Journal of Industrial Technology 17(1), 2008, 181-190

STEADY-STATE VOLTAGE STABILITY ANALYSIS USING CONTINUATION POWER FLOW : A REVIEW

J. Jasni, H.Hizam, M.Z.A Kadir, N. Mariun, S. Bahari
Department of Electrical and Electronics, Universiti Putra Malaysia,
43400 UPM Serdang, Selangor, Malaysia
(jas@eng.upm.edu.my)

ABSTRAK : Aliran kuasa penerusan boleh ditafsirkan sebagai penyelesaian aliran kuasa, yang mana digunakan untuk menganalisa kestabilan sistem kuasa pada keadaan normal dan gangguan. Tujuan utama aliran kuasa penerusan ialah untuk mencari kesinambungan penyelesaian aliran kuasa untuk perubahan beban yang diberikan. Walaupun kaedah ini mempunyai beberapa kelemahan, ramai penyelidik telah mendapati bahawa kaedah ini masih merupakan kaedah yang baik untuk menyelesaikan masalah yang dihadapai oleh kaedah sebelum ini (Aliran Beban Newton-Raphson dan Fast Decoupled). Langkah-langkah untuk penerusan, perubahan parameter dan kebolehpercayaan pada sistem penerusan ini masih lagi menjadi tandatanya. Kertas kerja ini membincangkan beberapa isu termasuklah keperluan, permintaan dan pengharapan pada aliran kuasa penerusan ini. Beberapa penyelesaian yang telah diajukan oleh penyelidik sebelum ini telah dibincangkan.

ABSTRACT : Continuation power flow can be described as a power flow solution, which is used to analyze the stability of power system under normal and disturbance conditions. The main purpose of Continuation Power Flow is to find a continuity of power flow solution for a given load change. Although this approach has several deficiency, many researchers found out that this is still a better approach to cater the problem faced by the previous method (Newton-Raphson dan Fast Decoupled Load Flow). The continuation step, parameter variation and the reliability of the system are still in question. This paper discusses several issues including the needs, demands and expectations of continuation power flow. Several solutions have been proposed by the previous researchers is been discussed.

KEYWORDS : Bifurcation, contingency, continuation power flow, parameter variation, voltage stability

INTRODUCTION

Power system involves generation, transmission and distribution. The major concern of the power utilities is to maintain the supply to customers without any failure. The power flow solution, which is closely related to voltage stability, is an important tool, which is needed to calculate the total power that needs to be transferred to customers. Since voltage stability determined the quality and availability of power, it has been recognized as the main issue for power system utilities.

Voltage stability can be described as the capability of the system to maintain the adequate voltage under normal operating conditions and after the disturbances arise. Massive system interconnections, demands increase, insufficient generation and transmission expansion, economical and environmental factors have led power system to operate with its equipment very close to their limits. Voltage instability and voltage collapse situation become very likely to occur, imposing important limitations on power system operation. According to C.W. Taylor (1994), voltage instability or collapse is a dynamic process. He also mentioned that voltage instability is the absence of voltage stability and results in progressive voltage decrease or increase.

The conventional power flow computation began with Gauss-Seidal method. Then the alternative Newton-Raphson iterative method was used which is reliable, computationally faster and more economical in storage requirement (Stevenson, 1982). Most researchers found that the Jacobian of the Newton-Raphson power flow calculation became singular at the steady state voltage stability limit (Ajjarapu and Christy, 1992). The stability limit or critical point is defined as the point where the power flow Jacobian is a singular. Therefore when the power flow approaches the critical point, it will diverge and give a large error.

The saddle node bifurcation (SNB) is one approach that can be used to solve this singularity problem. The Jacobian can reach the SNB in many ways, such as increase the impedance in a key tie line, increase the generation level at a generator with weak transmission while decreasing generation at all other generators, increase the load at a single bus or increase the load at all buses. But this method requires modification for solving singularity problem. For example when the critical point differs from the SNB point, the critical point may not provide a security measure and the curve may not provide a forecast of the system trajectory.

Continuation power flow was introduced to solve this singularity problem. The continuation power flow can be described as a power flow solution that can maintain the stability of the power system under normal and disturbances conditions. Therefore the main purpose of Continuation Power Flow is to find the continuity of power flow solution for a given load change.

BACKGROUND NEEDS, DEMANDS AND EXPECTATIONS OF CPF

Background

Modern living condition and the power demand from industry contribute to the increase in electricity usage. Because of that unpredicted bad situation may occur in future. Power flow is the key tool in power system planning and operation. Previously the Newton-Raphson method was used for power flow calculation. Research has proven the Jacobian matrix of the power flow analysis becomes singular at the voltage stability limit. Consequently, conventional power flow algorithms are prone to convergence problems at operating condition near the stability limit.

The use of continuation power flow analysis can solve this problem by reformulating the power flow equations so that they remain well-conditioned at all possible loading conditions (Ajjarapu and Iba *et al.,* 1991/1992). This solution allows the system to be stable at stable and unstable equilibrium points. Researchers have proved that this continuation method can solve the singularity problem faced by Newton-Raphson method. However after some modifications, the effectiveness and efficiency of these methods are doubtful. When the continuation step is large the computational effort becomes heavier (Canizares, 1996). This situation can delay the process in the system. Voltage collapse can occur due to the computational delay. From the conventional continuation method the curve that is generated is not proven to remain close to the actual solution curve. If the solution curve is not proven to be close to the solution curve, the solution can be questionable. Therefore the reliability of the system is still in question. Another aspect that needs to be considered is the parameter (load or voltage) variation. Before this, in the previous research the determination of the parameter variation was done by the operator. This situation might not be possible if the parameter that varies is not the one being determined by the operator. Many researchers concentrate in doing this for static analysis. In real life the dynamic analysis is of more concern. No research is done on the robustness of the continuation system. The robustness of the system is important to ensure that the system works properly. Without proving the robustness of the system people can argue whether the system is reliable or not. The approach should cater for all the contingencies that might occur and not concentrate only on what had happened before.

The power providers and researchers need to find the best way to tackle the contingencies, which are unpredictable. The robust method is needed to ensure the continuity of power flow. The contingencies of the system should be determined and fixed as fast as possible. The main problem to be discussed here is how to prepare a method that can cater for all contingencies whilst reducing computational effort, robust system, more reliable, ensure the curve is near to solution curve and finally ensure the continuity of the power flow.

Review of Continuation Power Flow

In early 1990's researchers proposed a new method to replace conventional Newton-Raphson for calculation of the power flow. They believed that the conventional method has a convergence problem when it reaches the critical loading point. This is due to singularity problem in the Newton-Raphson method when it reaches ill conditioned point (Ajjarapu, 1992). From Newton-Raphson, the so-called nose curve for stability was drawn using saddle-nose bifurcation step.

i) Homotopy Continuation Method

Kenji Iba *et al* (1991) proposed a homotopy continuation method to calculate the critical loading continuation with nose curve. They showed that the nose curve, which denoted the relationship between total load and system voltage was calculated by a new approach based on the Homotopy continuation method. This method is based on the conventional Newton-Raphson load flow calculation. Although the author claimed that it can overcome the numerical difficulties related with the singularity of the Jacobian matrix, the problem is not fully solved and the system is still facing the singularity problem. For the convergence to critical condition, 20 to 30 steps are needed by the system, provided that the step size is appropriately selected. The parameter that varies is then fixed to the load demand.

The principle of the proposed method is a homotopy parameter t, which implies load and generation growth, is introduced to the Newton-Raphson-based load flow formula. The expression $Ys(t) = Yso + tYd$ describes the loading pattern as linear above base load Yso with the homotopy parameter t following an arbitrary direction specified by the elements of Yd with real and reactive power entries. The upper or lower sides of the nose curve are obtained by solving the load flow equations for $Ys(t_i)$, i=1,2,....,n, where step size $\Delta t_i = t_i - t_{i-1}$ is selected mathematically using the Homotopy Continuation Method. Therefore, the cut-and-try or go-and-back procedure is not applied. Both sides of the curve can be obtained by combining the method for finding multiple load flow solutions described in Iba *et al*, 1991. The critical loading condition is found as a terminal point of the curves. However this approach does not truly solve the singularity problem.

ii) UWPFLOW

Ajjarapu *et al* (Ajjarapu, 1992) proposed a tool in finding the continuation of power flow solution starting from the base load until reaching the steady-state voltage stability limit of power system called UWPFLOW.

This paper presents the capability and usefulness of continuation power flow in the power system. The main feature of this method is it remains well conditioned at and around the critical point. As a general principle, this method employs a predictor-corrector scheme to find the solution path of a set of power flow equations, which have been reformulated to include a load parameter. Starting with the known solution, it then uses the tangent predictor to estimate a subsequent solution corresponding to a different value of the load parameter where this parameter variation is being fixed to the reactive power.

The authors proposed a tool for steady state voltage stability analysis using Continuation method. This paper presents a method for finding a continuum of power flow solutions starting at some base load and leading to the steady state voltage stability limit or known as critical point (Ajjarapu, 1992). (Ajjarapu 1992) demonstrates how slightly reformulating the power flow equations and applying a locally parameterized continuation technique can avoid singularity in the Jacobian. This continuation power flow employs a predictor-corrector scheme to find a solution path of a set of power flow equations that have been reformulated to include a load parameter. It starts with known solution and uses a tangent predictor to estimate a subsequent solution corresponding to a different value of the load parameter. This estimation is then corrected using the same Newton-Raphson technique employed by a conventional power flow. The local parameterization provides a means of identifying each point along the solution path and plays an integral part in avoiding singularity in the Jacobian. The assessment of this method had been done only to linear load model. To make this assessment more accurate for voltage stability performance the nonlinear model needs to be incorporated into the process.

iii) Point of Collapse and Continuation

Canizares and Alvarado (1996) proposed a combination of two methods; point of collapse and continuation method; used in voltage stability studies to determine the bifurcation points. These two methods were shown to be computational feasible and a means to determine an acceptable load increment before facing voltage collapse in power network. Canizares and Alvarado also introduced a new method of determining energy functions for power system models, particularly when dc links are included. Without mentioning the reliability of the continuation method, he stated that the system will run under continuation method until it comes to saddle-nose, before turning to the point of collapse method. Point of collapse (PoC) and continuation methods for large AC/DC systems shows the implementation of PoC and continuation method for computation of voltage collapse. The author did mention the advantages of continuation power flow; producing voltage profile, but it also creates unstable equilibrium points that can be useful for system stability analysis, able to detect immediate instabilities due to reactive power limits, although in practice these points and the bifurcation are very close (Canizares, 1996). The disadvantage here is the system needed to run under two different methods and it needs more computational effort. From the results, it can be found that convergence problems are observed when using continuation method due to sharp turning point. The time consumed is more than seven seconds. The authors state that continuation methods have the advantage of producing voltage profiles and as a result yield unstable equilibrium points that can be useful for system analysis. Another advantage of the continuation method is that they are able to detect immediate instabilities due to reactive power limits, although in practice these points and the bifurcation are very close (Canizares and Alvarado 1996).

In 1993, they published another paper on bifurcations, voltage collapse and load modeling (Canizares and Alvarado, 1993). They discussed relationship between bifurcation and power system stability through a thorough analysis of several examples, to clarify some ideas regarding the usefulness and limitation of bifurcation theory in network studies and operation. They also discussed the limitation of saddle-nose bifurcation.

iv) CPFLOW

In 1995, Chiang *et al* proposed another computer package called CPFLOW (Continuation Power Flow) to overcome problem of UWPFLOW. This CPFLOW is a comprehensive tool for tracing power system steady state stationary behavior due to parameter variations. The main differences between the previous works are the level of modeling capability, the level of applicability (through different schemes of parameterizations) and the computational speed and reliability (through different predictor, correctors and step-size control) (Chiang 2002; Chiang *et al.*, 1995). The authors have developed a new performance index based on the center manifold voltage collapse model. The disadvantage of this tool is it does not give appropriate treatment of physical constraint. It is constrained by the delicate balance between speed and robustness. Therefore the trade-offs between robustness and minimum computational effort is still open for further research.

CPFLOW is also being used to investigate the installed real power transfer capability of a large-scale power system under a proposed multi area interchange (Flueck, 1996). The paper shows the studies of real power transfer capability under multi area interchange schedule of large-scale power systems.

This CPFLOW can generate P-V, Q-V and P-Q-V curves with the capability of the controlling parameter λ (loading parameter), where λ can be either general busloads or real power generation at P-V buses or area loads or real power generation at P-V buses or system loads or real power generation at P-V buses (Chiang *et al*, 1995). For this system authors proposed to use two-step of predictor, tangent method and secant method. The key issue here is whether a predictor-corrector continuation method can be designed wherein the predictor point produced by the predictor remains close to the solution curve for robustness and yet overall amount of computational effort required to solve a given problem is minimized.

v) Others

In 1995, results from continuation power flow have become a benchmark for contingency ranking and screening as shown by Ejebe *et al*. This approach is used for contingency screening and ranking of voltage stability analysis in power system. This shows that continuation is one of the good approaches in voltage stability study for credible contingencies.

Souza *et al*(1996) have compiled several techniques to perform voltage collapse computations based on network partitioning and voltage stability indices to accelerate the computation of voltage collapse points using continuation technique. The authors proposed the continuation method for the analysis of fast computations of voltage collapse points. The system is fast but need network partitioning before performing the continuation method.

Scott *et al*(1997) have demonstrated that effective contingency analysis for voltage collapse can be done by computing the load margin sensitivities for a nominal nose curve (Scott, 1997). Unfortunately Scott found that the slowest step in the procedure is continuation to find the nominal nose.

In 2001, Song *et al*(2001)introduced a new concept in determination of interface flow using the modified continuation power flow in voltage stability analysis. This technique is to trace interface flow-voltage curves by applying continuation method and the parameter variation is active power.

Mori *et al*(2002) made use of the langrage polynomial interpolation formula as the predictor of the predictor-corrector method and rule-based step-size control to speed up the computational time. The author proposed a new continuation power flow method with the non-linear approximation predictor of the Lagrangeís polynomial interpolation formula. The authors have modified CPFLOW to improve the performance with regards to the robustness and computational efficiency of the algorithm (Mori, 2002). The authors manage to compare the computational efficiency using four methods, the Homotopy, Ajjarapu-Christy method, CPFOW and proposed method. However the robustness of the method and how close it is to solution curve is still not answered.

In 2002, Chen *et al.* come out with a brief review of the recent development in voltage stability studies in computing fold bifurcation (Chen, 2002) The authors suggested test function as a solution that can provide useful indicators to determine if a fold point has been reached but are not useful in predicting the index (Chen, 2002). Later Chen et al proposed combination of Q limits index and a performance index to achieve computational efficiency and index reliability (Chen, 2003). The authors claimed that this approach is fast because the continuation step size is efficiently guided by a Q limit index that can pinpoint the limit reaching points much better than the conventional method. This has been shown in the experiments for IEEE systems.

New algorithms to compute singular points and singularity-induced bifurcation points of differential algebraic equation for multimachine power system model have been proposed by Ayasun *et al*, (2004). These algorithms are for determining the singular point only and does not check the stability of the system. The authors also give suggestion to include energy function approach as future work.

In 2004, Flueck *et al* proposed a new technique for evaluating the severity of branch outages contingencies based on two-parameter continuation. This approach uses two parameter continuation technique for evaluating severe branch outage contingencies whether they correspond to SNB points or breaking point, given a power system operating point, a load demand forecast and a generation dispatch demand (Flueck, 2004).

Later Yorino *et al.* (2005) proposed a new continuation power flow method for tracing QV constraint exchange points (CEP) at which generators regulating voltages hit the reactive power limits. This approach is based on a predictor/corrector scheme to obtain CEPs in succession. For this method step length selection become heuristic for the selection of farther points existing near a specified distance of λ SNB calculated by PoC. The problem with this method is that it requires heavy computations. The result shows that the method can predict when and where the individual generator hits the Q-limit under expected loading condition with Q-limit as the continuation parameter.

Echavarren *et al.* (2006) proposed a power flow solvability identification and calculation algorithm. This algorithm is based on continuation and optimization algorithm to detect power flow unsolvability. The author also used least square minimization based Langrange multipliers estimation. This method considers only the upper equilibrium point. The algorithm is the combination of three different techniques. Therefore it requires large computational effort and convergence margin is subject to the augmented power flow equation.

CONCLUSION

Previous researches showed that continuation power flow can be a good tool to run power flow. Many methods or strategies have been used in order to employ continuation power flow. The continuation method can avoid ill-conditioning problems and avoid the usual convergence problems seen in AC power flow methods near the turning point. Many analyses can be done such as stability analysis and contingency analysis. However, the questions are whether these method can deal with all credible contingencies and how much time the systems need in order to solve all the cases and how reliable the systems are. These need to be answered in order to make the continuation power flow more useful.

As mentioned before, the main purpose of Continuation Power Flow is to find the continuity of the power flow solution when there is load changing in the power system. The continuation step, parameter variation and the reliability of the system are still in question. Several things such as computational effort, memory of the computation and how near to the solution curve still need to be considered and proven before this method can be said as the best to solve the voltage stability problem.

REFERENCES

Ajjarapu, V., Christy, C. "The Continuation Power Flow : a Tool for Steady-State Voltage Stability Analysis." IEEE Trans. Power System 7, no. 1(1992):304-311

Alves, D.A., da Silva, L.C.P., Castro, C.A., da Costa, V.F. Continuation Load Flow Method Parameterized by Transmission Line Power Losses, IEEE Transactions on Power System, 2000:763-768.

Alves, D.A., Luiz, C.P, Castro, C.A., de Costa, V.F. Alternative Parameters For The Continuation Power Flow Method. Electric Power System Research, 66 (2003):105-113.

Ayasun, S., Nwankpa, C.O., Kwanty, H.G.. Computation of Singular and Singularity Induced Bifurcation Points of Differential-Algebraic Power System Model. IEEE Transaction On Circuits And System: Regular Papers, Vol 51, No 8 (2004): 1525-1538

Canizares, C.A. and Alvarado, F.L. "Description on Uwpflow:continuation and Direct Methods to Locate Fold Bifurcations in Ac/dc.facts Power Systems." In Power and Energy Systems Group University Waterloo, Canada,

Canizares, C.A. and Alvarado, F.L. "Point of Collapse and Continuation Methods for Large Ac/dc Systems." IEEE Trans. Power System 8, no. 1 (1993): 1-8

Chen, K., Hussein, A., Bradley, M.E., Wan, H. "A Performance-Index Guided Continuation Method for Fast Computation of Saddle-Node Bifurcation in Power Systems." IEEE Transactions on Power Systems 18, no. 2 (2003): 753-60.

Chen, K., Hussein, A.,Wan H.B. On a Class of New And PracticalPerformance Indexes For Approximation of Fold Bifurcations Of Nonlinear Power Flow Equation. Journal of Computational And Applied Mathematics 140(2002):119-141

Chiang, H.D. "Cpflow for Power Tracer and Voltage Monitoring:final Report." Power System Engineering Research Centre, 2002.

Chiang, H.D., Flueck, A.J., Shah, K.S., Balu, N. "Cpflow: A Practical Tool for Tracing Power System Steady-State Stationary Behavior Due to Load and Generation Variations." IEEE Trans. Power System 10, no. 2 (1995): 623-34.

Echavarren, F.M., Lobato, E., Rouco, L.. A Power Flow Solvability Identification and Calculation Algorithm Electric Power Systems Research 76 (2006): 242-250

Flueck, A.J. and Qiu, W (2004). New Technique for Evaluating The Severity of Branch Outage Contingencies based on Two-Parameter Continuation. IEEE Transactions on Power Systems, 2004: pp 1-7.

Iba, K., Suzuki, H., Egawa, M., Watanabe, T. "Calculation of Critical Loading Condition With Nose Curve Using Homotopy Continuation Method." IEEE Trans. Power System 6, no. 2 (1991): 548-93

Jr, W.D.Stevenson. Element of Power System Analysis 4 ed. UK: McGraw-Hil, 1982

Mori, H.,Yamada, S. "Continuation Power Flow With the Nonlinear Predictor of the Lagrange's Polynomial Interpolation Formula." Paper presented at the Transmission and Distribution Conference and Exhibition 2002:Asia Pacific

Scott, G., Ian, D., Fernado, L.A. Contingency Ranking for Voltage Collapse via Sensitivities from a Single Nose Curve, IEEE Power Engineering Society Summer Meeting, Berlin Germany, July 1997, paper SM97-707

Song, H., Kim, S., Lee, B., Kwon, S.H., Ajjarapu, V. Determination of Interface Flow Margin Using The Modified Continuation Power Flow in Voltage Stability Analysis, IEEE Proceeding Transmission. Distribution, vol 148, No 2, March 2001:128-132

Souza, Antonio Carlos Zambroni de Souza. "New Techniques to Efficiently Determine Proximity to Static Voltage Collapse.", University of Waterloo, 1996.

Souza, Antonio Carlos Zambronide. "New Techniques to Efficiently Determine Proximity to Static Voltage Collapse.", University of Waterloo, 1996

Taylor, C.W. Power System Voltage Stability US:McGraw Hill, 1994

Yorino, N., Li, H.-Q., Sasaki, H. "A Predictor/corrector Scheme for Obtaining Q-Limit Points for Power Flow Studies." IEEE Transactions on Power Systems 20, no. 1 (2005): 130-37.

JOURNAL OF INDUSTRIAL TECHNOLOGY

SCOPE

The journal is published twice a year by SIRIM Berhad. It reports on a wide range of industrial research findings in science and technology, research identified in the Industrial Master Plan 2, the Promotion of the Investment Act (revised 1998) and other strategic technologies approved by the government. Such research include: Advanced Materials, Advanced Manufacturing, Biotechnology, Chemical Technology, Environmental, Electrical & Electronics, Energy and Multimedia.

TYPES OF CONTRIBUTIONS

We are interested in unpublished work on original research, review articles, short communications and Science and Technology policies. The paper should be written in English or Bahasa Malaysia, but abstracts in both languages should be given.

SUBMISSION OF ARTICLES

General. Please submit three copies of the manuscript (the original and two copies) and a diskette written in Microsoft Word (Helvetica; 11pts). Papers should be typewritten double spaced on one side of A4 paper, and with a margin of one inch all round. Manuscripts should not normally exceed 5,000 words and specialist terminology and footnotes should be avoided.

Title Page (separate page). The title should be concise, descriptive and preferably not exceed 15 words. The name(s) of the author(s), affiliation(s) and full address(es) should be included.

Abstract. The abstract should precede the article and, in approximately 150 words, outline briefly the objectives and main conclusions of the paper. It should be followed by no more than 10 keywords (separated by commas) identifying the matter for retrieval systems.

General Form. Papers reporting original research should be cast in the form: Introduction - Materials and Methods - Results and Discussion - Conclusion - Acknowledgements - References. Reviews and short communications need not follow this arrangement.

References. References in the text should be denoted by giving the name(s) of the author(s) with year of publication in parentheses. If there are more than two authors, it is in order to put "*et al*" after the first name.

Bibliographical references should be listed in alphabetical order of author at the end of the paper. The following style should be adopted:

Journal citation: Chan, T.K., Herlina, S. and Ruangsap, B. (1993). Cloning of promoter sequences from *Escherichia coli. J. Mol. Biol.* **45**: pp 567-575.

Book: Chan, T.K. (1992). Plasmids of enterobacteria. In: *Pathogenesis of bacterial infections*, ed. Ramirez, A. and Aquino, S., Protea Press, Kuala Lumpur, pp 235-245.

Report: Dubin, F.S., Mindell, H.L. and Bloome, S. (1976). *How to save energy and cut costs in existing industrial and commercial buildings.* An energy conservation report, May, Noyes Data Corporation, Park Ridge, USA.

Illustrations. All illustrations should be photographed in sharp black and white, high-contrast, glossy prints. Illustrations (including formulae) generated using computer programs should be saved in JPEG/TIFF format, they may also be scanned (300 dpi). Graphs and diagrams should be large enough to permit 50% reduction and be numbered consecutively in the same order as in the text, where they should be referred as "Figure" and not "Fig.". Legends for figures should be listed consecutively on separate sheet of paper.

Tables. These should have short descriptive titles, be self-explanatory and typed on separate sheets. They should be as concise as possible and not larger than a journal page.

Units, symbols, abbreviations and conventions. These must follow SI units.

The Editor reserves the right to make literary corrections and adjust style for uniformity.

Review. All manuscripts will be refereed for relevance and quality. Authors are required to submit the names and addresses of two qualified reviewers.

Proofs. One set of proofs will be sent to the main author to be checked for printer's errors, and it is the responsibility of the author to submit corrections to the Editor.

Reprints. Twenty copies of Reprints will be given free to the main author. Additional reprints may be ordered when proof is returned.