An Optimization-based Framework for the Quick Analysis of Power Transactions

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Abstract - Effective power transactions can reduce generation costs for a utility. Making good transaction decisions, however, is not an easy task since transactions are coupled with the scheduling of units through system demand and reserve requirements. The speed and quality of transaction decisions are nonetheless becoming critical to capture frequently emerging opportunities in the increasingly competitive power market. As transaction opportunities emerge, the known opportunities can be analyzed one at a time. When large number of such opportunities emerge one by one as time proceeds, this kind of analysis will however lay a huge burden on transaction analysts. A different framework is presented in this paper. While analyzing a known set of opportunities, the economic effects of further purchasing/ selling fixed sizes of power blocks are also analyzed. Within the framework, the integrated scheduling and transaction problem is solved by using the Lagrangian relaxation method. Four transaction modes that optimize transaction level and/or duration are developed to deal with various transaction opportunities. A reference table is then established to help transaction analysts quickly deal with emerging opportunities. The algorithm can also be re-run periodically to update the reference table while solving another set of known transactions. Numerical testing results based on Northeast Utilities data sets show that results can be obtained in reasonable computational times to help transaction analysts make quick and prudent decisions.

I. INTRODUCTION

The power industry is in a transition to a deregulated and competitive market-based structure. In this new environment, the reduction of operation cost has become a necessity for a utility to survive and thrive. As inter-utility power transactions can reduce the total generation costs, they have gained significant importance among electric utilities. Large number of transaction opportunities are thus emerging one by one as time proceeds. The speed and quality of the transaction decisions are becoming critical to promptly analyze and respond to these opportunities.

A literature review on the analysis of power transaction with respect to the new market structure is presented in section II. The known transaction opportunities can be analyzed one by one as they emerge. In view of the increasing competitiveness of the power market, the decisions have to be made in almost real time to lock in on favorable opportunities. These transaction problems are difficult to solve as they are coupled with the scheduling of units through system demand and reserve requirements. The scheduling problem alone is "NP hard," i.e., the computational requirements for obtaining an optimal solution grows exponentially with problem size. The above analysis will therefore lay a huge burden on transaction analysts when the number of transactions becomes large. In this paper, a different framework is presented to analyze the effect of purchasing or selling fixed sizes of power blocks after analyzing the known opportunities (Fig. 1). The results of the analysis will help transaction analysts make quick and prudent decisions on emerging transactions.

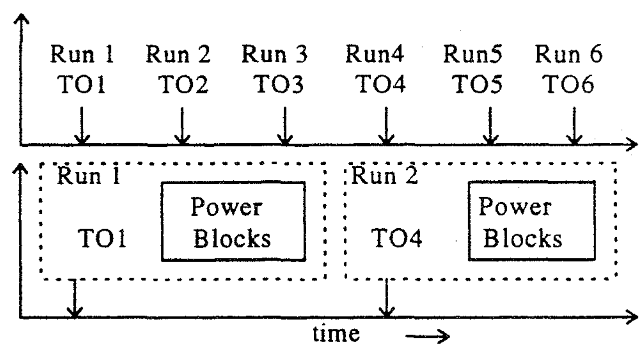

Fig. 1. One set at a time analysis and the New Framework. (TO represents a known transaction opportunity)

Within the framework, the integrated problem is solved in four phases. The scheduling problem integrated with the accepted transactions is solved initially to obtain the base case that will be used to initialize subsequent phases and to calculate individual transaction savings. The known transaction opportunities are analyzed in the second phase and the decisions are incorporated into the formulation before subsequent phases. Then selected combinations of anticipated purchase blocks and sale blocks are integrated and analyzed in phases 3 and 4 respectively. For a purchase transaction the offering utility may place constraints on optimizing the level and/or duration. The purchase transactions are thus optimized in four different modes. The sale problem is included by increasing the system demand by the sale amount over the sale

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period. The problem is solved and the resulting marginal cost will be used to guide the setting of sale prices. Within each phase, the problem is to minimize the total costs subject to system demand and reserve requirements. The problem formulation is presented in section III.

The Lagrangian relaxation technique is used to solve the problems in each phase. Subproblems related to generating units and purchase transactions are solved by using the methods previously reported in the literature. Results from a previous phase are used to initialize a subsequent phase and to cut short computational time. Finally, a method is developed to estimate the savings of individual transaction opportunities and power blocks. The solution methodology is described in section IV.

From the results of the above analysis, a reference table is established. This reference table can give transaction analysts an idea about the marginal generation cost with respect to the combination of power blocks selected. The algorithm can be re-run periodically to update the reference table. The results of numerical testing using the Northeast Utility's data presented in section V show that the transaction analysts can use this reference table to make speedy decisions on transactions as they emerge, without repeatedly solving the problem.

II. LITERATURE SURVEY

Driven by deregulation, the global trend in the power industry is a transition to a market-based structure from the traditional rate of return environment. The process of deregulation is explained as sequence of six steps in [1] with explanation of its impact and consequences. The analysis of the impact of deregulation of power industry in various South American countries such as Chile and Argentina is presented in [2]. The consequences and the lessons learned from the deregulated market structure of UK and Norway are discussed in [3,4,5]. These structural changes are expected to fundamentally alter the pricing of electric power. Several futuristic pricing schemes have been presented in the literature. An auction-based pricing of electric power using linear programming is presented in [6]. A sequential sealed-bid sealed-offer auction is applied to an example and the results show that auction approach to electric power pricing is a possibility. Game theory is used to simulate the decision making process in [7]. The goal is to discourage unfair coalitions in the game where the participants are interested in maximizing their own profits. The objective of this paper is to develop a framework to help transaction analysts promptly analyze and respond to emerging transaction opportunities.

III. PROBLEM FORMULATION

As mentioned earlier, the framework consists of four phases, and each phase solves a scheduling/transaction problem. For simplicity of presentation the problem is formulated with only thermal units and transactions, though the algorithm has been developed for a system with thermal, hydro and pumped-storage units.

Consider a system with I thermal units, M purchase transactions and N sale transactions. It is required to determine the intervals and levels of power purchases based on the optimization mode, the price guidelines of sale transactions and the start-up, shut-down, and generation levels of thermal units over a specified planning horizon T. To formulate the problem, the following notation is first introduced:

- $c_i(p_i^t(t))$: fuel cost of thermal units i for generating power $p_i^t(t)$ at any time t, a piece-wise linear function of $p_i^t(t)$, in dollars;
- $c_m^b(t)$: price for purchase transaction m at a time t, in dollars per MW;
- $d_m(n)$: zero-one variable to indicate if purchase transaction m has to be included in phase n;
- $d_s(n)$: zero-one variable to indicate if sale transaction m has to be included in phase n;
- I: number of thermal units;
- i: index of thermal units;
- K(m): total number of purchase periods for transaction m;
- k: index for purchase periods;
- M: number of purchase transactions;
- m: index of purchase transactions;
- n: index for phases, n=1 to 4;
- $p_d(t)$ system demand at time t, in MW;
- $p_i^t(t)$: generation of thermal unit i at time t, in MW;
- $p_m^b(t)$: power level of purchase transaction m at time t, in MW;
- $p_s(t)$: power level of sale transaction s at time t, in MW;
- $p_r(t)$: system reserve requirement at time t, in MW;
- $r_i^t(p_i^t(t))$: reserve contribution of thermal unit i at time t;
- $s_i(t)$: start-up cost of thermal unit i, in dollars;
- T: time horizon, in hours;
- t: hour index;
- $t_s(k)$: starting hour of purchase period k;
- $t_e(k)$: ending hour of purchase period k;

Objective function

$$J = \sum_{t=1}^{T} \{ \sum_{i=1}^{I} [c_i(p_i^t(t)) + s_i(t)] \} + \sum_{m=1}^{M} \{ \sum_{k=1}^{K(m)} [\sum_{t=t_s(k)}^{t_e(k)} d_m(n) c_m^b(t) p_m^b(t)] \}. \tag{3.1}$$

where J represents the total cost which include the generation and startup costs of thermal units and the purchase transaction costs. Based on the scenarios developed, the values of $d_m(n)$ are set to zero or one and the purchase transactions are included in a particular phase based on these values. The sale blocks are included by increasing the system demand by sale amount during the sale period as shown in (3.2). The minimization of J is subject to the following system-wide demand and reserve requirements:

System-wide constraints:

- system demand:

$$\sum_{i=1}^{I} p_i^t(t) + \sum_{m=1}^{M} d_m(n)\, p_m^b(t) = p_d(t) + \sum_{s=1}^{S} d_s(n)\, p_s(t); \qquad (3.2)$$

The sum of system demand and sale power should be equal to the sum of the total generation and purchase power.

- system reserve:

$$\sum_{i=1}^{I} r_i^t(p_i^t(t)) \geq p_r(t). \qquad (3.3)$$

The total reserve available should be greater than or equal to the reserve requirement. Individual thermal constraints include capacity, minimum up/down time and ramp rate, as detailed in [8].

A. Transaction Constraints and Modes

Power transactions are offered for one or more off peak and on peak periods. In the current practice of New England, a transaction can be accepted satisfying the following constraints. Within an on/off peak period, the transaction level should be constant. There is a requirement for minimum transaction time per load period since thermal units with minimum up/down time constraints are generally used to provide the power. The minimum may be different for off peak and on peak period. If transaction is done for consecutive on peak and off peak period, no gap is allowed in between the periods. The purchase and sale constraints are explained in detail in [9,10].

The decision variables for the purchase problem depends on the mode of optimization. In mode 'both', the purchase level and the duration of each load period are optimized, and the decision variables are $p_m^b(t)$, $t_s(k)$ and $t_e(k)$. In mode 'duration', the duration alone is optimized, and the decision variables are $t_s(k)$ and $t_e(k)$. Similarly the decision variables are $p_m^b(t)$ for mode 'level'. In 'none' mode, the decision 'to take' or 'not to take' a transaction is obtained. For sale transactions, the resulting marginal costs are used to guide the sale pricing corresponding to the four purchase modes.

IV. SOLUTION METHODOLOGY

The flow of the method is represented in Fig. 2. The numbers indicate the phase number and the flow indicated is used for re-initialization. The method of solving the problem in each phase and the various interconnections between the phases are explained in this section.

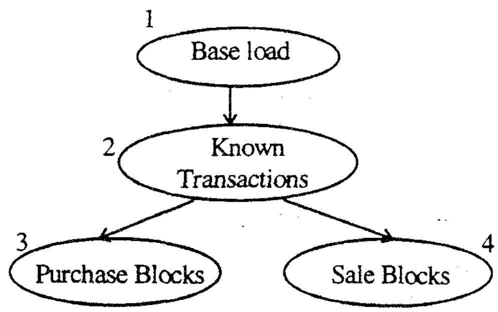

Fig. 2. Representation of the flow

A. Lagrangian Relaxation Method

The problem in each phase is solved using the Lagrangian relaxation technique, presented in detail in [8,9]. The basic idea is to relax all the constraints by using Lagrange multipliers. The individual subproblems are solved at low level and the multipliers are updated in the high level. This two level structure is formulated using the decomposable structure of the relaxed problem and the duality theorem. The dual solution thus obtained is generally not a feasible solution heuristic methods are therefore used to obtain a feasible solution. This method is described in detail in [8]. The thermal and purchase subproblems are solved following the methods presented in [9]. The sale subproblems are solved using the simple price setting scheme presented in IV. E.

B. Purchase Subproblems

After appending the system wide constraints to the objective function, the purchase subproblem can represented as

$$\min L_m^b \ \text{ with } \ L_m^b = \sum_{k=1}^{K} \{ \sum_{t_s(k)}^{t_e(k)} [c_m^b(t)\, p_m^b(t) - \lambda(t)\, p_m^b(t)] \} \qquad (4.1)$$

subject to individual purchase constraints. Any interval within a load period complying with the purchase constraints is called a 'purchase interval'. In the purchase mode 'both', the purchase level and the purchase intervals are to be optimized. Since the levels are same across each interval, the level optimization can be efficiently done by minimizing a single variable function. Each purchase interval can thus be associated with an optimum purchase level and a corresponding cost. Purchase intervals in consecutive load periods should not have a gap in between them as explained in III. A. The optimal intervals with optimum levels for transaction m across the entire planning horizon can be obtained based on the above constraint by using the dynamic programming approach [9]. The above optimization provides the optimum values of ts(k), te(k) and $P_m^b(t)$ for period k for purchase mode 'both'. For mode 'duration', the offered level is taken as the purchase level and the interval is optimized. For mode 'level', the offered intervals are taken as purchase intervals and level is optimized. For mode 'none', the offered level and intervals are taken and purchase decision 'to take' or 'not to take' is made.

C. Re-initialization procedure

The multipliers obtained from the previous phase (as per the flow shown in Fig. 2) are used as initial multipliers for the current phase. The multipliers are however modified for the hours in which new transactions are included. The modifications are done based on the priority table (it contains blocks of power arranged in ascending order of their cost per MW) and commitment status from the previous phase. Based on the price/level of the new transactions, some of the units that are previously off because of minimum up/down time constraints can be switched on and vice versa. New initial multipliers are obtained based on this new commitment. Since the previous results are effectively used to get good initialization, the total computational time can be substantially reduced.

D. Individual Savings Estimation

With the presence of multiple transactions, savings contributed by individual transactions are estimated to help the transaction analysts make effective individual decisions.. The different between current total cost and the base cost gives total savings T_s. The approximate individual savings s_m' is calculated as

$$s_m' = \sum_{t=t1}^{t2} [\lambda(t) - c_m^b(t)] * p_m^b(t), \tag{4.2}$$

where $\lambda(t)$ is the hourly marginal cost, $p_m^b(t)$ is the hourly accepted purchase power level, and t1 and t2 are the starting and ending hours of the transaction period respectively. The individual savings are then normalized to get the estimate of individual savings s_m.

$$T_s' = \sum_{m=1}^{M} s_m', \tag{4.3}$$

$$s_m = (s_m' / T_s') * T_s . \tag{4.4}$$

The savings for the non-accepted transactions are zero, as the accepted power level is zero.

E. Price Setting of Sale Transactions

When a utility offers a sale price, the price should be competitive enough in the market to attract purchasers. On the other hand, it is important to ensure that the competitive price yields a profit. The selling utility should keep enough margin to get profit even if the transaction is made for the costliest time span satisfying the minimum number of transaction hours. The sale transactions are included by increased the system demand by the sale amount for the total sale period and the scheduling problem is solved. The final value of the multipliers are used to calculate the average cost for each sale period. This gives a lower bound for the sale price for that period. A search is also done for the costliest span satisfying the minimum transaction hours, and the average cost for this span is calculated. This cost will help the analysts to ensure profit when quoting a market based competitive price.

F. Reference Table

The price, level and the duration of the power blocks along with the accepted level, duration and the savings obtained from the results are tabulated to form the reference table. Evaluation of the results with respect to the purchase blocks can provide valuable information about the current marginal generation cost. For example, a full acceptance level for a purchase block with very high savings indicates that the price offered is significantly lesser than the marginal cost. On the other hand, a low acceptance level indicates that the price is close to the marginal cost. By using all these information from the reference table, decisions can be made for the emerging opportunities very quickly.

V. IMPLEMENTATION AND TESTING RESULTS

The algorithm was implemented in FORTRAN on a SUN Ultra 1. All the rules of New England Power Pool are satisfied and many practical considerations are included. Numerical testing is done using a Northeast Utility's data set, week 4 in July 95 (7/17/95 - 7/24/95). Two test cases are derived to illustrate key features of the method.

A. Testing results for Case 1

This test case is used to explain the different purchase modes, the calculation of savings for individual transactions and the sale price setting. Four purchase transactions (one in each optimization mode) and a sale transaction are introduced. The transaction details are given in Table 1. B, L, N and D are used for both, level, no and duration optimization modes, respectively. The prices and savings are in dollars and the levels in MW.

Type	Name	Mode	From	To	Price	Level
Sale	T1	-	18/08	19/23	-	400.0
Pur.	T2	B	19/08	20/23	27.0	300.0
Pur.	T3	L	22/24	23/23	28.0	250.0
Pur.	T4	N	17/23	18/23	24.0	400.0
Pur.	T5	D	21/01	22/23	25.0	200.0

Table 1. Transactions included in Test Case 1.

The results for sale pricing is presented in Table 2 and for purchase transactions in Table 3.

Per.	From	To	Aver. cost	Maximum cost Span		
				Cost	From	To
1	18/08	18/23	26.00	26.83	18/15	18/22
2	18/24	19/07	20.07	20.20	18/24	19/04
3	19/08	19/23	27.06	28.48	19/12	19/19

Table 2. Sale price setting for transaction T1.

To guide the pricing of sale transactions, the average cost can be used for modes N and L and the maximum cost can be used for modes B and D.

Name	Per.	Accepted Details			
		From	To	Level	Savings
T2	1	19/11	19/18	257.0	2,319
	2	19/23	20/06	No purchase	
	3	20/10	20/17	179.0	1,263
T3	1	22/24	23/07	No purchase	
	2	23/08	23/23	No purchase	
T4	1	17/23	18/07	No purchase	
	2	18/08	18/23	400.0	10,010
T5	1	21/01	21/07	No purchase	
	2	21/09	21/22	200.0	4,353
	3	22/07	22/23	No purchase	
	4	22/11	22/22	200.0	1,313

Table 3. Purchase transactions results.

It can be inferred from Table 3 that the transactions in different modes are optimized accordingly. Depending on the constraints placed by the offering utility, the purchase transaction can be optimized in the suitable mode. It can be seen from the savings column that the total savings of $19,258 is split among the accepted transactions. The total CPU time required was 168.28 seconds.

B. Testing results of Case 2

This test case is used to explain the reference table. First the case is tested in the methodology presented here and then in 'one at a time' method. A comparison of the two results is also provided.

I. Analysis based on the framework

Phase	Name	From	To	Level	Price
2	T1	21/08	21/23	100	26.5
3	B1	20/08	20/23	400	27.0
	B2	22/08	22/23	300	25.0

Phase	Name	From	To	Level	Savings
2	T1	21/11	21/18	100	6,224
3	B1	20/10	20/22	225	14,782
	B2	22/10	22/23	250	2,829

Tables 4 and 5. Reference table

As shown in Table 4, a known transaction T1 is analyzed in phase 2 (basic scheduling is done in phase 1) and the decision is incorporated. A combination of two purchase blocks B1 and B2 is included in phase 3. The accepted levels, duration, and the savings are presented in Table 5. The significant savings for B1 indicates that the marginal cost is substantially less than the price of $27. The accepted level of 225 MW, however, indicates that the marginal cost will be less than $27 when the demand is reduced by 400 MW. For B2, small savings indicates that the marginal cost is very close to $25. The CPU time required for this testing was 131.22 seconds.

II. 'One at a time' analysis

Run	Name	From	To	Level	Price
1	T1	21/08	21/23	100	26.5
2	T2	20/08	20/23	150	25.0
	T3	22/08	22/23	100	27.0
3	T4	20/08	20/23	200	27.0
	T5	22/08	22/23	200	25.5

Run	Name	From	To	Level	Savings
1	T1	21/11	21/18	100	6224
2	T2	20/09	20/22	150	14786
	T3	22/08	22/23	No Purchase	
3	T4	20/08	20/23	No Purchase	
	T5	22/08	22/23	No Purchase	

Tables 6. and 7. 'One at time analysis' data and results

As shown in Table 6, five transactions are included in three separate runs and the results are presented in Table 7. The results obtained in a particular run is incorporated into the system before starting the next run. The total CPU time required for the three runs was 298.32 seconds.

III. Comparison of the two methods

The results in Table 7 reflects the analysis done on Table 5. The non-acceptance of T5 indicates that the marginal cost is very close to $25 for the period 22/08 to22/23. For the period 20/08 to 20/23, T2 with 150 MW at $25 was accepted and included into the system load. T4 with 200 MW at $27 MW was not accepted. This shows that for this period, the marginal cost is less than $27 for a demand reduced by 350 MW. These results thus agree with the analysis done using the reference table.

VI. CONCLUDING REMARKS

Driven by the deregulation, inter-utility transactions have gained significance in bringing down the generation costs of a utility. The speed and quality of the transaction decisions will however become critical. When number of transaction opportunities emerge frequently, it is difficult to analyze them one at a time as they emerge. A framework has been presented in this paper to analyze the economic effects of selling/purchasing selected combinations of power blocks. Numerical testing results show that the transaction analysts can deal with emerging opportunities quickly using the reference table. A study to enfold future uncertain transaction opportunities in making current transaction decisions is currently underway.

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