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Assessment of branch outage contingencies using the continuation method

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ABSTRACT

This paper provides a contribution to the contingency analysis of electric power systems under steady state conditions. An alternative methodology is presented 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 parameterised 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 applicability and effectiveness of the proposed methodology have been investigated on IEEE test systems (14, 57 and 118 buses) and compared with the continuation power flow, which obtains the post-contingency loading margin starting from the base case solution. In general, for most of the analysed contingencies, few iterations are necessary to determine the post-contingency maximum loading point. Thus, a significant reduction in the global number of iterations is achieved. Therefore, the proposed methodology can be used as an alternative technique to verify and even to obtain the list of critical contingencies supplied by the electric power systems security analysis function.

1. Introduction

Modern electric power systems are becoming subject to an increase in the number of insecure contingency cases in which the power flow equations have no feasible solution. Both the static analysis and dynamic analyses have gained acceptance by the electric utilities and are now considered the two most common methods for analysing power system stability [1,2]. Long-term dynamic simulations are used for benchmarking contingencies, the validation of results for steady-state analysis and load shedding strategies [1–3]. However, the static analysis is used to reveal the loss of an equilibrium point of a system [3], to rapidly provide valuable information and to find critical areas for establishing preventive measures and the amount of control actions. The static and dynamic tools complement rather than compete with each other.

For a better use of generation resources and the transmission capacity, the voltage stability margins and control actions must be determined in the planning and in the real-time operation phases, not only for normal operating conditions (base case) but also for different operating points and contingency conditions. Therefore, it is common to run hundreds of contingency cases. Thus, for each contingency and several operating conditions, the LM must be obtained through P–V curve tracing [1–4]. The WSCC requires its member utilities to possess at least a 5% P–V margin under the worst single element contingency [1]. In [5], an asymptotic numerical method was used to solve branch outage continuation power flow (CPF) problems, and the method can be considered as a higher-order predictor without any corrections. In [6], three new schemes using Fuzzy Logic were developed to determine the maximum load margin. The iterative process can be started with random initialisation using the proposed Fuzzy Logic schemes, which reflects the superiority of the proposed schemes over the traditional Newton–Raphson technique.

The computation of the load margin (LM) using power flow (PF), or the Continuation Power Flow (CPF), is a very time-consuming process when a considerable number of contingencies need to be analysed. Over the past several years, many approaches have been proposed in this subject [9–24]. A large number of research studies have attempted to develop faster and more accurate algorithms for the computation of the post-contingency margin [7,8]. Many other methods have been proposed for voltage stability contingency

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screening and ranking [11,12]. The purpose of the algorithm is to accelerate the process of contingency analysis by identifying a relatively short list of critical contingencies from a large list of credible contingencies and rank them according to the degree of severity. In [13–15], methodologies to quickly calculate or estimate *P–V* margins by using a curve fitting technique that requires one to three PF solutions for each contingency were proposed. The main disadvantage of this method is that it relies heavily on the shape of the *P–V* curve, and thus it may fail when the tap limits of the OLTCs and the reactive power limits on the generators are considered. Moreover, a PF solution close to the MLP and a bus that presents a *P–V* curve with an appropriate geometry for curve fitting are required. The multiple PF solution method computes a first-order approximation of the systems margin using voltage gradients determined at a pair of PF solutions [16]. However, the test results obtained in [13] showed that the accuracy of the method is not satisfactory. In [17], a second-order approximation of the *Q–V* curve was proposed that requires three PF solutions to estimate the approximate margin to collapse. The method proposed in [10] uses the linear and quadratic sensitivities for a faster post-contingency *P–V* margin calculation. Although it is a very rapid method and could be reasonably good for contingency ranking, the results showed that the obtained margins are practically unacceptable for many analysed contingencies.

The convergence of the CPF is associated with the chosen parameter and the solution path. Therefore, in contingency analysis, depending on the variable chosen as the continuation parameter, the CPF cannot converge. In this case, using λ as a parameter is the cause of the PF divergence. In [25], a new, robust and efficient CPF was presented that uses branch admittance as a continuation parameter to evaluate the effects of the branch parameter variations rather than estimating or predicting the effects of their removal. The technique provides a robust second-stage verification tool. In the technique presented in [9] for LM determination, the pre-contingency maximum loading point (i.e., the MLP of the base case) is first computed using a CPF. Next, the post-contingency voltage magnitude of a chosen bus (the reference bus voltage) is estimated, and its value is fixed (adopted as parameter) while the loading factor is considered as a dependent variable in the CPF. According to these considerations, the contingency is applied, and the post-contingency maximum loading point (MLP_{post}) and the respective margin are computed. In the cases where the procedure fails to obtain a solution, the authors propose to use a damped Newton method to identify the systems post-contingency reference bus and to estimate its voltage magnitude, which is used as an estimate of the actual voltage at the MLP_{post} for the reference bus. However, if the post-contingency critical bus is not known a priori, the voltage stability margin determination can become a difficult and computationally heavy process [9].

In this paper, the features of the proposed alternative methodology for the static contingency evaluation are presented. The post-contingency loading margins are obtained starting from the pre-contingency (base case) maximum loading point (MLP) and by using the voltage magnitude of an appropriated bus as the continuation parameter during the transition from one *P–V* curve to another. First, the numerical difficulties that can appear when a PF or a CPF is used for the post-contingency loading margin determination are presented. Next, the proposed methodology used to assure the CPF convergence for the analysis of any transmission line (TL) or transformer contingency is presented. Finally, the results obtained with the new methodology for the IEEE test systems are presented and discussed. Even though a few cases required a few more iterations, the main advantages of the proposed methodology are the characteristic of guaranteeing the computation of the post-contingency solution and the significant reduction in the global number of iterations. Thus, the method can be used as an alternative technique to verify and even to obtain the list of critical contingencies supplied by the electric power systems security analysis function.

2. Formulation of the proposed continuation power flow

The objective of this section is to highlight the difficulties that can appear when using the PF and CPF methods for the static contingency analysis of electric power systems.

2.1. Characterisation of the problem

Fig. 1 presents the base-case *P–V* curve (curve 1) and the post-contingency *P–V* curves for the outage of a transmission line of a system. Consider the system operating at point "P" in the pre-contingency curve (case base). From the loading margin (LM) definition, the system presents a positive LM (LM > 0). Three contingencies will be analysed: the first one is related to the positive LM (curve 2) of the operating system and the two others are under negative LM conditions (curves 3 and 4).

If the system loading (λ) of the base case is maintained fixed, i.e., λ is considered as a parameter, in the case of curve 2, the system will remain stable and will operate at point "A". However, for both curves 3 and 4, it will collapse because there is no post-contingency feasible solution for this λ and either the PF or CPF will diverge. Starting from the solved base case, the conventional PF or the CPF using λ do not converge to a solution because the post-contingency MLP is smaller than the MLP of the base case operating point ($\lambda = 1$), i.e., in the base case, there will be no local solution to the PF equations when the network faces the transmission line outage. Therefore, for the cases where the LM is negative, 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. Thus, using the CPF parameterised by λ, the LM determination is possible only for curve 2, and the determination of the other two LM is not possible.

Although both the conventional PF and the CPF using λ as the parameter do not converge to a solution, there are no guaranties that this situation is due to either a bad initial voltage setting, a singularity (MLP), a deficiency of the numerical method, the existence of multiple solutions, or unsolvability for the desired operating point. The user has to resort to either a trial and error process or to using some heuristic techniques to determine which parameters

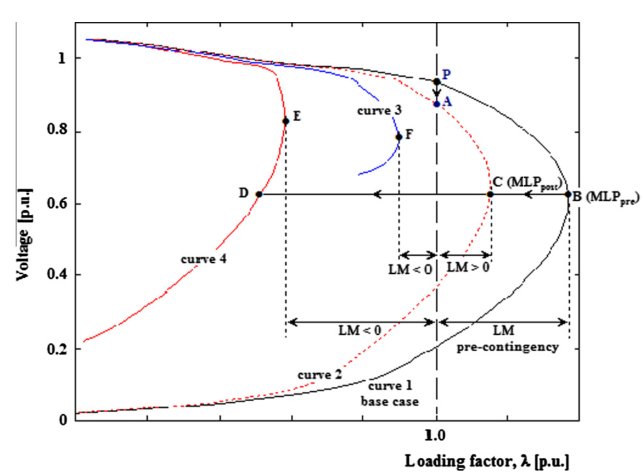

Fig. 1. P-V curves for the base-case (pre-contingency) and for the outage of transmission lines.