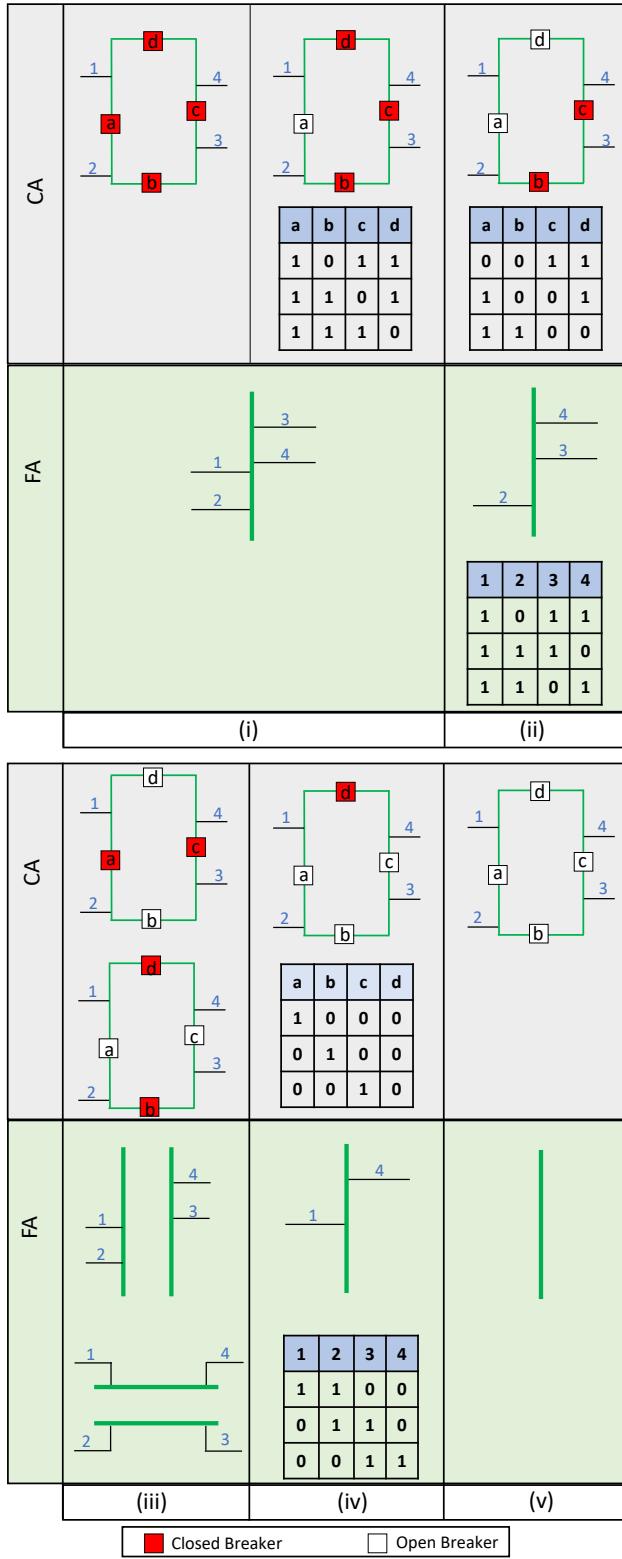


Fig. 12. Identified functional arrangements using proposed substation configuration identification approaches for the RBA substation shown in Fig. 1 (b).

breaker malfunction won't affect the power system operation.

(iii) category shows system separation conducted by the RBA substation. This characteristics can be used for islanding part of the power system or limit cascading power system failures. In the four-node RBA, there are two possible system separation CAs and respective two FAs. These two separation can be done either opening only breakers "a" and "c" or breakers "b" and "d". (iv) category shows two consecutive branches were disconnected from the system in four-node RBA substation by opening three consecutive breakers. There are four possible CAs and respective four FAs. (v) category shows the four-node RBA substation is isolated from the power system by disconnecting all branches from the substation. This scenario can be occurred under major maintenance or a post blackout scenario. There is a single CA resulted under this category and the a respective single FA.

The FAs for SBA substation are shown in Fig. 13. Under SBA, all branches are connected through a common node. SBA arrangement is used in non-priority substation due to lack of reliability. There are 64 different CAs and respective 64 FAs in the six-branch SBA test case. As mentioned in the Section II - subsection C, SBA CAs are identical to FAs. These 64 FAs can be considered under seven categories as shown in Fig. 13. (i) category shows all the branches connected to the substation single bus. There is one possible FA. (ii) category shows single breaker is opened, which result in single branch disconnected from the substation. There are six possible FAs. (iii) category shows any two breakers are opened simultaneously, which result in two branches disconnected from the substation. There are 15 possible FAs. (iv) category shows any three breakers are opened simultaneously, which result in three branches disconnected from the substation. There are 20 possible FAs. (v) category shows any four breakers are opened simultaneously, which result in four branches disconnected from the substation. There are 15 possible FAs. (vi) category shows any five breakers are opened, which result in five branches disconnected from the substation. There are six possible FAs. (vii) category shows all six breakers are opened, which result in substation isolation from the power system. There is one possible FA.

V. CONCLUSION

Artificial intelligence based approaches for power system substation configuration identification for main and transfer bus arrangement, ring bus arrangement, and single bus arrangement has been presented in this paper. AI based approaches for substation configuration identifications were developed offline with the knowledge of the physical structure of the substation arrangement type and number of branches or bus-sections (nodes). The AI based substation configuration identifications were implemented and tested using data from phasor measurement units collected on a real-time simulation of a modified two-area four-machine power system model with two grid connected solar PV plants. The substation functional arrangements were identified accurately and fast for different power system operating states. Ongoing studies include extension of AI approaches for more complex substa-

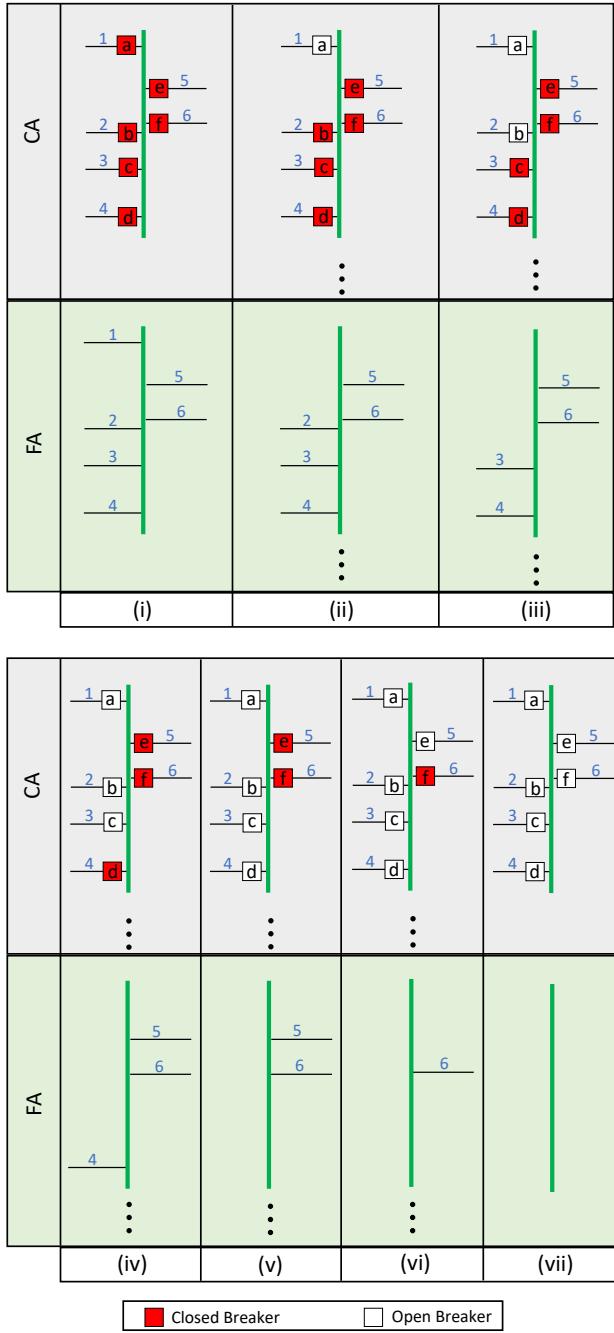


Fig. 13. Identified functional arrangements using proposed substation configuration identification approaches for the SBA substation shown in Fig. 1 (c).

tion arrangements and integrating the substation configuration identification into the transmission network topology processor for energy management system applications.

REFERENCES

- [1] Power World Corporation, "Unified Power System Models through Integrated Topology Processing (ITP)," <https://www.powerworld.com/files/PowerWorld-Integrated-Topology-Processing1.pdf>, [Last visited: 18-Feb-2022].
- [2] S. Grijalva, "Direct utilization of planning applications in the real-time environment," in *2008 IEEE/PES Transmission and Distribution Conference and Exposition*, 2008, pp. 1-6.
- [3] M. Farrokhabadi and L. Vanfretti, "State-of-the-art of topology processors for ems and pmu applications and their limitations," in *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, 2012, pp. 1422-1427.
- [4] L. Zhang, A. Bose, A. Jampala, V. Madani, and J. Giri, "Design, testing, and implementation of a linear state estimator in a real power system," *IEEE Transactions on Smart Grid*, vol. 8, no. 4, pp. 1782-1789, 2017.
- [5] B. Park, J. Holzer, and C. L. DeMarco, "A sparse tableau formulation for node-breaker representations in security-constrained optimal power flow," *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 637-647, 2019.
- [6] T. Wu, Z. Alaywan, and A. Papalexopoulos, "Locational marginal price calculations using the distributed-slack power-flow formulation," *IEEE Transactions on Power Systems*, vol. 20, no. 2, pp. 1188-1190, 2005.
- [7] A. V. Ramesh, X. Li, and K. W. Hedman, "An accelerated-decomposition approach for security-constrained unit commitment with corrective network reconfiguration," *IEEE Transactions on Power Systems*, vol. 37, no. 2, pp. 887-900, 2022.
- [8] M. Kezunovic, "Monitoring of power system topology in real-time," in *Proceedings of the 39th Annual Hawaii International Conference on System Sciences (HICSS'06)*, vol. 10, 2006, pp. 244b-244b.
- [9] G. Liang, S. R. Weller, J. Zhao, F. Luo, and Z. Y. Dong, "The 2015 ukraine blackout: Implications for false data injection attacks," *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 3317-3318, July 2017.
- [10] G. Liu, C. Yuan, X. Chen, J. Wu, R. Dai, and Z. Wang, "A high-performance energy management system based on evolving graph," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 67, no. 2, pp. 350-354, 2020.
- [11] M. A. Judge, A. Manzoor, F. Ahmed, S. Kazmi, Z. A. Khan, U. Qasim, and N. Javaid, "Monitoring of power transmission lines through wireless sensor networks in smart grid," in *Innovative Mobile and Internet Services in Ubiquitous Computing*, L. Barolli and T. Enokido, Eds. Cham: Springer International Publishing, 2018, pp. 162-170.
- [12] K. D. Jones, J. S. Thorp, and R. M. Gardner, "Three-phase linear state estimation using phasor measurements," in *2013 IEEE Power Energy Society General Meeting*, 2013, pp. 1-5.
- [13] J. De La Ree, V. Centeno, J. S. Thorp, and A. G. Phadke, "Synchronized phasor measurement applications in power systems," *IEEE Transactions on Smart Grid*, vol. 1, no. 1, pp. 20-27, June 2010.
- [14] M. Delimar, I. Pavic, and Z. Hebel, "Artificial neural networks in power system topology recognition," in *The IEEE Region 8 EUROCON 2003. Computer as a Tool.*, vol. 2, 2003, pp. 287-291 vol.2.
- [15] D. M. V. Kumar and S. C. Srivastava, "Power system network topology processing based on artificial neural networks," *Electric Machines & Power Systems*, vol. 26, no. 3, pp. 249-263, 1998. [Online]. Available: <https://doi.org/10.1080/07313569808955820>
- [16] G. Korres, P. Katsikas, and G. Chatzarakis, "Substation topology identification in generalized state estimation," *International Journal of Electrical Power & Energy Systems - INT J ELEC POWER ENERG SYST*, vol. 28, pp. 195-206, 03 2006.
- [17] M. Heidarifar and H. Ghasemi, "A network topology optimization model based on substation and node-breaker modeling," *IEEE Transactions on Power Systems*, vol. 31, no. 1, pp. 247-255, 2016.
- [18] J. D. McDonald, *Electric Power Substations Engineering*, third edition ed. CRC Press, 2012.
- [19] NERC, "Node-Breaker Modeling Representation," <https://www.nerc.com/comm/PC/Model%20Validation%20Working%20Group%20MVG%202013/December%202016%20-%20Node%20Breaker%20Model%20Representation%20Webinar.pdf>, [Last visited: 15-April-2022].
- [20] Q. Wang and S. Bu, "Deep learning enhanced situation awareness for high renewable-penetrated power systems with multiple data corruptions," *IET Renewable Power Generation*, vol. 14, no. 7, pp. 1134-1142, 2020.
- [21] G. K. Venayagamoorthy, "Computational approaches for bad data handling in power system synchrophasor networks," *IFAC Proceedings Volumes*, vol. 47, no. 3, pp. 11 269-11 274, 2014, 19th IFAC World Congress. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1474667016434075>
- [22] P. Kundur, "Power system stability and control," McGraw-Hill, 1994.