Fast and Accurate Solution for SCUC Problem using an Enhanced Dual Neural Network

M. Shafie-khah, *Member, IEEE*, M. Parsa Moghaddam, *Member, IEEE*, M. K. Sheikh-El-Eslami,
Member, IEEE, and João P. S. Catalão, *Senior Member, IEEE*

Abstract—In this paper a new hybrid method based on neural network (NN) models is presented to solve the security constrained unit commitment (SCUC) problem. The proposed method requires less computation time in comparison with other methods while taking into account the precision of the results. Furthermore, the framework provided here allows including a precise description of warmth-dependent start-up costs, valve point effects, multiple fuel costs, prohibited operating zones and AC load flow limits. To solve the non-convex problem, a modified branch-and-bound method and an enhanced dual neural network model are utilized as optimization tools, and a new algorithm for modeling AC power flow is developed. Unlike the traditional SCUC algorithms, by using the mentioned NN-based model, solving SCUC problems is accomplished without decomposition. The IEEE 118-bus test system has been used to demonstrate the effectiveness of the proposed method in comparison with previous works.

Index Terms—AC power flow, branch-and-bound, dual neural network, security constrained unit commitment.

NOMENCLATURE

$a_{i,f}$, $b_{i,f}$, $c_{i,f}$	Coefficients of the quadratic fuel cost function of unit i with fuel type f.
B	Number of binary variables.
BSI	Index for sorting the binary variables list.
$FC_{i,t}$	Fuel cost of unit i at time t.
j	Index for prohibited operating zones.
$m_{i,f}$	Coefficient of the sinusoidal model of valve point effect in cost function of unit i with fuel type f.
N	Number of generation units.
$P_{i,t}$	Active generation of unit i at time t.
$P_{i,t}^q$	Active generation of q-th segment of unit i at time t.
$P_{i,j}^{LB}$, $P_{i,j}^{UB}$	Lower and upper boundaries of POZ j of unit i, respectively.
$P_i^{\min}$, $P_i^{\max}$	Lower and upper limits of active generation of unit i, respectively.
$P_{i,f}^{\min}$, $P_{i,f}^{\max}$	Lower and upper limits of active generation of unit i with fuel type f, respectively.
q	Index for segments of active generation cost.
Q	Reactive generation.
RU_i, RD_i	Ramp-up and down rate limits of unit i, respectively.
s	Index for warmth-condition of start-up.
$SSU_{i,t}^s$	Binary value equal to 1, if unit i starts up in the warmth-condition s at time t, and 0 otherwise.
SUC_i, SDC_i	Start-up and shut-down cost of unit i, respectively.
$u_{i,t}$	Binary value equal to 1, if unit i is on at time t, and 0 otherwise.
U	Voltage magnitude.
V	Number of variables.
x	Index for problem variables.
X	Value of variable x.
$y_{i,t}$	Binary value equal to 1, if unit i starts up at time t, and 0 otherwise.
$\alpha_{i,f}$, $\beta_{i,f}$, $\gamma_{i,f}$	Coefficients of the quadratic valve point effect function of unit i with fuel type f.
$\lambda_{i,s}^{up}$	Start-up cost of unit i in the warmth-condition s.
δ	Voltage angle.

M. Shafie-khah and João P. S. Catalão are with the University of Beira Interior, R. Fonte do Lameiro, 6201-001 Covilha, Portugal, with INESC-ID, R. Alves Redol, 9, 1000-029 Lisbon, Portugal, and with IST, Technical University of Lisbon, Av. Rovisco Pais, 1, 1049-001 Lisbon, Portugal (e-mails: miadreza@ubi.pt; catalao@ubi.pt).

M. Parsa Moghaddam and M. K. Sheikh-El-Eslami are with the Tarbiat Modares University, 14115-111 Tehran, Iran (e-mails: parsa@modares.ac.ir; aleslam@modares.ac.ir).

I. INTRODUCTION

THE security constrained unit commitment (SCUC) provides a secure and economic hourly generation schedule program. Decomposition of very complex SCUC problems is a good simplification technique to divide the problem into a master problem, unit commitment (UC), and network security check sub-problems. Benders decomposition (BD) is the most conventional method that is used to divide SCUC problems into master and sub-problems [1]-[5]. Then, Lagrangian relaxation (LR) or dynamic programming (DP) are generally used for UC, while linear programming (LP) is applied to solve sub-problems.

Since DP is not appropriate for large-scale power systems [6], and obtaining a feasible solution is very difficult by using LR [1], [7], due to unreasonable relaxations for the discrete variables [6], some other methods were used in previous works [8]-[11]. In [8], the SCUC problem has been divided into the UC and the optimal power flow (OPF) problems, using a genetic algorithm (GA) to solve each problem separately. In [9], combination of BD and improved integer coded genetic algorithm (ICGA) is implemented to reduce the computation time of SCUC solving. In [10], a solution methodology has been presented based on the combination of BD and the outer approximation technique. In [12], an extended BD with linear feasibility and optimality cuts has been proposed to solve the mixed-integer programming at two stages. In [11], the combination of an adaptive binary particle swarm optimization and an adaptive real coded genetic algorithm (ABPSO-ARCGA) was reported to solve the SCUC problem. In [13] a hybridization of BD and outer approximation (OA) methods has been proposed to solve the SCUC problem.

Nevertheless, some of the previous methods have some inherent limitations such as unstable computing efficiency for GA and excessive decomposition of the problem for BD [6]. On this basis, in [14] a methodology was presented based on an enhanced harmony search technique (EHS) for solving the UC and an analytical nonlinear programming optimization approach for solving the security constrained economic dispatch (SCED). Although the accuracy achieved in the results of the mentioned reference is appropriate, the high computation time and the requirement to repeat the algorithm to obtain the best solution pose serious disadvantages.

According to the importance of solving the SCUC in daily energy markets, some worthwhile studies have been presented to decrease the computation time of the problem. In [7], a fast SCUC method has been presented for large-scale power systems. In the mentioned reference, reducing the number of integer variables has been accomplished by applying infeasible criteria of SCUC solution. Since elimination of inactive constraints can accelerate solving the SCUC problem, identification of the constraints has been studied in some references. In [15], an analytical approach has been suggested to quickly identify inactive security constraints in the problem. Moreover, in [16], a systematic method based on branch-and-bound (BB) has been presented to construct feasible solutions in LR framework of the SCUC problem. However, in the mentioned methods, many practical features such as multiple fuel costs (MFCs), prohibited operating zones (POZs), valve point effects (VPEs) and even AC load flow limits have been disregarded.

Since SCUC is a very complex problem, in most of the solution methods, the UC problem and the network security are solved separately. However, LP [17], semi-definite programming (SDP) [6] and combination of modified BB with quadratic programming (MBB-QP) [18] have been developed for an unified solving of the SCUC problem. In these works, the SCUC problem has been solved directly, so that there is no need to divide it into sub-problems.

Although unified methods are able to obtain more accurate solutions than decomposition-based methods, they needed some simplifications and their speed solutions are also not as good as desired.

As mentioned previously, several methods have been used to solve the SCUC problem, whereas the fast and accurate problem solving still constitutes a major challenge for the conventional optimization methods.

It is noteworthy that no previous reference has ever applied neural network (NN) models to solve the SCUC problem, so this powerful modeling tool has always been neglected in the previous works. Yet, the features of high parallelism, speed of computation and adaptability of NNs can be indeed utilized to solve SCUC problems. Hence, in this paper a NN model is successfully applied to solve the quadratic programming (QP) problem with equality and two-sided inequality constraints. In order to solve the QP, NN models pose several advantages in comparison with traditional methods. They have the parallelizable property, thus they can easily overcome large-scale problems. Moreover, because of the global convergence property, without depending on the input changes, solution of NNs is convergent to the optimal solution [19].

In this paper, an optimization method that is a combination of modified BB with dual neural network (DNN) is proposed to solve the SCUC problem and its effectiveness is compared with previous methods.

In the original BB method, the optimal solution can only be achieved by the successive elimination of a set of incorrect solutions, and finding the upper bounds would require implementing the time-consuming economic dispatch (ED) problem repeatedly. The BB is known as being a time-consuming method and only in a few works it was used to solve UC problems or to eliminate the inactive constraints, being rarely suggested for SCUC solutions [16], [20]. In addition, computational results of the traditional BB method (e.g. in CPLEX packages) is not stable [20]. Therefore, in this work, according to the features of the SCUC problem, both optimization methods are modified to overcome the unstable computing efficiency and to obtain more effectiveness.

It should be noted that, unlike traditional SCUC algorithms that first solve the UC problem and then check the network constraints to satisfy the network flow limits, in this paper both steps are conducted simultaneously.

On this basis, by using the proposed method in addition to an appropriate computation time, the accuracy of the solution is guaranteed. Therefore, the method is able to become a perfect alternative to decomposition based methods (e.g. BD), even in solving stochastic SCUC problems.

In order to solve the SCUC problem, one of the most effective parts on the both accuracy and computation time is the power flow model. There are three general approaches for considering the power flow in the SCUC problems [21], but they have some disadvantages.

In this paper, an algorithm for modeling AC power flow for SCUC solution is presented. The proposed method is more accurate compared with methods based on DC model and is faster in comparison with nonlinear AC methods.

The proposed algorithm overcomes disadvantages of existing methods and can be used in real-time and large-scale power systems with higher accuracy. The framework provided here allows including a precise description of warmth-dependent start-up costs, MFCs, AC power flow, ramp rates, minimum up/down time constraints, POZs and VPEs.

The rest of the paper is organized as follows. In Section 2 the problem formulation is expressed. Optimization methods are discussed in Section 3. Section 4 is devoted to the numerical studies. Finally, Section 5 concludes the paper.

II. PROBLEM FORMULATION

A. Objective function

The objective is to find the optimal schedule such that the total operating costs can be minimized while satisfying the operational and security constraints. The objective function in common form is expressed as [22]:

$$Min\ \{\sum_{t=1}^{T}\sum_{i=1}^{N} FC_{i,t} * u_{i,t} + \sum_{i=1}^{N} SUC_i + \sum_{i=1}^{N} SDC_i\} \tag{1}$$

Some units might supply with multiple fuels. For the units, the cost function is formulated by some piecewise functions. Therefore, using this formulation the effects of fuel type changes are considered. In addition, the VPEs are usually modeled using an absolute of the sinusoidal term that induces non-convexity and introduces ripples to the cost curve.

In this paper, an alternative quadratic formulation is applied and the nonlinear term is converted into some quadratic terms. The mean square error of the fitting is about 1e-5 and other details have been presented in [18].

Fuel cost considering VPEs can be expressed as:

$$\begin{aligned} FC_{i,t} = &\ a_{i,f}P_{i,t}^2 + b_{i,f}P_{i,t} + c_{i,f} \\ &+ \alpha_{i,f}\{P_{i,t}^q - P_{i,f}^{\min} - (q-1)\pi/m_{i,f}\}^2 \\ &+ \beta_{i,f}\{P_{i,t}^q - P_{i,f}^{\min} - (q-1)\pi/m_{i,f}\} + \gamma_{i,f} \\ &, q \in (1,2,...,\lfloor m_{i,f}(P_{i,f}^{\max} - P_{i,f}^{\min})/\pi \rfloor) \end{aligned} \tag{2}$$

In this paper, a linear formulation of the warmth-dependent start-up cost is applied for each generating unit. The number of warmth-dependent start-up cost is dependent on the number of warmth conditions (e.g. hot, warm, cold), as determined by the time that unit has been decommitted. On this basis, the warmth-dependent start-up cost is linearly formulated as below:

$$SUC_i = \sum_{t=1}^{T} \begin{Bmatrix} \lambda_{i,s}^{up} * y_{i,t} + (\lambda_{i,s+1}^{up} - \lambda_{i,s}^{up}) * SSU_{i,t}^{s+1} \\ + (\lambda_{i,s+2}^{up} - \lambda_{i,s+1}^{up}) * SSU_{i,t}^{s+2} + ... \end{Bmatrix} \tag{3}$$

B. Unit ramp-up and ramp-down constraints in linear form

$$u_{i,t} * u_{i,t-1} * (P_{i,t} - P_{i,t-1}) \le RU_i \tag{4}$$

$$u_{i,t} * u_{i,t-1} * (P_{i,t-1} - P_{i,t}) \le RD_i \tag{5}$$

C. Prohibited operating zones

In real operation the generation output of a unit must avoid the unit operations in prohibited zones. Based on this, the feasible operating zones of a unit are described as follows:

$$P_{i,j}^{LB} * u_{i,t} \le P_{i,t} * u_{i,t} \le P_{i,j}^{UB} * u_{i,t} \tag{6}$$

D. The proposed power flow calculations

Solving power flow for the SCUC problem is divided into base case and contingency case. Prior to this study, three general approaches were applied for modeling the power flow in the SCUC problems [21]:

- Linear DC model (pre- and post-contingency).
- Nonlinear AC model (pre-contingency), and linearized DC model for contingency analysis.
- Nonlinear AC model (pre- and post-contingency).

The full AC modeling increases the computation time and decreases the convergence capability. In addition, DC modeling even only in post-contingency decreases the accuracy because the voltages may deviate considerably from their base case values.

Because of the limitations of existing methods, none of the aforementioned approaches is suitable for SCUC solution in real-time or large-scale power systems. Hence, there is a need to develop a new power flow algorithm for SCUC solution that is both fast and accurate, being used in real-time or large systems. In the proposed algorithm, the base case load flow solution and the sensitivity properties of the Jacobian matrix are used. The iterative solution of linear equations is involved by Newton-Raphson load flow. The state vector is iteratively computed and updated for small changes in power injections. The linear equation is shown as below:

$$\begin{bmatrix} \Delta\delta \\ \Delta U \end{bmatrix} = [J_0]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{7}$$

The iterative procedure should be repeated until the change in the state vector between successive iterations is smaller than a specified value. Thus, the final calculated Jacobian matrix is available for use. In the proposed algorithm, the Jacobian obtained at base case load flow is applied to calculate the changes in voltage magnitudes and angles in post-contingency. Then, the obtained changes are added on the base case complex voltages, to obtain post-contingency complex voltages. The calculation of the complex bus voltages is always feasible and the accuracy is appropriate. Thus, branch power flows, bus injections and generator quantities are calculated by the new bus voltages in post-contingency.

III. OPTIMIZATION METHOD

In the previous works, two major approaches have been utilized to optimize the SCUC problem as a large-scale mixed integer nonlinear program.

The first approach is the decomposition of the SCUC problem into the UC and the SCED in order to decrease the size of the time-consuming problem [1]-[5].

The second approach is the unified solution of the SCUC problem using hybrid evolutionary algorithms [6]-[17].

In this paper, another approach is proposed. The approach is based on decomposition of the SCUC problem into the QP and Binary Programing (BP). This type of decomposition is more accurate than traditional decomposition methods and much faster than previously unified ones.

In this study, an Enhanced Dual Neural Network (EDNN) is used to solve the quadric problem, as a new contribution in SCUC solving. Binary variables must be checked to be 0 or 1. If after solving the QP some of the binary variables stay different from 0 or 1, the BB method is used as a binary programming technique to satisfy the binary constraints. Using the BB method makes sure that the BP is deterministically optimized, which is a considerable advantage of the proposed method in comparison to evolutionary algorithms.

Various NN models have been developed to solve the QP problems [23]-[26]. However, according to the high complexity of the SCUC problem, especially in real-world power systems and considering AC power flow even in post-contingency, most NN models with a complex architecture could not preserve the desired convergence and many models with one-layer structure might not be stable [19], [27]. In addition, two-sided inequality constraints should be satisfied by the NN model. Based on this and according to the requirements for solving the SCUC problem with less computation time, the EDNN has been applied to solve strictly the QP problem. The general quadratic optimization problem can be expressed as:

$$\text{Min } \frac{1}{2} X^T W X + C^T X \tag{8}$$

$$\text{s.t. } AX = B, \quad LB \le EX \le UB$$

The dual problem of (8) can be expressed as:

$$\text{Max } -\frac{1}{2} X^T W X + B^T Y + LB^T V - UB^T W \tag{9}$$

$$\text{s.t. } WX + C - A^T Y - E^T Z = 0$$

where Y,V and W are dual decision variables and Z=V-W.

In accordance with the conditions of Karush-Kuhn-Tucker (KKT), (9) and (10) have the same solutions:

$$WX + C - A^T Y - E^T Z = 0$$
$$AX = B \tag{10}$$
$$EX = g(EX - Z)$$

where $g(x)$ is a piecewise linear function related to LB and UB. By obtaining X from the first term of (10) and substituting it into the second term, we can achieve:

$$AW^{-1}(A^T Y + E^T Z - C) = B \tag{11}$$

Therefore, Y can be formulated as:

$$Y = (AW^{-1}A^T)^{-1}(AW^{-1}C - AW^{-1}E^T Z + B) \tag{12}$$

On this basis and according to the projection theorem, the equation of the proposed EDNN can be presented as:

$$E \frac{dz}{dt} = g(EH - I)z - EHz + (g - 1)Es \tag{13}$$
$$x = Hz + s$$

where $\quad H = W^{-1}E^T - W^{-1}A^T(AW^{-1}A^T)^{-1}AW^{-1}E^T \quad$ and $s = W^{-1}(A^T(AW^{-1}A^T)^{-1}(AW^{-1}C + B) - C)$.

The block diagram of the EDNN is presented in Fig. 1. In Fig. 1, e and h are respectively the arrays of E and H. The proposed EDNN is able to lessen the architectural complexity of the model while preserving the appropriate convergence properties.

It should be noted that many nonlinear and non-convex features of power system, such as VPEs, can be formulated and solved by a series of quadratic optimization problems as presented in [18]. Thus, as it is shown in this paper, the proposed method is able to consider the mentioned features.

SCUC problem using the combination of a modified binary branch-and-bound (MBBB) with EDNN consists of several stages that are shown in Fig. 2.

As it can be seen, at first all essential information for the SCUC problem should be imported. Then, for considering the network limits (in pre- and post-contingency), the proposed algorithm in Section 2 is used to obtain AC power flow equations. For this purpose, an AC power flow is implemented in base case for all commitment states of units and for all hours. After obtaining the Jacobian matrices for the base cases, the linearized AC power flow equations (for post-contingency) are placed with the other linearized constraints of SCUC problem (presented in Section 2).

In addition, in order to improve the effectiveness of the proposed method, some crucial modifications have been accomplished. On this basis, all variables in simulation time are considered together and the loop of times is not applied. Moreover, for considering impact of the order of variables, the variables are sorted based on the greater difference from their bounds. Therefore, the variables are sorted according to the Binary Sorting Index (BSI) that is calculated as follows:

$$BSI = \begin{cases} X, & 0 \le X \le 0.5 \\ 1 - X, & 0.5 < X \le 1 \end{cases} \tag{14}$$

The reason of the above definition for BSI is that in the formulation of QP, LB and UB of the binary variable are assigned to 0 and 1, respectively. Therefore, commitment variables are never out of the bounds. Moreover, whatever variable is closer to 0 or 1 is placed at the bottom of the list and vice-versa. This calculation and sorting of the variables is repeated after each divergence of EDNN.
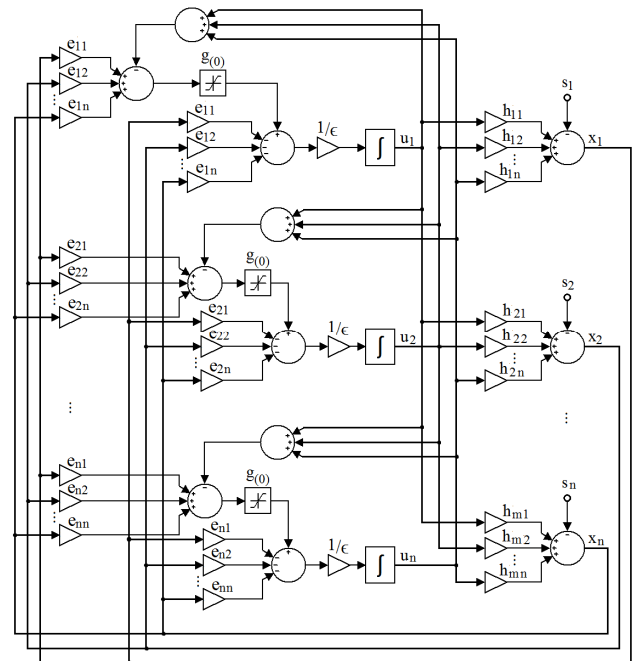

Fig. 1. Block diagram of the enhanced dual neural network.

In addition, two other modifications are applied in MBBB-EDNN algorithm, which are very useful for convergence speed. Accordingly, instead of setting the variable to 1 or 0 randomly, the variable is set to the value of a bound that is closer. Moreover, the ramp rate constraints (4) and (5) are not considered in solving the EDNN model, but if the model has converged they will be checked in each iteration. If the constraints are not satisfied, the assigned value to the related variable should be changed. There are two reasons for separating the ramp rate constraints from the other equations. First, checking the equations in QP generally wastes much computation time. Second, removing the loop of times and considering all the variables together cause (4) and (5) to become nonlinear.

IV. NUMERICAL STUDIES

The experiment of this study is performed on the IEEE 118-bus test system with 54 units, 186 branches, 9 tap-changing transformers, 14 capacitors, and 91 demands [28].

To show the proficiency of the proposed SCUC methods, the obtained UC and SCUC results are compared with the results of BD [2], ABPSO-ARCGA [11], MBB-QP [18] and EHS [14] methods, as can be seen in Table I. The platform used for running the proposed methods is a Pentium IV CPU 2.0 GHz. It should be noted that, for the sake of a fair comparison, in these results warmth-dependent start-up cost, VPEs, MFCs, and POZs constraints are not considered.

As Table I clearly illustrates, the accuracy of the proposed MBBB-EDNN method is better than BD, ABPSO-ARCGA and MBB-QP. The results are also better than the average results of the EHS method. Moreover, in spite of a weaker processor, the solution speed of the proposed MBBB-EDNN method is much faster than the EHS method. Accordingly, it has been demonstrated that the proposed MBBB-EDNN method is very useful for SCUC solution of large-scale power systems and real-time market operation.

In order to investigate the effectiveness of the proposed models considering VPEs, MFCs and POZs constraints, an advanced case is considered in Table II. As can be seen in Table II, because of considering the VPEs, fuel cost function of the generating units and consequently the daily cost have been dramatically increased. It is noteworthy that considering the VPEs, MFCs and POZs constraints makes a more practical SCUC model, but it increases significantly the complexity of the problem, imposing discontinuity of the solution space, non-convexity, nonlinearity and non-smoothness.

The proposed methods overcome all mentioned complexities and obtain appropriate results. As Table II shows, despite the smallest computation time, the accuracy of the proposed methods is far better than previously reported methods.

TABLE I
THE RESULTS FOR THE IEEE 118-BUS TEST SYSTEM

Solution method		Daily cost ($)		Computation time (s)	
		UC	SCUC	UC	SCUC
BD [2]		849,291.48	851,274.38	30	100
ABPSO-ARCGA [11]		840,150.56	850,843.63	1262	3144
MBB-QP [18]		840,204.17	849,042.93	116	198
EHS [14]	Best result	839,359.05	848,363.97	968	2388
	Average result	840,127.33	850,741.76		
	Worst result	841,471.12	854,247.35		
MBBB-EDNN		839,831.65	848,639.03	92	146

TABLE II
THE RESULTS FOR THE IEEE 118-BUS TEST SYSTEM IN ADVANCED CASE

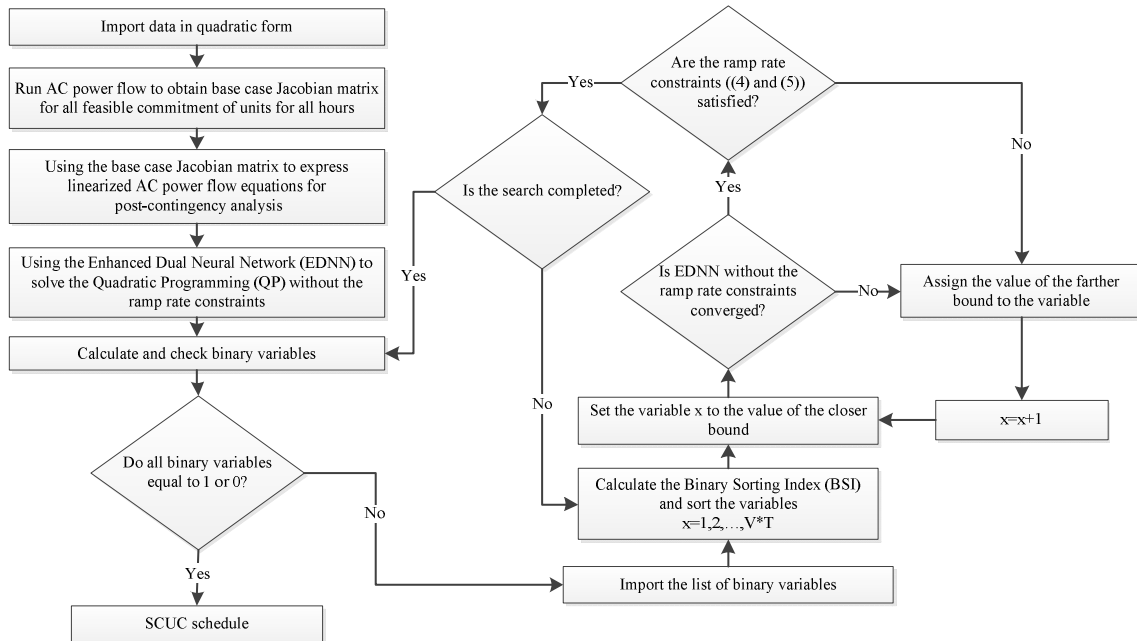| Solution method	Daily cost ($)	Computation time (s)
ABPSO-ARCGA [11]	1,089,845.65	3152
MBB-QP [18]	1,084,371.31	208
MBBB-EDNN	1,067,150.84	174

Fig. 2. Flowchart of SCUC using the proposed method.

V. Conclusion

A new algorithm based on the BB method and EDNN has been developed and successfully tested to solve the SCUC problem without decomposition. In addition, a new algorithm has been developed for modeling AC power flows in SCUC problems that gives fast solution speeds with desired accuracy. The proposed MBBB-EDNN method provides excellent results in practical size systems, superior to previously reported results using other methods, alongside a much faster solution speed. Hence, the proposed method represents an interesting and valuable alternative to decomposition methods for solving SCUC problems of large-scale power systems in real-time market operation.

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Miadreza Shafie-khah (S'08, M'13) received the M.Sc. and Ph.D. degrees in electrical engineering from Tarbiat Modares University, Tehran, Iran, in 2008 and 2012, respectively. He is currently pursuing his postdoctoral studies in the laboratory of Sustainable Energy Systems with Professor João P. S. Catalão, University of Beira Interior (UBI), Covilha, Portugal. His research interests include power market simulation, market power monitoring, power system optimization, operation of electricity markets, price forecasting and smart grids.

Mohsen Parsa Moghaddam (M'05) received the B.Sc. degree in electrical engineering from Sharif University of Technology, Tehran, Iran, in 1980, the M.Sc. degree from Toyohashi University of Technology, Toyohashi, Japan, in 1985, and Ph.D. degree from Tohoku University, Sendai, Japan, in 1988. He is currently a Professor of the Faculty of Electrical and Computer Engineering, Tarbiat Modares University, Tehran, Iran. His research interests include power system planning, energy management, and smart grids.

Mohammad Kazem Sheikh-El-Eslami (M'11) received the B.Sc. degree in electrical engineering from Tehran University, Tehran, Iran, in 1992 and the M.Sc. and Ph.D. degrees from Tarbiat Modares University, Tehran, Iran, in 2001 and 2005, respectively. He is currently an Assistant Professor of the Faculty of Electrical and Computer Engineering, Tarbiat Modares University. His research interests include power market simulation and generation expansion planning.

João P. S. Catalão (M'04-SM'12) received the M.Sc. degree from the Instituto Superior Técnico (IST), Lisbon, Portugal, in 2003 and the Ph.D. degree from the University of Beira Interior (UBI), Covilha, Portugal, in 2007.

He is currently a Professor at UBI, Director of the M.Sc. in Electromechanical Engineering (EUR-ACE label) and Researcher at INESC-ID. He is the Primary Coordinator of the EU-funded FP7 project SiNGULAR. He is an author or co-author of more than 200 papers published in journals, book chapters and conference proceedings, having supervised more than 20 post-docs, Ph.D. and M.Sc. students. His research interests include power system operations and planning, distributed renewable generation, demand response and smart grids.

Prof. Catalão is the Guest Editor-in-Chief of the Special Issue on "Real-Time Demand Response" of IEEE TRANSACTIONS ON SMART GRID, Editor of IEEE TRANSACTIONS ON SUSTAINABLE ENERGY and Associate Editor of *IET Renewable Power Generation*. Also, he is the Editor of the book entitled "Electric Power Systems: Advanced Forecasting Techniques and Optimal Generation Scheduling", published by *CRC Press* in 2012.