Studies of Contingencies in Power Systems through a Geometric Parameterization Technique, Part II: Performance Evaluation

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Received November 26, 2014; Revised December 02, 2014; Accepted December 05, 2014

Abstract In the evaluation of voltage stability where must trace P-V and Q-V curves for each contingency, static analysis methods are used, as the method of load flow and continuation power flow, it should be efficient and reliable in order to meet the requirements needed for applications in the planning and operation stage in real-time. Geometric parameterization schemes have been proposed by the authors in Part I of this paper. In this part of the paper, the results are presented graphically and in terms of numbers of iterations, showing that the proposed methods obtain all P-V curves of the IEEE-14 and 30 buses systems (loading margin of pre-contingency N-0) and all loading margin post-contingency (N-1 simple contingency and N-2 severe contingency), both with a reduced number of iterations.

Keywords: contingency, voltage instability, continuation power flow, maximum loading point, parameterization


1. Introduction

The mathematical formulation of the geometric parameterization schemes based on physical parameters has been presented in Part I of this paper [1]. Power flow (PF) methods are very important tools for the analysis of voltage problems in power systems [2]. The conventional PF is not considered an appropriate tool for static voltage stability studies because it often fails to converge or takes a long time for compute a solution at or near the maximum loading point (MLP). The success for obtaining the PF solution will depend on the characteristics of the solution process of the nonlinear algebraic equations, such as the existence of the solution or multiple solutions, the presence of singularity, the solution method, and the initial conditions. The singularity of the Jacobian matrix (J) at the MLP is the main cause of numerical breakdown of PF methods during the P-V curve tracing process. Continuation power flow (CPF) methods have been successfully applied to static voltage stability assessment.

In Figure 1 and Figure 2 are presented the P-V curves and some of the preventive evaluation criteria of voltage collapse used in various energy companies, as well as the definitions of the terms involved.

An alternative methodology is presented in [8] for static contingency analyses that only use Continuation Methods and thus provides an accurate determination of the loading margin. Rather than starting from the base case operating point, the proposed continuation power flow obtains the post-contingency loading margins starting from the maximum loading and using a bus voltage magnitude as a parameter. The branch selected for the contingency evaluation is parameterized using a scaling factor, which allows its gradual removal and assures the continuation power flow convergence for the cases where the method would diverge for the complete transmission line or transformer removal.

The stability margin is the measured of the distance of an event that causes the instability and should be defined in order to be easily understood by the operator. The loading margin (LM) is the most basic index and widely accepted, the LM for the voltage collapse is defined as the greatest increase load that the system can support, without causing the voltage collapse.

Consider a stable operating point (O) called base case. This point may have been obtained through the state estimator or by means of a program of power flow (PF). The method of the P-V curve will determine the system capacity through of gradual increasing of the total load system, accordance with a load prediction at short term or else, with a predetermined pattern. Generally, as the load increases, the system voltage will tend to decrease, as shown in Figure 1. There is a limit to this increase of the load after which the system will enter in collapse, this corresponds to the loading limit of pre-contingency (P_{max-pre}) or also called maximum loading point (MLP). The loading may be interpreted in a broadest sense, i.e. as not only an increase of the load, but also as an increase power
transfer between areas, of the load of certain areas (A), or of the load of specific bus (B). Also, the increase can be defined in terms of real power (P), reactive power (Q), or apparent power (S) [3,4]. In the case of the combination of increase of specific load bus in terms of Q, for example, the V-Q curve would be obtained.

The most usual limits is called of loading limit post-contingency (P_{max-post}) used to measure the robustness of the system after contingencies [5]. In some cases, is usually used the criterion of minimum voltage (V_{low} = 0.9 p.u.) [6]. In this case, the maximum operational load for each condition is the load at which the voltage decreases to the acceptable level of voltage (V_{low}), as indicated in the Figure 1 by P_{op} (base case) and P'_{op} (contingency). The system margin would be measured by [7]:

Figure 1. Definition for loading margin of pre and post-contingency

- Maximum Margin [MW] = P_{max-pre} - P_0.
- Maximum Margin (%) = (P_{max-pre} / P_0 - 1)100, for cases without contingencies.
- Maximum Margin [MW] = P_{max-post} - P_0.
- Maximum Margin (%) = (P_{max-post} / P_0 - 1)100 for cases with contingencies.

In the case of consider the minimum voltage level [6].

- Operational margin = P_{op} - P_0, for cases without contingency.
- Operational margin = P'_{op} - P_0, for cases with contingency.

In the case of normal operating conditions of the IEEE-14 bus system, it may be noted that the tracing of the P-V curve was restricted in steps 1 and 2 of the general procedure adopted, is observed a pre-contingency loading margin (LM_{pre}) of 0.7658. Figure 3(b) shows the number of iterations used to obtain the P-V curves. In Figure 3(b) is also presented the number of iterations used by the Newton-Raphson method through successive solutions of the PF near (due the singularity of the Jacobian matrix (J)) of the MLP. The singularity of the matrices J and J_{m} can be proven by the values of the determinants shown in Figure 3(c), it is observed that the PF using successive...
solutions becomes singular at the point $S_1$ \( \det(J) = 0 \), the opposite is shown in the proposed method, where $J_m$ is not singular \( \det(J_m) \neq 0 \). Figure 3(d) shows the curves of all the buses of the IEEE-14 bus system to contingency N-0, i.e., under normal operating conditions.

Figure 3. Performance of the method for the IEEE-14 bus system: (a) voltage magnitude of the critical bus ($V_{14}$) in function of $\lambda$, (b) number of iterations for the proposed method and conventional PF, (c) determinants of the matrix $J$ and $J_m$, (d) P-V curve of all system buses for contingency N-0.

Figure 4 shows the corresponding P-V curves for certain contingencies, curve 1 in Figure 4(a) corresponds to the base case without contingency (N-0) and shows a $LM_{pre}$ of 0.7751 p.u. The curve 2 in the Figure 4(a) represents the P-V curve by contingency N-2 (outage of the TL between the buses 1 and 2), double contingency, see Figure 5 and shows that occurred a reduction of 0.7942 in the $LM$, i.e., in this condition, it will be necessary to establish a load shedding strategy to...

Figure 4. Performance of the method for the IEEE-14 bus system: (a) voltage magnitude of the critical bus ($V_{14}$) in function of $\lambda$ for contingency N-2, (b) number of iterations for the proposed method, (c) P-V curve of all system buses for the contingency N-2 (outage of the TL between the buses 1 and 2), (d) voltage magnitude of the bus PQ ($V_{14}$) in function of $\lambda$ with insertion of the capacitor bank of 35.281 MVAr.
maintain voltage stability, i.e., to move the system to a secure voltage operating point. This is because the point of post-contingency loading margin (MLP\textsubscript{post} = 0.9809 pu) is lower than the value of the base case (1.0 pu), i.e., the LM is negative. It is observed in Figure 4(b) the number of iterations used to obtain the curve 2 (N-2, severe contingency, Figure 5) and in the Figure 4(c) shows all the system buses for the contingency N-2. With the insertion of the capacitor bank of 35.281 MVAr in bus 14, the system has reactive power enough to support the contingency and still presents a positive LM of 0.057 pu, as can be seen in curve 3 of Figure 4(d) obtained with the proposed method and thus, obeying the criteria of theWSCC [2].

Figure 5. Diagram of the IEEE-14 bus system with the contingencies N-2 and N-1

Figure 6 shows the IEEE-14 bus system with the contingency N-1 (outage of the TL between the buses 2 and 3, see Figure 5). In Figure 6(a) shows the complete tracing of the P-V curve of the generation bus 2 (PV buses) of the system with the contingency N-1, obtained with the proposed method, the LM\textsubscript{post} is 0.2991. It is observed in Figure 6(b) the number of iterations used to obtain the curve 2 (contingency N-1) and the Figure 6(c) shows the tracing of the P-V curve of the bus 13 for the same contingency N-1. In Figure 6(d) P-V curve for all system buses to contingency N-0, i.e., under normal operating conditions.

Figure 7(a) shows the P-V curve of the critical bus under normal operating conditions of the IEEE-14 bus system, it may be noted that the tracing of the P-V curve was also restricted in steps 1 and 2 of the general procedure adopted, is observed a pre-contingency loading margin (LM\textsubscript{pre}) of 0.7658. Equations (4) and (5) presented in Part I of this paper [1] were used, i.e., λ-θ will be the plan used for obtaining the P-V curve. Figure 7(b) shows the number of iterations used to obtain the P-V curves and the number of iterations used by the Newton-Raphson method through successive solutions of the PF near (due the singularity of the Jacobian matrix (J)) of the MLP. The singularity of the matrices J and J\textsubscript{m} can be proven by the values of the determinants shown in Figure 7(c), it is observed that the PF using successive solutions becomes singular at the point S\textsubscript{2} [det(J) = 0], the opposite is shown in the proposed method, where J\textsubscript{m} using the equations (4) and (5) of the part I of this paper is not singular [det(J\textsubscript{m}) ≠ 0]. Figure 7(d) shows the curves of all the buses of the system IEEE-14 to contingency N-0, i.e., under normal operating conditions.
Figure 7. Performance of the method for the IEEE-14 bus system: (a) voltage angles of the critical bus ($\theta_{14}$) in function of $\lambda$, (b) number of iterations for the proposed method and conventional PF, (c) determinants of the matrix $J$ and $J_m$, (d) $P$-$V$ curve of all system buses for contingency N-0.

Figure 8 shows the IEEE-14 bus system with the contingency N-2 (outage of the TL between the buses 1 and 2, see Figure 5) using the equations (4) and (5) of the proposed method, Part I of this paper. In Figure 8(a) shows the complete tracing of the $P$-$V$ curve of the load bus 14 (PQ buses) of the system with the contingency N-2, obtained with the proposed method. It is observed an $\text{LM}_{\text{post}}$ negative, because the $\text{MLP}_{\text{post}}$ is lower than base case (1.0). The bus used as plan to obtain the $\text{LM}_{\text{post}}$ was also the 14 (critical bus), it will be necessary to establish a load shedding strategy to maintain voltage stability, i.e., to move the system to a secure voltage operating point. It is observed in Figure 8(b) the number of iterations of the proposed method. Figure 9(a) shows the tracing of the $P$-$V$ curve of the load bus 5 for the same contingency N-2. In Figure 9(a) $\lambda$-$0$ curve for all system buses to contingency N-2 is also displayed and in Figure 9(b) is presented the number of iterations used to tracing of the $\lambda$-$0$ curve for the bus 5 of the system with contingency N-2. For the IEEE 14-bus system it takes only six iterations using mismatch criterion to reduce the step size and to switch to a new set of lines for all tests.

Figure 8. Performance of the method for the IEEE-14 bus system: (a) voltage angles of the critical bus ($\theta_{14}$) obtained in function of $\lambda$ for contingency N-2, (b) number of iterations for the proposed method.

Figure 9. Performance of the method for the IEEE-14 bus system: (a) voltage angles of the load bus ($\theta_5$) in function of $\lambda$ for contingency N-2, (b) number of iterations for the proposed method using the equations (4) and (5) of Part I of this paper.
From the results presented, it is noted that the proposed method obtained all P-V curves of the IEEE-14 bus system to any contingency applied.

2.2. Performance of the Proposed Method for the IEEE-30 Bus System

Figure 11(a) shows the P-V curve of the critical bus under normal operating conditions of the IEEE-30 bus system, it may be noted that the tracing of the P-V curve was restricted in steps 1 and 2 of the general procedure adopted, is observed a $LM_{pre}$ of 0.5329. Figure 3(b) shows the number of iterations used to obtain the P-V curves by the proposed method and the Newton-Raphson method through successive solutions of the PF near (due the singularity of the Jacobian matrix ($J$)) of the MLP. Figure 3(c) shows the curves of all the buses of the IEEE-30 bus system to contingency N-0, i.e., under normal operating conditions.

Figure 12 represents the diagram of the IEEE-30 bus system with the site where occurred the contingencies N-1 and N-2.

Figure 13 shows the IEEE-30 bus system with the contingency N-2 (outage of the TL between the buses 1
and 2, double contingency, see Figure 12). In Figure 13(a) shows the complete tracing of the P-V curve of the critical bus 30 (PQ buses) obtained with the proposed method, the LM_post is -0.1151 (negative margin). It is also observed in Figure 13(a) the tracing of the P-V curves of all system buses and the Figure 13(b) shows the number of iterations used to obtain the P-V curve of the critical bus 30 (contingency N-2).

Figure 12. Diagram of the IEEE-30 bus system with the contingencies N-2 and N-1

Figure 13. Performance of the method for the IEEE-30 bus system: (a) voltage magnitude of the critical bus \(V_{c0}\) in function of \(\lambda\) for contingency N-2, (b) number of iterations for the proposed method

Figure 14 shows the IEEE-30 bus system with the contingency N-1 (outage of the TL between the buses 1 and 3, see Figure 12). In Figure 14(a) shows the complete tracing of the P-V curve (lower and upper part of the P-V curve) of the generation bus 2 (PV buses) of the system with the contingency N-1, obtained with the proposed method, the LM_post is 0.235. It is observed in the Figure 14(b) the points of the P-V curves of the buses 2, 5 and 30 stored during the obtaining of the curve of the bus 2 of the Figure 14(a) for the same contingency N-1and Figure 14(c) shows the number of iterations used to obtain the curve of the bus 2 (contingency N-1).

For the IEEE 30-bus system it takes only seven iterations using mismatch criterion to reduce the step size and to switch to a new set of lines for all tests.

Figure 15(a) shows the \(\lambda-\theta\) curve of the critical bus under normal operating conditions of the IEEE-30 bus system, it may be noted that the tracing of the \(\lambda-\theta\) curve was also restricted in steps 1 and 2 of the general procedure adopted, is observed a pre-contingency loading margin (LM_pre) of 0.5329. Equations (4) and (5) presented in Part I of this paper [1] were used, i.e., \(\lambda-\theta\) will be the plan used for obtaining the P-V curve. Figure 15(b) shows the number of iterations used to obtain all the \(\lambda-\theta\) curves of the IEEE-30 bus system of the Figure 15(c).
Figure 14. Performance of the method for the IEEE-30 bus system: (a) voltage magnitude of the generation bus ($V_2$) in function of $\lambda$ for contingency N-1, (b) P-V curves of pre-contingency (N-0) and post-contingency (N-1) of the load buses 30 (green points), 5 (blue points) and 2 (red points), (c) number of iterations

Figure 16 shows the IEEE-30 bus system with the contingency N-2 (outage of the TL between the buses 1 and 2, see Figure 12). In Figure 16(a) shows the complete tracing of the $\lambda$-$\theta$ curve (lower and upper part of the $\lambda$-$\theta$ curve) of the load bus 3 (PQ buses) of the system with the contingency N-2, obtained with the proposed method, the $L_{M_{post}}$ is -0.1151 (negative margin, severe contingency). It is observed in the Figure 16(b) the points of the $\lambda$-$\theta$ curves of the buses 2, 3 and 30 stored during the obtaining of the curve of the bus 3 of the Figure 16(a) and in the Figure 16(c) shows the number of iterations used to obtain the curve of the bus 9 (contingency N-1).

Figure 17 shows the IEEE-30 bus system with the contingency N-1. In Figure 16(a) shows the complete tracing of the $\lambda$-$\theta$ curve of the load bus 9 of the system with the contingency N-1, obtained with the proposed method, the $L_{M_{post}}$ is 1.2350. It is observed in the Figure 17(b) the points of the P-V curves of the buses 2 and 30 stored during the obtaining of the curve of the bus 9 of the Figure 17(a) and in the Figure 17(c) shows the number of iterations used to obtain the curve of the bus 9 (contingency N-1).

Figure 15. Performance of the method for the IEEE-30 bus system: (a) voltage angles of the critical bus ($\theta_30$) in function of $\lambda$, (b) number of iterations for the proposed method, (c) P-V curve of all system buses for contingency N-0

It is observed that the proposed method obtains all the P-V curves for the two systems presented without problems of singularity of the Jacobian matrix ($J$) at the MLP.
Figure 16. Performance of the method for the IEEE-30 bus system: (a) voltage angles of the load bus ($\theta_3$) in function of $\lambda$ for contingency N-2, (b) $\lambda$-$\theta$ curves of pre-contingency (N-0) and post-contingency (N-2) of the buses 3 (green points), 2 (blue points) and 30 (red points), (c) P-V curves of pre-contingency (N-0) and post-contingency (N-2) of the buses 2 (blue points) and 30 (red points), (d) number of iterations.

Figure 17. Performance of the method for the IEEE-30 bus system: (a) voltage angles of the load bus ($\theta_9$) in function of $\lambda$ for contingency N-1, (b) P-V curves of pre-contingency (N-0) and post-contingency (N-1) of the buses 2 (green points) and 30 (red points), (c) number of iterations.

3. Conclusion

This paper presents a new geometric parameterization technique that associates robustness to simplicity and, it is of easy understanding. The proposed continuation power flow allows the successful computation of the MLP with the desired precision and it is used to trace the complete P-V curves of any power systems, showing its robustness. The singularity of the Jacobian matrix is avoided by the addition of a line equation, which passes through a point in the plane determined by the bus voltage magnitude or voltage angles and the loading factor variables.

The main advantage of the proposed methodology is that it simplifies the development and implementation of the continuation methods for the static contingency analysis of electric power systems. In other words, the contingencies are efficiently analysed without considerable modifications to the CPF algorithms found in the literature.
Finally, the proposed mismatch criterion produces a reduction in the number of iterations, i.e., by analyzing the mismatch evolution it is possible to identify the ill-conditioning before the predefined maximum number of iterations.

Acknowledgement

The authors are grateful to the financial support provided by CNPq (Brazilian Research Funding Agencies) and UNESP campus of Tupã.

References


