INTERNAL REPORTS IN

SIMULATION, OPTIMIZATION AND CONTROL

No. SOC-265

SENSITIVITY ANALYSES AND REDUCED GRADIENT EVALUATION FOR OPTIMIZATION OF POWER SYSTEMS

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April 1981

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McMASTER UNIVERSITY
HAMILTON, ONTARIO, CANADA

Proc. ECCTD, The Hague, August 1981

SENSITIVITY ANALYSES AND REDUCED GRADIENT EVALUATION FOR OPTIMIZATION OF POWER SYSTEMS

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Abstract

This paper reviews important approaches to sensitivity calculations in power system analysis and design problems. We employ a unified notation to classify, describe and compare methods of evaluating first-order changes and reduced gradients of functions of interest with respect to power system control and design variables. The contribution of these methods to solving some practical problems is also outlined.

1. INTRODUCTION

In the context of steady-state computer-aided power system analysis and planning, functions of system variables are routinely defined in various studies to incorporate cost criteria, security assessment, reliability indices, etc. The system variables are related through a set of equality constraints representing, for example, power flow equations. Inequality constraints may also be defined to indicate, for example, physical limitations on practical variables.

The ratio between a small change Δf in a function f which may denote a dependent variable and a related small change Δu_j in an independent variable u_j indicates [1] the sensitivity of f with respect to u_j. This ratio is generally a function of other system variables. It is very valuable in numerous power system analysis and planning problems [2]. Using the Taylor series expansion, which relates Δf to increasing powers of Δu_j, the change in f may be calculated to any degree of accuracy.

First-order changes of functions of interest play a very important role in sensitivity calculations not only because they are relatively easy to calculate but also due to their direct contribution to gradient evaluations required by most optimization techniques used in different planning studies [3].

The use of second-order sensitivities, although requiring more elaborate calculation, also finds applications in investigations of the sensitivity of a function w.r.t. certain variables at an optimal solution represented by a stationary point of the function w.r.t. these variables.

In this paper, important methods of sensitivity analysis and reduced gradient evaluation in power system operation and planning problems are classified and described in general. The notation used and the modes of formulation which contribute to developing a successful sensitivity approach are presented. Applications to some practical power system problems are also discussed.

This work was supported by the Natural Sciences and Engineering Research Council of Canada under Grant A7239.

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Due to the inherently large size of power networks, with various branch types, simplicity of derivation and formulation, flexibility in modelling different components of the power system and efficiency in computations represent basic requirements for a successful sensitivity approach.

Some techniques [4-7] address the previous requirements by approximating the a.c. load flow model describing the steady-state behaviour of the power system. Other methods [8-10] employ the exact a.c. load flow model. In some applications [11] both exact and approximated models have been used. The elements of the Jacobian matrix of the load flow solution are exploited in some approaches [8,10,12] while the flexibility in modelling different power system elements provided by using suitable network theorems is gained in others [3,6].

2. NOTATION

The different interpretation of the variables used to describe various power system components in equations poses a difficulty in choosing a suitable notation which facilitates the derivation and subsequent formulation of equations and expressions employed [1].

2.1 State Variable Notation

The most successful notation used in describing the power flow equations and other physical constraints and interpreting the relationships between different variables is the state variable notation [1,12,13] commonly used in control theory. Throughout the paper this notation, which contributes significantly to an easier understanding of the equations, will be used.

The control or design variables are denoted by the column vector $\underset{\sim}{u}$ of n_u components. We also denote by the n_x - component vector $\underset{\sim}{x}$ the state variables or the dependent variables to be determined by solving the set of equality constraints, denoted by $\underset{\sim}{h}(\underset{\sim}{x},\underset{\sim}{u}) = \underset{\sim}{0}$, describing the steady-state behaviour of a particular power system.

2.2 Classification of Independent Variables

In the literature, the vector $\underset{\sim}{u}$ may be either classified further [3] into subvectors associated with different bus and line branches in the power network or restricted [8] to represent only the practically controllable variables, e.g., the real power P_g at a generator bus while some other variables, called fixed parameters, are assigned other symbols.

In general, we shall use $\underset{\sim}{u}$ to denote the independent variables to be specified in the equations describing a particular system. We may classify $\underset{\sim}{u}$ and $\underset{\sim}{x}$, whenever necessary, into appropriate subvectors associated with different power system steady-state component models [14].

3. GENERAL FORMULATION

3.1 Power Flow Equations

Most of the literature in the area of power system analysis and design employs the real mode of formulation to describe the power flow equations and to derive, subsequently, the sensitivity expressions required in a particular study.

The power flow equations [15] are basically expressed in the complex form

$$V_m^* \sum_{i=1}^{n} (Y_{mi} V_m) = S_m^*, \quad m = 1, \ldots, n, \qquad (1)$$

where V_m is the mth bus voltage, Y_{mi} is an element of the bus admittance matrix [14], $S_m = P_m + jQ_m$ is the mth bus power, P_m and Q_m denoting, respectively, the injected real and reactive powers, $j = \sqrt{-1}$, n denotes the number of buses and * denotes the complex conjugate.

The variables in (1) are, generally speaking, functions of the state $\underset{\sim}{x}$ and control $\underset{\sim}{u}$ variables of the system. Equations (1), whether written in the rectangular or in the polar form [15] are usually separated into real and imaginary parts in solving the load flow problem.

3.2 The Real Mode of Formulation

The real mode of formulation has been suggested upon the application [15,16] of the well-known Newton-Raphson method, which is superior in its quadratic convergence and ability to solve ill-conditioned problems, to the solution of the load flow problem. The reason [17] is that the Newton-Raphson method is a derivative-based method and, mathematically speaking, the complex load flow equations are nonanalytic and cannot be differentiated in complex form. In this respect, it has recently been shown [3,18] that the Newton-Raphson method can also be applied to the compact complex form of power flow equations.

The subsequent sensitivity calculations have been automatically performed in most of the literature in the same real mode.

3.3 First-Order Changes of Functions and Constraints

In general, we write the first-order change of a continuous function f in the form

$$\delta f = \sum_{i=1}^{n_x} \left(\frac{\partial f}{\partial x_i} \delta x_i \right) + \sum_{k=1}^{n_u} \left(\frac{\partial f}{\partial u_k} \delta u_k \right), \qquad (2)$$

where δ denotes first - order change, x_i is the ith state variable and u_k is the kth control variable. We also write the first-order changes of the set of equality constraints $\underset{\sim}{h}(\underset{\sim}{x},\underset{\sim}{u}) = \underset{\sim}{0}$ in the form

$$\delta h_j = \sum_{i=1}^{n_x} \left(\frac{\partial h_j}{\partial x_i} \delta x_i \right) + \sum_{k=1}^{n_u} \left(\frac{\partial h_j}{\partial u_k} \delta u_k \right) = 0, \qquad (3)$$

$$j = 1, \ldots, n_x,$$

where h_j denotes the jth equality constraint.

The basic forms (2) and (3) are essential for the techniques employed to evaluate total derivatives of f w.r.t. $\underset{\sim}{u}$ by expressing δf solely in terms of the δu_k.

4. METHODS OF SENSITIVITY CALCULATIONS

Excluding the method based on approximate explicit expression of $\underset{\sim}{x}$ in terms of $\underset{\sim}{u}$ [19], there are basically three methods for eliminating $\delta\underset{\sim}{x}$ from (2) and (3): the sensitivity matrix method, the adjoint or Lagrange multiplier method and the method based on Tellegen's theorem [20,21].

4.1 The Sensitivity Matrix Method

In the sensitivity matrix method [1,8], the sensitivity matrix $\underset{\sim}{S}$ is defined by

$$\underset{\sim}{S} \triangleq - [(\frac{\partial \underset{\sim}{h}^T}{\partial \underset{\sim}{x}})^T]^{-1} (\frac{\partial \underset{\sim}{h}^T}{\partial \underset{\sim}{u}})^T, \qquad (4)$$

where $(\partial \underset{\sim}{h}^T/\partial \underset{\sim}{x})^T$ and $(\partial \underset{\sim}{h}^T/\partial \underset{\sim}{u})^T$ are the Jacobian matrices of $\underset{\sim}{h}$ w.r.t. $\underset{\sim}{x}$ and $\underset{\sim}{u}$, respectively. Hence, from (3)

$$\delta \underset{\sim}{x} = \underset{\sim}{S}\ \delta \underset{\sim}{u}, \qquad (5)$$

where $\delta\underset{\sim}{x}$ and $\delta\underset{\sim}{u}$ are column vectors of δx_i and δu_k, respectively, of (2). Substituting (5) into (2), we get

$$\delta f = [\frac{\partial f}{\partial \underset{\sim}{u}} + \underset{\sim}{S}^T \frac{\partial f}{\partial \underset{\sim}{x}}]^T \delta \underset{\sim}{u}, \qquad (6)$$

from which

$$\frac{df}{d\underset{\sim}{u}} = \frac{\partial f}{\partial \underset{\sim}{u}} + \underset{\sim}{S}^T \frac{\partial f}{\partial \underset{\sim}{x}}. \qquad (7)$$

The application of the sensitivity matrix method requires n_u repeat solutions of a system of linear equations formed from (4) for the elements of $\underset{\sim}{S}$. This task usually makes this method less preferable [8] unless the sensitivity matrix is needed for other purposes.

4.2 The Method of Lagrange Multipliers

The method of Lagrange multipliers [8,13] is the most common one not only because it requires only one solution of a set of linear adjoint equations (as compared with the sensitivity matrix method) but also because it utilizes, in various applications, the elements of the Jacobian matrix available from the basic load flow solution.

The Lagrange multiplier method is commonly referred to for a general set of equality constraints [22]. When the equality constraints represent power flow equations, the method may be interpreted as an adjoint network method [23].

The Lagrange multipliers are defined by

$$\underset{\sim}{\lambda} \triangleq \left(\frac{\partial \underset{\sim}{h}^T}{\partial \underset{\sim}{x}} \right)^{-1} \frac{\partial f}{\partial \underset{\sim}{x}} , \tag{8}$$

hence, from (2) and (3)

$$\delta f = \left[\frac{\partial f}{\partial \underset{\sim}{u}} - \left(\frac{\partial \underset{\sim}{h}^T}{\partial \underset{\sim}{u}} \right) \underset{\sim}{\lambda} \right]^T \delta \underset{\sim}{u}, \tag{9}$$

from which

$$\frac{df}{d\underset{\sim}{u}} = \frac{\partial f}{\partial \underset{\sim}{u}} - \frac{\partial \underset{\sim}{h}^T}{\partial \underset{\sim}{u}} \underset{\sim}{\lambda}. \tag{10}$$

In practice, the set of linear equations formed by (8) is solved for the Lagrange multipliers $\underset{\sim}{\lambda}$ and the first-order change and total derivatives of f are then calculated from (9) and (10), respectively.

When the set of equality constraints $h(x,u) = 0$ represents the power flow equations (1), the 2n x 2n matrix of coefficients $(\partial h^T/\partial x)$ of (8) may constitute the transpose of the Jacobian matrix of the load flow solution by the Newton-Raphson method. The exploitation of this fact necessitates expressing f in terms of $\underset{\sim}{x}$ which, in this case, represents 2n bus quantities (the unknown variables in power flow equations). Transformations are required to handle functions of other variables, e.g., line variables.

We remark that an extended vector $\underset{\sim}{x}$ which contains all variables of interest can be defined [22] so that general functions of line quantities may be directly handled. In this case, the size of the matrix of coefficients in (8) is determined by the total number of states considered.

4.3 Method Based on Tellegen's Theorem

The method based on Tellegen's theorem exploits the powerful features of the theorem to achieve both the compactness of the adjoint system of equations to be solved and the flexibility in handling line quantities.

Tellegen's theorem, which depends solely upon Kirchhoff's laws and the topology of the network, states that

$$\sum_b \hat{I}_b V_b = 0 \text{ and } \sum_b \hat{V}_b I_b = 0, \tag{11}$$

where I_b and V_b are, respectively, the current and voltage of branch b of the network and ^ distinguishes the corresponding variables associated with the topologically similar adjoint network. The summations in (11) are taken over all branches. In addition to the current and voltage variables, the inclusion of the power variables S_b is required to accommodate the power flow model. Hence, we may use

$$S_b = V_b I_b^*. \tag{12}$$

Tellegen's theorem has been successfully applied to power system analysis and design problems since 1972 [4]. In the beginning, the approximated d.c. load flow model was used. This found applications in transmission system planning problems in which the d.c. model may be considered of sufficient accuracy. The d.c. load flow model is, however, characterized by the restrictive assumptions of neglecting transmission losses, excluding reactive power flows and considering flat voltage profiles which make it inadequate [24] for other studies requiring a more accurate model and more information.

Different versions of improved, approximate a.c. load flow models have been successively developed for application to different power system studies. The relatively difficult steady-state component models in power networks impose an observed difficulty in applying Tellegen's theorem to the exact a.c. load flow model. A proper methodology has been required [3,9,25-28] to overcome this difficulty.

In general, a method of sensitivity calculations based on Tellegen's theorem incorporates the following steps. A perturbed Tellegen sum is formulated as

$$\hat{\underset{\sim}{\eta}}_x^T \delta \underset{\sim}{x} + \hat{\underset{\sim}{\eta}}_u^T \delta \underset{\sim}{u} = 0, \tag{13}$$

where the state $\underset{\sim}{x}$ and control $\underset{\sim}{u}$ variables are defined in accordance with the power flow model considered and the vectors $\hat{\underset{\sim}{\eta}}_x$ and $\hat{\underset{\sim}{\eta}}_u$ are, in general, linear functions of the formulated adjoint network current and voltage variables. Hence, the $\hat{\underset{\sim}{\eta}}_x$ and $\hat{\underset{\sim}{\eta}}_u$ of (13) are related through Kirchhoff's current and voltage laws formulating a set of linear network equations to be solved for the unknown adjoint variables. The adjoint network is defined by setting

$$\hat{\underset{\sim}{\eta}}_x = \frac{\partial f}{\partial \underset{\sim}{x}} , \tag{14}$$

hence, from (2) and (13), we get

$$\delta f = \left(\frac{\partial f}{\partial \underset{\sim}{u}} - \hat{\underset{\sim}{\eta}}_u \right)^T \delta \underset{\sim}{u}, \tag{15}$$

from which

$$\frac{df}{d\underset{\sim}{u}} = \frac{\partial f}{\partial \underset{\sim}{u}} - \hat{\underset{\sim}{\eta}}_u. \tag{16}$$

In practice, the adjoint network is defined for a given function by (14) and solved for the variables $\hat{\underset{\sim}{\eta}}_u$ which are then substituted into (15) and (16) to obtain first-order changes and total derivatives of f w.r.t. control variables.

The matrix of coefficients of the adjoint system of equations has to be calculated at a base-case point. The LU factors of this matrix may be stored and different functions can be treated by repeat forward and backward substitutions.

4.4 Discussion

Based upon the foregoing description, we may conclude that the Tellegen theorem-based method has the advantage over the method of Lagrange multipliers regarding the flexibility of modelling the different elements of the network. It has, however, the disadvantage that the adjoint matrix of coefficients has to be calculated at a load flow solution [3,29].

It is important to notice that when optimal solutions are required upon altering one or more system parameters from the base-case point, the adjoint matrix of coefficients in both methods has to be calculated at different iterations of the load flow solution included in each of the main optimization iterations towards the optimum.

The choice of a suitable method for sensitivity calculations depends on various factors such as the kind of application considered, the types of elements defined in the power system and the available storage and facilities in computations.

5. APPLICATIONS

Efficient sensitivity calculations may be performed to evaluate first-order changes of functions of interest corresponding to certain variations in the control variables defined in a particular study. These first-order changes are valuable in estimating the effects of transmission system contingencies and ranking them [30], generation outages, device malfunctions and other defects expected in power systems operation which may result in subsequent service deterioration.

In contingency analysis the changes in system performance, upon sustaining some of the above contingencies, are calculated using the d.c., the approximate a.c. or the exact a.c. load flow model. As illustrated before, the a.c. load flow models have the advantage of both accurate contingency evaluation and inclusion of the reactive power flows. Fig. 1 [31] illustrates the contingency evaluation for line or generator loss.

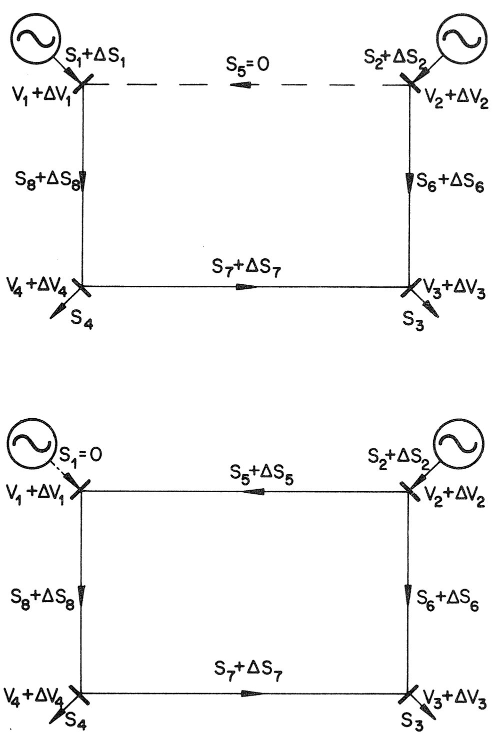

Fig. 1 Illustration of contingency evaluation

As stated before, sensitivity calculations are performed to evaluate gradients of functions of interest subject to equality constraints relating the state and control variables of the system. These gradients may be supplied to optimization routines employed in different power system design problems.

In practice, functional inequality constraints as well as upper and lower limits on the control variables must be considered in optimization to reflect the physical limitations on different system components.

5.1 Power System Design Problem

A typical power system design problem may be stated as the general nonlinear programming problem

$$\underset{\underset{\sim}{u}}{\text{Minimize}}\ f(\underset{\sim}{x}, \underset{\sim}{u}) \qquad (17)$$

subject to

$$\underset{\sim}{h}(\underset{\sim}{x}, \underset{\sim}{u}) = \underset{\sim}{0} \qquad (18)$$

and

$$\underset{\sim}{g}(\underset{\sim}{x}, \underset{\sim}{u}) \geq \underset{\sim}{0}, \qquad (19)$$

where the column vector $\underset{\sim}{g}(\underset{\sim}{x},\underset{\sim}{u})$ represents n_g inequality constraints.

Considering the general formulation of the problem (17)-(19) with continuous real variables and assuming proper convexity, the Kuhn-Tucker relations [32] provide a set of necessary conditions which the solution must satisfy at the minimum of f. Techniques of constrained optimization [33] are employed.

A wide variety of problems in computerized operation and planning of power systems falls into the form (17)-(19). The type of the objective function f as well as the existence and the nature of both equality and inequality constraints depend on the study performed.

Several approaches have been described and successfully applied to handle functional inequality constraints in many power system problems. For example, some of the approaches [34] utilize the generalized reduced gradient (GRG) method. Others [35] employ penalty function methods.

In these approaches, the total derivatives (called the reduced gradient) of a formulated objective function w.r.t. control variables may be evaluated by methods of sensitivity calculations described before.

5.2 The Optimal Load Flow Problem

In the optimal power flow problem [8] a feasible power flow solution w.r.t. constraints on both control and state variables is found which minimizes some cost criterion.

In general, the adjustable control variables assigned include the real power P_g from generating plants available for adjustable dispatch, voltage magnitude $|V_g|$ at P, V-buses, tap transformer and phase shifter ratios and parameters of shunt control elements.

Some of the inequality constraints represent limits on the capability of adjustable control devices, e.g., real and imaginary transformer tap ratios, and other equipment capacities such as the generating capacity. The others represent the system security requirements which include line flow current and power constraints under normal and contingency conditions. The violation of inequality constraints may lead to inadequate service due to component outages.

A number of problems can be defined by a different choice of the objective function of (17) and constraints (18) and (19). The economic dispatch and minimum loss problems [8], optimal load curtailment under emergency conditions [36] and VAR flow control [37] are examples.

5.3 Power System Planning Studies

Many power system planning problems can be formulated as nonlinear programming problems in the form (17)-(19). The objective function f, the design variables and the constraints are defined in a particular planning study to reflect economy, reliability, security and efficiency requirements.

The power flow model which simulates the steady-state power flows and voltages in the network under planning considerations is described either exactly or approximately according to accuracy requirements.

In automated power network design problems [4,22] for example, the objective function f may be formulated to represent line overloading. The control variables to be adjusted are line admittances representing the required additions to support the existing transmission capacity. The inclusion of inequality constraints imposed on the design variables by, for example, the right-of-ways may be included.

A contingency analysis may be required after designing a nominal network. In this kind of study, first-order changes of functions of interest simulating line overloading due to assigned parameter changes and line or generator outages are employed in the adequacy checks.

Many other applications of the methods of sensitivity evaluation described before can be identified in which either first-order changes or total derivatives of functions of interest are concerned.

6. CONCLUSIONS

In this paper, important approaches to sensitivity analysis and reduced gradient evaluation in power system problems have been classified and generally described. Two of these approaches, namely the Lagrange multiplier approach and the Tellegen's theorem approach, represent the most efficient techniques currently available for sensitivity calculations in power networks. The merits and drawbacks of the two approaches when applied to the approximate or to the exact a.c. power model have been illustrated. Their contribution to solving some power system analysis and optimization problems has also been discussed.

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SOC-265

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April 1981, No. of Pages: 6

Revised:

Key Words: Sensitivity calculations, sensitivity matrix, Lagrange multipliers, Tellegen's theorem method, reduced gradients, power system sensitivities

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Description: Proc. European Conf. Circuit Theory and Design (Hague, Netherlands, August 1981), pp. 69-74.

Related Work: SOC-237, SOC-238, SOC-243, SOC-247, SOC-250, SOC-253, SOC-256, SOC-257, SOC-258.

Price: $3.00.