Real-Time System Strength Estimation using PMU Data for Modern Grids with High IBR Penetration

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***Abstract*—With the increasing penetration of Inverter-Based Resources (IBRs) in power grids, real-time estimation of system strength has become a critical requirement for system operators to ensure grid stability and reliability. This paper introduces a robust method for system strength estimation using Phasor Measurement Unit (PMU) data, eliminating the need for model-based information. The proposed approach leverages Thevenin equivalent parameters to evaluate system strength at a specific bus. To address the phase angle drift in voltage and current measurements caused by continuous system frequency variations, corrections are applied, followed by synchronization of three consecutive phasor measurements to a common reference frame. These synchronized measurements are used to compute Thevenin equivalent parameters. Key features of the proposed method include a novel directional detection algorithm that addresses the impact of power flow directions on system strength estimation, ensuring accurate real-time evaluation. Unlike previously published literature, which primarily focused on system strength estimation at load buses, this method provides a comprehensive approach applicable across various operating scenarios. Additional enhancements, such as outlier removal through advanced filtering techniques, further improve the robustness and practical applicability of the approach. Validation using actual field PMU data from 161 kV, 275 kV and 500 kV systems demonstrates its effectiveness, while integration into a Wide Area Monitoring System (WAMS) platform underscores its readiness for operational use. Results from simulations and field data confirm the reliability and accuracy of the method for real-time applications in modern grids.**

***Index Terms*—Inverter based resources (IBRs), phasor measurement units (PMUs), system strength, short circuit capacity (SCC).**

I. Introduction

With the increasing penetration of renewable energy sources, which often lack physical rotating masses, the system strength of the grid is reducing, thereby posing new challenges in terms of system reliability. Synchronous generators are a major source of system strength. The system strength was produced as a byproduct when electric power was generated by synchronous generators. As Inverter based resources (IBRs) such as wind and solar plants replacing synchronous generators, the power grid is no longer strong enough to support stable operation of power system. The system strength at a given location is inversely proportional to inverter-based resource (IBR) penetration at that location [1]. The higher the penetration of IBR, more likely system will experience increased system frequency and voltage deviation following a disturbance.

System strength is defined as the ability of a power system to maintain stable voltage levels and support large power flows under various operating conditions, ensuring reliable and secure grid operation. The system strength describes the stiffness of the grid in response to small perturbations [2]. The change in voltage and other variables due to disturbance is small in case of stronger system. Low system strength leads to generator-fault ride-through failures, protection relay malfunctions, and fault-induced voltage recovery delay etc [3]. On 28th September 2016, Blackout occurred in South Australia (SA) region of National Electricity Market (NEM). The Australian Energy Market Operator (AEMO) investigated this event and published a report [4]. In [4], AEMO suggested that sufficient system strength is required to control over voltages, and to make sure correct operation of protection systems and IBRs.

Reference [5] reviewed NEM operating procedures which address the potential issues of system strength and inertia shortage. In [5], system strength was discussed including definition, concern, mitigation and quantification techniques. The authors in [6] reviewed system strength measurement techniques with integration of large number of IBRs in the power system. This paper also discussed mitigation strategies, future challenges, and research directions for system strength shortfalls. References [7], [8] developed algorithm to find optimal size and location of synchronous condenser to improve the system strength of wind dominated grid by considering the long-term financial viability. In [8], the post-fault voltage recovery capability is also investigated to choose between Static VAR Compensator (SVC) and synchronous condenser. The authors in [7] proposed weighted short circuit ratio (WSCR) concept to determine system strength for wind integrated grid. They investigated that commonly used short circuit ratio approach gives overly-optimistic value of system strength in wind dominated grid. Reference [9] proposed recursive least square method to estimate TE parameters for voltage stability problem.

With the increasing installations of phasor measurement units (PMUs) in the grid, system strength can be estimated using PMU data. Typically modelling is based on Thevenin equivalent (TE) parameters calculation [10]–[16] using PMU data. Reference [10] developed PMU measurements based improved recursive approach to determine TE parameters using differential variable to reflect parameters change. The

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authors in [11], [12] proposed least square optimization technique for estimating short circuit current using synchronized phasor measurements obtained during normal load variation. Reference [13] presented Thevenin equivalent based method to identify fault location for series compensated line using PMU measurements. It is reported in [13] that the method gives significant error to locate fault in case of line parameter uncertainty.

References [15], [16] developed algorithm to determine online TE parameters using three consecutive PMU measurements. The authors in [17] proposed angle sensitivity based method for estimation of system strength using PMU measurements. This method is validated by comparing results with WSCR approach using field PMU data. Reference [14] proposed algorithm to estimate TE parameters and system inertia constant using PMU data. The authors in [18] developed machine learning based forecasting technique for system strength estimation. The methodology developed in [18] has ability to predict system strength for next seven days by using last thirty days datasets.

References [19], [20] derived new indices network response short circuit ratio (NRSCR) and interactive short circuit ratio (ISCR) to assess system strength for IBR dominated grid. There are several metrics used to evaluate the power system strength with wind farms; they are short circuit capacity (SCC), short circuit ratio (SCR), effective short circuit ratio (ESCR), and weighted short circuit ratio (WSCR). In this paper, SCC has been used as index to determine system strength. The SCC is capacity of the system to supply power or current during faults. It provides an absolute measure of system strength and measured in MVA or per unit (PU). It can be calculated using Thevenin equivalent voltage and impedance.

The aim of this paper is to enhance the methodology referred to in [16] for system strength estimation, focusing on its applicability with real field measurement data from PMUs. Unlike many published studies that rely on simulated data, this paper emphasizes the use of practical measurement data to develop a robust technique for system strength estimation. Building upon the approach reported in [16], where TE parameters are calculated using three consecutive voltage and current measurements, the proposed method enhances to account for system frequency variations by correcting drift in voltage and current phase angles. Additionally, it incorporates an advanced filtering process for outlier removal and introduces a novel concept to detect the instantaneous direction of input and output phasor currents at each bus, ensuring practical applicability. The performance of the method is validated using both field PMU data and simulation results, demonstrating its effectiveness in real-world scenarios.

The organization of rest of the paper is as follows. Section II describes the methodology to estimate system strength using PMU measurements. Section III discusses case studies with simulation and field PMU data. Section IV concludes the work.

II. Methodology

The source side of power system can be represented by Thevenin equivalent circuit consists of single Thevenin voltage source in series with Thevenin impedance. Consider the Thevenin equivalent circuit as shown in Fig. 1.

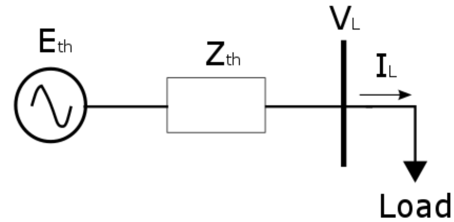


Fig. 1. Thevenin Equivalent Circuit.

For the system shown in Fig. 1, the relationship between voltage and current is

$$V_L = E_{th} - Z_{th} I_L \tag{1}$$

Estimating Thevenin equivalent using PMU data typically requires at least two voltage and current phasor measurements under different loading conditions. However, due to small variations in system frequency, and in order to synchronize the samples to the same time frame reference, two measurements are insufficient. Therefore, three measurements are used to address this limitation. System frequency fluctuations cause phase angle drift due to the slip frequency between the system frequency and PMU sampling frequency. To resolve this, a method is developed to correct phase angles and synchronize all three measurements to a common reference using triangulation.

The steps for calculating system strength using the proposed PMU-based method are:

1) Collect voltage (V) and current (I) data from PMUs.
2) Select three samples of V and I, remove spikes, and validate the data.
3) Validate the directional power flow, determine input, and output current phasors
4) Correct phase angle drift for all three samples.
5) Synchronize the samples to a common time frame.
6) Estimate Thevenin equivalent parameters E_{th} and Z_{th}.
7) Evaluate System Strength.

Fig. 2 illustrates the algorithm for determining system strength with the proposed method. To remove outliers or spikes in input voltage and current data, a median filter is used. This filter will remove all voltage and current values which are not in the range of $\pm 3\sigma$ (σ = standard deviation) from the median value.

A. Impact of Power Flow Direction on System Strength

The assessment of system strength plays a critical role in maintaining grid stability, particularly in systems with varying power flow patterns. System strength quantifies the ability of a power system to maintain voltage stability and ensure robust operation under different loading and fault scenarios. This section explores the impact of power flow direction on system strength under three distinct cases: a simple two-bus system, a tie-line system, and a meshed network.

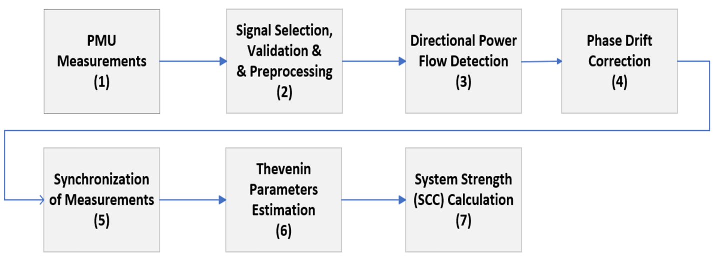


Fig. 2. Proposed Algorithm for System Strength Calculation.

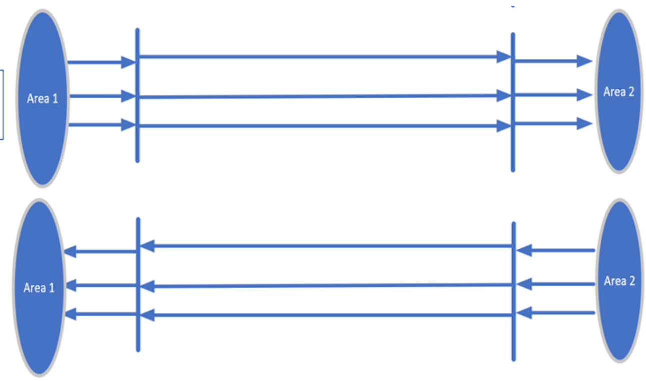


Fig. 4. Tie line system with two Areas import or exporting.

1) Simple Two-Bus System: In a simple two-bus system (Fig. 3) with load connected at one end (Bus 2), the power flow is unidirectional, flowing from the source at Bus 1 to the load at Bus 2. Since the load is fixed at Bus 2, the direction of power flow remains constant. As a result, the system strength calculations are unaffected by power flow direction in this scenario. This case demonstrates a straightforward relationship between system topology and system strength, where the absence of power flow reversals simplifies the computational process.

Fig. 3. Simple two bus system with unidirectional power flow to the load

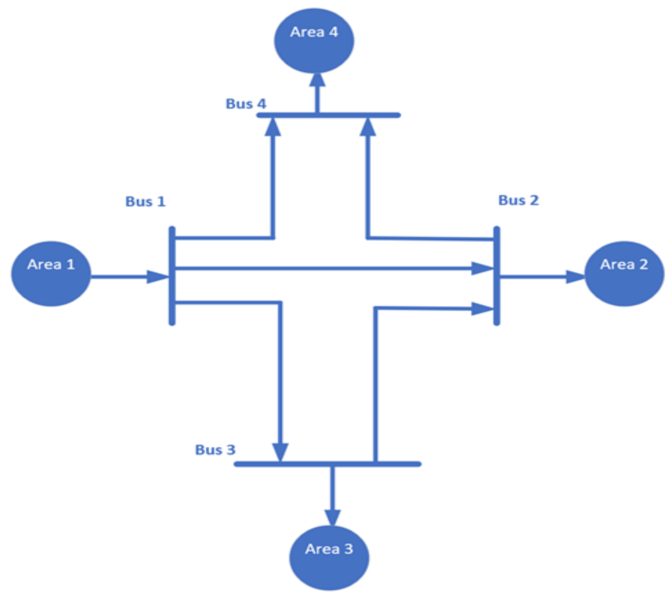


Fig. 5. Meshed Network with changing power flow directions.

2) Tie-Line System: In the case of a tie-line configuration (Fig. 4) connecting two areas, Area 1 and Area 2, the direction of power flow depends on the export or import dynamics between these areas. For example, if Area 1 is exporting power, the flow direction is from Area 1 to Area 2, and vice versa when Area 2 is exporting. Despite these variations in power flow direction, the system strength calculations remain consistent. However, the roles of load and generation may shift depending on the direction of power exchange between the two areas. This case highlights the importance of distinguishing between the functional roles of different areas in the network while maintaining accurate system strength assessments.

3) Meshed Network: A meshed network (Fig. 5) introduces complexity due to the interconnection of multiple buses, where power flow direction can change dynamically. Unlike the previous cases, system strength calculations in a meshed network are sensitive to variations in power flow direction. Accurate estimation of system strength at a specific bus requires a mechanism to detect the direction of input and output currents. This ensures that the appropriate set of current data either input or output is utilized in the final calculation.

To address this challenge, a unique direction detection algorithm is employed to identify the instantaneous direction of input and output currents at each bus. This algorithm enables the proper classification of currents, ensuring that system strength calculations remain accurate under varying power flow conditions. By dynamically adapting to the changes in power flow direction, the algorithm guarantees reliable assessments of system strength across all scenarios.

The instantaneous detection of power flow direction at a given bus is achieved by leveraging PMU data, specifically voltage and current phasors. By estimating the active power for all elements connected to the bus, the direction of power flow can be determined. For each element connected to the Bus where the System Strength estimation is required, the active power is calculated using the voltage and current phasors. If the computed active power is negative, the corresponding element is categorized as an incoming line, indicating that power is flowing into the bus. Conversely, if the active power is positive, the element is classified as an outgoing line, signifying that power is flowing out of the bus. This classification of incoming and outgoing lines is critical for system strength estimation. The Thevenin's impedance, a key metric for assessing system strength, is estimated using either the currents from incoming lines or outgoing lines, depending on the analysis requirements. By incorporating the direction of power flow into this estimation process, the impact of power flow dynamics is inherently accounted for. This approach ensures a more accurate and representative assessment of system strength, as it reflects the real-time behaviour of the network power flow topology and the influence of power flow direction on the system's impedance characteristics.

In summary, the impact of power flow direction on system strength varies depending on the network configuration. While unidirectional and bidirectional systems (Cases 1 and 2) exhibit minimal sensitivity to power flow direction, meshed networks (Case 3) require advanced detection mechanisms to ensure accurate calculations. The integration of direction detection algorithms ensures robust system strength evaluations, supporting grid stability and reliability in diverse operational conditions.

B. Triangulation of PMU Measurements

This method assumes that there is no noticeable change in grid side of the system during time span of three measurements under consideration. The necessary and sufficient condition for the unique Thevenin equivalent of a system at a given location using a set of three different measurements at that given location can be expressed as,

$$det \begin{bmatrix} 1 & 1 & 1 \\ V_1 & V_2 & V_3 \\ I_1 & I_2 & I_3 \end{bmatrix} = 0 \tag{2}$$

where, subscripts 1, 2 and 3 refer to the first, the second and the third measurements, respectively. All measurements are in positive sequence domain. Assume that the drift in phase angle for second (V_2, I_2) and third measurements (V_3, I_3) are $-\alpha_1$ and α_2, respectively. Therefore, second and third measurement phasors synchronized to reference phasor will be $(V_2 e^{j\alpha_1}, I_2 e^{j\alpha_1})$ and $(V_3 e^{-j\alpha_2}, I_3 e^{-j\alpha_2})$, respectively. Now, above equation can be written as,

$$det \begin{bmatrix} 1 & 1 & 1 \\ V_1 & V_2 e^{j\alpha_1} & V_3 e^{-j\alpha_2} \\ I_1 & I_2 e^{j\alpha_1} & I_3 e^{-j\alpha_2} \end{bmatrix} = 0$$

$$\therefore det \begin{bmatrix} 1 & e^{-j\alpha_1} & e^{j\alpha_2} \\ V_1 & V_2 & V_3 \\ I_1 & I_2 & I_3 \end{bmatrix} = 0 \tag{3}$$

Expanding above equation (3), we have

$$A + Be^{-j\alpha_1} + Ce^{j\alpha_2} = 0 \tag{4}$$

where, A, B, and C are complex numbers given by,

$$A\angle\delta_a = V_2 I_3 - V_3 I_2,$$

$$B\angle\delta_b = V_3 I_1 - V_1 I_3,$$

$$C\angle\delta_c = V_1 I_2 - V_2 I_1.$$

Phase angle drifts α_1 and α_2 can be derived by triangulating the A, B, and C vectors as shown in Fig. 6. Now taking A as reference,

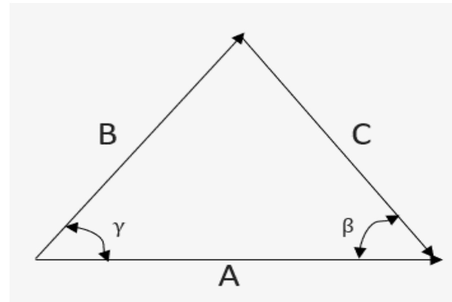


Fig. 6. Triangulation of the PMU Measurements.

$$A = A \times e^{j\delta_a - j\delta_a},$$

$$B = B \times e^{j\delta_b - j\delta_a},$$

$$C = C \times e^{j\delta_c - j\delta_a},$$

Now applying cosine rule, the angles γ and β can be calculated as,

$$\gamma = \cos^{-1}\left(\frac{|C|^2 - |A|^2 - |B|^2}{2|A||B|}\right),$$
$$\beta = \cos^{-1}\left(\frac{|B|^2 - |A|^2 - |C|^2}{2|A||C|}\right) \tag{5}$$

Having γ and β, phase angle shift α_1 and α_2 can be determined as,

$$\alpha_1 = \gamma + \delta_b,$$
$$\alpha_2 = \beta - \delta_c \tag{6}$$

Once α_1 and α_2 are calculated, the Thevenin equivalent impedance and voltage can be calculated using any two pairs of voltages and current measurements.

$$Z_{th} = \frac{V_1 - V_2 e^{j\alpha_1}}{I_1 - I_2 e^{j\alpha_1}} = \frac{V_1 - V_3 e^{-j\alpha_2}}{I_1 - I_3 e^{-j\alpha_2}} \tag{7}$$

$$E_{th} = V_1 - Z_{th} I_1 = (V_2 - Z_{th} I_2) e^{j\alpha_1} \tag{8}$$

Once Z_{th} and E_{th} is known, short circuit capacity (SCC) can be determined as,

$$\text{SCC} = \frac{|E_{th}^2|}{|Z_{th}|} \tag{9}$$

III. Results and Discussions

Multiple case studies have been carried out with both simulation and field PMU data to check the effectiveness of the proposed method. We first discuss the simulation test cases. Subsequently, we show validation of the proposed method with field PMU data.

A. Simulation Results

The proposed method is implemented on simulated PMU data for WSCC 9 bus system. The ATP/EMTP software is used to model WSCC 9 bus system. All the generators are modelled as constant voltage sources. Table I shows the calculated TE parameters and SCC values for bus 1, bus 6, and bus 8 in case of WSCC 9 bus system. It is seen that both TE parameters and SCC values estimated with proposed approach are very close to simulation values. Further, several simulations for different switching events such as generator outage, transmission line outage, load outage have been carried out to check the performance of proposed algorithm. It can be seen from the Table II that both TE parameters and SCC values estimated with proposed method are closely matching with that determined with simulations.

TABLE I
ESTIMATED SCC AND TE PARAMETERS USING PROPOSED METHOD FOR WSCC 9 BUS SYSTEM.

Bus Details	Parameters	Simulation Value (pu)	Proposed Method Value (pu)
Bus 1	$\lvert Z_{th}\rvert$	0.2987	0.2974
	$\lvert E_{th}\rvert$	1.0452	1.0478
	SCC	1.3673	1.3797
Bus 6	$\lvert Z_{th}\rvert$	0.1301	0.1321
	$\lvert E_{th}\rvert$	1.0039	1.0024
	SCC	7.7461	7.6085
Bus 8	$\lvert Z_{th}\rvert$	0.0986	0.0987
	$\lvert E_{th}\rvert$	1.0538	1.0536
	SCC	11.2595	11.2455

TABLE II
ESTIMATED SCC AND TE PARAMETERS WITH DIFFERENT SWITCHING EVENTS USING PROPOSED METHOD FOR BUS 6 IN CASE OF WSCC 9 BUS SYSTEM.

Case	Parameters	Simulation Value (pu)	Proposed Method Value (pu)
Generator 2 outage	$\lvert Z_{th}\rvert$	0.1492	0.1562
	$\lvert E_{th}\rvert$	0.9548	0.9536
	SCC	6.1102	5.8209
Line 7-8 outage	$\lvert Z_{th}\rvert$	0.1319	0.1292
	$\lvert E_{th}\rvert$	0.9747	0.9751
	SCC	7.2037	7.3594
Bus 5 50% load cut	$\lvert Z_{th}\rvert$	0.1304	0.1324
	$\lvert E_{th}\rvert$	1.0118	1.0115
	SCC	7.8488	7.7284

B. Field Results

The performance of proposed method is also checked on real field PMU data obtained from different utilities for key substations. The proposed method gives real time system strength estimation every second. It requires 3 samples of voltage and current phasors to calculate system strength. Hence, if sample rate is 30 samples per second (60 Hz system) and there is no bad data then 10 values of TE parameters and SCC are calculated per second. By taking an average of these 10 values, one value is generated every second.

The field PMU data have been collected over period of 5 minutes to test the proposed approach. Fig. 7 shows the estimated Thevenin equivalent voltage, impedance, and SCC value for one of 500 kV Substation (named as Substation 1) of Utility 1. It is observed that proposed method estimates SCC value almost same to simulated SCC value provided by Utility 1. Further, Fig. 8 shows the estimated TE parameters and SCC value for IBR connected bus at 161 kV Substation (named as Substation 2) of Utility 1. It can be seen that estimated mean value of SCC is close to value provided by Utility 1. Further, to validate the accuracy of proposed algorithm for different frequency systems, field PMU data from Utility 2 which is operating at 50 Hz (50 samples per second) were used. In this case, the data have been collected over period of 10 minutes to test the proposed approach. The estimated Thevenin equivalent voltage, impedance, and SCC value for one of 275 kV Substation (named as Substation 3) of Utility 2 is shown in the Fig. 9. It can be seen that the proposed method accurately estimates TE parameters and SCC value.

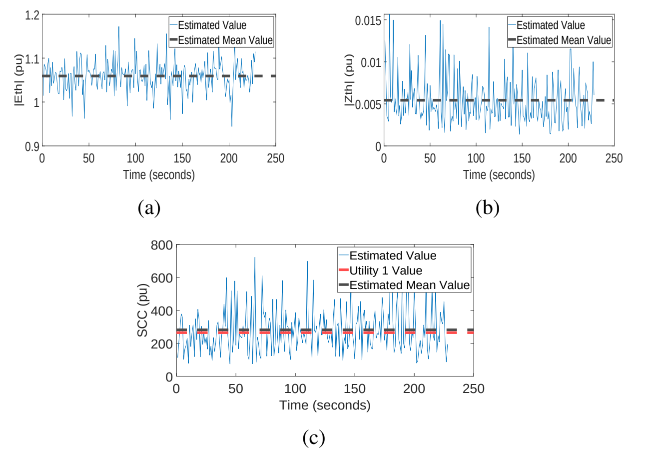
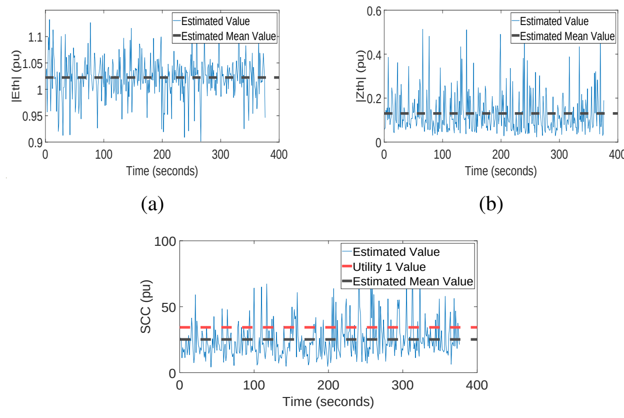


Fig. 7. Estimated TE parameters and SCC for 500 kV Substation 1 (a) E_{th} (b) Z_{th} (c) SCC.

We have validated TE parameters and SCC estimation with benchmark IEEE models like WSCC 9 bus system, IEEE 30 bus system. The estimated values with proposed method are closely matching with those simulation values. However, the utility simulated case contingency did not match with field PMU data and was confirmed with the utility. These discrepancies arise due to mismatches between the simulated system contingencies and actual field conditions, as well as potential modeling inaccuracies within the simulation framework. Addressing these issues requires careful validation of test case inputs and model parameters to align simulations more closely with real-world scenarios.

C. Challenges and Implementation Considerations

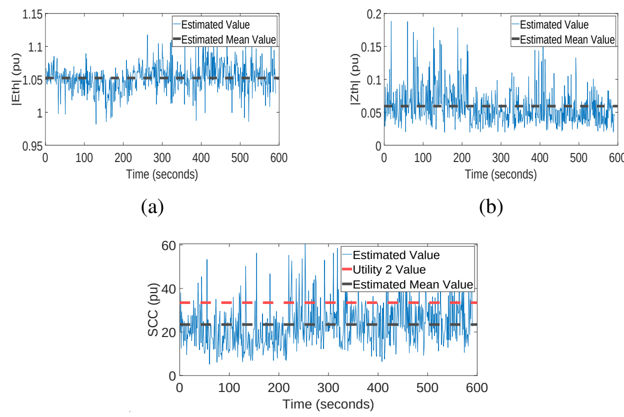
Real-time system strength monitoring using PMU data involves several operational challenges, especially across wide-



(a) (b)

(c)

Fig. 8. Estimated TE parameters and SCC for IBR connected 161 kV Substation 2 (a) E_{th} (b) Z_{th} (c) SCC.



(a) (b)

(c)

Fig. 9. Estimated TE parameters and SCC for 275 kV Substation 3 (a) E_{th} (b) Z_{th} (c) SCC.

area deployments. Network latency, data loss, and variable communication quality from remote PMUs can affect timely and synchronized data collection. Handling high-rate PMU streams (30 samples per second) demands robust bandwidth, buffering, and real-time processing infrastructure. Time synchronization inaccuracies due to GPS deviations can impact phasor alignment. High PMU volumes may overwhelm the Phasor Data Concentrator (PDC), leading to frame drops or processing delays. Computational loads may limit real-time performance, especially for advanced analytics. As deployments scale, maintaining execution speed while ensuring system redundancy becomes complex. These challenges highlight the need for fault-tolerant architecture, continuous performance monitoring, and scalable design strategies.

D. Architecture and Performance

The bock diagram of various components involved in architecture and the performance of real-time system strength execution process is depicted in the Fig. 10. The real-time system strength monitoring architecture comprises a sequential flow of data from PMUs to the end-user interface, through intermediate processing and analytics layers. This architecture

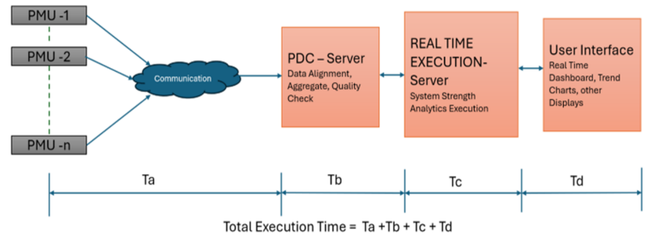


Fig. 10. Real-time system strength data flow architecture and execution time.

is designed to ensure accurate and timely situational awareness for grid operations using high-resolution synchrophasor data.

For this implementation, we have considered P-class PMUs operating at a 30 samples per second rate, which provides sufficient resolution for system strength monitoring and supports fast response requirements typically needed in operational environments. The total real-time execution time is composed of four main components:

1) Ta - PMU to PDC Communication Delay (150 ms): This includes the time for PMU measurements to traverse the communication network and reach the PDC Server. Based on statistical measurements from multiple deployments, a conservative estimate of 150 milliseconds is assumed, accounting for network variability.
2) Tb - PDC Data Alignment and Quality Processing Time (10 ms): Once data reaches the PDC, it undergoes alignment, aggregation, and quality checks. These processes are streamlined and optimized for minimal latency, with typical processing time observed to be around 10 milliseconds.
3) Tc - Real-Time Analytics Execution Time (50 ms): The aligned and validated PMU data is then processed in the Real-Time Execution Server. For system strength analyticssuch as Thevenin equivalent estimation, strength index calculations, and spatial aggregationa conservative processing time of 50 milliseconds is allocated.
4) Td - User Interface Update and Display Time (50 ms): The final step involves updating the user interface with real-time dashboards, trend plots, and visualization tools. Display rendering and communication overheads typically contribute to an additional 50 milliseconds.

Total Execution Time = Ta + Tb + Tc + Td = 150 ms + 10 ms + 50 ms + 50 ms = 260 milliseconds

This cumulative delay of 260 milliseconds ensures that grid operators are equipped with near-real-time visibility into power system strength metrics. These values reflect conservative estimates based on empirical data and system testing and are subject to variation depending on communication infrastructure, processing loads, and system architecture.

E. Real-Time Tool

The objective of System Strength Estimation Application project is to provide a sophisticated, real-time analytical tool specifically designed to estimate and monitor the system

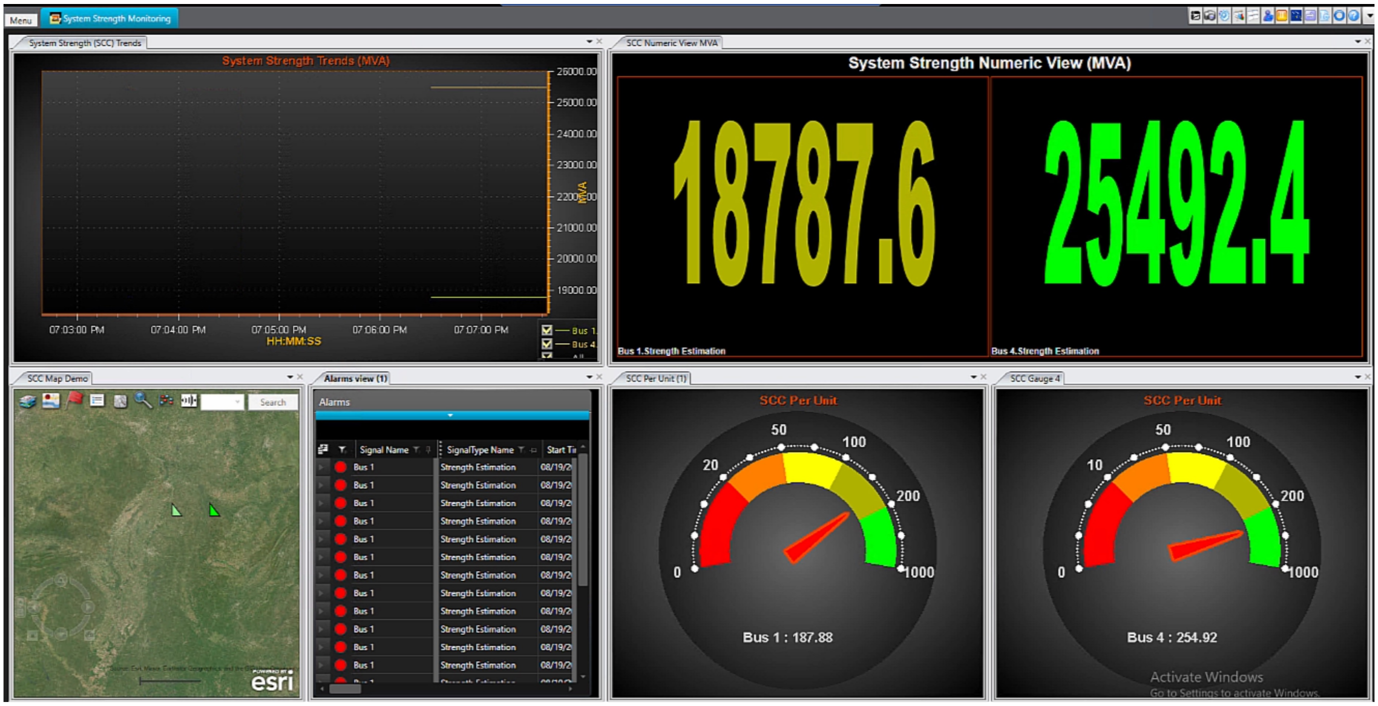


Fig. 11. System strength estimation visualization in the real-time tool integrated with Wide Area Monitoring platform.

strength. This tool will play a crucial role in ensuring the stability of the power grid as the region transitions towards more sustainable energy sources.The scope of work for this project includes the development and deployment of an application capable of utilizing advanced data analytics, particularly phasor measurement data, to accurately assess the strength of the system in real-time. This tool is not just a response to current needs but is designed with the foresight to adapt to future expansions and changes in the network topology, ensuring its long-term utility and relevance. The system strength tool is integrated with real-time Wide Area Monitoring System (WAMS) platform in use at grid operators and utilities around the world. Integration with WAMS provides operators and engineers to visualize analytics, results and alarms for system strength in conjunction with other real-time metrics and analytics such as monitoring of oscillations, inertia, phase angle differences etc.

System strength estimates can be visualized in real time using Geographical map view, Numerical displays, Gauge charts, and Trend charts. The Fig. 11 shows the SCC values on a trend chart in the top left. To the right of the map, the short circuit capacities of the system are shown in a numerical view. Below these views are the Short Circuit Capacity gauge, alarm panel, and system strength estimate on the map. These displays assist operators and engineers in control rooms to assess system strength at various key locations in the power grid and take preventive and corrective actions as required.

IV. Conclusion and Future Directions

System strength maintains frequency and voltage stability of power system following a disturbance. In this paper, a robust method to determine system strength using PMU measurements is presented. This method does not require any model and network data but use only voltage and current measurements obtained from PMUs. A drift in phase angles of voltage and currents caused by system frequency variation is also considered and corrected. The reference phasor concept is used to synchronize corrected three consecutive phasors to compute TE parameters. Further, the features like outlier removal using filter, a unique algorithm to identify the instantaneous direction of input and output currents at each bus, and consideration of system frequency variation are useful for practical applicability of this approach. The validation on simulation and field PMU data with IBR penetration shows the effectiveness and robustness of the proposed method.

While the current methodology focuses on real-time system strength monitoring for operational visibility and situational awareness, its potential extends beyond this immediate scope. Future directions include integrating this approach with dynamic stability assessments (DSA), adaptive protection schemes (APS), and real-time control strategies, especially in grids with high penetration of IBRs. The methodology could also support predictive grid analytics by correlating system strength trends with oscillation events, enabling proactive mitigation. Additionally, it may be adapted for resilience assessment during contingencies or cyber-physical disturbances, as the real-time system strength proposed in this paper provides ability to analyze real time Thevenins Equivalent network over wide area. As power systems evolve toward more decentralized and digital architectures, this framework can serve as a foundational layer for wide-area autonomous grid management. Far from being the end of exploration, this represents the beginning of broader applications where system strength becomes a key metric in intelligent grid operation.

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References

[1] A. E. M. Operator, "System strength in the nem explained," *AEMO Information & Support Hub*, 2020.

[2] NERC, "Integrating inverter-based resources into low short circuit strength systems," 2017.

[3] D. Sanford, "System strength requirements methodology system strength requirements & fault level shortfalls," 2018.

[4] A. E. M. Operator, "Black system south australia 28 september 2016," *Report of the Australian Energy Market Operator Limited (AEMO)*, 2017.

[5] H. Gu, R. Yan, and T. Saha, "Review of system strength and inertia requirements for the national electricity market of australia," *CSEE Journal of Power and Energy Systems*, vol. 5, no. 3, pp. 295–305, 2019.

[6] M. O. Qays, I. Ahmad, D. Habibi, A. Aziz, and T. Mahmoud, "System strength shortfall challenges for renewable energy-based power systems: A review," *Renewable and Sustainable Energy Reviews*, p. 113447, 2023.

[7] Y. Zhang, S.-H. F. Huang, J. Schmall, J. Conto, J. Billo, and E. Rehman, "Evaluating system strength for large-scale wind plant integration," in *2014 IEEE PES General Meeting— Conference & Exposition*. IEEE, 2014, pp. 1–5.

[8] S. U. Mahmud, M. N. Ansary, S. R. Deeba *et al.*, "Improvement of system strength under high wind penetration: A techno-economic assessment using synchronous condenser and svc," *Energy*, vol. 246, p. 123426, 2022.

[9] S.-J. S. Tsai and K.-H. Wong, "On-line estimation of thevenin equivalent with varying system states," in *2008 IEEE Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century*. IEEE, 2008, pp. 1–7.

[10] M. Wang, B. Liu, and Z. Deng, "An improved recursive assessment method of thevenin equivalent parameters based on pmu measurement," in *2011 IEEE Power Engineering and Automation Conference*, vol. 1. IEEE, 2011, pp. 372–375.

[11] S. C. Verma, Y. Nakachi, Y. Wazawa, Y. Kosaka, T. Kobayashi, K. Omata, and Y. Takabayashi, "Short circuit current estimation using pmu measurements during normal load variation," in *2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*. IEEE, 2012, pp. 1–5.

[12] T. Ogane, T. Nakajima, Y. Ota, Y. Nakachi, R. Yamaguchi, and S. Verma, "Pmu based short circuit capacity estimation and experimental verification on an analog simulator," in *2020 International Conference on Smart Grids and Energy Systems (SGES)*. IEEE, 2020, pp. 522–526.

[13] A. H. Al-Mohammed and M. Abido, "A fully adaptive pmu-based fault location algorithm for series-compensated lines," *IEEE Transactions on Power Systems*, vol. 29, no. 5, pp. 2129–2137, 2014.

[14] B. Alinejad and H. K. Karegar, "Online inertia constant and thévenin equivalent estimation using pmu data," in *2015 30th International Power System Conference (PSC)*. IEEE, 2015, pp. 106–110.

[15] S. Abdelkader *et al.*, "Online thevenins equivalent using local pmu measurements," in *Proc. Int. Conf. Renewable Energies and Power Quality*, 2010, pp. 1–4.

[16] S. M. Abdelkader and D. J. Morrow, "Online tracking of thévenin equivalent parameters using pmu measurements," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 975–983, 2012.

[17] T. Kim, A. F. Bastos, S. Santoso, W. M. Grady, P. Gravois, M. Miller, N. Kadel, J. Schmall, S. H. F. Huang, and B. Blevins, "Pmu-based evaluation of transmission bus strength through angle sensitivity metrics," in *2020 IEEE Power & Energy Society General Meeting (PESGM)*. IEEE, 2020, pp. 1–5.

[18] M. O. Qays, I. Ahmad, D. Habibi, and M. A. Masoum, "Forecasting data-driven system strength level for inverter-based resources-integrated weak grid systems using multi-objective machine learning algorithms," *Electric Power Systems Research*, vol. 238, p. 111112, 2025.

[19] S. O. Sanni, M. F. Akorede, and G. A. Olarinoye, "Strength assessment of electric power systems containing inverter-based distributed generation," *Electric Power Systems Research*, vol. 207, p. 107825, 2022.

[20] L. Liyanarachchi, N. Hosseinzadeh, A. Gargoom, and E. M. Farahani, "A new index for the assessment of power system strength considering reactive power injection and interaction of inverter based resources," *Sustainable Energy Technologies and Assessments*, vol. 60, p. 103460, 2023.