ABSTRACT

The economics of power system operation is gaining importance all over the world. Reduction of operating costs in the short run and capacity addition in the long run is particularly relevant in the Indian context where the addition of capacity is severely constrained by investment availability and the utilities continue to show poor financial performance over the years. Though the Indian power system has grown in terms of installed capacity from 1,363 MW in 1947 to 72,000 MW in 1992, capacity is falling short of rapidly growing demand. The economics of such a large system is extremely important and there exists large scope of improving the system operation, which could lead to savings of billions of rupees. The present studies focused on identification and analysis of options to improve upon the sub-optimal operation of Indian power system. The reduction of operating costs in the short run and capacity addition in the long run is particularly relevant in the Indian context where the addition of capacity is severely constrained by investment availability and the utilities continue to show poor financial performance for years.

The major issues associated with the operation of power system in India which have been examined in the present thesis are the following:

(a) Integrated operation of the nearly independent State Electricity Boards (SEBs) through formation of a National Grid

Various important policy issues like joint generation scheduling of State Electricity Boards, interstate and interregional power exchange, trading prices, optimal transmission expansion and optimal allocation of central sector generation has been addressed.

(b) Coal production and transportation issues

Optimal coal production and transportation strategies have been developed and compared against the actual performance of the base year 1989-90. The transportation links which need to be strengthened on a priority basis have been identified and the optimal coal production expansion in short run has been worked out.

(c) Coordination of power trading among SEBs on a day-to-day basis

Several organizational and methodological issues relevant to day-to-day management of power trading among State Electricity Boards' have delineated *viz.* who should coordinate the power trading and what should be the mechanism of deciding the generation scheduling of individual utilities, setting up optimal transactions and allocating cost savings resulted from

coordination.

(d) CentraIized maintenance scheduling of generating units under integrated operation of SEBs incorporating fuel supply decisions

Methodological issues pertaining to modelling maintenance scheduling of generating units have been discussed and an integrated modelling framework has been proposed that integrates the fuel supply decisions with those of generation and inter-utility transmission to form a least-cost maintenance plan. Comparison of this method with the traditional methods and the significance of incorporating fuel supply and inter-utility transfer decisions have been illustrated with a case-study for the Maharashtra-Gujarat interconnected system.

(e) Environmental issues associated with thermal power generation

The existing planning for meeting emission reduction targets often ignored the role of cheaper "non-abatement" options like altering generation schedule, coal import, changing fuel-mix etc. An attempt has been made to quantify the potential benefits from these options in Indian context and formulate a comprehensive emission-reduction plan incorporating both abatement and "non-abatement" options.

(f) Demand-Side Management options and Integrated Resource Planning

While energy supply planning is done with a reasonable degree of articulation, the analysis on DSM tends to be vague in terms of mere possibility without specific targets. This is because there is no satisfactory methodology to formulate a DSM plan. Several methodological issues *viz.* the superiority of simultaneous integration technique to the sequential integration technique, multiple benefits from DSM options and the need for a multi-objective framework and the need for modelling specific characteristics of DSM options.

AN OVERVIEW OF THE MODELLING FRAMEWORK

Power system planning models can be categorized into three classes based on the time-frame under consideration:

1. Unit Commitment models with time-frame of hours and days to a week
2. Operational Planning models with time period of months and quarters to a year, and
3. Investment Planning models with time periods of several years.

The present analysis makes use of models of all three types:

- The integration of SEBs, transmission expansion, inter-SEB power trading, maintenance scheduling and emission reduction strategy development problems are considered in an operational planning framework

- The day-to-day coordination of power trading require a short-term unit-commitment model in combination with a brokerage model

- Integration of DSM options in utility planning, on the other hand, calls for a long-term decision making framework and an Integrated Resource Planning model is developed for this purpose.

The analysis is also carried out at different levels keeping in view the organizational structures and the decision making bodies in Indian power system. While the integration of SEBs, analysis of emissions reduction options are considered at the national level, the coordination of power trading through a brokerage system, maintenance scheduling decisions are carried out by individual REBs and accordingly are considered at the regional level. Though, DSM is yet to find a place in power planning in India, it is expected that the individual SEBs would develop their own DSM plans and hence the DSM modelling exercise is confined to a SEB level.

Some of the salient features of the models are outlined here:

- The integration of SEBs and evaluation of interconnection benefits and other related issues have been discussed in an operational planning model NATGRID. NATGRID simulates the operation of four major regional grids of India viz. Western, Southern, Eastern and Northern on a quarterly basis, using a linear programming framework. The system comprises 19 State Electricity Boards in the four regions. It contains details of 210 units and 90 inter-utility transmission lines for the existing system. It minimizes the total system operating costs (generation costs and unmet energy costs) subject to the power system operational constraints;

- NATGRID model has been extended in this section to include the coal supply side constraints which has been termed as NATGRID1 ;

- The NATGRID1 model has been extended to include new variables viz. quantity of coal import for coastal stations and quantity of emissions of different pollutants to be reduced from each station and new constraints viz. Limits on pollutant emissions at local and aggregate level. The modified objective function includes the cost of imported coal and cost of abatement for S02, NOx and fly ash;

- The NA TGRID model has been extended to include maintenance decisions of generating units in a monthly time-frame. The unit availability decisions are endogenized in the form of integer (ON/OFF) variables;

- Analysis of coordination of power trading on a day-to-day basis has been carried out using a linear programming framework. The LP brokerage model is combined with a unit commitment model for evaluating bids for buy and sell of power. Allocation of cost savings is done on basis of an index *Shapley Value* which is the weighted average of marginal contribution of a utility to all possible coalitions in which it may participate. The brokerage model is applied to the Western Regional Electricity System of India. The brokerage system has three distinct levels:

1. Unit commitment for determination of costs and bids,
2. Brokerage model for setting transactions,
3. Allocation of cost savings among utilities;

- An Integrated Resource Planning model has been developed to consider the demand and supply-side resources incorporating multiple objectives. Compromise programming technique is applied for simultaneous integration of DSM options in a supply side model. The supply side model incorporates the capacity addition decision of various types of generating capacity along with the operational characteristics of NA TGRID model at an independent SEB level. The three objectives are the following.
    1. Minimize the annual system cost that includes operating costs and capacity costs for new plants.
    2. Minimize annual emissions of CO2 emission
    3. Minimize loss of load expectation (LOLE) of electricity supply;

SUMMARY OF FINDINGS

(a) lotegrated Operation of SEBs through National Grid

Integrated optimal operation of SEBs in India through formation of national grid is shown to be a promising option to reduce system operating costs and prevailing peak and energy shortages. The study bas been carried out for the base year 1989-90. The key findings of the study are summarized below:

1. Integrated optimal operation could lead to a reduction of 23.9 billion kWh (bkWh) which is 9.4% of the total energy requirement;

2. The total system generation would increase by 26 bkWh (10.9% of actual generation) through better capacity utilization;

3. The inter-SEB transfers increase from 10.1 bkWh under actual operation to 33.1 bkWh under integrated operation indicating the importance of national grid operation;

4. Four inter-regional transmission links - three between Western and Southern region and one connecting Eastern and Southern regions have been identified for strengthening, since additional transfers through these links could reduce power shortages in the southern states;

5. The Short Run Marginal Costs of electricity supply for all states vary considerably across peak and off-peak hours (base and intermediate time blocks) indicating the need for time-of-day pricing mechanism for inter-SEB power trading;

6. Optimization of central sector generation allocation to various states could reduce the average generation cost by 3.0% over and above the integrated optimal operation scenario. More importantly, it would eliminate largely the unnecessary power wheeling under fixed quota system of operation and as a result the total interstate transfers are reduced to 47.3% of the total transfer in integrated optimal operation with fixed quota system.

(b) Streamlining coal supply side for optimal operation

The results of NATGRID1 for the base year show that

1. The optimal generation schedule under integrated optimal operation would demand for a much higher coal production and large scale expansion of the existing coal transportation facilities;

2. Comparison with actual operations (Apri1'89-Mar'90) shows that even with the existing coal production capacity and coal allocation schedule, significant benefits could be

obtained from integrated optimal operations of different electricity regions. Relaxing the coal linkages by 25% could result in considerable cost savings and additional generation;

3. If coal allocation schedules are optimized, the generation could increase by 8.7 bill. units at additional operating costs of Rs. 4.4 millions. However, it would also involve large scale increase in coal transportation facilities to the extent of 1230 million ton-km.

(c) Central Broker role of Regional Electricity Board for coordination of power trading

The brokerage system simulation for Western regional power system shows that,

1. The unit commitment solution gives the optimal way of operating the thermal generating units and water release schedule for the hydro plants. The marginal generating cost for Madhya Pradesh (MP) in the off-peak hours is the lowest and that of Gujarat is the highest. MP and Maharashtra has the maximum surplus capacities for export;

2. The brokerage schedule suggests import of power by Maharashtra from MP and exporting part of it to Gujarat and Goa. Maharashtra plays a crucial role in the transaction as it is connected to all the utilities;

3. The cost savings allocation scheme given by Shapley value of the utilities show that Maharashtra gets the highest share because of its higher bargaining power. The hourly savings is Rs. 1,63,788 (about 5.6% of the total system cost in the independent mode) indicating that the brokerage system could lead to improved system operation in the Indian power system.

(d) Centralized Maintenance Scheduling by Regional Electricity Board

Following are the key findings of the Maharashtra-Gujarat study,

1. though the LOLP minimization method ensures minimum annual LOLP, the system operating costs are significantly higher by 15.5%;

2. capacity on outage during low-demand months is high in case of least-cost schedule. This enables more number of relatively expensive units to operate at lower PLFs during the high demand months and thus reduce the costs;

3. The least-cost schedule offers significant cost advantages without increasing the system risk considerably as compared to the earlier methods.

4. The fuel supply decisions has significant bearing on the maintenance decisions. Any change in the coal production schedule or linkages could change the maintenance decision considerably. The hydro energy availability also must be considered while taking the maintenance decision to optimally utilize the available hydro energy;

5. Interconnected system operation through economy exchanges require a centralized maintenance schedule and it is significantly different from the schedules obtained without taking into account inter-system transfers. The operating cost reduction due to co-operation of the utilities is considerable (2.7%).

(e) Emissions Reduction Strategy

The emissions reduction strategy for fly ash, S02 and NO., carried out for the base year, are summarized below:

1. The total volume of fly ash reduction could be achieved both in terms of changing the coal supply-power generation schedule as well as installation of Electro Static Precipitators (ESP). While 73% of fly ash could be removed through ESPs and coal import in coastal plants, 27% reduction could be achieved through adjustment within the system referred in the literature as "emission dispatching". The "emission dispatching" option for the first 27% reduction could work out to be cheaper at an average cost Rs.324/ton as compared to the ESP cost of Rs.850/ton. The emission dispatching option, however, may not be adequate for meeting the reduction target and some plants would require installation of ESPs;

2. The coal import option seems to be an attractive option for reducing fly ash emissions in the coastal coal based plants rather than changing the generation schedule of these plants or installing ESPs;

3. The total S02 emission reduction amounts to 236,000 tons of which 72,000 tons reduction could be achieved through Flue Gas Desulphuriser (FGD) installation, 55,000 tons by fuel substitution in favour of gas and the rest 109,000 tons through "emission dispatching". Again, the adjustment option would work out to be the cheapest at an average cost of Rs.9.1/Kg. Some of the plants particularly in sensitive areas would need flue gas desulphurisation to the extent of 100% e.g. Obra (all units). Paricha, Ramagundam B etc. Very high gas generation could be demanded in Maharashtra, Gujarat and AP. Coal import and total transfers would not change significantly. Thus, a combination of abatement, fuel substitution and "emission dispatching" could work out to be the optimal strategy to achieve the S02 target;

4. Most of the NOx emission reduction targets could be achieved through installation of Low Nox burners. Low NOx burners with relatively lower capital costs seems to be an attractive option for reducing NOx emissions;

5. If a 5% carbon emissions reduction is imposed, there could be a small increase of 2.4% in total generation costs. But, if CO2 emissions are to be reduced by 10%, the operating costs would go up by 5.4% and with 15% emissions reduction this increase would be 12.9%. Marginal cost of reduction of every additional ton of carbon would go up from Rs.840 to Rs. 1,480 and Rs. 2,538 corresponding to 5%, 10% and 15% reduction constraint respectively.

(f) Integrating DSM Options in SEB Planning

Integrating DSM options in utility planning using the proposed multi-objective simultaneous integration offers a number of advantages in terms of the policy analysis:

1. determination of optimal mix of supply side resources and demand side resources. The model can be used to choose the power plants (of all types), coal mines to be developed, coal transportation links and different DSM options to meet the electricity demand for a future period in an optimal way;
2. scope of analyzing the trade-off among various objectives viz. cost minimization, emissions minimization, loss of load expectation minimization. Power system planning may not be guided by the motive of minimizing cost alone and the model allows the planner to choose the best compromise among these conflicting objectives;

3. setting the guidelines for utility controllable measures like direct load control options. The model also provides useful information on optimal utilization pattern of indirectly controllable measures like industrial cogeneration. It could help the utility setting guidelines for buy-back arrangements of cogenerated power;

4. decision making on inclusion of new DSM options. The upper limit on cost of saved energy for various types of DSM options could be used as a cut-off point for considering new DSM options.

The methodological issues have been addressed in the context of integration and evaluation of DSM measures and illustrated with an application for Maharashtra State Electricity System. The findings are summarized below:

1. Benefits from DSM options could be substantial not only in terms of cost but also in terms of other criteria. The cost savings for MSES for a 9,386 GWh DSM plan (13% of total energy requirement) is 10.2% as compared to base case. It could reduce the peak demand by 16.3% and save 1.260 MW capacity addition. The supply system LOLE, as a result, could be reduced from 193.6 hours/year to 1.59 hours/year. Coal consumption would be reduced by 21% and coal transportation requirement would go down by 28.8%. CO_2 emissions could be reduced by 20.5% as a result of lower coal consumption;

2. Simultaneous integration scores over the sequential method on the following grounds:
    - The selection of DSM options is determined by system parameters like supply side resource mix and costs. DSM option characteristics, load characteristics etc;
    - The load curve modification in simultaneous integration is endogenous while it has to be performed exogenously based on certain assumptions in sequential methods. This may lead to erroneous estimates of the benefits from DSM options;

3. Specific characteristics of DSM options need to be considered because of the following reasons:
    - different upper limits on cost of saved energy for different types of DSM options. Options like direct load control measures which can be used in any hour of the day by the utility has a higher value of upper limit as compared to conservation measures that give constant energy savings for all hours;

- for utility controllable measures, it would be useful to know the specific time of usage of that option;
- DSM options like load shifting can influence the selection of other options and utilization of other options.

4. Multiple criteria analysis may lead to different selection of DSM options.