OPTIMAL VAR DISPATCH TO ALLEVIATE BUS VOLTAGE VIOLATIONS

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ABSTRACT

This paper presents an optimal strategy of VAR dispatch for alleviating bus voltage violations. The reactive power control variables are related to the dependent variables and the objective function through sensitivity calculations, which are required to obtain the optimal control of reactive power dispatch. The paper discusses optimal reallocating of reactive power generations in the system by adjusting transformer taps, generator voltages, and switchable VAR sources in order to keep the bus voltages within their permissible limits. Several cases of control variable adjustments are examined and discussed.

1. INTRODUCTION

The problem of optimal reactive power dispatch is directly concerned not only with service quality and reliability of supply but also with economy and security of power systems. In the past two decades, the problem of optimal VAR dispatch has received much attention. Generally, some load bus voltage might violate their upper or lower limits during system operation due to disturbances and/or system configuration changes. The power system operator can alleviate this situation and the voltages can be maintained within their permissible limits by reallocating reactive power generations in the system *i.e.* by adjusting transformer taps, generator voltages, and switchable VAR sources. Generally, the optimal VAR dispatch problem has many objectives such as: reducing the fuel costs; ameliorating the supply quality and reliability by improving the voltage profile over the system; and enhancing the system security by uploading the system equipment.

Several methods [1-15] for VAR control have been developed to minimize the real power losses and to improve the voltage profiles. These methods are complex and require significant computational effort to find the required adjustments of the control variables. Mamandour [5,6] presented an algorithm to improve voltage profile and minimize the real power losses. This algorithm depends on the sensitivity of the inverse Jacobian matrix for Newton-Raphson load flow technique which consumes more computation time and therefore, not suitable for no-line computation. An efficient technique for real time control of system voltages and reactive power is presented in [7-8]. The sensitivity parameters of this technique are complicated and should be recalculated in case of emergency. The VAR control adjustments determined by the previous approaches are not the easiest to perform during emergency.

In this paper, the problem of optimal reactive power dispatch using EDSA software package is presented and discussed. The effectiveness of the various reactive power sources in alleviating the bus voltage violations is investigated. Analytical validation of the EDSA results through sensitivity calculation is also presented. The problem is applied to 6-bus test system. Different cases of operating conditions are considered. In each case, reallocation of reactive power generation is necessary to improve system voltage profile.

2. PROBLEM FORMULATION

Reactive power dispatch is achieved through suitable adjustment of one or more of the controllable variables; transformer tap settings, generator voltages, and switchable shunt capacitors. These control variables have their upper and lower permissible limits. Any change in these variables affect system voltage profile, reactive power output of generators, and reactive power flow in the transmission line.

The proposed approach formulates the reactive power allocation problem as a fast decoupled load flow equation [9]. The linearized objective function and network performance constants in terms of control variables are established by the use of sensitivity calculations.

2.1 Sensitivity Parameters

The sensitivity parameters can be derived from the second equation of the fast-decoupled load flow [9]. The general form of this equation is given as;

$$\begin{bmatrix} \Delta Q_g / V_g \\ \Delta Q_l / V_l \end{bmatrix} = \begin{bmatrix} B_{gg} & B_{gl} \\ B_{lg} & B_{ll} \end{bmatrix} \begin{bmatrix} \Delta V_g \\ \Delta V_l \end{bmatrix} \qquad (1)$$

$\Delta Q_g / V_g$ = the change in reactive current at generator bus.
$\Delta Q_L / V_L$ = the change in reactive current at load bus.

a. Sensitivity due to generator bus voltage

From Eqn. (1), the changes in load bus voltages due to changes in generator bus voltage can be obtained by assuming that the load reactive current remains constant, i.e.

$$\Delta V_L = [SV_g^L] . \Delta V_g \qquad (2)$$

where,

$$SV_g^L = - [B_{LL}]\text{-}1. B_{Lg} \qquad (3)$$

Also, the change in generation reactive power due to changes in generator bus voltages can be obtained directly as;

$$\Delta Q_g / V_g = [B_{gg}]. \Delta V_g + [B_{gL}] \Delta V_L \qquad (4)$$

By substituting Eqn. (2) in Eqn (4), then;

$$\Delta Q_g = [SQ_g^g]. \Delta V_g \qquad (5)$$

where,

$$[SQ_g^g] = V_g . [B_{gg} + B_{gl} + SV_g^L] \qquad (6)$$

b. Sensitivity due to switchable shunt capacitors:

Since the capacitors are put at load buses, no change occurs in generator voltage with the change in their susceptences, i.e., $\Delta V_g = 0$. So, the sensitivity parameters relating the changes in load-bus voltages due to changes in switchable capacitors can be obtained by using Eqn. (1) as;

$$\Delta Q_L / V_L = [B_{LL}] \Delta V_L \qquad (7)$$

where, $\Delta Q_L / V_L$ is a vector of zeros except at positions corresponding to the buses at which the capacitor bank are installed. Then;

$$\Delta V_L = [SV_S^L].\Delta Q_S \qquad (8)$$

where,

$$[SV_S^L] = [B_S]. V_S^{-1} \qquad (9)$$

B_S is the matrix of columns of $[B_{LL}]$ corresponding to the buses at which the capacitor banks are installed, and “S” is the No. of switchable capacitor banks. From Eqn. (1), the change in generator reactive power can be calculated as:

$$\Delta Q_g / V_g = [B_{gL}] \Delta V_L \qquad (10)$$

i.e;

$$\Delta Q_g = [SQ_S^g]. \Delta Q_S \qquad (11)$$

where,

$$[SQ_S^g] = V_g. [B_{gL}].[SV_S^L] \qquad (12)$$

c. Sensitivity due to transformer tap settings

The additional reactive power flow due to transformer off nominal tap setting from bus i to j and from j to i are given in Appendix. A small change, Δt_{ij}, in transformer tap, t_{ij}, will cause an incremental power flow as:

$$\Delta Q_{ij} = [-V_i V_j B_{ij} \cos\theta_{ij}/t^2_{ij} + 2 V^2_i B_{ij} t^3_{ij}]\Delta t_{ij} \qquad (13)$$

$$\Delta Q_{ij} = -V_i V_j B_{ij} \cos\theta_{ij}/t^2_{ij} \Delta t_{ij} \qquad (14)$$

So, the change in transformer tap is simulated as change in the injected reactive power at the end nodes of the transformer. The injected reactive power at ends must be added with opposite sign to eliminate the change in reactive power flow due to off-nominal tap. Then;

$$\Delta Q_{ij} = [V_i V_j B_{ij} \cos\theta_{ij}/t^2_{ij} - 2 V^2_i B_{ij}/ t^3_{ij}]\Delta t_{ij} \qquad (15)$$

$$\Delta Q_j = V_i V_j B_{ij} \cos\theta_{ij}/t^2_{ij}. \Delta t_{ij} \qquad (16)$$

In the general form, Eqn. (15) and Eqn. (16) can be written as:

$$\Delta Q_L = [S_t^L] \Delta t \qquad (17)$$

where $[S_t^L]$ is the sensitivity matrix relates the change in reactive power at load buses with change in injected reactive power at load buses. So, $\Delta V_g = 0$. in Eqn. (1), therefore

$$\Delta Q_L / V_L = [B_{LL}] \Delta V_L \qquad (18)$$

or;

$$\Delta Q_L = V_L [B_{LL}] \Delta V_L \qquad (19)$$

By equating Eqn. (17) to Eqn. (19), then;

$$\Delta V_l = [SV_t^L] \Delta t \qquad (20)$$

where,

$$[SV_t^L] = [V_L . B_{LL}]^{-1} [S_t^L] \qquad (21)$$

Similarly, the change in generation reactive power due to the changes in transformer off-nominal tap settings can be obtained as:

$$\Delta Q_g = [SQ_t^g]\ \Delta t \qquad (22)$$

where,

$$[SQ_t^g] = V_g \cdot [SV_t^L] \qquad (23)$$

2.2 Dependent Variable Constraints

The load-bus voltages and reactive power output of generators must be kept within certain limits given as;

$$V_L^{miv} \le V_L \le V_L^{\max} \qquad (24)$$

$$Q_g^{\min} \le Q_g \le Q_g^{\max} \qquad (25)$$

The inequalities of Eqns. (24) and (25) are expressed in term of control variable as:

$$\begin{bmatrix} \Delta V_L \\ \Delta Q_g \end{bmatrix} = \begin{bmatrix} SV_g^L & SV_s^L & SV_t^L \\ SQ_g^g & SQ_s^g & SQ_t^g \end{bmatrix} \begin{bmatrix} \Delta V_g \\ \Delta Q_s \\ \Delta t \end{bmatrix} \qquad (26)$$

2.3 Objective Function

The objective function can be achieved through the control of generator voltages, transformer taps and VAR sources. The objective used here is the minimization of voltage deviations

It is preferred to keep the voltage as close as possible to 1.0 p.u., i.e.;

$$F = \sum_{i=1}^{N} (V_i^{init} - 1.0)^2 \qquad (27)$$

This equation can be linearized as;

$$\Delta F = (\partial F_2 / \partial V_j) \cdot \Delta V_i$$

$$\Delta F = \sum_{g=1}^{NG} C_g \cdot \Delta V_g + \sum_{L=1}^{NL} C_L \cdot \Delta V_L \qquad (28)$$

where, $C = 2\,(\,|\,V_i^{init} - 1.0\,|\,)$

Substituting ΔV_L, the voltage deviation due to the control variables is given as;

$$\Delta F = \begin{bmatrix} C_g + SV_g^l & SV_s^l & SV_t^l \end{bmatrix} \begin{bmatrix} \Delta V_g \\ \Delta Q_s \\ \Delta t \end{bmatrix} \qquad (29)$$

3. APPLICATION

2.4 Test Systems

The 6-bus test system shown in Fig. 1 is used for applying the proposed optimal control procedure of reactive power problem required to maintain system constraints within their limits and achieving the objective function. The line and bus data of the test system are given in Tables 1 and 2 respectively.

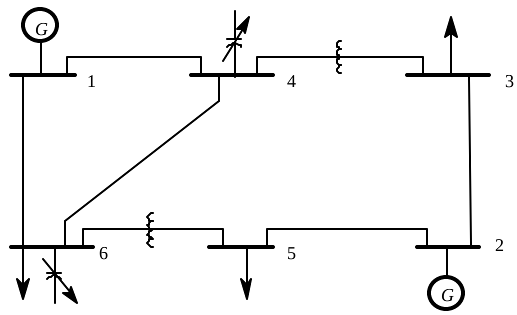

Fig. 1: single-line diagram of 6-bus test system

TABLE 1: LINE DATA ON 100 MVA BASE

Line#	From	To	R (pu)	X (pu)	Tap Ratio
1	1	6	0.123	0.518	---
2	1	4	0.080	0.370	---
3	4	6	0.097	0.407	---
4	6	5	0.000	0.300	1.025
5	5	2	0.282	0.640	---
6	2	3	0.723	1.050	---
7	4	3	0.000	0.133	1.100

TABLE 2: BUS DATA ON 100 MVA BASE

Bus#	V (pu)	P_g (pu)	P_L (pu)	Q_L (pu)
1	1.05	----	----	----
2	1.10	0.50	0.00	0.00
3	1.00	----	0.55	0.13
4	1.00	----	0.00	0.00
5	1.00	----	0.30	0.18
6	1.00	----	0.50	0.05

The above data has been provided to EDSA to run the initial load flow study. The results of the initial load flow study are given in Table 3. It is clear that the voltage at bus 3 severely violates its lower limit. Hence, readjusting of reactive power sources to alleviate this violation must be carried out. Table 4 illustrates different control strategies to solve the problem. In all cases studied, the bus voltages are kept within their permissible limits.

4. CONCLUSIONS

This paper presents optimal control strategies of system voltage and reactive power. A simple sensitivity parameter based on the fast-decoupled load flow equations is presented. This sensitivity gives the relation between the control variables, dependent variables, and the optimized objective function. Optimal adjustments of the control variables have been carried out to keep the load bus voltages within their allowable limits.

5. REFERANCES

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6. APPENDEX

I. Line Without Transformer

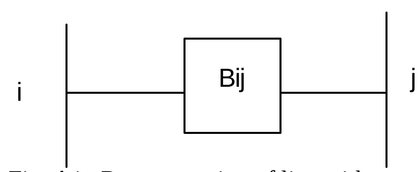

Fig. A1 . Representation of line without transformer

the action reactive power flow from bus I to bus j are given as :

$$\Delta P_{ij} = -V_i V_j B_{ij} \sin\theta_{ij} \qquad (A.1)$$

and

$$\Delta Q_{ij} = -V_i V_j B_{ij} \cos\theta_{ij} \qquad (A.2)$$

But from bus j to bus I they are;

$$P_{ji} = V_i V_j B_{ij} \sin\theta_{ij} \qquad (A.3)$$

and

$$Q_{ji} = -V_i V_j B_{ij} \cos\theta_{ij} \qquad (A.4)$$

II. Line With Transformer

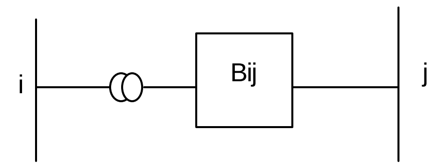

Fig. A.2 Representation of line with transformer

The abve equation will be as ;

$$P_{ij} = - V_i V_j B_{ij} \sin\theta_{ij} / t_{ij} \qquad (A.5)$$

and

$$Q_{ij}=-V_i^2 B_{ij}/t^2_{ij}+V_i V_j B_{ij} \cos\theta_{ij} \qquad (A.6)$$

But from bus j to bus I they are ;

$$P_{ji}= - V_i V_j B_{ij} \sin\theta_{ij} / t_{ij} \qquad (A.7)$$

and

$$Q_{ji}=-V_i^2 B_{ij}/t^2_{ij}+V_i V_j B_{ij} \cos\theta_{ij} \qquad (A.8)$$

The additional power flow from bus I to bus j due to the transformer off-nominal tap settings is given by ;

$P_{ij}^T = P_{ij}$ (with transformer) – P_{ij} (without transformer)

i.e.,

$$P_{ij}^T =(1 - 1/t_{ij}) V_i V_j B_{ij} \sin\theta_{ij} \qquad (A.9)$$

and

$$Q_{ij}^T=(1/t_{ij}-1)V_iV_jB_{ij} \cos\theta_{ij}-(1/t^2_{ij}-1)V^2_iB_{ij} \qquad (A.10)$$

Similarly,

$$P_{ji}^T=(1 - 1/t_{ij}) V_i V_j B_{ij} \sin\theta_{ij} \qquad (A.11)$$

and

$$Q_{ji}^T=(1/t_{ij}-1)V_iV_jB_{ij}\cos\theta_{ij}-(1/t^2_{ij}-1)V^2_iB_{ij} \qquad (A.12)$$

TABLE 3: INITIAL LOAD FLOW RESULTS

Variable		*Lower Limit*	*Upper Limit*	*Initial Solution*
Control Variables				
Transformer Taps	t_4	0.90	1.10	1.025
	t_7	0.90	1.10	1.100
Generator Voltages	V_1	1.00	1.10	1.050
	V_2	1.10	1.15	1.100
Shunt Capacitors	Q_{c4}	0.00	5.00	0.000
	Q_{c6}	0.00	5.50	0.000
Dependent Variables				
Generator MVAR	Q_{g1}	-20.0	100.0	38.11
	Q_{g2}	-20.0	100.0	34.80
Voltages at load Buses	V_3	0.90	1.00	0.855
	V_4	0.90	1.00	0.953
	V_5	0.90	1.00	0.901
	V_6	0.90	1.00	0.933

TABLE 4: DIFFERENT CONTROL STRATEGIES TO ALLEVIATE V_3 VIOLATION

Control by	V_2	V_3	V_4	V_5	V_6	Adjustments
G_2 & T_1	1.1262	0.9029	0.952	0.9009	0.9332	T_1 = 1.046
G_2&T_1&T_2	1.1280	0.9033	0.9559	0.9183	0.9407	T_1=1.046,T_2= 1.021
G_2&C_4&T_1	1.1277	0.9061	0.9591	0.9170	0.9428	T_1=1.046, C_4 = 0.0120
G_2&C_6&T_1	1.1278	0.9045	0.9572	0.9177	0.9436	C_6=0.0082, T_1=1.046
G_2&C_4&C_6&T_1	1.1264	0.9011	0.9601	0.9178	0.9445	T_1=1.053, C_4 = 0.0112, C_6 = 0.0070
G_2&C_4&C_6&T_1&T_2	1.283	0.9015	0.9603	0.9211	0.9444	C_4=0.0111, C_6=0.0070 T_1= 1.053, T_2= 1.021
G_2&T_1&T_2&C_4	1.1255	0.9023	0.9568	0.9163	0.9427	T_1=1.05, T_2=1.025, C_4 = 0.0113
G_2&T_1&T_2 &C_6	1.1258	0.9006	0.9023	0.9587	0.9422	T_1=1.05, T_2 =1.025,C_6 = 0.0074
T_1	1.1	0.9010	0.9452	0.9002	0.9294	T_1= 1.033
T_1&T_2	1.1	0.9051	0.9433	0.9012	0.9269	T_1= 1.026, T_2= 1.015
T_1&C_4	1.1	0.9024	0.9588	0.9015	0.9362	T_1= 1.046, C_4 = 0.0500
T_1&C_6	1.1	0.9041	0.9487	0.9022	0.9372	T_1= 1.033, C_6 = 0.0293
T_1&C_4&C_6	1.1	0.9092	0.9516	0.9016	0.9366	T_1=1.03, C_4 =0.0191, C_6 =0.0191
T_1&C_4&C_6&T_2	1.1	0.9007	0.9505	0.9021	0.9333	T_1= 1.039, C_4 = 0.0158, C_6 = 0.0092, T_2= 1.021