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A Modular Approach to Power Flow Regulation Solution

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Abstract: The operating modes of generations and the voltage states of power system must be solved when calculating and analyzing the power flow problem with operation demands. The generation variable differential were derived as well as the complete principle of variable differential analysis was formed, based on the model of expanded power flow with constraints, by using the implicit function differential method, the linear composing relation between the voltage variable differential and the expanded correction equations which included the equations of PQV node and branch power, solutions were also proposed. This new solving method is not featured in minimum variables however it is featured as a one-time simultaneous solution. Through the IEEE 5 bus system, the analyzing cases of total differential sensitivity and operation under conditions of constant line power and constant node voltage were carried out, these cases described the fact that the mixed variable solving method of power flow regulation has a simple form, small calculation volume and efficiency.

Keywords: Power flow regulation, expanded power flow, PQV node, constrained sensitivity, optimal power flow (OPF).

1. INTRODUCTION

This paper revolves around the question of how to solve the operation point of the system generations, according to the power grid steady-state operation requirement [1-8] based on a given load. i.e.; the problem of power flow regulation or control.

The power system operating level analysis problem is the continued part of the unit commitment, peak-load regulation, and economic analysis, as well as the basic point of the security analysis, stability analysis and frequency control analysis.

Generating power for new energies and distributed generation contains uncertain variation which may result in large change of grid power flow. The current challenge in smart grid development is how to use the conventional generations to maintain the operating condition required by the grid through technical means. However, by making good use of adjustability of conventional generations to be responsible for basic distribution of grid power flow can help FACTS equipments to fully exert their flexible and rapid adjusting functions and produce twice the results with half the effort.

1.1. Basic Form of Power Flow Control Problem

Let the generations operating model be y, grid voltage be x; model that describes the power system electrical characteristics is the power flow equation $g(x, y) = 0$. Grid voltage x is the implicit function of y, which is determined by power flow equation. The grid operating condition can be represented by state variable x and the equality and inequality of its function. In the calculation process, the functioned grid operating conditions can be processed as determined values, i.e.; voltage of certain central point of the grid should be $V_i = V_i^S$, and the transmission power of certain branch should be $P_{ij}(\dot{V}_i, \dot{V}_j) = P_{ij}^S$ and $Q_{ij}(\dot{V}_i, \dot{V}_j) = Q_{ij}^S$.

Set the voltage $x = x_1 \bigcup x_2$, among which the node voltage of the grid operating condition concerned part e is x_1, voltage of other not required nodes (including phase angle) which should be x_2. The grid operating index can be represented as $h(x_1)=0$ (*e.g.* [1, 2, 8, 22]) so that the basic form of the power flow adjusting problem is the simultaneous equation of power flow equation and operating condition equation, i.e.:

$$\begin{cases} g(x, y) = 0 \\ h(x_1) = 0 \end{cases} \tag{1}$$

In Formula (1), part of voltage x_1 in $g(x_1, x_2, y) = 0$ of power flow equation becomes known quantity or function correlation quantity, and part of power supply y_1 becomes the quantity that is to be solved to made x_1 meet the requirements of h. power flow control problem becomes a mixed variable solving form not only to solve x, but also to solve y.

1.2. Solution Methods for Power Flow Control Problem

The generation operation mode arrangement with grid operation conditions, namely the solving method of power flow equation with restriction conditions has always been discussed and researched since the born of power system.

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1874-1290/15 2015 Bentham Open

Table 1. The calculation features of two methods.

	Solving Equation Scale	Equation Solving
Trial and error method	$x = n_g$	multi-time trial solving y
Extreme condition value method	$x = n_{g,}$ $y = n_{f,}$ $\lambda = n_{g,}$ $\gamma = n_h$	one-time simultaneous equation solving x *and* y

The study and discussion for such problem continuously go deeper with the development of the power system and the improvement of operating level. And up till now, there are three types of methods.

1.2.1. Trial and Error Procedure

Since the power flow equation is featured in the state of solving system stable operation status, according to the given generating operation model and system wiring model [5]. So that the power flow adjust problems according to the response. Trial and error procedure comparison is a kind of thought. Early trial method was to make proper adjustment for generations according to the initially excitation set, then solve the grid voltage according to the power flow equation. And then observe the differences between the voltage and the conditions, till it satisfies the requirements [10, 11]. The sensitivity matrix can be used to perform composing adjustment for multiple operative conditions, multiple power supplies and multiple variables [12]. However, the explicit function between the operative object and the generation variables is hard to get which also results in inconvenience for determining the required gradient correction direction.

Applying integration methods in circuit solving such as, probability point/group and optimization modern trial method, shows a good performance in the improved correction methods and reduces the trial times [13, 14].

1.2.2. Condition extreme value method

Condition extreme value method is an optimized method that gets rid of trial and error. Such single point optimization seeking method takes advantage of necessary condition equations for extreme conditions to perform one-time simultaneous equation group solving to satisfy the solution of operating conditions and power flow equation [1, 15].

During recent years, the most optimal power flow model, inequality restrictions, condition effective processing, and algorithm improvements have been applied in the power system which has led to new developments [15-21]. Regarding the power flow control problem, according to the objective of seeking optimized method for single point, the following steps can be taken: ⊖ convert the operating condition $h(x_1)$=0 to be scalar quantity or weighed scalar quantity smooth object function thus, to use the extreme condition method which finally forms the power flow algorithm featured in powerful calculation rules and Newton convergence speed; ⊜ add an optimized objective function additionally which can enrich the analysis contents. And meanwhile, the operating condition can be taken as the inequality restriction condition meanwhile the power flow equation can be taken as the equation restriction condition in order to form the most optimal power flow form.

Make the equation amount of power flow equation $g(x,y_0)$=0 be n_g which is also the amount of voltages x to be solved. The vector dimensions of inequality restriction condition $h(x_1)\geq 0$ is n_h which should also be the amount of relaxation variables. The extreme condition equation amount of scalar quantity object function f should be n_f which is also the amount of generation variable y that are to be solved. As a result the calculation features from the trial and error method and extreme condition value method are given in Table **1**.

1.2.3. Expanded power flow method

Based on the power flow equation, other electricity transmission equations are supplemented to form an expanded power flow model. General power flow in reference [3] points out the solvability and the concept of relaxation generations. Reference [7] indicates that the operation condition shall be the steady-state equilibrium point of the system control. Reference [24] points out that the method for using slack bus function, is to solve branch function type with extreme power. In references [8] and [22], a generator's power supply is based on remote voltage control calculation method which requires, finding the shortest route between the controlling nodes meanwhile the controlled node is being researched upon. Rapid decomposing method based node type expanded power flow calculation solvability is discussed in reference [23]. And the calculation method is applied in power flow control problems. In reference [9], regional exchange power is taken, as the expanded equation to compose simultaneous equations with the power flow equation used for solving it. In conclusion, learners have conducted certain researches in the field of branch power, node voltage operating conditions and simultaneous solving the power flow equation according to the circuit adjustment concept. However, they haven't acquired a comparatively complete theory and algorithm up till now, especially, they haven't acquired any research in sufficient analysis for multiple operating conditions for implicit function and composing function forms. The prospect that whether it can be used for commonly complex function or not, hasn't been represented up till now.

In this paper, based on the expanded power flow concept and through the total differential of power flow equation, the following conclusions have been made:

⊖ Linear composing relation between the corresponding differential *dx* and excitation differential *dy* has been made clear thus, the total differential relation between implicit function and composing function is obtained.

⊜ During the iterative simultaneous solving, the total differential can be used to determine relevant excitation correction Δy according to responding difference Δx. Such mixed variable's simultaneous solving method is not featured in simple form and small calculation volume, but also featured in one-time simultaneous solving of extreme condition method.

2. POWER FLOW CONTROL MODEL AND ITS MIXED VARIABLE SOLVING METHOD

2.1. Power Flow Control Model

The generation shall be represented as PV node which active power P_{Gi} and generator terminal voltage V_{Gi} are adjustable, and a slack bus with adjustable voltage shall be set as well.

Set grid node amount is n, slack bus voltage is V_n, PV node amount is m, PQ node amount is n_{PQ}= n-m-1, make PQ node voltages to be V_D and θ_D, PV node and slack bus voltages to be V_G and θ_G, active power of PV node to be P_G.

Voltage vector x and generation vector y are respectively:

$$x=\begin{bmatrix} \theta_D^T & \theta_G^T & V_D^T \end{bmatrix}^T, y=\begin{bmatrix} P_G^T & V_G^T & V_n \end{bmatrix}^T$$

Where $y=y_1\cup y_2$, y_1 is the generation variable with adjustable capacity. y_2 is the un-adjustable constant generation variable.

Nodal power equations of PQ node and PV node are respectively:

$$g_{PDi}=P_{Gi}^S-P_{Di}-V_i\sum_{j=1}^{n}V_j(G_{ij}\cos\theta_{ij}+B_{ij}\sin\theta_{ij})=0 \qquad (2\text{-}1)$$

$$g_{QDi}=Q_{Gi}^S-Q_{Di}-V_i\sum_{j=1}^{n}V_j(G_{ij}\sin\theta_{ij}-B_{ij}\cos\theta_{ij})=0 \qquad (2\text{-}2)$$

$$g_{PGi}=P_{Gi}-P_{Di}-V_i\sum_{j=1}^{n}V_j(G_{ij}\cos\theta_{ij}+B_{ij}\sin\theta_{ij})=0 \qquad (2\text{-}3)$$

Formula (2) is the power flow equation describing the electrical characteristics of the grid of Formula (1).

The grid operating object equation is: branch power and nodal voltage are the required values, *i.e.*:

$$P_{ij}=-V_i^2G_{ij}+V_iV_j(G_{ij}\cos\theta_{ij}+B_{ij}\sin\theta_{ij})-P_{ij}^s=0 \qquad (3\text{-}1)$$

$$Q_{ij}=V_i^2B_{ij}+V_iV_j(G_{ij}\sin\theta_{ij}-B_{ij}\cos\theta_{ij})-Q_{ij}^S=0 \qquad (3\text{-}2)$$

$$g_{Vk}=V_k^S-V_k=0 \qquad (3\text{-}3)$$

$$V_{l\min}\le V_l\le V_{l\max} \qquad (3\text{-}4)$$

Formula (3) is the grid operating condition equation of Formula (1). Formula (2) and (3) simultaneous equations are the simultaneous power flow form of power flow equations and operation condition equations.

2.2. Sensitivity of Generation Variable to Voltage Variable

Under power flow equation conditions, the sensitivity of grid state variable x to generation variable y is the key point for solving generation derivative dy according to the requirement of voltage derivative dx. Total differential for Formula (2) implicit's function equation is

$$dg=\frac{\partial g}{\partial x}dx+\frac{\partial g}{\partial y}dy=0 \qquad (4)$$

Where

$$dx=\begin{bmatrix} d\theta_1\\ \vdots\\ d\theta_{n-1}\\ dV_1\\ \vdots\\ dV_{n-m-1}\end{bmatrix},\quad dy=\begin{bmatrix} dV_{G1}\\ \vdots\\ dV_{Gm}\\ dP_{G1}\\ \vdots\\ dP_{Gm}\\ dV_n\end{bmatrix}$$

Specific form $g(x,y)=0$ of Formula (2), total differential Formula (4) is

$$\begin{bmatrix} \frac{\partial g_{PD}}{\partial\theta} & \frac{\partial g_{PD}}{\partial V_D}\\ \frac{\partial g_{PG}}{\partial\theta} & \frac{\partial g_{PG}}{\partial V_D}\\ \frac{\partial g_{QD}}{\partial\theta} & \frac{\partial g_{QD}}{\partial V_D}\end{bmatrix}\begin{bmatrix} d\theta_1\\ \vdots\\ d\theta_{n-1}\\ dV_1\\ \vdots\\ dV_{n-m-1}\end{bmatrix}=-\begin{bmatrix} \sum_{i\in m}\frac{\partial g_{PD1}}{\partial V_{Gi}}dV_{Gi}\\ \vdots\\ \sum_{i\in m}\frac{\partial g_{PDn-m-1}}{\partial V_{Gi}}dV_{Gi}\\ dP_{G1}+\frac{\partial g_{PG1}}{\partial V_{G1}}dV_{G1}\\ \vdots\\ dP_{Gm}+\frac{\partial g_{PGm}}{\partial V_{Gm}}dV_{Gm}\\ \sum_{i\in m}\frac{\partial g_{QD1}}{\partial V_{Gi}}dV_{Gi}\\ \vdots\\ \sum_{i\in m}\frac{\partial g_{QDn-m-1}}{\partial V_{Gi}}dV_{Gi}\end{bmatrix} \qquad (5)$$

Setting $dy_i=1$, $dy_j=0$ (i=1,2,…,2m+1, $j\ne i$),solving dxi successively:

$$\frac{\partial g}{\partial x}dx_i = -\frac{\partial g}{\partial y}\begin{bmatrix} 0 \\ \vdots \\ 1 \\ \vdots \\ 0 \end{bmatrix} \tag{6}$$

$-J^{-1}\dfrac{\partial g}{\partial y} = D \in R^{(n-1+n_{PQ})\times\blacklozenge 2m+1\blacklozenge}$, which is composed of dx, is the sensitivity matrix of the load node voltage to the adjustable generation excitation. D reflects the rate of change of x to y. and J^{-1} reflects the rate of change of x to g.

Therefore, the differential coefficient relation formula of dx and dy shall be:

$$dx = Ddy \qquad x \in R^{n-1+n_{PQ}}, y \in R^{2m+1} \tag{7}$$

Generally, D is not a square matrix which reflects the multiple solutions feature when determining y by x.

2.3.. PQV Node Sensitivity Correlation Solving

The nodes, with active power, reactive power and nodal voltage amplitude shall all be given values, and can be called the PQV nodes. When the voltage of PQ node becomes a fixed value due to the restriction of operating conditions, this PQ node shall become the PQV node.

Among the node voltage x, make x_1 be the node voltage that is concerned by the grid operating condition or reaches inequality boundary for functioning, let x_2 be the voltage meeting other operating restrictions of the grid or within the inequality boundary for not functioning, and $x = x_1 \cup x_2$. Make x_1' be the voltage that reaching their boundaries in Formula (3-3) and (3-4), x_1'' be the node voltage required by the branch power equation represented by Formula (3-1) and (3-2).

According to the above classification for the node voltage, Formula (7) can be represented to be

$$\begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix}\begin{bmatrix} dy_1 \\ dy_2 = 0 \end{bmatrix} \tag{8}$$

Where, dx_2 can be of any value. And since y_2 is not adjustable, $dy_2=0$. And then

$$dx_1 = D_{11}dy_1$$

According to the different functions of x_1, the following can be got:

$$\begin{bmatrix} dx_1' \\ dx_1'' \end{bmatrix} = \begin{bmatrix} D_{11}' & D_{12}' \\ D_{21}' & D_{22}' \end{bmatrix}\begin{bmatrix} dy_1' \\ dy_1'' \end{bmatrix} \tag{9}$$

Operating condition Formulas (3-1) and (3-2) are the composite function of x_1'', and the value of x_1'' shall be determined by the composite function of its value.

For the operating requirement of x_1', if the control method of "one control variable is required for one operating object" it is adopted, for No. i component x_{1i}' in x_1', y_{1i}' corresponding to the comparatively large diagonal element value of No.i line of D_{11}' shall be selected as the generation for the adjustment of x_{1i}'. This is one of the methods used for solving the Formula (1) which is also the most sensitive generation adjustment way for adjusting dx'_1 according to dy'_1 with the minimum adjustment amount and variables.

Therefore, reversible square matrix D_{11}' can be used to connect dx_1' and dy_1' in linear relation, i.e.:

$$dx_1' = D_{11}'dy_1' \tag{10}$$

PQV node voltage x_1' can be represented by loosening corresponding generation voltage y_1'. Under this condition, other y_1'' can be used for other purposes.

D. Solving Iterative Format for Mixed Variable Model

For simultaneous solving power flow equation Formula (2) and branch power condition equation Formula (3-1) and (3-2), since the iterative process involves step by step imminent calculations, whereas the correction quantity each time is comparatively small and according to the purpose of simplifying calculation, it shall be considered that x, y, and their component elements are independent in iterative calculation process. Therefore, the linear forms of Formula (2) and (3-1), (3-2) shall be:

$$\Delta g_{PD} = \frac{\partial g_{PD}}{\partial \theta_D}\Delta\theta_D + \frac{\partial g_{PD}}{\partial \theta_G}\Delta\theta_G + \frac{\partial g_{PD}}{\partial V_D}\Delta V_D + \frac{\partial g_{PD}}{\partial V_G}\Delta V_G + \frac{\partial g_{PD}}{\partial P_G}\Delta P_G$$

$$\Delta g_{PG} = \frac{\partial g_{PG}}{\partial \theta_D}\Delta\theta_D + \frac{\partial g_{PG}}{\partial \theta_G}\Delta\theta_G + \frac{\partial g_{PG}}{\partial V_D}\Delta V_D + \frac{\partial g_{PG}}{\partial V_G}\Delta V_G + \frac{\partial g_{PG}}{\partial P_G}\Delta P_G$$

$$\Delta g_{QD} = \frac{\partial g_{QD}}{\partial \theta_D}\Delta\theta_D + \frac{\partial g_{QD}}{\partial \theta_G}\Delta\theta_G + \frac{\partial g_{QD}}{\partial V_D}\Delta V_D + \frac{\partial g_{QD}}{\partial V_G}\Delta V_G + \frac{\partial g_{QD}}{\partial P_G}\Delta P_G$$

$$\Delta P_{line} = \frac{\partial P_{line}}{\partial \theta_D}\Delta\theta_D + \frac{\partial P_{line}}{\partial \theta_G}\Delta\theta_G + \frac{\partial P_{line}}{\partial V_D}\Delta V_D + \frac{\partial P_{line}}{\partial V_G}\Delta V_G + \frac{\partial P_{line}}{\partial P_G}\Delta P_G$$

$$\Delta Q_{line} = \frac{\partial Q_{line}}{\partial \theta_D}\Delta\theta_D + \frac{\partial Q_{line}}{\partial \theta_G}\Delta\theta_G + \frac{\partial Q_{line}}{\partial V_D}\Delta V_D + \frac{\partial Q_{line}}{\partial V_G}\Delta V_G + \frac{\partial Q_{line}}{\partial P_G}\Delta P_G$$

For the specific form of the simultaneous equation, the correct equation adopted when taking Newton method for solving the simultaneous equation shall be

$$\begin{bmatrix} \Delta g_{PD} \\ \Delta g_{PG} \\ \Delta g_{QD} \\ \Delta P_{Line} \\ \Delta Q_{Line} \end{bmatrix} = \begin{bmatrix} H_{DD} & H_{DG} & N_{DD} & \frac{\partial g_{PD}}{\partial V_{G_{y_1}}} & 0 \\ H_{GD} & H_{GG} & N_{GD} & \frac{\partial g_{PG}}{\partial V_{G_{y_1}}} & \frac{\partial g_{PG}}{\partial P_{G_{y_1}}} \\ M_{DD} & M_{DG} & L_{DD} & \frac{\partial g_{QD}}{\partial V_{G_{y_1}}} & 0 \\ \frac{\partial P_{Line}}{\partial \theta_D} & \frac{\partial P_{Line}}{\partial \theta_G} & \frac{\partial P_{Line}}{\partial V_D} & \frac{\partial P_{line}}{\partial V_{G_{y_1}}} & 0 \\ \frac{\partial Q_{Line}}{\partial \theta_D} & \frac{\partial Q_{Line}}{\partial \theta_G} & \frac{\partial Q_{Line}}{\partial V_D} & \frac{\partial P_{line}}{\partial V_{G_{y_1}}} & 0 \end{bmatrix} \bullet \begin{bmatrix} \Delta\theta_D \\ \Delta\theta_G \\ \Delta V_D \\ \Delta V_{G_{y_1}} \\ \Delta P_{G_{y_1}} \end{bmatrix} \tag{11}$$

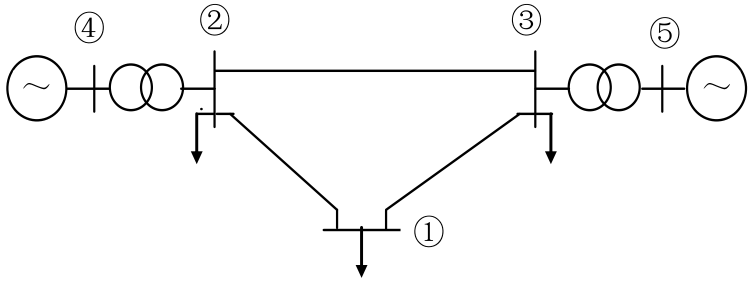

Fig. (1). IEEE 5 buses system.

Table 2. J^{-1} **of IEEE5 system.**

$\partial\theta_1$	**0.2916**	**-0.1302**	**-0.0030**	**-0.1301**	**-0.0025**	**-0.0002**	**-0.0007**
$\partial\theta_2$	-0.1409	-0.2255	-0.0029	-0.2263	0.0354	0.0011	0.0002
$\partial\theta_3$	-0.0030	-0.0022	-0.0029	-0.0022	-0.0006	-0.0001	-0.2259
$\partial\theta_4$	-0.1405	-0.2259	-0.0029	-0.2406	0.0037	0.0120	0.0002
∂V_1	-0.1098	0.0357	-0.0002	0.0369	-0.2759	-0.0017	-0.0022
∂V_2	-0.0008	0.0005	-0.0000	0.0006	-0.0018	-0.0015	-0.0029
∂V_3	0.00004	0.0016	-0.0002	0.0016	-0.0252	-0.0003	-0.0030
	$/\partial P_1$	$/\partial P_2$	$/\partial P_3$	$/\partial P_4$	$/\partial Q_1$	$/\partial Q_2$	$/\partial Q_3$

And

$$\Delta V_k' = \frac{\partial V_k'}{\partial V_{Gy1}'} \Delta V_{Gy1}' \tag{12}$$

Therefore, the unbalanced power of Formula (2), (3-1), (3-2) can be equalized by the node voltage correction.

That is, voltage correction quantity Δx corresponding to the unbalance quantity can be obtained by (11).

For PQV node of Formula (3-3) and (3-4), among Δx, $\Delta x_1'$ is required for power balance for the equation; also, x_1' is a determined value or limited by boundary values. Relevant generation correction shall be taken to convert the voltage difference of PQV node, then, according to Formula (12), relevant generation correction quantity shall be:

$$\Delta y_1' = -D_{11}'^{-1} \Delta x_1' \tag{13}$$

Formula (13) is generation correction $\Delta y_1'$ according to $\Delta x_1'$. Since $\Delta x_1'$ difference has been adjusted by $\Delta y_1'$, it needs not to perform x_1' correction, so:

$$\Delta x_1' = 0$$

Thus x_1' of PQV node is fixed without the "adhere" phenomenon during solution. Therefore, the variable correction is:

$$x^{(k+1)} = x^{(k)} + \Delta x^{(k)} \tag{14-1}$$

$$y^{(k+1)} = y^{(k)} + \Delta y_1^{(k)} \tag{14-2}$$

The above algorithm process, it is a relaxed equation, taking the operating condition as the power flow equation variable y to satisfy the operating condition and power flow equation solutions. Solving for the correction equation is the decoupling alternative calculation of power equation and voltage value equation which constitutes a solving model concerning no intermediate variables and minimum variables.

3. EXAMPLE AND ANALYSIS

Fig. (**1**) is the IEEE 5 buses system which is featured in both-sided power supplies and has a large impact on generation adjusting to power flow change. That's why the author choose it for the principle analysis in this paper.

3.1. Characteristics of Sensitivity of Generation Variable to Voltage Variable

For IEEE 5 buses system, under the commonly power flow model, assuming P_{G4}=5.0,V_{G4}=1.05 for *PV* node and V_{G5}=1.05 for slack bus, Jacobi reverse matrix of the system, namely the sensitivity matrix J^{-1} of nodal voltage to nodal power is as listed in Table **2**.

According to Formula (4), taking J^{-1} as the linear composing, the sensitivity matrix *D* of power supply variable to node voltage can be got:

Table 3. Sensitivity Matrix of IEEE5 system.

$\partial\theta_1$	**-0.130063**	**0.104065**	**0.3094748**
$\partial\theta_2$	-0.226278	-0.752479	0.0101792
$\partial\theta_3$	-0.022318	0.0385760	0.1479132
$\partial\theta_4$	-0.240640	-0.887581	0.0040555
∂V_1	0.036850	1.171819	0.7170643
∂V_2	0.006373	1.061348	0.0946380
∂V_3	0.016022	0.2183929	0.9949665
	$/ \partial P_{G4}$	$/ \partial V_{G4}$	$/ \partial V_{G5}$

Table 4. Example schemes of power flow regulation.

	Operating Conditions	Generation Composing Adjusting Model
solution 1	V_3=1.05, P_{23}= 0.2	P_{G4} adjusts line active power P_{23} V_{G5} adjusts voltage V_3
solution 2	V_3=1.05, P_{23}=Q_{23}=0.2	P_{G4} and V_{G4}adjusts line active power P_{23} and reactive power Q_{23} V_{G5} adjusts voltage V_3
solution 3	V_1=0.87 branch 2-3 stops working	P_{G4}=4.7 V_{G4} adjusts voltage V_1
solution 4	V_1=0.87 branch 1-3 stops working	P_{G4}=4.7 V_{G4} adjusts voltage V_1

$$D = -J^{-1}\frac{\partial g}{\partial y}$$

D matrix of this system is listed in Table **3**.

Comparing J^{1}-Matrix of Table **2** and D-matrix of Table **3**, there are obvious differences which are stated as follows:

①D is the linear composing of J^{1}, D is easy to be acquired by calculation based on J^{1}.

②Since the reactive power Q_G of generation model of PV node is a value to be solved and is not listed in reactive balance equation, J^{1} doesn't concern the generation adjusting sensitivity $\frac{\partial V}{\partial V_G}$ or $\frac{\partial V}{\partial Q_G}$, so that J^{1} is not proper to be used in voltage adjustable operating model. Whereas, D is suitable for being used in the analysis of the impact of the generation adjustment to the grid voltage.

③It is not difficult to choose the adjustable generation with obvious adjusting effect according to the values of $\frac{\partial V}{\partial V_G}$ in D-Matrix.

3.2. Power Flow Calculation Case with Branch Power and Node Voltage Condition

The operating conditions for values required by line transmission power or load point voltage are set in the power flow adjusting model listed in Table **3**. And the generation composing adjusting model adopted according to the operating condition requirements are also listed in Table **3**. The power flow calculation results from the power flow adjusting solutions listed in Table **4** are listed in Table **5**.

From the view of control, in order to realize good control effect, the control model with best effect shall be selected from multiple control solutions. For the calculation case in this paper, the adopted power supply composing adjusting model is a " one-to-one" model which takes one control power supply for one control object. This is an easy and visual classic single variable control model which can also be used for instructing the feasibility and effectiveness of mixed variable direct solving method.

This IEEE 5 system contains three generation variables, including adjustable voltage V_{G5} of the slack bus, adjustable active P_{G4} of PV node, and adjustable voltage V_{G4}. In Solution-1, two generation variables are adopted for two operating objects, there is still one generation variable V_{G4} that can

Table 5. Calculations of power flow regulation.

	Solution 1 V_3=1.05 P_{23}= 0.2	Solution 2 V_3=1.05 P_{23}= 0.2 Q_{23}= 0.2	Solution 3 V_1=0.87 branch 2-3 stops working	Solution 4 V_1=0.87 branch 1-3 stops working
V_1 / P.U	0.88679	0.91699	0.87	0.87
V_2 / P.U	1.08191	1.11728	1.23144	1.19945
V_3 / P.U	1.05	1.05	1.02956	1.07193
V_4 / P.U	1.05	1.08493	1.20863	1.17290
V_5 / P.U	1.04732	1.04095	1.05	1.05
θ_1 / rad	-0.32009	-0.31583	0.28155	-0.24647
θ_2 / rad	-0.07064	-0.08155	0.86753	0.12169
θ_3 / rad	-0.11881	-0.11906	-0.08796	-0.07875
θ_4 / rad	-0.02523	-0.03886	0.91728	0.17433
P_{23} / P.U	0.2	0.2		
*Q_{23} / P.U	-0.22647	-0.11208		
Ploss /P.U	0.11233	0.10648	0.41506	0.21122

* Grounding capacitance branch is calculated in Q_{23}. The power transmission condition of the calculation case doesn't include the grounding capacitance branch.

be used for other purposes. Therefore, the correction equation format of the mixed variable direct solving of Formula (8) is:

$$\begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta P_{23} \end{bmatrix} = \begin{bmatrix} H & N & \frac{\partial P}{\partial P_{G4}} \\ M & L & 0 \\ \frac{\partial P_{23}}{\partial \theta} & \frac{\partial P_{23}}{\partial V} & 0 \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \\ \Delta P_{G4} \end{bmatrix},$$

And $\Delta V_3 = \frac{\partial V_3}{\partial V_{G5}} \Delta V_{G5}$

It solves the correction quantity of voltage θ, V and generation P_{G4} and V_{G5} according to the node power unbalance ΔP and ΔQ, and the branch power difference ΔP_{23} and node voltage difference ΔV_3. It is also a solution model concerning the fact that there are no intermediate variables and minimum variables.

Solution 1 takes two generation variables to control two operating objects. Solution 2 takes three generation variables to control three operating objects. The calculation results of Solution 1 and Solution 2 in Table **5** show that, the adoption of mixed variable simultaneous solving algorithm is convenient for realizing the analysis and calculation of multi-objective line power or transmission interface power.

The impedances of the loop network for this IEEE 5 system is seriously differed. The grid feature can have big change resulted by the branch removal event of electromagnetically coupled power loop. When taking V_{G5}=1.05 for slack bus and P_{G4}=4.7,V_{G4}=1.05 for PV node, the N-1 analysis is performed when any element of branch 1-2, 2-3 and 3-1 stops working, the failure of required load power supply will lead to system blackout.

The results of Solution 3 and 4 in Table **4** show that V_{G4} could be adjusted in order to maintain V_1=0.87, in the condition where branch 2-3 or branch 1-3 stops working. This expanded power flow could be easily calculated, also the analysis of loop network could be performed by means introduced in these paper.

CONCLUSION

Total differential coefficient can be further constituted based on the implicit function total differential coefficient of the power flow equation, which reflects the impact of the generation variable increment to the operating conditions. By using these differential relations, during the process of mixed variable simultaneous iterative solving between the power flow equation and operating condition, the solving model concerning no intermediate variables and minimum variables can be performed, which can be considered as a power flow equation from single point calculation method with restricted conditions. In this case, through the comparison with Jacobi matrix reverse J^1, it instructs the sensitivity of matrix D from the generation variable to the voltage variable, which can reflect the linear composing relation between the generation differential coefficient and the voltage differential coefficient more accurately. Through the IEEE 5 bus system, it describes the fact that the mixed variable's direct solving method for power flow control problem can search for direction in gradient manner and correctly reach single or multi-operating conditions.

It is hoped that Power flow solving method with restriction conditions will become the simple form of restriction condition processing in order to obtain the most optimal power flow calculations.

Based on the mixed variable direct simple point solving and the power flow equation total differential coefficient sensitivity matrix D, the composing function differential relation analysis can be performed. It is recommended for performing the analysis of multiple single point optimizations.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

This paper belongs to the project of the "Innovation Project of Guangxi Graduate Education", No. GXU11T31069

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Received: December 15, 2014 Revised: January 04, 2015 Accepted: February 25, 2015