APPLICATION OF NEWTON-BASED OPF IN DEREGULATED POWER SYSTEMS

T. Nireekshana[1], G. Kesava Rao[2] and S. Siva Naga Raju[3]
[1]Department of EE Engineering, VNR VJIET, Hyderabad, India.
[2]Department of EE Engg., Vasireddy Venkatadri Institute of Tech., Nambur, A.P., India.
[3]Department of Electrical Engineering, J.N.T.U College of Engg., Kakinada, India.

ABSTRACT

In this work, a Newton-based optimal power flow (OPF) is developed for implementation into a power system simulation environment. The OPF performs all system control while maintaining system security. System controls include generator megawatt outputs, transformer taps, and transformer phase shifts, while maintenance of system security ensures that no power system component's limits are violated. Special attention is paid to the heuristics important to creating an OPF which achieves solution in a rapid manner. Finally, sample applications of the OPF are discussed. These include transmission line overload removal, transmission system control, available transfer capability calculation (ATC), real and reactive power pricing, transmission component valuation, and transmission system marginal pricing.

KEYWORDS: *OPF, Available Transfer Capability (ATC), Short Run Marginal Cost (SRMC), Marginal Pricing, Power World Simulator.*

I. INTRODUCTION

Throughout the entire world, the electric power industry has undergone a considerable change in the past decade and will continue to do so for the next several decades. In the past the electric power industry has been either a government-controlled or a government-regulated industry which existed as a monopoly in its service region. However, countries have begun to split up these monopolies in favor of the free market which can be referred as Restructuring. One of the cornerstones of any restructuring plan is the ability to operate the transmission system in a manner which is fair to all participants in the industry. As stated in [1], "participants in wholesale power markets will have non-discriminatory open access to the transmission systems of public utilities." In order to achieve the ideal of open access, many outstanding engineering problems will need to be investigated and tools created for their solution. It is very important that these problems be addressed early in the restructuring process. If these engineering problems become overshadowed by short term economic concerns, then the result could be decreased electricity reliability.

The primary goal of a generic OPF is to minimize the costs of meeting the load demand for a power system while maintaining the security of the system. The costs associated with the power system may depend on the situation, but in general they can be attributed to the cost of generating power (megawatts) at each generator. It should be noted that the OPF only addresses steady-state operation of the power system. A secondary goal of an OPF is the determination of system marginal cost data. This marginal cost data can aid in the pricing of MW transactions as well as the pricing ancillary services such as voltage support through MVAR support. In solving the OPF using Newton's method, the marginal cost data are determined as a by-product of the solution technique.

A first comprehensive survey regarding optimal power dispatch was given by H.H.Happ [41] and subsequently an IEEE working group [42] presented bibliography survey of major economic-security functions in 1981. Thereafter in 1985, Carpentair [43] presented a survey and classified the OPF algorithms based on their solution methodology. In 1990, Chowdhury [44] did a survey on economic dispatch methods. In 1999, J.A.Momoh *et al.* [45] presented a review of some selected OPF techniques. S.Chen *et al.* [49] proposed a new algorithm based on Newton-Raphson (NR) method with sensitivity factors incorporated to solve emission dispatch in real-time. Execution time is lesser than that of the conventional one. K.L.Lo *et al.* [50] proposed two Newton-like load flow methods, the Fixed Newton method and the modification of the right-hand-side vector method for line outage simulation that is a part of contingency analysis. These two methods are compared with the Newton-based full AC load flow method and the fast decoupled load flow to show their better convergence characteristics. X. Tong *et al.* [51] presented the semi smooth Newton-type algorithms for solving OPF problems. It treated general inequality constraints and bounded constraints separately. The method saves computing cost.

In this paper after giving the introduction to the title, in section II, the development of Newton – based OPF is explained with Problem formulation considering equality and Inequality constraints. The applications of Newton's method of OPF is mentioned and given the flow chart. In section III, heuristics of the OPF solution is explained with implementations of sparse matrix technique and in section IV, comparisons are made with different considerations of the power system conditions to explain the uses of an OPF in a Power system simulation environment.

II. DEVELOPMENT OF NEWTON – BASED OPF

2.1 Problem Statement

Newton's method is a very powerful solution algorithm because of its rapid convergence near the solution. This property is especially useful for power system applications because an initial guess near the solution is easily attained. System voltages will be near rated system values, generator outputs can be estimated from historical data, and transformer tap ratios will be near 0.1 p.u.

A general minimization problem can be written in the following form.

The objective function

$$\text{Minimize } f(x) \qquad \text{----------------------------- (1)}$$

Subject to:

$$h_i(x)=0,\ i=1,2,\ldots..\ m \quad \text{Equality constraints} \qquad \text{-------------------- (2)}$$

$$g_j(x)\leq 0,\ j=1,2,\ldots..\ n \quad \text{Inequality constraints} \qquad \text{-------------------- (3)}$$

There are m equality constraints and n inequality constraints and the number of variables is equal to the dimension of the vector x.

2.2 Application of Newton's Method to OPF

The goal of the OPF is to minimize the costs of meeting the load demand for a power system while maintaining the security of the system. This section of the thesis will discuss the application of Newton's method in a manner that will achieve this desired goal. First, the objective function, *f(x)*, will be introduced. It will reflect the desire to minimize the costs of the system. Then the equality and inequality constraints will be discussed. These constraints model the physical laws of the power system as well as the need to maintain system security.

The objective function

The objective function for the OPF reflects the costs associated with generating power in the system. The quadratic cost model for generation of power will be utilized:

$$C_{P_{gi}} = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \qquad \text{---------------------- (4)}$$

Where P_{Gi} is the amount of generation in megawatts at generator i. The objective function for the entire power system can then be written as the sum of the quadratic cost model at each generator.

$$f(x) = \sum_i (a_i + b_i P_{Gi} + c_i P_{Gi}^2) \qquad \text{---------------------- (5)}$$

This objective function will minimize the total system costs, and does not necessarily minimize the costs for a particular area within the power system.

Equality constraints

The equality constraints of the OPF reflect the physics of the power system as well as the desired voltage set points throughout the system. The physics of the power system are enforced through the power flow equations which require that the net injection of real and reactive power at each bus sum to zero.

$$P_k = 0 = V_k \sum_{m=1}^{N} [V_m [g_{km} \cos(\delta_k - \delta_m) + b_{km} \sin(\delta_k - \delta_m)]] - P_{Gk} + P_{lk} \quad \text{------------- (6)}$$

$$Q_k = 0 = V_k \sum_{m=1}^{N} [V_m [g_{km} \sin(\delta_k - \delta_m) - b_{km} \cos(\delta_k - \delta_m)]] - Q_{Gk} + Q_{lk} \quad \text{------------ (7)}$$

$$V_{Gi} - V_{Gisetpo\,\text{int}} = 0 \quad \text{---------------------- (8)}$$

For multi area power systems, a contractual constraint requires that the net power interchange be equal to the scheduled power interchange. This adds an equality constraint for all but one area.

$$P_{\text{int}\,erchange} - P_{scheduled\,\text{int}\,erchange} = \sum_{tielines} [P_{low}] - P_{scheduled\,\text{int}\,erchange} = 0 \quad \text{------------- (9)}$$

This last area must not have the equality constraint and essentially becomes a "slack area."

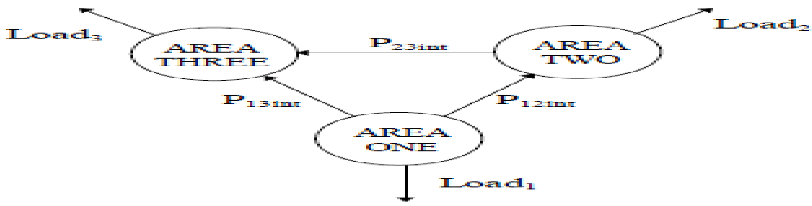


Figure 1: Multi area System with Scheduled Interchanges

Inequality constraints

Generators have maximum and minimum output powers and reactive powers which add inequality constraints.

$$P_{Gi\,\min} \le P_{Gi} \le P_{Gi\,\max} \quad \text{--------------------- (10)}$$

$$Q_{Gi\,\min} \le Q_{Gi} \le Q_{Gi\,\max} \quad \text{--------------------- (11)}$$

Load tap changing transformers have a maximum and a minimum tap ratio which can be achieved and phase shifting transformers have a maximum and a minimum phase shift, which can be achieved. Both of these create inequality constraints.

$$t_{km\,\min} \le t_{km} \le t_{km\,\max} \quad \text{---------------------- (12)}$$

$$\alpha_{km\,\min} \le \alpha_{km} \le \alpha_{km\,\max} \quad \text{---------------------- (13)}$$

$$|S_{km}|^2 - |S_{km\,\max}|^2 \le 0 \quad \text{---------------------- (14)}$$

To maintain the quality of electrical service and system security, bus voltages usually have maximum and minimum magnitudes. These limits again require the addition of inequality constraints.

$$V_{i\,\min} \le V_i \le V_{i\,\max} \quad \text{----------------------- (15)}$$

One issue sometimes encountered when trying to solve a minimization problem is the nonexistence of a feasible solution. Essentially this means that too many constraints have been added to the problem and no solution exists which obeys all of the constraints. A well-suited penalty function for use in Newton's method is the quadratic penalty function [3] which meets the requirements of a penalty function and is also easily differentiated for use by Newton's method. In the OPF presented in this thesis, soft inequality constraints are available for transmission line MVA limits as well as bus voltage limits.

Penalty Functions

$$W_{km} = k(|S_{km}|^2 - |S_{km\,\max}|^2)^2 \quad \text{------------------- (16)}$$

$$W_i = k(V_{i\,\min} - V_i)^2; V_i < V_{i\,\min} \quad \text{------------------- (17)}$$

$$W_i = k(V_i - V_{i\,\max})^2; V_i > V_{i\,\max} \quad \text{------------------- (18)}$$

$$W_i = 0; V_{i\,\min} \le V_i \le V_{i\,\max} \quad \text{------------------- (19)}$$

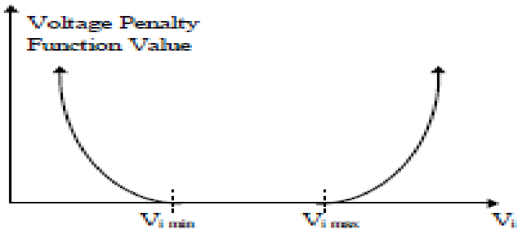


Figure 2: Penalty Function for Bus Voltage

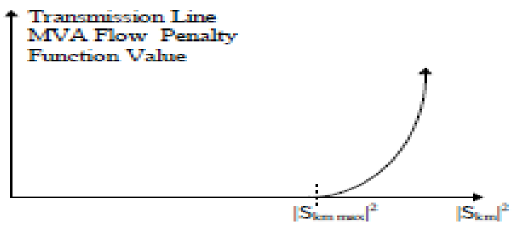


Figure 3: Penalty Function for Line MVA Flow Limit

After doing trial and error experimentation, values for k were chosen for use in the OPF of this work. For soft bus voltage constraints, k was chosen to be $200/V2. For soft transmission line constraints, k was chosen to be $100/MVA.

2.3 Solution of the optimal power flow

The Newton's method algorithm is summarized in the flowchart.

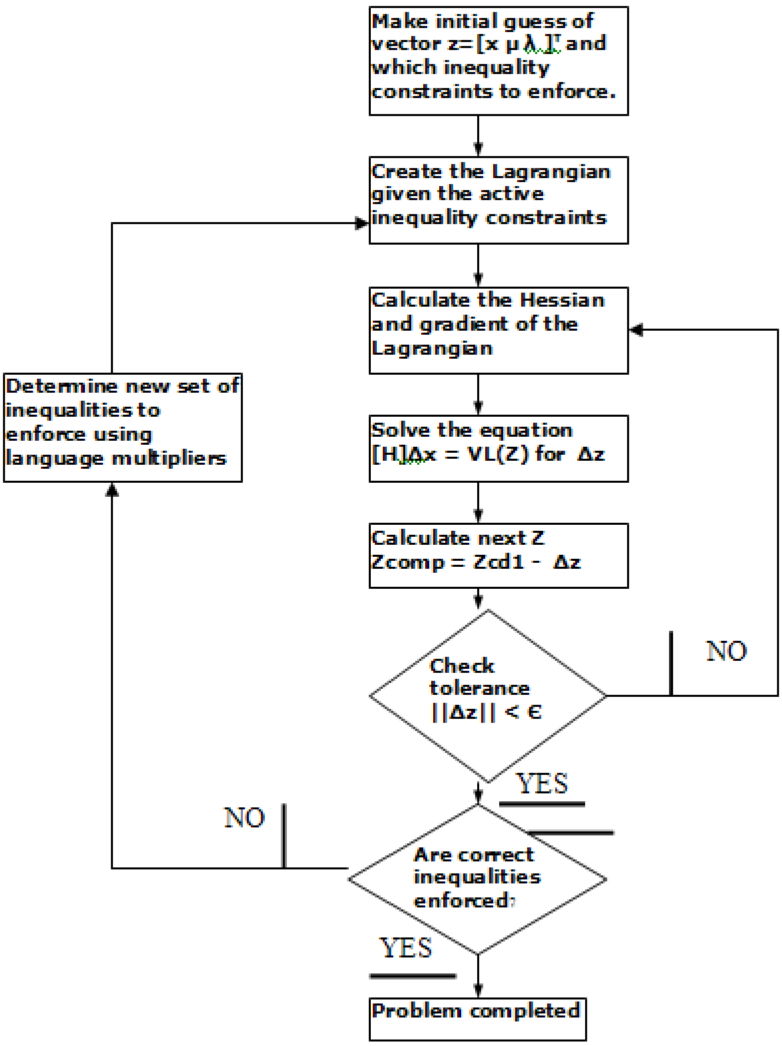


Figure. 4: Flow chart of Newton's method

III. Heuristics of the OPF Solution

3.1 Classification of OPF Variables

While writing software to perform an OPF solution, a primary concern is identification of variables during the process. Because of this, in order to handle the variables in the OPF problem efficiently, it is convenient to separate them into three categories: controls, states, and constraints. The control variables correspond to quantities that can be arbitrarily manipulated, within their limits, in order to minimize the costs.

3.2 Implementation of Sparse Matrix Techniques

At the heart of the solution of the OPF using Newton's method is the solution of the linear system of equations, [H]Dz = ÑL(z). During the Newton's method solution process, this system of equations is solved repeatedly. Because of this, and because one of the primary objectives of an OPF is to find its solution in a short amount of time, the speed of the solution of this linear system of equations is essential to a successful OPF solution. Fortunately, as is the case with many power system matrices, the Hessian matrix is extremely sparse. By implementing sparse matrix routines, the equations can be quickly solved.

Much of the structure of the Hessian matrix for the OPF problem is known prior to any calculation. In general, for any Newton's method routine, the Hessian takes the following form

$$H = \begin{pmatrix} W & J^T \\ J & 0 \end{pmatrix} \qquad \text{---------------------- (20)}$$

Already, it is seen that the lower right quadrant of the matrix has entries of zero. By a closer examination of the Hessian structure for the OPF problem, advantage can be taken of this sparsity. The first step was to reorder the variables to include the generator megawatt controls first, Followed by the remaining controls, states, and then constraints. This resulted in the following structure.

$$H = \begin{pmatrix} W_{PG} & 0 & n_{PG}{}^T \\ 0 & W_{remaining} & J_{remaining}{}^T \\ a_{31} & J_{remaining} & 0 \end{pmatrix} \qquad \text{--------------------- (21)}$$

where W_{PG} is a purely diagonal matrix with entries of $2ci$, n_{PG} is a matrix with a (-1) entry in each column corresponding to the net power injection constraint, and possibly an entry of (±1) in a column corresponding to a generator with a maximum or a minimum MW constraint being enforced, and $W_{remaining}$ and $J_{remaining}$ are the remaining parts of the Hessian matrix.

Due to this structure, the sparse LU factorization up to the rows of $W_{remaining}$, using Gauss's method [24], will result in the following matrix.

$$H_{\mathrm{mod}\,ified} = \begin{pmatrix} W_{PG} & 0 & W_{PG}{}^{-1} n_{PG}{}^T \\ 0 & W_{remaining} & J_{remaining}{}^T \\ n_{PG} & J_{remaining} & -n_{PG} W^{-1} n_{PG}{}^T \end{pmatrix} \qquad \text{---------------------- (22)}$$

$W_{remaining}$ and $J_{remaining}$ are unaffected by these steps and fills are only created by the term $n_{PG}\, W^{1}{}_{PG}\, n_{PG}{}^{T}$. In order to determine the fills created by this matrix, consider only its zero/nonzero structure. One will find that most fills created by this term are actually desired.

$$H = \begin{vmatrix} W_{PG} & 0 & 0 & 0 & n_{PG}{}^T \\ 0 & I & 0 & 0 & 0 \\ 0 & W_{rvset} & I & W_{rvset}{}^T & J_{rvset}{}^T \\ 0 & W_{rvset} & 0 & W_r & J_{rr}{}^T \\ n_{PG} & J_{rvset} & 0 & J_{rr} & 0 \end{vmatrix} \qquad \text{--------------------- (23)}$$

Given this ordering, the sparse LU factorization up to the rows of W_r, using Gauss's method [4], will result in the following matrix.

$$H_{\mathrm{mod}\,ified} = \begin{vmatrix} W_{PG} & 0 & 0 & 0 & W_{PG}^{-1} n_{PG}{}^T \\ 0 & I & 0 & 0 & 0 \\ 0 & W_{rvset} & I & W_{rvset}{}^T & J_{rvset}{}^T \\ 0 & W_{rvset} & 0 & W_r & J_{rr}{}^T \\ n_{PG} & J_{rvset} & 0 & J_{rr} & -n_{PG} W_{PG}^{-1} n_{PG}{}^T \end{vmatrix} \qquad \text{--------------- (24)}$$

The fills created by this method would be identical to those created by the previous ordering. However, in addition, the sparse matrix routines could also take advantage of simply "skipping" over the processing of the second- and third-row partitions because the only operations required by Gauss's method would be divisions by 1.

3.3 Solution of an OPF Repeatedly Over Time

By keeping the solved OPF solution, the speed of solution in the simulation environment will be greatly increased. These modifications will greatly enhance the power system simulation over time. In calculating the Hessian a time step, further advantage could be gained by implementing partial re-factorization schemes for the Hessian as seen in [5]. These schemes only update those elements of the L and U factors of the Hessian that are affected by changes to the Hessian. While this holds great promise for future work, these schemes have not yet been implemented into the OPF written for this work.

IV. USES OF AN OPF IN A POWER SYSTEM SIMULATION ENVIRONMENT

In this environment, simulation of a system over time can be done while maintaining it at its optimal condition. In this way, a vast amount of economic data can be gleaned from the simulation. The OPF code as implemented into the power system simulator, POWERWORLD [25].

4.1 Line Overload Removal

A simple power system not operating under the OPF control is shown in Figure 5.

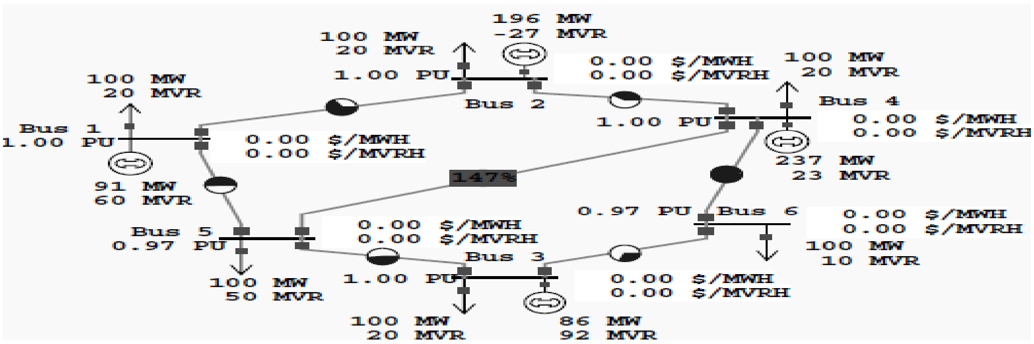


Figure 5: Six-bus, Single-Area System Not on OPF Control

In order to remove the line constraint, the OPF control is turned on, and the line overload is removed as shown in Figure 6.

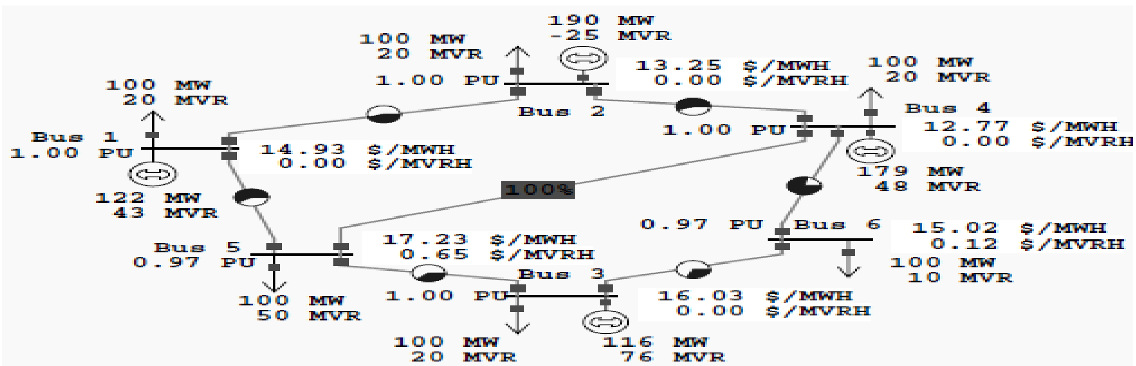


Figure 6: Six-bus, Single-Area System on OPF Control

As can be seen, the generators have redispatched themselves in order to remove the line overload.

4.2 Use for Bus Real and Reactive Power Pricing

To illustrate the real and reactive power pricing potentials of the OPF solution, the same system shown in Figure 6 is placed on OPF control with its line limit raised. See Figure 7. Note that the OPF results in the same dispatch seen in Figure 6 now that the line limit has been removed.

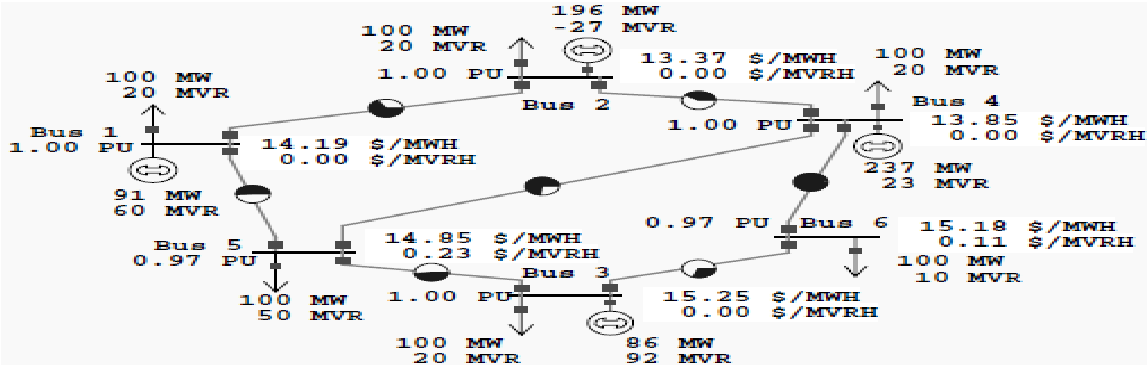


Figure 7: Line Limit from Bus 5 to 4 raised to 100 MVA

4.3 Use for Area Real Power Pricing

The OPF solution method may also be used with multi area power systems. The OPF will enforce the scheduled area interchange in these systems. In Figure 5, the simple six-bus system from before is split into two areas as shown.

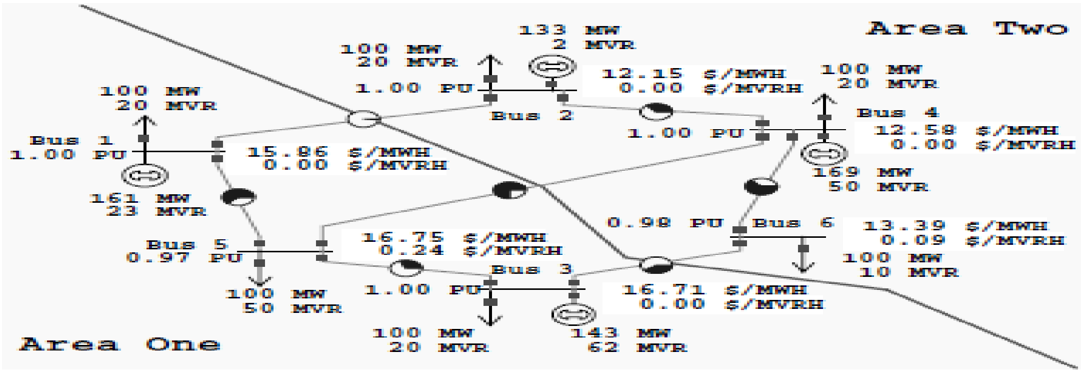


Figure 8: Six-bus, Two-Area System on OPF Control

As can be seen, for this case the generation in Area Two is less expensive than in Area One; therefore, it would be advantageous for both areas if Area One were to purchase some power from Area Two. Using the capabilities of the POWERWORLD Area Transactions/Information display [2], scheduled transactions can be set up between the two areas to optimize their costs.

Table 1: summarizes several possibilities.

Transaction [MW]	Area-One Cost [$/hr]	Area-Two Cost [$/hr]	Sum of Both Areas [$/hr]
None	4564	3496	8060
50.0	4489	3423	7912
65.5	4482	3413	7895
70.0	4481	3415	7896
80.0	4481	3428	7909

From table 1, the least expensive scenario for the sum of the areas is when an interchange of 65.5 MW is undertaken. This transaction scenario is shown in Figure 9.

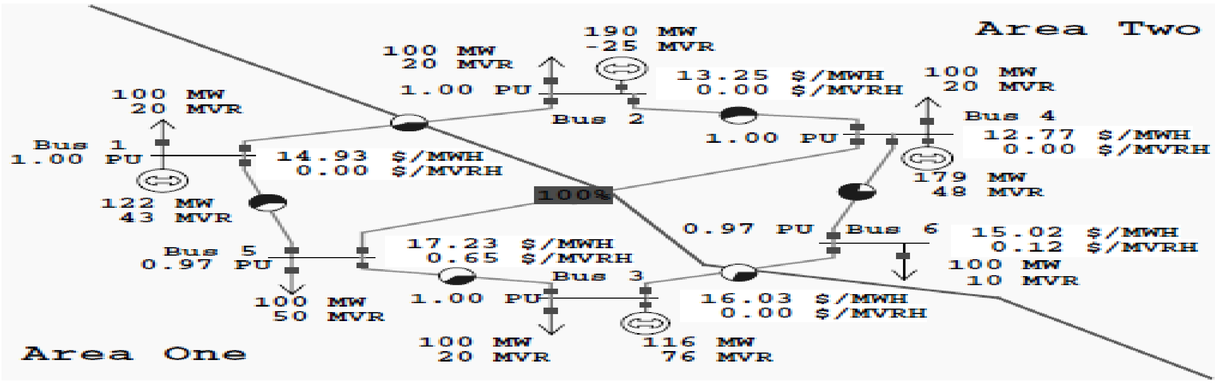
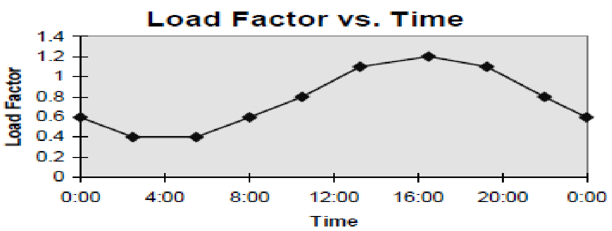


Figure 9 : Transaction of 65.5 MW Undertaken

4.4 Transmission Line Valuation by Time-Domain Simulation

One of the most intriguing potential uses of an OPF is its use as a pricing tool by doing time domain simulations of a power system. As a simple example, consider again the six-bus, one area power system. Assume that the loads of the system vary as shown in Figure 10. The load at a given bus is then equal to its base value multiplied by the load factor.



Time	Load Factor	Time	Load Factor
0:00	0.6	13:15	1.1
2:30	0.4	16:30	1.2
5:30	0.4	19:15	1.1
8:00	0.6	22:00	0.8
10:30	0.8	23:59	0.6

Figure 10: Load Factor Curve for six-bus System

Entering this load factor curve into the POWERWORLD simulation software and simulating the power system for a full 24 hours yield a total cost in dollars for operating the power system over that period of time. By re-simulating the system repeatedly with variations in system structure, one can gain useful economic insights from the comparison of total system costs. Note that the case was simulated at 600 times real time for the first 23 hours and at 60 times real time for the last hour. The POWERWORLD simulation software utilizes trapezoidal rule integration to calculate the total system cost from the incremental costs at each time point [18]-[20].

Using this technique, the six-bus system was simulated with various transmission lines removed. The results are summarized in Table 2.

Table 2: Simulation data for six-bus system with transmission lines removed

System Configuration	Total Cost for 24 Hour Simulation	Difference from No Change Configuration	Percent Increase from No Change Configuration
No Changes	$ 148,240	N/A	N/A
Line from Bus 3 to Bus 5 Removed	$ 148,377	$137.00	0.09%
Line from Bus 3 to Bus 4 Removed	$ 148,632	$392.00	0.26%
Line from Bus 1 to Bus 2 Removed	$ 149,311	$1,071.00	0.72%
Line from Bus 4 to Bus 5 Removed	$ 150,309	$2,069.00	1.40%

By comparing the total system cost with all lines connected to the cost with a line removed, one can find the approximate cost a company would incur per day while taking a line out for maintenance. It is very important to note, however, that this does in no way take into account the possibility that another line may unexpectedly go out, in which case all lines may be needed to take up the slack. In other words, the pricing of redundancies in the transmission system is not considered in this methodology.

4.5 Limit on Available Transfer Capability (ATC) Due to a Voltage Constraint [6]

Another use for the OPF algorithm is for the calculation of the available transfer capability for a system. The OPF is able to take into account system security concerns including voltage limits and transmission line limits while calculating the ATC [31]-[35].

The three-bus system of Figure 11 can be used to illustrate and examine the value of reactive power support at a system load bus. Area one consists only of the generator and load at bus 1 plus two tie lines. Area two consists of the generator and load at bus 3 plus the load at bus 2, and the line from bus 2 to bus 3. Area one has expensive generation, while area two has cheaper generation. For the indicated loads and no area transfers the cost of operation for the total system is $25,799/hr.

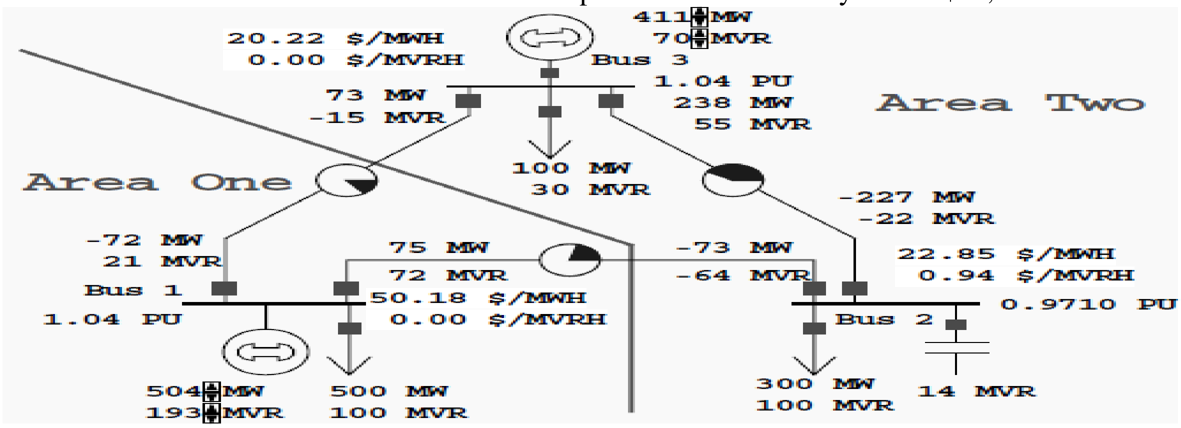


Figure.11: Three-Bus Base Case with No Area Power Transfer

Note that the incremental cost for reactive power at a generator bus is $0.00. This is true as long as no MVAR limits are reached because no cost is associated with generation of MVARs by a generator in the OPF formulation of this work. Consider the situation where area one wants to purchase power at considerable savings from area two. Similarly, area two wants to sell power to area one. We first examine the available transfer capability of this system for transfer from area two to area one. An OPF solution with bus voltage constraints is used to find the maximum power which can be transferred from area two to area one. The voltage constraint for power quality used in this example is

$$0.96 \leq V_i \leq 1.04.$$

Both generators have their excitations set to give 1.04 p.u. voltages for serving their local area load within the voltage constraints. A global OPF solution which minimizes the total cost of providing the total load will attempt to increase area-two generation and decrease area-one generation. This power transfer will change the voltage at bus 2. When the transfer is such that the voltage reaches its lower limit (0.96), the OPF solution will stop at that constraint.

4.6 Transmission System Pricing Through Short-Run Marginal Costing (SRMC)

In the restructured environment of the future, it may be necessary to determine the cost incurred to the transmission system due to a power transaction between two companies. This cost would be charged to the two companies undergoing the transaction and would be paid to the operator of the transmission system. Two methods proposed for the determination of this cost is through short-run marginal costing (SRMC) and long-run marginal costing (LRMC). These two topics are extensively discussed in both [7] and [8]. A brief, albeit simple, explanation of these follows. The SRMC takes into account only the operating costs of the power system. The operating costs include fuel costs, losses, as well as system constraints such as transmission line limits. The LRMC, however, includes both the operating costs and the capital costs of the power system. The capital costs include the costs of future expansion to the transmission system as well as the generation capacity.

Through the use of the OPF, the SRMC technique can easily be implemented as discussed in [8]. The SRMC of a power transaction can be estimated by solving the OPF for both the system with the transaction and the system without the transaction in place. After these solutions are obtained, the SRMC can be found as follows.

Define BMC_i = (marginal cost of power at bus i after the Transaction)

$P_{i,\ transaction}$ = the net power injection at bus i due to the Transaction

= (- power generation at bus I Before Transaction + power generation at bus i after transaction)

From these definitions a definition for SRMC can then be made [8].

$$SRMC_{transaction} = \sum_{allbuses in transaction} BMC_i * P_{i,transcation} \text{ --------------- (26)}$$

As a simple example consider the six-bus, two-area system with no transactions Figure 8, and with a transaction of 65.5 MW undertaken between the two areas Figure 9. Taking the data from these two figures, a calculation of the SRMC for the transaction can be made. This calculation is summarized in Table 4.

Table 4: SRMC calculation for six-bus, two-area system

Bus Num	Generation Before Transaction [MW]	BMC Before Transaction [$/MWhr]	Generation After Transaction [MW]	BMC After Transaction [$/MWhr]	$P_{i,trans}$ [MW]	$BMC_i * P_{i,trans}$ [$/hr]
1	161	15.86	122	14.93	-39	-582.27
2	133	12.15	190	13.25	57	755.25
3	143	16.71	116	16.03	-27	-432.81
4	169	12.58	179	12.77	10	127.70
					$SRMC_{transaction} = \sum_{\text{all buses in transaction}} BMC_i * P_{i,transaction} =$	-132.13

Thus, the SRMC for this transaction is (- $132.13)/hour. As mentioned in [7], SRMC can be a negative value.

For comparison, consider the same system undergoing the same 65.5 MW transaction, but with the line between buses 4 and 5 doubled to 100 MVA from 50 MVA. The simulation of this system is shown in Figure 12.

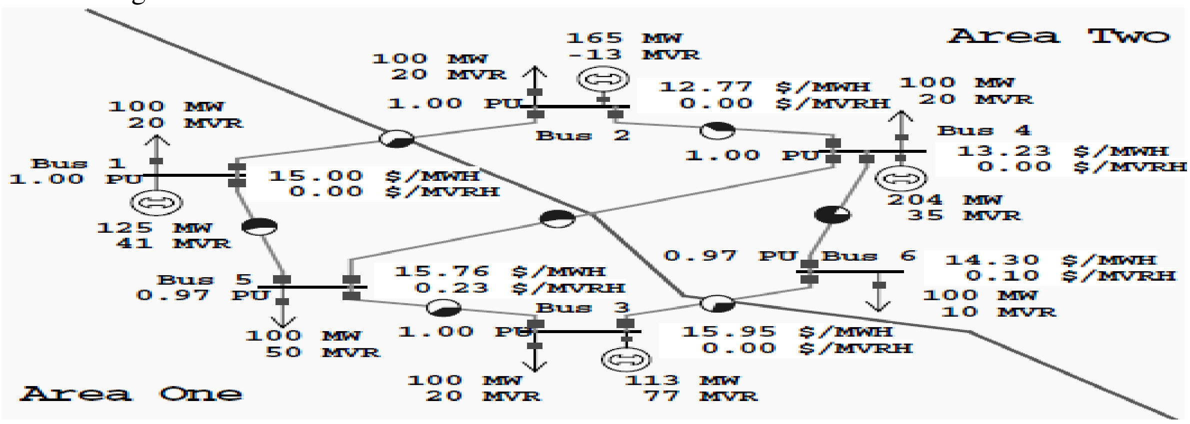


Figure.12: Six-bus, Two-Area System Undergoing Transaction with Line Limit Doubled

Again, Figure 12 shows this system with no transactions, and Figure 9 shows the system with a transaction of 65.5 MW undertaken between the two areas. Taking the data from these two figures, a calculation of the SRMC for the transaction can be made for the system where no line limit will be encountered. This calculation is summarized in Table 5.

Table 5: SRMC calculation for six-bus, two-area system where no limit is encountered

Bus Num	Generation Before Transaction [MW]	BMC Before Transaction [$/MWhr]	Generation Aafter Transaction [MW]	BMC After Transaction [$/MWhr]	$P_{i,trans}$ [MW]	$BMC_i * P_{i,trans}$ [$/hr]
1	161	15.86	125	15.00	-36	-540.00
2	133	12.15	165	12.77	32	408.64
3	143	16.71	113	15.95	-30	-478.50
4	169	12.58	204	13.23	35	463.05
					$SRMC_{transaction} = \sum_{\text{all buses in transaction}} BMC_i * P_{i,transaction} =$	-146.81

Thus, the SRMC for this transaction is (- $146.81)/hour. This is not unexpected. The previous system encountered a transmission line constraint, while this one has not; therefore, the incentive to do the transaction should be large, i.e., the SRMC should be less. While this discussion is not entirely complete, it does display the basic use of the OPF to calculate the SRMC. More study will be done on this topic in the future.

V. RESULTS AND DISCUSSIONS

A six- bus single area with not an OPF control and on OPF control are simulated and compared.
Comparison of the OPF solutions in Figure 6 and Figure 7 yield valuable insight. The total system cost without the line limited as in Figure 6 is $7824/hr. With the line limited as in Figure 7 this costs increases, as would be expected, to $7895/hr. Also note the differences between the bus MW marginal costs in Figure 7 and Figure 6. Because the generators at buses 2 and 4 were forced to decrease their output in order to remove the overload, their bus MW marginal costs also decreased. Conversely, the bus MW marginal costs at buses 1, 3, and 5 increased. As might be expected, the largest changes occurred at the ends of the limited line, buses 4 and 5.
Comparing the OPF solution in Figure 6 and Figure 9 shows the same solution. This is of course not unexpected, because the two-area economic negotiations should yield the same solution that an OPF solution disregarding areas would. This must happen so that all areas are at their optimal solution.
SRMC calculation for 6-bus 2-area with line limit double and where no limit is encountered are compared and concluded as When the capacitor bank at bus 2 is increased from a nominal 15 MVAR rating to a nominal 30 MVAR rating, the OPF solution is given. The available transfer capability for these constraints is increased to 325 MW. The cost of operation for the total system is $20,890/hr. Thus the increase in available power transfer capability has resulted in an additional reduction of total cost by $451/hr. Again, additional transfers are not possible without violation of the voltage constraint at bus 2. Note that the incremental cost for MVARs has reduced as the OPF approaches a more economical dispatch. When the capacitor bank at bus 2 is increased from a nominal 30 MVAR rating to a nominal 45 MVAR rating, the OPF solution is given.
The work presented in this paper utilizes an optimal power flow program, OPF, as the tool for solving these problems. The OPF is a natural choice for addressing these concerns because it is basically an optimal control problem. The OPF utilizes all control variables to help minimize the costs of the power system operation. It also yields valuable economic information and insight into the power system. In these ways, the OPF very adeptly addresses both the control and economic problems.
After creating the OPF program, the user-interface and simulation problems may also be addressed by implementing the OPF into a power system simulator. In this way, the results of the economic and control operations of the OPF can easily be utilized by the user of the program. This paper will explore the application of Newton's method to the OPF problem. Specifically, it will explore the implementation of a Newton's method based OPF in the power system simulator POWERWORLD [25].

VI. CONCLUSION

Minimization of system costs, while maintaining system security, was accomplished through the implementation of Newton's method to the OPF problem. Newton's method has proven to be very adept at solving the OPF problem. The OPF performs generator control and transmission system control while taking into account system limits. The marginal cost data from the OPF were shown to aid in the available transfer capability (ATC) calculation, real and reactive power pricing, transmission system pricing, and transmission system component valuation. The author would like to reiterate that while the applications of the OPF as discussed in this thesis are extremely valuable, they do not take into account the possibility of random outages of transmission line components or generators. Also, the pricing schemes discussed do not take into account the need for future expansion of the power system.

REFERENCES

[1]. Federal Energy Regulatory Commission of the United States of America, "Promoting wholesale competition through open access non-discriminatory transmission services by public utilities," Docket No. RM95-8-00, March 1995.

[2]. T. J. Overbye, P. W. Sauer, C. M. Marzinzik and G. Gross, "A User-Friendly Simulation Program for Teaching Power System Operations," IEEE Transactions on Power Systems, Vol. 10, No. 4, November 1995, pp. 1725-1733.
[3]. D. G. Luenberger, Linear and Non-Linear Programming, Reading, MA: Addison-Wesley Publishing Company, 1984, pp. 295-392,423-450.
[4]. G. E. Forsythe and C. B. Moler, Computer Solution of Linear Algebraic Systems, Englewood Cliffs, N.J.: Prentice-Hall, 1967, Chapters 9 and 16.
[5]. S. M. Chan and V. Brandwajn, "Partial Matrix Refactorization," IEEE Transactions on Power Systems, Vol. PWRS-1, No. 1, February 1986, pp. 193-200.
[6]. J. D. Weber, M. J. Laufenberg, T. J. Overbye and P. W. Sauer, "Assessing the Value of Reactive Power Services in Electric Power Systems," Conference on Unbundled Power Quality Services, Key West, Florida, November 17-19, 1996.
[7]. R. D. Tabors, "Transmission System Management and Pricing: New Paradigms and International Comparisons," IEEE Transactions on Power Systems, Vol. 9, No. 1, February 1994, pp. 206-215.
[8]. D. Shirmohammadi, X.V. Filho, B. Gorenstin and M. Pereira, "Some fundamental technical concepts about cost based transmission pricing," IEEE Transactions on Power Systems, Vol. 11, No. 2, May 1996, pp. 1002-1008.
[9]. A.F. Zooba, W.J. Lee, "The Globalization of Energy Markets in Asia," IEEE PES General Meeting 2006, pp. 1-6, Oct. 2006.
[10]. S.N. Singh, S.C. Srivastava, "Electric Power Industry restructuring in India: Present Scenario and Future Prospect," IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies (DRPT2004), vol.1, pp. 20-23, April 2004.
[11]. P. Bajpai, S.N. Singh, "An Electric Power Trading Model for Indian Electricity Market," IEEE PES General Meeting 2006, Oct. 2006.
[12]. J. Wernerus, "A Model for studies related to Deregulation of an Electricity Market," KTH-Stockholm, Master Thesis TRITA-EES-9503, November 1995.
[13]. S. Mohammad & A. Muwaffaq, Restructured Electric Power systems- Operation, Trading & Volatility, Markcel Dekker, Inc., Basel, Switzerland, 2001.
[14]. S.N. Singh, S.C. Srivastava, "Electric Power Industry restructuring in India: Present Scenario and Future Prospect," IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies (DRPT2004), vol.1, pp. 20-23, April 2004.
[15]. P. Wolfgang, Preface: Competition and Long-Term Dimensions of Electricity Supply, Jacobs University Bremen, Page (29- 36).
[16]. http://en.wikipedia.org/wiki/Electricity_tariff
[17]. E. Hirst & B. Kirby, The Function, Metrics, and Prices for Three Ancillary Services, Edison Electric Institute, Washington, DC, October 1998.
[18]. S. G. Kim, "LMP as Market Signal for Reserve Supply in Energy and Reserve Integrated Market," IEEE PES PSCE 2006, pp.896-900, Nov. 2006.
[19]. B. Kankar, B.H.J. Math & E.D. Jaap, Operation of Restructured Power systems, Kluweir Power Systems series Series Editor: M.A. Pai, 2001.
[20]. B. Joseph, The PJM Market, Chapter 13, pp. 451-477, PJM Interconnection LLC, Pennsylvania, USA, 2006.
[21]. G.Terge, G. jan Ove, F. Roger, "Ancillary Services in Deregulated Power Systems; What are they; Who need them and who pays," IEEE POWERCON'98, vol.1, pp. 704-709, August 1998.
[22]. Kwon W. Cheung, Ancillary Service Market Design and Implementation in North America: From Theory to Practice, IEEE Third International Conference on Electric Utility Deregulation, Restructuring and Power Technologies (DRPT2004), pp. 66-67, April, 2008.
[23]. S.Mohammad & S. Muwaffaq, Restructured Electrical Power Systems- Operation, Trading & Volatility, Marcel Dekker, Inc., NY, 2001.
[24]. S.N. Singh, S.C. Srivastava, "Electric Power Industry restructuring in India: Present Scenario and Future Prospect," IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies (DRPT2004), vol.1, pp. 20-23, April 2004.
[25]. http://www.powerworld.com/products.asp
[26]. IEEE Reliability Test System, IEEE transactions on power apparatus and systems, Vol.PAS-98, No.6, Nov/Dec. 1979.
[27]. Power Electronics in Electric Utilities: Static Var Compensators Proceedings of the IEEE, VOL. 76, NO. 4, APRIL 1988.
[28]. V. Ajarapu, and C. Christie, "The continuation power flow: a practical tool for tracing power system steady state stationary behavior due to the load and generation variations," IEEE Trans. Power Systems, Vol. 7, No. 1, Feb. 1992,416-423.

[29]. M.Noroozian, G.Anderson, "Power Flow Control by Use of Controllable Series Components", IEEE Transactions on Power Delivery, VO1.8, No.3, July 1993, 1420-1428.
[30]. Vladimiro Miranda, J.V. Ranito, L. M. Proenca, "Genetic Algorithms in Optimal Multistage Distribution Network Planning", IEEE Trans. Power Systems, Vol. 9, o. 4, Nov. 1994, 1927-1933.
[31]. Transmission Transfer Capability Task Force, "Available transfer capability Definitions and determination," North American Electric Reliability Council, NJ, June 1996.
[32]. G. C. Ejebe, J. Tong, J. G. Waight, J. G. Frame, X. Wang, and W. F. Tinney, "Available transfer capability calculations," IEEE Trans. Power Systems, Vol. 13, No.4, Nov.1998, 1521-1527.
[33]. Y. Dai, J. D. McCalley, V. Vittal, "Simplification, expansion and enhancement of direct interior point algorithm for power system maximum loadability", Proc. 21st Int. Conf. Power Ind. Comput. Applicat, pp. 170-179, 1999.
[34]. Richard D. Christie, Bruce F. Wollenberg and Ivar Wangensteen, "Transmission Management in the Deregulated Environment", Proceedings of the IEEE, Vol.88, No.2, February 2000.
[35]. Y. Xiao, Y. H. Song, Y. Z. Sun, "Available Transfer Capability Enhancement Using FACTS Devices", Proceedings of the 2000 IEEE/PWS Summer Meeting,, Seattle, vol.1, pp. 508-515, July 2000.
[36]. Wang Feng, G.B.Shrestha "Allocation of TCSC Devices to Optimize Total Transmission Capacity in a Competitive Power Market" IEEE Trans. Power Systems, Feb 2001, 587-592.
[37]. Stephane Gerbex, Rachid Cherkaoui, and Alain J. Germond, "Optimal Location of Multi-Type FACTS Devices in a Power System by Means of Genetic Algorithms," IEEE Trans. on Power Systems, vol. 16, no. 3, August 2001.
[38]. Dr. Tapan Kumar Saha "Required Shunt Compensation for an EHV Transmission Line" The University of Queensland, Australia, May 2003.
[39]. R.C. Bansal, A.F.Zobaa, K.A.Nigim "Technology of VAr Compensators for Induction Generator Applications in Wind Energy Conversion Systems" Journal of Electrical System, 2006, 172-184.
[40]. MATLAB Genetic Algorithm Tutorials
[41]. H. H. Happ, "Optimal power dispatch-A comprehensive survey", *IEEE Trans. Power Apparat. Syst.,* vol. PAS-90, pp. 841-854, 1977.
[42]. IEEE working group, "Description and bibliography of major economic-security functions part-II and III, *IEEE Trans. Power Apparat. Syst.,* vol. PAS-100, pp. 215-235, 1981.
[43]. J. Carpentier, "Optimal power flow, uses, methods and development", *Planning and operation of electrical energy system Proc. Of IFAC symposium*, Brazil, 1985, pp. 11-21.
[44]. B. H. Chowdhury and Rahman, "Recent advances in economic dispatch", *IEEE Trans. Power Syst.,* no. 5, pp. 1248-1259, 1990.
[45]. J. A. Momoh, M. E. El-Harwary and Ramababu Adapa, "A review of selected optimal power flow literature to 1993, part- I and II", *IEEE Trans. Power Syst.,* vol. 14, no. 1, pp. 96-111, Feb. 1999.
[46]. T. S. Chung and Ge Shaoyun, "A recursive LP-based approach for optimal capacitor allocation with cost-benefit consideration", *Electric Power Syst. Research,* vol. 39, pp. 129-136, 1997.
[47]. E. Lobato, L. Rouco, M. I. Navarrete, R. Casanova and G. Lopez, "An LP-based optimal power flow for transmission losses and generator reactive margins minimization", in *Proc. of IEEE porto power tech conference,* Portugal, Sept. 2001.
[48]. F. G. M. Lima, F. D. Galiana, I. Kockar and J. Munoz, "Phase shifter placement in largescale systems via mixed integer linear programming", *IEEE Trans. Power Syst,* vol. 18, no. 3, pp. 1029-1034, Aug. 2003.
[49]. S. D. Chen and J. F. Chen, "A new algorithm based on the Newton-Raphson approach for real-time emission dispatch", *Electric Power Syst. Research,* vol. 40, pp. 137-141, 1997.
[50]. K. L. Lo and Z. J. Meng, "Newton-like method for line outage simulation", *IEE proc.- Gener. Transm. Distrib.,* vol. 151, no. 2, pp. 225-231, March 2004.
[51]. X. Tong and M. Lin, "Semismooth Newtontype algorithms for solving optimal power flow problems", in *Proc.* o*f IEEE/PES Transmission and Distribution Conference,* Dalian, China, 2005, pp.1-7.

Biography of Authors

T. Nireekshana obtained her B.Tech and M.Tech from JNT University in 2002 and 2005 respectively. She is Assistant professor in EEE, VNR VJIET Engineering College, Hyderabad. She has been pursuing Ph.D work, part-time with JNTU.

G. Kesava Rao obtained his PhD from Moscow Power Engineering Inst. Moscow, U.S.S.R. He worked in Institute of Technology at Banaras Hindu University, Varanasi, India in various administrative and academic positions. Currently, he is working at Vasireddy Venkatadri Institute of Technology, Nambur, A.P., India. His fields of interest are power system deregulation and renewable energy sources.

S. Sivanagaraju, is graduated in 1998, Masters in 2000 from IIT, Kharagpur and did his Ph.D from J.N.T.University in 2004. Working as Associate Professor in the Department of Electrical Engineering, J.N.T.U College of Engg. (Autonomous), Kakinada, Andhra Pradesh since November 2006. He has received two National awards (Pandit Madan Mohan Malaviya memorial prize award and Best Paper Prize award) from the Institute of Engineers (India) for the year 2003-2004. He is Referee for IEE Proceedings- Generation Transmission and Distribution and International Journal of Emerging Electric Power System. About 40 publications in National and International Journals and Conferences to his credit. His areas of interest are in Power Systems, Distribution Automation, Genetic Algorithm applications to distribution systems and power system.