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Power Flow, Voltage Stability Analysis and Enhancement of Power System using Continuation Power Flow Method

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Abstract—*In recent years, greater demands have been placed on the transmission network, and these demands will keep rising. Added to these risen demands on transmission and absence of long-term planning, and the need to serve open access to generating companies and consumers, all together have created tendencies toward less security and reduced quality of supply. In a deregulated electric service environment, an effective electric grid is essential to the competitive environment of reliable electric service. The best use of the transmission system is to maximize the loading capability. One of the stability issues that limit the loading capability of the system is voltage collapse. This paper studies the voltage stability using continuation power flow method. Voltage collapse scenario is analyzed which can be a severe result on voltage instability and the parameters that affected by the voltage collapse are also discussed. Using the continuation power flow method and using the change in load parameter, the maximum loading of the system is analyzed. Case studies are carried out on IEEE 30-bus system and PV curves for various buses are obtained. MATLAB programming is used to run the voltage stability analysis on IEEE 30-bus system. The continuation power flow method solves a set of augmented power flow equations to obtain the solution curve passing through the critical point without encountering the numerical difficulty of ill-conditioning. In this paper the effect of shunt capacitor, line reactance and new generator addition on voltage stability are also studied and results shown proper performance of enhanced loading capability and voltage margin of power system.*

Keywords: *Loading capability, Continuation power flow method, Voltage stability, Critical point.*

1. INTRODUCTION

The complexity of electricity is increasing with increasing growth of electricity consumption and causing power system to work near the instability. In particular the voltage stability is the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating point. In power systems, the electrical generation and load must balance at all times to make the system stable. This instability may cause the up and downs in voltages at the buses and also the voltage stability problems will occur when the power system is stressed beyond its capability and this disturbance leads to voltage collapse. In most of the research papers voltage stability has been considered as fixed circumstance. This is due to sluggish change in voltage over a prolonged period of time, observed in most of the cases until it reaches to the critical point and then it drops rapidly to the voltage collapse. There exist different voltage stability analysis methods such as saddle node bifurcation theory, particle swarm optimization technique, static and dynamic approach and modal analysis. Here continuation power flow method is employed for voltage analysis. This technique involves the identification of the system's critical point or voltage collapse point where the relevant power flow equation turns to singular. Singularity in the Jacobian can be fending off by slightly reformulating the power flow equations. Continuation power flow is employed to unfold the set of augmented power flow equations to get the curve passing through the critical point without encountering the numerical difficulty of ill conditioning.

2. CONTINUATION POWER FLOW METHOD

The formal power flow has a complication in the Jacobian matrix which becomes singular at the voltage stability limit. The continuation power flow method approach overcomes this problem of singularity. Fig. shows the Predictor-corrector scheme employed in the continuation power flow method.This technique includes state variable load parameter and step length for load parameter. Continuation power flow employs successive load flow solution in agreement with a load scenario. Here a tangent predictor is employed to evaluate next solution for a stated pattern of load rise.Later the corrector step determines the exact solution by Newton-Raphson method employed by a conventional power flow [1-4]. Consequently a new prediction is made for a given rise in load based on the new tangent vector. Later corrector step is applied. This process continues until critical point is attained. The critical point is the notch at which tangent vector becomes zero. Fig. 1 shows this process clearly.

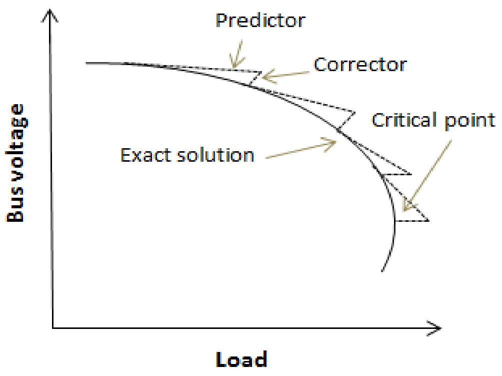

Fig. 1: Schematic representation of Predictor-Corrector steps

2.1 Mathematical Reformulation of Load Flow Equation

As the formal load flow equation is attaining the problem of singularity, those equations are reformulated by including a load parameter λ. The formal load flow equations are

$$P_i = \sum_{k=1}^{m} |V_i||V_k|\left(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}\right) \quad (1)$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_k|\left(G_{ik}\cos\theta_{ik} - B_{ik}\sin\theta_{ik}\right) \quad (2)$$

$$P_i = P_{Gi} - P_{Di} \; (3)$$

$$Q_i = Q_{Gi} - Q_{Di} \; (4)$$

Here the subscripts G and D stand for generation and load demand respectively on the corresponding bus. In order to enter a load change, a load parameter λ is inserted real and reactive power demands.

$$P_{Di} = P_{Di0} + \lambda(P_{\Delta base}) \quad (5)$$

$$Q_{Di} = Q_{Di0} + \lambda(Q_{\Delta base}) \quad (6)$$

Where P_{Di0}, Q_{Di0} are initial load demand on i th bus and $P_{\Delta base}$, $Q_{\Delta base}$ are given quantities of power selected to scale λ appropriately. The reformulated power flow equation which has a chance to increase generation for the load rise may as follows

$$F(\theta, v) = \lambda K \quad (7)$$

Here λ is the load parameter, ϴ represents vector of bus voltage angles, V is the vector belongs to bus voltage magnitude and F is the vector corresponding to present load change at bus. The above set of equation is solved by putting the value of λ such that the value should be in $0 \le \lambda \le \lambda_{critical}$.

2.2 Predictor

Here a linear approximation is used for the assessment of next solution for a variation in one of the state variable. Applying derivation on both sides with respect to the state variable corresponding to the basic solution results the following equations,

$$F_\theta d\theta + F_v dv + F_\lambda d\lambda = 0 \quad (8)$$

$$\begin{bmatrix} F_e & F_v & F_\lambda \end{bmatrix} \begin{bmatrix} d\theta \\ dv \\ d\lambda \end{bmatrix} = [0] \quad (9)$$

As the insertion of λ in the equation added a foreign variable and that is compensated by adding +1 or -1 as one of the component in tangent vector.

2.3 Corrector

Here the formal set of equations $F(\theta, v, \lambda) = 0$ is augmented by an equation that sets the chosen state variable as continuation parameter. The new set of equation is,

$$\begin{bmatrix} F(\theta, v, \lambda) \\ X_k - \eta \end{bmatrix} = [0] \quad (10)$$

In this equation X_k is the state variable chosen as continuation parameter and η is the predicted value of X_k where this X_k makes the Jacobian non-singular at the critical point.

3. STUDY ON IEEE-30 BUS SYSTEM USING CONTINUATION POWER FLOW METHOD

Continuation power flow approach is applied to the following system using MATLAB programming. IEEE-30 bus system having 6 generators, 40 transmission lines and 24 loads is considered for the analysis [2]. IEEE-30 bus system is shown in fig.2. At various loading conditions continuation power flow method is performed.

At first load parameter is zero then P-V curve is plotted for all buses and weakest bus is detected by gradually increasing the load parameter (λ). Continuation power flow approach is run till critical point is attained andafter that point the power flow will stops. To study the voltage stability under various loading conditions, primitively N-R load flow is run to obtain the basic load flow at normal conditionsof the system and obtained accurateresults.Then continuation power flow program isexecuted forthe reconstructed structure and achieved results are evaluated [5].

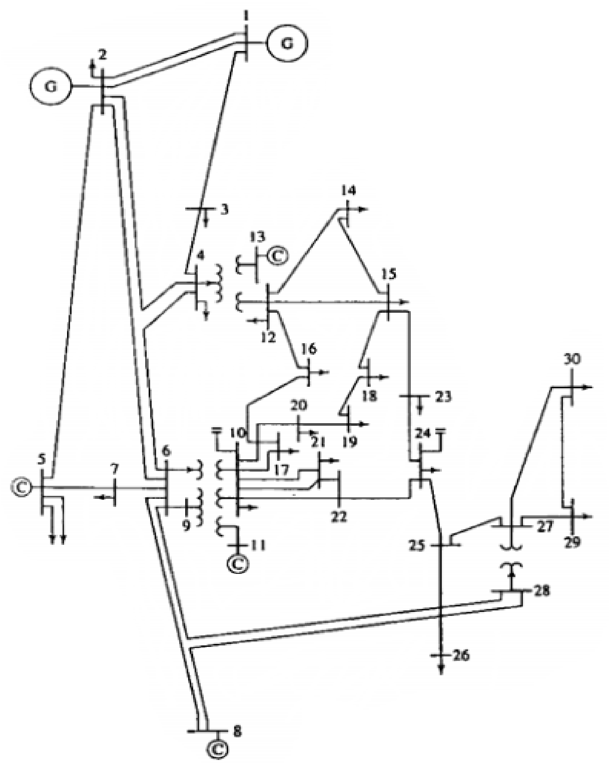

Fig. 2: 30-bus IEEE sample system

4. CONTINUATION POWER FLOW ANALYSIS WITHOUT THE EFFECT OF LOAD PARAMETER VARIATION

It is well observed from the fig. 3 that buses 26, 29, 30 have the most loading so that they have less security margin than other buses. Bus 30 with the voltage of magnitude 0.9945 pu identified as the weakest bus. The basic power flow results are shown in table no.1 in detail. Here bus 01 is slack bus hence its voltage magnitude is 1.0 pu and angle is zero. The real and reactive powers for generation and demand are also shown. From this we can simply know the total generation and load. Table no.2 shows the real and reactive power flow through the lines and also losses.

Table 1: Power flow results

POWER FLOW RESULTS							
Bus	**V**	**Phase**	**P_{gen}**	**Q_{gen}**	**P_D**	**Q_D**	**$Q_{inj.}$**
	[pu]	**[rad]**	**MW**	**MVar**	**MW**	**MVar**	**MVar**
01	1.060	0.00	260.9	17.02	0.00	0.00	0.0
02	1.043	-5.49	40.0	48.82	21.70	12.7	0.0
03	1.021	-8.00	0.00	0.00	2.40	1.2	0.0
04	1.013	-9.66	0.00	0.00	7.60	1.6	0.0
05	1.010	-14.38	0.00	35.97	94.20	19.0	0.0
06	1.012	-11.39	0.00	0.00	0.00	0.0	0.0
07	1.003	-13.15	0.00	0.00	22.80	10.9	0.0
08	1.010	-12.11	0.00	30.82	30.00	30.0	0.0
09	1.051	-14.43	0.00	0.00	0.00	0.0	0.0
10	1.044	-16.02	0.00	0.00	5.80	2.0	19.0
11	1.082	-14.43	0.00	16.12	0.00	0.0	0.0
12	1.057	-15.30	0.00	0.00	11.00	7.5	0.0
13	1.071	-15.30	0.00	10.42	0.00	0.0	0.0
14	1.042	-16.19	0.00	0.00	6.20	1.6	0.0
15	1.037	-16.27	0.00	0.00	8.20	2.5	0.0
16	1.044	-15.88	0.00	0.00	3.50	1.8	0.0
17	1.039	-16.18	0.00	0.00	9.00	5.8	0.0
18	1.028	-16.88	0.00	0.00	3.20	0.9	0.0
19	1.025	-17.05	0.00	0.00	9.50	3.4	0.0
20	1.029	-16.85	0.00	0.00	2.20	0.7	0.0
21	1.032	-16.46	0.00	0.00	17.5	11.2	0.0
22	1.027	-16.45	0.00	0.00	0.00	0.0	0.0
23	1.021	-16.66	0.00	0.00	3.20	1.6	0.0
24	1.019	-16.83	0.00	0.00	8.70	6.7	0.0
25	1.001	-16.42	0.00	0.00	0.00	0.0	0.0
26	1.025	-16.84	0.00	0.00	3.50	2.3	0.0
27	1.020	-15.91	0.00	0.00	0.00	0.0	0.0
28	1.010	-12.05	0.00	0.00	0.00	0.0	0.0
29	1.006	-17.13	0.00	0.00	2.40	0.9	0.0
30	0.994	-18.01	0.00	0.00	10.60	1.9	0.0
	Total		300.9	125.1	283.4	126.0	23.0

Table 2: Load flow results

LINE FLOWS						
Line	**From Bus**	**To Bus**	**P_{Flow}**	**Q_{Flow}**	**P_{Loss}**	**Q_{Loss}**
			MW	MVar	MW	MVar
01	01	02	177.7	-19.18	5.46	16.36
02	01	03	83.22	7.42	2.80	11.50
03	02	04	45.71	4.70	1.10	3.37
04	03	04	78.01	-2.72	0.77	2.21
05	02	05	82.99	3.97	2.99	12.58
06	02	06	61.91	1.07	2.04	6.21
07	04	06	70.12	-17.06	0.60	2.10
08	05	07	-14.2	11.54	0.15	0.38
09	06	07	37.5	-1.01	0.36	0.12
10	06	08	29.52	-3.3	0.1	0.36
11	06	09	27.69	-18.64	0.0	2.21
12	06	10	15.82	-5.42	0.0	1.47
13	09	11	0.0	-15.65	0.0	0.46
14	09	10	27.69	6.74	0.0	0.81
15	04	12	44.12	-16.72	0.0	5.17
16	12	13	0.0	-10.29	0.0	0.13
17	12	14	7.85	2.44	0.07	0.15
18	12	15	17.85	6.94	0.21	0.42
19	12	16	7.20	3.36	0.05	0.11
20	14	15	1.58	0.68	0.0	0.0
21	16	17	3.65	1.45	0.01	0.02
22	15	18	6.01	1.74	0.04	0.08
23	18	19	2.77	0.76	0.00	0.01
24	19	20	-6.73	-2.64	0.01	0.03
25	10	20	9.02	3.56	0.08	0.18
26	10	17	5.37	4.14	0.01	0.03
27	10	21	15.37	4.41	0.01	0.03
28	10	22	7.58	4.49	0.05	0.10
29	21	22	-1.87	-1.59	0.0	0.0

30	15	23	5.0	2.95	0.03	0.06
31	22	24	5.65	2.78	0.04	0.06
32	23	24	1.77	1.29	0.0	0.01
33	24	25	-1.32	1.6	0.0	0.01
34	25	26	3.54	2.36	0.01	0.06
35	28	27	18.18	-3.34	0.0	1.28
36	27	29	6.18	1.66	0.08	0.16
37	27	30	7.09	1.66	0.16	0.30
38	29	30	3.70	0.6	0.03	0.06
39	8	28	-0.57	-0.18	0.0	0.0
40	6	28	18.81	-2.96	0.06	0.21

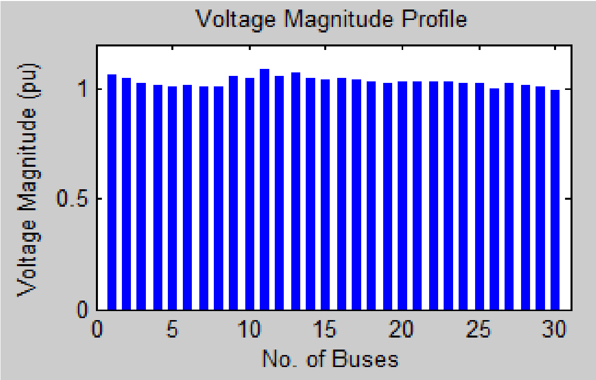

Fig. 3: Voltage magnitude profile

5. CONTINUATION POWER FLOW ANALYSIS WITH THE EFFECT OF LOAD PARAMETER VARIATION

5.1 Base Case

It is observed from fig that bus 30 has most loading so it is less secure than other buses. The maximum loading parameter is λ = 0.6234 and the real power demand is 460.071 MW. When the value of λ=0.6234 the peak value of loading will occur. So if we kept any compensating device then the voltage stability of the system may occur. Fig. 4 shows the Voltage magnitude profile at critical point and fig. 5 shows the voltage angle profile at critical point for all buses. The P-V curves for all 30 buses are shown in fig. 6.

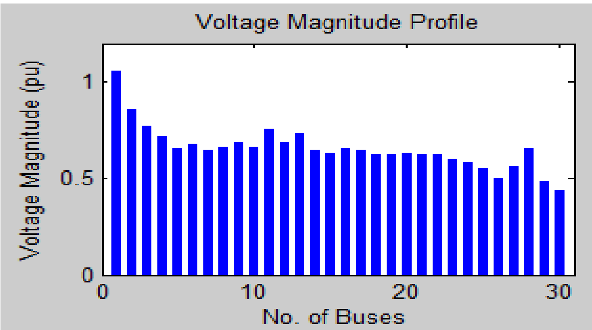

Fig. 4: Voltage magnitude profile at critical point.

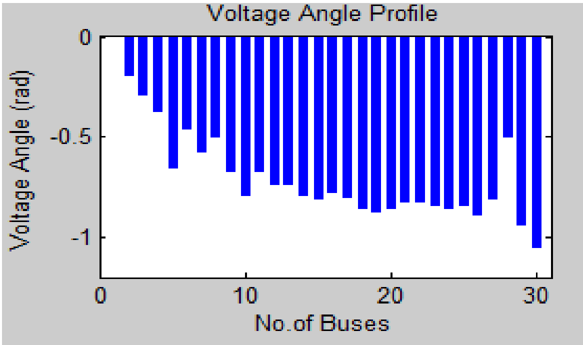

Fig. 5: Voltage angle profile at critical point.

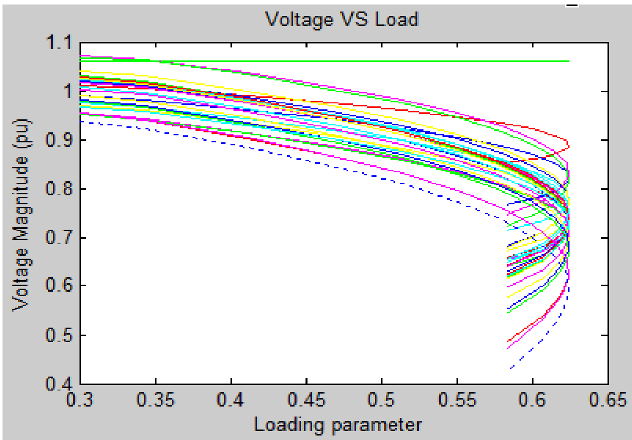

Fig. 6: P-V curves for all 30-buses

4.2 Effect of Shunt Capacitor

The purpose of shunt compensation is to change the natural electrical characteristics of the transmission line to make it more adaptable with the prevailing load demand [3]. In order to illustrate this effect a shunt capacitor of 0.05(pu) is connected to the weakest bus. By this the maximum loading capability is increased to 0.6313. By adding shunt capacitor to the power system the voltage stability limits will be enhanced and also for some situations it prevents the voltage collapse. Here addition of shunt capacitor to bus 30 improves the voltage stability limit not only in bus 30 but also in rest of the buses. When the voltage in table.3 for C=0.05 is compared with base case, it clearly shows the enhancement in voltage stability.

4.3 Effect of Line Reactance

The influence of line reactance on the power transfer characteristics (P-V curve) is analyzed.As the line reactance decreases the transfer capability of that line will increases and also the loading capability of the system will increases. To analyze this effect of line reactance on voltage stability, the line reactance of line (27-30) is made as 0.05*X(27-30) .By this the maximum loading of the system is increased from 0.6234 to 0.6301.

5.4 Effect of New Generators

Finally four new generators are connected at buses 5, 8, 11, 13 in sample system. Here the critical point is moved to right and the maximum loading capability is raised to 0.7555.

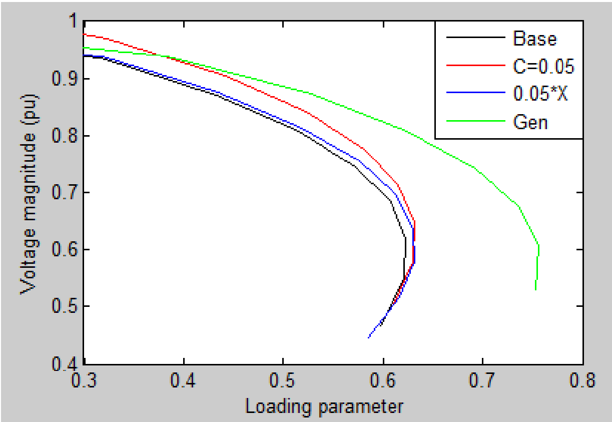

Fig. 7: P-V curves of 30th bus for four cases

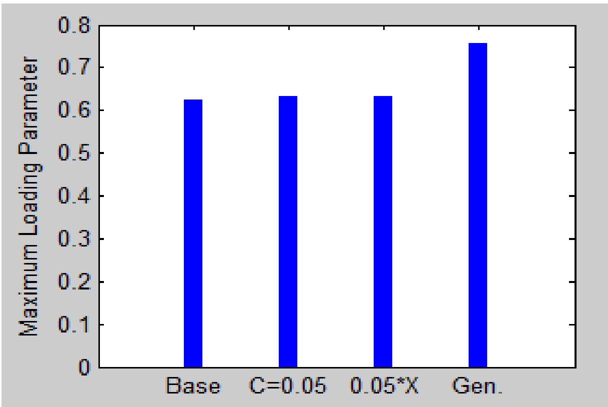

Fig. 8: Maximum loading parameter variation.

Table 3: λ_{max}, V_{mag} of 30th bus and P_{load} of system in 4 cases

	Base	C=0.05 pu	0.05*X pu	Gen.
λ max	0.6234	0.6313	0.6301	0.7555
V_{mag}	0.6195	0.6488	0.6383	0.6070
P_{Load} (MW)	460.071	462.31	461.97	497.51

Table 3 shows the effect of shunt capacitor, line reactance and new generator on λ(max) , total real power load on the system and voltage magnitude of 30th bus. And the P-V curvesof 30th bus for the four cases are shown in fig 7. Fig 8shows the maximum loading of the system in all four cases.

6. CONCLUSION

In this paper, for analyzing the greatest loading , we determined the effects of change in load parameter on the system and also the voltage stability phenomena using continuation power flow method is analyzed. The process is applied to IEEE 30-bus sample system. Voltage magnitude, voltage phase angle graphs are obtained and P-V curves are drawn for several cases using MATLAB programming. The effect of compensation is examined by adding shunt capacitor, effect of line reactance is examined by changing the line reactance of the weakest bus and the effect of new generator addition is also examined. Voltage profiles for various cases proven the enhancement in voltage stability. Finally we performed the comparison between all the four cases and realized that adding generators to the system made a greater impact on voltage stability and loading capability is increased compared to shunt capacitor and tuned down line reactance. The continuation power flow method is simple and more accurate for voltage stability analysis.

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