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A Modified Approach for Continuation Power Flow

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ABSTRACT

One of the conventional static voltage stability analysis methods is PV curve, which is obtained by continuation power flow (CPF) in regular manner. This method is robust; however has some weakness in large electric power system considering generators reactive power limits. This paper takes the advantage of a predictor/corrector scheme to obtain generators reactive limit hitting points as well as determining the type of bifurcation (saddle node or limit induced), and then uses these as the given data in continuation power flow algorithm. This will eliminate the weakness of continuation power flow in handling generators reactive limits. The proposed method is tested on IEEE 118 bus system trough numerical examination. Results showed good performance and robustness of the proposed method.
Keywords: voltage stability, saddle node bifurcation, limits induced bifurcation, continuation power flow, generators reactive power limit.

1. Nomenclature

λ	Loading Parameter
x	State variables
K_{Li}	Variation Coefficient of load at bus *i*
K_{Gj}	Variation Coefficient of generation at bus *j*
P_{Li0}	Base active load at bus *i*
Q_{Li0}	Base reactive load at bus *i*
P_{Gj0}	Base active generation at bus *j*
$P_{Li}(\lambda)$	Active load of bus *i as a function of* λ
$Q_{Li}(\lambda)$	Reactive load of bus *i as a function of* λ
$P_{Gj}(\lambda)$	Active generation of bus *j as a function of* λ
$F(x,\lambda)$	Power flow equations set
Q_G^{max}	Maximum reactive power of the generator *G*
V_G^s	AVR set point of the generator *G*
V_G	Terminal voltage of the generator *G*
z^0	Operating point
z_k	The k^{th}CEP in the stable operating region
I_k	The interval which is corresponding to z_k
$F^{(k)}(x,\lambda)$	Equality constraint set in I_k
$G^{(k)}(x,\lambda)$	Inequality constraint set in I_k
$g_i^{(k)}(x,\lambda)$	The i^{th}element of $G^{(k)}(x,\lambda)$
$F_x^{(k)}(x,\lambda)$	Derivative of $F^{(k)}(x,\lambda)$ with respect to x
$F_\lambda^{(k)}(x,\lambda)$	Derivative of $F^{(k)}(x,\lambda)$ with respect to λ
n_{pc}	Primary correction iteration
n_{sc}	Secondary correction iteration

2. INTRODUCTION

Voltage stability is a very complex subject that has been challenging power system engineers in the past two decades [1]. Voltage collapse typically occurs in power systems which are heavily loaded. It associates with reactive

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power demands not being met because of limitations on the production or transmission of reactive power and is usually initiated by 1) a continuous load increase and/or, 2) a major change in network topology resulting from a critical contingency [2].

A perfect remedial action to prevent voltage collapse requires an effective voltage stability assessment method as well as a good offline system planning process. A wide variety of modeling principles of computation and control methods have been developed for power system voltage stability assessment and control. The research is mainly based on analytical methods such as static analysis and dynamic simulation. Static studies such as P-V curves have been used for many years. The conventional method to obtain P-V curves is continuation power flow (CPF).

Generators reactive power limits are a key factor in voltage instability. Therefore, it is necessary to consider the reactive capability of generators in voltage stability analysis of a power system. In a large power system with many generators, considering generators reactive power limits may leads to several difficulties in using the conventional CPF method, e.g., if some of generators hit their reactive power capability limits in the prediction step, then the correction step may not act properly in determining exactly which generator and by which loading parameter has hit the limit. By using iterative step length selection or very small step length in the prediction step, this weakness is eliminated; however, computation time will become very longer.

Relating to generators reactive power limit points, an interesting method first had been proposed in [3-4] and then has been extended in [5], where the basic idea to obtain generators reactive power limit hitting point (which is named as constraint exchange point or CEP in those papers) is a predictor/corrector scheme. The reference [5-6] demonstrated the computation of CEPs, stability judgment of the obtained operating condition, and the type of instability. However, some key issues such as correction of prediction error which leads to an unrealistic CEP, and handling the divergence of correction step which may occurred because of prediction error near SNB point were not yet solved. The term prediction error is defined later. In addition to above mentioned problems, in order to identify the SNB, the point of collapse (PoC) [7-9] or optimization method must be used together with proposed method in that paper.

This paper first extends the previous method in [5] and resolves above problems. Proposed predictor scheme is almost the same as proposed one in [5], except defining a priority to hit limit list (PHL list) for generators in prediction of each CEP. However, the corrector is divided into primary and secondary correction steps in this paper. The proposed correction algorithm is robust and fast in handling the predictor error as well as the occurrence of divergence. Obtained CEPs by the proposed predictor/corrector scheme are then used as the given data in continuation power flow. The combination of these two methods (predictor/corrector scheme and continuation power flow) is named as modified continuation power flow (MCPF) in this paper. This will eliminate the weakness of CPF in a large power system with multiple generators and hence multiple reactive power constraints. In addition, instabilities of SNB or LIB type are exactly recognized by MCPF method and there will not be any need for other methods such as PoC or optimization based methods.

The organization of the paper is as follow: Section 3 introduces the continuation power flow, proposed predictor/corrector scheme, and MCPF approach principles. The effectiveness and performance of the MCPF is demonstrated by numerical examination trough IEEE 118 bus system in Section 4. Results show good performance and robustness of the algorithm. Finally, conclusions are drawn in Section 5.

3. Proposed Method

3.1 Continuation Power Flow (CPF)

The algorithm of the continuation method simply considers a set of nonlinear equations including one or more parameters. In order to use continuation method, the power flow equations must become reformulated to include a load parameter by using the generation and load variation scenarios which is represented in (1)-(3), while equation (4) stands for power flow equations. The power flow equation in this technique is solved for continuous changes in load parameter using a predictor/corrector scheme that remains well conditionedat and around critical point, and is named bifurcation point in the literature.

$$P_{Li}(\lambda) = (1 + \lambda.K_{Li}).P_{Li0} \quad (1)$$

$$Q_{Li}(\lambda) = (1 + \lambda.K_{Li}).Q_{Li0} \quad (2)$$

$$P_{Gj}(\lambda) = (1 + \lambda.K_{Gj}).P_{Gj0} \quad (3)$$

$$F(x, \lambda) = 0 \quad (4)$$

Fig.1 illustrates the iterative process of a typical CPF method. The upper portion of the curve is the stable region, while the lower portion is the unstable region. The algorithm starts from a known solution “A” which corresponds to the power flow solution at the current operating point. Then, it takes advantage of a “predictor” to estimate a solution

"B" corresponding to an increased value of the load parameter, and finally it uses a "corrector" to find the exact solution "C" by means of the Newton-Raphson technique. The advantage of CPF method is that additional information regarding the behavior of some system variables can be obtained during the solution. Details of the continuation power flow approach are discussed in [10]. Although CPF algorithm is very robust, it is computationally expensive for a large system with multiple constraints such as generators reactive power limits.

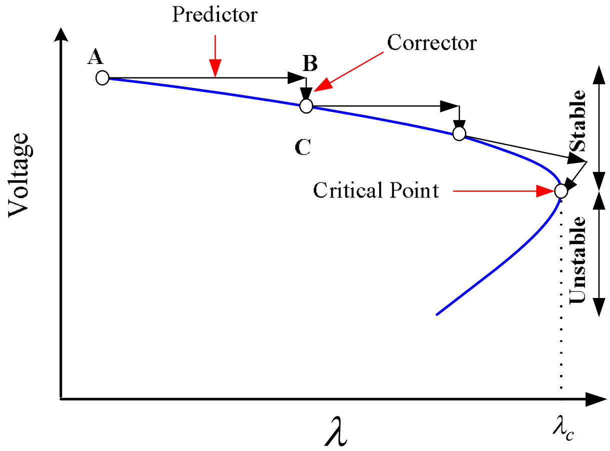

Fig.1: Predictor-corrector scheme in the CPF method

3.2 Predictor-corrector scheme for obtaining generators reactive power limit points

The main objective in this approach is to obtain generators reactive power limit points using a predictor/corrector scheme. Generally the constraint of a generator varies depending on the value of loading parameter. For each generator of a power system, a pair of equality and inequality constraints exists and their roles are exchanged to each other when the generator reaches reactive power capability limit. Therefore, the point at which a generator hits its reactive power capability limit is named constraint exchange point (CEP). The pair of equality and inequality constraints for a generator before and after the CEP is represented in (5) and (6) respectively.

$$\begin{cases} v = V_G{}^s - V_G = 0 \\ q = Q_G{}^{max} - Q_G \geq 0 \end{cases} \qquad (5)$$

$$\begin{cases} v = V_G{}^s - V_G \geq 0 \\ q = Q_G{}^{max} - Q_G = 0 \end{cases} \qquad (6)$$

The power flow solution is obtained under a set of equality and inequality constraints for a specified load parameter as follow:

$$F(x,\lambda) = 0 \qquad F : R^{N+1} \to R^N \qquad (7)$$

$$G(x,\lambda) \geq 0 \qquad G : R^{N+1} \to R^M \qquad (8)$$

For a given load parameter, the solution of (7) and (8), if exists, will be unique. In a multi machine system there are several CEPs each of which corresponds to the reactive power limit of a specific generator. Considering $z^0 = (x^0, \lambda^0)$ as a stable operating point which is shown in Fig.2, the CEPs are expressed as z_1, z_2, …, in order along the stable operating region of the power system. On the other hand, the intervals which are divided by CEPs are defined as $I_1, I_2, \ldots$, such that the constraint exchange point z_k belongs to the interval I_k. At the interval I_k the equality and inequality constraints will be expressed as follow:

$$F^{(k)}(x,\lambda) = 0 \qquad F : R^{N+1} \to R^N \qquad (9)$$

$$G^{(k)}(x,\lambda) \geq 0 \qquad G : R^{N+1} \to R^M \qquad (10)$$

Starting from an operating point in the interval I_k, the goal is to find the minimum loading parameter for a specific load and generation variation scenarios so that at least one of the inequality constraints will be exchanged to an equality constraint. At this point, which is denoted as z_{k+1}, the equality constraint would be as follow:

$$F^{(k)}(x,\lambda) = 0 \qquad (11)$$

$$h^{(k)} = \min_i \{g_i{}^{(k)}(x,\lambda)\} = 0 \qquad (12)$$

Where $g_i^{(k)}(x,\lambda)$ represents the i^{th} element of inequality set $G^{(k)}(x,\lambda)$ at the interval I_k and $h^{(k)}$ stands for new equality constraint.

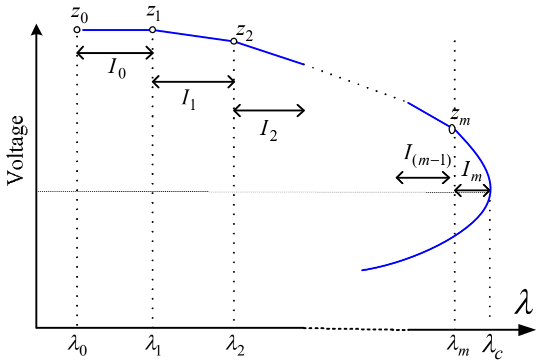

Fig.2: CEPs and corresponding intervals

If we show the differential change of inequality and equality constraints at the point z_{k+1} with $\Delta h^{(k)}$ and $\Delta \bar{h}^{(k)}$ respectively, then the stability of the new CEP, z_{k+1} will be determined according to table 1 [5]. Each CEP may be stable (in the upper portion of P-V Curve), unstable (in the lower portion of P-V curve), or critical (boundary between the stable and unstable portions). The critical CEP, if exists, corresponds to the limit induced bifurcation in power system. In table 1, $\Delta h^{(k)}$ is obtained using equations (13) and (14), assuming that $\Delta\lambda$ is positive. Also, equations (15) and (16) are applicable to calculate $\Delta \bar{h}^{(k)}$ for $\Delta\lambda > 0$.

$$\begin{bmatrix} F_x^{(k)}(x,\lambda) & F_\lambda^{(k)}(x,\lambda) \end{bmatrix}_{z_{k+1}} \begin{bmatrix} \Delta x \\ \Delta\lambda \end{bmatrix} = 0 \qquad (13)$$

$$\Delta h^{(k)} = \begin{bmatrix} h_x^{(k)} & h_\lambda^{(k)} \end{bmatrix}_{z_{k+1}} \begin{bmatrix} \Delta x \\ \Delta\lambda \end{bmatrix} \qquad (14)$$

$$\begin{bmatrix} F_x^{(k+1)}(x,\lambda) & F_\lambda^{(k+1)}(x,\lambda) \end{bmatrix}_{z_{k+1}} \begin{bmatrix} \Delta \bar{x} \\ \Delta\bar{\lambda} \end{bmatrix} = 0 \qquad (15)$$

$$\Delta \bar{h}^{(k)} = \begin{bmatrix} \bar{h}_x^{(k)} & \bar{h}_\lambda^{(k)} \end{bmatrix}_{z_{k+1}} \begin{bmatrix} \Delta \bar{x} \\ \Delta\bar{\lambda} \end{bmatrix} \qquad (16)$$

Table 1: identification the type of a CEP

CEP Type	$\Delta\bar{h}^{(k)}$	$\Delta h^{(k)}$
Stable	+	–
Critical (LIB)	–	–
Unstable	–	+

3.2.1 Prediction of the next CEP and prioritization of generators

Starting from an operating point in the interval I_k, the nearest CEP is first estimated by a predictor. Assume that an operating point has been obtained in the interval I_k as z^0 , which may or may not be a CEP. The first step is to calculate the tangent vector at this point by the following equation:

$$\begin{bmatrix} \Delta x \\ \Delta\lambda \end{bmatrix} = \begin{bmatrix} F_x^{(k)} & F_\lambda^{(k)} \\ 0 & 1 \end{bmatrix}_{z^0}^{-1} \cdot \begin{bmatrix} 0 \\ \varepsilon \end{bmatrix} \qquad \varepsilon \in R^+ \qquad (17)$$

In equation (10) the notation $[*]_{z^0}$ implies the evaluation of * at the point z^0.The tangent vector is denoted as $\Delta z = (\Delta x, \Delta\lambda)$, which has become normalized. Then, the locus of the solution of equation (9) is approximated using tangent vector as follow:

$$z = z^0 + s.\Delta z \qquad s \in R \qquad (18)$$

Let the i^{th} element of inequality constraint be shown as $g_i^{(k)}(x,\lambda)$. Then, by using equation (18) the element $g_i^{(k)}(x,\lambda)$ will be approximated as follow:

$$g_i^{(k)}(x,\lambda) \approx g_i^{(k)}(x^0,\lambda^0) + \left[\frac{\partial g_i^{(k)}}{\partial x} \quad \frac{\partial g_i^{(k)}}{\partial \lambda}\right]_{z^0} .s. \begin{bmatrix}\Delta x \\ \Delta\lambda\end{bmatrix} \tag{19}$$

The value of s which makes the above equation null is represented by s_i and is calculated as:

$$s_i = \frac{-g_i^{(k)}(x^0,\lambda^0)}{\left[\frac{\partial g_i^{(k)}}{\partial x} \quad \frac{\partial g_i^{(k)}}{\partial \lambda}\right]_{z^0} . \begin{bmatrix}\Delta x \\ \Delta\lambda\end{bmatrix}} \tag{20}$$

Above s_i is defined for all the elements of $G^{(k)}(x,\lambda)$. The predicted loading parameter which corresponds to reactive power limit point of the i^{th} generator is shown by $\tilde{\lambda}_i$ and could be obtained as follow:

$$\tilde{\lambda}_i = \lambda^0 + s_i.\Delta\lambda \tag{21}$$

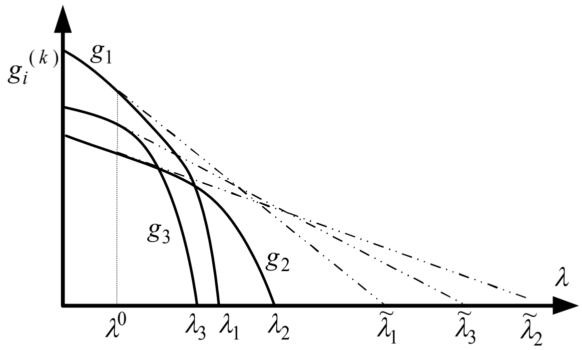

Fig. 3: reactive power reserve as a function of loading parameter

It is expected that generators with lower values of $\tilde{\lambda}_i$ (or s_i) hit the reactive power limit before those with higher $\tilde{\lambda}_i$ (or s_i). Thus, for each generator, an index called priority to hit limit (PHL) is defined and generators are sorted according to this index. A generator with lower $\tilde{\lambda}_i$, has a higher PHL and vice versa. The sorted list is named PHL list and the first generator in PHL list, is estimated to be the corresponding CEP for the next interval.

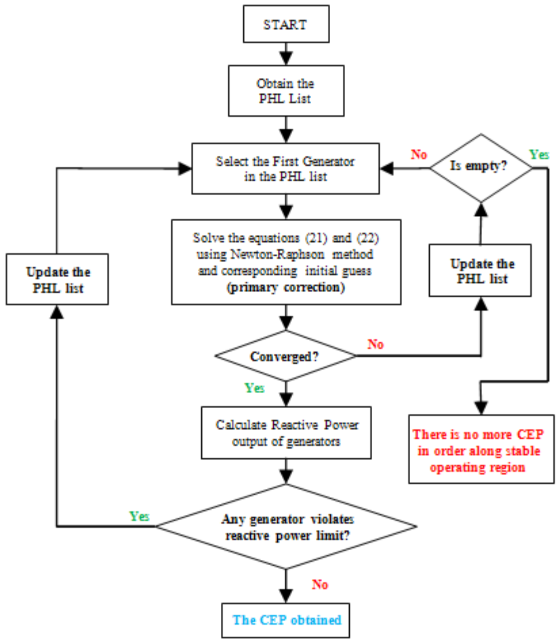

Fig. 4: proposed corrector scheme

3.2.2 Correction of the predicted CEP

Since the relationship between voltage and reactive power is extremely nonlinear, the linear prediction may lead to error in identification of which generators are associated with the CEP, e.g., variation of reactive power reserves of three generators as a function of loading parameter is shown in Fig.3. At initial point which is depicted by λ^0 , it is predicted that the first generator corresponds to CEP, however the third one reaches its reactive capability limit before others. We refer to this as prediction error in this paper. To overcome prediction error, secondary corrector step may be needed. The secondary corrector step is defined and explained in Fig.4. The proposed method for secondary corrector step contains two correction loops:

1) The power flow equations are converged: in this case, if there is one or more generators in the obtained CEP by primary corrector step which are violating their reactive power limits, then the PHL list is updated and only these generators are sorted in PHL list and the equations (22) and (23) are solved again.

2) The power flow equations are not converged: divergence of power flow equations in obtaining the predicted CEP is caused by singularity in Jacobian matrix. In this case, updating of PHL list is done by deletion of the first element and the equations (22) and (23) are solved again. If the updated PHL list becomes empty, then there is no more CEP in orderalong stable operating region.

3.2.3 Computational procedure of CEPs:

The procedure of the proposed method in order to obtain all CEPs in the stable operating region is summarized as follow:

Step 1) (Initial computation)
Determine initial values for state variable by solving power flow equations at loading parameter λ^0.

Step 2) (Computation of the tangent vector)
Compute tangent vector using equation (16). If $\Delta\lambda = 0$ then the point is SNB and stop, otherwise go to step 3.

Step 3) (Assessment of inequality constraints)
In the inequality constraint set, if $h^{(k)}$ which is obtained by equation (12), fulfills in the condition $\left|h^{(k)}\right| \le \varepsilon$, then the point is CEP and go to step 4, otherwise go to step 5.

Step 4) (Determining the type of the CEP)
Determine the type of the obtained CEP according to table 1. If the CEP is stable then go to step 5, otherwise go to step 7.

Step 5) (Estimating the next CEP)
Calculate s_i and $\tilde{z}_m$ using equation (20) and (24) respectively, then obtain PHL list for the next CEP and Go to step 6.

Step 6) (Correction of the estimated CEP)
Compute the exact CEP using corrector scheme in figure 5. If CEP exists go to step 2, otherwise go to step 8.

Step 7) (Identification of critical CEP)
If the CEP is critical then the type of instability is LIB and stop. Otherwise go to step 8.

Step 8) (SNB detection)
If the CEP doesn't exist or is in the unstable operating region then the type of instability is SNB and stop.

If the algorithm reaches step 8, it indicates the existence of SNB. In this step the obtained CEP is unstable or the computation of correction step is diverged. The divergence of the solution is newly considered and we demonstrated that in some situations where there is not any unstable CEP near the critical point, it leads to inability of computation of unstable CEPs by predictor/corrector scheme. However, the aim here is to identify all of the CEPs in the stable operating region and also the type of instability which is properly done by proposed predictor/corrector scheme.

3.3 Modified Continuation Power Flow (MCPF)

As mentioned before considering generators reactive power limits in a large electric power system may lead to several difficulties in using the conventional CPF method. The proposed predictor/corrector based method calculates CEPs more accurate and faster than the CPF approach. Then, the obtained CEPs are used as known solutions in the CPF method in order to trace P-V curves and voltage stability analysis. This eliminates the weakness of continuation power flow in considering the reactive power limit of generators. This method is called modified continuation power flow (MCPF) method in this paper. Starting from a known solution which corresponds to the current operating condition in the interval I_0 the procedure is summarized as follow:

Step 1) (Identification of CEPs and type of instability)
First obtain CEPs using predictor/corrector scheme. The type of instability is also identified in this step.

Step 2) (Primary determination of the intervals)

Define current and the next interval by increasing loading parameter λ. Primarily the intervals I_0 and I_1 is selected as current and next intervals which is shown by I_C and I_N respectively.

Step 3) (Prediction using the CPF approach)
Approximate the next solution in the current interval using the predictor of the continuation power flow approach.

Step 4) (Interval identification)
Indentify the interval to which the approximated solution belongs. If the predicted solution doesn't belong to the current interval go to step 6, otherwise go to step 5.

Step 5) (Correction of the approximated solution)
Correct the approximated solution to obtain exact solution using Newton-Raphson method, go to step 8.

Step 6) (Selecting the CEP as the solution)
Select the CEP which corresponds to the next interval as the exact solution. Set the next interval as the current interval, go to step 7.

Step 7) (Updating the equations)
Exchange the role of equality and inequality constraints of the corresponding generator to each other, go to step 8.

Step 8) (Evaluation of stopping rule)
If the sign of loading parameter λ in CPF method becomes negative, then stop otherwise go to step 3.

The computation process consists of CEPs identification and the continuation power flow. The computation time for CEPs identification is almost equivalent to $(1+\bar{n}_{pc}).mT$, where T stands for single iteration time of the ordinary power flow computation, m equals to overall number of CEPs along the stable operating region, and $\bar{n}_{pc}$ is average of overall primary correction iteration step. The computation time for the continuation power flow depends on the step length; however no step length reduction (which would be in an iterative manner) is needed for obtaining generators reactive power limit points, also these points are computed more accurately and faster. This improves the performance of continuation of power flow in a large power system analysis.

4. Case Study

4.1 Study system

A modified IEEE 118 bus system is used to test the proposed method. In this system, 54 buses include generators (PV bus) and 64 buses are load buses (PQ bus). The total active and reactive power in operating point is 4,242 (MW) and 1,436 (MVar) respectively and the 69th bus is considered as the reference bus. In the load variation scenario, the active and reactive power of each PQ bus is increased proportional to the load of operating point. However, the loads of PV are assumed to be fixed. Also, generation variation scenario is defined so that all generators except the reference one provide the load variation proportional to their operating point generations and the reference generator compensates the losses. In other words, the load variation coefficient "K_L" of active and reactive power for PQ and PV buses equals to 1 and 0 respectively. Where, the generation variation coefficient "K_G" is the same for all generators except the reference, and calculated from the equation (22).

$$K_{Gn} = \frac{\sum_{i \in PQ} K_{Li}.P_{Di}{}^{0}}{\sum_{j \neq ref} P_{Gj}{}^{0}} \qquad n \in \{PV\} \qquad (22)$$

4.2 The computation of CEPs

The obtained CEPs of IEEE 118 bus system in normal operating condition, are listed in table 2. In the developed program, the maximum iteration of both primary and secondary correction steps equals to 5. As it can be seen, the computation of CEPs by predictor/corrector scheme is fast and accurate. The average iteration of overall primary correction step is 1.72 and the iteration of secondary correction for all CEPs, except the 32th CEP, equals to 1. In computation of the 32th CEP, the secondary correction step includes 2 iterations, because of the error of the predictor in estimating the corresponding generator for this CEP.

The first five elements of the PHL list for estimating the 32th CEP is shown in table 3. The generator of the bus 113 is first estimated to be CEP. After primary correction the generators of buses 66 and 10 violate their reactive power limits. Thus in secondary correction step, the generator of bus 66 is estimated as CEP and then the primary correction confirms the rectitude of this prediction. In table 4, the PHL list for CEP 33 is shown. The generator of bus 10 is estimated as CEP which is accepted after the primary correction step. This point is the last CEP in the stable operating region which is identified as LIB point or critical CEP in table 2. In other words, the type of instability in normal operating condition for the considered load and generation variation scenario would be the limit induced bifurcation and occurs in total loading of 7,850 MW.

The computed CEPs for contingency condition, where two lines are faulted, are listed in table 5. It is assumed that the line between buses 44 and 45 and also the lines from bus 105 to 107 are faulted. The type of instability in this condition will be a saddle node bifurcation (which is identified by proposed corrector scheme) and the last CEP in the stable operating region corresponds to the generator of the bus 104. The average of overall iteration of primary correction step in the considered contingency condition will be equal to 2.96. The reason for this increase in comparison to the table 3 is the existence of 7 and 25 iteration in computation of the CEPs 24 and 25 respectively.

Table 2: Obtained CEPs in the normal operating condition

No.	P_{total} (MW)	λ	Generator Bus	CEP Type	n_{sc}	n_{pc}
1	4,740	0.347	12	Stable	1	2
2	4,746	0.352	92	Stable	1	1
3	4,878	0.444	85	Stable	1	2
4	4,896	0.456	74	Stable	1	1
5	5,155	0.637	77	Stable	1	2
6	5,182	0.656	76	Stable	1	1
7	5,206	0.673	1	Stable	1	1
8	5,236	0.694	56	Stable	1	1
9	5,255	0.707	15	Stable	1	1
10	5,443	0.838	36	Stable	1	2
11	5,465	0.854	100	Stable	1	1
12	5,570	0.927	34	Stable	1	2
13	5,633	0.970	70	Stable	1	1
14	5,759	1.059	6	Stable	1	2
15	5,823	1.103	49	Stable	1	1
16	5,931	1.179	19	Stable	1	2
17	6,159	1.338	80	Stable	1	2
18	6,194	1.362	18	Stable	1	1
19	6,302	1.438	105	Stable	1	2
20	6,505	1.579	103	Stable	1	2
21	6,640	1.673	46	Stable	1	2
22	6,690	1.709	62	Stable	1	2
23	6,698	1.714	104	Stable	1	1
24	6,762	1.759	8	Stable	1	2
25	6,988	1.916	55	Stable	1	2
26	7,127	2.014	65	Stable	1	2
27	7,158	2.035	110	Stable	1	1
28	7,388	2.195	32	Stable	1	2
29	7,563	2.318	89	Stable	1	2
30	7,630	2.364	4	Stable	1	2
31	7,719	2.426	99	Stable	1	2
32	7,845	2.516	66	Stable	2	5
33	7,850	2.517	10	(LIB)	1	2
				Average	1.03	1.73

Table 3: PHL list for the 32th CEP in normal operating condition

Rank	Generator Bus	$\tilde{\lambda}$
1	113	2.531
2	66	2.535
3	10	2.536
4	40	2.701
5	91	2.781
⋮	⋮	⋮

Table 4: PHL list for the 33th CEP in normal operating condition

Rank	Generator Bus	$\tilde{\lambda}$
1	10	2.517
2	113	2.518
3	40	2.615
4	91	2.705
5	54	2.728
⋮	⋮	⋮

Table 5: Obtained CEPs in the considered contingency condition

No.	P_{total} (MW)	λ	Generator Bus	CEP Type	n_{sc}	n_{pc}
1	4,738	0.346	12	Stable	1	2
2	4,746	0.351	92	Stable	1	1
3	4,878	0.444	85	Stable	1	2
4	4,894	0.455	77	Stable	1	1
5	5,111	0.606	34	Stable	1	2
6	5,143	0.629	74	Stable	1	1
7	5,175	0.651	76	Stable	1	1
8	5,205	0.672	1	Stable	1	1
9	5,207	0.674	36	Stable	1	1
10	5,217	0.681	15	Stable	1	1
11	5,240	0.697	56	Stable	1	1
12	5,447	0.841	100	Stable	1	2
13	5,548	0.911	70	Stable	1	2
14	5,743	1.047	19	Stable	2	4
15	5,746	1.050	6	Stable	1	1
16	5,964	1.201	49	Stable	1	2
17	5,976	1.210	18	Stable	1	1
18	6,153	1.333	80	Stable	1	2
19	6,351	1.472	105	Stable	1	3
20	6,505	1.579	103	Stable	1	3
21	6,623	1.662	8	Stable	1	3
22	6,655	1.684	65	Stable	1	2
23	6,674	1.697	62	Stable	1	3
24	6.692	1.710	104	Stable	2	7
25	-	-	-	SNB	5	25
				Average	1.24	2.96

The generator of bus 55 has the highest priority in the PHL list of CEP 24 which is shown in table 6. By selecting this generator, the primary correction step leads to divergence of solution. Then in the secondary correction step, the generator of bus 104 will be selected and primary correction confirms that. After identification of the 24th CEP, the PHL list for CEP 25 will be according to table 7. Generators of buses 55, 40, 32, 110, and 113 have the first to fifth priority respectively. Choosing each of these generators as CEP and performing primary correction leads to divergence of the solution and it is concluded that there is no more CEP in the stable operating region. In other words the type of instability would be saddle node bifurcation.

As explained above the main reason for the increase in the average iteration of primary and secondary correction steps is the divergence of computation in CEPs 24 and 25. Our experience showed that the maximum obtained iteration of secondary correction would be 2. Also the iteration of the primary correction step for a good predicted CEP does not exceed 3 iterations. Neglecting the iteration of computing the 25thCEP (which does not exist), the average iteration of overall primary correction step would be equal to 2.04. Also the computation time of CEPs for considered contingency condition is almost equals to $73\times T\ (=(1+2.04)\times 24\times T)$ where T is the computation time of an ordinary power flow equations.

Table 6: PHL list for the 24th CEP in the considered contingency condition

Rank	Generator Bus	$\tilde{\lambda}$
1	55	1.725
2	104	1.726
3	32	2.054
4	40	2.098
5	46	2.136
⋮	⋮	⋮

Table 7: PHL list for the 25th CEP in the considered contingency condition

Rank	Generator Bus	$\tilde{\lambda}$
1	55	1.714
2	40	1.896
3	32	1.942
4	110	1.960
5	113	1.984
⋮	⋮	⋮

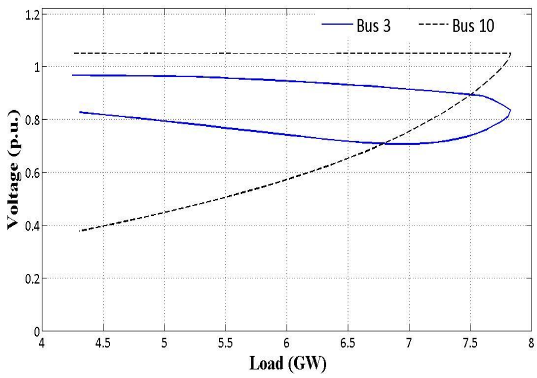

Fig. 5: PV Curves in normal operating condition

4.3 Tracing P-V curves using MCPF

Using MCPF algorithm, traced P-V curves for normal and considered contingency conditions are shown in figures 5 and 6 respectively. In figure 5, the voltage versus loading parameter for buses 3 and 10 is shown. Both of these buses are PV, at which the critical CEP corresponds to the generator of bus 10. As it can be seen from figure 5, in normal operating conditions the type of instability is LIB which occurs in total loading of 7,850 and this is in accordance with listed CEPs of table 2.

The voltages of buses 43 and 44, which are both PQ buses, have been shown in figure 6. In the considered contingency condition, as mentioned before in table 5, the type of instability is identified as SNB and using MCPF, the total loading of SNB point in this condition is 6,695 MW.

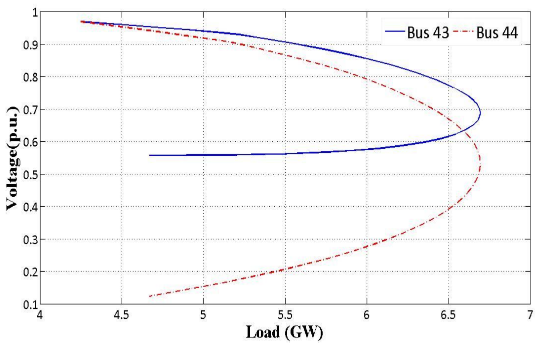

Fig. 6: PV Curves in the considered contingency condition

4.4 Comparison between CPF and MCPF

Conventional continuation power flow method provides all CEPs and maximum loading point on the P-V curves, however, in order to obtain the exact CEPs, iterative step length selection or very small step length is needed. This is very time consuming in a large electric power system with many generators. In proposed method all CEPs and the type of instability are first identified and then used as the given data in continuation power flow. As the result shows, the MCPF algorithm computes all CEPs as well as the type of instability, exactly and as fastest as possible, which is because no step length reduction or iterative step length selection is needed in tracing P-V curves. However, in computation of other points which are not CEP, CPF and MCPF act exactly the same.

5. Conclusions

In this paper a new method of tracing P-V curves considering generators reactive power limits is presented. The proposed method, which is named as MCPF, first computes the generators reactive power hitting point using predictor/corrector scheme and then uses these point as given data in continuation power flow. This will eliminate the weakness of conventional CPF in a large electric power system with multiple generators, which very small step length or iterative selection of step length is needed in this method.

The proposed predictor/corrector scheme is an extension of proposed method in [5] by defining a PHL list for each CEP, and optimizing the corrector step in order to handle the predictor error which may lead to an unrealistic CEP or divergence of equations. The results show a good performance of the proposed method. The aspiration for our future work is to compute other constraints of power system in a predictor/corrector manner. For example, transmission lines thermal capability limits are another key factor in voltage stability analysis and can be included in MCPF algorithm.

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