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Contingency Analysis in Power System Using 14 Bus System

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Abstract – Continuation Power Flow (CPF) is a fundamental technique for evaluating voltage stability and operating limits in power systems as they move through varying conditions. This thesis presents and illustrates a CPF framework for a benchmark 14-bus system that combines the Newton–Raphson (NR) method with Jacobian-based predictor–corrector iterations. The nonlinear real and reactive power balance equations are solved by the NR solver, while the Jacobian—derived from their partial derivatives—is used to select and correct steps as a loading/generation parameter is varied continuously. The implementation follows P–V and, where applicable, Q–V characteristics through a variety of operating conditions, including incremental load increase, generator dispatch adjustment, reactive limit activation, and selected topology adjustment.
Results indicate the proposed CPF consistently tracks the power-flow solution manifold into areas where traditional load flow has difficulty converging, precisely pinpointing critical points related to voltage collapse (nose points) and indicating weak buses and branches. Voltage profile and power transfer qualitative analyses demonstrate how reactive power supply and network structure influence stability margins. A step-by-step, reproducible explanation of the algorithmic process—model initialization, Jacobian building and update, predictor–corrector iteration, and convergence monitoring—illuminates pragmatic aspects like step-size management and near-singularity treatment of the Jacobians.

***Keywords**: 14 Bus System, Contingency Analysis, Voltage Stability, Power Flow, Active Reactive Analysis*

I. Introduction

Contingency Contingency analysis is a foundation of power-system planning and real-time security evaluation. Contingency analysis examines methodically how the network reacts to plausible disturbances—such as the loss of a transmission element or generator—and allows operators to measure security margins, rank reinforcements, and construct corrective actions. Within the steady-state (post-disturbance) context, this routine is commonly called static security assessment and concerns itself with voltage profiles and thermal loadings for N-1 (single element) and, when necessary, N-k contingencies.
The IEEE 14-bus test case is commonly employed as a benchmark for such analyses due to the balance it strikes between realism and manageable size. It includes the salient features that appear in real systems—slack and PV buses, multiple generators, transformer branches with taps, and reactive-power limits—yet is small enough to accommodate complete scenario analysis and comparison of methods. Here in this thesis, we use the conventional IEEE 14-bus model having 14 buses, 5 generator buses (usually at buses 1, 2, 3, 6, and 8), and 20 branches in total—17 transmission lines and 3 transformers—connecting the network. That specification is relevant: some accounts loosely refer to "20 lines," but the standard case differentiates lines from transformer branches.

Our contingency analysis analyzes the system's response under a typical collection of outages, i.e., single line/transformer outages and single-generator outages. For each of these scenarios we solve the AC power-flow equations and analyze the important security metrics: bus-voltage magnitudes and violations, branch loading percentages and thermal overloads, reactive-power reserve margins, and weak bus sensitivity. Where appropriate, we also comment on how generator reactive limits and PV→PQ switching affect post-contingency voltages. Outside individual instances, aggregated performance indices are utilized to order contingencies in terms of severity and point out key aspects.

Applying the IEEE 14-bus benchmark is additionally beneficial. First, it allows transparent comparison with previously reported algorithms and control strategies in the literature (e.g., various linearized screening approaches versus complete AC re-dispatch checks). Second, its simplicity allows reproducibility: contingency lists, base-case data, and solver configurations can be defined exactly so others can replicate and further extend the study for larger IEEE test systems or utility models.
In short, this research utilizes the IEEE 14-bus system to (i) illustrate a deterministic AC contingency-analysis process, (ii) determine the most critical elements of the network under N-1 disturbances, and (iii) give a transparent, reproducible reference point for testing mitigation strategies like reactive-power support, transformer tap settings, and generation re-dispatch.

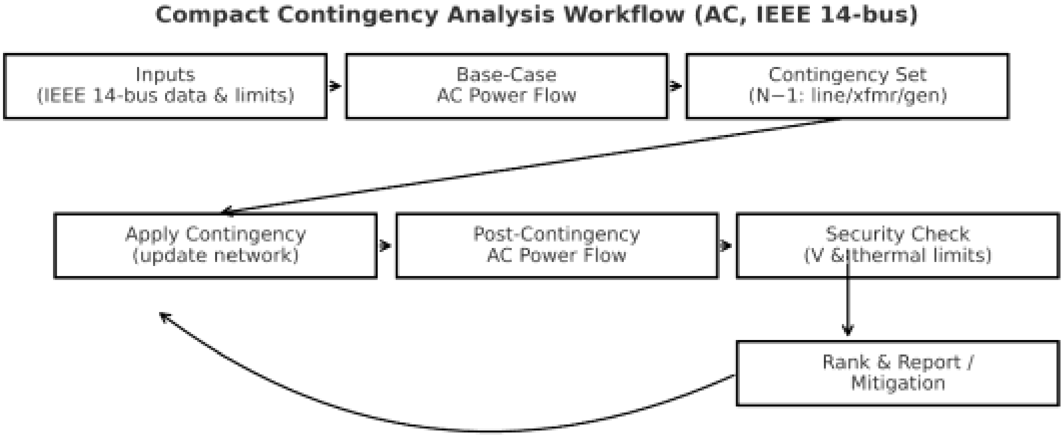

Figure 1 Compact Contingency Analysis Workflow (AC, IEEE 14-bus)

II. Method

The Continuation Power Flow process involves the following key steps:

Base Case Initialization:
Start with the base case, representing the initial operating condition of the power system using the IEEE 14 Bus System. This includes the specification of load demands, generator settings, and network parameters.

Selection of Continuation Parameter:
Choose a continuation parameter, often the system loading parameter (e.g., active power demand or reactive power demand), that will be incrementally varied to explore different operating points. The parameter should be selected strategically to capture system behavior under realistic conditions.
Formulation of Power Flow Equations:
Formulate the power flow equations for the IEEE 14 Bus System, considering both real and reactive power flows. These equations are typically nonlinear and describe the relationship between bus voltages, power injections, and impedances.
Jacobian Matrix Calculation:
Derive the Jacobian matrix, which contains the partial derivatives of the power flow equations with respect to the state variables (bus voltages and phase angles). The Jacobian matrix guides the iterative solution process and ensures convergence.
Iterative Solution with Newton-Raphson Method:
Employ the Newton-Raphson method to iteratively solve the nonlinear power flow equations. At each iteration, update the system variables based on the calculated corrections, considering the Jacobian matrix.
Continuation Process:
Incrementally vary the continuation parameter, adjusting the system loading conditions in a controlled manner. At each step, perform the Newton-Raphson iterations to obtain the updated solution for the power flow equations.
Identification of Critical Points:
Monitor the system's response throughout the continuation process. Identify critical points where the system exhibits signs of voltage instability or approaching voltage collapse. These points are indicative of operational limits.

Analysis of Voltage Stability Limits:
Analyze the obtained results to determine voltage stability limits and assess the impact of varying loading conditions on the IEEE 14 Bus System. Voltage stability limits can provide valuable insights into the system's robustness under different scenarios.
Significance:
Continuation Power Flow for the IEEE 14 Bus System is significant for:
Voltage Stability Assessment: Identifying critical loading conditions and voltage instability limits.
Operational Planning: Providing information for optimal operational planning and preventive control strategies.
System Resilience: Enhancing understanding of the system's resilience to changing demand and operational uncertainties.
The Continuation Power Flow (CPF) method involves solving a set of nonlinear power flow equations iteratively. The general power flow equations for a bus i in a power system can be expressed as follows:

$$P_i = \sum_{j=1}^{n} V_i V_j \left(G_{ij}\cos(\theta_i - \theta_j) + B_{ij}\sin(\theta_i - \theta_j)\right) - V_i^2 G_{ii}$$

$$Q_i = \sum_{j=1}^{n} V_i V_j \left(G_{ij}\sin(\theta_i - \theta_j) - B_{ij}\cos(\theta_i - \theta_j)\right) + V_i^2 B_{ii}$$

Where:
- P_i and Q_i are the real and reactive power injections at bus i,
- V_i is the voltage magnitude at bus i,
- θ_i is the voltage angle at bus i,
- G_{ij} and B_{ij} are the real and imaginary components of the admittance between buses i and j,
- G_{ii} and B_{ii} are the real and imaginary components of the shunt admittance at bus i,
- n is the total number of buses in the system.

The Jacobian matrix J for the Newton-Raphson method can be derived from the partial derivatives of the power flow equations with respect to the state variables (voltage magnitudes and angles):

$$J_{ij} = \frac{\partial P_i}{\partial \theta_j} = -V_i V_j \left(G_{ij}\sin(\theta_i - \theta_j) + B_{ij}\cos(\theta_i - \theta_j)\right)$$

$$J_{ij} = \frac{\partial P_i}{\partial V_j} = V_i \left(G_{ij}\cos(\theta_i - \theta_j) + B_{ij}\sin(\theta_i - \theta_j)\right)$$

$$J_{ij} = \frac{\partial Q_i}{\partial \theta_j} = V_i V_j \left(G_{ij}\cos(\theta_i - \theta_j) + B_{ij}\sin(\theta_i - \theta_j)\right)$$

$$J_{ij} = \frac{\partial Q_i}{\partial V_j} = V_i \left(G_{ij}\sin(\theta_i - \theta_j) - B_{ij}\cos(\theta_i - \theta_j)\right)$$

These equations form the basis for the Newton-Raphson method, where the iterative process involves updating the state variables (θ andV) using the inverse of the Jacobian matrix.For the Continuation Power Flow, the continuation parameter (e.g., active power demand) is incrementally varied, and the power flow equations are solved iteratively for each step, guiding the system through different loading conditions. The process continues until critical points are identified, providing insights into the system's behavior under various scenarios.

Parameter Switching — Using a Bus Voltage as the Continuation Parameter

Near the nose, using λ as the parameter is numerically fragile because the solution curve is almost vertical in the (V,λ) plane. To bypass the singularity, we switch to a voltage-parameterized continuation. Select a critical bus k (typically the one with the lowest V) and define a new parameterμ:=Vk. The augmented system becomes

$$\mathcal{G}(x,\lambda;\mu)=\begin{bmatrix} F(x,\lambda) \\ e_k^{\top}V(x)-\mu \end{bmatrix}=0,$$

where the second row constrains the k-th bus voltage magnitude to a prescribed value.

Voltage-based predictor. Hold λ at its last successful value λ⋆(just before divergence) and step the voltage parameter by a small decrement:

$$\mu^{pred}=\mu^{\star}-\sigma\mu,\sigma\mu \text{ small (e.g., 0.005 p.u.).}$$

Predict xpredwith the tangent of G=0, or simply reuse the last state as a good initial guess.

Voltage-based corrector. Now solve the augmented Newton system for (x,λ) with μ fixed:

$$\begin{bmatrix} J(x,\lambda) & F_{\lambda}(x,\lambda) \\ e_k^{\top}\frac{\partial V}{\partial x} & 0 \end{bmatrix}\begin{bmatrix} \Delta x \\ \Delta\lambda \end{bmatrix}=-\begin{bmatrix} F(x,\lambda) \\ e_k^{\top}V(x)-\mu^{\text{pred}} \end{bmatrix}$$

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This removes the turning-point singularity (one extra equation for one extra unknown) and lets us trace around the nose and, if desired, onto the unstable branch. During this phase, as μ is stepped down, the solved typically decreases even while Vk is forced lower. We continue until λ has fallen to a safe fraction (e.g., ≈75%) of its peak, which both limits excursions into non-operational points and indicates it is safe to revert to λ-based continuation.

Switching Back to the Load Parameter and Continuing

After clearing the nose region with voltage parameterization, we switch back to λ as the continuation parameter and resume the standard predictor–corrector with fixed λ correctors. On the post-nose (unstable) branch, λ will typically be decremented if further tracing is needed. In planning studies the main objective is to locate the maximum loadability, so we generally stop once the peak λ is identified with sufficient numerical confidence.

Continuation Power Flow (CPF)

This repository contains MATLAB Code for the calculating Continuation Power Flow (CPF) for IEEE-14 bus system.

3.3 Steps to perform CPF using the developed program:

- Get bus and branch data
- Form Y bus matrix
- Calculate scheduled values of real and reactive power

3.4 Upper Part: Load As Continuation Parameter

- Find out the Jacobian Matrix
- Predictor Step:

o Step size (sigma) = 0.1

o Lambda = 0.1

o Find out the voltage and angles

- Corrector Step:

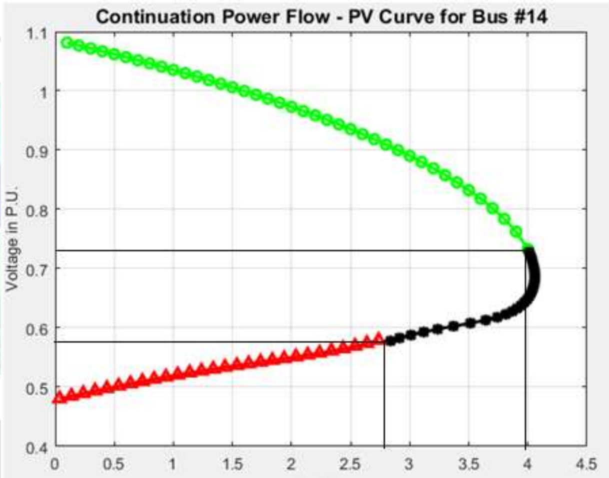
o Perform Newton Raphson load flow by increasing scheduled real and reactive power by a factor of lambda from predictor step.

o Make sure the power flow converges within a certain number of iterations. If the power flow converges, the final value of voltage and lambda is saved. It is used to plot the loadability curve.

o If power flow converged, perform the next iteration of the predictor step (Step 5), and get the next point to plot, and carry on until the power flow stops to converge in the predictor step. OR, If power flow did not converge, then move to Voltage As Continuation Parameter

III. Result

For the IEEE-14 bus system, a PV curve plots active-power loading on the horizontal axis and bus-voltage magnitude on the vertical axis. In our three-phase study, the loading is increased simultaneously on phases A–B–C, and each plot shows three traces: VA(·),VB(·),VC(·). As loading rises, voltages typically decrease monotonically until a nose point (maximum loadability) is reached; beyond this point no feasible steady-state solution exists (voltage collapse). When the three traces lie nearly on top of each other, the network is effectively balanced; noticeable separation indicates phase imbalance or asymmetric reactive support.

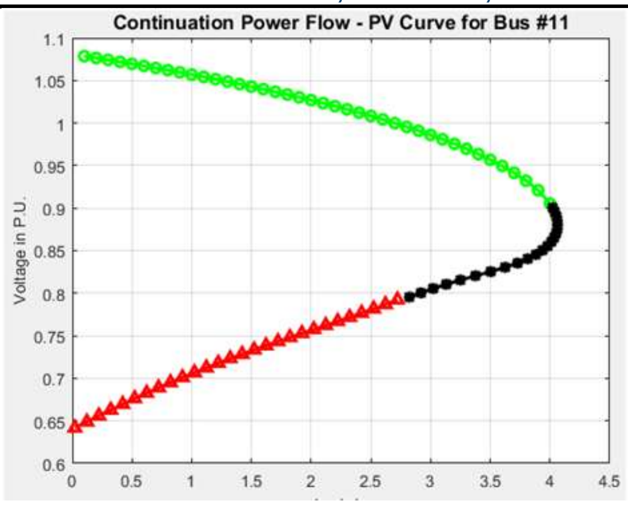


Power(P)

Figure 2: IEEE-14 Bus: System-Wide PV Characteristics

A PV curve in the context of Continuation Power Flow (CPF) represents the relationship between active power (P) and voltage magnitude (V) in a power system. It's a graphical representation that shows how changes in active power generation or load demand impact the voltage levels at different buses in the system. PV curves obtained through CPF simulations provide insights into the system's voltage stability limits and operational constraints.

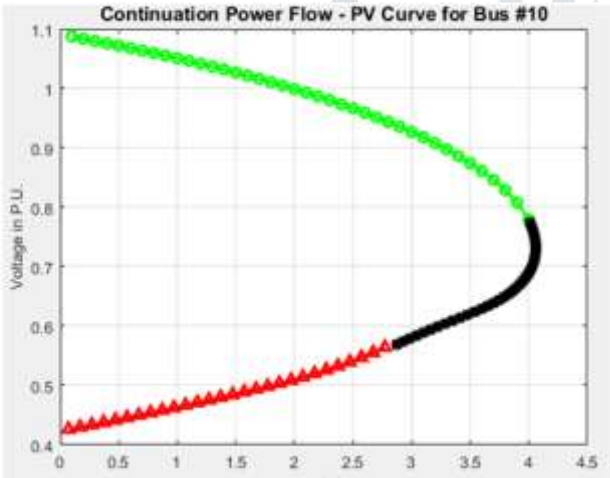
Figure 2 show this overview confirms the expected CPF behaviour: voltages decline smoothly with loading, then flatten as the Jacobian becomes ill-conditioned near the stability limit. The three phase traces are almost coincident over most of the range, indicating near-balanced operation; a small divergence appears close to the nose point, reflecting phase-coupled reactive stress under heavy load.



Power(P)

Figure 3: PV Curve at Bus 11 (Phases A/B/C)

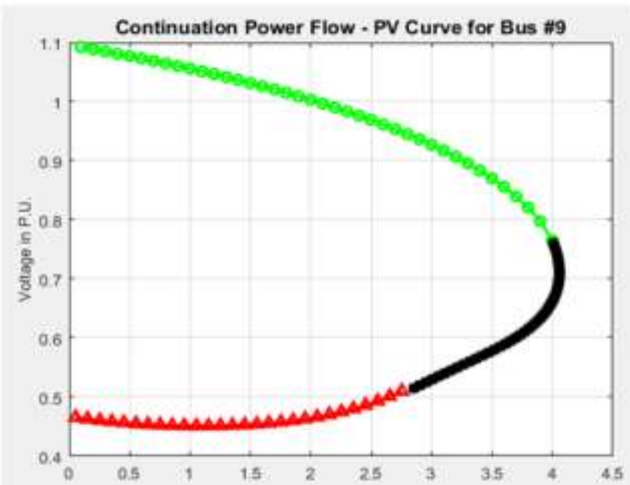
Figure 3 show Bus 11 maintains comparatively higher voltage across the loading range, with a late-occurring knee. Phase separation remains minimal until very near the nose, where phase-A shows a slightly earlier drop than phases B/C—consistent with mild unbalance introduced by network asymmetries under stress. This behaviour marks Bus 11 as less vulnerable than downstream load buses.



Power(P)

Figure 4.3: PV Curve at Bus 10 (Phases A/B/C)

Figure 4.3 show Bus 10 exhibits a steeper mid-range slope than Bus 11, indicating higher sensitivity to incremental loading. The three phases track closely in the linear region; a small phase spread appears approaching the knee, signposting growing VAR demand and transformer tap limitations..



Power(P)

Figure 4.4: PV Curve for Bus 9

Figure 4 show Bus 9 shows an earlier onset of nonlinearity: the PV curve bends sooner and the knee appears at a lower voltage than at Buses 10–11. A slight A–B–C separation just before the knee suggests unbalanced reactive flows along the corridor feeding Bus 9 when the system is heavily stressed.

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IV. Conclusion

This paper have explored the application of the Continuation Power Flow (CPF) technique using the Newton-Raphson method and the Jacobian matrix on a simplified 14-bus power system model. Through this analysis, we aimed to demonstrate the effectiveness of CPF in understanding power system behavior and its response to varying operational conditions. Our investigation underscores the significance of this approach in assessing stability, identifying critical points, and offering insights into power system dynamics.

The combination of the Newton-Raphson method and the Jacobian matrix has proven to be a robust and efficient means of studying power system behavior. By simulating load changes, generation variations, and network modifications, we observed how the power system transitioned through different operating states. This allowed us to track the voltage magnitudes, phase angles, and power flows at each bus accurately.

The simulation results revealed several key findings. We observed that as load demands increased, certain buses experienced voltage drops, indicating potential voltage stability concerns. Similarly, variations in generation levels led to changes in power flows and affected the overall system performance. Furthermore, we identified critical operating points and constraints that, if crossed, could lead to instability.

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