

A New and Fast Method for Preventive Control Selection in Voltage Stability Analysis

Objective:

Preventive control approach for voltage stability improvement using voltage stability constrained optimal power flow based on static line voltage stability indices.

Abstract:

Voltage stability improvement is a challenging issue in planning and security assessment of power systems. As modern systems are being operated under heavily stressed conditions with reduced stability margins, incorporation of voltage stability criteria in the operation of power systems began receiving great attention. This study presents a novel voltage stability constrained optimal power flow (VSC-OPF) approach based on static line voltage stability indices to simultaneously improve voltage stability and minimise power system losses under stressed and contingency conditions. The proposed methodology uses a voltage collapse proximity indicator (VCPI) to provide important information about the proximity of the system to voltage instability. The VCPI index is incorporated into the optimal power flow (OPF) formulation in two ways; first it can be added as a new voltage stability constraint in the OPF constraints, or used as a voltage stability objective function. The proposed approach has been evaluated on the standard IEEE 30-bus and 57-bus test systems under different cases and compared with two well proved VSC-OPF approaches based on the bus voltage indicator L-index and the minimum singular value. The simulation results are promising and demonstrate the effectiveness of the proposed VSC-OPF based on the line voltage stability index.

Introduction:

During recent years, the planning and the operation of large interconnected power systems while improving system stability and security have become important concerns in the daily operation of modern power networks. Therefore there is a renewed interest in developing optimal power flow (OPF) models that incorporate additional constraints and new objective functions to enhance the security of electricity markets. As several blackouts around the world have been related to voltage phenomena [1, 2], much more interest has been devoted by planning engineers to the voltage stability constrained OPF (VSC-OPF) problem. The present paper deals with including the voltage stability issue in the conventional OPF to effectively improve system voltage stability as well as to reduce power losses when subject to unexpected contingencies such as generation outages, tripping of a

transmission line in a heavily loaded system or an unpredictable increase in load demand.

Line VSI:

The VCPI was proposed by Moghavvemi and Faruque that has rigorously demonstrated its accuracy and reliability on the standard IEEE test systems with different load nodes. This indicator is adopted in our study to investigate the stability of each line of the system by determination of the critical line referred to a bus. The VCPI index is based on the concept of maximum power transferred through the lines of the network as presented in Fig. 1 and it is defined as follows.

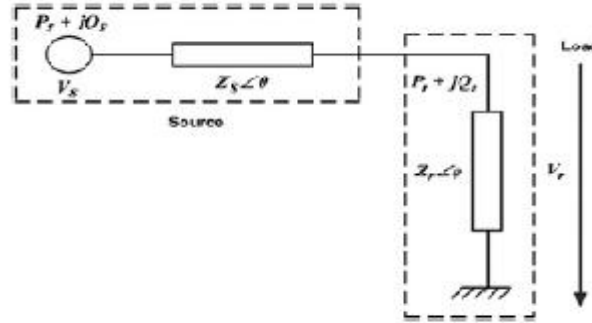


Fig. 1 Single transmission line model

$$\text{VCPI (power)} = \frac{P_r}{P_{r(\max)}} = \frac{Q_r}{Q_{r(\max)}} \quad (1)$$

$$P_{r(\max)} = \frac{V_S^2 \cos \phi}{Z_S 4 \cos^2((\theta - \phi)/2)} \quad (2)$$

$$Q_{r(\max)} = \frac{V_S^2 \sin \phi}{Z_S 4 \cos^2((\theta - \phi)/2)} \quad (3)$$

The numerator is the real or reactive power transferred to the receiving end and it is obtained from the power flow calculations. The denominator is the maximum active or reactive power that can be transferred through a line. It can be calculated by the following equations where V_S is the sending end voltage; Z_S is the line impedance; θ is the line impedance angle and $f = \tan^{-1} (Q_r/P_r)$ is the phase angle of the load impedance.

VSC-OPF approach for preventive control

The purpose of the VSC-OPF based on the VCPI index is mainly to move the power system operation state far away from the voltage collapse by increasing the system stability margin. The proposed algorithm is incorporated into an automatic security monitoring and control system (ASMCS) as the preventive control scheme as

illustrated in Fig. 2. Two approaches could be implemented by the block VSC-OPF to design a preventive control system for the voltage stability improvement and the power losses minimization. The VSI is embedded in the OPF formulation as the new voltage stability inequality constraint, or as an objective function with the minimisation of the total VSI. Fig. 2 summarizes the general view of an ASMCS. The output of the state estimator is used to compute the vulnerability [40] and the line voltage stability [16] indices in order to verify the system security. When the network is overloaded and the voltage instable, the ASMCS is in corrective mode. In this situation, a first threshold (Threshold 1) for the voltage indices is designed to evaluate whether the system is stable or not. According to the definition in the previous section, the VCPI values increase with the increasing of the power flow transferred by the transmission lines and vary from 0 (no load condition) to 1 (voltage collapse). Therefore a threshold of 90% is considered appropriate in this work, if the maximum VCPI index values exceed this threshold it means that the voltage of the critical line is very likely to collapse. Then, fast control actions such as fuzzy-logic-based generation rescheduling approach [40], load shedding, flexible AC transmission systems (FACTS) controllers, high voltage direct current (HVDC) links and corrective switching (line and bus switching) should be initially carried out to move the system into a voltage secure operating point. On the other hand, if the contingency is already screened, a solution exists, and the preventive control is applied automatically to the system. After applying the corrective control actions, the system restores the voltage stability and the values of the VCPI index will definitely move below Threshold 1. In that case, a contingency analysis is performed to provide a list of the most severe contingencies, in terms of voltage stability margins from a set of credible contingencies. If after a contingency study the voltage stability margin is insufficient, then it is necessary to further perform the preventive control based on the VSC-OPF to move the system operating point away from the critical point (the VCPI max value is limited by Threshold 2) and thus obtaining adequate security margins.

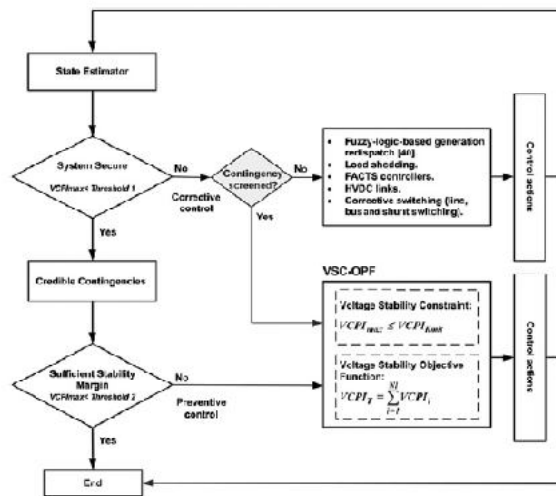


Fig. 2 General flowchart of an ASMCS

Implementation of the VSC-OPF algorithm

The proposed VSC-OPF defined in the previous section is solved by using the `fmincon` function provided by the standard optimization . In this optimisation algorithm, an approximation of the Hessian matrix of the Lagrangian function is calculated at each iteration and the problem is solved by using a line search procedure. The following steps describe the computational procedure for solving the VSC-OPF presented in the diagram of Fig. 3.

- (1) Read the system data.
- (2) Initialise the VSC-OPF by a conventional OPF that consists of minimising (7) subjected to power flow (9) and (10) and technical limits (11)–(13).
- (3) Calculate the VCPI for all the transmission lines by using (1). Find the critical line with the highest VCPI index value.
- (4) If the objective of the optimisation study is to restrict the value of the VCPI index within a range of 0 to $VCPI_{limit}$ to achieve a required voltage stability level and to study the effect of the security voltage on the generation cost, then the approach with the VCPI as the voltage constraint is completed as follows:
 - † Formulate the cost objective function (7).
 - † Construct the conventional constraints given by (9)–(13).
 - † Construct the voltage stability constraint given by (14).
 - † Calculate the first and the second derivatives of the conventional constraints.
 - † Calculate the first and the second derivatives of the voltage stability constraint.
 - † Solve the optimisation problem by the line search method.
- (5) If the aim of the problem is the improvement of the overall voltage stability of the system and the minimization of the power losses, then the VCPI index is used as an objective function and the OPF is executed as follows:
 - † Formulate the voltage stability objective function (8).
 - † Calculate the conventional constraints given by (9)–(13).
 - † Calculate the derivatives of the conventional constraints.
 - † Solve the optimisation problem by the line search method.
- (6) The voltage stability condition has been achieved when the objective function and the control variables converge. At that time, the execution of the algorithm stops, if not, it is repeated from Step 3.

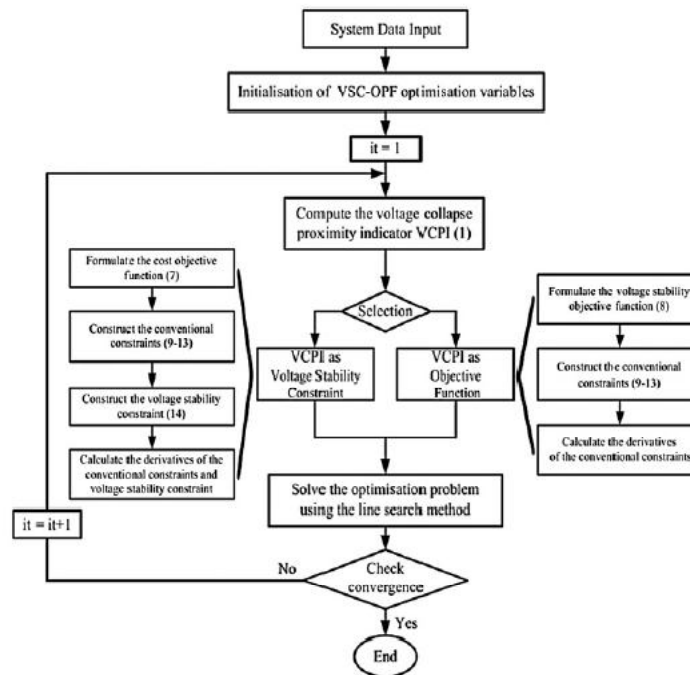


Fig. 3 VSC-OPF computational algorithm

Conclusions and Future Work

In this paper, a novel VSC-OPF approach for the voltage stability preventive control has been presented. The proposed approach is addressed by incorporating the VCPI into the classical OPF problem. The VCPI index is first used as the voltage stability constraint, this requires only one additional voltage constraint added to the conventional OPF constraints. Hence, the dimension of the resulting optimization problem is similar to that of a conventional OPF, and this feature help in reducing the complexity and improving the numerical solution feasibility of the problem. On the other hand, this index is formulated as the OPF objective function and minimized to improve the voltage stability of the system. The effectiveness and the robustness of the proposed VSC-OPF based on the VCPI index are tested and demonstrated. The simulation results obtained under the stressed and the line outage contingency conditions are promising and clearly show the potential of the proposed approach to enhance the power system voltage security by improving the system voltage stability and minimizing the power losses. It is also found that the approach based on the VCPI index achieves a performance comparable with the other reported approaches (min L_{max} and max MSV) with a superiority in terms of the computational efficiency and the solution cost.

The proposed technique is based on a simple concept and can be practically applicable for the online voltage security assessment. In future works, this technique could be easily combined with other stability constraints such as the transient stability or the small signal stability and could be implemented in multi-objective optimisation problems.

Reference :

- [1] Blackout in the United States and Canada: Causes and Recommendations, Power System Outage Task Force, U.S. and Canada, Tech. Rep., Aug. 2004.
- [2] V. Ajjarapu and C. Christy, "The continuation power flow: A tool for steady state voltage stability analysis," in *Proc. Power Industry Computer Application Conf.*, May 1991, pp. 304–311.
- [3] H.-D. Chiang, A. Flueck, K. Shah, and N. Balu, "Cp flow: a practical tool for tracing power system steady-state stationary behavior due to load and generation variations," *IEEE Trans. Power Syst.*, vol. 10, no. 2, pp. 623–634, May 1995.
- [4] H. Mori and S. Yamada, "Continuation power flow with the nonlinear predictor of the Lagrange's polynomial interpolation formula," in *Proc. IEEE/PES Transmission and Distribution Conf. Exhib. 2002: Asia Pacific*, Oct. 2002, vol. 2, pp. 1133–1138.
- [5] W.-M. Lin, W.-C. Hung, C.-H. Huang, and K.-H. Lu, "A preventive control for contingencies security," in *Proc. Int. Conf. Power Electronics and Drive Systems (PEDS)*, Nov. 2009, pp. 252–256.
- [6] H.-D. Chiang, H. Li, J. Tong, and P. Causgrove, "On-line voltage stability monitoring of large power systems," in *Proc. IEEE Power and Energy Society General Meeting*, July 2011, pp. 1–6.
- [7] J. Zhao, Y. Wang, and P. Xu, "A comprehensive on-line voltage stability assessment method based on continuation power flow," in *Proc. Int. Conf. Sustainable Power Generation and Supply (SUPERGEN)*, Apr. 2009, pp. 1–5.
- [8] S. Granville, J. C. O. Mello, and A. C. G. Melo, "Application of interior point methods to power flow IEEE unsolvability," *Trans. Power Syst.*, vol. 11, no. 2, pp. 1096–1103, May 1996.
- [9] X. Wang, G. Ejebe, J. Tong, and J. Waight, "Preventive/corrective control for voltage stability using direct interior point method," *IEEE Trans. Power Syst.*, vol. 13, no. 3, pp. 878–883, Aug. 1998.
- [10] Z. Feng, V. Ajjarapu, and D. J. Maratukulam, "A comprehensive approach for preventive and corrective control to mitigate voltage collapse," *IEEE Trans. Power Syst.*, vol. 15, no. 2, pp. 791–798, May 2000.
- [11] S. Greene, I. Dobson, and F. Alvarado, "Sensitivity of the loading margin to voltage collapse with respect to arbitrary parameters," *IEEE Trans. Power Syst.*, vol. 12, no. 1, pp. 262–272, Feb. 1997.
- [12] J. Zhao, H.-D. Chiang, H. Li, and B. Zhang, "A novel preventive control approach for mitigating voltage collapse," in *Proc. IEEE Power Engineering Society General Meeting*, Jun. 2006, pp. 1–6.
- [13] M. Tang, Q. Zhu, K. Yang, H. Zhang, X. Li, Y. Huang, L. Chen, and W. Hu, "Simplified algorithm of voltage security correction based on sensitivity analysis method," in *Proc. Power and Energy Engineering Conf. (APPEEC)*, Mar. 2012, pp. 1–4.
- [14] B. Gao, G. K. Morison, and P. Kundur, "Toward the development of a systematic approach for voltage stability assessment of large-scale power

- systems,” *IEEE Trans. Power Syst.*, vol. 11, no. 3, pp. 1314–1324, Aug. 1996.
- [15] B. Gao, G. K. Morison, and P. Kundur, “Voltage stability evaluation using modal analysis,” *IEEE Trans. Power Syst.*, vol. 7, no. 4, pp. 1529–1542, Nov. 1992.
- [16] T. Kumano, A. Yokoyama, and Y. Sekine, “Fast monitoring and optimal preventive control of voltage instability,” *Int. J. Elect. Power En-ergy Syst.*, vol. 16, pp. 117–125, Apr. 1994.
- [17] H.-D. Chiang, C.-S. Wang, and A. Flueck, “Look-ahead voltage and load margin contingency selection functions for large-scale power systems,” *IEEE Trans. Power Syst.*, vol. 12, no. 1, pp. 173–180, Feb. 1997.
- [18] H. Li, H.-D. Chiang, and J. Tong, “An on-line tool for voltage stability assessment and control of large-scale power systems,” in *Proc. Institute for Research and Education in Power System Dynamics Symp. (IREP)*, Aug. 2004, pp. 1–11.
- [19] N. Varghese, D. Salem-Natarajan, S. Ghosh, H.-D. Chiang, and H. Li, “Design and implementation of real-time voltage stability analysis at CAISO,” in *Proc. IEEE Power and Energy Society General Meeting*, Jul. 2008, pp. 1–7.
- [20] W. F. Alves, “Proposition of test-systems to power systems analysis” Ph.D. dissertation, Univ. Federal de Fluminense, Niteroi, Brazil, 2007, [Online]. Available: <http://www.sistemas-teste.com.br/>, in Portuguese.
- [21] ONS, Submodule 23.3: Criteria Guidelines for Electrical Studies, Nov. 2011 [Online]. Available: <http://www.ons.org.br/procedimentos/index.aspx>, in Portuguese.
- [22] M. Dester and C. A. Castro, “Multi-criteria contingency ranking method for voltage stability,” *Elect. Power Syst. Res.*, vol. 79, no. 1, pp. 220–225, Jan. 2009.

