ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 2, February 2014

Solving Environmental Power Unit Commitment with POZ Constraint Using Memetic Evolutionary Algorithm

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Abstract: A multi-objective ecological power unit commitment problem is developed to consider the objectives of minimizing the operation cost and minimizing the emissions from the generation units. In a vertically integrated power system, UC determines when to start up or shut down units and how to dispatch online generators over a given scheduling horizon in order to reduce the operating costs, satisfying the prevailing constraints such as load balance, system reserve requirement, ramp rate limits, and minimum up/down time limits and also minimizing the emission from the generating units. Prohibited operating zones in units are mostly due to mechanical or unit's physical issues and this should be included as constraint to unit commitment problem so that considerable amount of maintenance cost can be saved. In this paper to minimize the production cost, and minimize emission from the generating unit using memetic evolutionary algorithm.

Keywords*:* Unit commitment, Prohibited operating zone, Memetic evolutionary algorithm.

NOMENCLATURE

UC	Unit Commitment
POZ	Prohibited operating zone
$p_{i,t}^{0}$	Power output of unit i at hour t
$SU_{i,t}$	Start- up cost of unit i at time t
$SD_{i,t}$	Shut-down cost of unit i at time t
a_i, b_i, c_i	Fuel cost co efficient for unit i
HS_i	Hot start-up cost
CS_i	Cold start-up cost
$T_{i,t}^{D}$	Minimum down time of unit i
MD_i^{ON}	Duration during which the unit is continuously ON
MD_i^{OFF}	Duration during which the unit is continuously OFF
CST_i	Cold start time of unit i
D_i	Demand during hour t
$p_{i,t}^{min}$	Minimum power generation of unit i
$p_{i,t}^{max}$	Maximum power generation of unit i
$p_{i,j}^{Lower}$	Lower bounds of the jth prohibited zone of unit i
$p_{i,j}^{Upper}$	Upper bounds of the jth prohibited zone of unit i
PZ_i	Number of prohibited zones of unit i
SR_t	Spinning reserve requirement time t
RUR_i	Ramp-up rate limit of unit i
RDR_i	Ramp-down rate limit of unit i

I. INTRODUCTION

Unit Commitment (UC), refers to premeditated choice to be made in way to determine which of the available power plants should be considered to supply power. UC is not the similar to dispatching. Dispatching consists of appropriate a given set of power plants into a convinced power demand. UC decides the set of plants from which dispatching can be chosen. The difference between both issues occurs in time. In [1] dispatching and allocating decisions, there is practically no time to rapidly start a power plant because the inertia of most plants will not allow this. UC therefore prepares a set of plants and stipulates in which time period they have to be on-line and ready for dispatching.

In [2], UC chooses plants taking into account a wide variety of parameters, technological aspects(such as minimum operating point, start-up and shut-down operation time and transient behavior) as well as economic considerations (such as start-up costs and operational costs) and social elements (such as availability of staff and work-schemes).However latter can be neglected sometimes. UC optimization helps to minimize electricity generation costs.

For utilities,[3][4] UC is a problem that is to be solved in time period of one day up to one week. The power systems these utilities need to optimize are usually limited to ten to fifty power plants. Most UC models have been developed for these types of utilities and therefore concentrate on short term UC of relatively smaller power systems. In [6], the broader context of energy, electricity or environmental modeling, however both the power systems and the time period considered are much larger.

In [7], such models (used for, e.g., the calculation of the emissions or the energy use of a country), UC is not the main objective. In order not to have a disproportional impact on the overall calculation time, a UC bottleneck in the model should be avoided. Therefore, a proper choice between accuracy and the utility of UC in the overall calculation time is to be made [10]-[18].

II. PROBLEM FORMULATION

The unit commitment problem (UCP) in power system is defined as determining the start-up and shut-down schedules of units to meet the forecast load demand and spinning reserve over a arrangement period so that the total production cost is minimized while satisfying various system and unit constraints.

The main issues in the UCP are complexity (high dimensions) of search space, generation of initial feasible schedules, generation of trial solutions, minimum up and down time and spinning reserve constraint handling, calculations of non linear economic dispatch sub problem, handling of non convexity in economic dispatch sub problem due to valve point effects.

A major source of infeasibility is the generation of infeasible schedules, which have to be unnecessary immediately. Another major source of infeasibility in feasible solutions is the violation of nonlinear minimum up/down-time constraints, which has to be checked and repaired. By considering the minimum up and down time constraints the operating fuel cost rises and an alternate solution needs to found. The unit commitment schedule is based on forecasted load and spinning reserve requirements.

The spinning reserve constraint also changes the on/off schedule of units; more units are to be operated to satisfy this constraint. These constraints introduce problems and complicate the unit commitment problem.

III. OBJECTIVE FUNCTION

UC involves determining the generation outputs of all of the units from an initial hour to satisfy the load demands related with a start-up and shut-down schedule over a time horizon. The objective is to find the most favourable schedule, such that the total operating costs can be minimized while satisfying the load demand, spinning the reserve requirement as well as other operational constraints.

The outage cost as well as the fuel cost of the generation units should be considered in power system operation as an objective function of a UC problem.

The objective function is a function that comprises the fuel costs of the generating units, the start-up costs of the committed units, and the shut-down costs of the recommitted units. The start-up cost is presented in 2 schemes, hot start-up costs (HSCs) and cold start-up costs (CSCs), while the shut-down cost is assumed. The objective function in common form is expressed by

$$\text{Minimize} \quad \{\sum_{t=1}^{T}\sum_{t=1}^{N} F_{i,t}\left(P_{i,t}^{0}\right) + u_{i,t} \\ +\sum_{t=1}^{T}\sum_{t=1}^{N} SUC_{i,t} * u_{i,t} * (1 - u_{i,t-1}) \\ +\sum_{t=1}^{T}\sum_{t=1}^{N} SDC_{i,t} * u_{i,t-1} * (1 - u_{i,t})\} \qquad (1)$$

Here, $P_{i,t}^{0}$ is the power output of unit i at hour t, $u_{i,t}$ is the on or off status of unit i at hour t, $\mathrm{SUC_{I,T}}$ and $\mathrm{SDC_{I,T}}$ are respectively the start-up cost and the shut-down cost of unit i at time t, N is the number of units, and T is the UC horizon.

The fuel costs of the generating units and the major components of the operating costs for the thermal units are generally given in a quadratic form, as is shown in Eq. (2). Operating cost coefficients can be given or they might be estimated using bidding strategies.

$$F_{i,t}\left(P_{i,t}^{0}\right) = a_i + b_i p_{i,t}^{0} + c_i (P_{i,t}^{0})^2 \qquad (2)$$

Here, a_i, b_i, c_i are fuel cost coefficients for unit i.

The start-up cost is defined as follows:

$$SUC_{i,t} = \{\, HSC_i,\ if \quad T_{i,t}^{D} \le MD_i^{ON} \le T_{i,t}^{D} + CST_i \\ CSC_i,\quad if \quad MD_i^{ON} > T_{i,t}^{D} + CST_i \} \qquad (3)$$

IV. OPERATIONAL LIMITATION AND CONSTRAINTS

The minimization of the objective function is subjected to a number of system and unit constraints, such as power balance, spinning reserve capacity of the generating units, prohibited operating zones (POZs), and minimum up/down time limit, as well as spinning reserve requirement. The initial conditions need to be considered in the scheduling problem.

A. Initial conditions

The initial conditions of the generating units include the number of hours that a unit has consequently been online or offline and its generation output at an hour before the scheduling.

B. Power balance constraint

$$\sum_{i=1}^{N}(P_{i,t}^{0}) * u_{i,t} = D_i \qquad 1 \le t \le T, i \in N \qquad (4)$$

Here, D_i is the demand during hour t.

C. Unit output limit

$$P_{-i,t} * u_{i,t} \le P_{i,t}^{0} * u_{i,t} \le P_{i,t}^{-} * u_{i,t} \qquad (5) \\ 1 \le t \le T,\ i \in N$$

Here, $P_{-i,t}$ and $P_{i,t}^{-}$ are the minimum generation and maximum generation of unit i, respectively.

D. Spinning reserve

Spinning reserve is the term used to describe the total amount of generation available from all units synchronized on the system, minus the present load and losses being supplied. Spinning reserve must be carried so that the loss of one or more units does not cause too far a drop in system frequency. Quite simply, if one unit is lost, there must be ample reserve on the other units to make up for the loss in a specified time period.

Spinning reserve must be allocated to obey certain rules; reserve must be capable of making up the loss of most heavily loaded unit in a given period of time. Other calculates reserve requirements as a function of the probability of not having sufficient generation to meet the load.

Unit commitment problem may involve various classes of scheduled reserves or off-line reserves. These include quick start diesel or gas turbine units as well as most hydro-units and pumped-storage hydro-units that can be brought on-line, synchronized, and brought up to full capacity quickly.

$$\sum_{t=1}^{N}\left(P_{i,t}^{-}\right) * u_{i,t} \ge D_t + SR_t \qquad 1 \le t \le T,\ i \in N \qquad (6)$$

Here, SR_t is the spinning reserve requirement at time t.

E. Prohibited operating zone

Some online generating units have generation limits, which cannot be exceeded at any time. Moreover, a typical thermal unit may have a steam valve in operation or a vibration in a shaft bearing, which may result in interference and discontinue the input/output performance-curve sections, called the POZ, as shown in Figure 4.1

Therefore, in practical operation, adjustment of the generation output of a unit must avoid all capacity limits and unit operations in the POZ.

The feasible operating zones of a unit can be described as follows:

$$P_i \leq P_i^0 \leq P_{i,1}^{Lower}$$
$$P_{i,j-1}^{Upper} \leq P_i^0 \leq P_{i,j}^{Lower} \quad ,j = 2,\ldots.,PZ_i \qquad (7)$$
$$P_{i,PZ_i}^{Upper} \leq P_i^0 \leq P_i^-$$

Where $P_{i,j}^{Lower}$ and $P_{i,j}^{Upper}$ are the lower and upper bounds of the j th prohibited zone of unit i , and PZ_i is the number of prohibited zones of unit i.

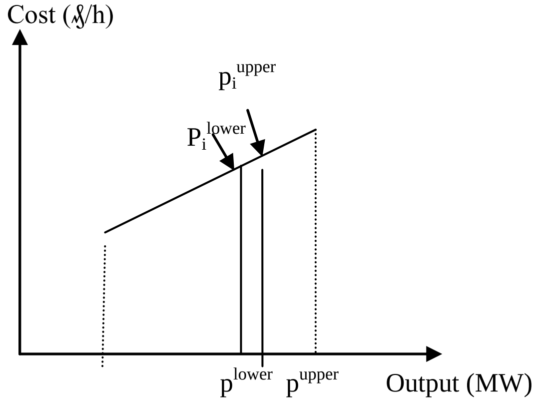

Fig.4.1 Prohibited operating zones and output limit of a generator

F. Minimum up time limit

The minimum up time limit is the minimum number of hours that a unit must be continuously online since it has been turned on.

$$MD_i^{ON} \geq T_i^U \qquad (8)$$

Here, MD_i^{ON}, is the duration during which the ith unit is continuously on.

G. Minimum down time limit

The minimum down time limit is the minimum number of hours that a unit must be continuously offline since it has been turned off.

$$MD_i^{OFF} \geq T_i^D \qquad (9)$$

Here, MD_i^{OFF}, is the duration during which the ith unit is continuously off.

H. Unit ramp-up constraint:

$$P_{i,t}^0 \leq P_{i,t}^-$$
$$P_{i,t}^- = min\{P_{i,t}^0 + RUR_i, P_i^-\} \qquad (10)$$
$$1 \leq t \leq T \ , i \in N$$

Here, RUR_i, is the ramp-up rate limit of unit i.

I. Unit ramp-down constraint

$$P_{-i,t} \leq P_{i,t}$$

$$P_{-i,t} = max\{P_{i,t-1}^0 + RDR_i, P_{-i}\} \qquad (11)$$
$$1 \leq t \leq T \ , i \in N$$

Here, RDR_i is the ramp down rate limit of unit i.

J. Crew constraints

If a plant consists of two or more units they cannot both be turned on at the same time since there are not enough crew members to attend both units while starting up.

K. Must run

Some units are given a must run status during certain times of the year for reason of voltage support on the transmission network or for such purposes as supply of steam for uses outside the steam plant itself.

L. Emission functions

Certain emissions (e.g SO_2 and CO_2) are directly related to the fuel consumed and, as such, are the products of the unit fuel I/O equation and an emission factor. Hence, in this paper we are using a second order emission function for SO_2 and CO_2,

$$E_{jit} = e_{fij}[K_{01} + P_{it}K_{1i} + P_{it}^2 K_{2i}] \qquad (12)$$

The emission factor e_{fij} is often estimated because of the lack of actual measurements.

A .Table of Emission factors for NO_X, SO_2, CO_2 for several type of units

S.No	**Power Generating unit**	**NO_X**	**SO_2**	**CO_2**
1	Coal conventional	100-330	60	94
2	IGCC	110	30	94
3	Combined cycle	80-180	-	56
4	Gas conventional	90-130	-	56
5	Gas turbine	90-220	-	56
6	Blast furnace gas	115-220	20	100

A reduced cubic equation is used to model the NO_X emission output.

$$E_{jit} = [B_{0ij} + B_{1ij}P_{it} + B_{2ij}P_{it}^2 + B_{3ij}P_{it}^3] \qquad (13)$$

Where b_{og}, b_{lij}, b_{2ij}, b_{3ij} are polynomial emission coefficients for unit i.

$$E_{up,i} = e_{0,ji} + e_{1,ji} + (1 - e^{T_{di}/\tau_i}) \qquad (14)$$

Where the $e_{0,ji}$ and $e_{1,ji}$ are the start up coefficient for pollutant j from unit i. Emission of pollutant j during shut-down of unit i is represented by a constant $E_{d,ij}$ In principle any other representation may be included, e.g., $E_{d,ji}$ may be a function of P_{it}.

M. Emission constrained solution

The multipliers λ_t, μ_t, γ_j corresponding to electricity demand and spinning reserve for t=1,2,..., T, and emission constraints for j=1,2 ,... J respectively, and imbed the constraints into the Lagrangian objective L is,

$$L = C_{tot} + \sum_{t=1}^{T} \lambda_t (D_t - \sum_{i=1}^{n} P_{it})$$
$$+ \sum_{t=1}^{T} \mu_t (R_t - \sum_{i=1}^{n} r_{it}) \qquad (15)$$
$$+ \sum_{j=1}^{J} \gamma_t \left[\sum_{t=1}^{T} \sum_{i=1}^{n} \left(E_{jit} + E_{up,ij} + E_{d,ji}\right) - E_{j,tot}\right]$$

Lagrangian relaxation algorithms maximize the dual iteratively. During every iteration, the multipliers are considered in given parameters, and the Lagrangian function L is minimized with respect to the unit dispatch and commitment variables and subject to local unit constraints. In the iterative process, it is recognized that the dual function is separable with respect to each unit.

Max! Q (λ,μ,γ) = Max [Min(L)!] (16)

The dual sub problem Q_i (λ,μ,γ) involving only the i'th unit, may be interpreted as the i'th unit's profit maximization when it sees the price vectors (λ,μ,γ). The procedure for a base or must-run unit is very simple since the commitment schedule is given. This problem is stated as to find the generator outputs subject to multipliers. The dual sub problem for peak or cycling units is more complex since the unit commitment variables are part of the optimization process. However, the problem can be efficiently solved by analytical techniques and dynamic programming. Since there are n units, n unit sub problems must be solved.

After the n sub problems are solved, the multipliers should be updated and Q reevaluated. A simple formula for updating the multipliers is based on the sub gradients of the dual objective. The term sub gradient stem from the fact that Q is not differential everywhere as Q is in general non-smooth. The sub gradients can be formed as a vector of the differences between the right-hand and left-hand sides of the coupling constraints:

$$\frac{d}{d\lambda_t} Q\,(\lambda, \mu, \gamma) = D_t - \sum_{i=1}^{n} P_{it} = \Delta D_t \qquad (17)$$

$$\frac{d}{d\mu_t} Q\,(\lambda, \mu, \gamma) = R_t - \sum_{i=1}^{n} r_{it} = \Delta R_t \qquad (18)$$

Convergence on maximizing the dual can be ensured by updating the multipliers on the k'th iteration by using the form

$$\lambda_t^{k+1} = \lambda_t^k + \beta_1 \Delta D_t^k \qquad (19)$$

$$\mu_t^{k+1} = \mu_t^k + \beta_2 \Delta R_t^k \qquad (20)$$

$$\gamma_t^{k+1} = \gamma_t^k + \beta_1 \Delta E_t^k \qquad (21)$$

where (β_1, β_2, β_3) are step sizes,

Feasibility the dual maximization does not generally yield a unit commitment schedule that is primal feasible. That is, one or more of the coupling constraints, given by demand, reserve or emission constraints, are violated.

The approach consists of the following steps:

1. Data input, initialize Lagrangian multipliers and Q.
2. For the given set of multipliers, solve the unit dual problem,
3. Feasibility test; If the dual solution is primal feasible go to step 5. If no, update multipliers according sub gradients, and go to step :2
4. Primal feasible solution. Perform emission constrained dispatch to find power outputs and marginal costs. Calculate primal objective.
5. Convergency test; is the duality gap within specified limit? If yes go to step 7, if no go to step 6.
6. Update multipliers using values from the emission constrained dispatch
7. Solution found. Stop.

The initial values for multipliers are obtained by using the heuristic unit-commitment algorithm, where sufficient capacity is committed according to a priority list. Multipliers (μ, λ) are set to zero. Emission dispatch constraints $E_{d,j}$ are calculated by subtracting emissions during start

$$\lambda_{sys,t} = \frac{\partial}{\partial P_{it}} \left[C_{it} + \sum_{j=1}^{J} \gamma_{dj}\, E_{ijt} \right] \qquad (22)$$

Then, the resulting emissions are calculated and compared to the emission dispatch constraints.

V. SOLUTION METHOD

A. *Memetic Evolutionary Algorithm*

Evolutionary algorithms can be regarded as the replication of the natural development process in computer. They also belong to probabilistic algorithms, but the searching solution is found by a inhabitants, not by an individual. From an primary population, we can apply genetic operators (selection, crossover, and mutation) to create new folks which inherit the previous generation's properties and have new properties, then select good individuals for the next production. Hence, one of the important factors of algorithm is to keep the multiplicity of the population. In the genetic operators, only intersect and mutation create new individuals. However, algorithms use the different operators as their main evolutionary workhorse; GA specially cares about crossover whereas ES mainly uses mutation.

The algorithm that can be regarded as the permutation between GA and ES called Blend Evolutionary Algorithm (BEA). Similarly as GA and ES, this algorithm has many superior properties particularly it still maintains the variety of the population. Moreover, BEA has more benefit properties than that of GA and ES.

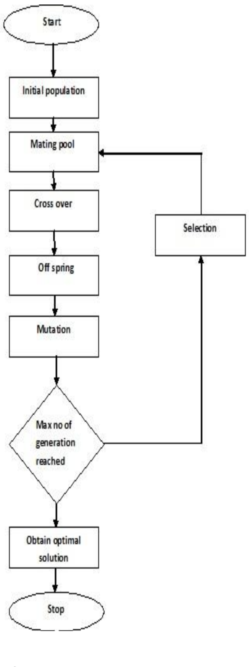

Fig.5.1Flowchart of Memetic Evolutionary algorithm

This algorithm uses both crossover and mutation in two phases. First crossover operator performs M times, two parents create only one adolescent, which is added in halfway population.

VI. RESULTS AND DISCUSSION

A. *Table of Unit characteristics and cost coefficients of a 10-unit base problem*

unit no	Pmax	Pmin	a	b	c	TU	TD	HSC	CSC	CST	UNIT CONDITION	POZ
1	455	150	100	16.19	0.00048	8	8	9000	4500	5	8	[150 165], [448 453]
2	455	150	970	17.26	0.00031	8	8	10000	5000	5	8	[90 110], [240 250]
3	130	20	700	16.6	0.002	5	5	1100	550	4	-5	
4	130	20	680	16.5	0.00211	5	5	1120	560	4	-5	
5	162	25	450	19.7	0.00398	6	6	1800	900	4	-6	
6	80	20	370	22.26	0.00712	3	3	340	170	2	-3	
7	85	25	480	27.74	0.00079	3	3	520	260	2	-3	
8	55	10	660	25.92	0.00413	1	1	60	30	0	-1	[20 30],[40,45]
9	55	10	665	27.27	0.0022	1	1	60	30	0	-1	
10	55	10	670	27.79	0.00173	1	1	60	30	0	-1	[12 17],[35,45]

B.*Table of Load demand of the 10-unit base problem*

HOUR	1	2	3	4	5	6	7	8	9	10	11	12
LOAD	700	750	850	950	100	1100	1150	1200	1300	1400	1450	1500
HOUR	13	14	15	16	17	18	19	20	21	22	23	24
LOAD	1400	1300	1200	1050	1000	1100	1200	1400	1300	1100	900	800

C.*Table of Simulation Output of Operation Cost, Schedule and Emission for 24 Hours in 10 Unit System with POZ constraint*

OPERATION COST, SCHEDULE AND EMISSION FOR 24 HOURS IN 10 UNIT SYSTEM															
HOURS	**POWER DEMAND (MW)**	**POWER GENERATION OF UNITS (MW)**										**GENERATION COST (Rs)**	**START UP COST (Rs)**	**EMISSION OUTPUT (Kg)**		
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**			**NOx**	**SO_2**	**CO_2**
1	700	455	245	0	0	0	0	0	0	0	0	615740.84	0.0	14343.1	13803.1	13871.1
2	750	455	295	0	0	0	0	0	0	0	0	654952.49	0.0	15214.5	14674.5	14742.5
3	850	455	395	0	0	0	0	0	0	0	0	733585.04	0.0	16961.9	16421.9	16489.9
4	950	455	365	0	130	0	0	0	0	0	0	838695.63	25200.0	19627.7	18817.7	18919.7
5	1000	455	390	0	130	25	0	0	0	0	0	900900.88	40500.0	21340.0	20260.0	20396.0
6	1100	455	455	0	130	40	20	0	0	0	0	1002436.86	7650.0	29326.4	22576.4	22746.4
7	1150	455	455	0	130	90	20	0	0	0	0	1047926.01	0.0	24937.2	23587.2	23757.2
8	1200	455	455	0	130	115	20	25	0	0	0	1123836.12	11700.0	26954.1	25334.1	25538.1

9	1300	455	455	0	130	162	63	25	0	10	0	1254256.42	2700.0	30182.4	28292.4	28530.4
10	1400	455	455	0	130	162	80	85	0	33	0	1375520.09	0.0	32877.1	30987.1	31225.1
11	1450	455	455	130	130	162	80	28	0	10	0	1405945.77	24750.0	33883.2	31723.2	31995.2
12	1500	455	455	130	130	162	80	78	0	10	0	1468549.18	0.0	35274.4	33114.4	33386.4
13	1400	455	455	130	0	162	43	25	0	0	0	1321467.68	0.0	31675.9	29785.9	30023.9
14	1300	455	455	130	0	162	73	25	0	0	0	1223904.02	0.0	29177.9	27557.9	27761.9
15	1200	455	455	130	0	95	20	25	0	10	10	1191400.02	5400.0	29115.6	26955.6	27227.6
16	1050	455	455	130	0	55	20	25	0	10	10	1072779.16	0.0	26479.5	24319.4	24591.5
17	1000	455	455	130	0	53	20	25	0	10	10	1035416.60	0.0	25649.3	23489.3	23761.3
18	1100	455	455	130	0	25	20	25	0	10	0	1070446.81	0.0	26097.7	24207.7	24445.7
19	1200	455	455	130	130	25	20	0	0	10	0	1142610.58	25200.0	27701.3	25811.3	26049.3
20	1400	455	455	130	130	162	0	0	55	13	0	1348631.47	2700.0	32279.6	30389.6	30627.6
21	1300	455	455	130	130	110	0	0	10	10	0	1243280.33	0.0	29938.5	28048.3	28286.5
22	1100	455	455	0	130	50	0	0	0	10	0	1016857.38	0.0	24246.8	22896.8	23066.8
23	900	455	455	0	130	25	0	25	10	0	0	897587.69	14400.0	21926.4	20306.4	20510.4

24	800	455	455	0	0	52	0	25	0	0	10	792120.15	2700.0	19252.7	17902.7	18072.7
Total											25778847.23		162900	619063	581263	586023

VII. CONCLUSION

In this method POZ, as a realistic constraint, has also been considered. The Proposed method has been successfully applied to a standard 10-unit system and a 10-unit system considering the POZ satisfactory results were compared with the other methods reported in the literature. There will be savings in the production cost if POZ constraint is considered because if unit operates in POZ region, maintenance cost would be very high that totally affects the production cost. POZ constraint also should be considered for economic operation of the units.

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