Analysis of Optimal Power Flow into A Power System Simulation Environment

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ABSTRACT

The analysis of OPF performs all system control while maintaining system security. System controls include generator megawatt outputs, transformer taps, and transformer phase shifts, while maintenance of system security ensures that no power system component's limits are violated. Different OPF methodologies are discussed especially conventional methodologies with their references and merit and demerits, including Newton method which achieves solution in a rapid manner. Finally, sample applications of the OPF are discussed. These include transmission line overload removal, transmission system control, available transfer capability calculation (ATC), real and reactive power pricing, and transmission system marginal pricing.

Keyword -, Swing, *Optimal Power Flow Formulation, Lyapunov stability theory, Kuhn-Tucker condition,*

1. INTRODUCTION

The economic loss due to losing synchronous operation through a transient instability is extremely high in modern power systems. Consequently, utility engineers often perform a large number of stability studies in order to avoid the problem. Mathematically, the transient stability problem is described by solutions of a set of differential-algebraic equations [1,2,3]. The simplest forms of the equations are the so-called swing equations. The current industry standard is to solve these equations via step-by-step integration (SBSI) methods. Since different operating points of a power system have different stability characteristics, transient stability can be maintained by searching for one that respects appropriate stability limits. Such a search using conventional methods has to be done by trial-and-error incorporating heuristics based on engineering experience and judgment. Recently, significant in computer technology have encouraged the successful implementation of on-line dynamic security assessment programs [4,5,6]. While these new programs greatly improve the ability to monitor system stability, they also reveal that trial-and error methods are not suitable for automated computation.

The disadvantage of SBSI methods has been recognized since the early stages of computer application in power systems. This encouraged extensive investigations into energy function methods [8,9,10,11]. These methods have their roots in Lyapunov stability theory and they provide a quantitative stability margin based on an assessment of the change in direction of the operating point [12,13,14]. Possibly for the same reason, research on pattern recognition and its variant, artificial neural networks, has also been rather active in the past two decades. Although these methods do not contain an explicit stability margin, they do provide for a simple mapping between controllable generation dispatch and indices such as an energy margin, rotor angles, etc. The simple mapping information can in turn be used in a preventive control formulation [15]. Other attempts to solve this preventive control problem can be found in, for example, references [4, 16, 17, and 18]. The unique feature of an OPF is that certain costs can be minimized while functional constraints such as line-flow and voltage limits are respected. Significant progress has been made in this area in recent years [19, 20, and 21]. Given State-of-the-art OPF software, power engineers can perform studies for large systems with n-1 steady-state constraints in a reasonable amount of time. It is relatively straightforward to include n-1 contingency constraints since these constraints can be modeled via algebraic equations or inequalities. It is, however, an open question as to how to include stability constraints since stability is a dynamic concept and differential equations are involved. Recently, OPF practitioners began to discuss the possibility of including stability constraints in standard OPF formulations [19,20,21]. A few attempts based on either energy function methods or pattern recognition techniques have been pursued [12, 13, 14, 15]. The importance of maintaining stability in power systems operation however calls for fundamentally strict, precise, yet flexible methodologies. Ease of Use It is also worth mentioning that the emergence of competitive power markets also creates the need for a stability-constrained OPF because the traditional trialand- error method could produce discrimination among market players in stressed power systems [13]. As reported in [14], “the past practice of maintaining reliability by following operating guidelines based on offline stability studies is not satisfactory in a deregulated environment”. In this paper, we develop a method for handling transient stability constraints. We demonstrate our idea by applying it to a stability-constrained OPF problem. The methodology is built upon a state-of-the-art OPF and SBSI techniques. By converting the differential equations into numerically equivalent algebraic equations, standard nonlinear programming techniques can be applied to the problem. We demonstrate via simulation results that stability constraints such as rotor angle limits and/or tie line stability limits can be conveniently controlled in the same way thermal limits are controlled in the context of an OPF solution.

2. A STABILITY-CONSTRAINED OPTIMAL POWER FLOW FORMULATION

A standard OPF problem can be formulated as follows [19]:

Min f Pg ( ) (1)

S.T.

$$P_g - P_L - P(V,\theta) = 0 \quad (2)$$

$$Q_g - Q_L - Q(V,\theta) = 0 \quad (3)$$

$$S(V,\theta) - S^M \le 0 \quad (4)$$

$$V^m \le V \le V^M \quad (5)$$

$$P_g^m \le P_g \le P_g^M \quad (6)$$

$$Q_g^m \le Q_g \le Q_g^M \quad (7)$$

Where f (.) is a cost function; (2) and (3) are the active and reactive power flow equations, respectively; Pg is the vector of generator active power output with upper bound Pg M and lower bound Pg m ; Qg is the vector of reactive power output with upper bound Qg M and lower bound Qg m ; PL and QL are vectors of real and reactive power demand; P(V,q) and Q(V,q) are vectors of real and imaginary network injections, respectively; S(V,q) is a vector of apparent power across the transmission lines and S_M contains the thermal limits for those lines; V and q are vectors of bus voltage magnitudes and angles with lower and upper limits V_m and V_M , respectively. Note that Pg ,Qg ,V , and q are the free variables in the problem. Now, assume that the dynamics are governed by the socalled classical model in which the synchronous machine is characterized by a constant voltage E behind a transient reactance X'_d . For the sake of illustration the load is modeled by constant impedance. Note that more complicated models could be used without loss of generality. We have the following “swing” equation [1]:

$$\frac{d\delta_i}{dt} = \omega_i \tag{8}$$

$$\frac{d\delta_i}{dt} = \frac{\pi f_0}{2H_i}\left[P_{gi} - \frac{1}{X'_{di}}\left(E_i W_{xi} \sin\delta_i - E_i W_{yi} \cos\delta_i\right)\right] \tag{9}$$

$$= D_i\left(P_{gi}, E_i, W_{xi}, W_{yi}, \delta_i, \omega_i\right)$$

$$\begin{bmatrix} G & -B \\ B & G \end{bmatrix} \cdot \begin{bmatrix} W_x \\ W_y \end{bmatrix} = \begin{bmatrix} I_x \\ I_y \end{bmatrix} \tag{10}$$

Where G and B contain the real and reactive part of the bus admittance matrix, respectively; W_x and W_y are vectors containing the real and imaginary part of the network (bus) voltages; f_0 is the nominal system frequency; H is the inertia of i^{th} generator; w_i and d_i are the rotor speed and angle of i^{th} generator.

A solution to a stability-constrained OPF would be a set of generator set-points that satisfy equations (1)-(10) for a set of credible contingencies. Unfortunately, this hard nonlinear programming problem contains both algebraic and differential equation constraints. Existing optimization methods cannot deal with this kind of problem directly. In the next section, we propose a method to attack the problem.

3. COMPUTATIONAL ISSUES

In this section, we outline the overall procedure of our method and discuss computational complexities associated with stability constrained OPF problem.

3.1 An Algorithm

A model algorithm that has been tested on small power systems is outlined in Fig. 1. We constructed the model algorithms from direct extension of the successive linear programming method with constraint relaxation [22]. In what follows we explain the procedure described in Fig. 1. Since individual stability constraints are typically not binding, it is only prudent to begin by solving a standard OPF to start and to check to see if the solution of the standard OPF respects stability constraints. If the solution does, then this solution is also the final solution of stability constrained OPF. If the solution does not respect stability constraints, then a complete stability constrained OPF must be solved.

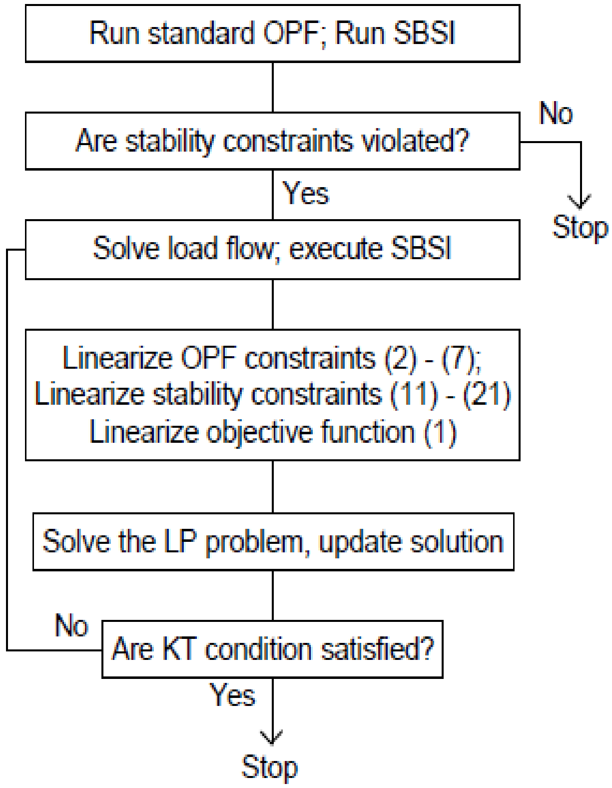

Fig. - 1. A procedure for the stability constrained OPF

The KT or Kuhn-Tucker condition alluded to in Fig. 1 is the optimality condition for the algebraic NP problem. Inside the main loop, load flow and swing equations are solved simultaneously. Based on our computational experience, this seems to be overly cautious. So in our prototype code, we solve load flow and swing equations sequentially. Our experience also indicates that the integration format used in SBSI and that in the algebraic NP problem should be consistent. Otherwise, the algorithm may not converge. Linearizing the objective function and constraints is trivial. The only thing we would point out is that the number of stability constraints is very large.

3.2 Computational Complexity

The algebraic NP problem (18) contains a very large number of constraints. At this point, we are not able to validate whether or not the LP-based method is efficient for this problem. Rather, we offer some observations that could lead to a practical solution to this problem. We start our discussion by making a comparison between steady-state security constrained OPF and dynamic security constrained OPF. As an example assume

- There 10 contingency constraint equations
- The integration step size is 0.1 second
- The integration period is 2 second

There are 2 network switches (the point in time where the fault is applied and cleared) Note that each integration step imposes one set of constraints (equations 12-16), so each contingency imposes a set of 22 constraints (2/0.1 + 2 constraints). Thus for this stability-constrained OPF problem, 220 constraints need to be appended to standard OPF. For steady-state security constrained OPF, 10 constraints would need to be appended to the standard OPF. This analysis is however overly simplistic for the following reasons: First, for many occasions one is only interested in transient stability constrained problems in which only one contingency is involved at a time. Second, we notice that the number of binding constraints for dynamic security is typically smaller than that for steady-state security. In perhaps any power system, the number of binding stability constraints is normally very small, say in the order of 5 or less. Third, for most stability studies, we can apply the constraint relaxation technique explained below. Suppose the maximum rotor angle at each integration step, that is max(i ,i 1,...,ng) d = , reaches its maximum point at 0.8

second, then the constraints associated with those integration steps after, say, 1.0 second can be excluded from the LP problem (see Fig. 2).

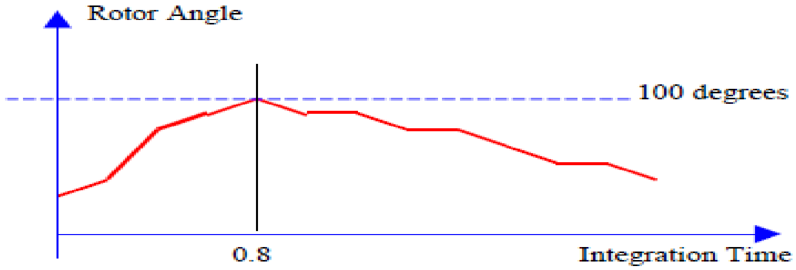

Fig. - 2. Constraint Relaxation for the Stability Constrained OPF

The above technique, which is conceptually different from that described in [22], can reduce the size of the LP problem significantly (note that a full SBSI should always be performed to make sure that no stability limit is violated).

4. ILLUSTRATIVE EXAMPLE

The integration-based method was implemented using the MATPOWER package [16], a MATLAB-based power system analysis toolbox that is freely available for download from the site at http://www.pserc.cornell.edu/matpower/. The prototype code has been tested on the WSCC 3-machine 9-bus system and the system New England 10-machine 39-bus System. The results of New England system are presented here. The parting point is given by a standard OPF. A three phase-to-ground fault is applied to bus 29, the fault is cleared 0.1 second later coupled with the removal of line 29-28. The integration step size is set to 0.1 seconds and the integration is executed for 1.5 seconds. We note that the operating point did not respect the stability constraint (the relative rotor angle of generator at bus 29 is about 700 degrees at time 1.5 second (See Fig. 3).

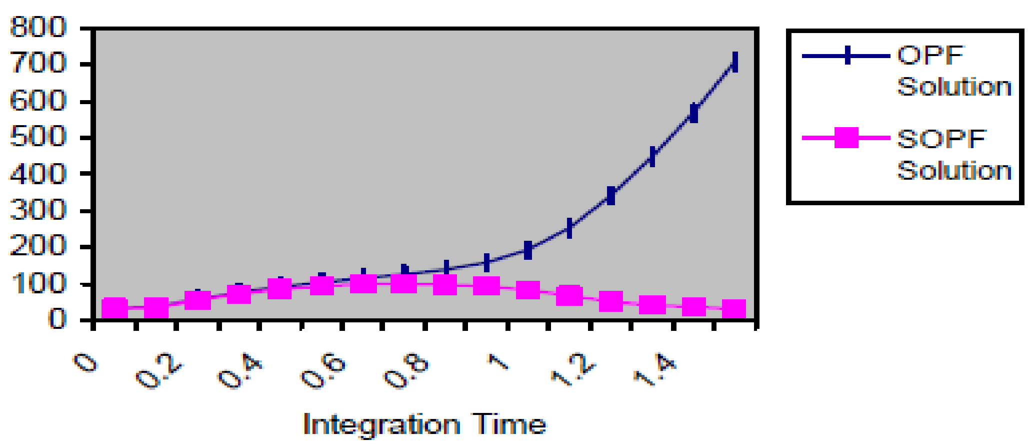

Fig. – 3. Maximum Angle (at each integration step)

The stability constrained OPF program was then run providing an operating point that respects stability constraints, as illustrated in Fig 3. The operating cost of the system was slightly increased. The iteration process in the stability constrained OPF is illustrated in Fig. 4.

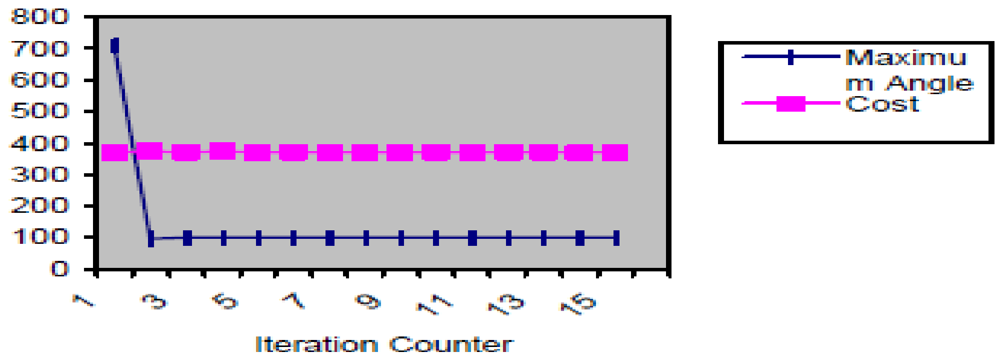

Fig. - 4. Iteration Process of Stability Constrained OPF

5. CONCLUSIONS

In the recent past tremendous effort has been spent on system stability issues. The objectives are to monitor and ultimately control the stability during power system operation. While the technology for stability simulation is rather stable now, little analytical development has been done for computing stability limits precisely. This is perhaps because computing the stability limits precisely has been thought to be impossible [20]. There is, however, an increasing need for solutions for this challenging problem. In this paper, we have developed a basis for one approach to this problem. The method naturally inherits the advantages of SBSI-based methods such as, it has little limitations on component modeling, it is robust, and it provides all relevant system swing information. We demonstrated that, using this general methodology, for the first time the stability limits of power systems can be precisely and automatically estimated. We are hoping that the methodology can be developed into a practical tool but this requires that it be efficiently implemented.

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