"IMPROVED REAL-POWER LOSS MINIMISATION"

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ABSTRACT:
The problem of the reactive control of a power system is formulated as a static optimisation technique to ensure the minimisation of the real-power system losses by controlling the switchable reactive power sources, generator terminal voltages, transformer tap ratios and phase shiftet's. The objective function as well as the constraints are established using the linearized sensitivity relationships of power system state and control variables and standard linear programming routines are used to determine the optimum operating condition; the fast-decoupled load flow technique is employed because it is fast, simple and has less computer storage. Results of the application of this development to the IEEE 14 bus system is presented.

NOTATION

a_i, b_j, c_k, d_m sensitivity relationship between the power loss and switchable reactive power sources, terminal generator voltages, transformer tap ratios and phase-shifting anglesrespectively

LP linear programming
NG number of generators including the slack
NN number of nodes
NP number of phase-shifting transformers
NR number of Switchable reactive sources
NT number of transformers
t_{ij} transformer tap positions i-j
t_{ij} max, t_{ij}min maximum and minimum transformer tap ratio
V_i load bus voltage
V^t generator terminal voltages
Vt_{max}, Vt_{min} maximum and minimum generator terminal voltages
Q changes in switchable reactive sources
P_L changes in the system power loss
X state variables
θ_i voltage angle at bus i
$\emptyset$ phase-shifting angle
$\emptyset^{max}$, $\emptyset^{min}$ maximum and minimum phase- shifting angles

1. INTRODUCTION

The advantage of reactive power dispatching has been presented by Aldrich et al [1] to include:

(i) Improved utilisation of reactive power sources, hence reduction in reactive power flows and real losses of the system.
(ii) Unloading of the system and equipment as a result of reactive flow reduction. The power factors of generation are improved as well as the system security enhanced.
(iii) Reduced voltage gradients and somewhat higher voltages result across the system from improved operation.

Therefore, the problem of reactive power dispatch has been studied and widely reported in the literature. Non-linear programming based approaches have been formulated [2-7) and a linear programming technique for constraint dispatch has been described in (8) and (9) with a consequent reduction in real power losses. Static optimisation of reactive power sources by the use of sensitivity parameters was described in [10] whereas Shoults and Chen [11] determined the changes in transformer taps and generator terminal voltages required to reduce the reactive power in lines and load bus voltages. This was extended in [12] to include reactive power injections using least-squares minimisation techniques. Other considerations for optimal reactive planning and VAR allocation has been described *in* [13 - 17]. The long range optimum VAR planning has been considered and the optimum amount and location of network reactive compensation so as to maintain the system voltage within the desired limitations while operating under normal and various insecurity states have also been determined by several techniques. Reichert in (18) reviewed the equipment currently available for reactive power control while outlining the modelling and simulation principles so involved. Mescua and Fischl in [19) developed a technique for determining the most secure voltage profile for an electric power system.

In this paper, reactive power control of power systems is formulated as a static optimisation technique by minimising real power losses through the proper control of switchable reactive P_o power sources, generator terminal voltages, transformer tap ratios and phase- shifters. The problem is static because a system design *is* required for a given set of conditions. The objective function is described by sensitivity analysis in terms of the control variables as well as in the constraint matrix, The approach described here is the same *in* principle as that of [9] but offers the following improvements:

(i) The use of the fast-decoupled load flow method as against the Newton-Raphson technique. The fast-decoupled approach is very fast, simple to implement and has considerable savings in computer storage [20],

(ii) The use of phase-shifters to reschedule real power flows, hence a consequent reduction in real power losses. The relationship between the real power losses and phase-shifting angles is incorporated in the objective function whereas the phase-shifters are constrained between limits and so defined in the constraint matrix.

The improved technique is demonstrated using the IEEE 14 bus system, (21) which is slightly modified by incorporating a phase-shifter.

2 MATHEMATICAL FORMULATION

The objective is to minimize the real power losses subject to limits on

(i) load bus voltages
(ii) generator terminal voltages
(iii) switchable reactive power sources
(iv) transformer tap ratios
(v) phase-shifting transformer angles

The LP static optimisation problem becomes

$$\Delta P_L = \sum f \Delta X \qquad (1)$$

Subject to

$$[A]\ [\Delta X] \leq [b] \qquad (2)$$

f is the cost function which incorporates the sensitivity relationships between the real power loss and the control variables. Expanding eqn. (1)

$$minimise\ \Delta P_L = \sum_{i=1}^{NR} a_i . \Delta X_i \sum_{j=1}^{NG} b_j \cdot \Delta X_j + \sum_{1=1}^{NK} c_k \cdot \Delta X_k + \sum_{m=1}^{NP} d_m \cdot \Delta X_{jm} \ldots \quad (3)$$

Since ΔX (the set of switchable reactive sources, changes in generator terminal voltages, transformer tap ratios and phase- shifting angles) can be positive, zero or negative, define

$$\Delta \mathbf{X} = \Delta \mathbf{X}^{+} - \Delta \mathbf{X}^{-} \text{ where } \frac{\Delta \mathbf{X}^{+}}{\Delta \mathbf{X}^{-}} > \mathbf{0} \quad \ldots(4)$$

Eqn, (1) becomes

$$\textbf{minimise } \Delta \mathbf{P_L} = \sum \mathbf{f}\,(\Delta \mathbf{X} = \Delta \mathbf{X}^{+} - \Delta \mathbf{X}^{-}) \qquad (5)$$

subject to Type equation here.

$$[\mathbf{A} - \mathbf{A}] \begin{bmatrix} \Delta \mathbf{X}^{+} \\ \Delta \mathbf{X}^{-} \end{bmatrix} \leq [\mathbf{b}] \ldots\ldots\ldots(6)$$

Eqns. (5) and (6) can now be solved using the revised simplex NAG (Numerical Algorithms Group) linear programming routine.

The flowchart of the program is described *in* Figure 1. It should be noted that the problem variables are reduced considerably by using only the rows corresponding to abnormal system voltages and columns having switch-able reactive injection in eqn. *(6). This* should equally be reflected in the objective function in eqn. (5).

3. CASE STUDY

The IEEE 14-bus system [21] (see Fig. 2) was modified to include a phase-shifter on line 4-5 with an initial angle of 0 degrees. The following constraints were enforced:

(i) for the load buses: $0.95 \leq V^i \leq 1.05$
(ii) for the phase-shifter - $5^0 \leq \Delta\emptyset \leq 5^0$
(iii) transformer tap ratios: $(1.0\pm0.05)t_{ij}$
(iv) reactive power injections: maximum of MVAr (capacitive) and 24 MVAr (reactive)
(v) generator terminal voltages: $1.045 \leq V^t \leq 1.07$

The detailed LP formulation in given in section 3.1 below and the voltages before and after the dispatch are given in Table 1 below. It will be seen that the only violated load bus voltages is that on bus 12 with a value of 1.0519 p.u. which is corrected to 1.0436 p.u

The system losses are reduced from 13.82 MW to 13.44 MW at the first iteration of the algorithm with all the constraints completely satisfied. The corrective actions are given in Table 2 below.

3.1 The LP Formulation and solution of the Case Study

Let X_1 = reactive power injection at bus 12

X_2, X_3 = generator terminal voltage changes on buses 2 and the slack, 14

X_2, X_5, X_6 = changes on the transformer taps

X_7 = changes on the phase-shifting angle

The LP problem becomes

Minimize $\Delta P_L = 19X_1 + 233.8X_2 - 191.9X3 - 15.4X_4 - 6.05X_5 - 40.7X6 + 0.74X_7$

Subject to

$-0.06 \leq X_1 \leq 0.24$

$0.29\ X_1 \leq 0.00189$

$0.0 \leq X_2 \leq 0.025$

$-0.015 \leq X_3 \leq 0.01$

$-0.0048 \leq X_4 \leq 0.0048$

$-0.00484 \leq X_5 \leq 0.00484$

$-0.00466 \leq X_6 \leq 0.00466$

$-0.00872 \leq X_7 \leq 0.00872$

The LP solution is

$X_1 = -0.06$

$X_2 = 0.0$

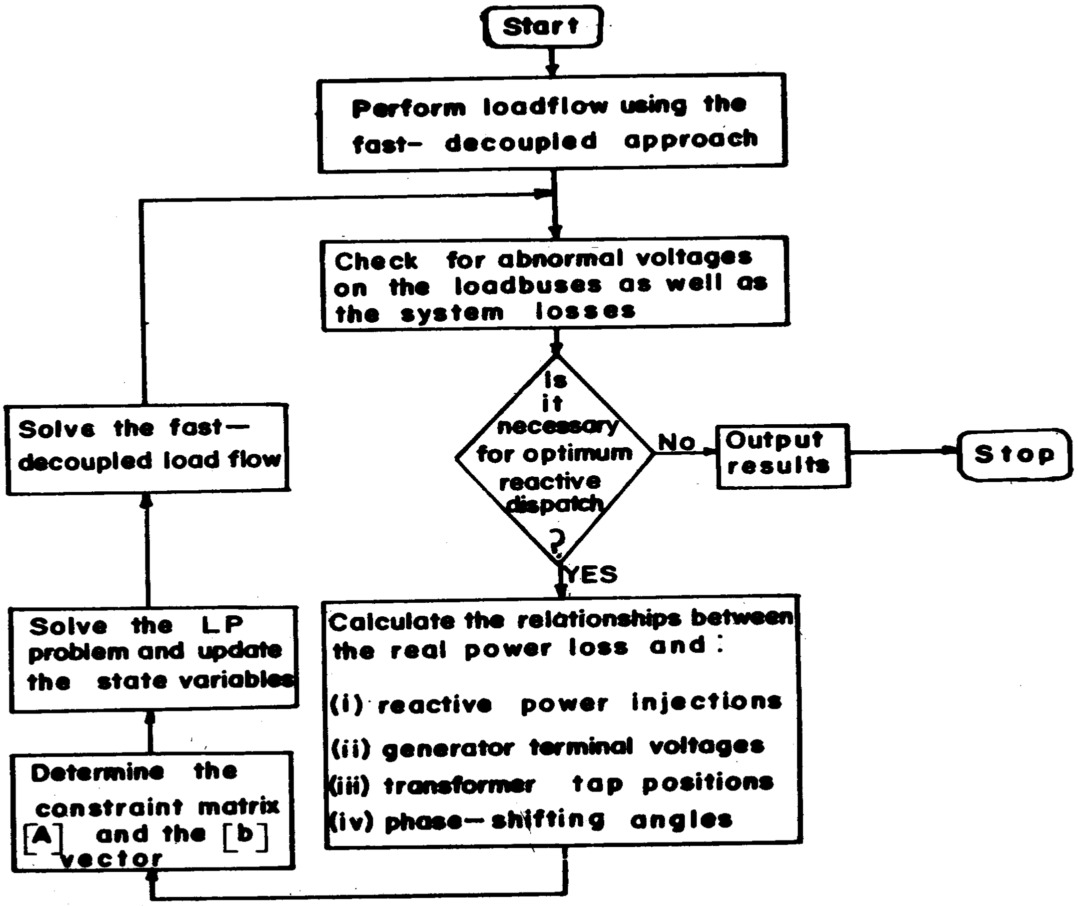
$X_3 = 0.01$

$X_4 = 0.0048$

$X_5 = 0.00484$

$X_6 = 0.00466$

$X_7 = 0.00872$



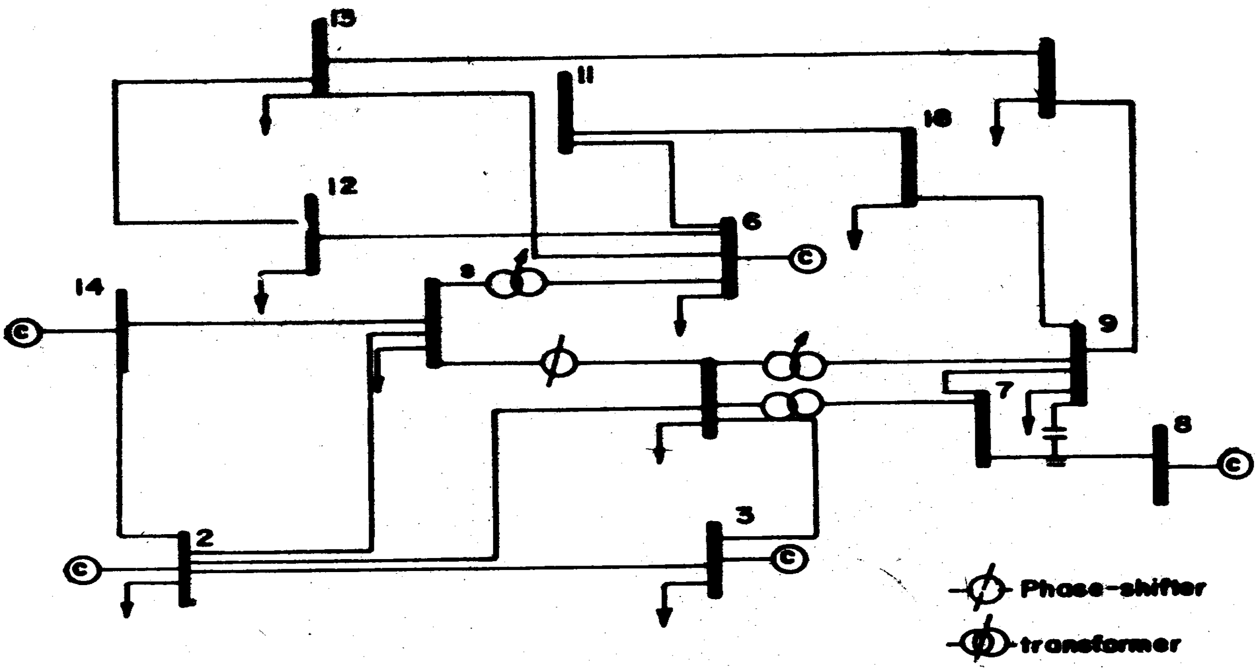


Fig. 2. Modified IEEE 14-bus system.

Table 1 Bus Voltages

Bus No	Bus voltages before reactive Dispatch	Bus voltages after reactive dispatch
1	1.0078	1.0065
2	1.0450	1 .045
3	1.0100	1.010
4	1.0118	1.0166
5	1.0158	1.0153
6	1.0700	1.070
7	1.0399	1.0399
8	1.090	1.090
9	1.0126	1.0125
10	1.0161	1.0162
11	1.0391	1.0392
12	1.0519	1.0436
13	1.044	1.0436
14	1.0600	1.0700

Table 2: Corrective actions

(i) changes in generation terminal voltages $\Delta V_2 = 0.0$

$\Delta V_{14} = .01$ (slack)

(ii) reactive injection of 6 MVAr at bus 12

(iii) changes of phase-shifting angle by -5^0

(iv) changes of transformer taps by

$\Delta^t{}_{4-9} = 0.0048$

$\Delta^t{}_{4-7} = .00484$

$\Delta t_{5-6} = 0.00466$

These values are used to update the control variables and obtain another load-flow run as given in Table 1.

4 CONCLUSION

The real power loss minimisation approach developed by Mamandur and Chenoweth in [9] has been improved to include:

(i) the use of the fast decoupled load- flow technique and (ii) the incorporation of phase-shifters for loss minimisation [22].

The algorithm will ensure that the voltage profiles are acceptable with a consequent reduction in system loss. It should be mentioned, however, that the changes in reactive power injections, phase-shifting angles and transformer tap ratios are continuous; in practice they are discrete and should be so reflected in future investigations. Also the sensitivities are valid over a small range [9].

It is hoped that the development described here can be implemented on-line since by using the fast decoupled loadflow method as opposed to the Newton-Raphson savings in computational time and computer accrue. Considerable reduction in computing time used to obtain the sensitivity relations can be attained by using the factors of the [B'] and [B''] matrices as well as for the admittance matrix stored using sparsity techniques. The initial network state can be determined by solving the base case loadflow (as in this paper) or from state estimates before the application of the technique described above.

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