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Optimal Reactive Power Flow (Orpf) Program For Voltage Profile Enhancement And Loss Minimization

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Abstract

The aim of this paper is to introduce a new technique to control the voltage and reactive power in power systems based on constrained optimization techniques introduced in MATLAB optimization toolbox. These optimization techniques include linear programming (LP) technique and sequential quadratic programming(SQP) included in the fmincon function. Generator voltages, reactive power sources and transformer taps are considered as control variables, and load bus voltages and generator reactive powers as state (dependent) variables. The relations are derived according to sensitivity relations based on Newton-Raphson load flow equations. The system losses are chosen as objective function so that the approach minimizes system real losses and enhances voltage profile. These techniques are tested by computer simulation on modified IEEE 30-bus power system and satisfactory results are obtained.

Keywords: Reactive power and voltage control, Power loss minimization, Optimization problem, LP and SQP.

برنامج (ORPF) لتعزيز مستوى الفولتية وتقليل الخسائر الفعالة

الخلاصة:

إن الهدف من هذا البحث إيجاد تقنيات للسيطرة على الفولتية والقدرة المتفاعلة في منظومات القدرة الكهربائية مستندة على تقنيات الأمثلية ذات المحددات الموجودة ضمن صندوق ادوات الأمثلية في(MATLAB). تشمل هذه التقنيات، تقنية البرنامج الخطي (LP) والبرنامج ألتربيعي المتتالي (SQP) ضمن دالة(fmincon).

تم اعتبار فولتية المولدات، مصادر القدرة المتفاعلة وكذالك المحولات ذات التفرع كمتغيرت سيطرة، واعتبار فولتية قضبان توصيل الأحمال والقدرة المتفاعلة للمولدات كمتغيرات معتمدة. العلاقات الرياضية اشتقت طبقا إلى علاقات الحساسية المستندة على معادلات سريان الحمل لطريقة نيوتن-رافسون. دالة الهدف المختارة تقليل الخسائر الحقيقية للمنظومة وتعزيز استقرارية الفولتية . هذه التقنيات اختبرت بمحاكاة الحاسبة على منظومة القدرة-30 (IEEE bus) وتم الحصول على نتائج مرضية.

List of Symbols

The following symbol definitions are used throughout the text. Most symbols are also defined in the text where they first appear.

F(.) : Cost or objective function.

x *or* k :Control variables vector.

u :State variables vector.

x^{min} , k^{min} *or lb*: Minimum values of control variables vector.

x^{max}, x^{max} or *ub* : Maximum values of control variables vector.

u^{min} : Minimum values of state variables vector.

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u^{min} : Maximum values of state variables vector.
$g(.)$: Nonlinear equality constraints.
$h(.)$: Nonlinear inequality constraints.
b :Vector of active and reactive specified load demand.
$P(.)$:Active power flow equation.
$Q(.)$:Reactive power flow equation.
$P_{spc.}$:Specified active load demand.

$Q_{spc.}$:Specified reactive load demand.
T: Transformer tap setting.
P_L :Total real power loss in the transmission system.
N :Number of buses.
$G(i, j)$:Conductance from bus i to j.
$V_i\angle\delta_i$:Voltage at bus i.
$V_j\angle\delta_j$:Voltage at bus j.
V_g :Generator voltage.
Q_c :Reactive power of swichable VAR sources.
V_l :Load bus voltage.
Q_g :Generator reactive power.
Δ :Change in variable.
[S]: Sensitivity matrix.
$\left[\partial P_L / \partial x\right]$:Coefficient matrix of the objective function.
A_1: Matrix of the linear equality constraints in *fmincon* function.
A_2: Matrix of the linear inequality constraints in *fmincon* function.
b_1:Vector specifying the right side of the linear equality constraints.
b_2: Vector specifying the right side of the linear inequality constraints.
t: Matrix transpose.

Introduction

One of the main requirements in power system is to keep the load bus voltage within limits specified for the proper operation of equipments. Any changes in the system configuration or in power
demands can result in higher or lower bus voltages in the system. The operator can improve this situation by reallocating reactive power generations in the system. This is done via control devices acting on transformer tap setting, generator voltage regulation and switching of VAR sources. The main objective function of reactive power control is [1]:

i) To improve the voltage profiles.
ii) To minimize the system losses.

In the past, several techniques have been employed using sensitivity relationships and gradient search approaches to solve this complex problem. References [1], [2] discuss the advantages and drawbacks of most existing techniques. Artificial intelligence (AI) methods have also been applied in the control of reactive power and voltage to be within acceptable limits. In [1] Artificial Neural Network (ANN) is applied to solve the control problem of the voltage and reactive power in electric power systems. The fuzzy logic theory [3] is applied to optimally control the reactive power flow. Fuzzy sets
operators of the coefficients in the objective functions are defined for each bus and
membership functions are defined for bus voltages. The
advantage of this technique is to overcome the limit of bus voltage variations by adjusting one of the control devices. Reference [4] focuses on the reactive power dispatch using a genetic algorithm (GA) to enhance voltage security.

This paper presents an efficient algorithm suitable for system power loss minimization simultaneously satisfying network performance constraints and the constraints on the control variables using linear programming (LP) technique and sequential quadratic programming (SQP) included in the *fmincon* function introduced in the MATLAB's optimization toolbox [5].

General Problem Formulation

The optimal power flow (OPF) problem is defined by choosing a cost function F(x) with respect to control variables ,x, subject to equality and inequality constraints of the forms[6], Minimize objective function

$$\left.\begin{array}{l} F(x) \text{ subject to} \\ \text{Equality constraint} \\ g(x,u)=0 \qquad (1a) \\ \text{Inequality constraint} \\ \text{(for control variables)} \\ x^{\min}\le x\le x^{\max} \quad (1b) \\ \text{Inequality constraint} \\ \text{(for state variables)} \\ u^{\min}\le u\le u^{\max} \quad (1c) \end{array}\right\} \qquad (1)$$

The equality constraints of equation (1a) represent the conventional power flow equations. Equation (1b) represents the constraints on, the generators voltage, transformers tap setting, and on switching VAR sources, while equation (1c) represents the limitations on the reactive power generation and voltage of the load buses.

The ORPF problem is a nonlinear problem because the power flow equations are nonlinear function of voltages, angle and transformers tap setting. Also , the objective function(such as active power losses) is a nonlinear function of the same variables [7]. The OPF problem can be formally expressed , defining the following notation:

$$\left.\begin{array}{ll} k=\begin{bmatrix} v \\ \delta \\ T \end{bmatrix} & (2a) \\ g(k)=\begin{bmatrix} P(k) \\ Q(k) \end{bmatrix} & (2b) \\ b=\begin{bmatrix} P_{spc.} \\ Q_{spc.} \end{bmatrix} & (2c) \end{array}\right\} \qquad (2)$$

Equation (2a) represents the vector of voltage magnitudes, angles and transformer tap settings, equation (2b) represents a vector of active and reactive power flow equations and equation (2c) represents a vector of active and reactive specified load demands. To solve the OPF , our task is to,

$$\left.\begin{array}{l} \textit{Minimize } F(k) \\ \textit{subjectto,} \\ g(k)-b=0 \\ k^{\min}\le k\le k^{\max} \end{array}\right\} \qquad (3)$$

Note that the above equality constraints involving $g(k)$ and b are the nonlinear power flow mismatch equation.

To solve the problem posed by equation (3) two algorithms are used in this paper, and to be presented in the following section.

Problem Formulation

The purpose of optimal reactive power control is to improve the voltage profile and minimize active power losses, P_L, in the system by the control of generators voltage, transformer tap setting, and switching of VAR sources. The relation between the active power loss and the control variables is given by the following nonlinear equation[8]:

$$P_L = \frac{1}{2}\sum_{i=1}^{N}\sum_{\substack{j=1 \\ j\neq i}}^{N} G(i,j)[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)] \tag{4}$$

The power loss optimization problem is tackled by the two following methods:

LP Technique

To establish the LP formulation, the objective function (P_L) is defined in terms of the control variables. The optimization problem can be posed as in equation (1) above, where:

$$\left.\begin{aligned} &F(x)= P_L \\ &x=[V_g\ T\ \ Q_c\ ] \\ &u=[\ V_l\ \ \ Q_g\ ] \end{aligned}\right\} \tag{5}$$

As the name LP implies, a linearized formulation of the problem is required. Therefore, instead of minimizing the nonlinear function P_L, a linear ΔP_L function is minimized. A linearized sensitivity model relating the state and control variables can be obtained by linearizing the power flow equations around the operating state[9]. The state variables can be expressed in terms of the control variables, as ;

$$[\Delta u] = [S][\Delta x] \tag{6}$$

where [S] is the sensitivity matrix, and the constraints as,

$$\Delta x^{\min} \le \Delta x \le \Delta x^{\max} \tag{7}$$

The upper and lower limits on the linearized state variables can be expressed as,

$$\Delta u^{\min} \le \Delta u = S.\Delta x \le \Delta u^{\max} \tag{8}$$

The overall linearized objective function may be expressed as,

$$\Delta P_L = \left[\frac{\partial P_L}{\partial x}\right]^t .[\Delta x] \tag{9}$$

The procedure starts by calculating the coefficient matrix of the objective function $\left[\partial P_L/\partial x\right]$ and sensitivity matrix [S]. Solution to LP problem gives the required changes to the state variables. The status of these variables is then modified and the Newton-Raphson load flow is performed. This completes one iteration of the VAR control problem. Iterations are repeated until the constraints are satisfied and further reductions in the system losses are no longer possible.
The corresponding flow chart is shown in Fig.1. This clearly shows the optimal reactive power flow (ORPF) and voltage control using LP.

SQP Technique *(fmincon function)*

Since the power loss problem in power system is a nonlinear function of the control variables (equation 4), therefore, this problem can be solved using the SQP (*fmincon* function) introduced in the MATLAB's optimization toolbox. The purpose of the *fmincon* is to find the minima of a constrained nonlinear multivariable function , stated as ;

$$\left.\begin{aligned} &Minimize \quad F(x) \\ &\text{subject to } g(x) = 0 \\ &\qquad h(x) \le 0 \\ &\qquad A_1.x = b_1 \\ &\qquad A_2.x \le b_2 \\ &\qquad lb \le x \le ub \end{aligned}\right\} \quad (10)$$

where x, b_1, b_2, lb and ub are vectors. A_1 and A_2 are matrices, $g(x)$ and $h(x)$ are functions that return vectors, and $F(x)$ is a function that returns a scalar. The *fmincon function* uses a sequential quadratic programming (SQP) technique. In this method, a quadratic programming (QP) subproblem is solved at each iteration. For more information about the *fmincon* function consult the MATLAB document [5].

A flow chart of the *fmincon* function based minimum power loss problem solution is shown in Fig.2.

Case Study : Results and Discussion

The modified IEEE 30-bus power system given in [10] and shown in Fig.3 has been studied and considered to test the performance of the built algorithms. Its bus data is given in Table-1. The limits of bus voltages, tap settings , shunt capacitors, and generators VAR's are given in Table-2. Load flow study was performed for the base case system state. The results of this state are presented in Tables(3 and 4) under the column "initial state". A review of Table-4 (for the limits) indicates that the voltage of buses (26, 29, 30) is in violation of its limits of (0.9 p.u.-1.05 p.u.). Initial system losses were 24.113 MW (approx. 7.5 % of total active load). The proposed techniques has been applied to improve this situation. The final optimal system state is described in Tables(3 and 4) in columns titled final state LP and *fmincon*. There are no limit violations in the final state calculated parameters. System real power losses in case of LP based solution are 19.336 MW and 19.549 MW in the *fmincon* based solution. It is obvious that both solutions produce about 20 % reduction in the system power losses. The improvement of the load buses voltage profile is quite evident from a comparison of the initial state and final states columns of Table-4.

Conclusions

A method of finding optimal reactive distributions in a power system using the optimization toolbox in the MATLAB is presented. The LP and the SQP optimization functions incorporated in the optimal load flow program produce a very close matched results for a sample test system. All possible control variables are considered, namely, transformer tap settings, generator voltages, and the switchable VAR sources. The built algorithms are principally useful in assisting the operator in making control decisions in order to improve the system voltage profile and achieving minimum power losses.

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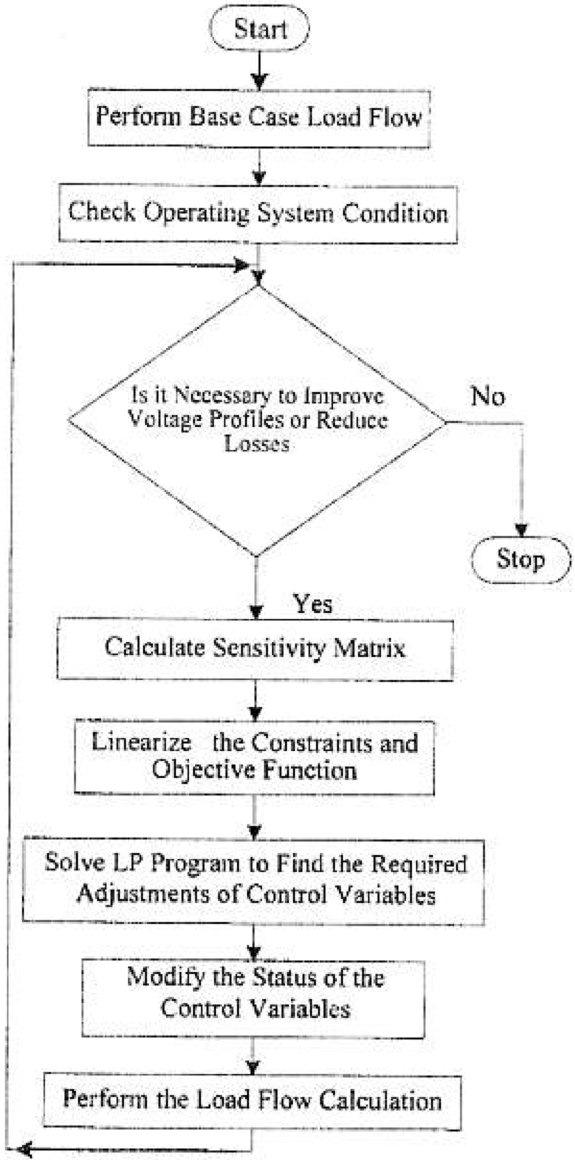

Fig. 1 Flow chart for the ORPF using LP

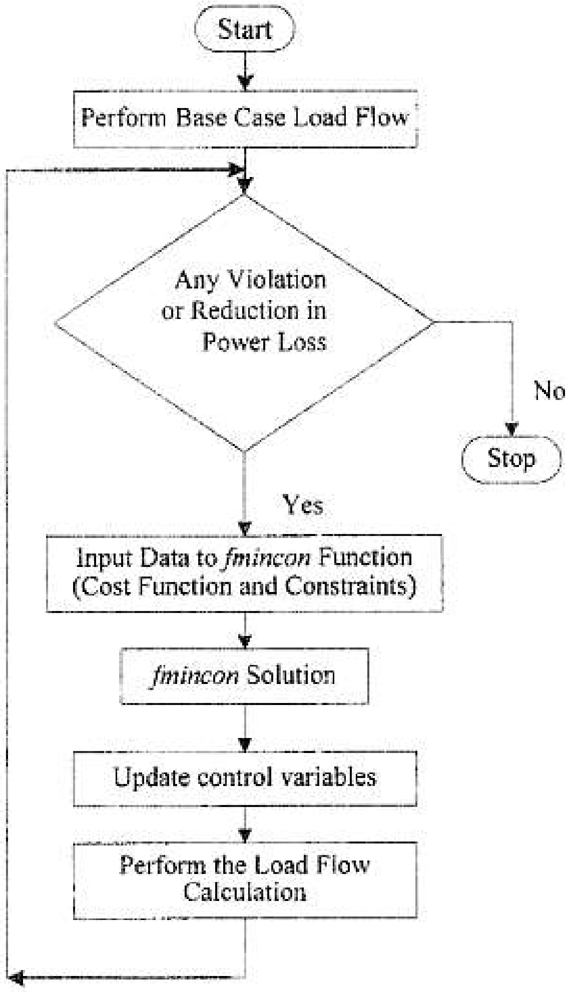

Fig. 2 Flow chart for the ORPF using *fmincon* function

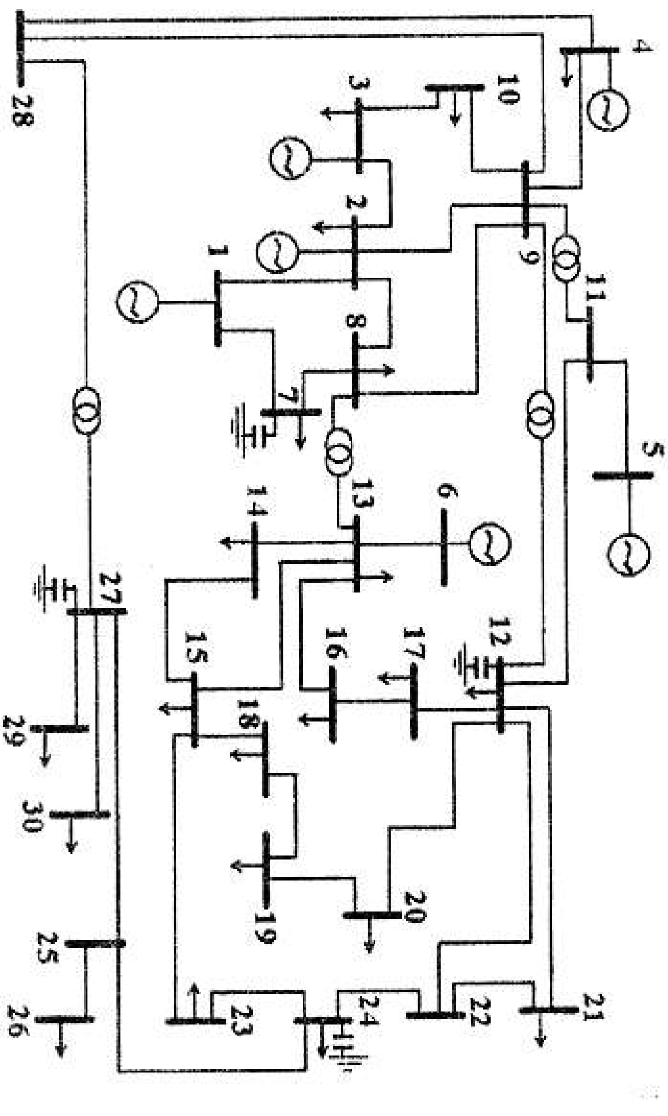

Fig.3 IEEE 30-bus system

Table-1: System bus data

Bus	Voltage		Generation		Load	
No.	V(p.u.)	δ deg,	P(MW)	Q(MVAR	P(MW)	Q(MVAR)
1	1.00	0.00	-----	-----	0.00	0.00
2	1.00	0.00	20.0	-----	21.7	12.7
3	1.00	0.00	10.0	-----	74.2	19.00
4	1.00	0.00	10.0	-----	30.0	30.00
5	1.00	0.00	5.0	-----	0.00	0.00
6	1.00	0.00	5.0	-----	0.00	0.00
7	1.00	0.00	0.00	0.00	25.4	1.2
8	1.00	0.00	0.00	0.00	7.6	1.6
9	1.00	0.00	0.00	0.00	0.00	0.00
10	1.00	0.00	0.00	0.00	18.8	10.9
11	1.00	0.00	0.00	0.00	0.00	0.00
12	1.00	0.00	0.00	0.00	15.8	2.00
13	1.00	0.00	0.00	0.00	11.2	7.5
14	1.00	0.00	0.00	0.00	6.2	1.6
15	1.00	0.00	0.00	0.00	18.2	2.5
16	1.00	0.00	0.00	0.00	3.5	1.8
17	1.00	0.00	0.00	0.00	9.0	5.8
18	1.00	0.00	0.00	0.00	3.2	0.9
19	1.00	0.00	0.00	0.00	9.5	3.4
20	1.00	0.00	0.00	0.00	2.2	0.7
21	1.00	0.00	0.00	0.00	12.5	11.2
22	1.00	0.00	0.00	0.00	0.00	0.00
23	1.00	0.00	0.00	0.00	3.2	1.6
24	1.00	0.00	0.00	0.00	14.7	6.7
25	1.00	0.00	0.00	0.00	0.00	0.00
26	1.00	0.00	0.00	0.00	11.5	2.3
27	1.00	0.00	0.00	0.00	0.00	0.00
28	1.00	0.00	0.00	0.00	0.00	0.00
28	1.00	0.00	0.00	0.00	12.4	0.9
30	1.00	0.00	0.00	0.00	10.6	1.9

Table-2: Limits of system variables

Variables			Limits	
			Low	High
Control variables	(Generator voltage) Vg	p.u.	1.00	1.10
	(Tap setting) T	p.u	0.95	1.05
	(VAR source) Q_C	MVAR	-15	36
Dependent variables	(Load bus voltage) V_l	p.u.	0.90	1.10
	(Generator reactive power) Q_g	MVAR	-40	100

Table-3: Results of the system study for control variables

Variable	Initial state	Final state (LP)	Final state (*fmincon*)
V_{g1} (p.u.)	1.00	1.05	1.03
V_{g2} (p.u.)	1.00	1.00	1.03
V_{g3} (p.u.)	1.00	1.00	1.02
V_{g4} (p.u.)	1.00	1.00	1.03
V_{g5} (p.u.)	1.00	1.09	1.01
V_{g6} (p.u.)	1.00	1.05	1.05
T_{9-11} (p.u.)	1.00	0.975	0.984
T_{9-12} (p.u.)	1.00	1.045	1.05
T_{8-13} (p.u.)	1.00	0.95	0.952
T_{28-27} (p.u)	1.00	0.99	0.9975
Q_{C7} (MVAR)	0.00	-12.0	-10.0
Q_{C12} (MVAR)	0.00	-12.0	-10.0
Q_{C24} (MVAR)	0.00	21.23	22.52
Q_{c27} (MVAR)	0.00	1.09	6.37

Table-4: Results of the system study for bus load voltages

Variable	Initial state	Final state (LP)	Final state (*fmincon*)
V_{l7}	0.98	1.00	1.01
V_{l8}	0.98	0.99	1.01
V_{l9}	0.98	1.00	1.02
V_{l10}	0.98	0.99	1.01
V_{l11}	0.97	1.01	0.99
V_{l12}	0.94	1.00	0.99
V_{l13}	0.97	1.02	1.02
V_{l14}	0.95	1.01	1.01
V_{l15}	0.93	1.00	1.00
V_{l16}	0.95	1.00	1.00
V_{l17}	0.94	0.99	0.99
V_{l18}	0.92	0.99	0.99
V_{l19}	0.92	0.98	0.98
V_{l20}	0.92	0.98	0.98
V_{l21}	0.93	0.99	0.98
V_{l22}	0.93	0.99	0.99
V_{l23}	0.93	1.00	1.00
V_{l24}	0.92	1.00	1.01
V_{l25}	0.90	0.99	1.01
V_{l26}	0.90	0.98	1.00
V_{l27}	0.85	1.00	1.03
V_{l28}	0.92	1.00	1.02
V_{l29}	0.88	0.98	1.01
V_{l30}	0.88	0.97	0.99
System real power losses (MW)			
	24.113	19.336	19.55