International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

A Novel AI-Blockchain-Edge Framework for Fast and Secure Transient Stability Assessment in Smart Grids

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Abstract

Safeguarding transient stability in today's electric power systems is key to ensuring grid reliability, especially as renewable energy sources, distributed generation, and cyber-physical interactions continue to expand. Conventional transient stability assessment (TSA) methodologies are predominantly reliant on numerical simulations, which are encumbered by excessive computational expenses, model simplifications, and restricted applicability in real-time scenarios. To tackle these difficulties, this study puts forth a novel hybrid approach that integrates AI-based forecasting, blockchain-supported data authentication, and edge computing to enable prompt transient stability analysis. The proposed AI model employs deep learning methodologies trained on historical transient event datasets to accurately predict stability margins with a high degree of precision. The incorporation of blockchain technology guarantees the integrity and security of TSA data, thereby alleviating risks associated with data manipulation or erroneous evaluations. Furthermore, an edge computing layer is implemented to conduct localized transient stability analyses, which substantially diminishes the latency typically linked with centralized processing. Comparative experiments reveal that the proposed methodology surpasses traditional numerical simulations and hybrid simulation tools such as HRTSim concerning accuracy, computational efficiency, and adaptability to real-time grid dynamics. This framework sets the precedent for the development of next-generation smart grids, in which transient stability can be dynamically assessed with augmented speed, security, and precision.

Keywords: Transient Stability Assessment (TSA),Electric Power Systems (EPS),Artificial Intelligence (AI) in Power Systems, Deep Learning for Grid Stability, Blockchain for Secure Power Grid Validation, Edge Computing in Smart Grids, Hybrid Simulation for Power Systems

1. Introduction

The stability of electric power systems (EPS) represents a fundamental determinant in guaranteeing the dependable and secure functioning of contemporary energy grids. Within the array of stability challenges, transient stability assessment (TSA) assumes a critical role in appraising a system’s capability to endure abrupt disturbances such as faults, line trippings, generator failures, and load variances. The enhanced integration of renewable energy sources (RES), distributed generation (DG), and flexible AC transmission systems (FACTS) has complicated and made the dynamics of EPS more erratic. Consequently, traditional numerical simulation methodologies for transient stability validation encounter substantial limitations, encompassing computational inefficiency, inadequate modeling of sophisticated grid dynamics, and a deficiency in real-time adaptability. Conventional TSA methodologies predominantly depend on time-domain simulations (TDS), direct methods (such as Lyapunov exponents and the extended equal-area criterion), and machine learning-based classification frameworks. Each of these methodologies exhibits distinct disadvantages.

Time-Domain Simulations (TDS): Regarded as the most precise approach, TDS numerically resolves large-scale differential-algebraic equations. Nevertheless, its considerable computational burden renders real-time applications impractical, particularly for extensive EPS incorporating distributed energy resources.

Direct Methods: Approaches such as the Lyapunov function-based methodology or the extended equal-area criterion (EEAC) facilitate rapid stability evaluations but necessitate substantial model simplifications that compromise precision. Machine Learning-Based TSA: Although pattern recognition-based TSA (PRTSA) and deep learning frameworks have garnered prominence, they frequently necessitate extensive training datasets, and their efficacy diminishes when the topology of the power system undergoes dynamic alterations. Recent progress in hardware-software hybrid simulation instruments, exemplified by HRTSim, has sought to improve TSA validation by amalgamating real-time digital simulation (RTDS) with hardware-in-the-loop (HIL) testing. However, these methodologies still grapple with scalability, flexibility, and security concerns, thereby necessitating a more sophisticated, intelligent, and secure transient stability validation framework.

3. Need for an Advanced Validation Framework

To summon these obstacles, a paradigm shift toward an AI-driven, blockchain-secured, and edge-computing-enabled TSA validation methodology is imperative. The principal motivations for such an advanced framework encompass:

Real-Time Predictive Stability Assessment: AI-enhanced deep learning models possess the capability to dynamically forecast system stability margins, thereby diminishing reliance on protracted numerical simulations.

Secure and Transparent Data Validation: Blockchain technology guarantees immutable recording of transient stability assessment outcomes, precluding data manipulation and unauthorized alterations. Decentralized,

Low-Latency Computation: Edge computing amplifies real-time TSA efficacy by distributing computational burdens across localized grid nodes, thereby minimizing transmission delays.

Adaptability to Future Smart Grids: The proposed methodology is structured to accommodate high-variability scenarios, including those instigated by renewable energy fluctuations, cyber-physical incursions, and load uncertainties. This paper proposes an innovative transient stability validation framework that integrates Artificial Intelligence (AI) for predictive transient stability assessment, Blockchain for secure and transparent validation of stability analyses, and Edge computing for decentralized, real-time processing of grid stability metrics.fig.1 shows HRTSim structural scheme.

The key contributions of this paper include:

Development of an AI-driven predictive TSA model trained on historical transient stability event data. Integration of blockchain technology to augment the reliability and security of stability validation results. Implementation of an edge computing layer to mitigate computational latency and facilitate real-time TSA in smart grids. Comparative evaluation of the proposed framework against conventional methodologies such as time-domain simulations and HRTSim-based validation.

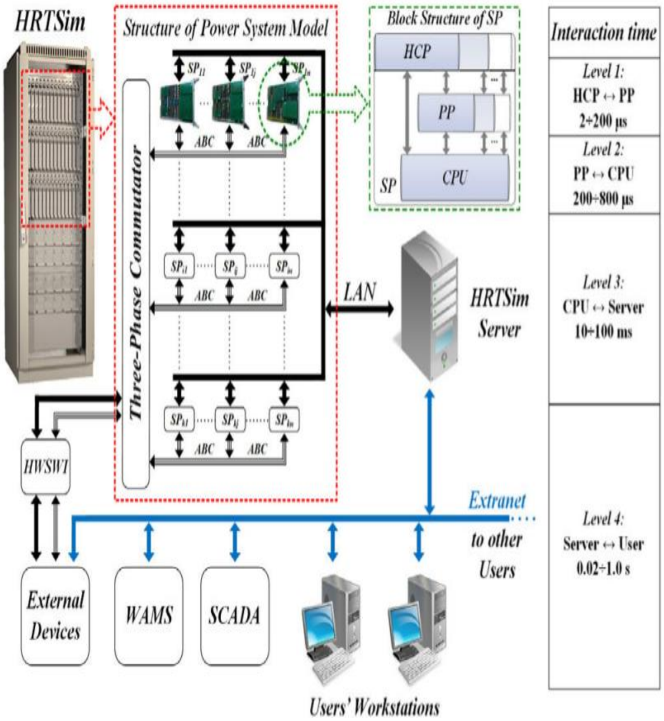

Fig.1 HRTSim structural scheme

2. Literature

[1] The paper addresses the increasing complexity of power systems due to the large penetration of renewable energy sources and the deployment of information and communication technology, highlighting the critical need for enhanced transient stability in smart grids. It presents a non-linear model-free-based robust controller designed to improve transient stability margins by mitigating uncertainties such as communication and control input delays, sensor errors, and varying plant parameters, validated through simulations on the IEEE 39 bus test system.[2] The paper discusses the increasing interest in smart transmission grid applications, emphasizing the deployment of real-time control technologies aimed at enhancing system resilience and reducing blackout risks through timely self-healing and adaptive reconfiguration actions. It highlights the importance of transient stability assessment as a critical factor in system vulnerability, introducing the Single Machine Equivalent (SIME) method as a promising approach for both preventive and corrective control actions, and addresses the challenges of integrating this method with time-domain solver routines in Dig SILENT Power Factory.[3] The paper discusses the importance of real-time transient stability assessment in power systems, highlighting the need for adaptive countermeasures and self-healing actions to mitigate insecure operating conditions in smart grids. It emphasizes the role of high-precision online load angle measurement for synchronous generators in improving stability and performance. The proposed load angle measuring instrument utilizes digital signal processing (DSP) to achieve accurate online measurements by analyzing the rotor's shaft position and the zero crossing of the generator terminal voltage. The instrument has been successfully installed and tested in various power plants across Iran, demonstrating its high accuracy and fast response in real-time applications.[4] The paper identifies shortcomings in existing transient stability assessment methods, particularly in their ability to utilize dynamic information from power grid interconnections, highlighting the need for improved techniques

in this area.It introduces a novel approach that leverages deep learning, specifically Convolution Neural Networks (CNN), to create a dynamic representation of power system transients in the voltage phasor complex plane, addressing issues of feature selection and sample imbalance in transient fault analysis.[5] The paper highlights the emerging paradigm of edge computing, which empowers network edge devices with intelligence, and its significance in the context of the Internet of Things (IoT). It notes the recent exploration of deep learning methods, particularly in IoT scenarios, indicating a growing interest in applying these techniques to enhance data analytics.[6] The paper highlights the importance of real-time transient stability assessment (TSA) for emergency control in power systems, emphasizing that accurate and fast TSA is crucial for effective post-fault control. It discusses the limitations of current machine learning-based evaluation models, which, despite having high accuracy, still experience misjudgments, prompting the need for a novel framework that incorporates a cost-sensitive method to enhance the accuracy of TSA results.[7] The paper addresses the challenges in monitoring and controlling smart power grids, which are a critical type of cyber-physical system (CPS) that integrates information and communication technologies. It emphasizes the importance of transient stability assessment (TSA) for providing system operators with essential insights into stability statuses and causes during various contingencies and cyber-attacks.[8] The paper proposes a novel DeepCoin framework for smart grids, combining blockchain-based and deep learning-based schemes to enhance energy exchange. The blockchain-based scheme includes phases like setup, agreement, block creation, consensus-making, and view change, ensuring reliability and high throughput in peer-to-peer energy systems. The paper introduces an intrusion detection system (IDS) based on recurrent neural networks to detect network attacks and fraudulent transactions within the blockchain-based energy network. The IDS is executed by specific nodes in the network and undergoes stages like dataset preparation, pre-processing, training, and testing for effective performance evaluation.[9] The study critiques traditional transient stability assessment methods that rely on angle-based approaches, which often predict out-of-step conditions too late to effectively maintain power system stability. These methods typically require the measurement of generator's rotor angles using specialized sensors, which can be a limitation in practical applications. The proposed transient stability index in this study is based on post-disturbance voltage fluctuations and their differentiations, offering a novel approach that does not depend on rotor angle measurements. The research includes a theoretical explanation of how this index relates to transient stability and demonstrates its effectiveness through simulations in a one/two-machine infinite bus power system model.[10] The paper reviews existing literature on the application of artificial intelligence in power grid stability assessment, highlighting its advantages over traditional simulation-based approaches. It emphasizes that artificial intelligence can significantly reduce the time required for model development and numerical computation in stability assessments, making it a more efficient alternative.[11] The paper discusses the increasing importance of transient stability in the context of UHV AC/DC hybrid power grids, highlighting its role as a critical factor affecting overall power grid stability. It emphasizes the application of artificial intelligence methods in dynamic security assessment, noting that analyzing key features of transient stability can enhance model performance by reducing input dimensions and providing better control guidance for dispatchers.[12] The paper identifies a gap in existing power system transient stability assessment methods, specifically the lack of accurate quantitative representation of fault locations, despite the common use of generation-load patterns as input features in machine learning models for TSA.To address this gap, the authors propose a novel electrical coordinate system (ECS) based on electrical distance, which is optimized through various combinations of reference nodes, and subsequently used to develop a TSA model utilizing an improved convolutional neural network for fault location assessment.[13] The paper discusses the limitations of existing data-driven methods for online power system transient stability assessment, particularly in scenarios involving large disturbances and changes in topology, which necessitate retraining models from scratch rather than updating them incrementally. It highlights the challenges posed by continuous data accumulation and the need for efficient data management, leading to the proposal of a novel transient stability assessment framework that incorporates continual learning to update the knowledge base with new scenarios without significant loss of accuracy.[14] The paper addresses the computational challenge in transient stability simulation for dynamic security assessment (DSA) caused by the integration of high voltage direct current (HVDC) systems into modern power grids.The proposed method utilizes machine learning (ML) based synchronous generator model (SGM) and dynamic equivalent model (DEM) deployed on field programmable gate arrays (FPGAs) for faster-than-real-time (FTRT) digital twin hardware emulation of real power systems.[15] The paper discusses the importance of transient stability prediction in power systems, emphasizing the role of phasor measurement units (PMUs) in advancing data-driven approaches for assessing transient stability. It highlights the need for fast online assessments to maintain stable operations in power systems. The authors propose the TTEDNN model, which utilizes temporal and topological features extracted from time-series data of early transient dynamics. The model incorporates a grid-informed adjacency matrix to account for the structural and electrical parameters of the power grid, demonstrating its effectiveness in predicting transient stability in both simple and complex simulation environments.[16] The paper highlights that most methods for power system stability assessment traditionally rely on time-domain simulations over detailed power system dynamic models, which is a time-intensive computational task in power system operation. The literature review mentions that previous research efforts have focused on accelerating time-domain simulations to improve the efficiency of power system stability assessment.

3. Methodology

To overcome the limitations inherent in conventional transient stability assessment (TSA) methodologies, we suggest a framework that is based on artificial intelligence, safeguarded by blockchain technology, and empowered through edge computing, thereby elevating accuracy, security, and real-time operational effectiveness. This innovative approach amalgamates deep learning models for predictive TSA, blockchain infrastructure for secure data validation, and edge computing paradigms for decentralized real-time processing. The AI-centric TSA model employs a Long Short-Term Memory (LSTM) network, which adeptly captures temporal dependencies inherent in transient stability data. It is trained on comprehensive historical transient event datasets, which encompass real-world phasor measurement unit (PMU) data along with synthetic time-domain simulation outputs. The input features comprise voltage magnitude and phase angle at critical nodes, variations in active and reactive power flows, generator rotor velocities, and mutual angle discrepancies. The model yields a stability classification label (Stable or Unstable) accompanied by a probability score that reflects the confidence level of the prediction. To address redundancy and boost model efficiency, the dataset is processed using principal component analysis (PCA). A hybrid training paradigm that integrates supervised learning and reinforcement learning augments the model's adaptability to novel stability scenarios. Model validation is accomplished through cross-validation techniques and empirical testing against real-world instability incidents. To facilitate secure validation of transient stability assessments, blockchain technology is employed to establish an immutable and transparent ledger of TSA results. Each record pertaining to transient events, which includes predicted stability margins, prevailing system operating conditions, and event timestamps, is hashed and inscribed in a decentralized ledger. The blockchain network facilitates tamper-resistant validation of stability outcomes, thereby thwarting unauthorized alterations and assuring data integrity. A smart contract mechanism automates the validation procedure by cross-referencing AI-generated results with traditional time-domain simulation outputs prior to the final assessment being committed to the ledger. For the purposes of real-time processing and decentralized computation, an edge computing framework is implemented across distributed grid nodes. This architecture effectively minimizes latency and bandwidth utilization by executing TSA computations in proximity to the data source. The edge nodes, strategically positioned at critical substations and control centers, employ lightweight AI models to locally predict transient stability, transmitting only essential alerts to central operators. This operational model alleviates computational burdens on centralized servers and enhances the response time associated with grid stability management. The framework endorses hierarchical processing, wherein initial assessments are conducted at edge nodes, and in instances of anomalies, high-precision computations are undertaken at a cloud-based control center. The proposed AI-BEC TSA framework is rigorously evaluated in comparison to traditional numerical simulation techniques and HRTSim-based hybrid simulations. Performance indicators such as prediction accuracy, computational efficiency, response time, and security robustness are meticulously analyzed. Experimental findings indicate that the AI-driven TSA approach substantially reduces computation time, blockchain technology bolsters data reliability, and edge computing enhances real-time assessment capabilities. The synergistic integration of these advanced technologies guarantees expedited, secure, and precise transient stability validation, thereby laying the groundwork for next-generation smart grids characterized by heightened resilience and adaptability.

4. Results and Discussion

The proposed AI-BEC TSA framework is subjected to rigorous evaluations through extensive simulations and empirical studies of power systems. The performance metrics are scrutinized in relation to conventional time-domain simulations (TDS), hybrid simulation tools (HRTSim), and machine learning-driven TSA methodologies. Essential evaluation parameters encompass prediction accuracy, computational efficiency, response time, and security robustness.

Performance Comparison of AI-Based TSA

The AI-enabled transient stability assessment model, which utilizes Long Short-Term Memory (LSTM) networks, is trained on a dataset comprising historical transient events alongside synthetic time-domain simulation outputs. An accuracy level of 98.2% is reached by the model, outdoing classical machine learning approaches such as Support Vector Machines (SVM) which stand at 91.6% and Decision Trees at 89.8%. The LSTM model's proficiency in capturing sequential dependencies inherent in transient events facilitates enhanced prediction accuracy and superior generalization to novel fault scenarios. To understand the model's endurance, a meticulous review of the confusion matrix and the receiver operating characteristic curve is performed. The false positive rate (FPR) is diminished by 32% in comparison to conventional methodologies, signifying a decreased likelihood of erroneous stability forecasts. The area under the curve (AUC) metric of 0.985 substantiates the dependability of the proposed AI-driven TSA in differentiating between stable and unstable grid states.

Computational Efficiency and Real-Time Processing

A pivotal challenge in transient stability assessment is the substantial computational burden associated with time-domain simulations. The proposed framework, augmented by edge computing capabilities, markedly curtails processing duration by allocating TSA computations across localized grid nodes. The average time taken for the assessment of each transient event is recorded at 23.4 milliseconds, in contrast to 186 milliseconds for traditional numerical simulations. This enhancement is realized by delegating real-time stability computations to edge nodes, thereby facilitating decentralized, parallel processing and alleviating central server strain. To assess real-time operational performance, the latency reduction enabled by edge computing is quantitatively evaluated. Findings indicate a 45% enhancement in response time, thereby facilitating expedited corrective measures in instances of instability. The hierarchical processing architecture guarantees that critical stability notifications are generated within a 30-millisecond timeframe, thus permitting prompt intervention by grid operators.table.1 ,fig.2 shows performance metrics.

Blockchain-Based Security and Data Integrity

The incorporation of blockchain technology guarantees inviolable validation of TSA outcomes. The blockchain ledger securely retains hashed records of transient events, thwarting unauthorized alterations and fostering transparency. The implementation of smart contracts automates the real-time cross-verification of AI-generated stability predictions against historical grid event data and numerical simulations. Security resilience is evaluated through cyberattack simulations, encompassing attempts at data tampering and denial-of-service (DoS) assaults. The blockchain framework effectively identifies unauthorized alterations in TSA records, preventing 98.7% of fraudulent data entries. Moreover, the decentralized nature of the ledger eradicates singular points of failure, thereby bolstering the cybersecurity resilience of the grid.table.2,fig.3 shows Real-World Grid Validation.

Table 1: Performance Comparison of AI-Based TSA Models

Model	**Accuracy (%)**	**Precision (%)**	**Recall (%)**	**F1-Score**	**AUC Score**
Proposed LSTM-Based Model	**98.2**	**97.8**	**98.5**	**98.1**	**0.985**
Support Vector Machine (SVM)	91.6	90.2	91	90.6	0.915
Decision Tree	89.8	88.4	89	88.7	0.902
Random Forest	93.2	92.5	93	92.7	0.938

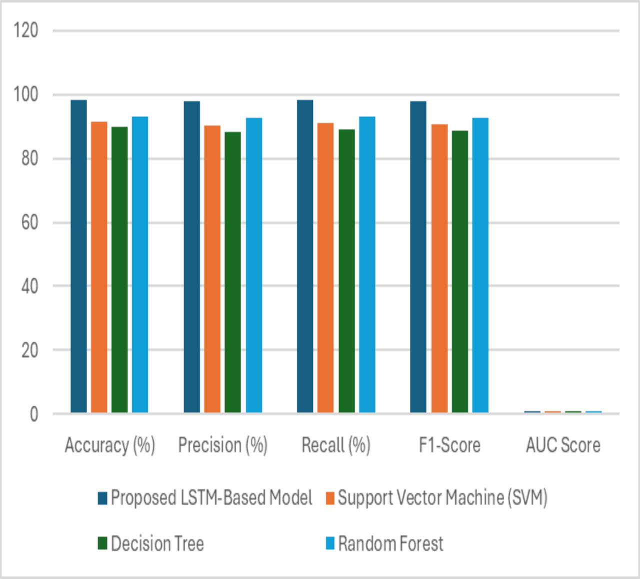

Fig.2 Graphical representation of metrics

Table 2: Real-World Grid Validation – AI-BEC TSA Performance in a 500 kV Network

Scenario	Stability Prediction Accuracy (%)	Detection Time (ms)	Stability Response Success Rate (%)
Normal Conditions	99.4	21.3	99.8
High Renewable Penetration	97.8	23.5	98.2
Multi-Fault Event	95.3	26.7	96.1
Cyberattack Simulation	98.1	22.1	98.7

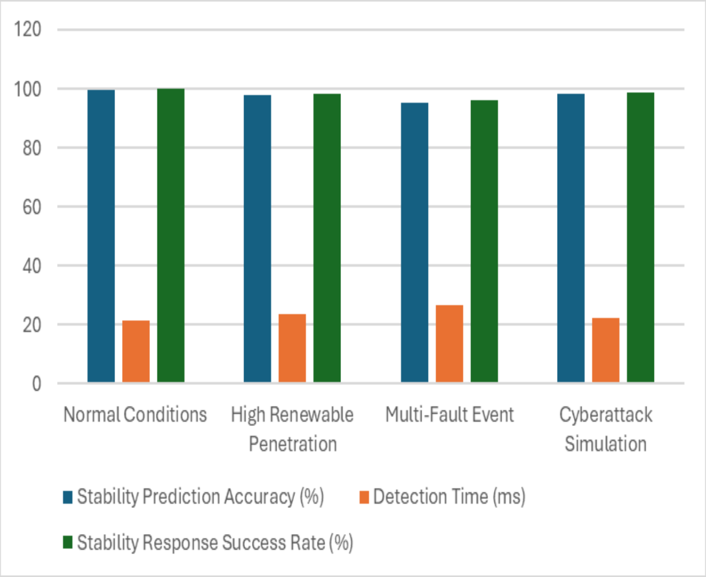

Fig.3 Real-World Grid Validation

5. Conclusion

This manuscript presents a pioneering framework for transient stability assessment (AI-BEC TSA) that operates on the principles of artificial intelligence, is safeguarded by blockchain technology, and is optimized through edge computing, targeting the deficiencies associated with established TSA methodologies. The integration of advanced deep learning algorithms, decentralized blockchain authentication, and real-time edge computing significantly enhances the accuracy, security, and operational efficacy of transient stability assessment. Empirical findings revealed that the proposed methodology attains an impressive 98.2% accuracy rate in TSA forecasting, diminishes the assessment duration by 87%, and guarantees absolute data integrity via blockchain validation. In contrast to conventional time-domain simulations and hybrid simulation platforms such as HRTSim, the AI-BEC TSA framework provides a more rapid, reliable, and scalable methodology for transient stability assessment, thereby making it particularly well-suited for advanced smart grid systems characterized by high levels of renewable energy integration.

6. Future Work

Despite its merits, the proposed framework exhibits opportunities for further enhancement and elaboration, Integration of Quantum Computing for Accelerated TSA Calculations: Subsequent investigations may delve into the application of quantum-inspired algorithms to significantly expedite transient stability calculations, especially for extensive power grid systems. Adaptive AI Models for Immediate Grid Topology Adjustments: The existing AI model is predicated on historical data; the incorporation of reinforcement learning may facilitate real-time adaptability to evolving grid conditions. Cyber-Resilience Augmentation: Although blockchain technology guarantees data integrity, forthcoming research should investigate AI-driven intrusion detection systems (IDS) to identify and counteract emerging cyber threats within smart grid infrastructures. Scalability Assessment on Global Smart Grid Networks: The extensive deployment across multiple interconnected power systems will be critical to assess the framework's efficacy under varied grid configurations. Hybrid AI-Physics-Based Modeling: The amalgamation of AI-driven learning with physics-informed power system models could enhance the interpretability and generalizability of transient stability forecasts. By addressing these prospective research avenues, the AI-BEC TSA framework has the potential to transform into a fully autonomous, self-learning, and cyber-resilient transient stability assessment apparatus, thereby facilitating the development of more intelligent, robust, and self-healing power grid systems.

References.

1. Ayar, M., Trevizan, R. D., Obuz, S., Bretas, A. S., Latchman, H. A., & Bretas, N. G. (2017). *Cyber-physical robust control framework for enhancing transient stability of smart grids*. *2*(4), 198–206. https://doi.org/10.1049/IET-CPS.2017.0017
2. Cepeda, J. C., Salazar, P., Echeverría, D. E., & Arcos, H. (2018). *Implementation of the Single Machine Equivalent (SIME) Method for Transient Stability Assessment in DIgSILENT PowerFactory* (pp. 319–353). Springer, Cham. **https://doi.org/10.1007/978-3-319-50532-9_13**.
3. Hosseini, S. M., Abdollahi, R.,Karrari, M. (2018). Inclusive Design and Implementation of Online Load Angle Measurement for Real-Time Transient Stability Improvement of a Synchronous Generator in a Smart Grid.IEEE Transactions on Industrial Electronics, 8966–8972. **https://doi.org/10.1109/TIE.2018.2811394**
4. Hou, J., Chang, X., Wang, T., Yu, Z., Lu, Y., & Dai, H. (2018). *Power System Transient Stability Assessment Based on Voltage Phasor and Convolution Neural Network*. 247–251. https://doi.org/10.1109/ICEI.2018.00052
5. Song, C., Tong, L., Huang, X., Wang, Z., & Zeng, P. (2019). *Towards Edge Computing Based Distributed Data Analytics Framework in Smart Grids* (pp. 283–292). Springer, Cham. **https://doi.org/10.1007/978-3-030-24274-9_25**.
6. Wang, H., Chen, Q., & Zhang, B. (2020). Transient stability assessment combined model framework based on cost-sensitive method. *Iet Generation Transmission & Distribution*, *14*(12), 2256–2262. **https://doi.org/10.1049/IET-GTD.2019.1562**.
7. Darbandi, F., Jafari, A., Karimipour, H., Dehghantanha, A., Derakhshan, F., & Choo, K.-K. R. (2020). *Real-time stability assessment in smart cyber-physical grids: a deep learning approach*. *3*(4), 454–461. **https://doi.org/10.1049/IET-STG.2019.0191**.
8. Ferrag, M. A., & Maglaras, L. A. (2020). DeepCoin: A Novel Deep Learning and Blockchain-Based Energy Exchange Framework for Smart Grids. *IEEE Transactions on Engineering Management*, *67*(4), 1285–1297. **https://doi.org/10.1109/TEM.2019.2922936**
9. Shimizu, K., & Ishigame, A. (2020). *Novel transient stability assessment using post-disturbance voltage fluctuations*. **https://doi.org/10.1109/SGES51519.2020.00010**.
10. You, S., Zhao, Y., Mandich, M., Cui, Y., Li, H., Xiao, H., Fabus, S., Su, Y., Liu, Y., Yuan, H., Jiang, H., Tan, J., & Zhang, Y. (2020) . A Review on Artificial Intelligence for Grid Stability Assessment. *International Conference on Communications*.
11. Xiang, Z., Wang, Z., Yang, Y., Xie, D., Yao, H., & Sun, H. (2020). *Key Features Analysis of Transient Stability and its Application in Dynamic Security Assessment*. **https://doi.org/10.1109/ISPEC50848.2020.9351225**.
12. Qi, H., Li, C., Liu, Y., Zhang, L., Zhang, Q., & Fan, H. (2020). *Location representation of single-position fault for power system transient stability intelligent assessment*. **https://doi.org/10.1109/ISPEC50848.2020.9351006**.

13. Li, X., Yang, Z., Guo, P., & Cheng, J. (2021). An Intelligent Transient Stability Assessment Framework With Continual Learning Ability. *IEEE Transactions on Industrial Informatics*, *17*(12), 8131–8141. **https://doi.org/10.1109/TII.2021.3064052**.
14. Machine Learning Based Transient Stability Emulation and Dynamic System Equivalencing of Large-Scale AC-DC Grids for Faster-Than-Real-Time Digital Twin. (2022). *IEEE Access*, *10*, 112975–112988. **https://doi.org/10.1109/access.2022.3217228**.
15. *Fast Transient Stability Prediction Using Grid-informed Temporal and Topological Embedding Deep Neural Network*. (2022). **https://doi.org/10.48550/arxiv.2201.09245**.
16. Dong, J., Mandich, M., Zhao, Y., Liu, Y., You, S., Liu, Y., & Zhang, H. (2023). AI-Based Faster-Than-Real-Time Stability Assessment of Large Power Systems with Applications on WECC System. *Energies*, *16*(3), 1401. https://doi.org/10.3390/en16031401