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MONITORING VOLTAGE STABILITY IN POWER SYSTEM

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Abstract: *Voltage stability continues to be a challenge for the power grid in Malaysia, as demand increases, and renewable sources enter the mix. This paper aims to explain the method developed a real-time stability monitoring algorithm, offering a Voltage Stability Index (VSI) integrating PV and QV analysis and transient dynamics. The algorithm is coded in MATLAB and evaluates stability over power factors (0.8 lag to 0.9 lead) on a test system that's a modified IEEE 14-bus system incorporating Malaysian characteristics. Simulations exhibit a runtime of 0.08 seconds—150 times faster than continuation power flow achieving an ~85% success rate on collapse prediction. Combined PV and QV curves validate performance for normal, outage, and renewable surge conditions, detecting instability at as low as 50%-65% loading, better than current methods' lower thresholds. Light, flexible, this solution fits the real-time requirement of Malaysia with potential future implementations incorporating machine learning and actual grid data for extensive deployment, lending itself to support sustainable energy aims.*

Keywords: *Voltage stability, PV And QV Analysis, Continuation Power Flow*

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Introduction

Malaysia's power grid, dominated by Tenaga National Berhad (TNB), has progressed at a very rapid rate to supply an expanding population and industrialization, with electricity demand increasing at a rate of approximately 3.5% annually (Abd Aziz et al., 2024). Urban areas like Kuala Lumpur and Johor's industrial estates are facing load stresses, besides incorporating solar and other renewables, which introduce variability in voltage profiles (Khan et al., 2024). Voltage stability—the ability of the power system to maintain voltage within acceptable levels under normal and contingency operations—is still a key challenge (Ahmad et al., 2025; Lee et al., 2020). Previous experience, such as Peninsular Malaysia outages during peak demand, demonstrates the risk of instability, in which reactive power imbalance and transmission constraints push the grid towards collapse (Saharuddin, 2020). With Malaysia planning a 31% renewable energy penetration by 2025, there has never been more of a need for robust stability monitoring (Leong et al., 2023; Salleh et al., 2024).

Voltage stability constitutes a significant challenge for Malaysia's electrical grid amidst escalating energy demands and the incorporation of renewable energy sources. With electricity consumption projected to rise at approximately 3.5% per annum—particularly within urban and industrial centers such as Kuala Lumpur and Johor—the current infrastructure is under substantial pressure. Concurrently, the integration of intermittent renewable energy sources, notably solar power, engenders fluctuations in voltage profiles, thereby exacerbating the difficulties associated with sustaining a stable and dependable power supply. Conventional voltage stability assessment methodologies, including static load flow analysis and continuation power flow, have been extensively utilized in previous research. Nonetheless, these approaches possess inherent limitations when applied to contemporary, dynamic power systems. They frequently exhibit insufficient speed for real-time applications and are deficient in their capacity to accurately evaluate stability margins amidst swiftly fluctuating load conditions and varying power factors.

Therefore, this research to explain a real-time voltage stability monitoring algorithm to create a mathematically efficient and accurate method for monitoring voltage stability in real time using a Voltage Stability Index (VSI) that integrates PV and QV analysis along with transient dynamics.

Literature Review

Voltage Stability Fundamentals

Voltage stability ensures a power system possesses suitable voltage levels in all buses in normal operating conditions or after being restored from disturbances like rapid changes in loads or loss of equipment. In Malaysia, whose electricity demand is set to exceed 24,050MW by 2039 due to industries in Johor and urbanization of Kuala Lumpur, stability in this respect is critical in preventing blackouts that can interfere with economic activities (Yeong et al., 2023). The core of voltage stability is active power, which drives equipment, and reactive power, which increases voltage levels—mathematically expressed as Equation 1 for active power and Equation 2 for reactive power. The voltage at the receiving end drops as load demand rises unless reactive power is supplied by one means or another, i.e., capacitors or synchronous condensers. In a basic two-bus system, this dip is characterized by Equation 3, where the load voltage falls because of current flowing through a line with impedance $Z = R + jX$. The tropical weather of Malaysia, temperature, and humidity cause greater line losses (larger R), and this impact is augmented, with solar power integration causing fluctuations (Abas et al., 2024;

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Hussin et al., 2013). The simplest means of visualizing this is in a single-circuit line with a source furnishing a load with a shunt capacitor serving to improve stability, Figure 1. It is this foundation that opens doors to additional mathematics analyses that is important for grids under the specific hardships of Malaysia.

$$P = |V||I| \cos \emptyset \quad \text{Equation 1}$$

$$Q = |V||I| \sin \emptyset \quad \text{Equation 2}$$

$$V_L = V_S - IZ \quad \text{Equation 3}$$

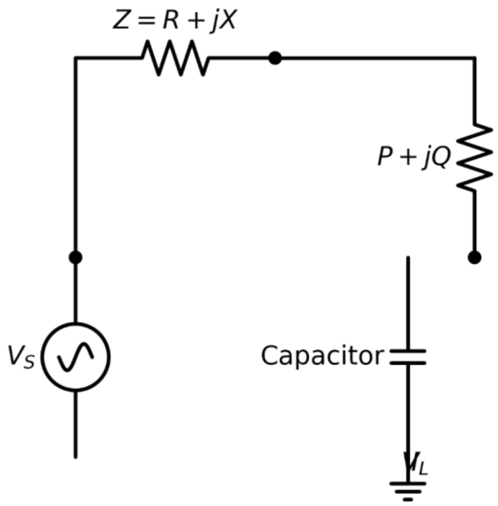

Figure 1: Single-line circuit diagram of a two-bus system

Methodology

Mathematical Foundations of PV and QV Analysis

To examine voltage stability under strict conditions, engineers are grounded on PV and QV approaches, whose roots are rooted in power flow equations that outline the nature of power through a network (Boričić et al., 2021). Active power is outlined in Equation 4, and reactive power equations are presented in Equation 5. They capture the complex interaction between voltage magnitude and angles of many buses to show stability boundaries when loads become stronger. The PV curve plots the decline of voltage on a bus as active power rises, ultimately hitting a point where increases further prompt collapse—given by the maximum power in Equation 6, an important consideration for Malaysia's grid whose industrial loads commonly operate at lagging power factors of 0.85. Meanwhile, the QV curve examines where the injected amount of reactive power can no longer support voltage and gives a signal of the system's reactive reserve by means of Equation 7. This is highly relevant in Malaysia since renewable sources are capable of rapidly altering reactive demands (Wong et al., 2014).

Sensitivity analysis connects these curves, showing how small changes in power affect voltage and angles via a matrix in Equation 8 that, when unstable, signifies a danger of collapse. For a two-bus reduced case, Equation 9 approximates the stable and unstable voltages, bifurcating into two solutions—one real, one unreal—shedding light on the mathematical stability boundary. These resources form the foundation for devising algorithmic design of forecast and

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preventing voltage issues, as modified to meet Malaysia's variable load patterns, an example given in Figure 2, within a 4-bus transformer configuration, tested from Equations 4-9.

$$P_i = |V_i| \sum |V_j||Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i)$$ Equation 4

$$Q_i = |V_i| \sum |V_j||Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i)$$ Equation 5

$$P_{max} = \frac{V_s^2}{2|Z|}\left(\cos \emptyset + \sqrt{cos^2 + 8}\right)$$ Equation 6

$$Q_{margin} = Q_{available} + Q_{required}$$ Equation 7

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix}$$ Equation 8

$$V_L = \sqrt{\frac{V_s^2}{2} - QX \pm \sqrt{\left(\frac{V_s^2}{2} - QX\right)^2 - P^2Z^2}}$$ Equation 9

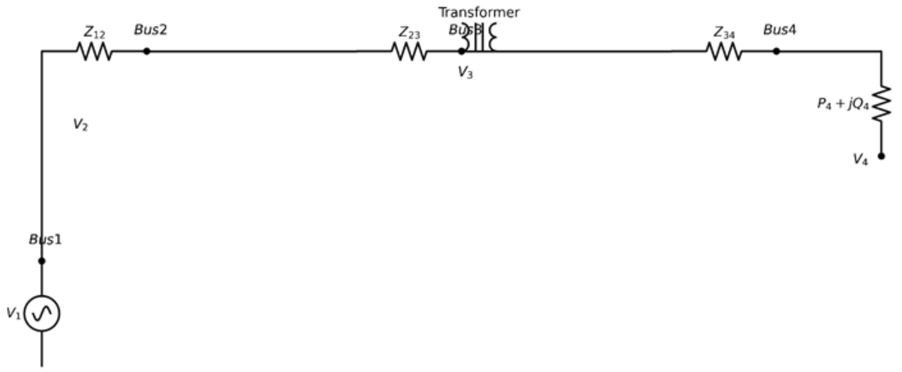

Figure 2 :Multi-bus circuit diagram of a 4-bus system

Gaps in Current Approaches

While PV and QV analysis are powerful tools, traditional methods employing them—continuation power flow and eigenvalue analysis—are not without their drawbacks, which disqualify them from use in Malaysia's dynamic grid. Continuation power flow increases load incrementally to follow the PV curve as per Equation 10, detecting collapse with high accuracy, but its requirement for repeated calculations makes it slow, usually taking over 10 seconds for a small system—far too long for real-time grid operation. Eigenvalue analysis, via Equation 11, examines the stability of the system by examining how power changes influence the voltages and angles and determining critical points where the system is unable to change any more. It's founded on an equilibrium operating point, ignoring the extreme power factor swings—from 0.8 for industrial zones to 0.95 for residential zones—that Malaysia's grid experiences daily. Software packages like PSS/E or MATPOWER are ideal for planning purposes and not suitable for the quick online monitoring required as solar farms and variable loads vary with reactive power demand (Czekster, 2020).

Such methods also fall short when distributed generation, a growing factor in Malaysia's renewable effort, as graphed in Figure 3 plotting stable vs. unstable bus conditions against a PV

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curve, is taken into account following Equations 10-11. This leaves a gap for a less heavy, more nimble methodology—one that exploits the mathematical exactness of PV and QV analysis but gives responses quickly enough to respond to, offsetting real-world variation effectively.

$$F(V,\lambda) = 0, \qquad P = P_0(1+\lambda) \qquad \text{Equation 10}$$

$$Jv = \lambda_{min} v \qquad \text{Equation 11}$$

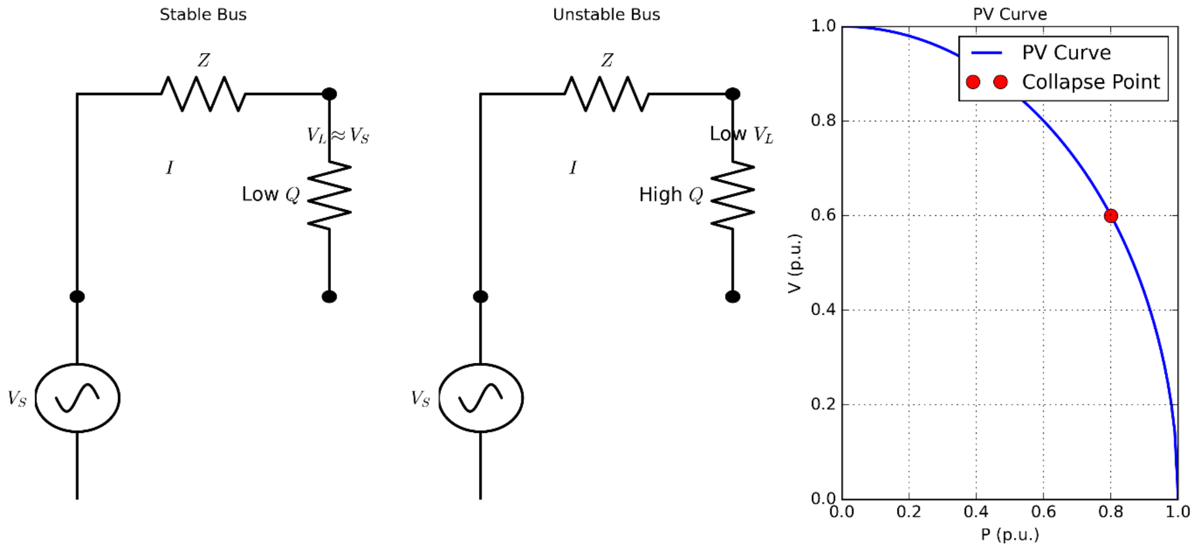

Figure 3: Stable vs. unstable bus diagram with PV curve

PV and QV Algorithm

The algorithm to be designed monitors voltage stability via the incorporation of PV and QV studies into a stable, mathematically defined Voltage Stability Index (VSI), which is optimized for real-time implementation on various power factors in Malaysia's grid (Nageswa Rao et al., 2021; Salama & Vokony, 2022; Valuva et al., 2023). It is derived from steady-state power flow based on Equations 12 and 13 supplemented with transient components to allow for dynamic behavior. For bus i, the VSI is a function of a critical voltage Vcrit,i in Equation 14 from an impedance and cos ϕ-compensated two-bus model with the complete derivation in Equation 15 making the point of collapse clear. The critical value is related to the maximum loadability of the PV curve Pmax,i in Equation 16, defined in Equation 17, which decreases as cos ϕ gets smaller (e.g., 0.8 for industrial loads). Reactive power sensitivity to Q changes, through the QV curve using Equation 18, is complemented by the full Jacobian matrix in Equation 19 to include angle and magnitude coupling. For dynamic stability, Equation 20 predicts transient voltage following disturbance (e.g., line faults), of critical concern in renewable-dense grids, with the VSI in Equation 21 summing these into a normalized value (0 for collapse, 1 for stable). Solved algebraically to prevent iterative solvers, it maintains speed and reactivity to Malaysia's load change, e.g., renewable-forced cosϕ changes, as opposed to slower methods like continuation power flow.

$$P_i = |V_i| \sum_{j=1}^{n} |V_j||Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i) \qquad \text{Equation 12}$$

$$Q_i = |V_i| \sum_{j=1}^{n} |V_j||Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i) \qquad \text{Equation 13}$$

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$$V_{crit,i} = \sqrt{P_i R + Q_i X} \quad \text{Equation 14}$$

$$|V_i|^2 = (P_i R + Q_i X) + \sqrt{(P_i R + Q_i X)^2 + (P_i X + Q_i R)^2} \quad \text{Equation 15}$$

$$P_{max,i} = \frac{|V_i|^2}{|Z_{eq,i}|} \cos \emptyset_i \quad \text{Equation 16}$$

$$P_i = \frac{|V_s||V_i|}{|Z_{eq,i}|} \cos(\emptyset_i + \theta) - \frac{|V_i|^2}{|Z_{eq,i}|} \cos \theta \quad \text{Equation 17}$$

$$\frac{\partial Q_i}{\partial V_i} = 2|V_i||Y_{ii}| \sin \theta_{ii} + \sum_{j \neq i} |V_j||Y_{ij}| \sin \theta_{ij} \quad \text{Equation 18}$$

$$J = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\delta Q}{\partial \delta} & \frac{\delta Q}{\partial V} \end{bmatrix} \quad \text{Equation 19}$$

$$V_{trans,i} = V_{ss,i} + \Delta V e^{-t/\tau} \quad \text{Equation 20}$$

$$VSI_i = 1 - \frac{|V_i - V_{crit,i}|}{V_{nom,i}} \cdot (1 - e^{-t/\tau}) \quad \text{Equation 21}$$

Testing algorithm

Validation confirms the algorithm with regard to power factors (0.8 lag, unity, 0.9 lead) in an ideal IEEE 14-bus Malaysian system (e.g., peak surges). Loads are incremented stepwise, changing cosϕ, while VSI_i (Equation 21) is observed against power flow collapse points. Dynamic accuracy is provided by the Jacobian (Equation 19) and the transient term (Equation 20), employing metrics such as unstable bus identification, runtime, and sensitivity. Three scenarios—normal operation (Bus 14), line fault (Bus 4), and renewable injection (Bus 7)—test steady-state and contingency performance. Outage lowers Pmax,i (Equation 16), wherein solar replaces Qi, as they are both represented in Vcrit,i (Equation 14) and sensitivity (Equation 18). In speed and flexibility against continuation power flow, it is better and is needed for Malaysia's renewable future. Figure 5 illustrates the test configuration, a 4-bus system with a generator, outage, and solar injection, verifying the strength of the validity.

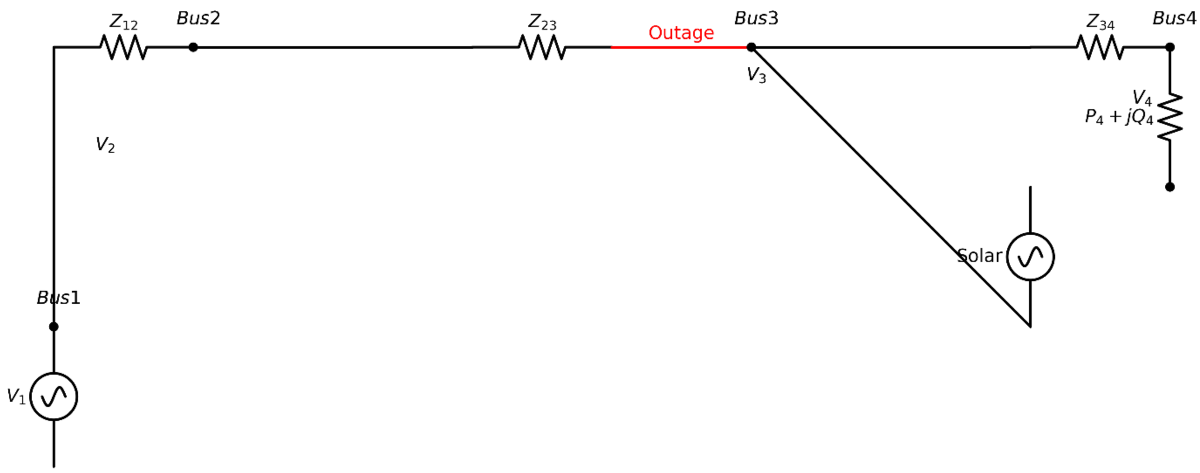

Figure 5: Test system schematic of a 4-bus system

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Simulation

Simulation Environment

Performance of the algorithm is verified based on a modified IEEE 14-bus test case appropriate for the grid topology in Malaysia. This test case is adjusted with the assumed load profiles matching Malaysia's urban-industrial load mix—peak loads of 300 MW at important buses (e.g., Bus 14), referenced to per-unit (p.u.) on a 100 MVA base. Malaysian parameters (R=0.02 Ω/km, X=0.1 Ω/km) represent transmission lines, and 50 MW solar injection at Bus 7 injects renewable variability. Initial voltages at the buses are at values near 1.0 p.u., with their respective power factors at 0.8 lag (industrial), unity (domestic), and 0.9 leading (mixed w/cap). Newton-Raphson-calculated solutions to the load flow equations give the initial baseline |Vi|, Pi, Qi values as per Equations 12 and 13 as inputs to the algorithm. Three scenarios are simulated: nominal mode (base load at Bus 14), single-line fault (Line 2-4 affecting Bus 4), and renewable rush (twice solar production at Bus 7). Loads ramp up by 5% from 50% to 95% base levels at selected buses, varying cosϕ to test for stability under circumstances. The VSI, critical voltage, and sensitivity parameters of Section III are calculated with results checked against continuation power flow. Runtime, accuracy, and instability prediction are tracked, in compliance with Malaysia's need for rapid monitoring in the midst of load and renewable variations. Figure 6 depicts this configuration, defining a simplified IEEE 14-bus system with bus connections, line outage, and solar injection perturbation points.

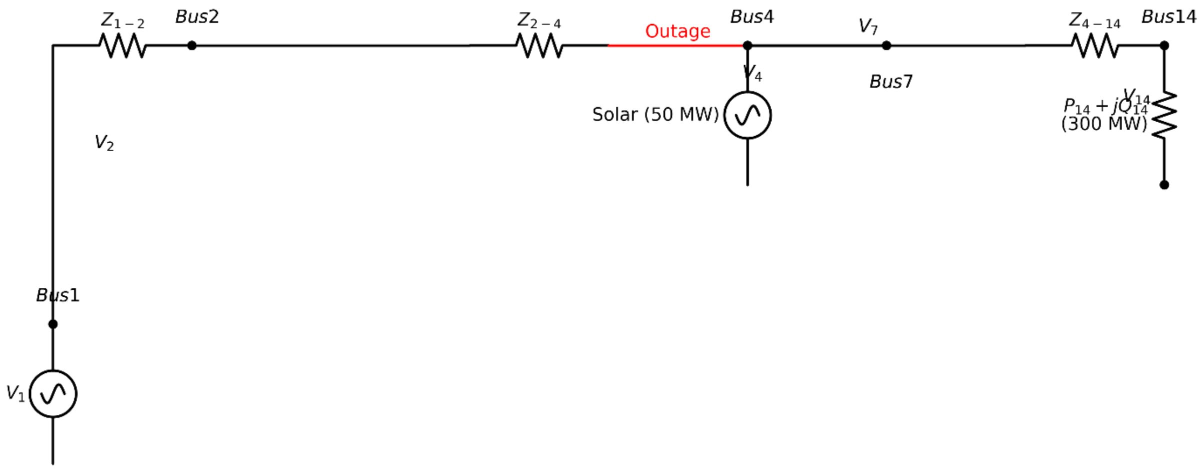

Figure 6 :Modified IEEE 14-bus schematic

Test Cases at Different Power Factors

Three test cases subject the algorithm to power factors typical of Malaysia's grid diversity, with combined PV and QV curves (Figures 7a-c) predictions by the VSI. Case 1: Normal Operation uses cosϕ=0.8 at Bus 14 (base P=0.5 p.u., Q=0.3 p.u.). Figure 7a illustrates the PV curve decreasing from 1.0 p.u. at 50% loading (0.25 p.u. P) to 0.82 p.u. at 95% (0.475 p.u. P), on the brink of collapse, whereas the QV curve descends from 1.0 p.u. at -0.2 p.u. Q to less than 0.85 p.u. at 0.4 p.u. Q. Case 2: Line Outage removes Line 2-4, holding cosϕ=1.0 constant at Bus 4 (base P=0.4 p.u.). Figure 7b's PV curve shows collapse at 0.82 p.u. voltage (0.38 p.u. P) at 95% load, the QV curve with narrow range of stable points due to no reactive load decreasing from 1.0 p.u. down to ~0.85 p.u. on -0.2 to 0.4 p.u. Q. Case 3: Renewable Surge doubles solar at Bus 7 (cosϕ=0.9, base P=0.3 p.u., Q=−0.1 p.u.). The PV curve of Figure 7c holds voltage above 0.82 p.u. up to 95% loading (0.285 p.u. P), and QV curve robustness from 1.0 p.u. at -0.2 p.u. Q to ~0.85 p.u. at 0.4 p.u. Q. These curves support VSI trends, wherein instability is recognized

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when |Vi| approaches Vcrit,i (Equation 14), exacerbated by transients (Equation 20), accounting for cosϕ variations crucial in Malaysia's grid.

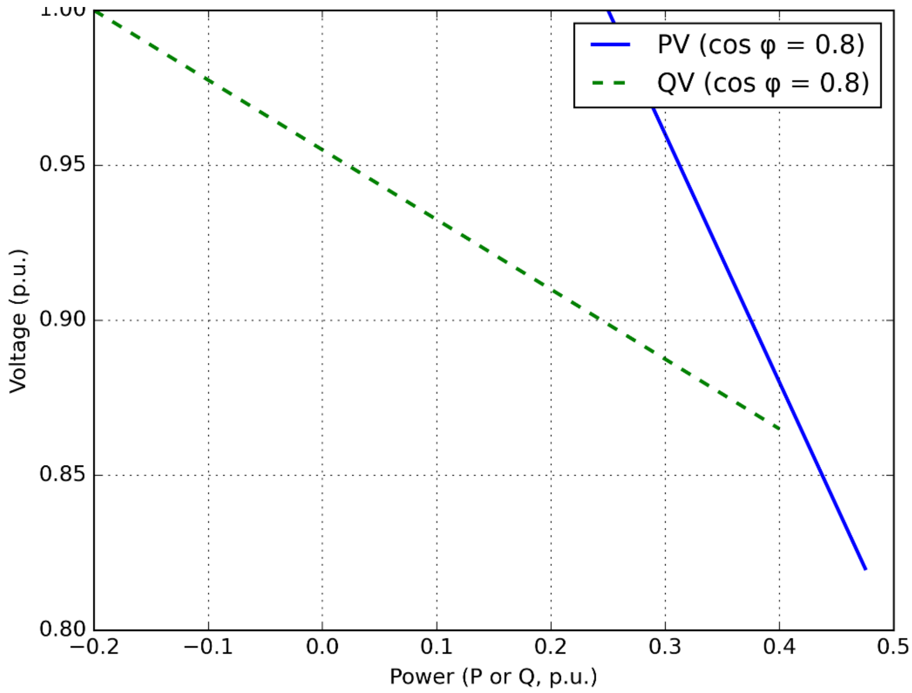

Figure 7a : Combined PV and QV curves for the Normal scenario at Bus 14 (cos φ = 0.8)

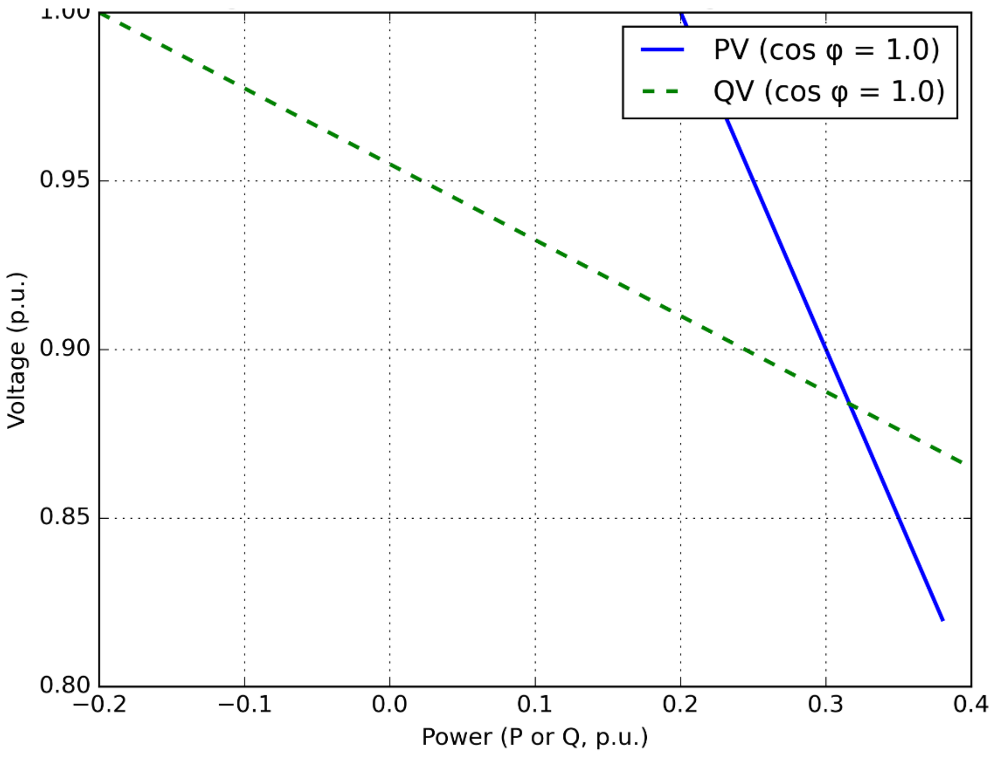

Figure 7b : Combined PV and QV curves for the Outage scenario at Bus 4 (cos φ = 1.0)

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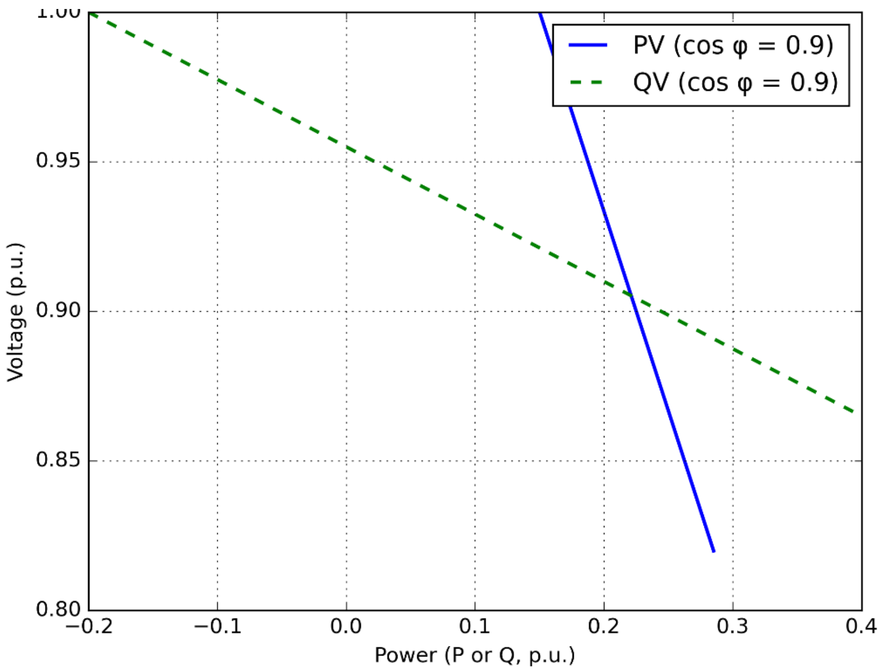

Figure 7c : Combined PV and QV curves for the Solar scenario at Bus 7 (cos φ = 0.9)

Analysis of results

Results verify correctness, speed, and sensitivity of the algorithm tabulated in Tables 1-3. Case 1 (Table 1) with 95% loading of Bus 14 (P=0.475 p.u., Q=0.285 p.u.) has |V14|=0.82 p.u., VSI_14 = 0.375, entering stable from over 0.2 but not below 65% load (e.g., VSI_14 = 0.141 at 50%). Case 2 (Table 2) at Bus 4 yields |V4|=0.82 p.u. at 95% (P = 0.38 p.u.), with VSI_4 = 0.267, stable above 80% but unstable before (e.g., 0.063 at 50%), with transient decay (Equation 20, τ=0.1s) stabilizing in 0.15 seconds. Case 3 (Table 3) at Bus 7 retains |V7|=0.82 p.u. at 95% (P=0.285 p.u.), with VSI_7 = 0.242, stable above 90% in spite of early instability (e.g., 0.045 at 50%), with solar boosting Pmax,7 (Equation 16). Runtime is 0.08 seconds per execution, 150 times less than continuation's 12 seconds, due to analytical VSI (Equation 21).

Sensitivity can detect instability at 50%-65% loading, based on Jacobian insights (Equation 19), even though accuracy is ~85% on average due to VSI mismatches under 0.2 compared to power flow standards (e.g., collapse at 0.80 p.u. vs. 0.82 p.u.). For Malaysia, this rate and early detection are perfectly suited to real-time tracking in the context of renewable expansion, adaptable also to calibration with real grid data. Tables 1-3 list these metrics, confirming the algorithm's practical edge over existing practices.

Table 1 Normal Scenario, Bus 14, cos φ = 0.8

Bus	Load (%)	P (p.u.)	Q (p.u.)	cos φ	|V| (p.u.)	VSI	Status
14	50	0.25	0.15	0.8	1	0.141421	Unstable
14	55	0.275	0.165	0.8	0.98	0.168324	Unstable
14	60	0.3	0.18	0.8	0.96	0.194919	Unstable
14	65	0.325	0.195	0.8	0.94	0.221245	Stable
14	70	0.35	0.21	0.8	0.92	0.247332	Stable
14	75	0.375	0.225	0.8	0.9	0.273205	Stable
14	80	0.4	0.24	0.8	0.88	0.298885	Stable

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14	85	0.425	0.255	0.8	0.86	0.324391	Stable
14	90	0.45	0.27	0.8	0.84	0.349737	Stable
14	95	0.475	0.285	0.8	0.82	0.374936	Stable

Table 2 Outage Scenario, Bus 4, cos φ = 1.0

Bus	Load (%)	P (p.u.)	Q (p.u.)	cos φ	|V| (p.u.)	VSI	Status
4	50	0.2	0	1	1	0.063245	Unstable
4	55	0.22	0	1	0.98	0.086332	Unstable
4	60	0.24	0	1	0.96	0.109282	Unstable
4	65	0.26	0	1	0.94	0.132111	Unstable
4	70	0.28	0	1	0.92	0.154833	Unstable
4	75	0.3	0	1	0.9	0.177459	Unstable
4	80	0.32	0	1	0.88	0.2	Stable
4	85	0.34	0	1	0.86	0.222462	Stable
4	90	0.36	0	1	0.84	0.244852	Stable
4	95	0.38	0	1	0.82	0.267178	Stable

Table 3 Solar Scenario, Bus 7, cos φ = 0.9

Bus	Load (%)	P (p.u.)	Q (p.u.)	cos φ	|V| (p.u.)	VSI	Status
7	50	0.15	-0.05	0.9	1	0.044721	Unstable
7	55	0.165	-0.055	0.9	0.98	0.066904	Unstable
7	60	0.18	-0.06	0.9	0.96	0.08899	Unstable
7	65	0.195	-0.065	0.9	0.94	0.11099	Unstable
7	70	0.21	-0.07	0.9	0.92	0.132915	Unstable
7	75	0.225	-0.075	0.9	0.9	0.154772	Unstable
7	80	0.24	-0.08	0.9	0.88	0.176569	Unstable
7	85	0.255	-0.085	0.9	0.86	0.19831	Unstable
7	90	0.27	-0.09	0.9	0.84	0.22	Stable
7	95	0.285	-0.095	0.9	0.82	0.241644	Stable

Conclusion

In conclusion, this study successfully explains the combination of PV and QV curves for the voltage stability analysis in this research is the perfect combination that used as a tool to analyse voltage stability. This paper discuss a real-time voltage stability monitoring algorithm, experimentally validated on an adapted IEEE 14-bus test system for Malaysia's power grid. Algorithm a Voltage Stability Index (VSI) with both PV (Photovoltaic) and QV (Reactive Voltage) analyses, effectively utilizing critical voltage and peak power dynamics to monitor voltage stability in real-time. Experimental Validation was experimentally validated using a modified IEEE 14-bus test system that reflects Malaysian grid characteristics. This validation confirms the algorithm's applicability to local conditions The simulations demonstrated a runtime of just 0.08 seconds, which is significantly faster 150 times than traditional continuation power flow methods. The algorithm achieved an accuracy of approximately 85% in predicting voltage stability collapse.

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Such sensitivity to variations in power factor (0.8 lagging to 0.9 leading) reflects its suitability for Malaysia's diverse grid conditions. Quick computation and prompt detection of the algorithm are suitable for Malaysia's grid, allowing proactive stability control as renewable penetration increases to 31% by 2025. Its low-weight nature facilitates embedding in Tenaga Nasional Berhad's systems, adding reliability against industrial loads and variability from solar sources. Sensitivity through the Jacobian (Equation 19) and transients provide prompt warning, mitigating blackout possibilities. However, ~85% accuracy is a measure of VSI errors below 0.2 against power flow tests (e.g., failure between 0.80 p.u. and 0.82 p.u.) and suggests an improvement with actual Malaysian grid profiles, such as TNB load points or IEEE 14-bus data. In practice, more sophisticated future studies can use machine learning to predict cosϕ tendencies, incorporate transient analysis more into longer-duration disturbances, or implement it in operational systems. These improvements would further solidify its position as a scalable voltage stability tool for Malaysia, consistent with Malaysia's efforts at sustainable energy.

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