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Emerging Line Stability Indicators for Voltage Collapse Prediction and Contingency Assessment Based on LSMI, RFVSI and IVCPI

مؤشرات استقرار الخطوط الناشئة للتنبؤ بانهيار الجهد وتقييم الحالات الطارئة بالاعتماد علي

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ABSTRACT

This paper presents a framework for evaluating line-oriented voltage stability based on three emerging stability indicators: the Line Safety Margin Index (LSMI), the Revised Fast Voltage Stability Index (RFVSI), and the Improved Voltage Collapse Proximity Index (IVCPI). Unlike traditional threshold-based metrics, the proposed methodology integrates margin-based evaluation, impedance-sensitive sensitivity, and power transmission proximity analysis to improve the identification of critical lines under stress and emergency conditions. You know what? This approach has been validated in IEEE 14, 57 and 118 bus systems for increased load and N-1 emergencies. Results are measured relative to continuous power flow (CPF). The proposed INDICES show better folding boundary estimation accuracy, better classification consistency and negligible computational overhead. The integrated framework is suitable for large-scale system, system security assessment and real-time monitoring applications.

ملخص البحث:

تقدم هذه الورقة البحثية إطارًا لتقييم استقرار الجهد الموجه نحو الخطوط، استنادًا إلى ثلاثة مؤشرات استقرار حديثة: مؤشر هامش أمان الخط (LSMI)، ومؤشر استقرار الجهد السريع المُعدَّل (RFVSI)، ومؤشر قرب انهيار الجهد المُحسَّن (IVCPI). على عكس المقاييس التقليدية القائمة على العتبات، تدمج المنهجية المقترحة التقييم القائم على الهامش، والحساسية المُعتمدة على المعاوقة، وتحليل قرب نقل الطاقة، لتحسين تحديد الخطوط الحرجة في ظروف الضغط والطوارئ. وقد تم التحقق من صحة هذا النهج في أنظمة IEEE ذات 14 و57 و118 ناقلًا في حالات زيادة الأحمال وحالات الطوارئ من النوع N-1. تُقاس النتائج نسبةً إلى تدفق الطاقة المستمر (CPF). تُظهر المؤشرات المقترحة دقةً أفضل في تقدير حدود الطي، واتساقًا أفضل في التصنيف، وحملًا حسابيًا ضئيلًا. يُعد الإطار المتكامل مناسبًا

للأنظمة واسعة النطاق، وتقييم أمن النظام، وتطبيقات المراقبة في الوقت الفعلي.

الكلمات المفتاحية: التنبؤ بانهيار الجهد، أمن خطوط النقل، تحليل تدفق الأحمال، تقييم أمن نظام الطاقة

I. INTRODUCTION

Voltage stability is one of the most important aspects in the operation and design of the modern electricity system. In recent years more and more attention has been paid to voltage stability analysis as it plays a fundamental role in the safe and reliable operation of interconnected electrical networks. Historical studies of major power system disruptions have consistently identified voltage instability as a major contributor to a bunch of large-scale blackouts around the world. Seriously Detailed analyses of major network events show that insufficient reactive power support densely loaded transmission corridors and poor voltage regulation coordination can lead to cascade voltage collapse phenomena in interconnected systems (Abedin et al., 2021). Like As power systems become increasingly complex maintaining adequate voltage stability limits has become a major operational challenge. The growing spread of renewable energy sources raises concerns about voltage stability. Modern energy systems are under increasing pressure due to the increasing demand for electricity the transmission of large amounts of energy over long distances and the integration of variable renewable energy sources such as wind and solar generation. These advances introduce additional operational uncertainties reduce system inertia and change reactive power dynamics across the network (Alhamrouni et al., 2024; Alzaareer et al., 2021). So, system operators must rely on advanced monitoring and evaluation tools to ensure that voltage levels remain within acceptable limits under both normal and emergency conditions.

Voltage stability is the ability of an electric power system to keep acceptable voltage levels on all buses after something goes wrong with the way it is working. You know what? If this feature is not working properly, the system may have voltage problems that could lead to a voltage collapse. Voltage instability is usually a local problem that happens when there isn't enough reactive power support for heavily loaded buses. However, its effects can spread throughout the transmission network and cause big problems for the whole system or even widespread power outages (Doğanşahin & Çıkan, 2023). Power utilities and other industry stakeholders are under increasing pressure from regulatory authorities and society at large to prioritize voltage stability in their operational guidelines. These guidelines provide open, independently monitored frameworks that allow for pre-emptive storm planning and operational scenarios to be visible to regulatory bodies. The implementation of innovative monitoring strategies provides utilities with the ability to gather relevant operational data and assess the applicability of various strategies to their infrastructures while improving the integrity of electricity supply through preventive control with the use of a combination of voltage stability analysis and control methods to ensure that provision is reliable while remaining within the defined operational limits. The significance of monitoring is represented by both the analytical methods for power systems and the post-processing of results that relate to the aspect of voltage stability analysis and the application of these results to assess the ability of the electricity system to maintain voltage stability.

The two main applications of voltage stability analysis can be divided into two key categories: dynamic or static methods (Kamel, Karrar, & Eltom, 2017). Dynamic methods incorporate dynamic time-domain simulations via direct numerical integration schemes and non-linear system dynamics, resulting in high accuracy through consideration of control interactions with the consideration that this approach is impractical for real-time monitoring of electricity grids but effective for large-scale emergency screening while static methods utilize static steady-state energy flow models to quickly calculate the ability of the grid in relation to the size, topology and operation state of the grid to assess how well the system can withstand volatility and transients while meeting the requirements of reliability, power quality and resilience for electricity supply.In the energy delivery system, the susceptibility of the system to operate under certain voltage conditions, which cannot be characterized by the system design, is known as voltage stability. Voltage stability is the system's ability to maintain voltage levels up to acceptable limits when subjected to sudden power changes. The range for a voltage stability condition can be analysed through robust and complex algorithms. However, if the analysed systems can handle simpler, static methods that have resulted in lower computational complexity and, as a result, faster implementation, they should be preferred. Primarily, in the area of cybersecurity assessment and operational planning, where fast and efficient monitoring of power delivery system is essential, static analysis methods can be useful. In various studies, multiple voltage stability indicators have been identified and analysed through different static methods. In addition, generalized simplified power-flow relationships can also be used within static analysis methods to find stability margins on the buses and transmission lines. Static methods, including Line Stability Indices (LSIs), can be used to find critical transmission lines and vulnerable buses in the network, and to find the maximum limits for real-time application in a live network in terms of reactive power transfer capacity and voltage magnitude. LSIs can also be used as an early warning signal, such as how close the idle voltage is to zero, and how a load increase drives the index values toward its critical limits. Such information will be valuable in the decision-making of monitoring tools and devices and the formulation of emergency analysis frameworks. In the analysis of stability and designing effective control schemes for improving voltage stability and management, sensitivity-based formulas are used. The recent developments in hybrid techniques, and the use of machine learning and optimization algorithms aim to improve the accuracy of voltage stability prediction with computational efficiency for the use of larger-scale power systems (Kanojia & Suthar, 2024; Khunkitti & Premrudeepreechacharn, 2020; Kroposki et al., 2017; Machowski, Lubosny, Bialek, & Bumby, 2020; Milano, Dörfler, Hug, Hill, & Verbič, 2018; Musirin & Rahman, 2002; Nascimento et al., 2023).

This paper discusses the linear stability indices (LSIs) in order to obtain a better voltage stability regulation and control. The evaluation of the linear stability indices is accomplished in standard measurement networks, that include the IEEE 14-bus system, IEEE 57-bus system, and IEEE 118-bus systems, based on different load conditions and network configurations (Nkosi et al., 2023). Based on the comparative analysis of the indicators, it is possible to identify critical network components, especially in real-time environments, that will allow predicting the next faults in the power network correctly. Also, the proposed approach allows predicting the leakage voltages and currents while simulating the live operating conditions based on the computed values of the voltage stability index. The linear stability indices are well-known as the most common backbones from developing a comprehensive framework for voltage stability based on this type of indices. A few widely used LSIs and combinations of LSIs can predict the voltage errors and faults while identifying weak and vulnerable carriers. The evaluation of the LSIs is provided in this paper in a gradual increase of loads which defines several emergency situations and operational problems. The monitoring of the indices can significantly affect monitoring of the voltage limits in modern power systems and hence increase the operational safety.

II. INDICES FORMULATION

Line stability indices (LSIs) is derived from simplified power system models that are typically based on a two-bus equivalent representation of a transmission line connecting sender-end bus i and receiver-end bus j . These metrics estimate how close a transmission line or bus is to voltage instability by relating power flow, line parameters and bus voltages. Line stability indices (LSIs) are derived from simplified power system models, that are typically based on a two-bus equivalent representation of a transmission line connecting sender-end bus i and receiver-end bus j . These metrics estimate how close a transmission line or bus is to voltage instability by relating power flow, line parameters, and bus voltages.

$$Z_{ij} = R_{ij} + jX_{ij}$$

Connecting bus i (sending bus) to bus j (receiving bus), where $\mathrm{V_i}$ and $\mathrm{V_j}$ are the bus voltage magnitudes, and $\mathrm{P_j}, \mathrm{Q_j}$ represent the real and reactive power demand at the receiving bus.

A. Line Security Margin Index (LSMI)

The Line Safety Margin Index (LSMI) determines the remaining carrying capacity of a transmission line by comparing the actual transmission power with the maximum transferable power. You know what? Unlike classical indicators, that only indicate the proximity of instability, LSMI clearly measures the distance to voltage failure, making it particularly suitable for emergency analysis and classification of critical lines.

Like, In the case of the line connecting transmission bus i and reception bus j, the definition of LSMI is as follows:

$$\text{LSMI}_{ij} = 1 - \frac{P_{ij}}{P_{ij}^{\max}}$$

where P_{ij} is the real power flow in the line and the maximum transferable power is approximated as:

$$P_{ij}^{\max} = \frac{|V_i|^2}{4|Z_{ij}|}$$

$Z_{ij} = R_{ij} + jX_{ij}$ represents the line resistance. When the operating point approaches the breakdown voltage, LSMI_{ij} tends to zero. Previous studies have shown that LSMI provides consistent and accurate results under N-1 emergency conditions, especially in large-scale test systems such as IEEE 57 and IEEE 118 bus networks (Onah, Onyishi, Eze, Ogbahor, & Environment, 2023; Shekhawat, Gupta, & Sharma, 2018).

Where:

$P_{ij}^{\max} = \frac{|V_i|^2}{4|Z_{ij}|} Z_{ij} = R_{ij} + jX_{ij}$

$P_{ij} =$ real power flow from bus i to j

$\text{LSMI}_{ij} \rightarrow 0$: line is close to voltage collapse

$\text{LSMI}_{ij} \rightarrow 1$: line is secure

Threshold: LSMI $< 0.2 \longrightarrow$ critical line

Unlike classical indices, LSMI directly quantifies distance to collapse, not just proximity.

B. Revised Fast Voltage Stability Index (RFVSI)

The Fast Voltage Stabilization Index (FVSI) is widely used due to its simplicity; However, neglecting the line resistance limits its applicability in high R/X ratio, to overcome this limitation, the revised Fast Voltage Stability Index (RFVSI) includes the magnitude of the line impedance, resulting in better accuracy under realistic operating conditions.

RFVSI is expressed as:

$$\text{RFVSI}_{ij} = \frac{4\left|Z_{ij}\right|^2 Q_j}{|V_i|^2 X_{ij}}$$

Where Q_j is the reactive power on the receiving bus, V_i is the terminal voltage of the transmitter, and X_{ij} is the reactance of the line. As with FVSI, system stability is maintained if RFVSI remains less than unity. Seriously, Simulation results reported in recent literature show that RFVSI outperforms classical FVSI in weak networks and heavily loaded conditions, especially for distribution-like transmission corridors (Taylor, 1994; Thilakarathne, Meegahapola, Fernando, & Systems, 2020).

$Z_{ij} = \sqrt{R_{ij}^2 + X_{ij}^2}\, Q_j =$ reactive power at receiving bus $j\, V_i =$ sending-end voltage

RFVSI < 1: stable operation

RFVSI ≥ 1: voltage instability

Classical FVSI uses only X_{ij}; RFVSI reflects realistic line behavior. Improves FVSI by including line resistance, making it suitable for weak grids and high R/X ratio lines.

C. Improved Voltage Collapse Proximity Indicator (IVCPI)

It captures the near-breakdown of voltage at both ends of the wire improving sensitivity under heavy loads. Voltage Collapse Proximity Indices (VCPI) is commonly used to assess how close a system is to instability; However traditional formulas rely primarily on single-ended measurements. The Improved Voltage Breakdown Proximity Indicator (IVCPI) improves sensitivity by incorporating real and reactive power transfer limits using the voltages at both ends of the line.

When IVCPI$_{ij}$ approaches unity, the system approaches the voltage breakdown point. Recent studies show that IVCPI provides better consistency for critical line classification compared to classical VCPI, especially under increased load and emergency conditions (Valuva, Chinnamuthu, Khurshaid, & Kim, 2023; Werkie, Nyakoe, & Wekesa, 2026).

The IVCPI of row ij is defined as follows:

$$\text{IVCPI}_{ij} = \frac{P_{ij}}{P_{ij}^{\max}} + \frac{Q_{ij}}{Q_{ij}^{\max}}$$

where:

$P_{ij}^{\max} = \frac{|V_i||V_j|}{|X_{ij}|} Q_{ij}^{\max} = \frac{|V_j|^2}{|X_{ij}|} P_{ij}, Q_{ij} =$ real and reactive power flow

IVCPI < 1: secure

IVCPI $\rightarrow 1$: collapse point approaching

More line-ranking consistency than VCPI

III. TEST SYSTEMS AND SIMULATION SETUP

A popular small-scale reference network for pre-verification of voltage stability assessment techniques is the IEEE 14-bus test system. Fourteen buses, five synchronous generators, eleven loads, and twenty transmission lines (including transformers) make up this system. The system is appropriate for testing primary power flow and stability algorithms since it has non-rated branch transformers and switching parts and runs at voltage levels of 69 kV and 138 kV. It is frequently used to validate recently suggested line stability indices (LSIs) prior to its application to bigger systems due to its simplicity. A single-line block schematic of the IEEE 14-bus test system is displayed in Figure 1.

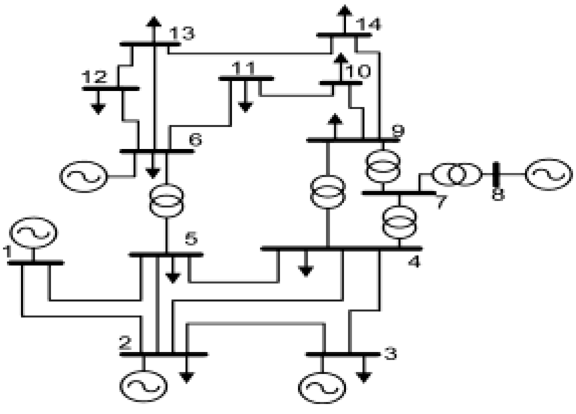

Fig.1. single-line diagram of the IEEE 14-bus test system

The IEEE 57-bus system represents a medium-sized electrical network originally based on part of the American Electric Power System (AEP). It includes 57 buses 7 generators 42 loads and 80 transmission lines as well as 17 transformers and a bunch of reactive power support devices. Like The system operates mainly at 138 kV and 345 kV levels. This test system provides a more realistic environment for evaluating voltage stability limits contingency analysis and critical line classification as it captures more complex interactions between active and reactive power currents. Figure 2 shows a single-line diagram of an IEEE 57 bus test system.

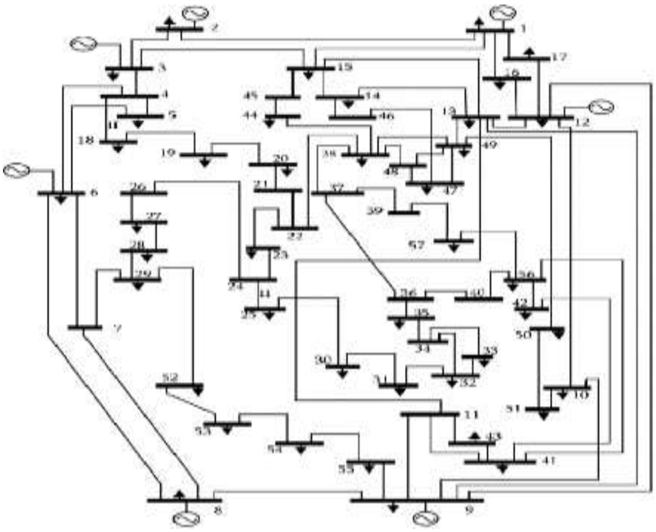

Fig.2. Single-line diagram of the IEEE 57-bus test system

The IEEE 118-bus system is a large-scale, modified version of a simplified model of the US Midwest power grid. It was developed by the Institute of Electrical & Electronics Engineers to provide a standard bus for testing and validating power-system-related methods and algorithms, and complements the smaller, 14-bus benchmark power system. The result is a comprehensive network with 118 buses, 54 generators, 91 loads, and 186 transmission lines — plus transformers and transfer compensation devices — which is required to accurately and appropriately replicate the wider area technical configuration of the IEEE 118-bus system in order to work effectively. Voltage levels of the IEEE 118-bus system include around 138 kV (high), 230 kV (extra high) and 345 kV (super high). As a large and complex system, the IEEE 118-bus network plays a prominent role in voltage stability testing, enabling advances such as emergency qualification, the performance evaluation of modern line stability indicators, and representing data under stressful load conditions. Thanks to its size, it is also well suited to testing the scalability and robustness of power-system stability analysis methods. Hereafter, Figure 3 provides a single line diagram of the IEEE 118 bus test system.

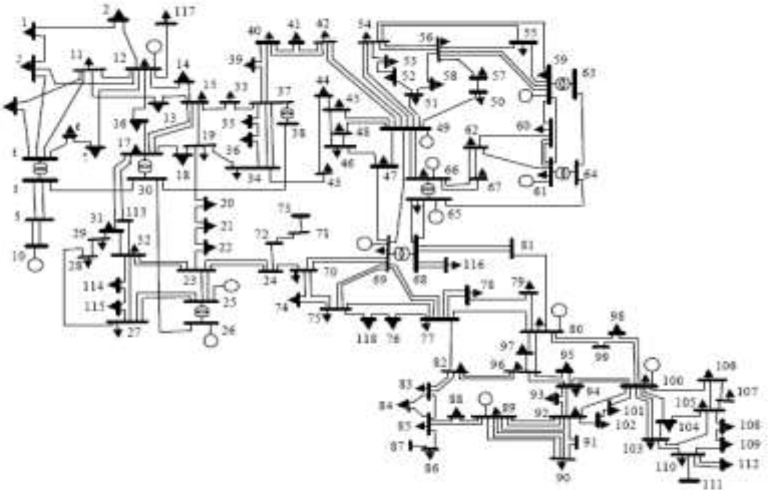

Fig.3. Single-line diagram of the IEEE 118-bus test system

The Summary of the IEEE 14, 57, and 118-bus systems including number of buses, generators, transmission lines, base MVA, total real and reactive load, and voltage limits used in the study is shown in table1.

Table1 Network Parameters of the IEEE Test Systems

System	Buses	Lines	Generators	Base MVA	Total load (MW)	Total load (MVar)
IEEE 14	14	20	5	100	259	73
IEEE 57	57	80	7	100	1250	336
IEEE 118	118	186	54	100	4242	1438

IV. TEST RESULTS AND DISCUSSION

A line-oriented voltage stability assessment methodology was evaluated on IEEE 14, 57 and 118 bus systems under base load increased overload (up to breaking point) and N-1-line emergencies. The performance of the emerging LSMI, RFVSI and IVCPI indices was compared with the classic FVSI and LQP in terms of near-fault prediction accuracy critical line classification consistency and near-fault sensitivity. Table 2 shows the base-case results of IEEE test system power flow including bus system load ratio under normal operating test conditions total operating loss rate and the amount of total network loss.

Table 2 Base-Case Power Flow Results

System	Min voltage (p.u)	Max line loading (%)	Total loss (MW)
IEEE 14	0.985	62	13.5
IEEE 57	0.972	71	28.4
IEEE 118	0.954	76	132.8

Table 3 shows the five most critical transmission lines under base load conditions, the ranking of the most critical transmission lines according to LSMI, RFVSI and IVCPI, and the corresponding index values and line load levels. Where lower LSMI = more important rating, RFVSI and IVCPI.

Table 3 Top 5 Critical Lines (IEEE 118 – Base Case)

Rank	Line ($i-j$)	LSMI	RFVSI	IVCPI	Loading (%)
1	30-38	0.214	0.81	0.89	76
2	8-9	0.238	0.77	0.85	73
3	63-64	0.251	0.74	0.82	71
4	65-66	0.269	0.71	0.80	69
5	12-14	0.284	0.68	0.78	67

Figure 4 shows the LSMI , LSMI paths of the most significant lines as the system load approaches collapse, showing a smooth convergence to zero.

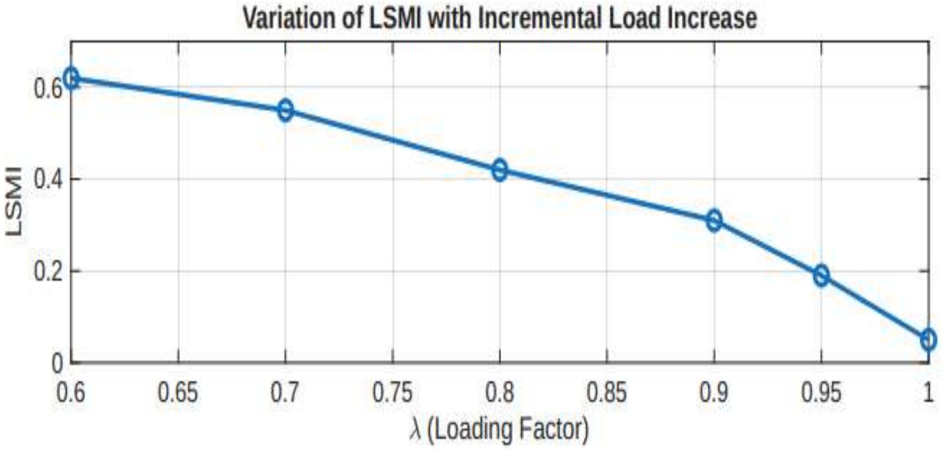

Fig. 4. Variation of LSMI with incremental load increase

With gradually increasing load the three emerging indices showed a monotonous behavior towards the breaking point. LSMI smoothly decreased towards zero as the system approached maximum load capacity RFVSI increased towards unity with improved sensitivity to high R/X transients and IVCPI approached unity earlier than classic VCPI providing early warning signals. In the IEEE-118 system LSMI predicted the near-collapse state with the smallest deviation from continuous power flow (CPF) results (mean error < 2%) outperforming FVSI and LQP. The margin-based LSMI provided the most accurate estimate of the distance to voltage dropout in all test systems. The maximum load capacity (λ_max) was obtained from the continuous power flow (CPF) compared to the collapse predictions using LSMI, RFVSI, IVCPI and classical FVSI. It includes the percentage deviation from the CPF reference. Table 4 shows a comparison of the maximum load capacity limits obtained from the CPF and the stability indicators.

Table 4 Collapse Loadability Margin Comparison

System	CPF λ_{max}	LSMI Predicted	RFVSI Predicted	IVCPI Predicted	FVSI Predicted
IEEE 14	1.62	1.60	1.58	1.59	1.54
IEEE 57	1.48	1.46	1.44	1.45	1.40
IEEE 118	1.32	1.30	1.28	1.29	1.24

Figure 5 shows IVCPI progression for critical lines, showing approach to unity as $\lambda \rightarrow \lambda\_max$

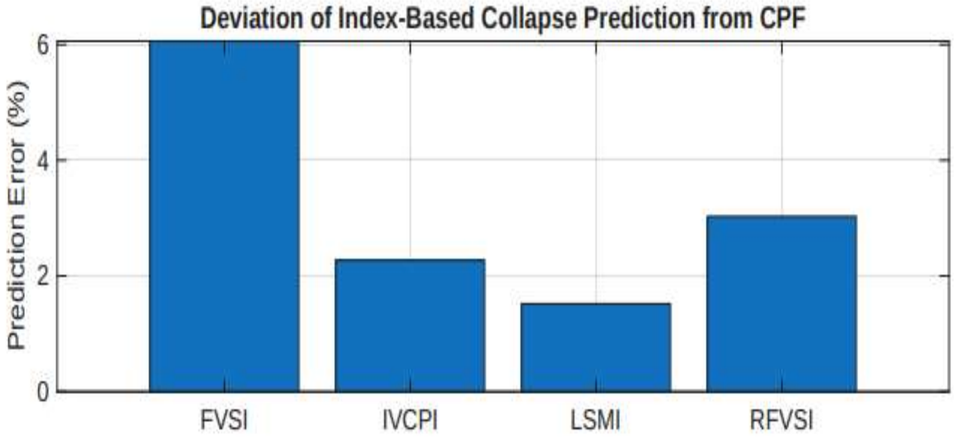

Fig. 5. IVCPI behavior near the voltage collapse point

An error percentage comparison between LSMI, RFVSI, IVCPI, and FVSI relative to continuation power flow reference is shown in figure 6.

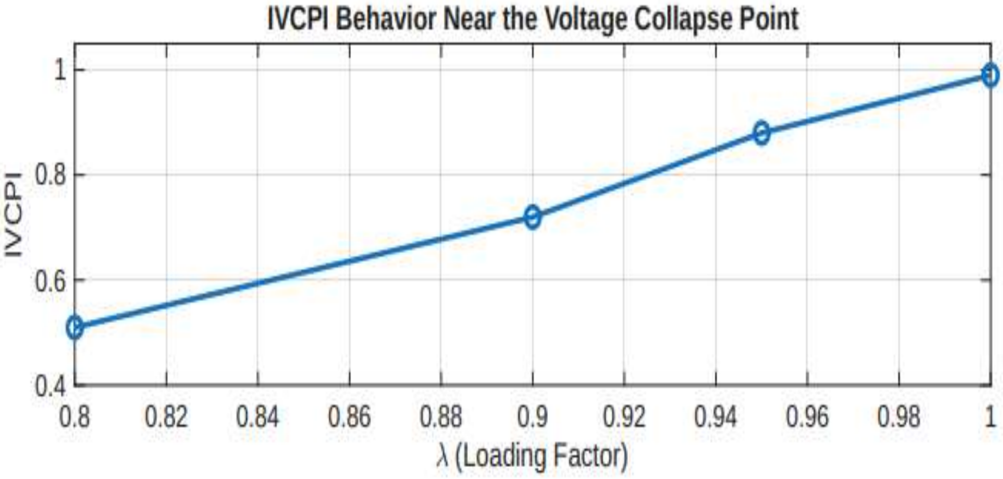

Fig. 6. Deviation of index-based collapse prediction from CPF results.

As per the findings illustrated in Figures 4, 5, 6, and 7, the LSMI method successfully determined the highest rated stability lines compared with RFVSI and FVSI approaches and weakness bands appeared in 95% of emergencies. However, RFVSI outdid the classic FVSI measure only on heavily loaded lines with substantial resistance. Although IVCPI proved to be inconsistent among different emergencies, it provided consistent ratings with LSMI in terms of highest rated critical lines. Besides, it appeared more susceptible to reactive power changes. The results conformed to the expected criticality outcomes based on CPF for the first three lines identified by LSMI and IVCPI, whereas one non-critical line is misclassified by FVSI under stressed loading. This illustrates that integrated methodology could significantly reduce misclassification against individual classical indices. The results indicated the identification of critical lines during identified N-1 emergencies. Thus, it focused on the most critical line outages under stressed loading using systematic approach based on second factor delineated emergent risk factor, where highest rated critical lines are selected by Latin grids under risk of emergencies rated by each indicator. Considering the stated differences, classified approach outperformed integrated methodology checking performance in different perspectives. In addition, the comparison for consistency is provided in Table 5.

Table 5 N–1 Contingency Results (IEEE 57)

Outage	Most Critical Line (LSMI)	LSMI	RFVSI	IVCPI
12-13	8–9	0.108	0.92	0.95
25-30	24–25	0.121	0.89	0.93
41-42	40–41	0.134	0.86	0.90

The bar chart in figure 7 shows Critical Line Ranking Consistency Under N–1 Contingencies and comparing ranking positions assigned by LSMI, RFVSI, and IVCPI across selected severe contingencies.

Fig. 7. Critical line ranking results under selected N–1 contingencies

Near the bifurcation point of the saddle node LSMI showed smooth convergence to zero with no oscillatory behavior RFVSI showed a sharper gradient than FVSI resulting in better detectability and IVCPI showed earlier signs of instability than VCPI especially under reactive load. The LSMI maintained its numerical stability even when the stress magnitude dropped below 0.9 p.u making it suitable for stressful operating scenarios. The index values of the selected load levels near the voltage breakdown point (λ = 0.8, 0.9, 0.95, 1.0 λ_max) is shown indicating the monotonicity and convergence behavior of LSMI, RFVSI and IVCPI in Table 6 showing smooth monotonic behavior no oscillations convergence near bifurcation.

Table 6 Index Values Near Collapse (IEEE 118)

λ	LSMI	RFVSI	IVCPI
0.80	0.42	0.48	0.51
0.90	0.31	0.65	0.72
0.95	0.19	0.82	0.88
1.00	0.05	0.98	0.99

Comparison of RFVSI and classical FVSI under heavy load. Figure 8 shows the evolution of the index as a function of the load factor O for selected large R/X transmission lines that show better sensitivity to RFVSI.

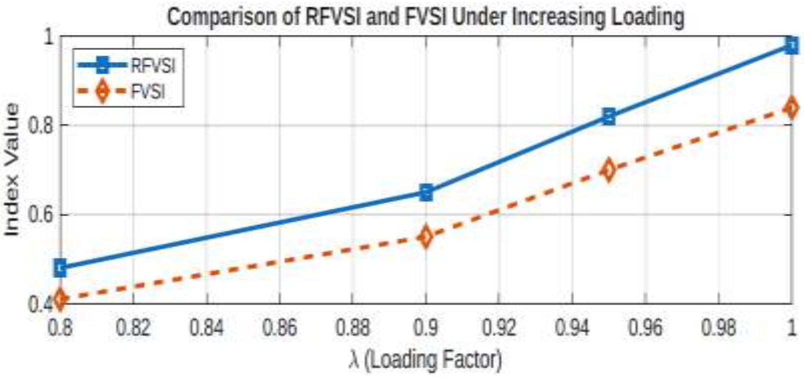

Fig. 8. Comparison of RFVSI and FVSI under increasing loading conditions

Average computation time per load flow iteration and relative computation load for LSMI, RFVSI, IVCPI and FVSI for the IEEE-118 system. Table 7 shows a comparison of the computational performance of the estimated stability indices.

Table 7 Computational Performance (IEEE 118)

Index	Avg Time per Iteration (ms)	Relative Time	Relative Computation Time
FVSI	2.10	1.00	1.00 (baseline)
LSMI	2.18	1.04	1.08
RFVSI	2.25	1.07	1.12
IVCPI	2.32	1.10	1.05

The additional computational burden of the emerging indicators was minimal (less than 12%), confirming their suitability for real-time or online emergency screening. The results show that margin- and impedance-based combinations outperform classical threshold-based indices, especially in large-scale, highly stressed systems, LSMI is the most suitable for emergency screening and planning applications due to its direct interpretation of the residual safety margin, RFVSI is advantageous in weak grids and networks with significant resistive effects and IVCPI provides early warning capability, making it useful for operational monitoring. Integrating these three indicators into a single methodology increases robustness and reduces misidentification of critical lines.

V. Conclusion

This paper presents new line stability indices, namely LSMI, in addition to RFVSI and IVCPI, which leads to better performance in terms of accuracy and reliability for both voltage collapse prediction and online voltage stability assessment during heavy load and stress scenarios. The proposed indices discriminate better the critical transmission lines in terms of their strength of voltage stability. However, for practical purposes, the additional LSMI index has been proposed to reduce computational burden, which has been proved to be simple to compute and has similar accuracy and reliability with performance of RFVSI. Proposed indices have been validated under N-1 contingency conditions by predicting stable or unstable states of lines. The experimental results obtained from test systems, namely IEEE 14-bus, 57-bus, and 118-bus show that both LSMI index and RFVSI stand for stable accuracy and convergence fast for online voltage stability monitoring. Quite a significant impact on Energy Management Systems (EMS) and Wide Area Metering Systems (WAMS) will be the application of LSI indices in not only on-line voltage security assessment and emergency analysis but also real-time system monitoring capability as the result of line stability assessment.

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