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Thermal power system analysis using a generalized network flow model

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Abstract

This paper analyzes an Integrated Thermal Power System using a Multiperiod Generalized Network Flow Model. The thermal system analysis is carried out by taking into account the complex dynamics involved in utilizing multiple energy carriers (coal, diesel and natural gas). The model comprises energy source nodes, energy transformation nodes, energy storage nodes, energy demand nodes and their interconnections. The solution to the integrated energy system problem involves the evaluation of energy flows that meet the electricity demand at minimum total cost, while satisfying system constraints. This is illustrated through the India case study using a minimum time-step of one hour. MATLAB based software was developed for carrying out this study. TOMLAB/CPLEX software was utilized for obtaining the optimal solution. The model and the methodology utilized for conducting the study would be of interest to those involved in integrated energy system planning for a country or a region.

Keywords: Integrated energy system; Generalized network flow model; Nodal prices; Optimization; Primary energy sources.

1. Introduction

An integrated energy system comprises multiple energy carriers and energy distribution networks [1]. The fossil based primary energy carriers are coal, diesel oil, and natural gas. Thermal electricity is derived from fossil fuels. The economic efficiency of an integrated energy system depends on the performance of the electric power system as well as the associated fossil fuel networks. A holistic approach is essential for studying the complex dynamics of an integrated energy system, which is a composite of these interconnected networks, fuel markets and infrastructures. With the rapid depletion of fossil fuels coupled with the ever increasing demand for energy the modeling and analysis of integrated energy systems is of global importance [2-9]. This paper addresses this problem of optimal allocation of energy resources to meet the electricity demand at minimum operating cost, subject to physical constraints, in an integrated energy system. The India case study presented in this paper illustrates the use of a multiperiod generalized network flow model for solving the integrated energy system problem.

2. Generalized network flow model

The integrated energy system is represented by a network of nodes and arcs. Energy flows between the nodes and over the arcs of a network. This constitutes a generalized minimum cost flow problem [10, 11]. The solution to the problem involves meeting energy demands using available fossil fuel supplies at minimum total cost, subject to system constraints. The costs considered include production, transportation, and storage cost of fossil fuels, operation and maintenance costs of electricity generating units, and electric power transmission costs. The interregional links between the regional power grids are represented by two directed arcs. The two arcs are oriented in opposite directions, and each has a lower bound of zero. In this model, the energy system is represented over time, since inventory is carried over from one time period to another. The multiperiod network flow model is made up of copies of a network with temporal linkages, and different simulation time steps for different energy subsystems. The model details are as follows:

Sets

L_{ij} Set of linearization segments on the energy flowing from node *i* to node j.

M Set of arcs.

N Set of nodes.

T Set of time periods.

Indices

i,j,k Nodes

Parameters

$c_{ij}(l,t)$ Per unit cost of the energy flowing from node *i* to node *j* corresponding the *l*th linearization segment, during time *t*.

$b_j(t)$ Supply (if positive) or negative of the demand (if negative) at node *j*, during time *t*.

$e_{ij.max}$ Upper bound on energy flowing from node *i* to node *j*.

$e_{ij.min}$ Lower bound on energy flowing from node *i* to node *j*.

$\eta_{ij(l)}$ Efficiency parameter associated with the arc connecting node i to node j, in the *l*th linearization segment

Variables

$e_{ij}(l,t)$ Energy flowing from node *i* to node *j*, corresponding to the *l*th linearization segment, during time t.

The mathematical formulation of the multiperiod generalized minimum cost flow problem is as follows:

$$\text{Minimize } z=\sum_{t\in T}\sum_{(i,j)\in M}\sum_{l\in L_{ij}} c_{ij}(l,t)e_{ij}(l,t) \tag{1a}$$

$$\text{Subject to: } \sum_{\forall k}\sum_{l\in L_{jk}} e_{jk}(l,t) - \sum_{\forall i}\sum_{l\in L_{ij}} c\eta_{ij}(l)e_{ij}(l,t) = b_j(t) \quad \forall j\in N, \forall t\in T \tag{1b}$$

$$e_{ij.\min} \le e_{ij} \le e_{ij.\max} \quad \forall(i,j)\in M, \forall t\in T \tag{1c}$$

The total costs ‘z’ associated with the energy flows from fossil fuel production sites to electricity end users is given in (1a). These costs comprise fuel production costs, fuel transportation costs, fuel storage costs, electricity generation, operation and maintenance costs, and transmission costs. The energy balance constraints for all nodes are given in (1b). The flow bound constraints are given in (1c).

The matrix representation of the problem is given as:

$$\text{Minimize } z = \underline{c}'\underline{e} \tag{2a}$$

$$\text{Subject to: } A\underline{e} = \underline{b} \tag{2b}$$

$$\underline{e}_{\min} \le \underline{e} \le \underline{e}_{\max} \tag{2c}$$

‘A’ is an n x m node-arc-incidence matrix. The number of nodes is ‘n’. The number of arcs is ‘m’. This system model is described in [12]. The solution to the minimization problem also gives the nodal prices. These nodal prices are related to each active constraint at the optimal solution of the decision variables, and they represent the marginal costs of enforcing the constraints.

3. India thermal power system model

The India thermal power system model is given in Figure 1. It includes coal, diesel and natural gas generation. Hydro, nuclear and renewables are excluded because they do not involve transportation of energy resources. Fossil fuel resources are represented by P1 through P12. Storage facilities for fossil fuels are represented by Res1 through Res8. These represent fuel inventories that are carried over from one time period to another. The lumped representation of the different facilities reduces the size of the optimization problem. Electricity Generation is represented by Gen1 through Gen12. They are distributed over the four regions. Load1 through Load4 represent loads met by the generation. The lumped representation of the different facilities reduces the size of the optimization problem. The inter-regional links, facilitate the flow of electric energy from regions with surplus energy to regions with inadequate generation. The regional thermal loads are given in Figure 2. The fuel prices are given in Figures 3 and 4. The generation and load data in Table 1 is based on [13]. Unit data, fuel characteristics, and Tie line and storage details are given in Tables 2 to 4. India National Grid details are given in Figure 5.

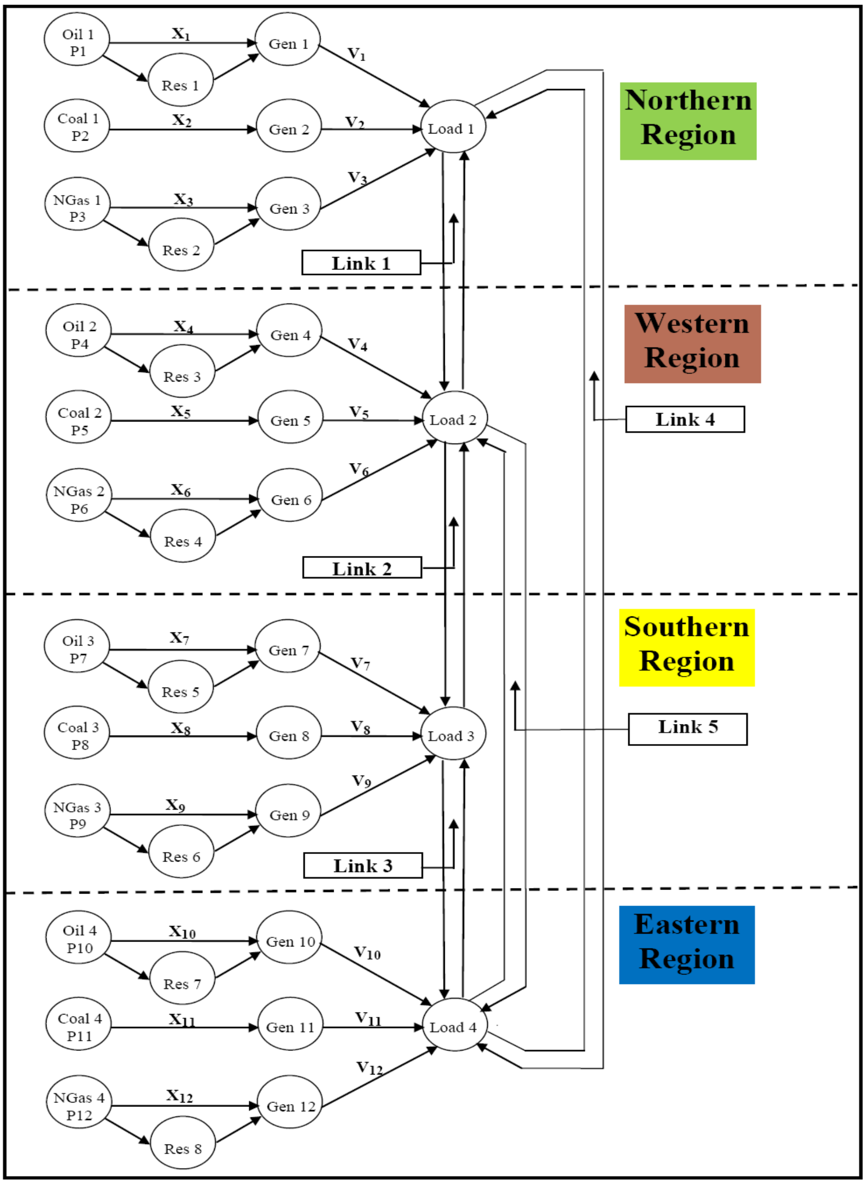

Figure 1. India Thermal Power System Model

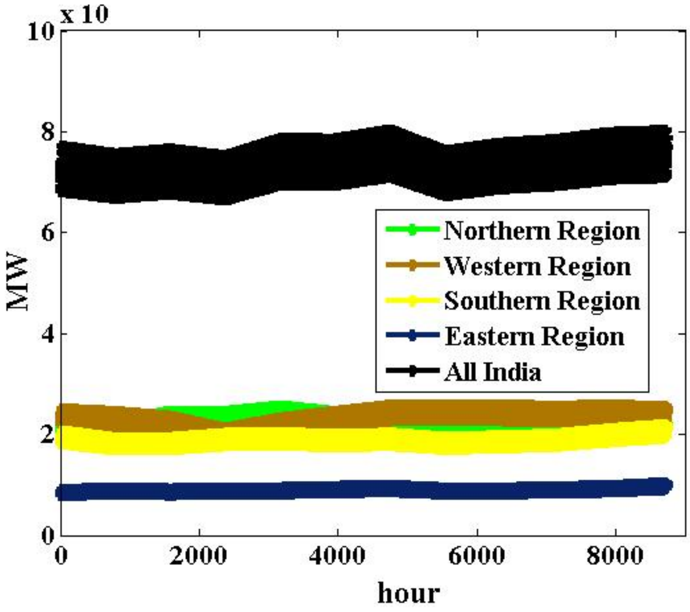

Figure 2. India regional loads

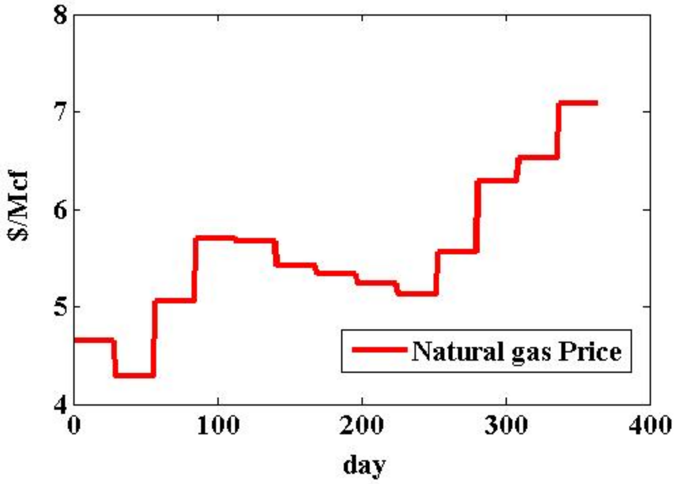

Figure 3. Natural gas prices

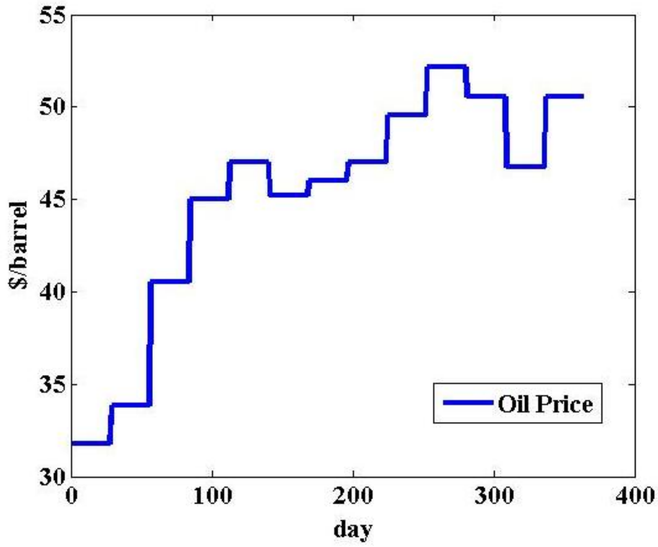

Figure 4. Diesel oil prices

Table 1. India thermal generation and load for 2010

Region	Generation (MW)				Load (MW)
	Coal	NGas	Diesel	Total	
North	21010	3885	13	24908	25597
West	17851	7904	17	25772	25732
South	15701	4691	939	21332	21901
East	12215	190	17	12423	10368
Total	66778	16669	987	54434	83598

Table 2. Unit characteristics

Region	Unit	Fuel	Minimum (MW)	Maximum (MW)	Heat Rate (Mbtu/MWh)
North	1	Diesel	3.25	13	9.95
	2	Coal	8404	21010	8.93
	3	NGas	0	3885	9.55
West	4	Diesel	4.25	17	9.95
	5	Coal	7140	17851	10.05
	6	NGas	0	7904	9.55
South	7	Diesel	235	939	9.95
	8	Coal	6280	15701	8.93
	9	NGas	0	4691	9.55
East	10	Diesel	4.25	17	9.95
	11	Coal	4886	12215	10.05
	12	NGas	0	190	9.95

Table 3. Fuel characteristics

Region	Unit	Fuel	Fuel cost	Fuel storage cost	Heat value
North	1	Diesel	*	1$/barrel	143500 Btu/gallon
	2	Coal	$40/ton	**	11500/Btu/lb
	3	NGas	*	0.1$/Mcf	1000 Btu/cf
West	4	Diesel	*	1$/barrel	143500 Btu/gallon
	5	Coal	$40/ton	**	10200/Btu/lb
	6	NGas	*	0.1$/Mcf	1000 Btu/cf
South	7	Diesel	*	1$/barrel	143500 Btu/gallon
	8	Coal	$40/ton	**	11500/Btu/lb
	9	NGas	*	0.1$/Mcf	1000 Btu/cf
East	10	Diesel	*	1$/barrel	143500 Btu/gallon
	11	Coal	$35/ton	**	10200/Btu/lb
	12	NGas	*	0.1$/Mcf	1000 Btu/cf

* The fuel costs for gas and oil are given in Figures 3 and 4.

** No storage cost is assumed for coal.

Table 4. Tie line and storage capacities

Name	Description	Capacity
Tie Line 1	West to North Link 1	5000 MW
Tie Line 2	South to West Link 2	3800 MW
Tie Line 3	East to South Link 3	3650 MW
Tie Line 4	East to North Link 4	11650 MW
Tie Line 5	East to West Link 5	6950 MW
Res1	Diesel storage for Gen1	3000 barrels
Res2	Gas storage for Gen3	13000 Mcf
Res3	Diesel storage for Gen4	3000 barrels
Res4	Gas storage for Gen6	26000 Mcf
Res5	Diesel storage for Gen7	170000 barrels
Res6	Gas storage for Gen9	16000 Mcf
Res7	Diesel storage for Gen10	3000 barrels
Res8	Gas storage for Gen12	650Mcf

Res1 through Res8 are storage facilities for Diesel and Natural Gas. Gen stands for Generator Unit.

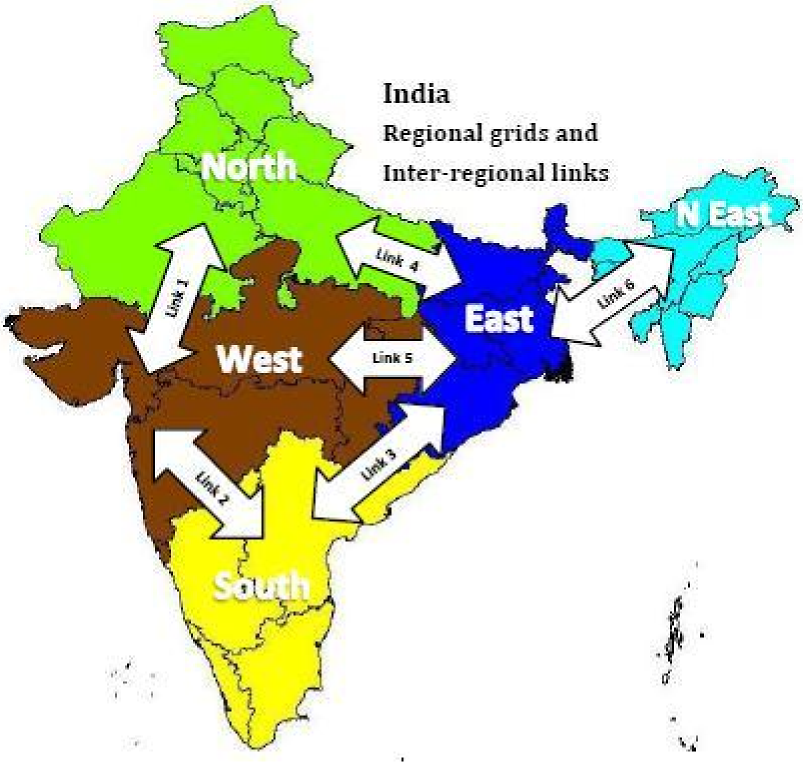

Figure 5. India national grid

4. Methodology

The procedure for solving the network flow model of the India Integrated Thermal Energy System comprises data collection, data file generation, optimization, and results visualization.

The input data file (text format), that is needed to carryout the energy system optimization is generated using MATLAB based software. The input data file includes node and arc data, bounds on the flows, capacity, efficiency, per unit costs, and time-variant parameters related to fuel costs and regional load data.

The optimization study was carried out using MATLAB/TOMLAB software. The CPLEX Dual Simplex LP solver was utilized for the same. The optimal solution is written to a standard solution file. The solution file contains optimal energy flows and the nodal prices associated with the constraints. The results of the simulation are plotted using MATLAB.

5. Results and discussion

Base case and 4 other cases have been studied. The weekly averages of tie line flows, generator schedules, generator nodal prices and regional nodal prices are given in Figures 6 through 40.

The India integrated thermal power system optimization study results are given in Table 5.

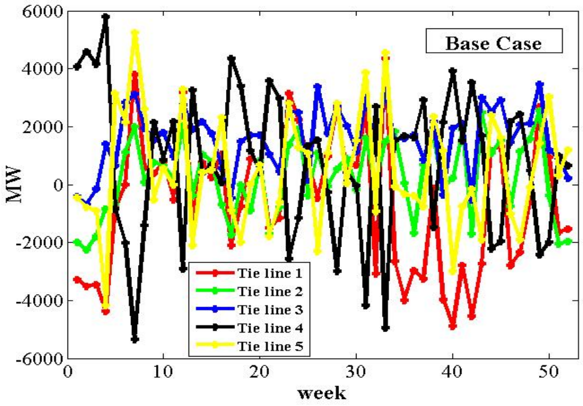

Figure 6. Base case tie line flows

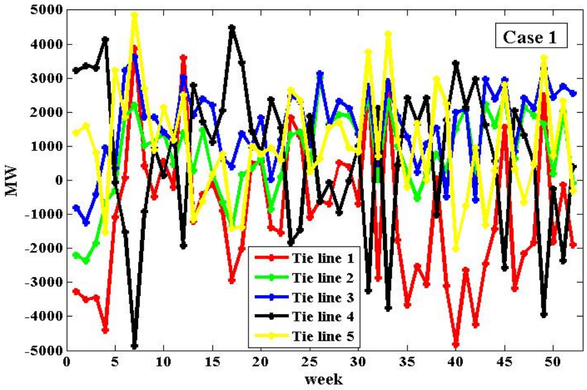

Figure 7. Case 1 tie line flows

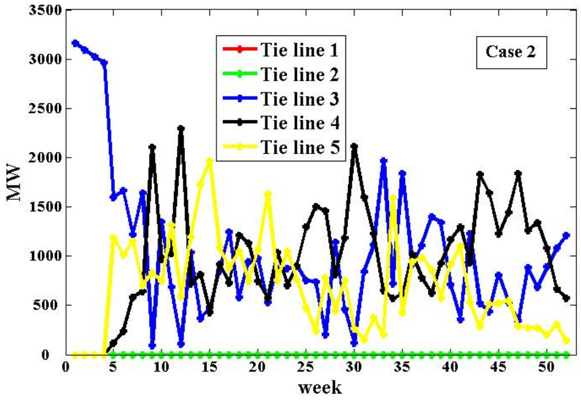

Figure 8. Case 2 tie line flows

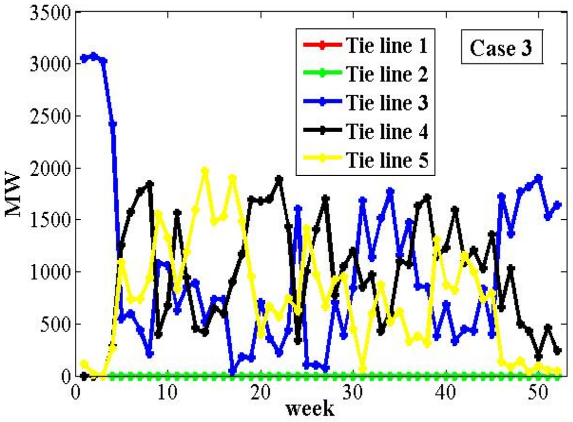

Figure 9. Case 3 tie line flows

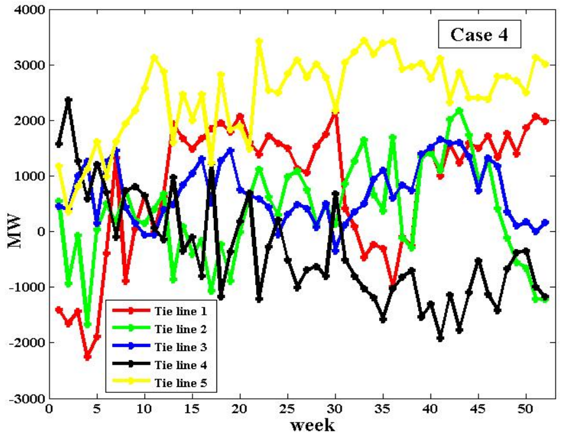

Figure 10. Case 4 tie line flows

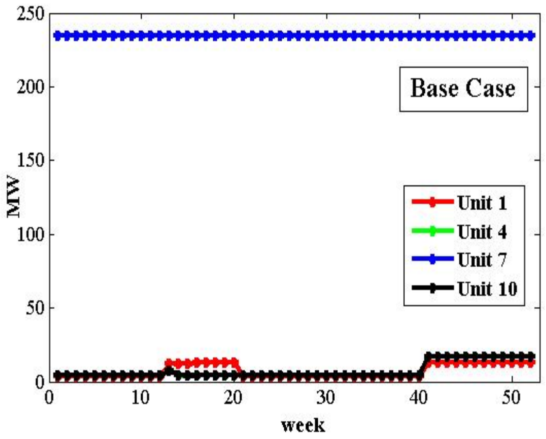

Figure 11. Base case generator schedules (a)

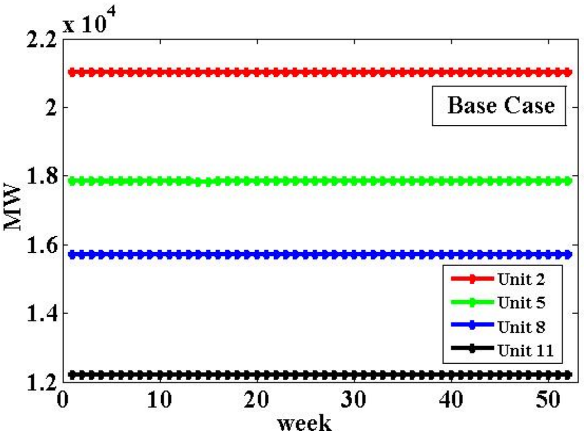

Figure 12. Base case generator schedules (b)

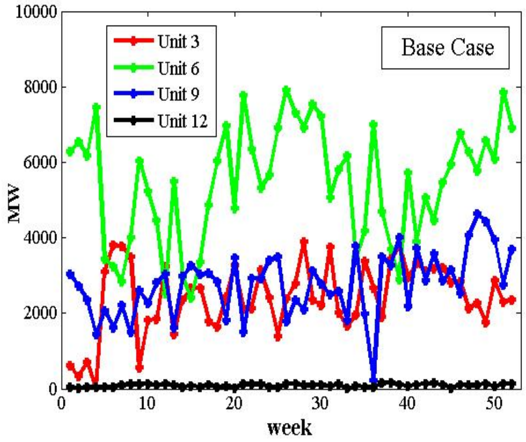

Figure 13. Base case generator schedules (c)

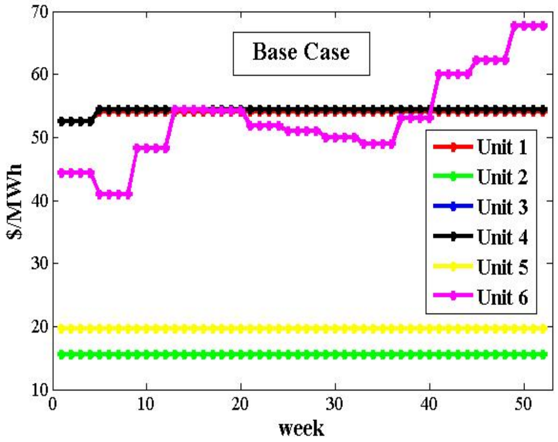

Figure 14. Base case generator nodal prices (a)

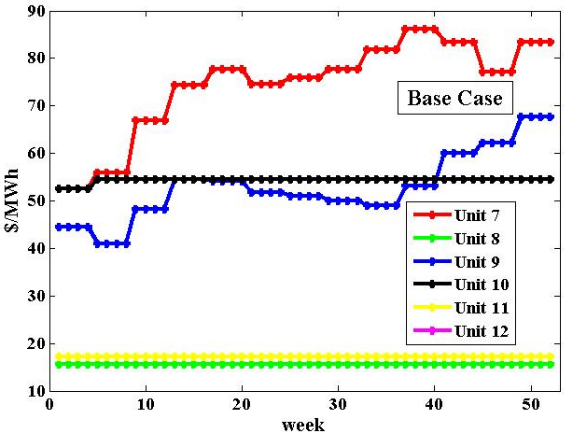

Figure 15. Base case generator nodal prices (b)

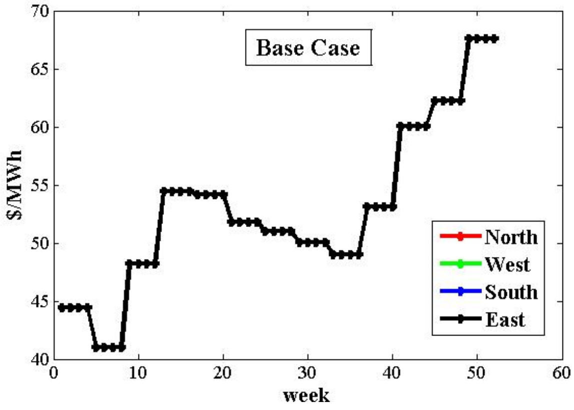

Figure 16. Base case regional nodal prices

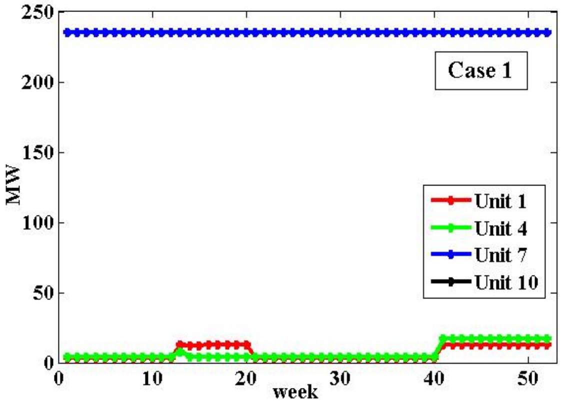

Figure 17. Case 1 Generator schedules (a)

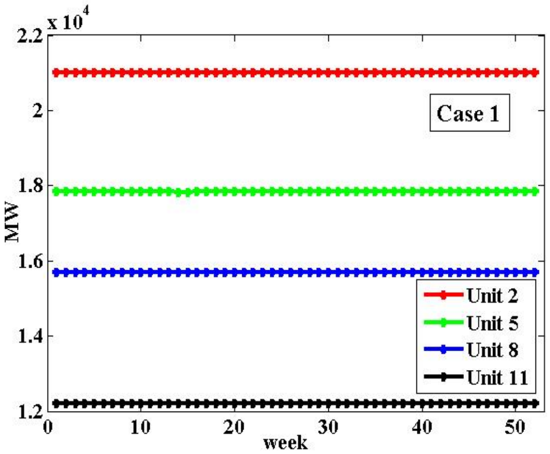

Figure 18. Case 1 Generator schedules (a)

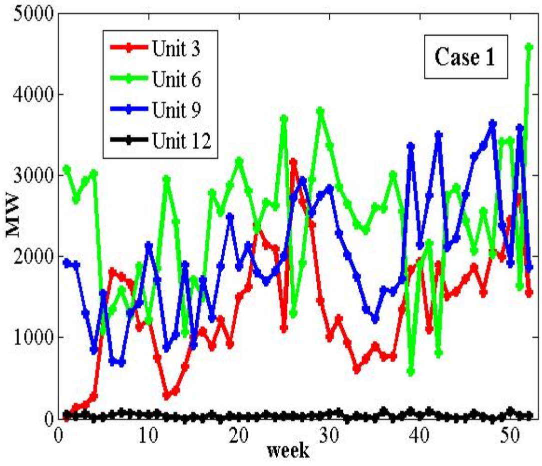

Figure 19. Case 1 Generator schedules (b)

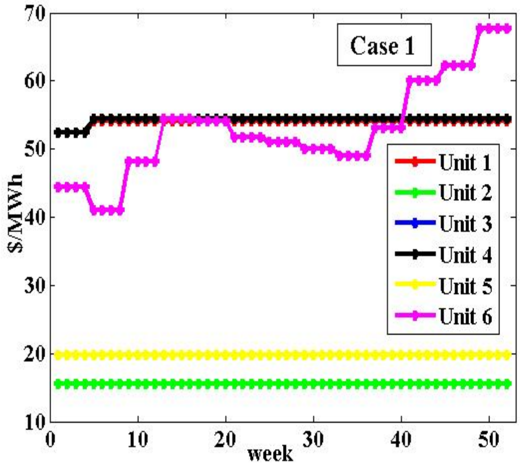

Figure 20. Case 1 generator nodal prices (a)

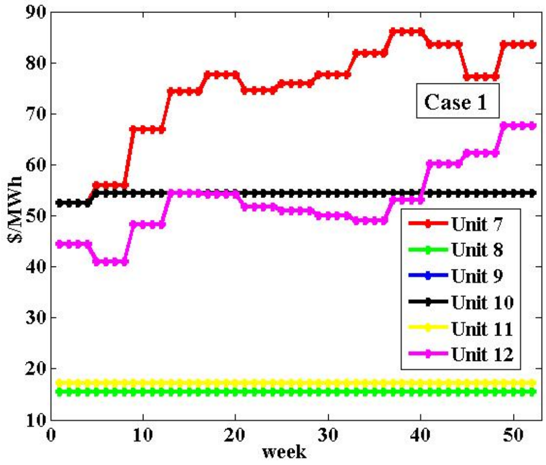

Figure 21. Case 1 generator nodal prices (b)

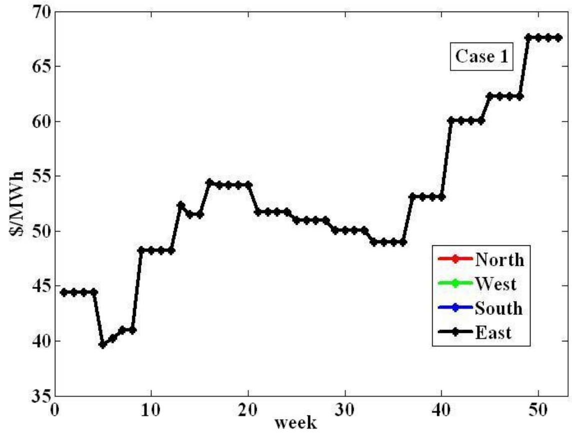

Figure 22. Case 1 regional nodal prices

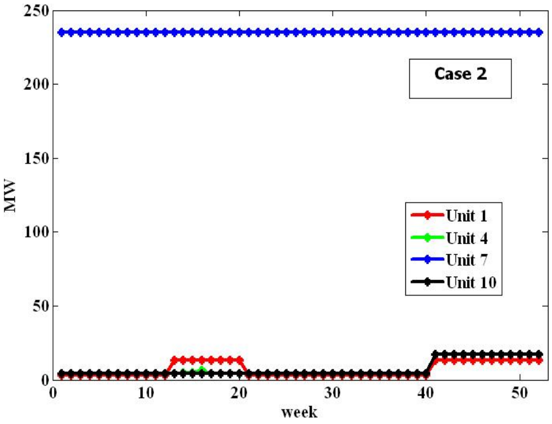

Figure 23. Case 2 Generator schedules (a)

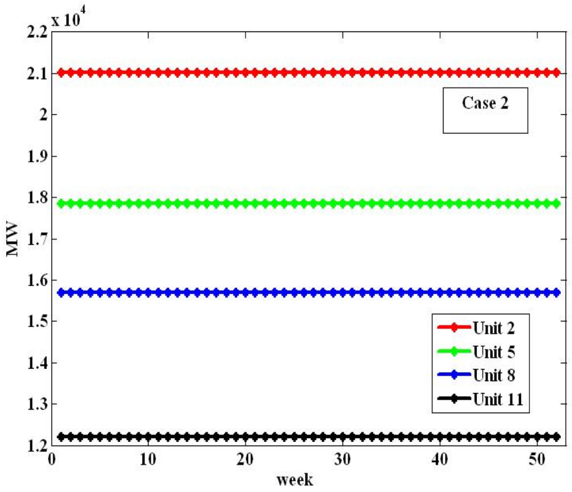

Figure 24. Case 2 Generator schedules (b)

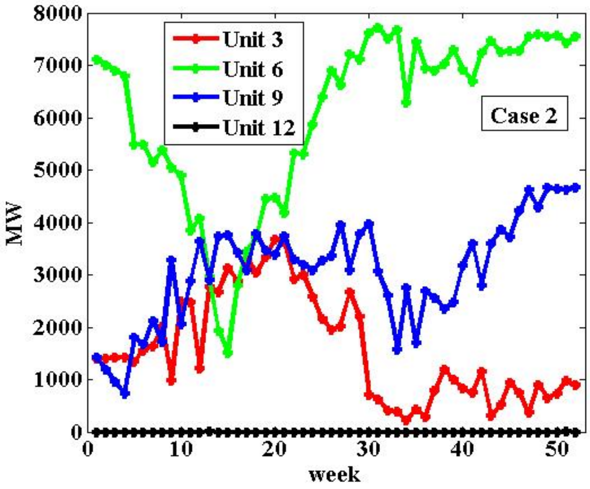

Figure 25. Case 2 Generator schedules (c)

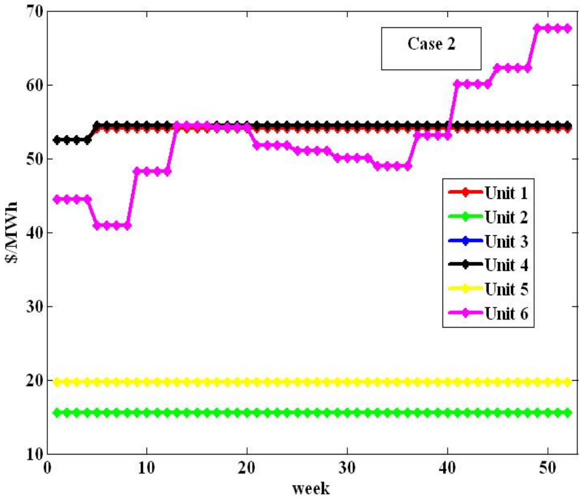

Figure 26. Case 2 Generator nodal prices (a)

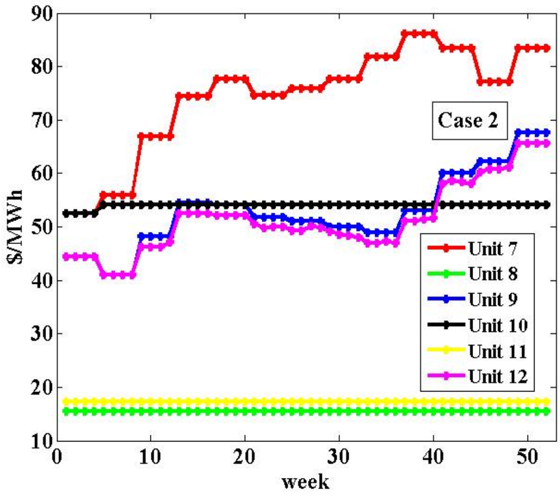

Figure 27. Case 2 Generator nodal prices (b)

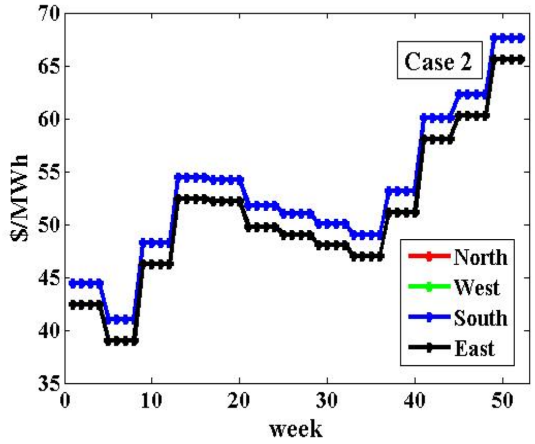

Figure 28. Case 2 Regional nodal prices

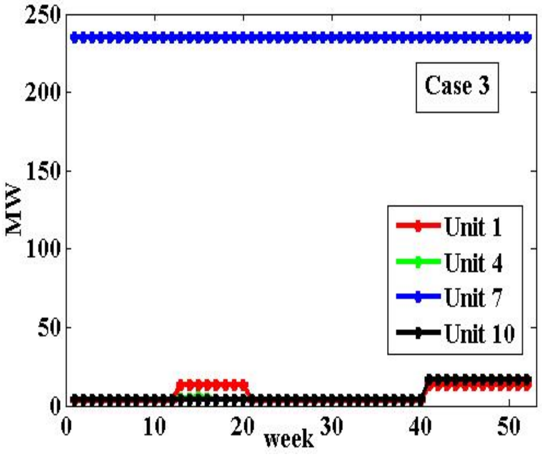

Figure 29. Case 3 Generator schedules (a)

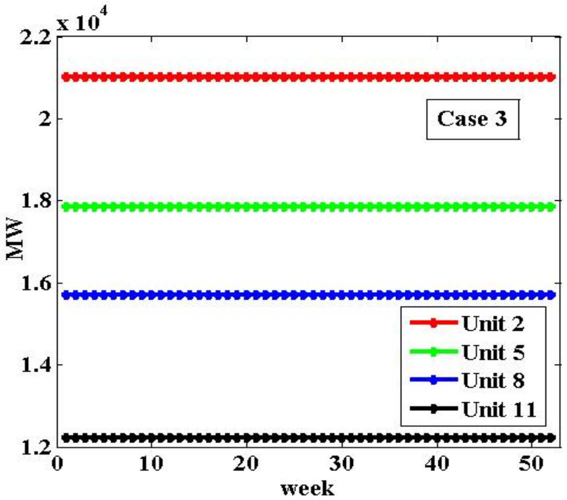

Figure 30. Case 3 Generator schedules (b)

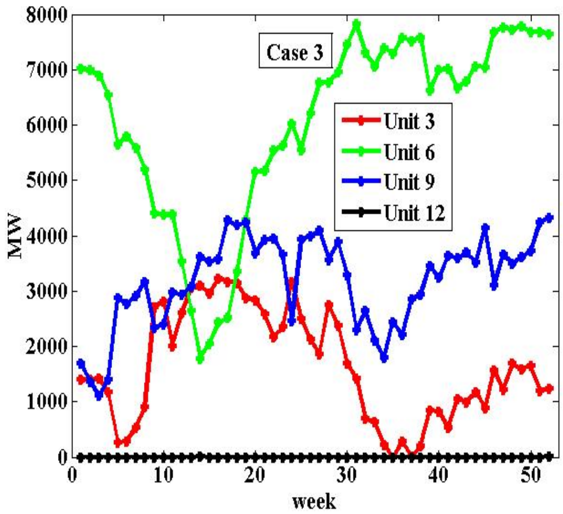

Figure 31. Case 3 Generator schedules (c)

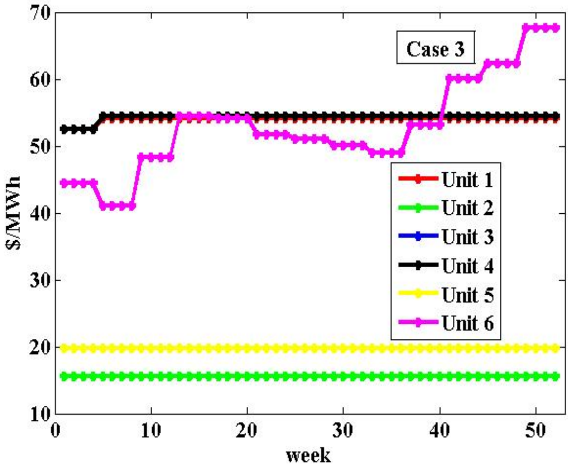

Figure 32. Case 3 Generator nodal prices (a)

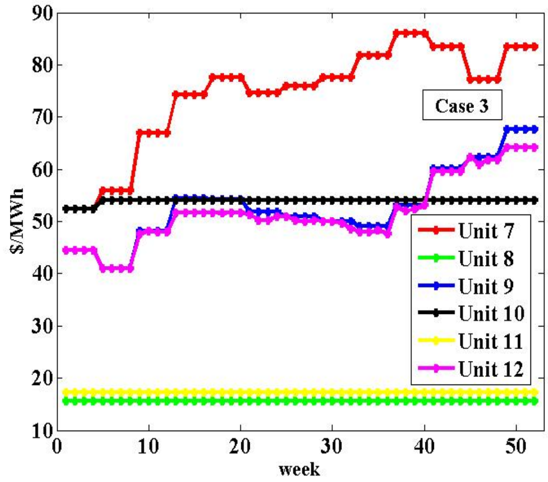

Figure 33. Case 3 Generator nodal prices (b)

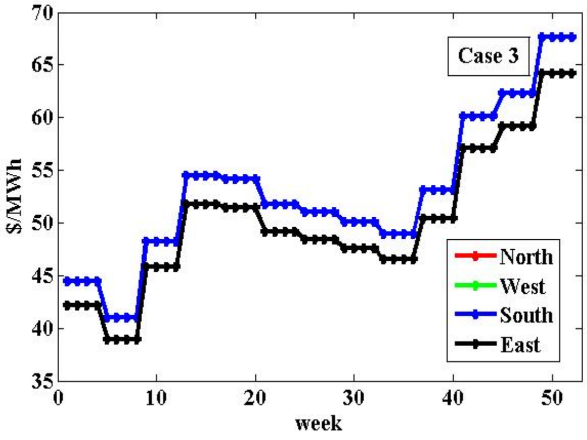

Figure 34. Case 3 Regional nodal prices

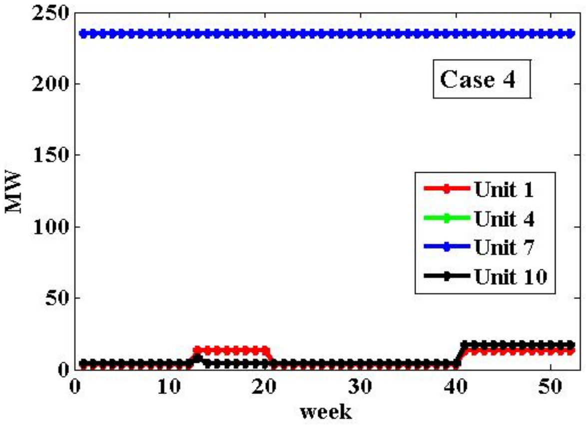

Figure 35. Case 4 Generator schedules (a)

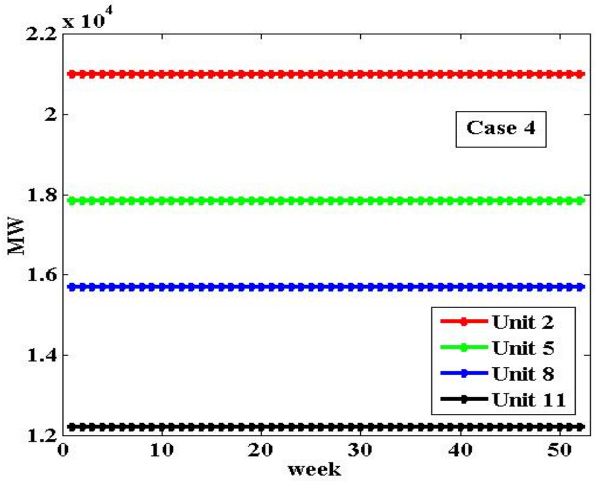

Figure 36. Case 4 Generator schedules (b)

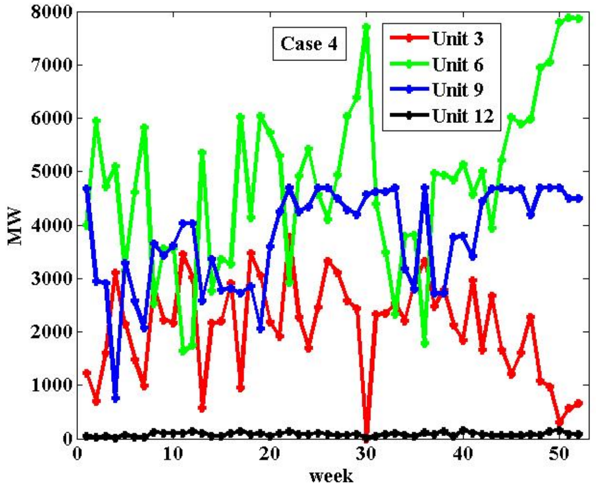

Figure 37. Case 4 Generator schedules (c)

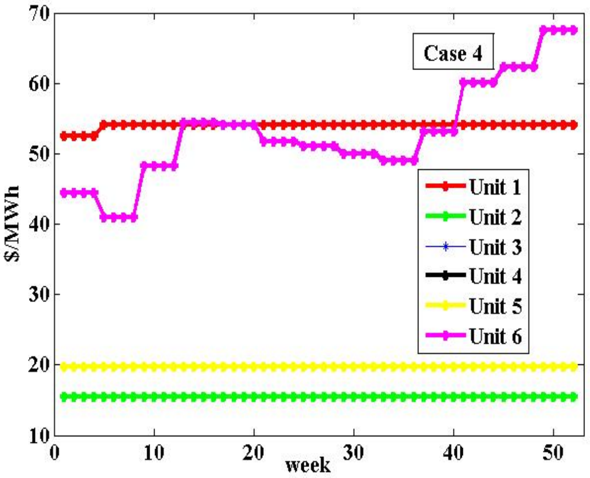

Figure 38. Case 4 Generator nodal prices (a)

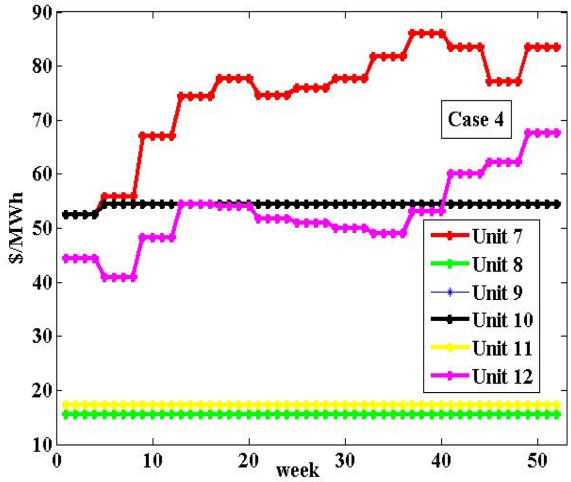

Figure 39. Case 4 Generator nodal prices (b)

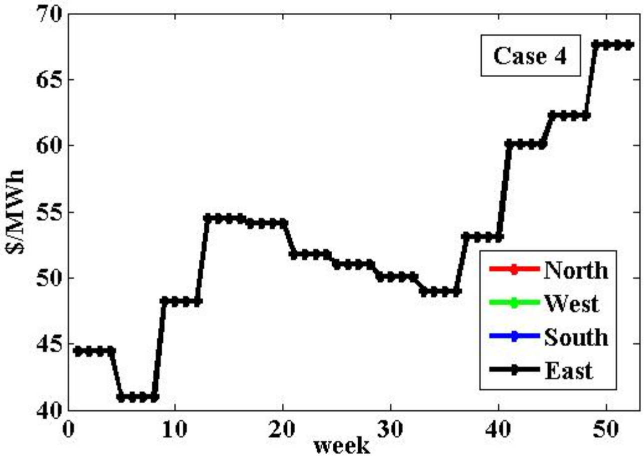

Figure 40. Case 4 Regional nodal prices

Table 5. India energy system optimization study

Name	Description	Total Cost (1000 US$)
Base Case	Tie line and storage capacities as per Table 4	15065055
Case 1	Decrease in Load	12790095
Case 2	Cost of 2$/MWh on Tie line flows	15112545
Case 3	Loss factor of 5% on tie line flows	15127218
Case 4	Tie line capacities reduced by 50%	15065055

Variables = 204040 Constraints = 44096 Solver: CPLEX

From the results of the India thermal power system studies the following conclusions may be drawn. Coal is the cheapest and dominant fossil fuel and also being readily available, it plays an important role in keeping power generation costs low. Adequate inter-regional tie line capacities will result in low line losses and optimal utilization of available generation capacities giving rise to energy security and reliability at minimum cost. Diesel and Natural gas based generation will continue to aid in meeting the load especially during peak demand. When there is no congestion, losses, and costs in the tie lines (vide base case, case1, and case 4), the nodal prices are the same in the interconnected regions.

When demand decreases as in base case to case1, nodal prices in the regions may decrease with the schedule of units with lower incremental costs. When a fuel production or transportation constraint becomes binding, it significantly affects the nodal price in the region (vide base case, case1 to 4).

The differences in regional nodal prices, caused by different situations, are highlighted by cases 2 and 3.

In general nodal prices indicate the opportunity cost of energy at each node of the integrated energy system. They can be utilized to bring about the efficient use of the electric energy system and the fuel production and delivery systems. Nodal prices, thus give correct economic signals for infrastructure development. The nodal prices for units 2, 5, 8, and 11 are constant, since there is no variation in coal prices. Since the prices of natural gas and diesel oil change, the nodal prices of units 1, 3, 4, 6, 7, 9, 10, and 12 vary throughout the year. The regional nodal prices become equal to one another when tie line capacities are not binding the solution. A simplified model of the India integrated energy system model has been utilized in this study. This was done so that the size of the optimization problem involved does not become too large. However, the model and the methodology used for solving the energy system problem can be utilized, incorporating greater granularity in representing the energy system [13]. TOMLAB was selected for carrying out the energy system optimization studies because it is a powerful environment for all sorts of optimization in MATLAB, and no algebraic modeling language offer such unique problem formulations [14]. For future study and research, stochastic fuel costs are to be considered for an integrated power and energy system [15].

6. Conclusion

This paper highlights the complex dynamics of an integrated national energy system through the India case study. It takes into account the interdependencies of electric power generation and transmission along with fuel production and delivery systems. The multiperiod energy network flow model is utilized for obtaining optimal solutions for the India energy system model. This approach is well suited for solving such large optimization problems. The methodology and the results of the study would be of interest to those involved in national energy system research and planning.

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