새로운 행렬 분할법을 이용한 최적 무효전력/전압 제어

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OPTIMAL REACTIVE POWER AND VOLTAGE CONTROL USING A NEW MATRIX DECOMPOSITION METHOD

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ABSTRACT
A new algorithm is suggested to solve the optimal reactive power control(optimal VAR control) problem. An efficient computer program based on the latest achievements in the sparse matrix/vector techniques has been developed for this purpose. The model minimizes the real power losses in the system. The constraints include the reactive power limits of the generators , limits on the bus voltages and the operating limits of control variables- the transformer tap positions, generator terminal voltages and switchable reactive power sources. The method developed herein employs linearized sensitivity relationships of power systems to establish both the objective function for minimizing the system losses and the system ' performance sensitivities relating dependent and control variables. The algorithm consists of two modules, i.e. the Q-V module for reactive power-voltage control, Load flow module for computational error adjustments. In particular, the acceleration factor technique is introduced to enhance the convergence property in Q-module, The combined use of the afore-mentioned two modules ensures more effective and efficient solutions for optimal reactive power dispatch problems. Results of the application of the method to the sample system and other worst-case systems demonstrated that the algorithm suggested herein is compared favourably with conventional ones in terms of computation accuracy and convergence characteristics.

I. INTRODUCTION

The control of reactive power and voltages represents one of the most important activities in the operation of modern power systems. This control is known as the "voltage/reactive power" or voltage/ VAR" control. Generically, any changes to the system configuration or in power demands can result in higher or lower voltages in the system. This situation can be improved by the operator by allocating reactive power sources in the system, i.e., by adjusting transformer taps, changing generator voltages and switching shunt capacitors/reactors. Also, it is possible to minimize active power losses or production cost in systems by reactive power reallocation. The main objective of this control can be regarded as an attempt to achieve an overall improvement of system security, service quality and economy. System security requires adequate voltage levels and reactive reserves in order to maintain voltage stability when critical contingencies occur. The service quality and economy require appropriate voltage control at all system nodes and consumer terminals within tolerable limits, in order to insure adequate reactive power line flows which result in minimal transmission losses.[1]

In the past, many methods using sensitivity relationships and gradient search technique have reported to solve reasonably the complexity of this voltage/VAR control problem.[2,3] Dommel and Tiney [4] minimized a nonlinear objective function of production costs or losses using Kuhn-Tucker conditions. Hano[2], Mamandur[5], Elangovan[6] developed sensitivity relationships to minimize the system losses. And, other investigators presented a method of minimizing the production cost by coordinating real and reactive power allocations in the system.[7]

This paper presents a new algorithm for solving reactive power-voltage control problem in order to obtain the economic operation condition of electric power system. The suggested method is based upon two modules coupled to each other. First, Q-module optimally determines the reactive power output of generators and shunt capacitor/reactor as well as transformer tap settings with the assumption that the real power generation is held constant. Second, the load flow module is used to make the fine adjustment of the error resulting from the Q-module. The main features of the algorithm suggested here are summarized as follows:

(1) The Q-V module takes over the objective function with bus voltages and transformer taps only as the independent variables. Here, the objective function is also a linearized version.
(2) Mathematical model is developed by using the sensitivity relationships between dependent and control variables for the objective function and all network performance constraints. This model is done by decomposing the jacobian matrix of NR load flow equation which is augmented to include coefficients representing the changes in real and reactive power with respect to the changes in tap settings of the transformer.[7,8]
(3) In order to preserve the sparsity of constraints matrix, the system voltages and the transformer tap settings are adopted as the independent variables, thus the sparsity technique is fully utilized in performing Q-module.
(4) By introducing the accelerating factor, the convergence property to the optimal operation condition, without zigzagging or oscillation, is obtained.

II. MATHEMATICAL MODEL

II-1. Constraints

All system performance constraints to be satisfied and control variable constraints to be maintained are as follows:

The generator voltage magnitudes are constrained by the limits on the excitation and the load bus voltage magnitudes have upper and lower limit by service performance sense.

$$V_{min} \le V \le V_{max} \quad \text{---- (1)}$$

where,

V : vector of bus voltage

$(\cdot)_{max}$: upper bound of $(\cdot)$

$(\cdot)_{min}$: lower bound of $(\cdot)$

The reactive power generation of all generators have their upper and lower values limited by the design specifications. Also the load bus which have reactive power compensation devices are assumed to have finite capacity.

$$Q_{min} \le Q \le Q_{max} \quad \text{---- (2)}$$

where,

Q : vector of reactive power generation

There are also physical limits for the upper and lower values of transformer tap settings.

$$T_{min} \le T \le T_{max} \quad \text{---- (3)}$$

where,

T : vector of transformer tap ratio

And the system is constrained by the real and reactive power supply and demand balance equation.

$$G(P, Q) = 0 \quad \text{---- (4)}$$

where,

P : vector of real power generation

In general, the transmission line capacity is constrained by the physical property of the conductor such as thermal capacity.

$$H(V, \delta) \le H_{max} \quad \text{---- (5)}$$

where,

δ : vector of bus voltage angle

Defining

$$\begin{aligned} \Delta V_{max} &= V_{max} - V \\ \Delta V_{min} &= V_{min} - V \\ \Delta Q_{max} &= Q_{max} - Q \\ \Delta Q_{min} &= Q_{min} - Q \\ \Delta T_{max} &= T_{max} - T \\ \Delta T_{min} &= T_{min} - T, \end{aligned}$$

constraints (1) - (5) can be modified as :

$$\left.\begin{aligned} \Delta V_{min} &\le \Delta V \le \Delta V_{max} \\ \Delta Q_{min} &\le \Delta Q \le \Delta Q_{max} \\ \Delta T_{min} &\le \Delta T \le \Delta T_{max} \\ G(\Delta P, \Delta Q) &= 0 \\ H(\Delta V, \Delta\delta) &\le H_{max} \end{aligned}\right] \quad \text{---- (6)}$$

II-2. Formulation of optimization problem

From equation (6), the optimal reactive power dispatch problem is mathematically formulated as follows:

$$\left.\begin{aligned} &\text{Minimize} \quad f(\Delta Q) \\ &\text{subject to} \\ &\quad \Delta V_{min} \le \Delta V \le \Delta V_{max} \\ &\quad \Delta Q_{min} \le \Delta Q \le \Delta Q_{max} \\ &\quad \Delta T_{min} \le \Delta T \le \Delta T_{max} \\ &\quad G(\Delta P, \Delta Q) = 0 \\ &\quad H(\Delta V, \Delta\delta) \le H_{max} \end{aligned}\right] \quad \text{---- (7)}$$

where, $f(\Delta Q)$: objective function for Q-optimization module which is derived in detail in the later section

Here, it is noted that ΔQ is a dependent variable depending on control variables ΔV, ΔT. The most important reason why the bus voltage V is adopted as control variable in Q-module, is to preserve the sparsity of constraints matrix. The consideration of line flow constraints is optional to avoid unnecessary restrictions that increase computation time and deteriorate the computational efficiency.

II-3 Derivation of sensitivity relationships

The sensitivity relationships between the control variables and the dependent variables are derived as:

Partitioning the jacobian matrix defined from the power flow calculation using the Newton Raphson method,

$$\begin{bmatrix} \Delta P_s \\ \Delta P_g \\ \Delta P_l \\ \Delta Q_{sgc} \\ \Delta Q_{l'} \end{bmatrix} = \begin{bmatrix} J_{pds} & J_{pvs} & J_{pts} \\ J_{pd} & J_{pv} & J_{pt} \\ J^{sgc}_{qd} & J^{sgc}_{qv} & J^{sgc}_{qt} \\ J^{l'}_{qd} & J^{l'}_{qv} & J^{l'}_{qt} \end{bmatrix} \begin{bmatrix} \Delta\delta_s \\ \Delta\delta_g \\ \Delta\delta_l \\ \Delta V \\ \Delta T \end{bmatrix} \quad \text{---- (8)}$$

where,

subscript/superscript s,g,c,l,l' : indices for the slack generator, other generator, load bus with the reactive power compensation devices, total load bus, load bus without the reactive power compensation devices, respectively.

Using the condition that the phase angle of slack bus does not change, $\delta_s = 0$, the incremental real power can be derived from equation (8) in terms of power angle as :

$$\Delta P_s = J_{pds} \begin{vmatrix} \Delta\delta_g \\ \Delta\delta_l \end{vmatrix} + J_{pvs}\cdot\Delta V + J_{pts}\cdot\Delta T \quad \text{---- (9)}$$

$$\begin{vmatrix} \Delta P_g \\ \Delta P_l \end{vmatrix} = J_{pd} \begin{vmatrix} \Delta\delta_g \\ \Delta\delta_l \end{vmatrix} + J_{pv}\cdot\Delta V + J_{pt}\cdot\Delta T \quad \text{---- (10)}$$

With the use of equations (9) and (10), we get

$$\Delta P_s = J_{pds}\cdot J_{pd}^{-1} \begin{vmatrix} \Delta P_g \\ \Delta P_l \end{vmatrix} + \left| J_{pvs} - J_{pds}\cdot J_{pd}^{-1}\cdot J_{pv} \right| \Delta V$$

$$+ \left| J_{pts} - J_{pds}\cdot J_{pd}^{-1}\cdot J_{pt} \right| \Delta T \quad \text{---- (11)}$$

Let $J_b \equiv J_{pvs} - J_{pds}\cdot J_{pd}^{-1}\cdot J_{pv}$, $\quad J_c \equiv J_{pts} - J_{pds}\cdot J_{pd}^{-1}\cdot J_{pt}$.

Supposing that the real power of load bus is constant value, $\Delta P_l = 0$, equation (11) is transformed into :

$$\Delta Ps = Ja \cdot |\Delta Pg| + Jb \cdot \Delta V + Jc \cdot \Delta T \qquad \text{---- (12)}$$

where,

Ja : row vector with the first [m - 1] elements of matrix product $Jpds \cdot Jpd^{-1}$

It is noted that the relation in equation (12) representing the mutual dependency among real generation powers replaces the conventional supply and demand balance equation. Also, using another assumption that the variation of phase angle does not have an effect on the reactive power, the incremental reactive power in equation (8) is redefined as:

$$\Delta Ql' = Jqv^{l'} \cdot \Delta V + Jqt^{l'} \cdot \Delta T \qquad \text{---- (13)}$$

$$\Delta Qsgc = Jqv^{sgc} \cdot \Delta V + Jqt^{sgc} \cdot \Delta T \qquad \text{---- (14)}$$

Consequently, from the above equations the Q-optimization module is summarized as follows:

III. Q-OPTIMIZATION MODULE

In constructing the objective function from equation (12) for Q-optimization module, it is assumed that the real power generation P is not changed since the system state with the optimal real power generation schedule is the starting point for this algorithm. With the use of above discussion, the equation (12) is transformed into:

$$\Delta Ps = Jb \cdot \Delta V + Jc \cdot \Delta T \qquad \text{---- (15)}$$

In this paper, equation (15) is used the objective function for Q-optimization module. Apparently it looks like an absurd job, however, this is attributed to the fact that an equivalent alternative to that of minimizing the system losses is to minimize the slack power generation.[5] Consequently, the objective function for Q-optimization module is converted into the function of variables, ΔV, ΔT only.

$$f(\Delta V, \Delta T) = [Jb \cdot \Delta V + Jc \cdot \Delta T] \qquad \text{---- (16)}$$

In order to develop the Q-module with objective function in equation (16), the system performance constraints are constructed by the equations (14) and (15). The results are summarized as :

$$\left.\begin{array}{l} \text{Minimize} \quad f(\Delta V, \Delta T) \\ \text{subject to} \\ \quad Jqv^{l'} \cdot \Delta V + Jqt^{l'} \cdot \Delta T = 0 \\ \quad \Delta Qmin \le Jqv^{sgc} \cdot \Delta V + Jqt^{sgc} \cdot \Delta T \le \Delta Qmax \\ \quad \Delta Vmin \le \Delta V \le \Delta Vmax \\ \quad \Delta Tmin \le \Delta T \le \Delta Tmax \end{array}\right] \qquad \text{---- (17)}$$

IV. LOAD FLOW MODULE

The above-mentioned Q-optimization problem is solved by using the optimization technique (G.P.) [9] with the assumption of the approximated linearized objective function and constraints as given in equation (17). Thus, its solutions are not exact optimal values. Therefore, it is necessary to use the load flow procedure for making fine adjustments on those optimal values.

V. COMPUTATIONAL PROCEDURE

The following steps describe how to find an optimal solution of the optimal reactive power dispatch problem discussed above.

step 1) Perform the initial power flow calculation to determine the state of system.

step 2) Calculate Jb, Jc matrices and construct Q-optimization problem in terms of information drawn from load flow calculation.

step 3) Solve the Q-optimization problem.

step 4) With the use of control variables ΔV, ΔT, obtained in step 3) and the acceleration factor introduced to enhance the convergence property, update the states as:

$$V \longleftarrow V + \alpha \cdot \Delta V$$
$$Q \longleftarrow Q + Jqv \cdot \alpha \cdot \Delta V + Jqt \cdot \alpha \cdot \Delta T$$
$$T \longleftarrow T + \alpha \cdot \Delta T$$

where,

α : acceleration factor to ensure the convergence, the recommended value is 0.55 ~ 0.75 (by simulation)

As the procedure is iterated, the value of acceleration factor is changed by the appropriate weighting value(AWV) (about AWV= 0.83 by simulation).

step 5) For the capacitor/reactor switching and transformer tap settings, the control actions have to be rounded to the nearest step, so the control action is realizable. (This step is also optional)

step 6) Perform the power flow calculation to adjust the error caused by linearization and obtain the improved state of system.

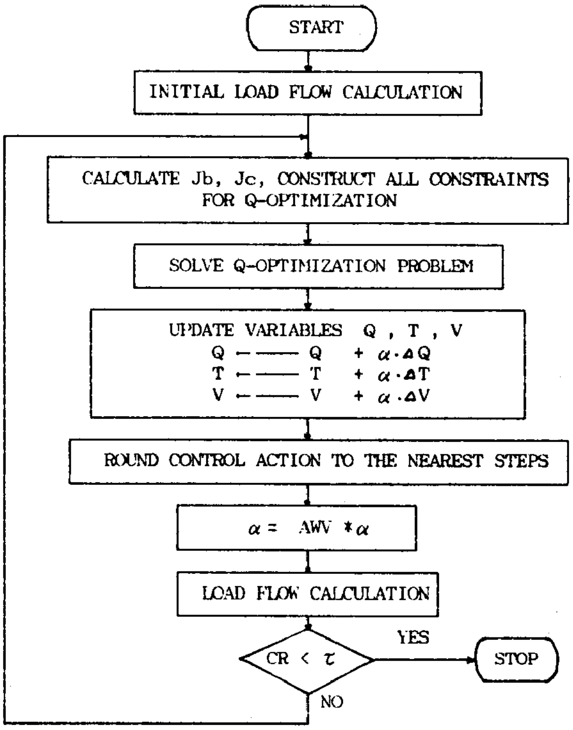

Fig.1. FLOW CHART OF ALGORITHM

step 7) Define the cost regulation as:

$$CR = \frac{\text{previous fuel cost} - \text{present fuel cost}}{\text{previous fuel cost}}$$

Check whether the absolute value of CR is within the predesignated limit (τ) or not. If the answer is negative, the process will be repeated from step 2), otherwise the results will be printed out and the process will be terminated.

The above computational procedure is schematized in the flow chart in Fig.1.

VI. SAMPLE STUDIES

The new algorithm developed in previous sections has been applied to the sample systems in order to demonstrate its efficiency and availability.

VI-1. Sample-1 system

The sample-1 system with, 12 buses, 13 lines, 3 generators, 3 tap-changing transformers and 1 shunt capacitor bank was used as the model system. Fig.2. shows one line diagram of this system.

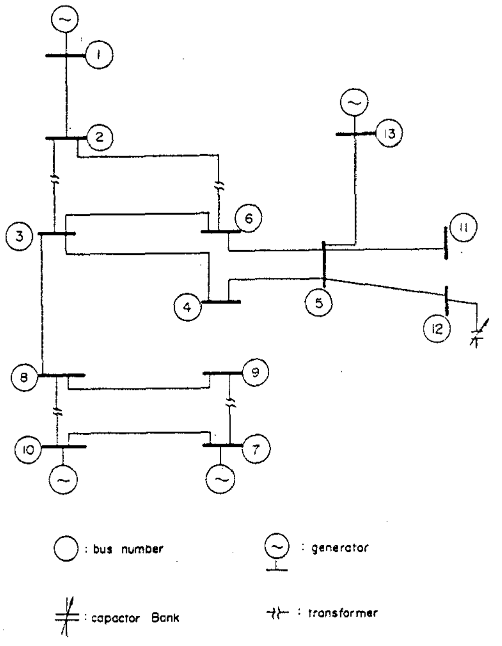

Fig.2. one line diagram of sample-1 system

Table 1 summarizes the line data for the sample-1 system on 100 MVA base, while Table 2 gives bus data.

Table 1 Line data for sample-1 system

line number	bus number from	bus number to	impedance R	impedance X	tap ratio	line charge
1	1	2	0.0015	0.0015		0.02
2	2	3	0.0092	0.2205	0.900	
3	4	5	0.0399	0.1276		
4	5	6	0.0399	0.1276		
5	6	3	0.0000	0.5000		
6	4	3	0.0000	0.5000		
7	3	8	0.0171	0.0458		
8	8	10	0.0000	0.6280	0.975	
9	8	9	0.0198	0.0150		
10	9	7	0.0000	0.6280		
11	10	7	0.1488	1.4126		
12	5	11	0.0399	0.1276		
13	5	12	0.0399	0.1276	1.050	

Table 2 Bus data of sample-1 system (in p.u.)

bus number	Generation P	Generation Q	Load P	Load Q
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.000	0.000	0.035	0.017
4	0.000	0.000	0.075	0.037
5	0.000	0.000	0.193	0.094
6	0.000	0.000	0.000	0.000
7	0.150	0.082	0.122	0.094
8	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
10	0.033	0.010	0.118	0.074
11	0.000	0.000	0.057	0.028
12	0.000	0.000	0.130	0.063

The operating limits of generator are summarized in Table 3.

Table 3 Operating limits (in p.u.) of generators

bus number	Pmin	Pmax	Qmin	Qmax	Vmin	Vmax
1	0.0	1.000	0.00	0.500	0.95	1.01
7	0.0	0.150	0.00	0.082	0.95	1.01
10	0.0	0.033	0.00	0.016	0.95	1.01

Also the limits of other control variables needed in simulating are shown in Table 4.

Table 4 Limits of other control variables (p.u.)

(i) Transformer tap ratio $1.0-0.0125*NT \le Ti \le 1.0+0.0125*NT$ NT = number of steps, i = transformer bus 0.0125 = step size of transformer (ii) Load bus voltage $0.95 \le Vi \le 1.01$ i = total load bus
(iii) VAR sources $0.0 \le Q12 \le 0.30$

The results drawn from the algorithm presented in this paper are summarized in Table 5, the convergence property of real power losses can be seen in Fig.3.

Table 5 Results for the sample-1 system

variable	initial state	final state
V1	1.0000 / 0.0000	1.0100 / 0.0000
V2	0.9980 / -0.0050	1.0080 / -0.0240
V3	1.0080 / -6.0760	1.0040 / -6.4830
V4	0.9340 /-13.3000	0.9790 /-13.3760
V5	0.9150 /-14.4520	0.9730 /-14.6160
V6	0.9400 /-12.8550	0.9850 /-12.9710
V7	0.9590 / -6.0400	0.9670 / -6.4960
V8	1.0040 / -6.1500	1.0000 / -6.5610
V9	1.0040 / -6.1520	1.0000 / -6.5450
V10	0.9800 / -8.3160	0.9620 / -8.7730
V11	0.9090 /-14.8750	0.9670 /-14.9900
V12	0.9010 /-15.4300	0.9820 /-15.8800
P1	0.5587	0.5562
P7	0.1500	0.1500
P10	0.3300	0.3300
Q1	0.4947	0.2638
Q7	0.0817	0.0819
Q10	0.0160	0.0170
Q12	0.0000	0.2000
T1	0.9000	0.9500
T2	0.9750	1.0000
T3	1.0500	1.0250
LOSS	1.1060	0.8570

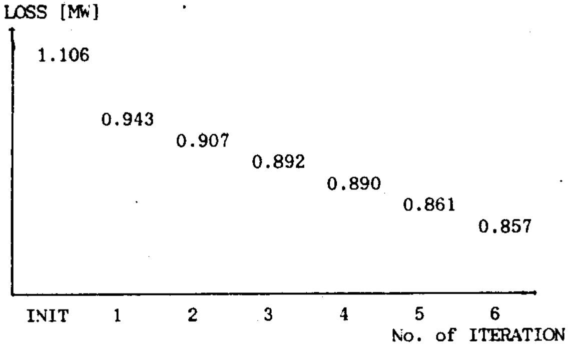

Fig.3. Variation in losses (sample-1 system)

VI-2. Other Sample systems

The suggested method was tested also by solving other sample systems. Results of these cases are not presented in detail in this paper, however, are satisfactory.

VII. CONCLUSIONS

This paper has presented the new algorithm for optimal reactive power / voltage control problem. The distinct advantages drawn from this study are summarized as follows:

(a) This algorithm is more accurate than the conventional methods since the sensitivity relation matrix is successively updated by the newly developed method.
(b) The convergence property is enhanced by the acceleration factor varying with the iteration steps.
(c) The computation time is much saved since the highly-sparse characteristics of constraints matrix can be preserved by adopting bus voltages as the control variables in Q-optimization module.
(d) The operator can make the reasonable control action by using the routine which the increment of capacitor/ reactor and transformer taps is rounded to the nearest steps.
(e) The reliable computation accuracy and fast convergence characteristics obtained in this methodology present the possibility for its application to the other areas.

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