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Voltage Stability Assessment Using Energy Function

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Abstract:
Voltage instability of a power system is its inability to maintain the steady state voltage after a disturbance in the system. The possible outcomes of voltage instability are loss of load in an area where the voltage values are relatively smaller than the voltage in other areas of the system. , Lyapunov stability based energy function has been considered to assess the proximity of the voltage instability in the presence of various operating and operational conditions. Continuation Power flow is used to obtain the solution corresponding to unstable region of a particular operating point. Studies have been carried out on IEEE 14-bus system to shown the effectiveness of the proposed method.

1. Introduction:

Main reason for the voltage collapse [1] is when the transmission lines are operating very close to their thermal limits and forced to transmit more power over a long distance or when the power system has insufficient reactive power for transmission to the area with increasing load. In large scale systems voltage collapse include voltage magnitude and voltage angle under heavy loading conditions. Two types of system analysis are possible; static system and dynamic system analysis and using each approach is appropriate for specific system conditions and each bear its own advantage and disadvantage. Many methods were developed to calculate the voltage stability and every single method is has its own credit in its area. In this work, Lyapunov energy function [2] has been used to evaluate voltage stability of the system. When fault occurs in power system, disturbance energy will be generated and injected into the network, then transformed into the form of branch potential energy and distributed in the power grid, which will bring the whole system develop in the direction of disorder. The spatial distribution of branch energy in power system shows not the consumptive ability of branches to disturbance energy, but also reflects the degree of cumulativeness of disturbance energy. If the branch energy distributes in each branch uniformly or heads towards in that direction, the system is stable; if the branch energy distribution of each branch is of great difference, that is, gathering in a few branches, the system stability depends on largely the stability of that few branches, gradually decreasing and likely to tear down from the cut set formed by these branches, resulting in the loss of power system stability. In a power system, if the load is increased the voltage drops up to a certain value of maximum loading of the system. That loading of the system is termed maximum loadability. Normally at any operating point (loading), the system has two solutions one is stable equilibrium point and other is unstable equilibrium point. This locus of voltage solutions with respective to loading parameters gives us PV curve.

2. Continus Power Flow method:

It is difficult to obtain unstable equilibrium point of operating system after certain loading. It means as the loading increases, the system solution diverges as the jacobian matrix becomes singular. To overcome this difficulty and to get the whole PV curve, we can go with the type-1 solution method or continuation power flow method [4]. In continuation power flow method, to make the solution to converge, it takes loading factor as another variable. It employs predictor and

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Corrector method to draw the whole PV curve. In this work, PSAT software (Power System Analysis Tool)[3] is use to obtain PV curve. Below figure (1.1) shows the PV curve obtained from Continuation power flow method.

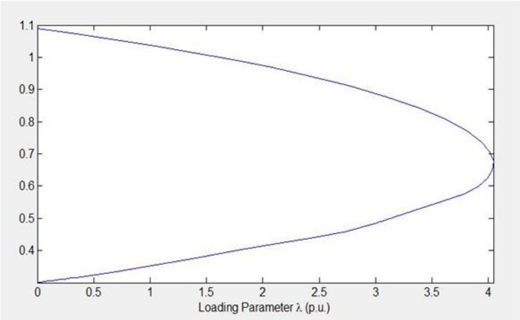

Figure 2.1 14th bus PV curve of IEEE 14 bus system

3. Lyapunov method:

In 1892, A. M. Lyapunov, in his famous Ph.D. dissertation [9], proposed that the stability of the equilibrium point of a nonlinear dynamic system of dimension n

$$\dot{x} = f(x) \quad ; \quad f(0) = 0; \qquad (1)$$

can be ascertained without numerical integration. He said that if there exists a scalar function V (x) for (3.6) that is positive definite, i.e., $V(\dot{x}) > 0$ around the equilibrium point "0" and the derivative $V(\dot{x}) < 0$, then the equilibrium is asymptotically stable. $V(\dot{x})$ is obtained as $\sum_{i=1}^{n} \frac{\partial V}{\partial x_i} \dot{x}_i = \sum_{i=1}^{n} \frac{\partial V}{\partial x_i} f_i(x) = \nabla V^T . f(x)$ where n is the order of the system in (1). Thus, f(x) enters directly in the computation of $V(\dot{x})$. The condition $V(\dot{x}) < 0$ can be relaxed to $V(\dot{x}) \leq 0$, provided that $V(\dot{x})$ does not vanish along any other solution with the exception of x = 0.

The swing equation of multi machine system is,

$$\frac{2H_i}{\omega_s} \frac{d^2\delta_i}{dt^2} + D_i \frac{d\delta_i}{dt} = P_{mi} - P_{ei} \;, \quad i = 1, \ldots \ldots \ldots, m \qquad (2)$$

Where

$$P_{ei} = E_i^2 G_{ii} + \sum_{j=1 \neq i}^{m} (C_{ij} \sin \delta_{ij} + D_{ij} \cos \delta_{ij}) \qquad (3)$$

Denoting $\frac{2H_i}{\omega_s} \cong M_i$ and $P_i \cong P_{mi} - E_i^2 G_{ii}$, we get

$$M_i \frac{d^2\delta_i}{dt^2} + D_i \frac{d\delta_i}{dt} = P_i - \sum_{j=1 \neq i}^{m} (C_{ij} \sin \delta_{ij} + D_{ij} \cos \delta_{ij}) \qquad (4)$$

Let α_i be the rotor angle with respect to a fixed reference. Then $\delta_i = \alpha_i - \omega_s t$. $\dot{\delta}_i = \frac{d\dot{\alpha}_i}{dt} - \omega_s \cong \omega_i - \omega_s$, where ω_i is the angular velocity of the rotor and ω_s is the synchronous speed in radians per sec.

4. Energy function based voltage proximity indicator:

The energy based stability margin to indicate vulnerability to voltage instability is obtained by integrating the function composed of f (α,V) and g (α,V) from a lower limit corresponding to a Stable Operating Point (SEP) $x^s = (\alpha^s, V^s)$ to an upper limit corresponding to a particular low-voltage power flow solution $x^u = (\alpha^u, V^u)$. As the loading on the system increases the two solutions x^s and x^u approach each other and the energy margin E steadily decreases [8]. The threshold loading level at which x^s and x^u coalesce and the energy margin reduces to zero represent the Voltage Instability Point. For a general '**n**' bus system, (3) and (4) at the i^{th} bus can be written as

$$f_i(\propto, V) = P_i - \sum_{j=1}^{n} B_{ij} |V_i| |V_j| \sin(\propto_i + \propto_j) - \sum_{j=1}^{n} G_{ij} |V_i^s| |V_j^s| \sin(\propto_i + \propto_j) \qquad (5)$$

$$g_i(\propto, V) = (V_i)^{-1} - \left[Q_i + \sum_{j=1}^{n} B_{ij} |V_i| |V_j| \sin(\propto_i + \propto_j) \right] - (V_i^s)^{-1} \left[\sum_{j=1}^{n} G_{ij} |V_i^s| |V_j^s| \sin(\propto_i^s - \propto_j^s) \right] \qquad (6)$$

The constant terms in (3.16) and (3.17) are induced so that f and g are identically zero at the SEP even when network transfer conductances are induced.

The energy function $\mathcal{E}(x^s, x^u)$ is defined as in (3.19) given below. This is a scalar quantity dependent on system on system state (bus voltage magnitudes and phase angles) with the property that the current operating state defines a local minimum of this energy. Normally, the small random variations in the system which disturb its state from the SEP and add a small amount of energy are compensated by the system damping. At a secure operating point, where the energy well is deep, these random effects are negligible. But as the system moves towards a state vulnerable to voltage collapse, the depth of the energy well decreases and the system states (particularly the voltage magnitudes) becomes highly sensitive to load changes. Under such conditions there is a possibility that these random variations could push the state out of the potential well that defines its stable equilibrium point. A necessary condition for the state to escape this well is that it receives energy greater than the energy value of the closest Unstable Equilibrium Point (UEP) on the boundary of the well. The UEPs or the saddle points correspond to alternative solutions of the load flow equations, referred to as the low-voltage solutions.

$$\varepsilon(X^s,X^u) = \int_{(\alpha^s,V^s)}^{(\alpha^u,V^u)} [f^T(\alpha,V)g^T(\alpha,V)]^T[d\alpha\; dV]^T \qquad (7)$$

$$\begin{aligned}\varepsilon(X^s,X^u) &= -\frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} B_{ij}\,|V_i^u|\,|V_j^u|\cos(\alpha_i^u-\alpha_j^u) \\ &+ \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} B_{ij}\,|V_i^s|\,|V_j^s|\cos(\alpha_i^s-\alpha_j^s) \\ &- \left[\sum_{i=1}^{n}\int_{V_i^s}^{V_i^u}\frac{Q_i(x)}{x}\,dx\right] - P^T(\alpha^u-\alpha^s) \\ &- \sum_{i=}^{n}\left[\sum_{j=1}^{n}\left(G_{ij}|V_i^s||V_j^s|\cos(\alpha_i^s-\alpha_j^s)\right)(\alpha_i^u - \alpha_j^u)\right) \right] \\ &+ \sum_{i=1}^{n}\left[(V_i^s)^{-1}\sum_{j=1}^{n}\left(G_{ij}|V_i^s||V_j^s|\sin(\alpha_i^s - \alpha_j^s)\right)(V_i^u - V_i^s)\right]\end{aligned} \qquad (8)$$

Therefore, the energy function $\mathcal{E}$ shows the height of the Potential Barrier between the operable solution and a low-voltage solution. As the system parameters (loads and generation) move towards the point of voltage instability, the low-voltage solutions decrease in number. Immediately before collapse, only the operable solution and a single low voltage solution exist. These two solutions eventually collapse and the steady-state equilibrium point in lost.

Since in the voltage security context one is only concerned with the energy differences between equilibrium points, (7) and (8) are only potential energy components of a total system energy function. In order for (7) to formally define a Lyapunov function, the kinetic energy term would have to be included and a number of restrictions [7] placed on allowable system dynamic models.

These would include

1) not allowing voltage dependence in the real power load, 2) restricting the method to networks with no transfer conductance terms.

In the realistic systems considered here, these restrictions are relaxed. and hence we use the term "energy function" rather than Lyapunov function[9].

5. Result:

IEEE 14 bus is taken for case study. The PV curve is obtained from CPF (Continuation power flow) method. From that curve, stable and unstable bus voltage (SEP and UEP) were extracted. Table 5.1 gives us the information of voltage stable and unstable equilibrium points at load factor of λ=0.

Table 5.1 SEP and UEP of Voltage vector at loading parameter λ=0

Busno	δ^s	V^s	δ^u	V^u
1	0	1.06	0	1.06
2	0.00427	1.045	-0.1128	1.045
3	0.01399	1.01	-0.2025	1.01
4	0.00406	1.04092	-0.15655	0.68731
5	0.005	1.03978	-0.05835	0.58049
6	0.00718	1.07	-3.0904	1.07
7	0.00281	1.08816	-0.50628	0.70646

8	0.00281	1.09	-0.50628	1.09
9	0.00217	1.09954	-0.75865	0.50732
10	0.0031	1.0793	-2.7198	0.67801
11	0.00499	1.07473	-2.93746	0.85767
12	0.00711	1.07217	-3.07911	0.96472
13	0.00624	1.07425	-3.01752	0.8689
14	0.00382	1.08851	-2.16507	0.30059

From the above information the energy margin of the system at different loading parameters are calculated to obtain the Energy Vs Loading factor curve. Table 5.2 shows the energy values at different loading factors, calculated from the energy function expressed in (8)

Table (5.2) Varying energy values according to the loading of IEEE 14 bus system

Loading factor	Energy Margin
0	15.1819
0.346	14.874
0.697	13.9199
1.048	12.2611
1.751	6.5611
2.102	2.3907

The energy margin Vs loading factor graph is shown in figure 2

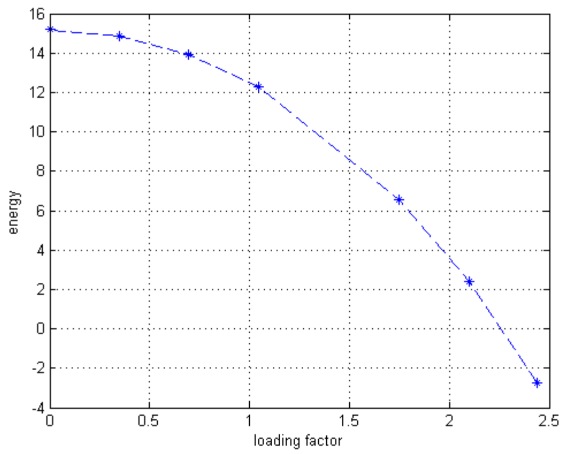

Figure 2.Energy plot of IEEE 14 bus system

Conclusion:

Due to the disturbances, sudden changes in the loads or due to the changes in the power system configuration, sometimes initiates progressive and uncontrollable decline in voltage magnitude leading to a Voltage instability condition of the system. Many a times, system operators require information about the system condition and sequence of actions to be initiated following a contingency, to make the system secure. In view of these circumstances, in this work, power system voltage stability monitoring using Energy Function has been considered. Lyapunov stability based energy function has been implemented to assess the proximity of the voltage stability in the presence of various operating and operational conditions. Energy function based analysis need the system states for stable and unstable solutions corresponding to a particular operating point. One of the challenging task in calculating the potential energy of the system is getting the system states corresponding to the unstable solution. In this work, Continuation Power Flow has been utilized to obtain the system states corresponding to unstable solution. Studies IEEE 14-bus systems shown promising results to monitor the voltage stability of the power system.

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