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OPTIMAL REAL AND REACTIVE POWER ALLOCATION FOR REAL POWER LOSS AND MARGINAL COST REDUCTION

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ABSTRACT
The transmission loss minimization is one aspect of power system operation that needs much attention. The real and reactive power generation scheduling that results in heavy flows tend to incur greater losses, threaten security, and ultimately making certain generation patterns undesirable. Generation levels mainly based on economic criteria may lead to higher losses and therefore diminished security is a serious concern for the systems. In this paper, network sensitivity between load voltages and source voltages is used as the basis to evaluate optimal real power generation allocation for loss and marginal cost reduction and a method for optimum allocation of reactive power in day –to-day operation of power system for loss reduction is presented The technique will try to utilize fully the reactive power sources in the system to improve the voltage profile and to minimize the real power losses besides meeting the optimal real power generation levels. The method involves successive solution of steady state power flows and optimization of reactive power control variables using linear programming techniques. The proposed method has been applied to few systems and the results obtained on a 24-bus Indian practical equivalent EHV system are presented for illustration

KEY WORDS
Optimal real power, reactive power allocation, real power loss, and marginal cost reduction.

1. Introduction

A poorly scheduled generation levels can cause higher losses and reduce a system's ability to transfer power while maintaining its security and stability. With open access transmission in the deregulated environment, poorly scheduled generation patterns and load patterns from competitive bidding, will be seen more and more often. These patterns might cause many stability problems. Intensive studies on the economic dispatch problem assume that the system can maintain its security and stability. The optimal power flow (OPF) program does consider both economic dispatch and stability, but it requires heavy computations. Between the power system generation pattern and load pattern, the generation pattern is easier to control [1]. The load pattern is relatively uncontrollable due to the uncontrollable consumer demand. Although load-shedding and price incentives can be used as way to adjust the load pattern, these are not generally recommended except under extreme conditions such as at peak load or under contingencies. On the other hand, a generation pattern has more flexibility in terms of supplying power.

Another reason for considering the generation pattern is that the generation pattern can cause more problems if not controlled properly. Normally there are more load buses than the generator buses in a common power system and these load buses are usually highly mesh (network) connected. A good generation direction (or pattern) should be maintained to have better operating state and to supply the maximum power possible to the load with reduced power losses before reaching the boundary of a system limit. To form a good generation direction, sometimes a generator needs to reduce its power output so that other generators can transfer more power to the load. Much work has been done in a load space to control the load direction [2, 3] to decrease losses and to avoid the system limits, while little work has been done in the generation space.

In this paper, network sensitivity between load voltages and source voltages is used as the basis for allocation of real power generation. In this method, a new concept called Optimal Generation Factors (OGF) is developed to obtain always the best real power generation levels under normal operation and also even under network contingency conditions.

Optimal reactive power allocation (ORPA) has received considerable attention for its significant influence on secure and economic operation of power systems. Reactive power dispatch has been researched extensively as a static snapshot problem, and the objective of ORPD is to minimize the active power transmission loss by means of dispatching reactive power sources while satisfying a lot of constraints, such as reactive power generation limits of generators, voltage limits of load buses, tap ratio limits, reactive power compensation limits, and power flow balance [4]–[10]. Such an objective is considered as a classic model of ORPD, or, for the sake of enhancing voltage stability, a multi-objective model that minimizes real power loss and maximizes voltage stability margin is considered [11], [12]. Although the number of controls has little effect on the CPU time in a Newton OPF [13], the operators cannot move so many control devices within a reasonable time. A curtailed number of control actions through selecting the most effective subset of controls have been investigated for a real time OPF [14]. Paper [15] present that ORPD should be seen as a time-based scheduling problem with the intention of avoiding unnecessary changes in status and output of a reactive control plant. They consider some transition constraints such as the number of control actions allowable within a time domain and the time interval required between actions performed. Paper [16] introduces the constraints of maximum allowable switching operations for on-load tap changer (OLTC) and capacitor of distribution systems. Its strategy is to minimize the power loss and improve the voltage profile for a whole day across the whole system and at the same time ensure that the number of operations is less than the maximum daily allowance. A model to minimize the energy loss over time intervals in which the transition of discrete variables is governed by the selection of time intervals is described [17].

In this paper, it is demonstrated that ORPD alone is not sufficient to reduce the losses but it also needs the best real power generation levels. To obtain the best real power generation levels a new concept called optimal generation factors is proposed to reduce loss and marginal cost. For optimal allocation of reactive power an ORPD technique presented. The technique will try to utilize fully the reactive power sources in the system to improve the voltage profile and to minimize the real power losses. The proposed method involves successive solution of steady state power flows and optimization of reactive power control variables using linear programming techniques.

2. Optimal Real Power Allocation

Consider an n-bus system with 1, 2…g, g number of generator buses, and g+1…n, remaining (n-g) buses. For a given operating condition it can be written as

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \qquad (1)$$

where I_G, I_L and V_G, V_L represent complex current and voltage vectors at the generator nodes and load nodes, $[Y_{GG}]$, $[Y_{GL}]$, $[Y_{LG}]$, and $[Y_{LL}]$ are the corresponding partitioned portions of network Y-bus matrix.

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \qquad (2)$$

From equation (2)

$$[V_L] = [Z_{LL}][I_L] + [F_{LG}][V_G]$$

$$\therefore \quad [V_L] \; \alpha \; [F_{LG}][V_G]$$

$$[F_{LG}] = -[Y_{LL}]^{-1}[Y_{LG}]$$

where $[F_{LG}] = -[Y_{LL}]^{-1}[Y_{LG}]$.

This matrix $[F_{LG}]$ gives the relation between load bus voltages and source bus voltages, which is used as basis for the optimal generation scheduling. For a given system, the optimal generation levels are obtained by using Optimal Generation Factors (OGF) which are obtained from the absolute value of the $[F_{LG}]$ matrix and are given by

$$Optimal\,Generation\;\;Factors(OGF) = |\,[F_{LG}]\,|$$

The optimal generation levels is obtained by multiplying the optimal generation factors with the real powers at load buses and are given by

$$P_{i \in n_G} = \sum_{j=1}^{n_L} \left(OGF\right)_{ji}^{norm} P_j$$

where P_i -represents the generation levels at bus –i

P_j - represents the load at bus j

2.1 Six-bus System

The radial six-bus system shown in Figure 1 is considered for illustrating the evaluation of the optimal real power scheduling. In this system, it is assumed that the lines L1, L2 and L3 are of 200, 300 and 100kms length respectively and each of 400kV line. The generators considered are two units of 250 MVA with step up transformers of 250 MVA each at both buses 1 and 2. The 400 kV line parameters in p.u. per 100 kms are r =0.0166, x =0.0206 and b/2=0.2692. The $[F_{LG}]$ matrix corresponding to the load/generator bus for the network is as given below.

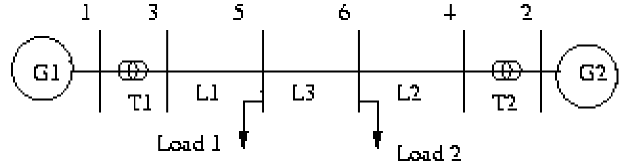

Figure 1 Six-bus system

$$[F_{LG}] = \begin{bmatrix} 0.8999 - 0.0040i & 0.1343 + 0.0021i \\ 0.1343 + 0.0021i & 0.8997 - 0.0040i \\ 0.6717 - 0.0043i & 0.4106 - 0.0017i \\ 0.5464 - 0.0035i & 0.5419 - 0.0030i \end{bmatrix}$$

The optimal generation factors for the six-bus system are given in Table 1. The optimal generation levels are obtained by multiplying the OG factors with the corresponding load at the load buses and are given in Table 2.

Table 1
OG Factors of the six-bus system

Load Bus No.	Generators	
	G1	G1
3	0.8999	0.1343
4	0.1343	0.8997
5	0.6717	0.4106
6	0.5464	0.5419

Table 2
Optimal generation scheduling

Load Bus No.	Generation levels at Bus		Load at Bus (MW)
	G1(MW)	G2(MW)	
3	0.8999x 0=0	0.1343 x 0=0	0
4	0.1343x 0=0	0.8997 x 0=0	0
5	0.6717x593 =398.3181	0.4106x593 =243.4858	593
6	0.5464x393 =214.7352	0.5419x393 =212.9667	393
Total Gen.	613.0533	456.4525	

Table 3
Real power loss and Marginal cost

		Without OGF	With OGF
Load (MW)	Load at bus 5	593	593
	Load at bus 6	393	393
%Power Loss		3.57	2.73
Power Loss (MW)		64.33	60.85
Generation (MW)	G1	661	594
	G2	393	456
Marginal Cost	G1(3.34P_1\$/MWhr)	2207.7	1984.0
	G2(2.00P_2\$/MWhr)	786.0	912.0
Total Marginal Cost (\$/MWhr)		2993.7	2896.0

Power flow results are carried out with the optimal generation levels and the system grid totals for maximum power transfer are given in Table 3.From the Table 3 ,it can be seen that the percentage power loss, power loss in MW is less when the load sharing is according to the OGF and also there is a reduction in the marginal cost when real power allocation is according to the OGF

3. Optimal Reactive Power Allocation

Minimization of real power losses in a system forms the basis for the reactive power optimization problem. The model uses linearized sensitivity relationships to define the problem. The constraints are, the linearized network performance equations relating to control and dependent variables and the limits on the control variables. The control variables are:

- The transformer tap settings (T)
- The generator excitation settings (V)
- The Switchable VAR compensator (SVC) settings (Q)

The dependent variables are:

- The reactive power outputs of the generators (Q)
- The voltage magnitudes of the buses other than the generator buses (V)

It is assumed that,

- 1,2…g are the generator buses,
- g+1,g+2,…,g+s are the SVC buses ,and
- g+s+1,g+s+2,…,n are the remaining buses

The optimization problem can then be defined as,

Minimize $P_{loss} = C^T x$

Subject to

$b_{\min} \le b = S\,x \le b_{\max}$,and $x_{\min} \le x \le x_{\max}$

Where, C is the row matrix of linearized loss sensitivity coefficients and S is the linearized sensitivity matrix relating the dependent and control variables and are evaluated using the load flow sensitivity matrix and the results of the load flow analysis [18]. A linear programming technique is applied to the above problem to determine the optimum settings of the control variables

3.1 Computational Procedure

In the day-to-day operation of the power systems, the following are the steps used to obtain the optimal reactive power allocation in the system for improvement of voltage profiles and minimization of losses.

Step 1: Input -data relating to system

- Network ,scheduled load and generation
- Upper and lower limits and step size for ransformers tap settings, generator excitation ettings and Switchable VAR compensator settings,
- Upper and lower limits of the generator reactive powers and voltage magnitudes at buses other than the generator buses.

Step 2: Perform the power flow to obtain the values of voltage violations in the system and advance the VAR control iteration count.

Step 3: Check for the satisfactory voltage profiles in the system

Step 4: Compute the column matrices $b^{\max}$, and $b^{\min}$ of the dependent variables.

Step5: Compute the column matrices x^{max} and x^{min} of the control variables.

Step6: Modify the matrices x^{max} and x^{min} to reasonably small ranges.

Step 7: Compute the sensitivity matrix (S), relating the dependent variables and control variables.

Step 8: Compute the row matrix (C) of the objective function sensitivities wrt the control variables.

Step 9: Solve the optimization problem using the linear programming technique.

Step 10: Obtain the optimum settings of the control variables.

Step 11: Perform the load flow with the optimum settings of the control variables.

Step 12: Check for satisfactory limits on the dependent variables.

Step 13: Check for the significant change in the objective function, if yes go to step 4.

Step 14: Print the results.

4. Typical System Studies and Results

A system of 24 buses (typical of Indian practical system including the voltage levels of 220kV and 400kV) is considered for studies. There are 4 generators in the system connected at buses 1, 2, 3, and 4. There are 7 tap regulating transformers, 4 non regulating transformers, and 17 transmission lines in the system. The loads are present at 220 kV side of regulating transformers. About 4 numbers of buses are considered as Switchable VAR Compensator (SVC) buses. The system has about 2620MW, 980 MVAR peak load. Results for real and reactive power allocation obtained for the peak load condition are presented.

4.1 Real Power Allocation

The proposed approach is applied for the practical system of 24-bus equivalent EHV power system shown in Figure 2.The optimal generation factors for the 24-bus system are obtained from the absolute values of $\left[F_{LG}\right]$ matrix and are given in the Table 4. The optimal generation levels are obtained by multiplying the load at a bus with the corresponding OG factors and are given in Table 5. Power flow results are obtained with the generation levels obtained using OGF and economic criteria and are given in Table 6.

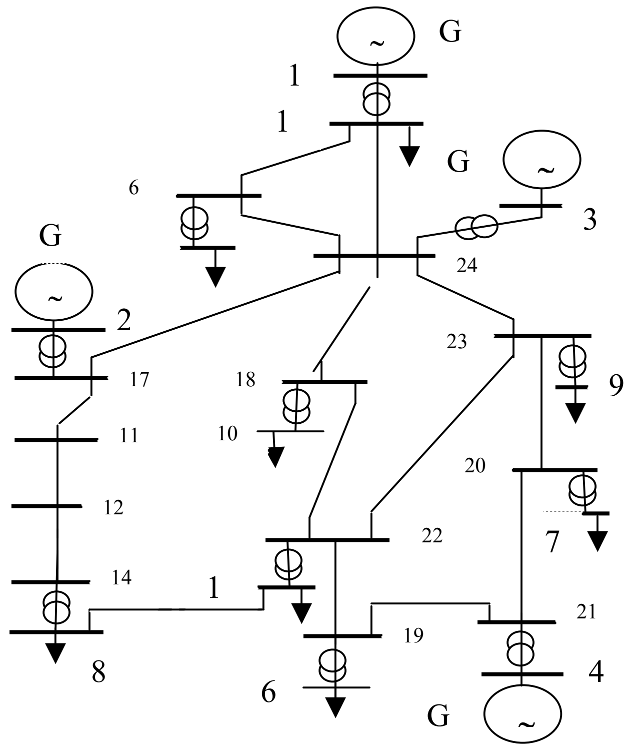

Figure 2 Practical 24-bus EHV equivalent system

Table 4
OG Factors of the 24-bus system

Load Bus No.	OG Factors				Load at the Bus (MW)
	G1	G2	G3	G4	
5	0.5265	0.0750	0.3172	0.0813	430
6	0.1258	0.0777	0.1651	0.6315	280
7	0.1600	0.0734	0.2100	0.5567	320
8	0.1924	0.2008	0.2525	0.3543	180
9	0.2508	0.1044	0.3292	0.3156	120
10	0.2669	0.1193	0.3503	0.2635	60
13	0.1962	0.1632	0.2575	0.3832	450
15	0.8234	0.0280	0.1183	0.0303	780

Table 5
OG Factors of the 24-bus system

Load Bus No.	Load taken by generators(MW)				Load at the Bus (MW)
	G1	G2	G3	G4	
5	226.4	32.25	136.4	34.96	430
6	35.22	21.75	46.22	176.81	280
7	51.20	23.48	67.19	178.13	320
8	34.63	36.15	45.44	63.77	180
9	30.10	12.52	39.50	37.88	120
10	16.01	7.16	21.02	15.81	60
13	88.28	73.42	115.87	172.43	450
15	642.27	21.81	92.27	23.65	780
Total	1124.1	228.6	563.9	703.5	2620

Table 6
Real power loss (MW)

Method	Real Power Generation Levels				P.Loss (MW)
	G1	**G2**	**G3**	**G4**	
Economic	768	575	644	697	63.299
OGF	1175.6	228.5	563.9	703.4	51.532

Table 7
Comparison of Marginal cost ($/MWhr)

	Method	
	Economic	OGF
G1(2.0$/MWhr)	1536.0	2351.2
G2(3.45$/MWhr)	1983.8	788.33
G3(3.21$/MWhr)	2067.2	1810.1
G4(2.15$/MWhr)	1498.6	1512.3
	7085.6	6641.9

It can be seen from the Tables 6 and 7 that the real power loss and marginal cost is reduced for the generation levels obtained using the optimal generation factors compared to the economic criteria. The improvement voltage profiles with both generation levels are shown in Figure 3.

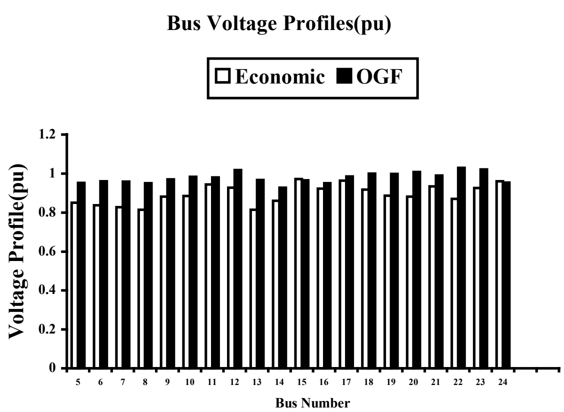

Figure 3 Bus voltage profile improvement

4.2 Reactive Power Allocation
The proposed algorithm for reactive power optimization is applied for the 24-bus system to improve further the real power loss reduction. The real power genera ration levels are maintained same as in the previous case. The step size taken for both the regulating transformers and generators excitations is 0.0125 p.u. The compensation at the selected places initially it is assumed to be zero. After eight iterations of the VAR optimization the voltages at all the buses and all the generators reactive power outputs (Q) are brought within the limits. The summarized results after optimization for the 24-bus system are given in Tables 8 and 9. The load bus voltage profiles improvement after optimization is shown in Figure 4.From the Table 9, one can see that there is a drastic reduction in power loss for optimal real and real power generation levels.

Table 8
System-Grid Totals after ORPA

	Method	
	Economic	**Economic**
Total P Gen.(MW)	2669.32	2660.56
Total Q Gen.(MVAR)	609.35	476.38
Total P Load(MW)	2620.00	2620.00
Total Q Load(MVAR)	980.00	980.00
Total P Loss(MW)	49.32	40.56
Total Q Loss(MVAR)	-1531.74	-1673.86
% P loss	1.85 %	1.52 %
Reduction in Loss (MW)	20.56 %	19.65 %

Table 9
Comparison of Loss reduction

Economic		OGF	
Without ORPA	With ORPA	Without ORPA	With ORPA
63.299	49.32	51.532	40.56

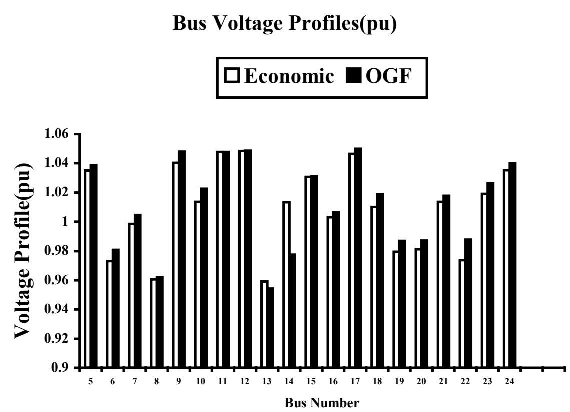

Figure 4 Bus voltage profile improvement

5. Conclusion

An approach for optimum allocation of real and reactive power in a practical system with an objective of improving the loss and marginal cost reduction has been presented in this paper. The proposed algorithm is demonstrated to give encouraging results for improving the operational conditions of the system under peak load conditions. In this paper a new concept, called optimal generation factors is used to best generation scheduling for loss reduction, which can be used under contingency condition also for optimal generation scheduling. The results on the equivalent practical system illustrate the application of the approach for large power systems.

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