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A Computer–Aided Methodology for Economic Management of Interconnected Power Systems

استخدام برمجة الحاسب الآلي في إدارة اقتصادية لنظم القوى الكهربية المترابطة

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خلاصة

إن الربط بين الأنظمة الكهربية المتجاورة يؤدى إلى مزايا فنية واقتصادية كبيرة منها خفض الاحتياطي الدائر لنفس مستوى الأمان وبالتالي تأجيل الإنفاق الاستثمارى لبناء محطات جديدة وخفض تكاليف التشغيل وأيضا الاستفادة من الفوارق الزمنية لأوقات الذروة و غيرها من المزايا التى أدت إلى النمو السريع فى تبادلات الطاقة خلال العقود الأخيرة. ومن أهم المشاكل التي تواجه مشغل نظم القوى الكهربية هي اتخاذ قرار شراء أم بيع الطاقة الكهربية. وتوجد بعض البرامج لمساعدة المشغل في حل هذه المشكلة منها مجموعة برامج MAPS ولكن لكى يصل المشغل إلى القرار يجب علية تشغيل أربعة برامج معتمدة على بعضها مما قد يزيد من احتمال الخطأ بالإضافة إلى طول الوقت المستهلك في اتخاذ القرار.

ويحتوى هذا البحث على برنامج تم إنشاؤه بلغة C++ يتعامل مباشرة مع المشكلة، وبمجرد إدخال المشغل لقيمة الحمل يقوم البرنامج بحساب هل هذا النظام يحتاج إلى شراء الطاقة الكهربية أم لدية فائض منه. وفي حالة وجود نقص في الطاقة يقوم البرنامج بحساب تكلفة تغذية هذا الحمل من عدة مصادر (احتياطي وحدات توليد النظام – شراء هذه الطاقة من الأنظمة المجاورة – خليط من المصدرين السابقين) ثم يقارن بين تكلفة كل منها ويختار أقلها تكلفة ثم يعطى القرار الأمثل للمشغل. في حالة وجود فائض في الطاقة يقوم البرنامج بحساب ثمن بيع هذه الطاقة. وقد تم تطبيق الطريقة المقترحة على مثالين وتمت مقارنة نتائجها مع النتائج التي تم الحصول عليها بطرق أخرى للتدليل على كفاءة الطريقة المقترحة.

Abstract:

Neighboring networks need to be interconnected for many reasons, such as: the benefits of power sales in either direction across the boundaries which take the advantages of differential power demand according to time of day or seasonal/weather changes. Sharing resources in this way would defer installation of new generation, it would also involve sharing the provision of spinning reserve and reduce the hot standby reserve requirements. In any interconnected power system, the most important problem facing the power system operators is the management of their own power system transactions (buying or selling the electric power) to achieve maximum benefits from interconnection. Some computer programs have been produced to deal with this problem such as Multi-Systems Production Simulation Program (MAPS) package. The operators have to run four dependent programs to make a decision to sell or purchase electric energy, which may take a long time and cause accumulated errors

This paper produces a new computer program developed by using C++ language. The program deals directly with the mentioned problem and helps the interconnected power system's operators to take fast and reliable decisions. Whenever the power system has a missing load, the program can calculate the minimum cost to supply that load by coordination between the system reserves and purchasing energy from other interconnected systems. On the other hand, whenever the system has surplus generation energy the program can detect the available power to be sold to other systems and calculate approximately the price of sale. The program also, determines the units' commitment, and develops the generating units' priority list. Two example

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systems are used to show applications of the proposed computer program in both purchasing and selling models.

List of symbols:

A = Total number of interconnected systems.
SS = Studied System.
U = Total number of units in studied system.
P (i) = Generation level in unit i (MW).
a_i, b_i, c_i = Cost coefficients in generating unit i.
C (i) = Generation cost of unit i ($/h).
P_B (j) = Power delivered from purchase transaction j (MW).
C_B (j) = Cost of purchased power in transaction j ($/h).
N_B = Number of transactions.
β_j = Per unit cost of purchased power ($/MWh).
P_{n-m} = Power flow from bus n to bus m (MW).
θ_n = Voltage angle at bus n (rad).
$Xn\text{-}m$ = Reactance of line n-m (Ω).
P_K = Price of sold power at bus k ($).
λ = Marginal generation fuel and maintenance cost.
$\eta_{L,K}$ = Marginal cost of transmission losses caused by an increment of demand at bus k
G_{QS} = Generation quality of supply cost ($/MWh).
T_{QS} = Transmission quality of supply cost ($/MWh).
ML = Missing load (MW).
MR = Maximum Rate of generating units (MW).
MC = Continuous rate of generating units (MW).
T_{gen} = Total maximum generation of system generating units (MW).
C_{gen} = Total continuous generation of system generating units (MW).
L = System load (MW).
Ares = Available power to interchange in the studied system (MW).
C_{res} = Cost of supplying missing load from studied system reserve ($/h).
C_{oth} = Minimum cost of supplying missing load form other systems ($/h).
C_{comb} = Minimum cost of supplying ML form a combination of studied system reserve and other interconnected systems ($/h).
FMC = Final (selected) Minimum Cost ($ /h).
Z_L, Y_L = Series impedance and Shunt admittance of the transmission line (Ω).
MP_t = Weighted generation cost of marginal generators in period t.
R_l = Resistance of tie line no. l (Ω).
$P_{tie}(l,t)$ = Power flow through tie line l at period t (MW).
S_i = Start up cost ($).
Ψ_k = Set of buses directly connected to bus k.
P_{off} = Offered Power (MW)

1- Introduction

Interconnection is a driving force like communications. Neighboring networks want to be interconnected for many reasons, such as for the benefits of sharing reserve capacities, and common exploitation of resources, or generally speaking, for the sake of economic and ecological benefits [1]. Every power system has quite different generating units and must meet time-varying system demand and reserve requirements. Any power system usually has different marginal generation costs. If the marginal costs of neighboring systems are substantially different, it would be mutually beneficial for the system to sell or purchase power and maximize the savings or profits from transactions [3].

The problem facing the interconnected power systems' operators is to take economic decisions of buying or selling the electric energy through the interconnected power systems according to the open market of electricity conditions. Selling, purchasing, transmission system facility and constraints, power market behavior are important tasks facing the interconnected power system operators.

The problem of energy transactions has been previously studied from different points of view [2]-[11]. References [2], [3] and [4] deal with the problem from the purchasing point of view. A limited power purchase problem was considered in [2] where the total amount of energy purchased within a time period was allocated among hours using a peak shaving method. Purchased transactions and scheduling of thermal units are considered as an integrated problem and solved using the Augmented Lagrangian decomposition and coordination technique in [3]. Calculating the range of control variables (local generation and purchasing power) which satisfying operational constraints with a total operation cost lower than defined goal was defined in [4].

References [5] and [6] have discussed the problem from the selling viewpoint. A model for calculating the spot price of electricity of a typical electric power system was described in [5], the model offers several different approaches for calculating generation curtailment premiums and transmission congestion charges. Power transactions were analyzed from a selling system viewpoint for a system consists of thermal, hydro and pumped storage units in [6].

Some other approaches deal with the problem from transmission point of view [7]-[9]. A model for security costing based on contingency analysis and customer security worth has been proposed in [7]. Whereas, the optimal pricing of transmission services of interconnected power systems was formulated in [8]. A decentralized operation of the transmission grid for scheduling inter–utilities power exchanges was analyzed in [9].

An improvement of bounding-based procedure for estimating expected production costs for a multi-area power system was presented in [10]. The procedure applied a state space characterization of equipment outages and loads, combined with linear optimization methods, standard load duration curve-based production costing techniques, and clustering nalysis. he ethod efined pper nd ower ounds o he true expected cost, and tightened those bounds by partitioning the outage and load spaces. Reference [11] presented a dynamic model that described the interplay of electric prices in a multi-market environment, and employed the basics of demand and supply to arrive at a closed loop price dynamics.

Some computer programs were implemented to deal with the problem such as Multi -Systems Production Simulation Program (MAPS) package, but it is so complex that the system operator has to run four dependent programs to take a decision to sell or purchase electric energy [12],[13].

A mathematical model is developed considering the conditions and constraints applied in References [4]-[9]. A computer program is then built up using Borland C++ language. The program performs most functions of interconnected power systems operation applied in MAPS package, but it is simpler and easier for a power system operator. In case that the studied interconnected system has a missing load, the program can calculate the minimum cost of supplying that load by coordination between this system reserves and purchasing power from other interconnected systems. On the other hand if the system has excess of generation the program can estimate the available power that can be sold to other systems and calculate the selling price for each period. The program also determines the units' commitment at certain period, and develops the generating units priority list.

2- Problem Formulation:

The main task of the algorithm presented in this paper is to help the interconnected power systems' operators to achieve maximum benefits from interconnection by supplying the system load at minimum cost and selling its surplus power at maximum benefits.

2.1 Short-Term Power Purchasing Model:

In earlier approaches a fixed price was considered [2], [3]. The model presented in Ref. [4] has solved the problem considering uncertain price. The mathematical model constructed in this paper solves the problem under uncertainty depending on the constraints in [4]. These constraints include: power generation limits, power balance limits and line flow constraints and will be illustrated later.

Figure 1, describes an interconnected system consists of three independent utilities, each system is interconnected with the other two systems and buses 1,2...n, are power producer. Index j represents purchase transaction. There may be more than one transaction (i.e. buy or sell) at each bus. The main objective is to co-ordinate power purchases with local generation to supply the system load at minimum cost. The computation will be done at peak load period [4].

Generation cost for each unit is represented by a second order polynomial as:

$$C(i) = a_i + b_i.P(i) + c_i.P^2(i) \quad (1)$$

Hence, the incremental cost of a generator is a linear function of generation. In general, the price per unit of purchased power in transaction j (i.e. β (j)) is a function of power level. Assuming that the price is a linear function of the imported power, then the system expenditure for a power purchase $P_B(j)$ is represented as [4]:

$$C_B(j) = \beta_0(j) + m(j).P_B(j) = \beta(j).P_B(j) \quad (2)$$

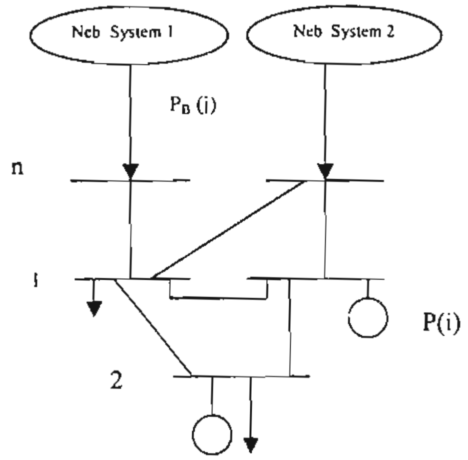

Fig. 1 Purchased Power in an Interconnected System

The optimal purchased problem can be formulated as follows:

$$\underline{\textit{Minimize}} \quad F = \sum_{j=1}^{n} C(i) + \sum_{j=1}^{n} \beta(j).P(j) \tag{3}$$

Subject to:

i) Power generation limits:

$$0 \le P_B(j) \le P_B^{max}$$
$$0 \le P(i) \le P^{max}$$
$$i=1,\dots,n \qquad j = 1,\dots N_B$$

ii) Power balance in each bus:

$$\sum_{i=1}^{n} P(i) + \sum_{j=1}^{N_B} P_B(j) + \sum_{n\in\Psi_k} P_{n-k} = L_m \qquad \text{For each } m \in \{1\dots N_{buses}\} \tag{4}$$

iii) Line flow constraints:

$$P_{n-m} = (\theta_n - \theta_m) / X_{n-m}$$
$$P_{n-m}^{min} \; ? \; P_{n-m} \; ? \; P_{n-m}^{max} \qquad \text{For all lines} \tag{5}$$

2.2 Short-Term Power Selling Model:

Most utilities always have quite different generating units and must meet their time-varying system demand and reserve requirements. The utilities usually have different marginal generation costs. If the marginal costs of neighboring utilities are substantially different, it is beneficial for these utilities to sell or purchase power and maximize the savings or profits from transactions. A selling system has to make an offer including prices, power levels and available durations, hence a purchasing system can select power levels and durations within the offered range subject to relevant constraints. The problem is complex because transactions are coupled with system demand and some other constraints. Therefore, it has to be solved in conjunction with the commitment and dispatching of units.

Selling prices can be estimated due to operators experiences with knowledge of the system's marginal costs and current market information. However, it is necessary for a utility to have an efficient tool to compute the selling price of surplus power at different durations and power levels. References [5] and [6] suggested mathematical models to calculate the price of selling power. The mathematical model constructed in Reference [5] has considered the power loss through transmission lines, but it neglected the start up cost of the units. Whereas, the model of Reference [6] took the start up cost into consideration, but it neglected the power loss through transmission lines. The mathematical model developed in this paper combines both models and also takes ancillary service into consideration to completely simulate the power selling. The price of selling power during a certain period can be estimated according to the following equations:

$$P_K = \lambda + \eta_{L,K} + G_{QS} + T_{QS} + \text{Ancillary services.} \tag{6}$$

λ is defined in Ref. [6] as:
$$\lambda = \sum_{i=1}^{n}\left[C_i(P_i'(t)) + S_i(t)\right] \tag{7}$$

$\eta_{L,K}$ is defined in Ref. [8] as:
$$\eta_{L,K} = 2MP_t * R_l * P_{tie}(l,t) \tag{8}$$

G_{QS} is defined in Ref. [5] as:
$$G_{QS} = 0_{QS,G} \quad \text{if } g(t) > g_{crit}$$
$$= 0 \quad \text{otherwise.} \tag{9}$$

and T_{QS} is defined in Ref. [5] as: $T_{QS} = \theta_{QS,T}$ **if $d(t) > d_{crit}$**

$= 0.0$ **otherwise.** **(10)**

A tariff period T is considered, for which the load duration curve is divided into a number of time slots $t = 1,2\ldots T$. [8]

Where

- $C_i(P_i^t(t))$:fuel cost of thermal unit i at generation level $P_i^t(t)$,
- $\theta_{QS,G}$: cost of unserved energy ($/MWh),
- $g(t)$: The amount of available generation at time t, (MW)
- g_{crit} : The fraction of the maximum amount of available generation at time t that can be used according to the operation constraints.
- $\theta_{QS,T}$: The cost of unserved transmission energy ($/MWh)
- $d(t)$: The amount of available transmission at time t (MW)
- d_{crit} : The fraction of the maximum amount of available transmission at time t that can be used according to the operation constraints.

Equation (6) is subjected to the following constraints:

System demand:

$$\sum_{i=1}^{n} P_i^t(t) - \sum_{s=1}^{N_s} P_n^s(t) = P_d(t) \quad (11)$$

System reserve:

$$\sum_{i=1}^{n} r_i^t(P_i^t(t)) \geq P_r(t) \quad (12)$$

Where

$r_i^t(P_i^t(t))$: reserve of the i *th* thermal power station (MW),

$P_d(t)$ & $P_r(t)$: system demand and reserve respectively (MW),

$P_n^s(t)$: the selling power during period t (MW),

Ns : number of selling processes.

3- Proposed Mathematical Model:

The flow chart of the suggested methodology is given in Figure 2, where the computations are made according to the following steps:

Step 1: Read input data: number of interconnected systems, studied system load, number of units in studied system, characteristics of each unit (maximum rate, continuous rate, start up cost and cost coefficients), the interchange power price between systems and maximum purchased power available from each system. Transmission lines data and studied system cost of generation and transmission quality.

Step 2: Determine the priority list of the studied system according to C(i) and calculate the reserve for each unit included in this system.

Step 3: Calculate maximum capacity of the system: $T_{gen} = \sum_{i=1}^{n} P_i^{max}$ **(13)**

Compute the total continuous generation: $C_{gen} = \sum_{i=1}^{n} P_i^{cont}$ **(14)**

Where, P_i^{max} & P_i^{cont} : maximum and continuous generation of unit i (MW).

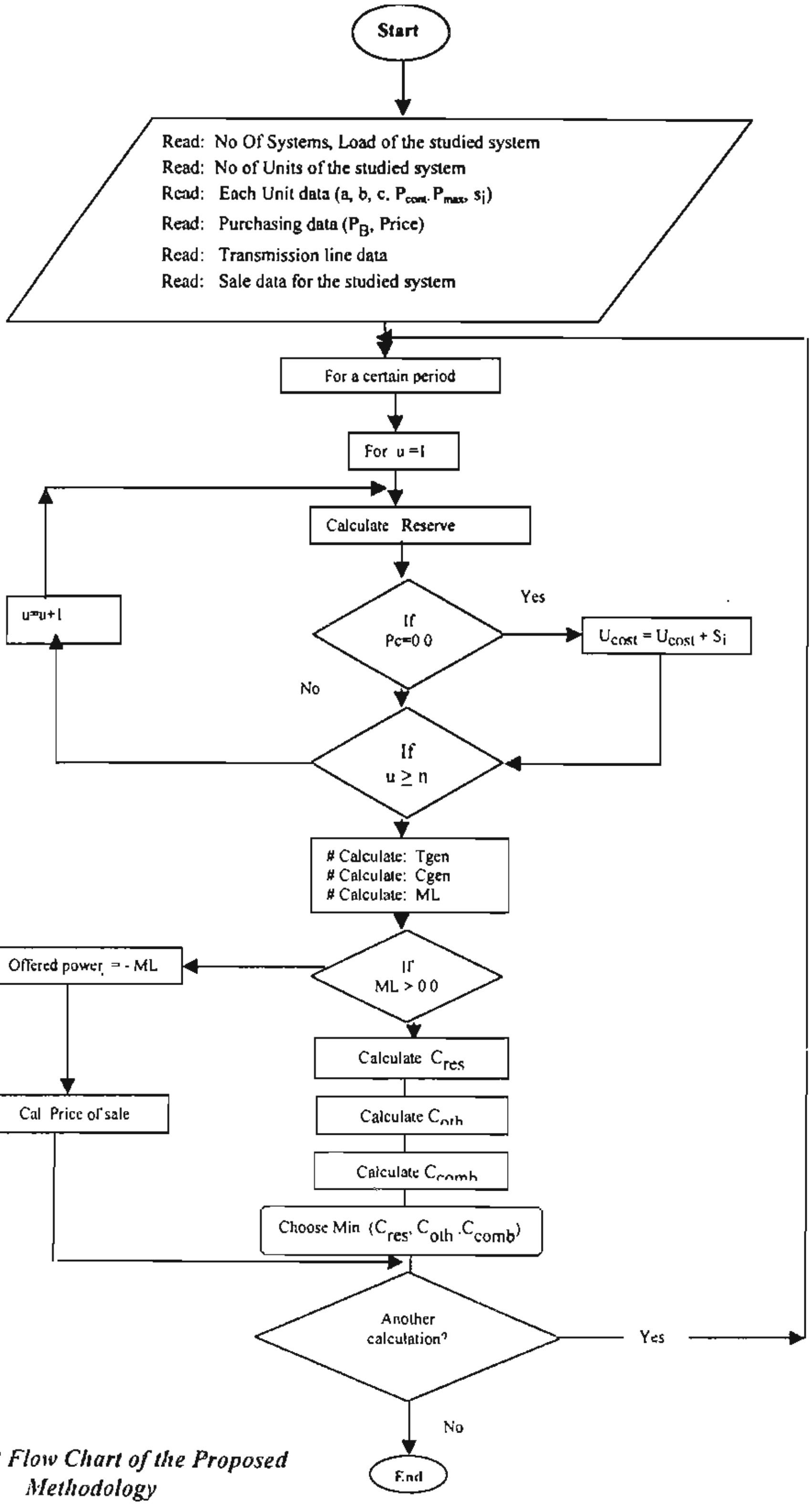

Fig.2 Flow Chart of the Proposed Methodology

Step 4:

- If $C_{gen} < L$ then

$$ML = L - C_{gen} \quad (15)$$

- Evaluate the cost of supplying missing load from studied system reserve

$$C_{res} = \sum_{i=1}^{n}[C(i) + S_i] = \sum_{i=1}^{n}[(a_i + b_i P(i) + c_i P(i)^2) + S_i] \quad (16)$$

- Estimate the minimum cost of supplying the ML from interconnection only

$$C_{oth} = C_B(j) = \sum_{j=1}^{N_B} \beta(j).P_B(j) = \sum_{j=1}^{N_B} \beta(j).ML \quad (17)$$

- Compute the minimum cost of supplying the missing load from a combination of system units' reserve and purchasing power from other systems.

$$C_{comb} = \sum_{i=1}^{n}[C(i) + S_i] + \sum_{j=1}^{N_B} \beta(j).P_B(j) \quad (18)$$

- **Then compare between (C_{res},C_{oth},C_{comb}) and choose the minimum one.**

Step 5:

- If $C_{gen} > L$ then the system can sell power to other systems during this period (off-peak period).

$$P_{Off} = C_{gen} - L \quad (19)$$

The price of selling this amount of power can be estimated according to Eq. (6) subjected to the constraints in Equations (11) and (12).

- **for new system calculation Go To Step 1**
  - **ELSE (Exit to Dos)**
- **END**

4- *Test Systems:*

The proposed methodology was implemented in **Borland C++** language, and the computer program is applied to the following two cases:

4.1 Purchase Case:

A test system is solved to check how efficient the proposed methodology is. The selected test system was solved before in Ref. [4], so that the results can be compared. The system consists of a five–bus utility with two local generators. Two independent utilities are interconnected with the studied system at busses 1 and 2. The topological connections, and capacity of lines are shown in Figure 3. The characteristics of the two local generators are shown in Table 1-a, whereas the offered power levels and prices are given in Table 1-b, for the two neighboring utilities.

Table 2, shows a comparison between the results obtained by the proposed computer program and that calculated by the method in [4]. The effect of the purchased power on the cost of supplying a certain load is illustrated in Figure 4.

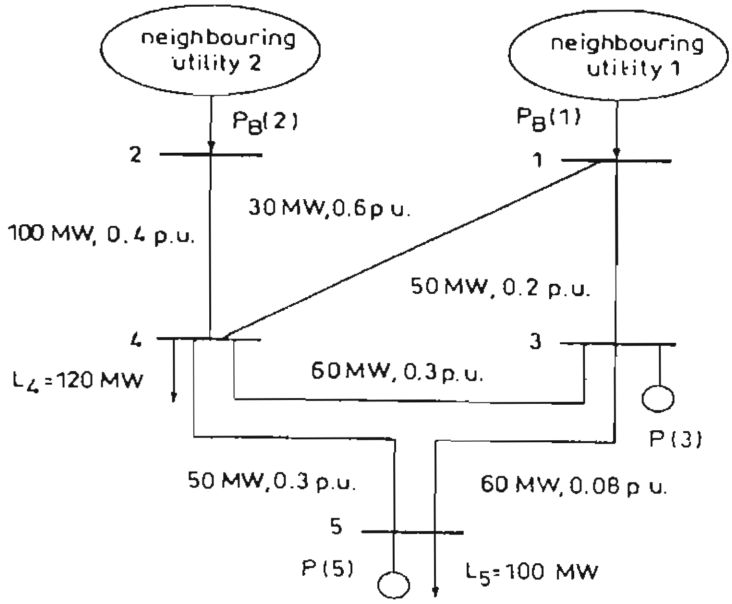

Fig. 3 Topological Connections of the Test System [4]

Table 1-a Characteristics of Local Generators

Bus no	a $/h	b $/MWh	c $/MW^{2}h	P_{max} MW	P_{cont} MW
3	0	1	0.008	130	0.0
5	0	3	0.015	110	0.0

Table 1-b Offered Power Levels and Prices

Offered In bus	λ_o $/MWh	λ_{max} $/MWh	P_B max MW	TL max MW
1	2.0	2.75	250	80
2	2.0	2.50	100	100

Table 2 Comparison Between the Proposed Computer Program and Another Method

	Method in Ref. [4]	Proposed computer program
P_B 1 (MW)	68.71	100.00
P_B 2 (MW)	91.28	32.00
P_g 3 (MW)	19.15	88.00
P_g 5 (MW)	42.05	00.00
FMC ($/h)	*550.58 ± 50.83*	*467.024*

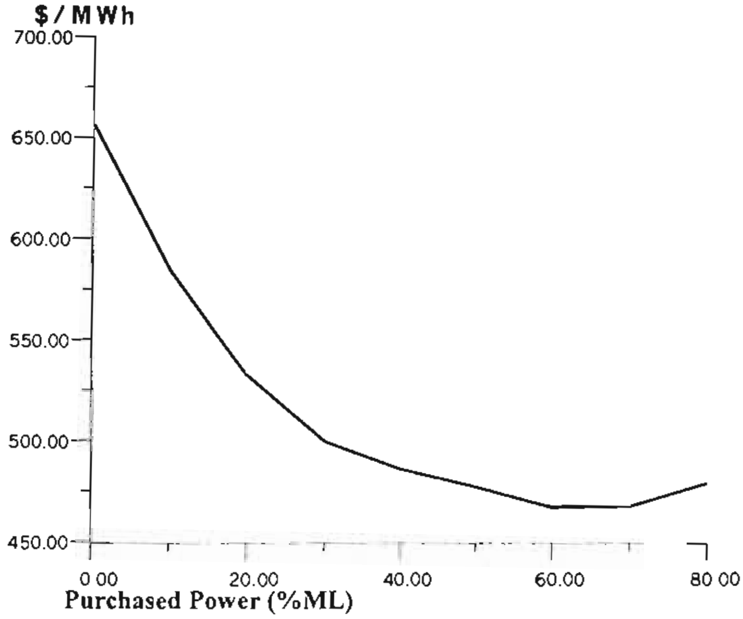

Fig. 4 Effect of Purchased Power on Cost of Supplying a Certain Load

Results analysis:

- From output of two methods the cost in Ref. [4] is ***550.58 $/h ± 50.83 $/h.*** and the cost of the proposed program is ***467.024 $/h,*** which mean that supplying the same load by the proposed program is more economic under the same condition and constraints.
- From Figure 4, the cost of supplying certain load is decreased as the purchased power is increased until certain value of purchased power at 70% from ML.

4.2 Sale Case:

To find the prices of surplus energy at different daytime the program is applied to a 10 units test system. The data for system's generating units and load pattern are given in Tables 3a, 3b and 3c [18]. Additional data are required to complete the calculation of estimated sale prices to other systems, these data are assumed as follows:

- Required spinning reserve is assumed as 10% of total available generation capacity at any time [5].
- The cost of unserved energy for both generation and transmission systems are 15 and 17.5 $/MWh respectively [18].
- Tie-line data that used in calculation of the losses through transmission lines are shown in Table 3-a.
- Ancillary services cost is assumed as 48% of production cost. [17]

The computer program is applied on the mentioned data at 24-hour load pattern shown in Table 3-c. The program determines the priority list of the studied system and calculates the reserve for each unit included in the system. In case that the system has surplus power (offered power), the program estimates the price of selling this amount of power to other interconnected systems. Table 4 illustrates the variation of the offered power and sale price with the system load and daytime.

Table 3-a Studied Area Generating Units Data

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
P_{max} MW	455	455	130	130	162	80	85	55	55	55
P_{min} MW	150	150	20	20	25	20	25	10	10	10
a $/h	1000	970	700	680	450	370	480	660	665	670
b $/MWh	16.19	17.26	16.6	16.50	19.70	22.26	27.74	25.92	27.27	27.79
c ¢/MW^2-h	0.048	0.031	0.200	0.211	0.398	0.712	0.079	0.413	0.222	0.173
Min up time (h)	8	8	5	5	6	3	3	1	1	1
Min down time (h)	8	8	5	5	6	3	3	1	1	1
Hot start up cost ($)	4500	5000	550	560	900	170	260	30	30	30
Cold start up cost ($)	9000	10000	1100	1120	1800	340	520	60	60	60
Cold start up hrs (h)	5	5	4	4	4	2	2	0	0	0
Initial status (h)	8	8	-5	-5	-6	-3	-3	-1	-1	-1

Table 3-b Transmission Lines Data

TL	Length (Km)	R_B (Ω/km)	MP_t ($/h)
TL connected between system 1 and the studied system.	100	0.0217	0.08
TL connected between system 2 and the studied system.	150	0.0122	0.16

Table 3-c Load Pattern

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Load MW	700	750	850	950	1000	1100	1150	1200	1300	1400	1450	1500

	13	14	15	16	17	18	19	20	21	22	23	24
	1400	1300	1200	1050	1000	1100	1200	1400	1300	1100	900	800

Results analysis

The system offered power variations with the day time according to the system load and available generation as shown in Figure 5. The offered power is minimum at hour 12 (peak time) and maximum at hour 1. The sale price is inversely proportional to the offered power as illustrated in Figure 6. Purchasing power at peak time (hour 12) make the generation to be more than 90% of its maximum capacity (an insecure case). The cost of generation quality is added to the price at this period, so that the price at this period is the greatest one of the day.

Table 4 Variation of the Offered Power and Sale Price with System Load and Daytime

Time (hour)	Load (MW)	Offered Power (MW)	Sale Price ($/MW)
1	700	962	19.98
2	750	912	20.16
3	850	812	20.50
4	950	712	20.93
5	1000	662	21.19
6	1100	562	21.91
7	1150	512	22.40
8	1200	462	22.97
9	1300	362	24.51
10	1400	262	27.05
11	1450	212	30.60
12	1500	162	49.93
13	1400	262	27.05
14	1300	362	24.51
15	1200	462	22.98
16	1050	612	21.49
17	1000	662	21.19
18	1100	562	21.91
19	1200	462	22.98
20	1400	262	27.05
21	1300	362	24.51
22	1100	562	21.91
23	900	762	20.70
24	800	862	20.32

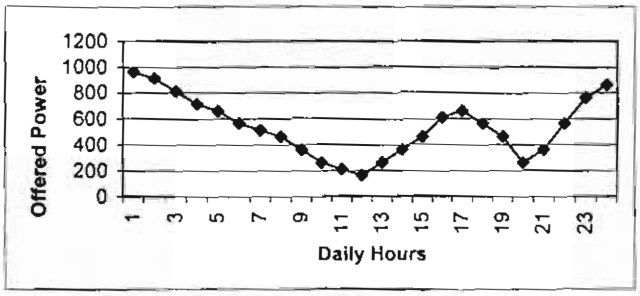

Fig. 5 Variation of Offered Power with Daytime

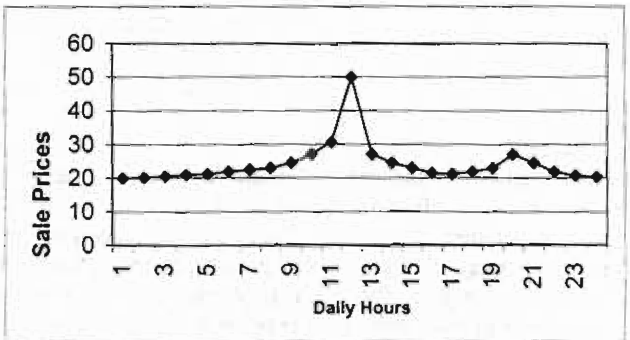

Fig. 6 Variation of Sale Prices with Daytime

5- ***Conclusions:***

This paper presents a computer-aided methodology to help the interconnected power systems' operators to achieve maximum benefits from interconnection by supplying the system load at minimum cost and selling its surplus power at maximum benefits.

A mathematical model and a computer program were developed based on most of the conditions and constraints listed in previous published models to fully simulate the behavior of interconnected power systems. It also performs economic dispatch and unit commitment for the studied system and estimate the priority list of its generating units.

Whenever the power system has a missing load, the program can calculate the minimum cost to supply that load by coordination between the system reserves and purchasing energy from other interconnected systems. On the other hand, at whatever time the system has surplus generation energy the program can detect the available power to be sold to other systems and calculate the prices of sale at different durations and power levels.

The computer program is applied to two test systems for both purchasing and selling cases. Compared with another published paper, the results obtained by the proposed program in purchasing case is more economic under the same condition and constraints. The costs of supplying a certain load is 467.024 \$/h compared to 550.58 \$/h ± 50.83 \$/h.

The program is then applied to a selling test system and calculate the sale prices at different offered power level and duration. The results show that the selling price is inversely proportional with the offered power. The system offered power varies with the day time according to the system load and available generation. Purchasing power at peak time may push the generation to an unsecure case so that a cost of generation quality must be added to the price at that period.

The importance of the presented computer program is that it can handle both purchase and selling cases so that it is an easy tool which can help the interconnected power systems' operators to take fast decisions.

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