Short Term Active/Reactive Operation Planning in Market Environment using Simulated Annealing

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Abstract**-- This paper addresses the short-term allocation of active/reactive power supplies in transmission systems in a market environment. The basic issue addressed by most papers is related to market mechanisms involving active power either in terms of a pool or by bilateral contracts. However, in several countries Volt/Var control started to be considered, at least partially, as a marketable service and so new methodologies are required to support this process. This paper presents an integrated mathematical formulation for the active power dispatch using bids from market agents and inherently taking into account the local nature of Volt/Var control by considering an AC model for the network. The discrete operation of several components as transformer taps and capacitor sections are accurately taken care by using Simulated Annealing. The proposed methodology is applied on the 30-bus IEEE test system highlighting its advantages and demonstrating the feasibility of its use in real systems.**

Index Terms**-- Ancillary Services, Volt/Var control, electricity markets, Simulated Annealing.**

I. Introduction

The operation of powers systems is not restricted to the dispatch of active power but includes a number of other issues known as ancillary services. Among them, these include the selection of primary, secondary and tertiary reserve levels, Volt control and reactive support, black start, teleregulation, etc. In several systems, some of these services, as secondary and tertiary reserves, are allocated using market procedures. Some others are considered as mandatory, that is, they must be provided according to the requirements of the ISO if generators want to participate in the active power market.

In the last years, several approaches were developed in order to enable the use of market procedures to allocate Volt control and reactive support [1-4]. These papers clearly identify the difficulties of contracting reactive power using market mechanisms arising from its local nature and its impacts on the voltage profile, on the operation points of generators and on the branch flows, eventually leading to the need to curtail active power transactions. All in all, these papers reveal the coupling between active and reactive power, and in some way stress the idea that active power markets and reactive power control should be treated as a whole. Some other papers, try to evaluate reactive power short term marginal prices [5, 6]. In [7] a number of approaches to reactive power allocation are proposed as the use of performance requirements for generators and reactive loads, the use of generation costs of synchronous capacitors to price reactive power supplied by other generators or capacitors and the development of local reactive power markets as a way to deal with the local nature of Volt/Var control.

More recently, the discrete nature of the problem, in terms of transformer taps and capacitor banks, was recognized leading to the use of Meta-Heuristics as Simulated Annealing and Genetic Algorithms [8-13].

This paper provides an integrated solution to the active/reactive scheduling problem using Simulated Annealing. Section II provides an overview of Simulated Annealing. In Section III, the mathematical formulation of the short term active/reactive operational planning is defined. This formulation uses bids for active power, incorporates the AC power flow equations, minimum and maximum voltage constraints and integer variables representing transformer taps and capacitor sections. Section IV describes the practical solution algorithm using Simulated Annealing. This means the final solution preserves the coupling between active and reactive power while it does not require any kind of approximations to deal with integer variables. Section V presents results obtained using the IEEE 30-bus test system and Section VI provides conclusions.

II. Simulated Annealing – An Overview

Several real life problems have a high degree of complexity, frequently related with the combinatorial nature of several variables. In most cases, this turns it unpractical to identify the optimal solution using traditional optimization tools. In most of these cases, one is often looking for a good solution, a solution that improves current practices or a satisfactory solution given some quality index. This is the main

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reason for using algorithms integrated in what is called Meta-heuristics. These algorithms are generally very easily implemented and very flexible in terms of the constraints to be considered or the variables to model. Meta-heuristics include algorithms as Simulated Annealing, Tabu Search, Genetic Algorithms and Neural Networks. In this paper we used Simulated Annealing as a way to balance obtaining credible results for the problem while ensuring a large flexibility of the approach, the objective function, constraints and variables.

Simulated Annealing was originally developed by Kirkpatrick et al [14] based on the Metropolis algorithm first presented in 1953. The basic idea of Simulated Annealing is based on an improved search procedure in the sense that one moves from one solution to another provided that there is an improvement of the value of the evaluation function (EF) of the problem. However, in an attempt to escape from local optima, one can transitorily relax the optimality condition in the sense that in some iterations one can accept solutions having a worse value of the evaluation function. In a graphical way, this process is illustrated in Fig. 1.

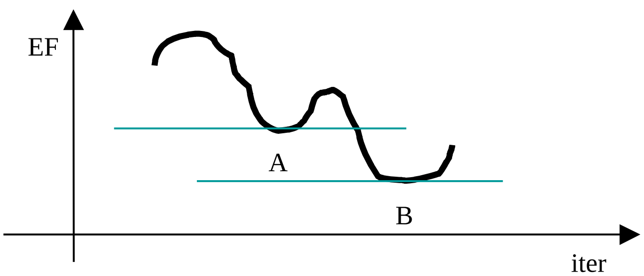

Fig. 1. Illustration of an optimization process with local optima.

If the objective function has local optima, several gradient based optimization techniques will be trapped in valleys as the one related with point A. Apart from that, the final solution can depend on the departure point. Specially in the beginning of the process, Simulated Annealing can accept worse solutions as an attempt to escape from A and eventually try to reach a more promising search area as the one related with B.

Simulated Annealing has a clear analogy with the cooling process of thermodynamic systems, TS. The possibility of reaching pure systems, or low energy systems, strongly depends on how temperature is lowered. The system must be cooled in a very slow pace so that particular subsystems have time to reorganize themselves leading to a low energy system. In this sense, there is an analogy between TS and a combinatorial problem, CP, whose evaluation function is subjected to a minimization process. Solutions, combinations or alternatives of the CP correspond to states in the TS. The energy of the TS corresponds to the evaluation function of the CP and the temperature of the TS corresponds to the control parameter of the CP. Using these analogies and aiming at minimizing a function *f*, the algorithm evolves as follows.

1. Initialization: Select an initial solution x_1 in the solution space *X*;
2. Evaluate x_1, $f(x_1)$;
3. Assign x_1 to x^* and $f(x_1)$ to $f(x^*)$. The sign * denotes the best solution identified until this step;
4. Step n=1, 2,…, n. x_n denotes the current solution at iteration n. Obtain a new solution x by using a sampling process on the neighborhood of x_n.
5. Testing:
   if $f(x) \leq f(x_n)$ then assign x to x_{n+1};
      if $f(x) \leq f(x^*)$ then assign
         x to x^* and $f(x)$ to $f(x^*)$;
   else
      get a random number p in $[0.0;1.0]$;
      evaluate the probability of accepting worse solutions at iteration n, $p(n)$ by

$$p(n) = e^{\frac{f(x_n) - f(x)}{K \cdot Temperature}} \quad (1)$$

      if $p \leq p(n)$ then assign x to x_{n+1};
6. End if a stopping rule is reached.

In expression (1) *K* is the Boltzman constant

At this point it is important to make some comments:

- in the first place, the identification of a new solution in the neighborhood of the current one can be achieved very easily in the case of discrete problems. As an example, just consider minimizing transmission losses in a network by changing transformer taps or capacitor banks. One can start at a solution on which all these components are at the nominal position. At a given iteration, a new solution can be obtained by sampling one of those components, and then by sampling a move of its tap upwards or downwards;
- the cooling process must be slow. Initially the temperature will be high leading to a larger probability of accepting worse solutions. This means that at the beginning the search is more disorganized in order to inspect more areas of the solution space. As the search goes on, the temperature is lowered and this turns it more difficult to accept worse solutions;
- the temperature is kept constant during a number of iterations. This is usually known as length of plateau. Once a plateau is finished, the current temperature is lowered by multiplying it by a constant α inferior but close to 1.0;
- finally, the process can be stopped if a minimum temperature was reached or if there was no significative improvement of the evaluation function for a specified number of iterations.

III. Mathematical Formulation

In this section we present a mathematical formulation of the short term active/reactive operation planning problem, considering bids for active generation while preserving the discrete nature of the problem in terms of transformer taps, start up costs and capacitor banks. Apart from that, the formulation includes the AC power flow equations and constraints related to voltage ranges, branch current thermal limits and apparent power generator limits.

A. Bid Format

It is assumed that each participant generator could submit a number of (EURO/MWh, MW) pairs, forming an offer curve such as in Fig. 2.

To transform the whole problem to an integer one, we assume that the active power injections are not represented by continuous variables but they increase or decrease by a pre-selected increment \ decrement accuracy (step). The selected accuracy should be selected to obtain a good final solution and to ensure an adequate power flow running. Thus, the available active power steps for each generator can be:

$$\left[0, P_{bid,i}^{\min}, P_{bid,i}^{\min}+1\cdot acc, P_{bid,i}^{\min}+2\cdot acc, ..., P_{bid,i}^{\min}+s\cdot acc = P_{bid,i}^{\max}\right]$$

where

acc is the accuracy in MW;

s is the number of the steps resulting from:

$$s = \left(P_{bid,i}^{\max} - P_{bid,i}^{\min}\right)/acc$$

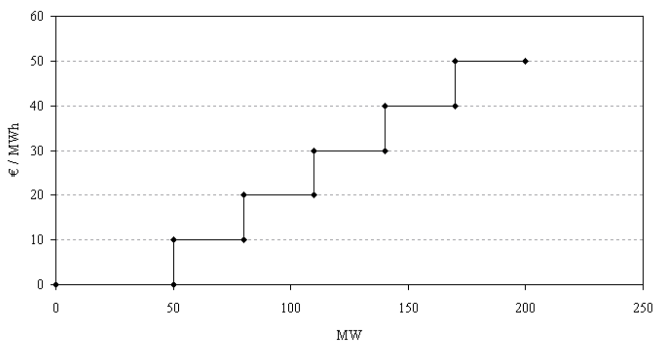

Fig. 2. Typical bid structure

B. Objective Function

The following objective function is considered:

$$\min \quad C_T^t = \sum_{i=1}^{N} C_i^t(P_{gi}^t) \tag{2}$$

where:

C_T^t : total cost

C_i^t : active power cost of the unit at bus i

P_{gi}^t : active power generation of unit at bus i

t : time interval

C. Constraints

The problem incorporates linear/nonlinear constraints related with voltage, flows, real generation, reactive sources, and transformer taps as follows:

$$P_{gi}^t - P_{di}^t - FP_i^t(V,\delta,ts_r,cb_c) = 0 \tag{3}$$

$$Q_{gi}^t - Q_{di}^t + cb_c^t - FQ_i^t(V,\delta,ts_r,cb_c) = 0 \tag{4}$$

$$\sum_{i=1}^{N} P_{gi}^t - \sum_{i=1}^{N} P_{di}^t - P_L^t(V,\delta,ts_r,cb_c) = 0 \tag{5}$$

$$P_{bid,i}^{\min,t} \le P_{gi}^t \le P_{bid,i}^{\max,t} \tag{6}$$

$$Q_{gi}^{\min} \le Q_{gi}^t \le Q_{gi}^{\max} \tag{7}$$

$$\sqrt{\left(P_{gi}^t\right)^2 + \left(Q_{gi}^t\right)^2} = S_i^t \le S_i^{\max} \tag{8}$$

$$cb_c \in \{cb_{c1}, cb_{c2}, cb_{c3}, ...\} \qquad c \in VAr\ sites \tag{9}$$

$$ts_r \in \{ts_{r1}, ts_{r2}, ts_{r3}, ...\} \qquad r \in TBR \tag{10}$$

$$V_i^{\min} \le V_i^t \le V_i^{\max} \tag{11}$$

$$\left[(V_i^t)^2 + (V_j^t)^2 - 2V_i^tV_j^t\cos(\delta_i^t - \delta_j^t)\right]/Z_l^2 \le I_l^{\max}, l \in NBR \tag{12}$$

where

N: the total number of buses

t : time interval

P_{di}^t : real power demand at bus i

Q_{gi}^t : reactive power injection at bus i

Q_{di}^t : reactive power demand at bus i

$FP_i^t(V,\delta,ts_r,cb_c)$: active power flow from bus i

P_L^t : active power losses

cb_c^t : the available capacitive Var support of capacitor banks

ts_r^t : the available transformer's taps positions.

$FQ_i^t(V,\delta,ts_r,cb_c)$: reactive power flow from bus i

$P_{bid,i}^{\min,t}, P_{bid,i}^{\max,t}$: bid limits of the unit at bus i for time interval t

$S_i^{\max}$: maximum apparent power capacity of unit at bus i

$Q_{gi}^{\min}, Q_{gi}^{\max}$: minimum, maximum reactive power capacity of unit at bus i

VAr: reactive support sites

$V_i^{\min}, V_i^{\max}$: limits of voltage magnitude for the bus i

$T_l^{\min}, T_l^{\max}$: limits of transformer tap position

TBR: set of transformer branches with taps

Z_l : impedance of transmission line *l*

$I_l^{\max}$: current limit for the transmission line *l*

NBR: set of network branches

Initial conditions for typical Economic Dispatch algorithms are obtained from Unit Commitment algorithms. These algorithms determine the operating status of the units (on or off) based on the start-up costs of the units, priority list or other approximate methods. The identification of the discrete "on or off" operating status of the generators in the scope of the Economic Dispatch, solved for instance using gradient based methods, becomes impossible since the problem assumes a mixed integer nature. Apart from this issue, it is also important to notice that in market environment generation companies can submit non-convex bid curves. This means that typical ED algorithms become unable to ensure the convergence to global optima.

IV. Solution Algorithm

The general algorithm of SA can be described in the following steps. In the first place, the solution vector comprises attributes as generators, transformers, and capacitor banks operation points:

$$x = [\ \underbrace{x_1,\dots,x_n}_{generators\ (MW)},\ \underbrace{x_{n+1},\dots,x_{n+m}}_{transformers\ (p.u.)},\underbrace{x_{n+m+1},\dots,x_{n+m+k}}_{capacitor\ banks\ (MVAr)}]$$

where

n is the number of the bidding generators
m is the number of the transformers with taps and
k is the number of the capacitor banks
$n+m+k$: the total attributes

We consider four types of solutions $x_{initial}$, $x_{current}$, x_{trial} and $x_{optimal}$.

STEP1) The initial solution can be an actual operation point with default positions of the transformer taps and the capacitor banks sections or can be randomly generated.

STEP2) For the initial solution an AC power flow study is run evaluating voltage magnitudes, line current flows and slack bus active and reactive power generation. This trial solution including the slack bus active/reactive power generation is set as the current solution as well as the optimal solution, i.e. $x_{trial} = x_{current} = x_{optimal}$.

STEP3) The cost for each solution is evaluated by the so-called evaluation function, *F(x)*. In this implementation the evaluation function is formed as:

$$F(x) = C_T^t + \sum_{i=1}^{N}\left(V_i - V_i^{\max}\right)\cdot f_1(V_i) + \\ + \sum_{i=1}^{N}\left(V_i^{\min} - V_i\right)\cdot f_2(V_i) + \\ + \sum_{l=1}^{NBR}\left(\frac{I_l - I_l^{\max}}{I_l^{\max}}\right)\cdot f_3(I_l) \tag{13}$$

The functions f_1, f_2, and f_3 penalize the objective function in order to ensure the enforcement of the constraints (11) and (12). The functions f_1, f_2, and f_3 are given by (14) to (16).

$$f_1(V_i) = \begin{cases} 0 & ,if\ V_i \le V_i^{\max} \\ Const(V) & ,if\ V_i > V_i^{\max} \end{cases} \tag{14}$$

$$f_2(V_i) = \begin{cases} 0 & ,if\ V_i \ge V_i^{\min} \\ Const(V) & ,if\ V_i < V_i^{\min} \end{cases} \tag{15}$$

$$f_3(I_l) = \begin{cases} 0 & ,if\ I_l \le I_l^{\max} \\ Const(I) & ,if\ I_l > I_l^{\max} \end{cases} \tag{16}$$

The constraints (3)-(5) are satisfied given that for each trial solution an AC power flow is run.
The constraints (6)-(8) are satisfied always while the available active generator power injections samples are limited within the bid curves solution space.

Assign $F(x_{current})$ to $F(x_{optimal})$.

STEP4) Generate a trial solution, x_{trial} in the neighborhood of the current solution $x_{current}$ from the solution space. A neighborhood is defined as the solution that differs from current one of one "unit". That is the algorithm samples one of the attributes (generators, transformers, and capacitor banks) and then samples increments or decrements of the transformer taps the bank capacitors sections or the generation active power injection by one unit from the solution space.

STEP5) A power flow is executed for the trial solution, x_{trial} and using Eq. (12) the $F(x_{trial})$ is evaluated.

STEP6) The acceptance criterion of this trial solution is check
If $F(x_{trial}) \le F(x_{optimal})$ then
$x_{trial} = x_{current} = x_{optimal}$.
$cw=0$ (set the Worse Solution Counter at 0)
else
$cw=cw+1$
a random number p uniformly distributed in the interval [0,1) is sampled.
If $p \le exp\left(\frac{F(x_{current}) - F(x_{trial})}{K\cdot Temperature}\right)$ then
Accept the new point as $x_{trial} = x_{current}$ and $F(x_{trial})= F(x_{current})$
else the trial solution in analysis is discarded.

STEP7) If the cw>maximum iteration number without improvement then go to STEP9

STEP8) If the iteration counter n for each temperature level is greater than the maximum allowable then
Cooling down Temperature $T=T*b$
If $T>T_{min}$ go to STEP4 else go to STEP9

STEP9) End

V. Case Study

A. System Data

The proposed algorithm is illustrated using the IEEE 30-bus system. The complete data for this network can be found in

[16]. The network consists of 41 lines, 4 generators, 4 transformers, and 2 capacitor banks. The tests that were conducted using this network considered 7 taps in each transformer. Each tap corresponds to 0.02 increment within the interval [0.94, 1.06]. Initially, the transformer's taps were considered at the nominal values (position 4 equivalent to 1p.u.). The capacitor banks available reactive powers are [0, 7.5, 15, 22,5 and 30 MVAr] and they are connected to buses 10 and 24 as shown in Fig. 3. Loads were set at the values referred in [16] multiplied by a factor of 0.6. The increment/decrement accuracy for the generators was set to 1MW/0.01p.u.

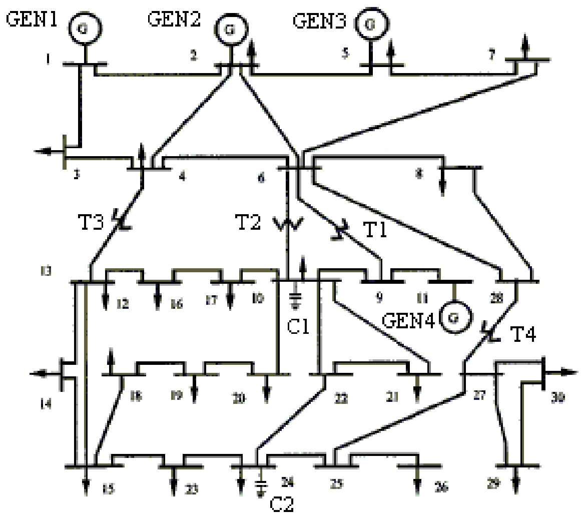

Fig. 3. IEEE 30-bus test system

The bid curves of each generator and the minimum and maximum submitted capacities are shown in Fig. 4 and 5.

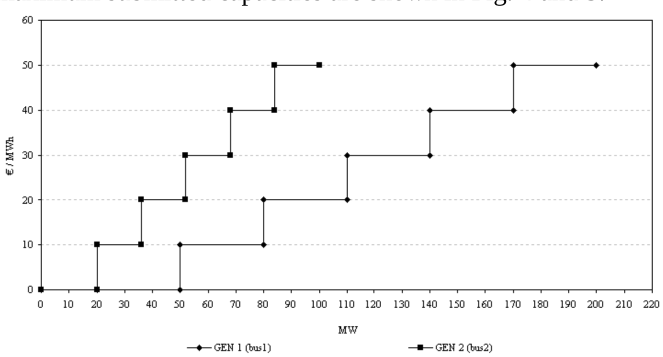

Fig. 4. Bid curves of GEN1 and GEN2

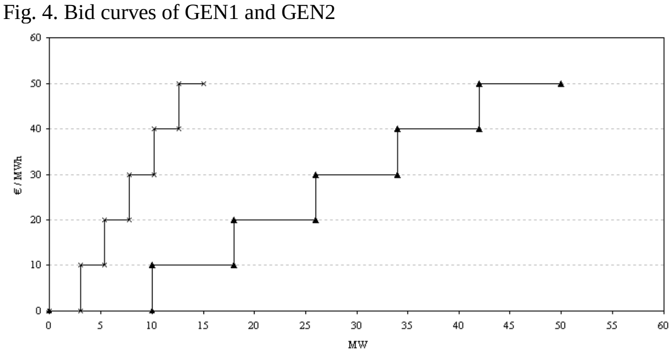

Fig. 5. Bid curves of GEN3 and GEN4.

B. Results

The selected Simulated Annealing parameters are:

- The number of iterations per temperature level n=90;
- The initial temperature level T=1.0;
- The lowering step determining the cooling scheme is b=0.95 of previous temperature;
- The minimum temperature level T_{min}=0.05;
- The Boltzman constant K=200;
- The maximum number of iterations without improvement of the evaluation function cw=70;
- The objective function penalties are $Const(V)=40$ and $Const(I)$=300;

The initial solution was set to the values:

$$x_{initial} = [\underbrace{130,30,15,6}_{\substack{generators\\(MW)}},\underbrace{1.00,0.98,1.06,0.98}_{\substack{transformers\\(p.u.)}},\ \underbrace{22.5,0.0}_{\substack{capacitor\\banks\,(MVAr)}}\ ]$$

For this solution, the initial value for the acceptance function was 4320€. The algorithm converged in 223 iterations and the final value of the acceptance function was 3141€.

The final dispatch of the units is shown in Fig. 6 while the bus voltages and the branch currents are illustrated in Fig. 7 and 8.

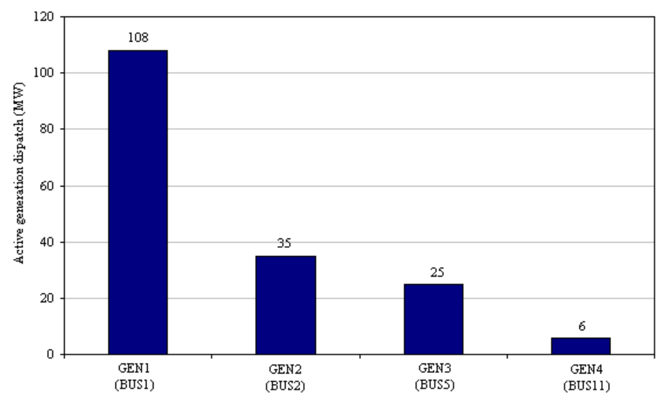

Fig. 6. Active generation dispatch

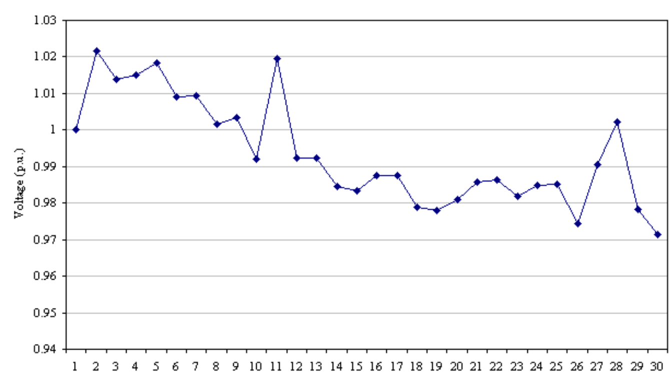

Fig. 7. Bus voltages

The bus voltages are within the acceptable voltage range of 0.95-1.05p.u. as shown in Fig. 7. According to Fig. 8 all branch current flows are much lower than the acceptable current thermal limits of each branch.

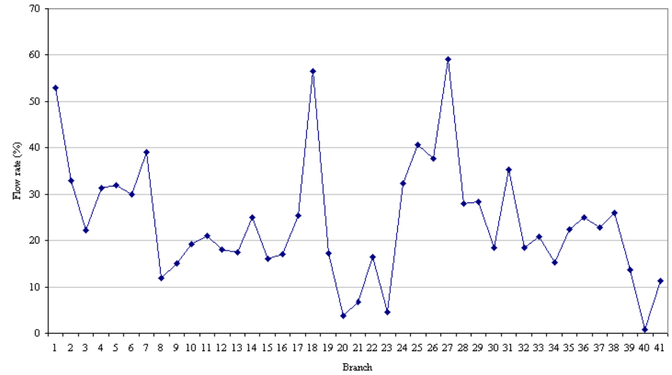

Fig. 8. Branches flow rates

The final transformers taps positions and capacitor bank sections are given in Table I and II

TABLE I
TRANSFORMERS TAPS POSITIONS

Transformer No.	Relevant Buses	Tap position (p.u.)
T1	6-9	1.02
T2	6-10	0.98
T3	4-12	1.04
T4	27-28	0.98

TABLE II
CAPACITOR BANKS SECTIONS

Capacitor bank No.	Bus	Section (MVAr)
C1	10	0
C2	24	7.5

In order to simulate the use of this approach in a day ahead market we considered a daily load time series produced by multiplying the values referred in [16] by a factor varying in the range [0.5,1.0]. In Fig. 9 we present the active generation dispatches for the four generators. It should be stressed that the Simulated Annealing algorithm departed, for each hour except the first, from the solution identified for the previous hour. This strategy was adopted in order to reduce the computational burden since one would depart from a good solution for a slightly different load value.

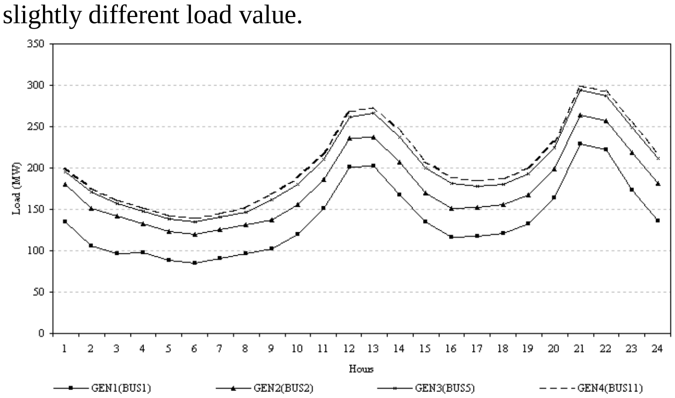

Fig. 9. 24 hours day ahead economic dispatch stack diagram

C. Evaluation of the results

Using the setting of the algorithm parameters as mentioned in the previous paragraph the temperature was lowered till 0.8574 and it was obtained an improvement of the evaluation function of the problem of 1179€ of the evaluation function regarding the initial value.

In Fig. 10 we present the evolution along the search process of evaluation function value (continuous line) for the best solution and for the current solution (dotted line) computed till the algorithm ended. The current solution suffered 101 changes along the whole iterative process while the best-identified solution was changed 23 times only. This fact illustrates the basic idea of Simulated Annealing as described in Section II. The algorithm accepts better solutions whenever they are sampled but, specially in the beginning, one can accept worse solutions. The algorithms finished, in this case, not because the minimum specified temperature was reached but, in fact, there were a significative number of sampling without improvement, as can be seen by the horizontal line on the lower right part of the continuous line. By using Simulated Annealing there is no insurance that the global optimal solution was identified. However, if the temperature lowering is slow enough and if a large number of iterations is performed there is an insurance that, at least, a good quality solution was obtained.

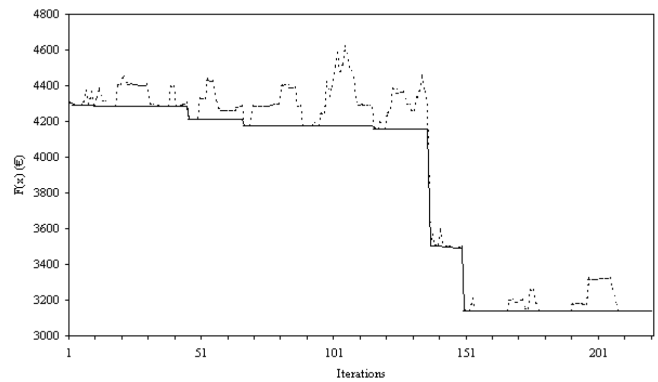

Fig. 10. Evolution of the evaluation function for the current solution (dotted line) and for the best solution (continuous line)

VI. CONCLUSIONS

In this paper we present a coupled approach to the dispatch problem in market environment. In most systems, economic issues are decoupled from technical ones leading to the possibility of obtaining a technically unfeasible economic dispatch as an outcome from the pool. This economic dispatch is then evaluated by the System Operator leading to the need to active subsequent adjustment markets to deal with congestion of to adopt market splitting strategies. The advantage of the approach proposed in this paper consists of treating the problem as a whole reflecting, in fact, that electricity is not a true commodity. In fact, one should not forget that flows and voltages have to be in accordance with Kirchoff Laws and that we can not easily force flows to go where we want. Therefore, approaches as the one described can be very useful to treat in a more realistic way the economic and technical problem of operation of power systems. Apart from this conceptual issue, it is important to stress the flexibility and easiness of implementation of the Simulated Annealing approach as well as its ability to inherently deal with discrete problems in a very efficient way. This is another advantage leading to a technically feasible solution, that is, a solution that does not require any kind of approximations to be put in place. As a whole, we would say that the developed approach is a promising one and that further research will now be conducted namely to incorporate couplings between several hourly periods and to allocate reactive power according to bids leading to some sort of reactive power market, that, in any case, is married to active power one.

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VIII. Biographies

K.A. Papadogiannis received his Electrical and Computer Engineering degree in 1995. He is a PhD student in the Electrical Engineering Department of NTUA. His research concerns loss allocation techniques and optimization methods in deregulated markets.

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