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OPTIMAL CORRECTIVE RESCHEDULING OF REAL AND REACTIVE POWERS FOR POWER SYSTEM SECURITY ENHANCEMENT

الجدولة المثلى للقدرة الفعالة والغير فعالة لتحسين درجة أمان نظم القوى الكهربية

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الخلاصة :-

يقدم هذا البحث أسلوب حل مثالى لاعادة جدولة القدرة الفعالة والغير فعالة لوحدات التوليد لتحسين درجة أمان نظم القوى الكهربية. تعتمد طريقة الحل على أسلوب البرمجة الخطية الازدواجية (Dual linear programming) لحل معادلات سريان القدرة الكهربية. تم استخدام هذه الطريقة للحصول على القيم المثلى للقدرة الفعالة والغير فعالة لوحدات التوليد، وكذلك ملفات التنظيم فى الجهد للمحولات الموجودة بالنظام مع أخذ شروط التشغيل لهذه المتغيرات فى الاعتبار، أيضا روعى فى الاعتبار القيود الموجودة بالنظام لسريان القدرة بالخطوط وجهود القضبان وذلك فى حالات التشغيل العادية والحالات الطارئة. تم تطبيق طريقة الحل على نظام قوى كهربى من النوع القياسى (IEEE-30 bus system) حيث أظهرت النتائج التى تم الحصول عليها مدى كفاءة ودقة الطريقة المقترحة للحل مقارنة بالطرق الغير خطية الأخرى، كذلك يمكن استخدام هذه الطريقة لتقييم درجة آمان نظم القوى الكهربية.

ABSTRACT

This paper presents an optimal technique for solving the corrective rescheduling problem in power system. A successive dual linear programming approach is used with linearized power flow model. The system real and reactive power generations and transformer tap ratios are optimized within their operating limits so that no limit voilations of the line flow and bus voltage magnitudes in either the base case and contengency cases. The test results on IEEE-30 bus test system show that the proposed technique can be successfully employed in conjunction with any fast security assessment scheme for a fast on-line security assessment and control.

1- INTRODUCTION

The operating point of a power system will change due to various contingencies and disturbances on the system. If the system survives the outage or disturbance, it will operate in a new steady state in which one or more transmission lines may be overloaded and hence voltage constraints at some buses may be violated. System dispatchers will resort to corrective rescheduling for removing constraints violations.

The operating state of a power system is characterized by two sets of constraints. The first type of constraints is the power flow equality constraint. The second type is the operating (inequality) constraints which represents the capability limits of generating sources and the limits on bus voltage magnitude and line flow variables. Additional set of constraints can be imposed on the power system. operating conditions to ensure a specified level of security.These constraints generally referred to as security constraints, describe the ability of the system to service major disturbances such as forced outages of

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generators or lines or fault conditions. For a given base case operating state of the system, security assessment scheme detects the potential overloads and unacceptable voltage levels for contingency conditions. Assuming that the base operating state could be corrected for the insecurity without modifying the network configuration, then the problem is a correction control to reschedule the controllable system quantities in such a way that the operating state of the system is steady state secure.

Though efficient nonlinear programming procedures with exact models have been proposed for the corrective rescheduling problem [1,2]. These techniques are not suitable for online applications because of problem size, problem dependent convergence characteristics and long solution time. An alternative is to use the linearized equations with linear programming technique. References [3,4] utilized dc power flow models. Recently in [5], a proposed successive linear programming formulation using a decoupled linearized ac power flow model is presented. All the above procedures considered only the real power control neglecting the reactive power and voltage control considerations.

The objective of this paper is to present a practical procedure to solve the corrective rescheduling problem for on line application. To achieve the objective, a successive dual linear programming approach is proposed which uses a linearized ac power flow model. In this rescheduling problem, the controllable system quantities (real and reactive power generations and transformer tap ratios) are optimized within their limits so that no limit violations of the line flow and voltage variables occur in either the base case or contingency cases of system operating conditions.

2- POWER SYSTEM MODEL

Consider the following well-known linear power flow equation :-

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=\begin{bmatrix}H & N\\ J & L\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta V/V\end{bmatrix} \qquad (1)$$

Where P and Q are the active and reactive power, δ and V are the bus angles and voltage magnitudes, and H, N, J, and L are the submatrices of the Jacobian matrix of the power flow equations evaluated at the operating point.

If transformer tap ratios are also considered as additional variable, an additional term appears in Eqn.1 to account for the changes in the transformer tap positions Δt as :-

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=\begin{bmatrix}H & N\\ J & L\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta V/V\end{bmatrix}+\begin{bmatrix}K\\ M\end{bmatrix}\left[\Delta t/t\right] \qquad (2)$$

where K and M are the corresponding sensitivity matrices. Rearranging equation (2), we get :-

$$\begin{bmatrix}\Delta\delta\\ \Delta V/V\end{bmatrix}=\begin{bmatrix}H & N\\ J & L\end{bmatrix}^{-1}\left[\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}-\begin{bmatrix}K\\ M\end{bmatrix}\left[\Delta t/t\right]\right] \qquad (3)$$

Let the incremental control vector Δu for a given system configuration (p) defined as :-

$$\Delta u = \begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta t / t \end{bmatrix} \tag{4}$$

Then the system state vector Δx is given by :-

$$\Delta x = [S]\,\Delta u \tag{5}$$

where $[S]$ is the sensitivity matrix evaluated at (x^0, u^0, p^0).

3- PROBLEM FORMULATION

The contingencies that can occur in a power system are outage of transformer, transmission line, and generator. The control applied to the k_{th} network outage is the same as that applied to the base case $(k=0)$ state, i.e. $u^k = u^0$. But the system configuration represented by the parameter p and the state vector x changes for the network outage. This is reflected in the sensitivity matrix [S]. Then base case state $(k=0)$ and the outage states $(k=1,2,\ldots\ldots No)$ are characterized by the individual model as :-

$$\Delta x^k = [S^k].\Delta u \quad , k=0,1,2,\ldots\ldots\ldots\ldots NO \tag{6}$$

where :- NO = Number of outage states.
This model is used to generate the security related constraints like line flow and bus voltage magnitude limits.

The corrective rescheduling problem can be stated as follows :-

3.1- Objective function

Determine the incremental control Δu such that the new base case control $(u^0 + \Delta u)$ minimizes the total system cost of generation. Representing the system cost of generation by a quadratic function, the objective function is :-

$$f = (a_s + b_s P_{Gs} + c_s . P_{Gs}^2) + \sum_{i=1}^{NP} (a_i + b_i . P_{Gi} + c_i P_{Gi}^2) \tag{7}$$

linearizing this cost function around the base case (x^0, u^0), the incremental cost function is :-

$$\Delta f = d_s^{\backslash} . \Delta P_{Gs} + d_1^{\backslash} . \Delta P_{G1} + d_2^{\backslash} . \Delta P_{G2} + \ldots\ldots\ldots\ldots + d_{NP}^{\backslash} . \Delta P_{GNP} \tag{8}$$

where :- the subscript s denotes the slack bus and $d_j^{\backslash} = b_j + 2C_j . P_{Gj}^0$, $j = 1,2 \ldots\ldots\ldots\ldots\ldots Np$;

NP = *number of generating units*

The network losses for the optimization process are taken into account by considering the changes in the slack bus real power due to changes in control variables. This is achieved through differential relation as :-

$$\Delta P_{Gs} = (\partial P_{Gs} / \partial x)\, \Delta X^0 = (\partial P_{Gs} / \partial x)[S^0].\Delta U = \alpha_1 . \Delta P_1 + \ldots\ldots\ldots + P_1 . Q_1 + \gamma_1 . \Delta t_1 / t_1^0 \tag{9}$$

Equation (9) is called the slack bus loss penalty factor and this equation is used in economic dispatching procedures [5]. Substituting (9) for ΔP_{GS}, in (8), the linearized objective function in terms of the incremental control is :-

$$\Delta f = \sum_{i=1}^{NP}(d_i^{\prime} + d_s^{\prime}.\alpha_i).\Delta P_i + \sum_{j=1}^{NQ} d_s^{\prime}.\beta_j.\Delta Q_j + \sum_{l=1}^{NT} d_s^{\prime}.\gamma_l.\Delta t_l / t_l^0 \qquad (10)$$

$$or:- \quad \Delta f = d^T.\Delta u \qquad (11)$$

where :- d^T is the new incremental cost vector.

3.2- Constraint Equations

The incremental control Δu must be determined such that the new base case control $(u^0 + \Delta u)$ minimizes the total cost of generation and satisfies :-

(i) Control variables constraints

$$u^{\min} \le u^0 + \Delta u \le u^{\max} \qquad (12)$$

(ii) The slack bus power constraints

$$P_{Gs}^{\min} \le P_{Gs}^0 + \Delta P_{Gs} \le P_{Gs}^{\max} \qquad (13)$$

$$Q_{Gs}^{\min} \le Q_{Gs}^0 + \Delta Q_{Gs} \le Q_{Gs}^{\max} \qquad (14)$$

Where ΔP_{Gs} and ΔQ_{Gs} are respectively the changes in the slack bus real and reactive powers.

(iii) Bus voltage magnitude and line flow variables constraints

$$h_{\min}^0 \le h(x^0, u^0, p^0) + \Delta h^0 \le h_{\max}^{o} \qquad (15)$$

(iv) Security Constraints

The security constraints imposed on bus voltage and line flow variable due to the next system contingencies are :-

$$h^{k,\min} \le h(x^k, u^0, p^k) + \Delta h^k \le h^{k,\max} \quad ;$$

$$k = 1,2,\ldots\ldots\ldots\ldots\ldots, NO \qquad (16)$$

where Δh^0 and Δh^k are the changes in the line flow and bus voltage variables in the base case and network outage conditions due to implementation of the incremental control ΔU applied to the base case of system.

3.3 Linear Programming Problem

The main requirements in the linear programming (LP) technique is that the problem variables are restricted to be non negative. But in the formulation proposed in this section, the incremental control Δu is unrestricted in sign (equation 12). To overcome this difficulty, a non-negative vector Y is defined as :-

$$Y = \Delta u - \Delta u^{\min} \qquad (17)$$

where $\Delta u^{min} = u^{min} - u^{0}$. Then the linearized objective function after neglecting the constant terms due to Δu^{min}, is as follows :-

$$\Delta f_1 = d^T.Y \tag{18}$$

The incremental inequality constraints (12),(13),(14) and (16) are expressed in terms of the defined vector Y as :-

$$-Z \geq U^{min} - U^{max} \tag{19}$$

$$-[\partial P_{Gs}/\partial x]^T.[S^0].Y \geq -P_{Gs}^{max} + P_{Gs}^0 + [\partial P_{Gs}/\partial x]^T.[S^0].\Delta U^{min} \tag{20}$$

$$[\partial Q_{Gs}/\partial x]^T.[S^0].Y \geq P_{Gs}^{min} - P_{Gs}^0 - [\partial P_{Gs}/\partial x]^T.[S^0].\Delta U^{min} \tag{21}$$

$$-[\partial Q_{Gs}/\partial x]^T.[S^0].Y \geq -Q_{Gs}^{max} + Q_{Gs}^0 + [\partial Q_{Gs}/\partial x]^T.[S^0].\Delta U^{min} \tag{22}$$

$$[\partial Q_{Gs}/\partial x]^T.[S^0].Y \geq Q_{Gs}^{min} - Q_{Gs}^0 - [\partial Q_{Gs}/\partial x]^T.[S^0].\Delta U^{min} \tag{23}$$

$$[\partial h^k/\partial x].[S^k].Y \geq -h^{k_1 max} + h^k + [\partial h^k/\partial x].[S^k].\Delta U^{min} \tag{24}$$

$$[\partial h^k/\partial x].[S^k].Y \geq h^{k_1 min} - h^k - [\partial h^k/\partial x].[S^0].\Delta U^{min} \tag{25}$$

$$where:- \quad k = 0,1,2,\ldots\ldots\ldots\ldots, NO$$

This is a linear programming problem with linear objective function and linear constraints. The overall problem can be stated as;

Determine Y which minimizes $d^T.Y$

$$\text{subjected to} \quad [A].Y \geq b \qquad \text{and} \quad Y \geq 0 \tag{26}$$

4- COMPUTATIONAL ASPECTS

The purpose of this section is to show the steps required to reduce the CPU memory and to increase the program speed so that the proposed technique is suitable for on-line applications.

4.1 Dual LP Formulation

The dual LP formulation is generally much superior to a primal formulation[6], especially when the number of constraints is very much larger than the control variables. The addition of a constraint equation to the primal problem is equivalent to an addition of a dual variable to the dual LP problem. That is, the linear dependent constraints can be neglected during the execution of the dual LP problem, without affecting the simplex tableau size and the optimal solution [6]. Moreover, post optimal solution can be easily obtained without increasing the simplex tableau size of the dual LP problem.

4.2 Decoupled Model

A decomposition which utilizes the weak interaction between P- δ and Q-V variables in the steady state operating condition of the system is used to further reduce the CPU computation memory. Then neglecting the submatrices N,J in equation (3), we get the decoupled model as :-

$$\Delta\delta = [S_1].\Delta P \tag{27}$$

and

$$\Delta V / V = [S_2] . \begin{bmatrix} \Delta Q \\ \Delta t / t \end{bmatrix} \quad (28)$$

This decoupled model is utilized to generate the slack bus power constraints, security constraints, and objective function. The decoupled model approach essentially makes the dual LP technique, a fast practical on-line algorithm with an acceptable accuracy as shown from results in the following section.

5- THE CORRECTIVE RESCHEDULING ALGORITHM

The solution procedure for corrective rescheduling algorithm is summarized as follows:-
1- For the system base case operating point X^0, obtain the solution for system variables.
2- The outage of one system element in the contingency list is simulated. The security constraints violation of the post-contingency state are checked.
3- Step (2) is repeated for all the outage cases in the postulated next contingency set.
If the base case state is increased, go to step 4. Otherwise, go to step 7.
4- The sensitivity matrix $[S^k]$, $(k=0,1,2,\ldots,No)$ is computed and the linearized objective function constraints on slack bus power generation and the violated seccurity constraints are determined. The dual LP problem is solved for the corrections ΔU.
5- The new system control is obtained by updating the old base case control u^0 as $u_{new} = u^0 + \Delta u$.
6- With the new schedule (U_{new}), obtain the new base case state x^0 and go to step 1.
7- Evaluate the system cost of generation of the new secure base case state, f_{new}.
(i) If $(f_{new} - f_{old})$ < specefied tolerance, stop.
(ii) If $f_{new} < f_{old}$, go to step 4.
(iii) If $f_{new} > f_{old}$, update the system control vector as $u_{new} = u^0 + C\Delta u$ where C is a positive constant and is less than or equal to 0.1 and go to step 6.

6. NUMERICAL APPLICATION

The corrective rescheduling algorithm is tested on IEEE-30 bus system[7]. The test system has 14 control variables (5 real power and 5 reactive power generations and 4 transformer tap ratios). There are 6 contingency cases specefied for this test system, each involving the outage of the line in the system. Table 1 shows the postulated next contingencies and the violated quantities for the specefied initial optimal operating state of the test system.

Table 1- The postulated outages and the violated variables for the test system

Case	Branch outage	Overloaded branches	Voltages violation at buses
1	2	1	17,27,29,30
2	4	1	18,27,29,30
3	5	6.8	18,27,29,30
4	7	None	30
5	33	None	30
6	35	None	26

Though the base case state was normal, in order to prevent the possible limit-violations of the line flow and voltage variables that may occur in the subsequent corrected base case state, the simple security constraints for all the bus voltage and line flow variables are generated and included in the violated-constraints set.

The dual LP formulation is employed to obtain the secure optimal solution. The control variables are real and reactive power generations and transformer tap ratios. The final secure optimum solutions are obtained for (i) full linearized power flow model and (ii) decoupled power flow model. The results for optimum secure active and reactive power generations are given in tables 2 and 3. The optimum tap settings for the regulated transformers are given in table 4, finally table 5 gives the voltage at controllable buses in the test system.

Table 2- Secure optimum results of active power generation

Control variable (MW)	Initial value	Secure optimum Values	
		Full model	Decoupled model
P_{G2}	40.03	44.60	47.12
P_{G5}	21.36	24.60	27.02
P_{G8}	21.08	34.80	35.01
P_{G11}	14.14	26.45	21.80
P_{G13}	13.43	13.64	17.70

Table 3- Secure optimum reactive power results

Control variable (MVAR)	Initial value	Secure optimum Values	
		Full model	Decoupled model
Q_{G2}	29.40	8.00	-12.15
Q_{G5}	31.26	31.16	59.95
Q_{G8}	38.74	49.00	35.87
Q_{G11}	11.02	21.98	-3.34
Q_{G13}	7.70	3.45	31.24

Table 4- Secure optimum tap settings

Transformer designation	Initial value	Secure optimum Values	
		Full model	Decoupled model
t_{4-12}	1.0196	1.100	1.0655
t_{6-9}	1.0410	0.930	0.9090
t_{6-10}	0.9289	0.938	1.0243
t_{28-27}	1.0058	0.976	1.0164

Table 5- Voltage at controllable buses

Controllable bus voltage (p.u.)	Secure optimum values Full model	Secure optimum values Decoupled model
V_1	1.0500	1.0500
V_2	1.0370	1.0356
V_5	1.0202	1.0459
V_8	1.0367	1.0285
V_{11}	1.0486	0.9797
V_{13}	1.0458	1.0634

Table 6 indicates the total system generation and the cost of generation. The results of table 6 show that the cost of generation in case of optimum solution is reduced.

Table 6- Total system generation and its cost

Case	Total generation		Cost $/hr
	P_G (MW)	Q_G (MVA)	
Initial case	239.15	108.93	816.11
Full model	290.70	127.35	803.90
Decoupled model	290.75	125.84	813.73

7. CONCLUSIONS

In this paper an optimal technique for solving the corrective rescheduling problem is introduced. The optimal technique utilized a successive dual linear programming approach. The system real and reactive power generations and transformer tap ratios are optimized within their operating limits, so that no limit violations of the lines power flow and bus voltages magnitudes in either the base case or contingency cases. The proposed technique is successfully implemented to the IEEE-30 bus test system.

The results obtained by the proposed dual LP method (full model) took 6 iterations to reach the secure optimum solution, where as the non linear programming procedure based on gradient method required 25 gradient steps to reach the secure optimum solution. This shows that a fast and reasonably accurate solution can be obtained by the proposed dual LP formulation. Also, the dual LP formulation with decoupled model can be successfully employed, in conjunction with any fast security assessment schemes which utilizes a decoupled approach for a fast on-line security assessment and control.

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