Simulation of Power Market Analysis

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Abstract : **In this paper, a Newton-based optimal power flow (OPF) is used for power market analysis. The OPF has features of line overload removal, enforce the constraints, bus marginal control, transmission line marginal control, super area control. The main purpose of using optimal power flow(OPF) in this paper is to determine the "best" way to instantaneously operate a power system, and also discussed the various ways to reduce the marginal cost of both buses and lines with constraints. Power world simulator employs linear programming method for finding optimal solution.**

***IndexTerms* - OPF (Optimal power flow), power market, constraints, super areas, Power World Simulator.**

I. INTRODUCTION

During past two decades, the increase in electrical energy demand has presented higher requirements from the power industry. To meet the increase in demand, more power plants, substations, and transmission lines need to be constructed. However, the most commonly used devices in power grid are the mechanically-controlled circuit breakers. The long switching periods and discrete operation make them difficult to handle the frequently changed loads smoothly. In order to compensate these drawbacks, large operational margins and redundancies are maintained to protect the system from dynamic variation and recover from faults. This increases the cost, complexity of the system and lowers the efficiency. The major blackouts in the northern grid system in the last several months happened and affected heavily. Severe black-outs happened recently in power grids worldwide and these have revealed that conventional transmission systems are unable to manage the control requirements of the complicated interconnections and variable power flow. 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. In countries like India, the Energy Regulatory Commission oversees the issues involving the transmission system. It presently believes that the only manner in which everyone will be on an equal playing field is to create open access to all. 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. In the past year, the north Indian grid has seen the consequences of pushing the transmission system too hard on two separate occasions.

The work presented in this paper utilizes an optimal power flow program, OPF, as the tool for solving many problems like line overloading removal, bus marginal cost control, line marginal cost, super area controls etc… 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 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.

II. OPTIMAL POWER FLOW CONTROL

The OPF program presented in this paper uses Newton's method as its solution algorithm. It will tackle all of the goals set forth for an OPF except the control of switched shunts and other FACTS devices. The control of these may be added at a later time as desired. The following section of this paper discusses the theory of the Newton-based optimal power flow. It will lay a framework for the mathematics and engineering behind the OPF computer source code along with several sample applications of the OPF. The sample applications include transmission line overload removal, super area control, bus marginal control and transmission marginal pricing control.

A. Role of OPF

Optimal Power Flow (OPF) plays an important role in power system operations and planning. In the normal operating condition OPF is used to determine the load flow solution which satisfies the system operating limits and minimize the generation costs. Before beginning the creation of an OPF, it is useful to consider the goals that the OPF will need to accomplish. 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. Each transmission line and transformer has a limit on the amount of power that can be transmitted through it, with the limit arising because of thermal, voltage as stability considerations. 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. From the viewpoint of an OPF, the maintenance of system security requires keeping each device in the power system within its desired operation range at steady-state. This will include maximum and minimum outputs for generators, maximum MVA flows on transmission lines and transformers, as well as keeping system bus voltages within specified ranges. It should be noted that the OPF only addresses steady-state operation of the power system. Traditionally, the transmission system is designed so that when the generation is dispatched economically there should be no limit violations. To achieve these goals, the OPF will perform all the steady-state control functions of the power system. Hence, with the worldwide trend towards de-regulation of the electric utility industry, the transmission system is becoming increasingly constrained. These functions may include generator control and transmission system control. However, when one or more elements loaded to their limits the economic dispatch becomes constrained and the bus marginal energy prices are no longer identical.

B. Solution method

Considering the issues discussed above, the solution of the minimization problem can be found by applying Newton's method to $\Delta zL\ (z) = 0$. A flowchart of this process is shown in Fig 1. This flowchart is useful for any generic minimization problem. The application of Newton's method to the optimal power flow problem is discussed.

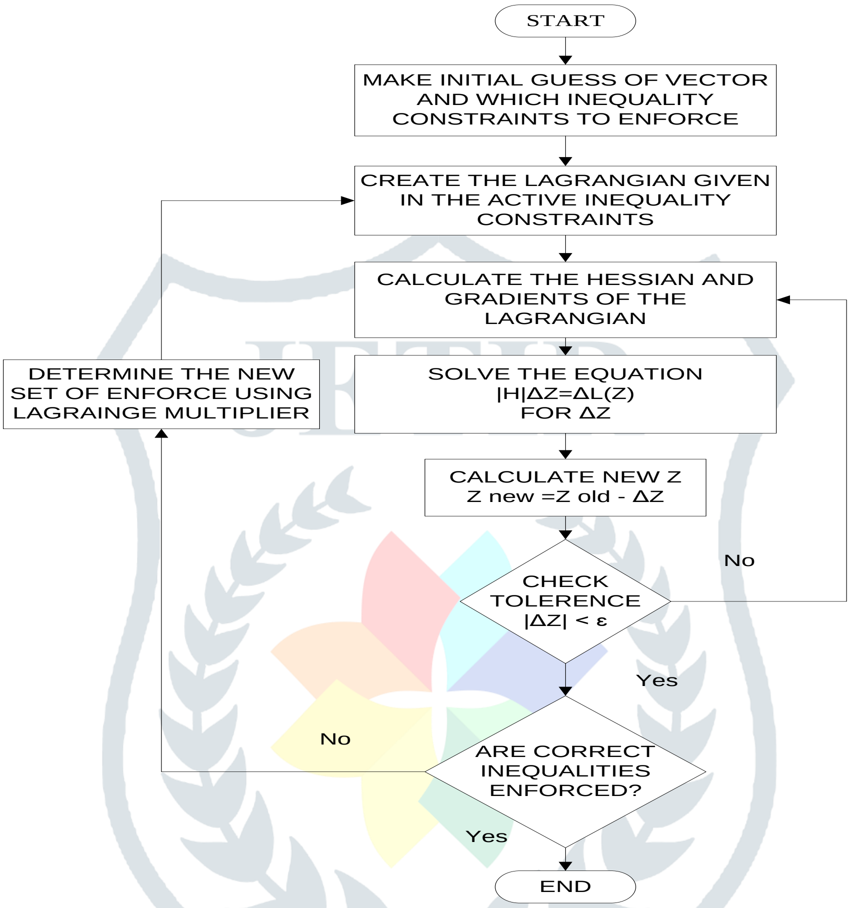


Fig 1 Newton's method flow chart

The inequality constraints of the OPF reflect the limits on physical devices in the power system as well as the limits created to ensure system security. Physical devices that require enforcement of limits include generators, tap changing transformers, and phase shifting transformers. This section lays out all the necessary inequality constraints needed for the OPF problem.

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

$$P_{Gi\ min} \le P_{Gi} \le P_{Gi\ max}$$
$$Q_{Gi\ min} \le Q_{Gi} \le Q_{Gi\ max}$$

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

$$\alpha_{km\ min} \le \alpha_{km} \le \alpha_{km\ max}$$
$$t_{km\ min} \le t_{km} \le t_{km\ max}$$

These ratings may come from thermal ratings (current ratings) of conductors, or from system stability concerns. In this work, the determination of MVA ratings may not be of concern because it is assumed that MVA values are given. Regardless, these MVA ratings result in another inequality constraint. To make the mathematics less complex, the constraint used in the OPF will limit the square of the MVA flow on a transformer or transmission line.

$$\left| S_{km} \right|^2 - \left| S_{km\ max} \right|^2 \le 0$$

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.

$$V_{i\,min} \leq V_i \leq V_{i\,max.}$$

III. SIMULATION ENVIRONMENT

While a single OPF solution yields valuable information regarding a power system, the implementation of the OPF into a power system simulation environment holds even greater promise. In this environment, simulation of a system over time can be made while maintaining it at its optimal condition. In this way, a vast amount of economic data can be carried from the simulation. This section gives several examples of the use of the OPF code as implemented into the simulator, called POWERWORLD SIMULATOR. It is a power system simulation package designed from the ground up to be user-friendly and highly interactive. Simulator is very much useful for serious engineering analysis, but it is also too interactive and graphical and also it can be used to explain power system operations to non-technical audiences. It consists of a number of integrated products. At its core is a comprehensive, robust Power Flow Solution engine capable of efficiently solving systems of up to 100,000 buses. This makes Simulator quite useful as a stand-alone power flow analysis package.

A. Line overload removal

A simple power system not operating under the OPF control is shown in Fig 2. It consists of 3 buses, 3 lines, 3 generators and one load which is located at bus 3 and it consumes 180 MW. The simulation is carried out and it is found that the line from bus 1 to bus 3 is overloaded by 120% and all the buses have the same marginal cost of $10MWh. All the buses are connected through 0.1 p. u of reactance transmission lines and hence there are no real power losses in the transmission lines. The maximum limit of each transmission lines is limited up to 100MVA. The output level of generators and marginal cost of buses are as follows,

Bus 1:10$MW/hr.; range-0-400MW.
Bus 2:12$MW/hr.; range-0-400MW.
Bus 3:20$MW/hr.; range-0-400MW.

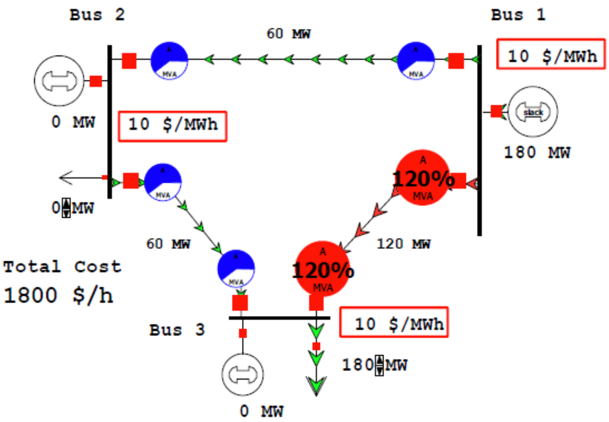


Fig 2 Three bus system without OPF

In order to remove the line constraint, the OPF control is turned on, and the line overload is removed as shown in Fig 3. During the optimal power flow simulation, the limitation of transmission lines needs to ignore and all load demand is met by the least cost generator at bus 1.

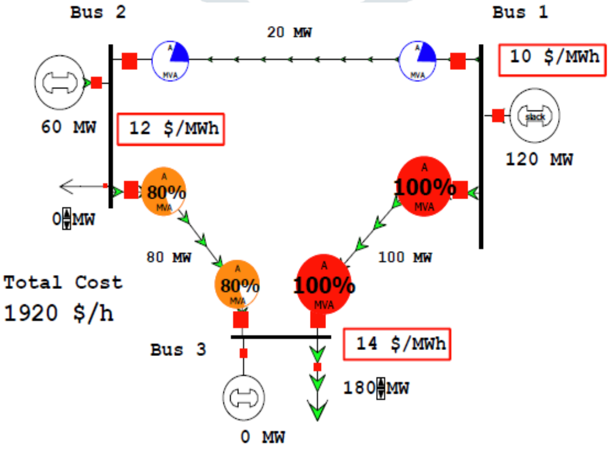


Fig 3 Three bus system with OPF

The OPF simulation re-dispatches to remove the transmission lines violation by adding the generation from the bus 2. Now the overloading of line from bus 1 to bus 3 is decreased from 120% to 100%. Then the line from bus 2 to bus 3 is increased from 60% to 80%. The marginal cost of bus 2 and 3 is increased from 10$/MW/h to 12$/MW/h and 14$/MW/h respectively.

B. Why is bus 3 LMP $14 /MWh?

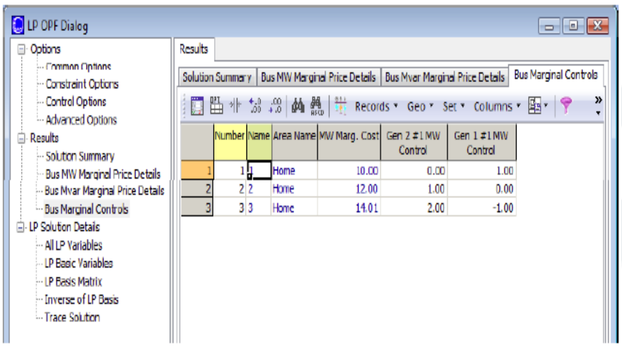
The least-cost source of marginal power at buses 1 and 2 is the local generator. Each LMP matches the marginal cost of the local generator. However, the generator at bus 3 has a marginal cost of $20, and no generator has a marginal cost of $14. Power flow in the network distributes inversely to line impedance, and all line impedances are equal.

1. For bus 1 to supply 1 MW to bus 3, 2/3 MW would flow on direct path from 1 to 3, while 1/3 MW would “loop around” from 1 to 2 to 3.
2. Likewise, for bus 2 to supply 1 MW to bus 3, 2/3 MW would go directly from 2 to 3, while 1/3 MW would go from 2 to 1 to 3

With the line from 1 to 3 limited, no additional power may flow on it. To supply 1 more MW to bus 3 it needs Pg1 + Pg2 = 1 MW and 2/3 Pg1 + 1/3 Pg2 = 0; (no more flow on 1-3). For solving the above case, we have to increase Pg2 by 2 MW and decrease Pg1 by 1 MW: a net cost increase of $14.

C. Bus Marginal Controls

In the OPF Options and Results tab in power world simulator, the bus marginal control tool is available to identify the marginal units for each bus.



	Number	Name	Area Name	MW Marg. Cost	Gen 2 #1 MW Control	Gen 1 #1 MW Control
1	1	1	Home	10.00	0.00	1.00
2	2	2	Home	12.00	1.00	0.00
3	3	3	Home	14.01	2.00	-1.00

Fig 4 Bus marginal identity and control

The marginal cost can be verified by tune the present case system as a base case. This can be achieved by using difference flow options available in simulator. The load located at bus 3 is now manually changed from 180 to 181MW. Again the OPF is solved and hence the power flow and marginal cost of the system is varies slightly due to the increase of 1MW of load at bus 3. To view the difference case of the system, again solve using the difference flows in the simulator and the power flow and marginal cost becomes quite interesting as shown in Fig 5.

The above diagram shows that one MW additional load at bus 3 raised the total cost by 14$/hr. The generator G2 went up by 2MW and the generator G1 went down by 1mw. Similarly, it has to calculate the marginal cost of enforcing a line constraint. For a transmission line, this represents the amount of system savings which could be achieved if the MVA rating was increased by 1.0 MVA.

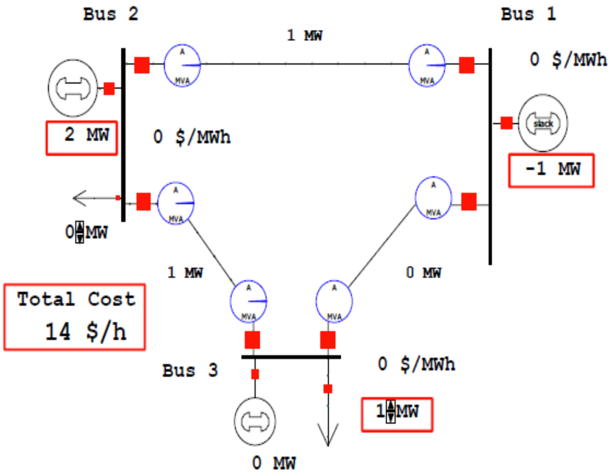
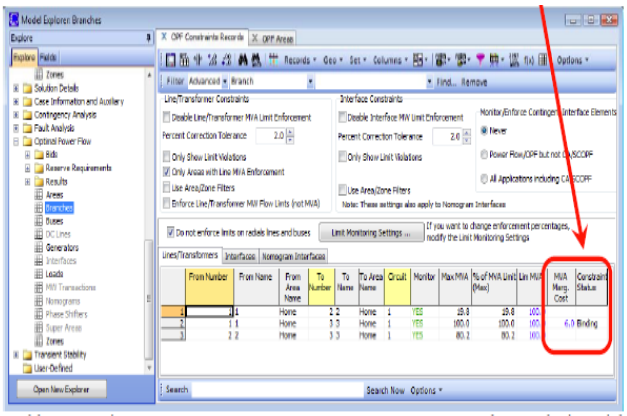


Fig 5 Difference flow due to 1MW change of load

The MVA marginal cost can be achieved by switch back the difference case to present case. This can be done by using model explorer branches tool present in the simulator options. This is shown in Fig 6.



Filter: Advanced, Branch

Line/Transformer Constraints

☐ Disable Line/Transformer MVA Limit Enforcement

Percent Correction Tolerance 2.0

☐ Only Show Limit Violations

☑ Only Areas with Line MVA Enforcement

☐ Use Area/Zone Filters

☐ Enforce Line/Transformer MW Flow Limits (not MVA)

Interface Constraints

☐ Disable Interface MW Limit Enforcement

Percent Correction Tolerance 2.0

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Note: These settings also apply to Nomogram Interfaces

Monitor/Enforce Contingent Interface Elements

● Never

○ Power Flow/OPF but not CA/SCOPF

○ All Applications including CA/SCOPF

☑ Do not enforce limits on radials lines and buses

Limit Monitoring Settings ...

If you want to change enforcement percentages, modify the Limit Monitoring Settings

Lines/Transformers | Interfaces | Nomogram Interfaces

	From Number	From Name	From Area Name	To Number	To Name	To Area Name	Circuit	Monitor	Max MVA	% of MVA Limit (Max)	Lim MVA	MVA Marg. Cost	Constraint Status
1	1	1	Home	2	2	Home	1	YES	19.8	19.8	100.		
2	1	1	Home	3	3	Home	1	YES	100.0	100.0	100.	6.0	Binding
3	2	2	Home	3	3	Home	1	YES	80.2	80.2	100.		

Fig 6 MVA marginal cost of transmission lines

The MVA marginal cost of the transmission lines is 6$MVA/hr which is shown in above indication.

D. Why is MVA Marginal Cost $6/MVAhr?

If 1 more MVA is allowed to flow on the line from 1 to 3, then this allows us to re-dispatch as follows.

Pg1 + Pg2 = 0 MW

2/3 Pg1 + 1/3 Pg2 = 1; (no more flow on 1-3). For solving above equation, it has to require that by dropping Pg2 by 3 MW and increase Pg1 by 3 MW. These results a net savings of $6. This can be verified by changing the line from 100 to 101MVA. The power flow and marginal cost after changing the line limit is shown in Fig 7.

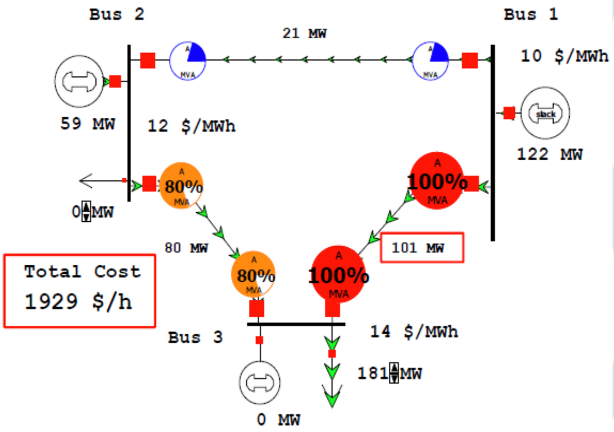


Fig 7.Increased the limit of line

After the change of line limit (1-3) of 1MVA, there is decrease of $6MVA/hr. Increasing output of Gen 2 by 1 MW decreases flow on the binding constraint (Line 1-3) by 1/3 MW. The values assume marginal power is absorbed at the slack. For bus 3 load above 200 MW, the marginal load must be supplied locally. Then restore the line limit of 1-3 from 101 to 100MVA. Again the load at bus 3 is increased up to 250MW. LMP at bus 3 is set by the cost of the generator at bus 3($20). The new power flow and marginal cost is shown in below Fig 8.

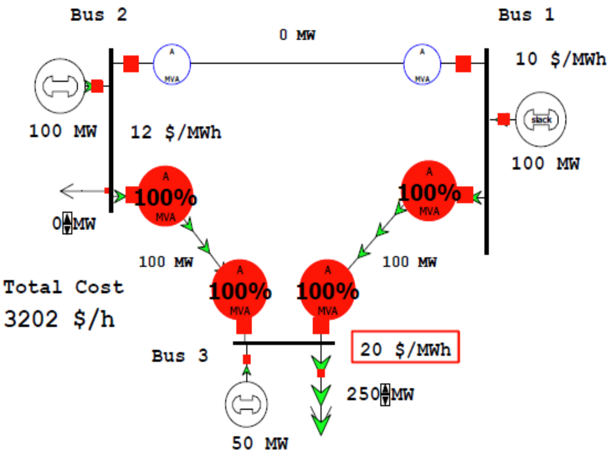


Fig 8 After change of load at bus 3.

E. Loss of Generator at Bus 3

Now if the generator at Bus 3 is taken out of service, the 250 MW load cannot be served without overloading the lines, which have a total capacity of 200 MW. It's not possible to enforce the both constraints. The marginal cost is now arbitrary, given by a penalty function. The Maximum Violation Cost is $1000/MWh by default, but may be changed on the OPF Options and Results dialog, Constraint Options tab. The un-enforceable constraints are shown in Fig 9. As we discussed above, both the constraints cannot be enforce, therefore bus 3 marginal cost is arbitrary.

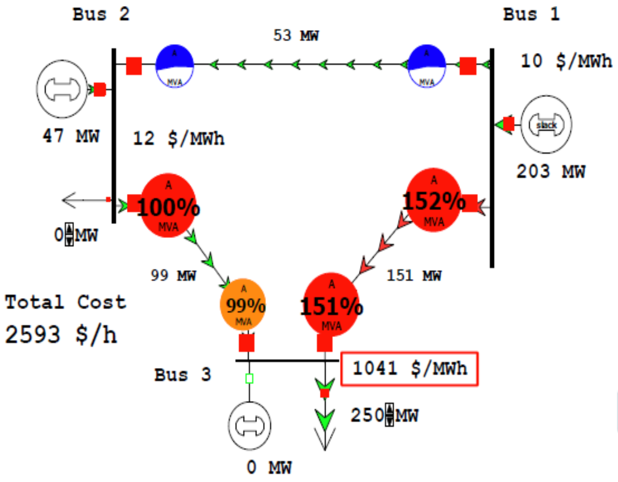
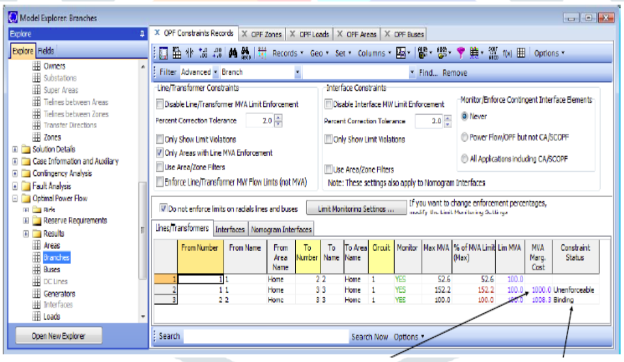


Fig 9 Un-enforceable constraints

The cost minimization algorithm naturally tries to remove the line violations. High marginal prices and the OPF Constraint Records will identify binding and unenforceable transmission limits. Look for generators that are in/out of service near the constraints. There may be a load pocket without enough transmission: the 3 bus case with generator 3 out of service is an example of a load pocket. The constraints records can be verified by using model explorer branches tab in simulator which is shown in Fig 10.



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2	1	1	Home	3	3	Home	1	YES	152.2	152.2	100.0	1000.0	Unenforceable
3	2	2	Home	3	3	Home	1	YES	100.0	100.0	100.0	1008.3	Binding

Fig 10 Verification of constraints records

The marginal cost is non-zero only for active constraints for line 1 to 3. The line 2 to 3 is in binding and it's not enforceable.

F. Cost of Energy, Losses and Congestion

Some ISO documents refer to cost components of energy, losses, and congestion. Simulator can resolve the LMP into these components. The Fig 11 shows the complex system to verify the details. It consists of 7 bus, 11 transmission lines, 5 generators and 6 loads. This full network is divided into three areas namely top, left and right.

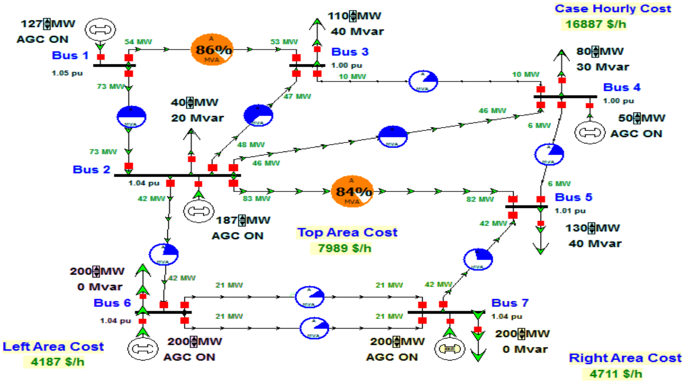
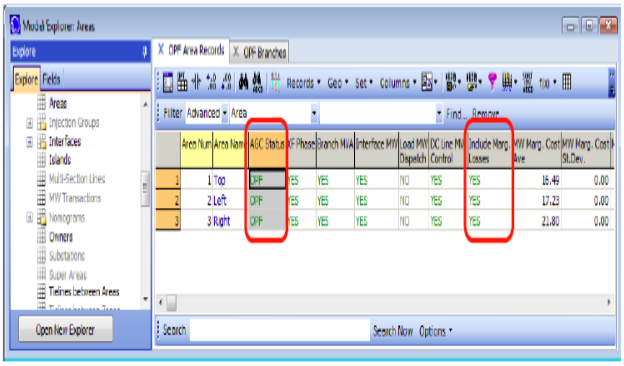


Fig 11 Seven buses with three area system

Open the OPF areas by using add on ribbon tab in simulator. The following changes has to made in the above network,

1. AGC status is selected for OPF for each area.
2. Include Marginal Losses column of each area to YES

This function can be accessed in following tab in simulator.



	Area Num	Area Nam	AGC Status	XF Phase	Branch MVA	Interface MW	Load MW Dispatch	DC Line M Control	Include Marg. Losses	MW Marg. Cost Ave	MW Marg. Cost St.Dev.
1	1	Top	OPF	YES	YES	YES	NO	YES	YES	16.49	0.00
2	2	Left	OPF	YES	YES	YES	NO	YES	YES	17.23	0.00
3	3	Right	OPF	YES	YES	YES	NO	YES	YES	21.80	0.00

Fig 12 Control tab for three area system

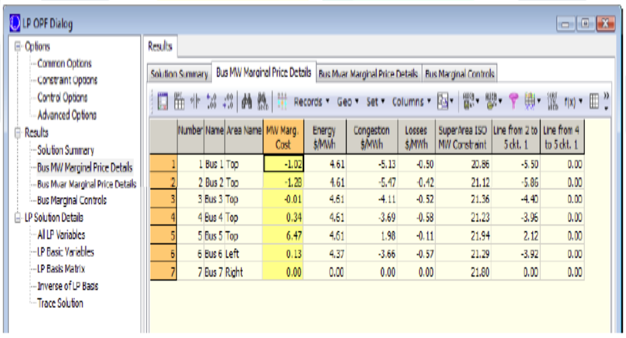
Now change the load at bus 5 from 130MW to 170MW, and then primal linear program is used to solve this new case. Due to this, the line between 2 and 5 become binding constraints. To access the bus marginal mw price details, the OPF tab is used to verify the Energy, Congestion, and Losses.

Return to OPF Case Info and set OPF Areas. The Cost of Energy, Loss, and Congestion Reference option group is in the lower left. Similar settings may be found on the Super Area dialog.

Super areas are a record structure used to hold a set of areas. This work like ISOs: a number of control areas are dispatched as though they were a single area, without fixed interchanges between the individual areas. Area records are preserved for calculation of average prices, exports, and other quantities. For a super area to be used in the OPF, its AGC status field must be OPF.

G. Super area control

To make the comparison, set the present case as the base case again using difference flows tab in simulator. Then select and insert the options by using OPF super areas control tab. By replacing the 3 area interchange constraints and with a single power balance constraint for the Super Area allowed a re-dispatch that decrease the total cost by $89/hour. The LMP changes vary by location. LMPs drop at buses 1-3, but increase at buses 4-6.



	Number	Name	Area Name	MW Marg. Cost	Energy $/MWh	Congestion $/MWh	Losses $/MWh	SuperArea ISO MW Constraint	Line from 2 to 5 ckt. 1	Line from 4 to 5 ckt. 1
1	1	Bus 1	Top	-1.02	4.61	-5.13	-0.50	20.86	-5.50	0.00
2	2	Bus 2	Top	-1.28	4.61	-5.47	-0.42	21.12	-5.86	0.00
3	3	Bus 3	Top	-0.01	4.61	-4.11	-0.52	21.36	-4.40	0.00
4	4	Bus 4	Top	0.34	4.61	-3.69	-0.58	21.23	-3.96	0.00
5	5	Bus 5	Top	6.47	4.61	1.98	-0.11	21.94	2.12	0.00
6	6	Bus 6	Left	0.13	4.37	-3.66	-0.57	21.29	-3.92	0.00
7	7	Bus 7	Right	0.00	0.00	0.00	0.00	21.80	0.00	0.00

Fig 13 Bus MW marginal price details

The generator MW output increased at buses 4 and 6, but decreased at buses 2 and 7. The line between buses 2 and 5 is still a binding constraint. The Change in bus marginal costs with ISO Super Area control versus individual area control.

IV. CONCLUSION

The OPF discussed in this paper has been very successful in achieving the goals set forth for an OPF. 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. Many applications of the OPF have also been shown as in above sections. The OPF performs generator control and transmission system control while taking into account system limits. The following discussions are made in this paper using optimal power flow,

1. Line overloading removal.
2. Bus marginal controls.
3. Transmission line marginal cost controls.
4. Loss of generator in the network.
5. Cost of energy, losses and congestion.
6. Super area controls.

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BIOGRAPHIES

R. Kannadasan Raju graduated from Vel tech Engineering College, Chennai in the year 2010. Presently he is doing his M.E. in Power Systems Engineering from College of Engineering Guindy, Anna University Chennai. His research area is location of FACTS devices on transmission system.

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