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Detecting Power System Voltage Stability in Large Test System

Ch. Hemanth Kumar[1], S. Mallikarjunaiah[2], Shailendra Kumar Mittal[3], Sudhakar Jyothula[4], Sumit Kumar Maitra[5], M. Kalyan Chakravarthi[6]
[1]Sr.Assistant Professor, Department of EEE, GMR Institute of Technology, Rajam, Vizianagaram, India
hemanthkumar.ch@gmrit.edu.in
[2]Professor, Department of EEE, VEMU Institute of Technology, P.Kothakota, Chittoor District, Andhra Pradesh, India
mallisuluru@gmail.com
[3]Professor, Department of Electrical Engineering, GH Raisoni College of Engineering & Management, Pune, Maharashtra, India
shailendramittal5@gmail.com
[4]Professor, Department of ECE, Vignan's Institute of Information Technology (A), Visakhapatnam, Andhra Pradesh, India
sudhakar.jyo@gmail.com
[5]Assistant Professor, Department of Electrical and Electronics Engineering, School of Engineering and Technology, Manav Rachna International Institute of Research and Studies (Deemed to be University), Faridabad, Haryana, India
sumitmaitra.set@mriu.edu.in
[6]Associate Professor, School of Electronics Engineering, VIT-AP University, Amaravathi, Andhra Pradesh, India
kalyanchakravarthi.m@vitap.ac.in

Abstract—The unpredictable changes in electricity demand, along with potential risks, require power system operators to act quickly to prevent voltage instability. To do this, real-time monitoring is crucial, especially in larger systems, but it is a challenging task for power system engineers. The existing methods for detecting voltage instability need to be tested and validated for complex systems. This study aims to validate a voltage instability detection index called SQLVIDI in a larger test system with 118 buses (IEEE 118 bus test system). The simulation results manifest that this index has the capability to detect potential voltage instability in the power system with larger number of buses.

Keywords- Voltage collapse; Node reactive power loss, Synchrophasor measurements, large test system.

I. INTRODUCTION

Voltage stability, within the intricate realm of power systems, delineates the system's intrinsic capability to steadfastly uphold voltages deemed acceptable, both in the antecedent equilibrium and the turbulent wake of perturbations, as conscientiously posited in the venerable tome [1]. The modern power system operates continuously under stressed conditions, with the operating point often close to stability limits. Such systems are known as stressed systems, which are vulnerable to voltage instability. Voltage instability is a process where there is a slow variation in voltage, followed by a sudden change that can lead to system collapse [1].

Contingencies, such as sudden disturbances or outages in a power system, can have a significant impact on voltage stability. When a contingency occurs, it disturbs the normal operation of the power system, and this disruption can lead to voltage instability. The effect of contingencies on voltage stability can be explained as follows [1]:

1. Voltage Drop: Contingencies, such as a branch or generator outage, can cause a sudden reduction in power supply or change in load demand. This drop in available power can lead to voltage reduction at various nodes in the system. If the voltage drops significantly below acceptable levels, it can result in voltage collapse, leading to a widespread blackout.
2. Reactive Power Imbalance: Contingencies can also cause imbalances in reactive power generation and consumption. Reactive power is essential for maintaining voltage levels within acceptable ranges. In the presence of imbalances, some areas may experience excessive reactive power consumption, while others may have excess generation. These imbalances can lead to voltage deviations and instability.
3. Induction Motor Loads: Certain loads, like induction motors, have inherent characteristics that can worsen voltage stability during contingencies. Induction motors can quickly draw large amounts of reactive power during voltage dips, potentially aggravating the voltage instability and accelerating system collapse.

4. Excitation System Response: Contingencies may trigger the operation of excitation system limiters, such as overexcitation limiters (OXL), which affect the reactive power support provided by synchronous generators. If the OXL is activated, it can reduce the generators' capability to support the system's reactive power needs, further destabilizing the voltage.
5. Cascading Effects: In a power system, contingencies can trigger a chain reaction of events, leading to cascading failures. For example, one contingency may cause an overload on a neighboring transmission line or generator, leading to further contingencies and voltage instability.
6. Control Actions: To mitigate the impact of contingencies on voltage stability, power system operators may take control actions, such as load shedding or reconfiguration of the network. However, these actions need to be executed swiftly and accurately to prevent voltage instability from spreading.

Overall, contingencies pose a risk to voltage stability in power systems. Proper planning, real-time monitoring, and effective control strategies are essential to minimize the impact of contingencies and maintain a stable voltage profile in the power system.

The voltage stability can also be influenced by the nature of the load on the system [2]. The load modeling in a power system refers to representing the characteristics and behavior of electrical loads, such as homes, industries, and commercial establishments. The accuracy of load modeling can have significant effects on voltage stability in the power system. In the event of a contingency, such as a branch or generator outage, a stressed system may collapse depending on the type of load it carries. Dominant induction motor loads, for example, can cause voltage collapse in a very short time.

Additionally, the way synchronous generators are controlled, and they're important for supplying reactive power in the system, also has a vital impact [2]. The pivotal role ascribed to the excitation system, ensconced within the power system's intricate fabric, resides in its august duty of shepherding and preserving the hallowed sanctity of voltage stability. It is responsible for regulating the field current of synchronous generators, which, in turn, controls the output voltage of the generator. The excitation system's characteristics and performance directly influence the power system's ability to maintain voltage stability. In the intricate tapestry of the power system, one must not overlook the ubiquitous presence of excitation systems adorning the synchronous generators, in conjunction with their vigilant over-excitation limiters (OXL). When, perchance, the siren call of the OXL limiter reverberates through the network's corridors, it ushers forth a consequential perturbation, one that reverberates through the delicate equilibrium of reactive power support within the system. Given these conditions for voltage instability, extensive research has been conducted over the past two decades, with a primary focus on early detection of voltage instability.

The next section (section 2) provides a brief literature review, while section 3 elaborates on the proposed method. The paper further details simulations conducted on the IEEE 118 bus test system, considering various cases, in section 4 of this manuscript.

II. Literature Review

A Recently, synchro phasor technology has opened up new possibilities for power system engineers and researchers to develop early detection methods. One such method is the L-index, which was developed by considering the roots of a voltage quadratic equation [3]. The L-index provides valuable information about the system's status from a voltage stability perspective. A value close to unity indicates that the system is vulnerable.

Amidst the rigors of exigent circumstances, the power flow Jacobian matrix metamorphoses into a state of malaise, rendering it amenable to an artful transformation which subsequently begets yet another index of pertinence [4]. The intricate power system, replete with its multitude of nodes, may be dissected into dual commensurate termini, wherein one end resides the emanating voltage coalescing with the impedance, itself a veritable epitome of a bus. Within this intricate framework, the condition of impedance congruence can be adroitly harnessed to extrapolate the tenuous echelons of voltage stability, ascertained through the sagacious comparison betwixt load impedance and source impedance.

Phasor measurement units (PMUs) constitute a formidable instrumentality for the expeditious estimation of load impedance. Nevertheless, within the expansive pantheon of methodologies dedicated to the estimation of source impedance, a multifarious array of techniques unfurls its manifold possibilities. Among these, an exemplar of erudition known as the 'recursive least squares approximation' method, as artfully demonstrated in [5], is harnessed for the scrupulous estimation of the pertinent parameters.

Through the judicious application of the impedance matching condition, a discerning observer may glean insight: as the load impedance draws nigh to the threshold of congruence with the source impedance, it serves as a harbinger, a signpost pointing toward the precipice of potential voltage instability within the system.

The intricacies surrounding the comportment of variables $\frac{dP_{loss}}{dP}$, $\frac{dP_{loss}}{dQ}$, $\frac{dQ_{loss}}{dP}$ and $\frac{dQ_{loss}}{dQ}$ they gracefully wend their mathematical path toward infinitude within the proximity of system collapse have been meticulously elucidated in the scholarly treatise [6]. It is, therefore, an endeavor of no trifling import to discern the delicate tremors heralding voltage instability's ominous approach. This intellectual odyssey beckons us to consider the cadence of voltage undulations and the rapidity with which they burgeon, a prescient elucidation promulgated by the erudite scholars of [7] in the annals of 2012.

Further still, the venerated corridors of academia usher us to a compendium of scholarship enshrined in the research of [8] dating back to the hallowed year of 2019. Within these scholarly tomes, the contemplation of reactive power losses and their metamorphic implications finds its resplendent embodiment. From this crucible, an ingenious index emerges, a harbinger of discord and potential cataclysm. Behold, for this index bequeaths unto us negative auguries for tranquil system operations and positive prognostications for the looming specter of voltage instability.

As we delve deeper into the annals of this paper, the hallowed pages unveil the momentous application of the index bequeathed by the venerable [9], an opus of 2019 vintage, unto grander test systems, notably the illustrious IEEE 118 bus test system, enacting a simulation of momentous import. For the elucidation of the index's intricate mechanics and its sacred rites, we beseech the reader to venture forth into the forthcoming section, where enlightenment and sagacity shall surely abound.

III. SUGGESTED INDEX

Reactive power loss in a power system refers to the dissipation of electrical energy as a result of the flow of reactive power (often denoted as "Q") through various components of the system. Reactive power plays a crucial role in maintaining voltage levels within acceptable limits. If there is a deficiency of reactive power, voltage can drop below safe operating levels, leading to voltage instability or even system collapse.

Reactive power losses within the system, coupled with the directions of real power flow, are employed in the calculation of nodal reactive power losses [10]. The index's foundation [9] is built upon the alteration in nodal reactive power loss at a specific node and the variation in nodal reactive power loss from the base load, expressed mathematically [11-14]

$$QLVID(t) = \frac{CQL(t)}{CQLB(t)} = \frac{Q(t) - Q(t-\tau)}{Q(t) - Q_{base}} \quad \textbf{(1)}$$

In this context, τ represents the sampling time, t denotes the current time, and (t- τ) represents the time instant before the current one. Qbase stands for the reactive power loss at the node under base load conditions. The expression for QLVIDI can be formulated as follows:

$$QLVIDI\,(t) = \frac{CQL(t)}{CQLB(t)} - \frac{CQL(t-\tau)}{CQLB(t-\tau)} \quad \textbf{(2)}$$

Contained within the tapestry of Equation (2) are two constituent elements of profound significance: the inaugural component, denoted as QLV ID(t), converges with the latter, being QLV ID(t - τ). In order to evoke a constructive ascent of the index value into the positive stratosphere, QLV ID(t) must ascend beyond the temporal shadow cast by its antecedent, QLV ID(t - τ). In typical operational scenarios of the system, even with an incremental load, CQL(t) slightly exceeds CQL(t - τ), whereas CQLB(t) significantly outpaces CQLB(t - τ).

The overall index value is governed by CQLB, and it carries a negative sign when the system operates healthily and stably. However, when the system undergoes high stress due to heavy loads or branch failures in heavily loaded conditions, CQL(t) substantially exceeds CQL(t - τ), resulting in a sharp increase in reactive power losses at the nodes. In this intricate conundrum, wherein CQLB(t) ostensibly surpasses its antecedent manifestation, CQLB(t - τ), a salient realization emerges: the mercurial complexion of the index, both in its valiant numerical magnitude and enigmatic polarity, finds itself inexorably beholden to the capricious whims of CQL.

The elusive predilection of the index, oscillating betwixt the realms of positivity and negativity, teeters upon the fulcrum of not one, but the dual sovereign influences of CQL and CQLB. In cases of a healthy system, the index's sign relies on CQLB, while for a stressed system, the sign of the index is determined by CQL. As CQL becomes the dominant factor in shaping the index under stressful conditions, the index registers a positive value.

Conversely, when the system is improving, the value of the index is determined by CQLB, resulting in a negative value.

IV. RESUTS AND DISCUSSIONS

To showcase the index's efficacy in larger-scale test scenarios, we selected the IEEE 118 bus test system for simulation, employing the MATLAB platform. The IEEE 118 bus test system encompasses 54 generator buses and 186 lines. An evaluation of the index's performance is conducted utilizing the Newton Raphson (NR) power flow technique. The simulation entails numerous iterations of load flow computations, which provide insights into voltage magnitudes, phasor angles, real power flows, and reactive power losses. In this study, we treat these values as if they were acquired from PMU measurements. Subsequent sections will present the simulation results for various test cases.

A. *Unceasing load progression*

Within the confines of the scrutinized testbed, a synchronized augmentation of loading besets each and every bus, wherein the augmentation proceeds at the measured cadence of 0.1 percent per second. In the wake of this orchestrated load escalation, the mantle of contingency analysis is donned, its task to unveil the Achilles' heels among the transmission lines. The ensuing narrative unfurls the symphony of simulation results, a symphony wherein the spotlight graciously alights upon those very nodes inextricably intertwined with these lines of fragility [14-25]. As depicted in Figure 1, as the load progressively rises, both voltage levels and nodal reactive power losses (as depicted in Figure 2) also experience an upward trend. This culminates in voltage instability occurring at 483 seconds, with a load of (6152.7+j2076.8) MVA.

Figure 3 illustrates the behavior of the SQLVIDI index, which turns positive at t = 403 seconds, serving as an early warning for an impending voltage instability event at a load of (5902.5+j1997.7) MVA. While the load continues to increase, nodal reactive power losses also grow, but the rate of change in losses between two instances remains relatively small and gradual until 400 seconds. Consequently, this leads to a negative value for the index, primarily influenced by CQLB.

However, at 400 seconds, the system experiences high stress, resulting in a rapid escalation of nodal reactive power losses. At this juncture, the index value is predominantly determined by CQD. Essentially, the index detects the abrupt surge in reactive power losses that occurs at 403 seconds in this specific example.

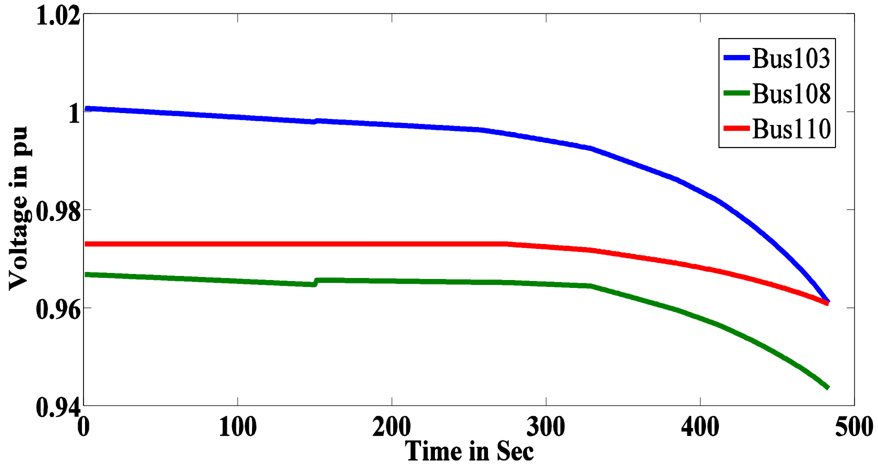

Figure. 1 voltage with load change

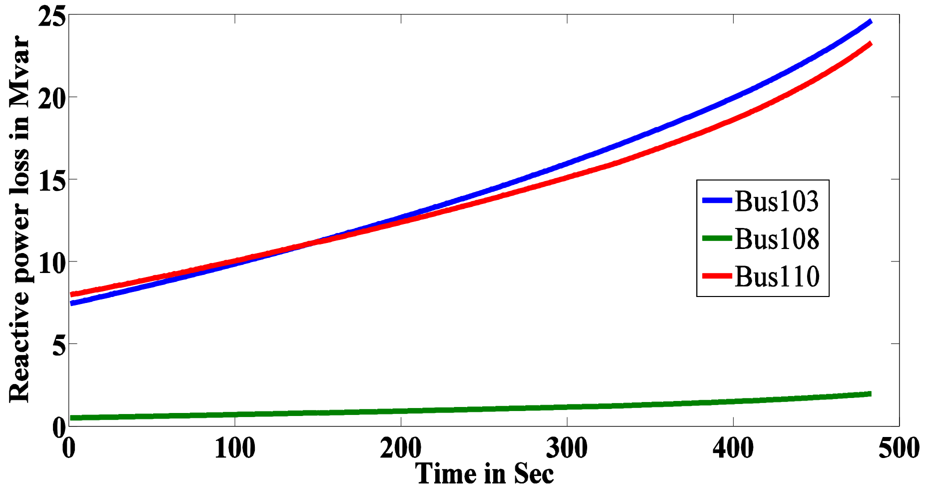

Figure. 2 Node reactive power loss

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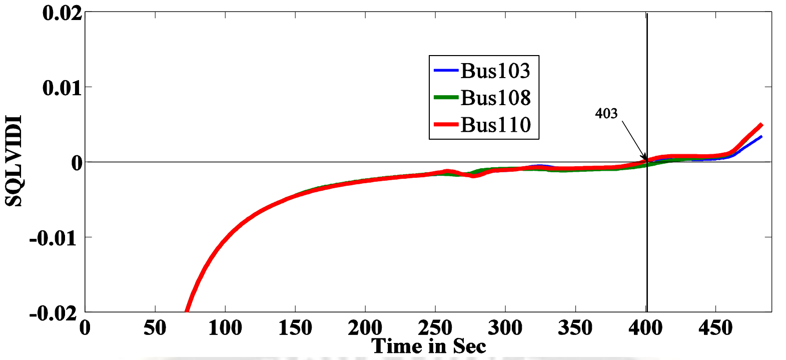

Figure. 3 SQLVIDI

B. Persistent Load Augmentation Amidst Contingent Scenarios

The effectiveness of the index is also assessed under contingency scenarios. At time t = 389 seconds, the branch connecting buses 110 to 112 is intentionally disconnected while maintaining the same load conditions as previously mentioned. As a consequence of this contingency event, voltage instability emerges at 464 seconds with a load of (6105.2+j2062.7) MVA, as depicted in Figure 4.

Interestingly, the index promptly identifies the voltage instability immediately following the line's disconnection, pinpointing it at a loading level of (5890.8+j1993.7) MVA, as illustrated in Figure 5. The system is already under significant stress, and the alteration in the network's topology resulting from the line outage at t=402 seconds induces a sudden, substantial increase in reactive power losses. This rapid surge in reactive power losses is also clearly observable in the nodal reactive power losses represented in Figure 5.

The substantial upswing in reactive power losses triggers a positive response from the index, triggering an alarm that signals the presence of voltage instability within the system.

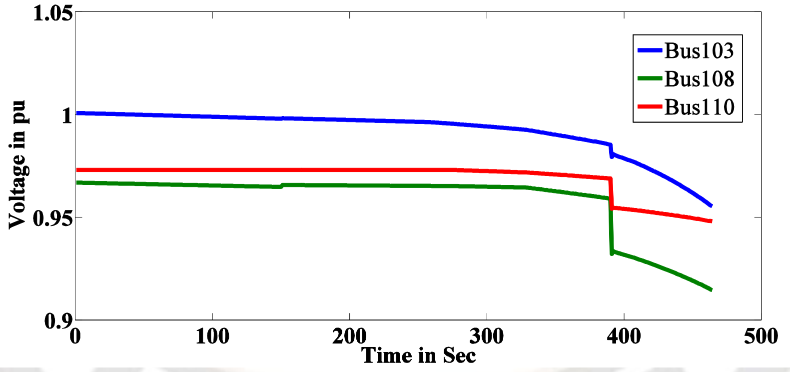

Figure. 4 voltages in contingency case

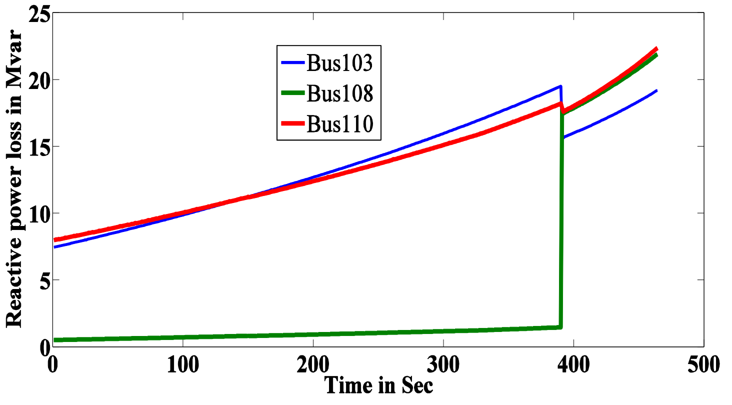

Figure. 5 Node reactive power loss in contingency case

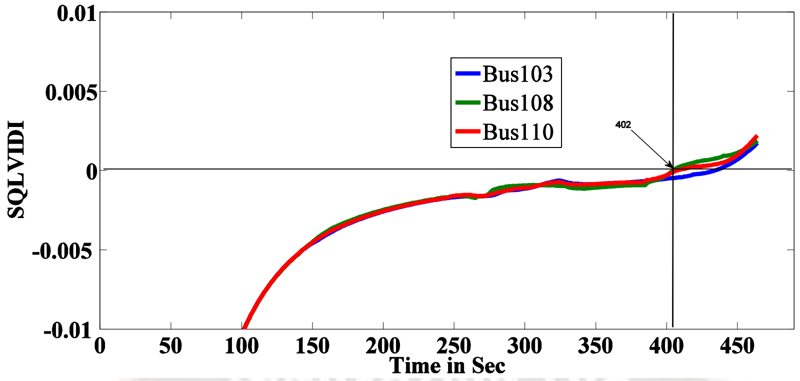

Figure. 6 SQLVIDI in contingency case

V. CONCLUSION

The proposed voltage instability detection index, known as SQLVIDI, is evaluated for its performance on a large test system, specifically the IEEE 118 bus system. The nodal reactive power losses are calculated based on the direction of line real power flows within the system. Derived from the multifarious tapestry of simulation outcomes, the ensuing deductions and inferences can be eloquently discerned as follows:

1. The index demonstrates a fast response in detecting imminent voltage instability.
2. The index proves effective in identifying instability even in the presence of contingencies.
3. As the index relies solely on PMU measurements and involves simple computations, it is well-suited for real power systems. It can serve as an early warning indicator for detecting voltage instability.

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