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

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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 obtains 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

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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 accepts, 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]:

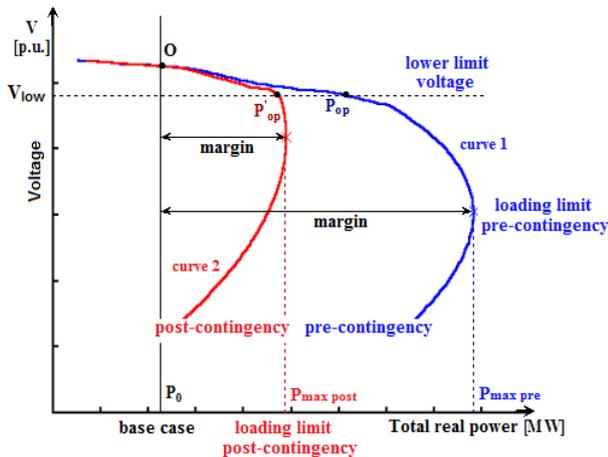**Figure 1**. Definition for loading margin of pre and post-contingency

- 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.
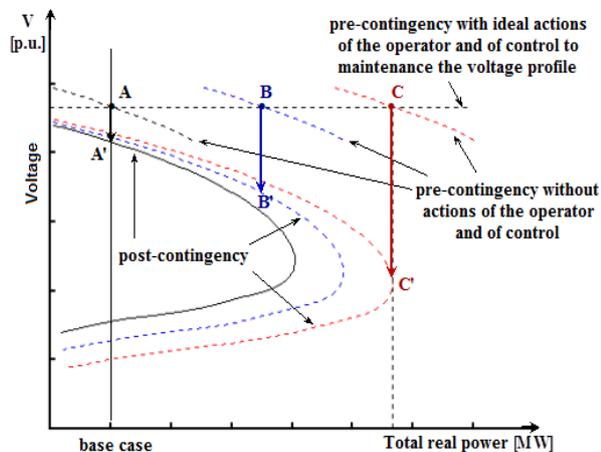

Figure 2. Definition of operation limit using P-V curves

The limit for safe operation (see Figure 2) corresponds the restriction to the system loading in the conditions of pre-contingency such that the system can support a

determined contingency. More precisely, given a predefined direction of loading, the actions performed by the operator and by controls during the system loading, and a contingency, the goal is to determine the value that the configuration of pre- contingency can be loaded without that the contingency, cause the instability [5].

A recommended methodology for contingency analysis is the use of the P-V curves.

This paper presents the results obtained of the a geometric parameterization scheme for the continuation power flow that enables the complete tracing of the P-V curve of a power system, aiming to obtainment of the MLP, and, subsequently, the assessment of voltage stability margin. Also verify what occurs after a contingency in the system and the behavior of the P-V curve, especially in the MLP region, because depending of the contingency, the system will operate very close to MLP.

2. Results

This Section discuss the results of applying the proposeds methods to some IEEE systems (14 and 30 buses). The goal is to pointing out its main features, considering the influence of reactive power and transformer tap limits. The first point of each curve is computed by a conventional Newton method. For all simulations the power mismatch convergence threshold was 10^{-4} p.u., and the values adopted for σ^0 and maximum number of iteration were 0.5 and 10, respectively. Upper and lower tap limits of, respectively, 1.05 and 0.95 were adopted. The loads were modeled as constant power and the parameter λ was used to simulate the real and reactive load increment, considering a constant power factor. The increase in load was followed by a generation increase using λ. The tap adjustment in the on load-tap changers (OLTC) transformers consisted of including the tap position as a dependent variable, whereas the controlled bus voltage magnitude was considered as an independent variable. The method of accounting for Q-limit at PV buses and tap limits is the same as in conventional PF methods. At every iteration the reactive generations at all PV buses are compared to their respective limits. In case of violation, a PV bus is switched to type PQ. This bus can be switched back to PV in future iterations. Tap limit violations are also checked.
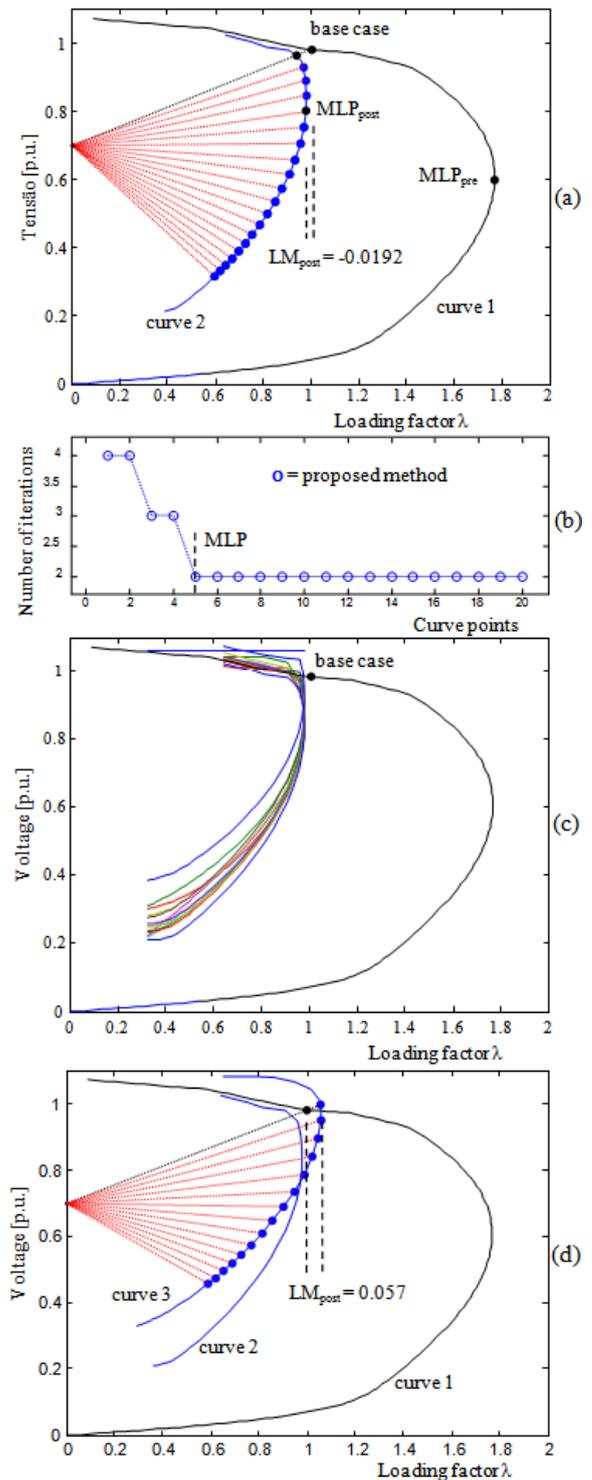
2.1. Performance of the Proposed Method for the IEEE-14 Bus System

Figure 3(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 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($\mathbf{J}$) = 0], the opposite is shown in the proposed method, where $\mathbf{J_m}$ is not singular [det($\mathbf{J_m}$) ≠ 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.
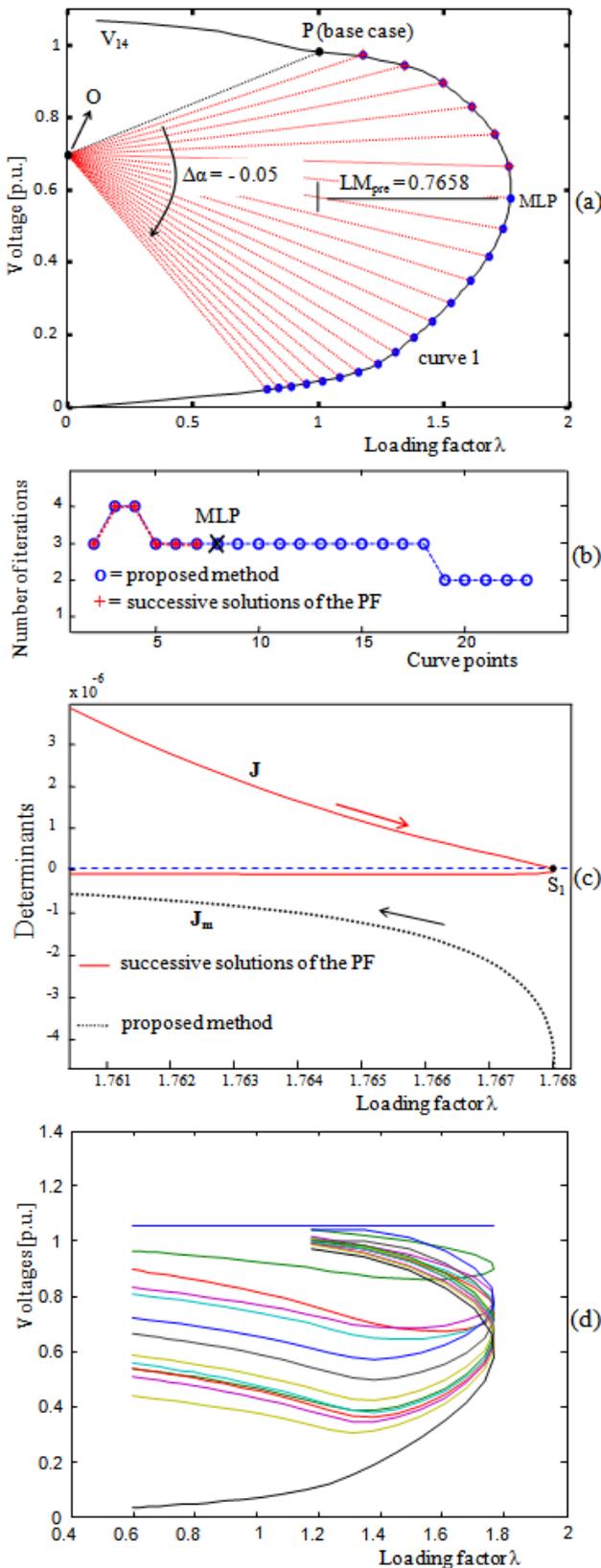
Figure 3. Performance of the method for the IEEE-14 bus system: (a) voltage magnitude of the critical bus (V_{14}) in function of λ, (b) number of iterations for the proposed method and conventional PF, (c) determinants of the matrix $\mathbf{J}$ and $\mathbf{J_m}$, (d) P-V curve of all system buses for contingency N-0

Figure 4. Performance of the method for the IEEE-14 bus system: (a) voltage magnitude of the critical bus (V_{14}) in function of λ 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 λ with insertion of the capacitor bank of 35.281 MVAr

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 transmission line (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

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 ($MLP_{post} = 0.9809$ pu) is lower than the value of the base case (1.0 p.u.), 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 p.u., as can be seen in curve 3 of Figure 4(d) obtained with the proposed method and thus, obeying the criteria of the WSCC [2].
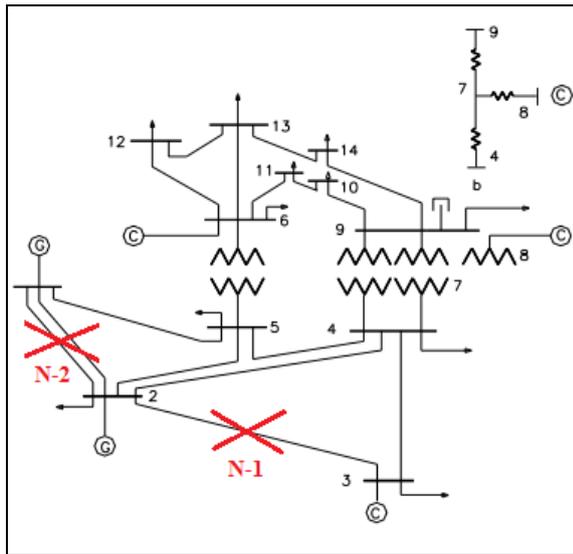

Figure 5. Diagram of the IEEE-14 bus system with the contingencies N-2 and N-1

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_{post} is 0.2991. It is observed in Figure 6(b) the number of iterations used to obtain 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-1 (outage of the TL between the buses 2 and 3) is displayed. 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 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_{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 $\mathbf{J_m}$ 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_2 [det(**J**) = 0], the opposite is shown in the proposed method, where $\mathbf{J_m}$ using the equations (4) and (5) of the part I of this paper is not singular [det($\mathbf{J_m}$) ≠ 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.
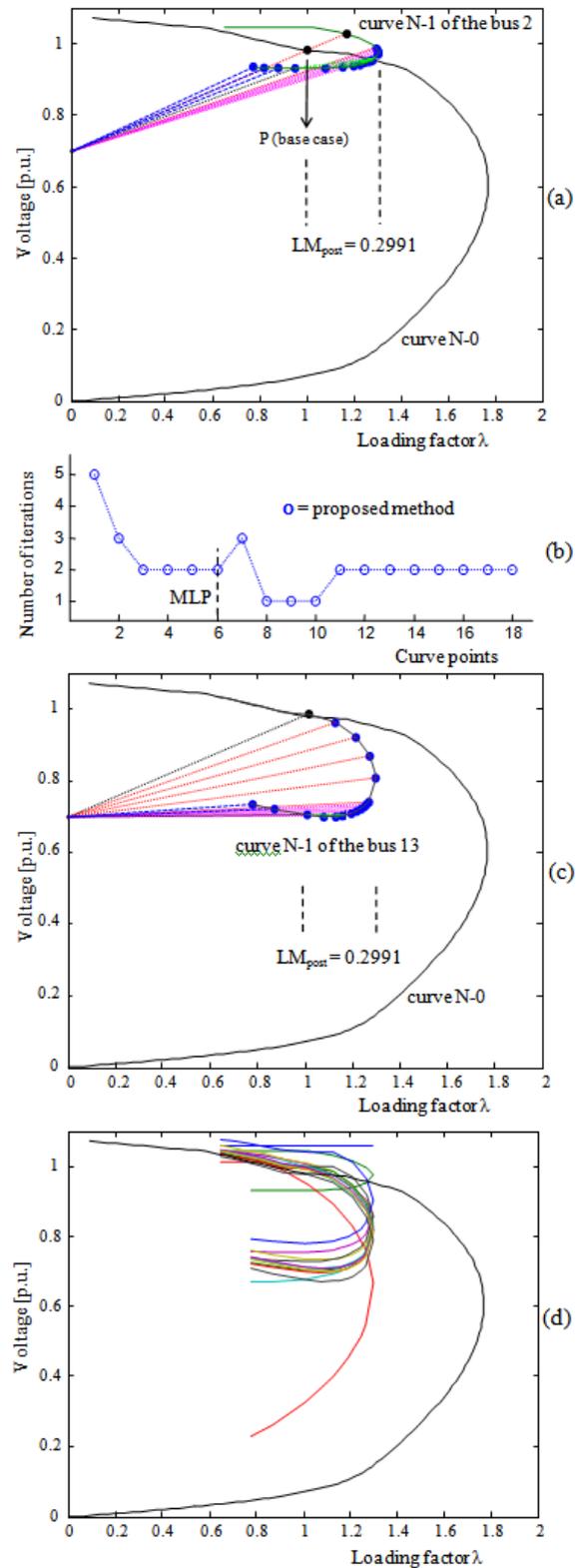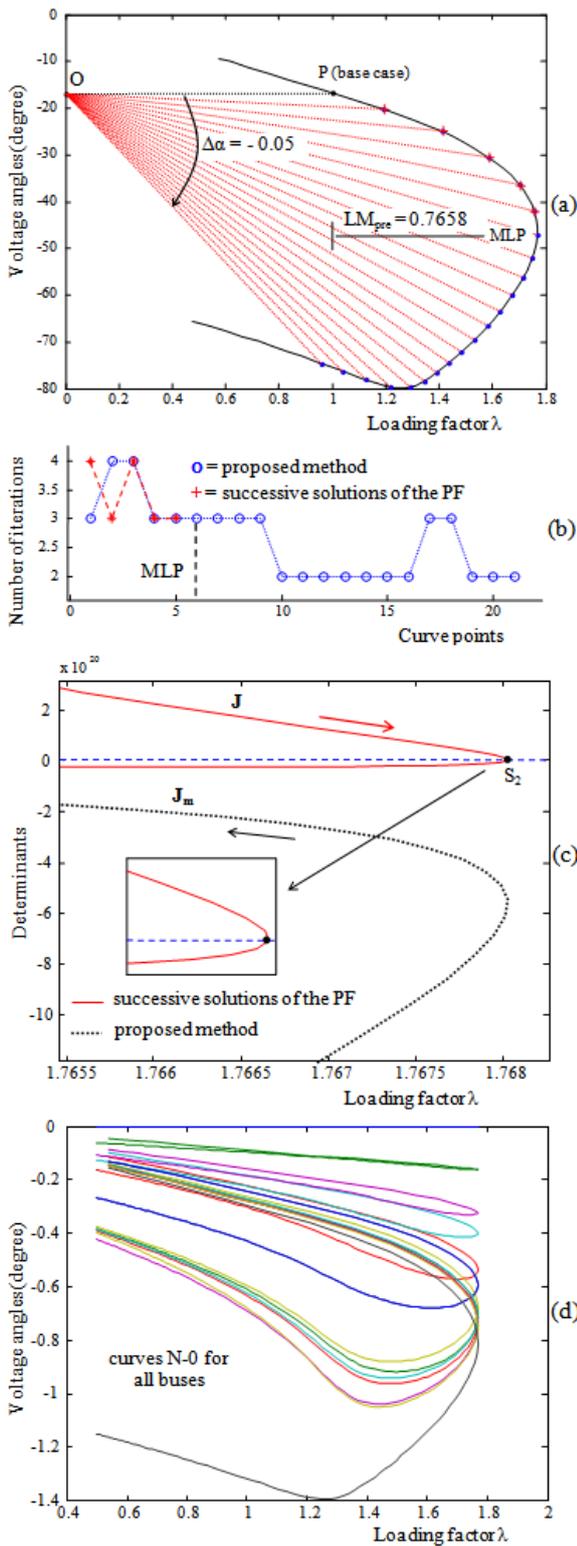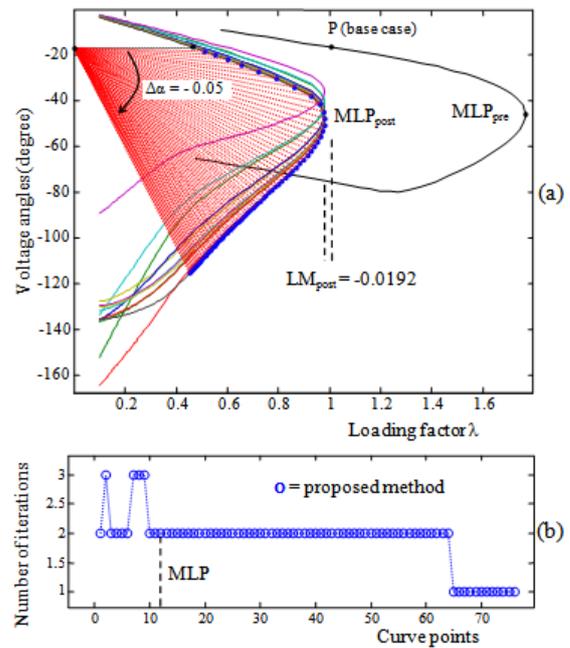

Figure 6. Performance of the method for the IEEE-14 bus system: (a) voltage magnitude of the PV bus (V_2) in function of λ for contingency N-1, (b) number of iterations for the proposed method, (c) voltage magnitude of the PQ bus (V_{13}) in function of λ, (d) P-V curve of all system buses for the contingency N-1 (outage of the TL between the buses 2 and 3)
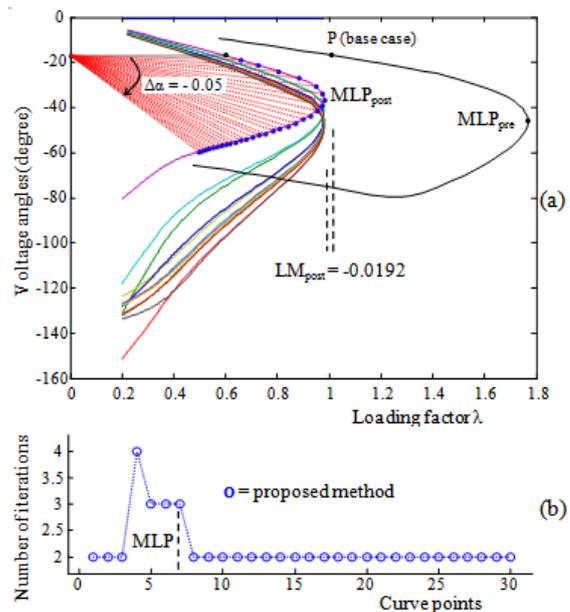
Figure 7. Performance of the method for the IEEE-14 bus system: (a) voltage angles of the critical bus (θ_{14}) in function of λ, (b) number of iterations for the proposed method and conventional PF, (c) determinants of the matrix $\mathbf{J}$ and $\mathbf{J_m}$, (d) P-V curve of all system buses for 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 LM$_{post}$ negative, because the MLP$_{post}$ is lower than base

case (1.0). The bus used as plan to obtain the LM$_{post}$ 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) λ-θ 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 λ-θ 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.
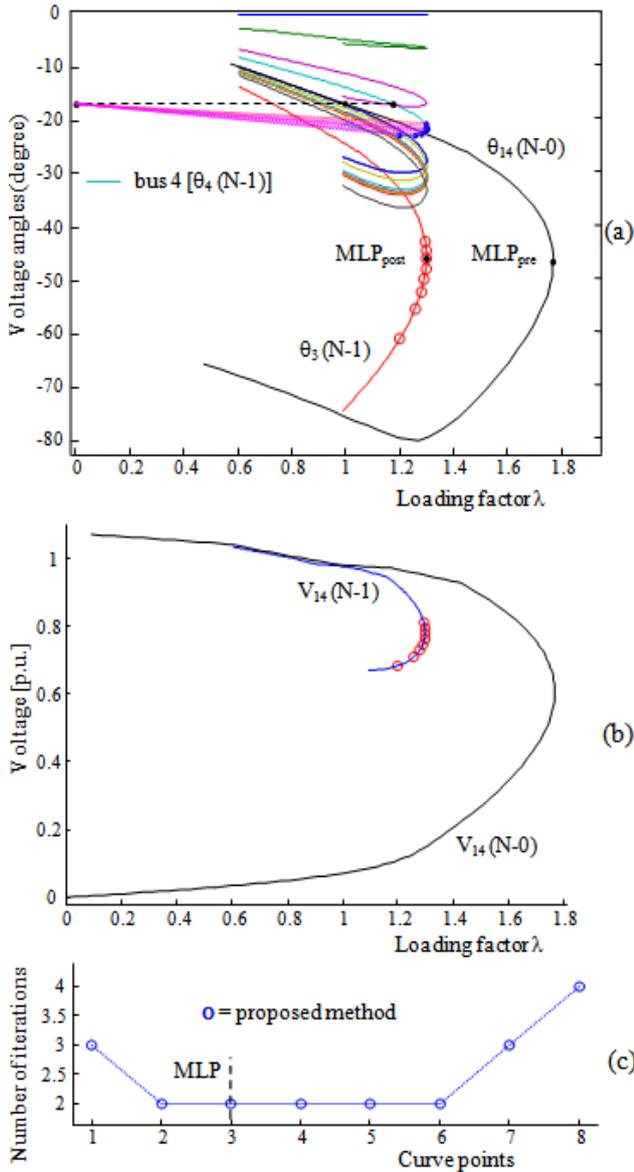

Figure 8. Performance of the method for the IEEE-14 bus system: (a) voltage angles of the critical bus (θ_{14}) obtained in function of λ for contingency N-2, (b) number of iterations for the proposed method

Figure 9. Performance of the method for the IEEE-14 bus system: (a) voltage angles of the load bus (θ_5) in function of λ 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.

Figure 10. Performance of the method for the IEEE-14 bus system: (a) voltage angles of the load bus (θ_4) in function of λ for contingency N-1, (b) P-V curve of pre (N-0) and post (N-1) contingency of the load bus 14, (c) number of iterations
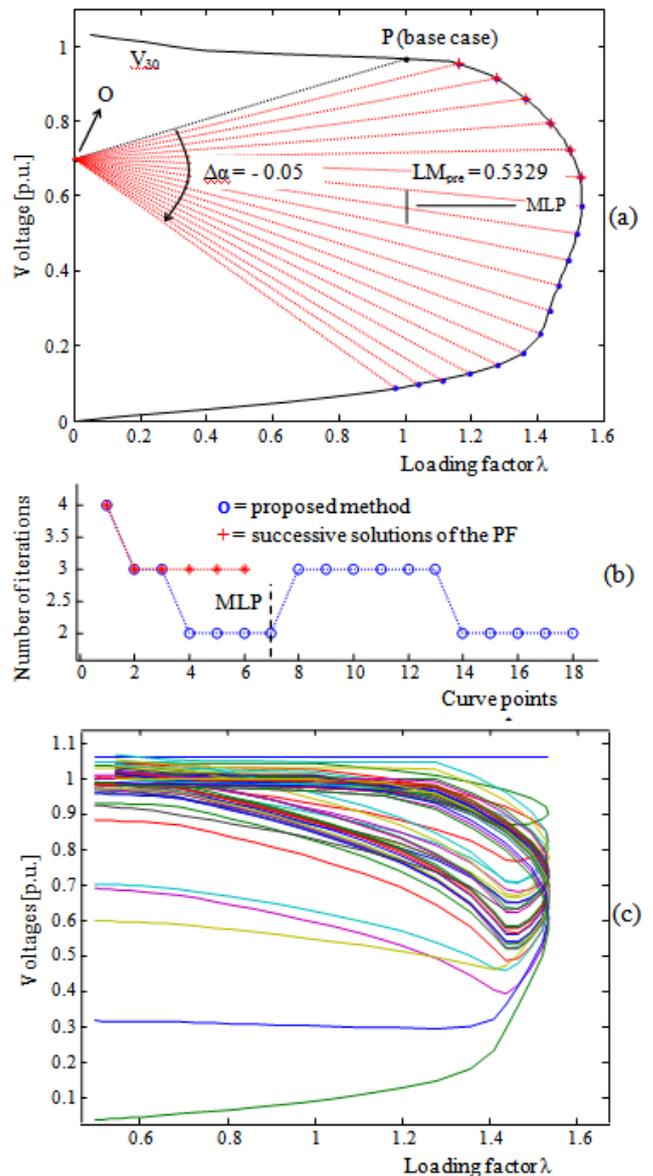
Figure 10 shows the IEEE-14 bus system with the contingency N-1 (outage of the TL between the buses 2 and 3, see Figure 5). In Figure 10(a) shows the complete tracing of the λ-θ curve of the generation bus 4 (PQ buses) of the system obtained with the proposed method, the LM_{post} is 0.2991. The red points of the bus 3 (θ_3) and the red points of the bus 14 (V_{14}, post-contingency P-V curve) in the Figure 10(b) are the respective points stored by the proposed method during the obtaining of the λ-θ curve of the bus 4 (θ_4).

It is observed in Figure 10(c) the number of iterations used to obtain the curve of the bus 4 (contingency N-1).

The tracing of any desired P-V curve is carried out with the corresponding desired values of voltage magnitude and loading factor, which are stored during the procedure used for tracing the λ-θ curve.

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 11. Performance of the method for the IEEE-30 bus system: (a) voltage magnitude of the critical bus (V_{30}) in function of λ, (b) number of iterations for the proposed method and conventional PF, (c) P-V curve of all system buses for contingency N-0

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 the number of iterations used to obtain the P-V curve of the critical bus 30 (contingency N-2).
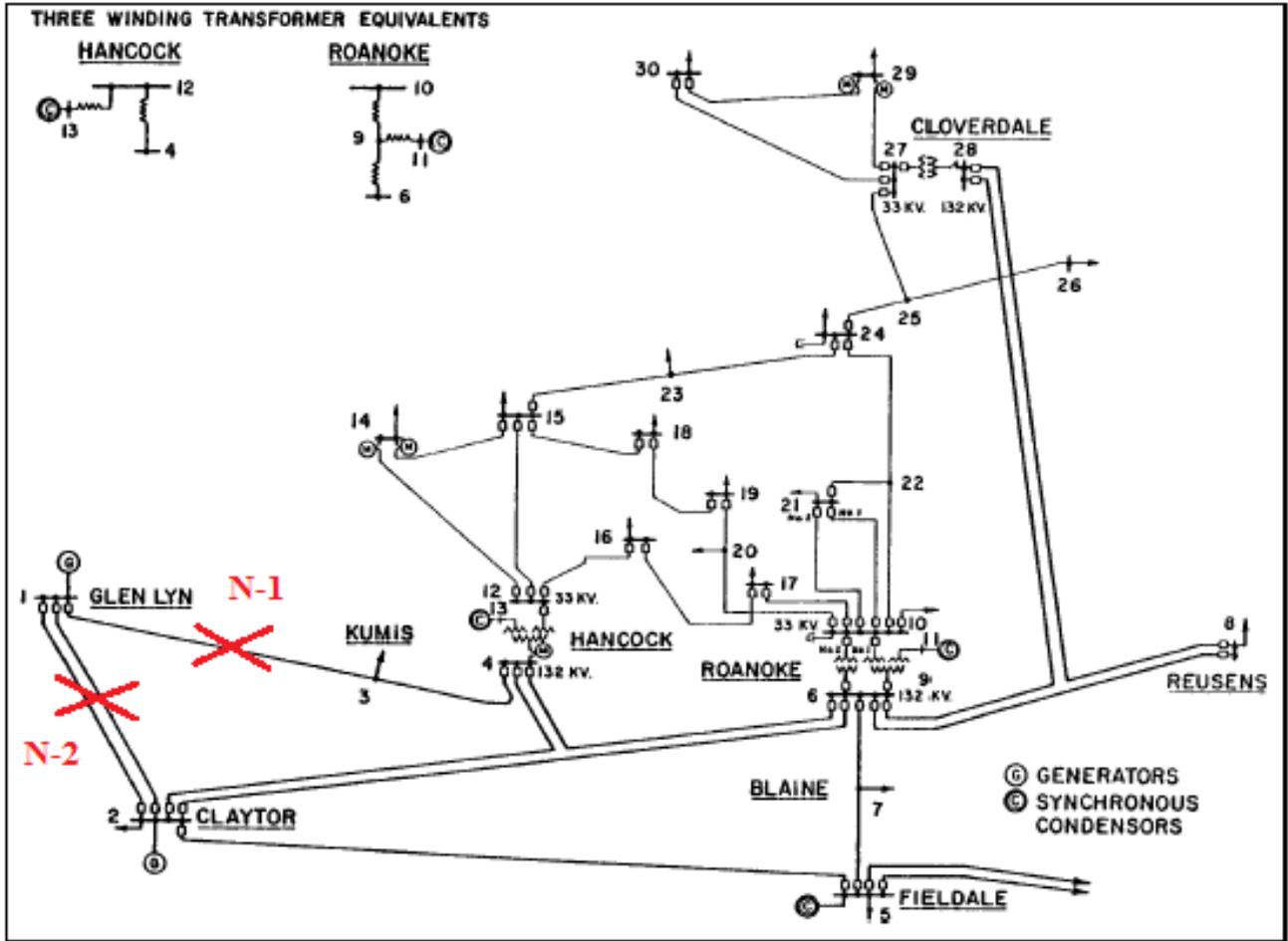

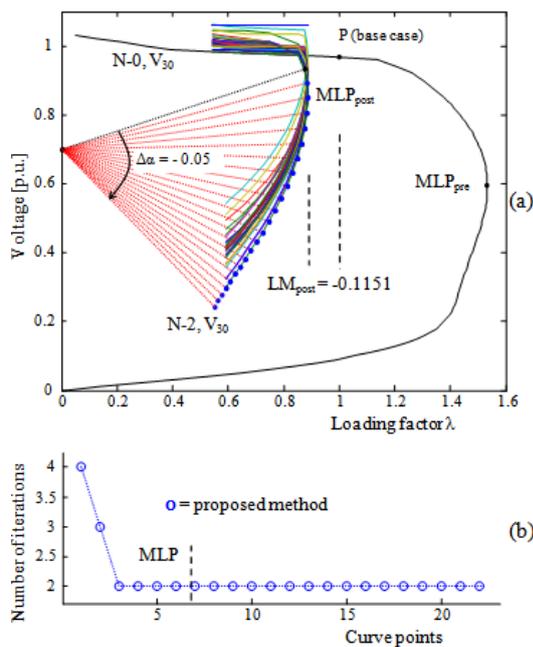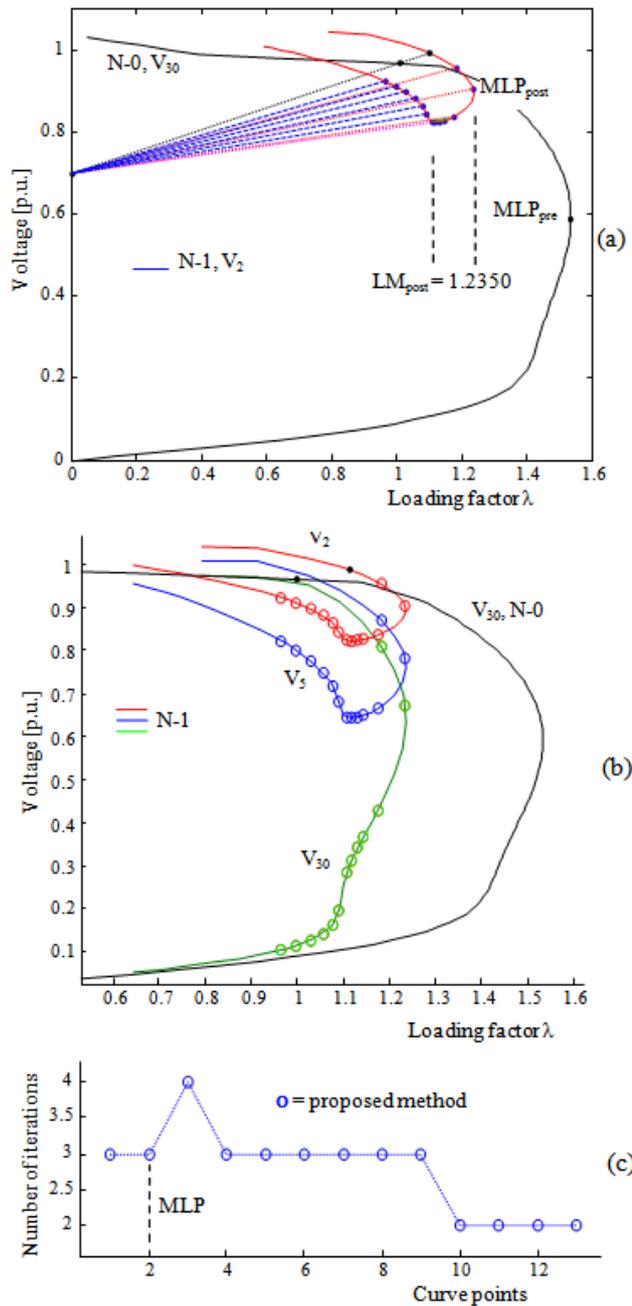**Figure 12**. Diagram of the IEEE-30 bus system with the contingencies N-2 and N-1

Figure 13. Performance of the method for the IEEE-30 bus system: (a) voltage magnitude of the critical bus (V_{30}) in function of λ 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 λ-θ curve of the critical bus under normal operating conditions of the IEEE-30 bus system, it may be noted that the tracing of the λ-θ 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., λ-θ will be the plan used for obtaining the P-V curve. Figure 15(b) shows the number of iterations used to obtain all the λ-θ curves of the IEEE-30 bus system of the Figure 15(c).
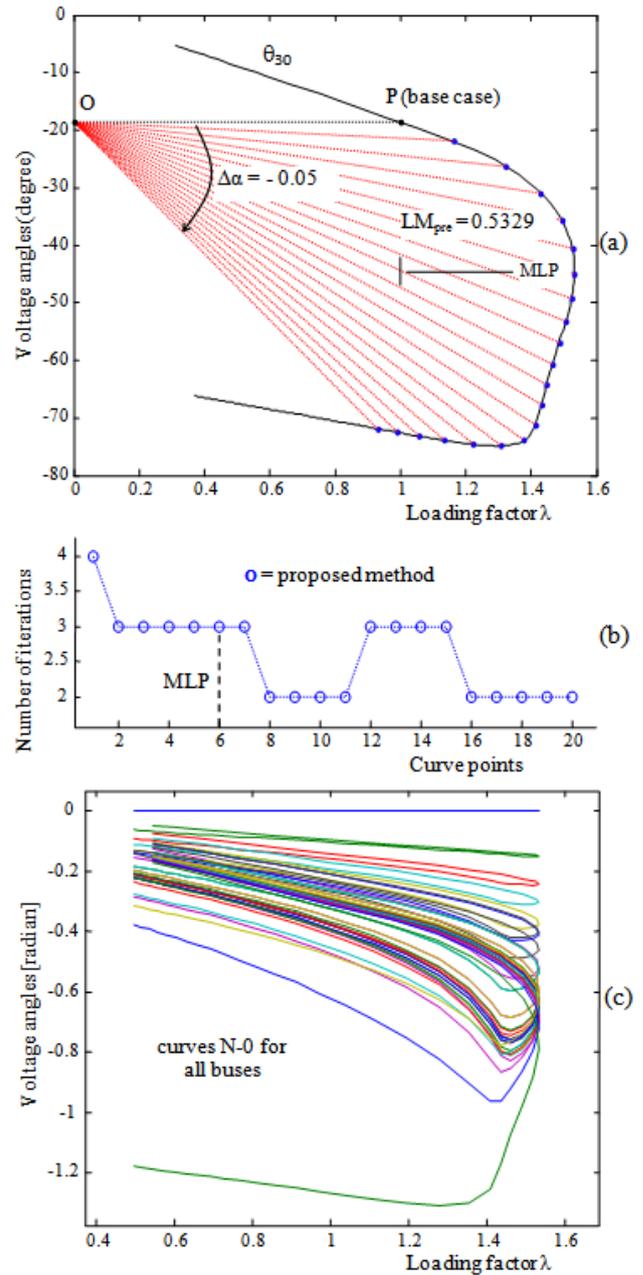
Figure 14. Performance of the method for the IEEE-30 bus system: (a) voltage magnitude of the generation bus (V_2) in function of λ for contingency N-1, (b) P-V curves of pre-contingency (N-0) and post-contingency (N-1) of the load buses 30 (green points), 5 (blue points) and 2 (red points), (c) number 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 λ-θ curve (lower and upper part of the λ-θ curve) of the load bus 3 (PQ buses) of the system with the contingency N-2, obtained with the proposed method, the LM_{post} is -0.1151 (negative margin, severe contingency). It is observed in the Figure 16(b) the points of the λ-θ curves of the buses 2, 3 and 30 stored during the obtaining of the curve of the bus 3 of the Figure 16(a) for the same contingency N-2 and Figure 16(c) shows the P-V curves of the buses 2 and 30, randomly chosen between the 30 buses of the system, also stored during the obtaining of the curve of the bus 3 of the Figure 16(a). Figure 16(d) shows

the number of iterations used to obtain the curve of the bus 3 (contingency N-2).

Figure 17 shows the IEEE-30 bus system with the contingency N-1. In Figure 16(a) shows the complete tracing of the λ-θ curve of the load bus 9 of the system with the contingency N-1, obtained with the proposed method, the LM_{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).
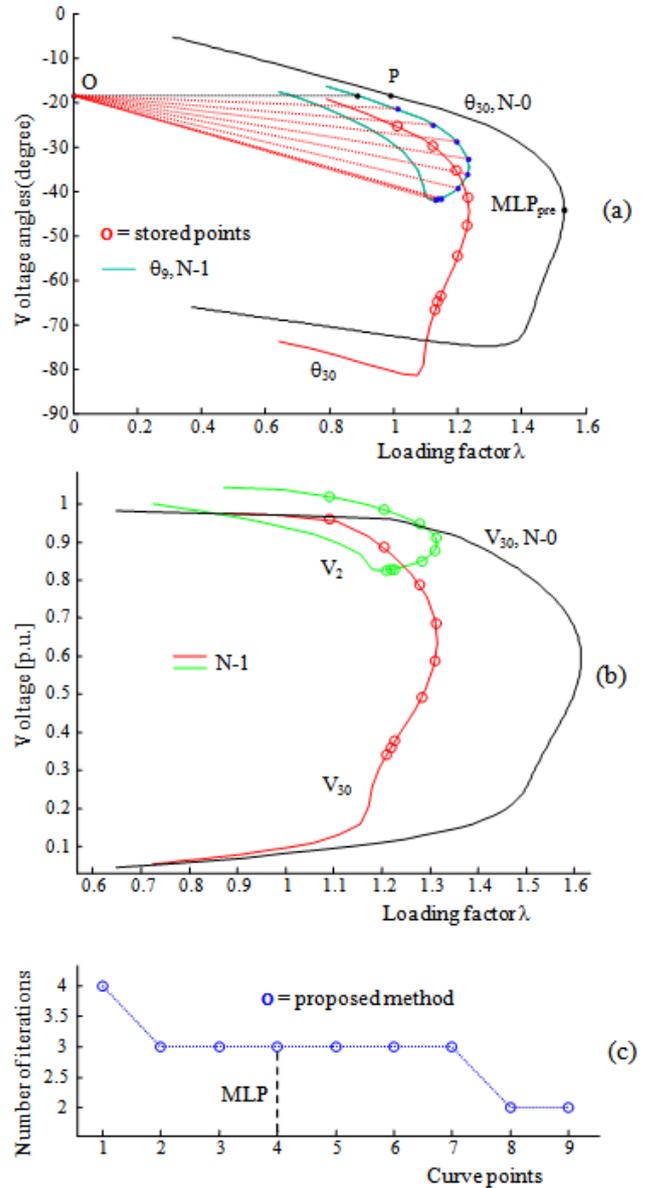

Figure 15. Performance of the method for the IEEE-30 bus system: (a) voltage angles of the critical bus (θ_{30}) in function of λ, (b) number of iterations for the proposed method, (c) P-V curve of all system buses for contingency N-0

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.
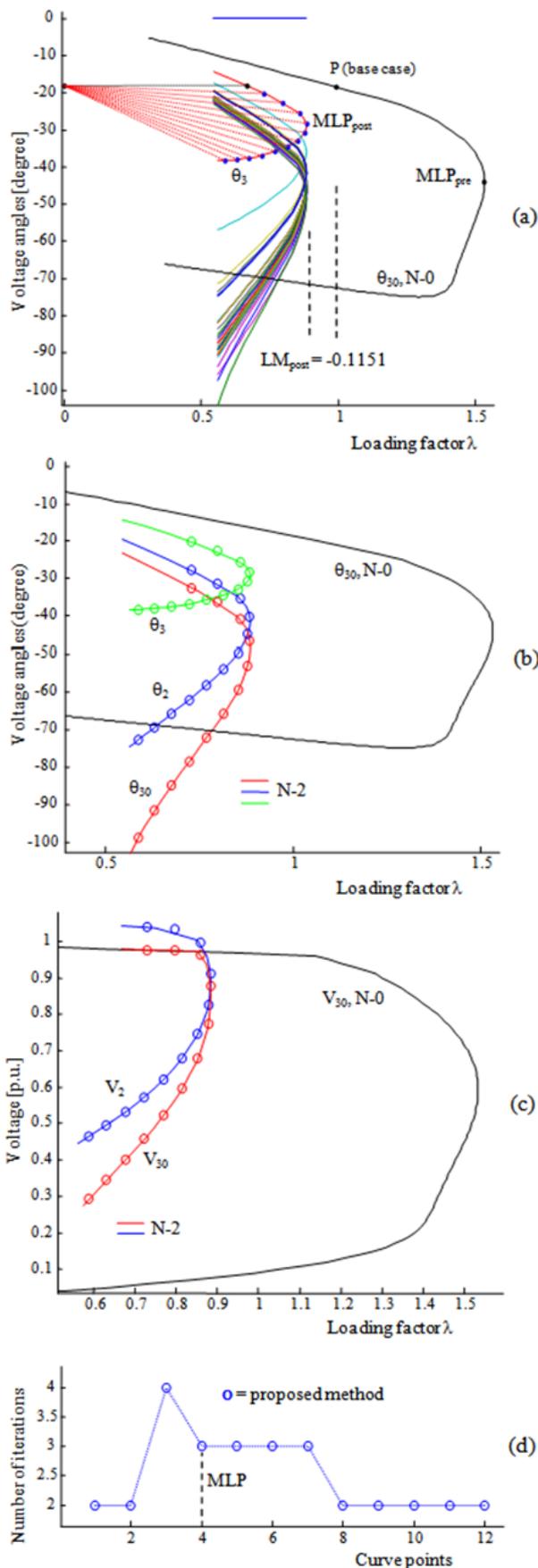
Figure 16. Performance of the method for the IEEE-30 bus system: (a) voltage angles of the load bus (θ_3) in function of λ for contingency N-2, (b) λ-θ curves of pre-contingency (N-0) and post-contingency (N-2) of the buses 3 (green points), 2 (blue points) and 30 (red points), (c) P-V curves of pre-contingency (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 (θ_9) in function of λ 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

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