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Tricarico, Gioacchino; Azuara-Grande, Luis Santiago; Wagle, Raju; Gonzalez-Longatt, Francisco; Dicorato, Maria; Forte, Giuseppe; Rueda, Jose Luis

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Gioacchino Tricarico
Dept. of Electrical and Information Engineering (DEI)
Polytechnic University of Bari
Bari, Italy
gioacchino.tricarico@poliba.it

Luis Santiago Azuara-Grande
Dept. of Electrical Engineering
Universidad Carlos III de Madrid
Leganes, Spain
lazuara@ing.uc3m.es

Raju Wagle
Dept. of Electrical Engineering
UiT, The Arctic University of Norway
Narvik, Norway
raju.wagle@uit.no

Francisco Gonzalez-Longatt
Dept. of Electrical Engineering and ICT
University of South-Eastern Norway
Porsgrunn, Norway
fglongatt@fglongatt.org

Maria Dicorato and Giuseppe Forte
Dept. of Electrical and Information Engineering (DEI)
Polytechnic University of Bari
Bari, Italy
maria.dicorato@poliba.it
giuseppe.forte@poliba.it

Jose Luis Rueda
Dept. of Electrical Sustainable Energy
Delft University od Tecnology
Delft, Netherland
J.L.RuedaTorres@tudelft.nl

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***Abstract*— The operation schedule of the power generation units in electrical power systems is determined by the optimisation problem known as unit commitment (UC), aiming at minimising the total cost considering the generation constraints. To obtain a feasible solution from the network perspective, the security-constrained UC (SCUC) problem has been defined to embed the network constraints in the optimisation problem as well. Also, the higher penetration of renewable energy sources (RES) has increased the difficulty of UC problem, mainly due to the uncertainty and the high variability of RES. This paper proposed a SCUC with economic dispatch (SCUCED) optimisation developed in two stages. The first one is the solution of a merit-order based zonal day-ahead market (ZDAM) optimisation to define a preliminary generation schedule. In the second stage, the SCUCED is solved based on AC load flow routines and sensitivity factors to embed the full network representation. The approach is applied to a modified version of the IEEE 39-bus test system.**

Keywords—Day-ahead market, economic dispatch test system, unit commitment.

I. INTRODUCTION

One of the most important and interesting problems of power system operation is the secure and economic scheduling of the power production of the generation units over a time horizon and is typically referred ad unit commitment (UC). The UC refers to a wide range of problems depending on the time horizon, generating units, representation of the network, load profile (forecast), reliability constraints, regulatory framework, etc. Despite the difficulty of the mathematical problem, due to the complexity of the objective function, the number of decision variables, the length of the time horizon, the number of system constraints and operational requirements, it must be solved in a small-time [1]. Also, the higher penetration of renewable energy sources (RES) has increased the difficulty of UC problem, mainly due to the complexity related to the uncertainty and the high variability of RES. However, a current challenge of the modern transmission system operator is to solve the UC problem by using an efficient optimisation formulation that offers the best possible scheduling (minimum cost) and secures the electrical power system's reliability.

In the scientific literature, many different techniques have been applied to find the solution to the UC problem. Those techniques have been improving over time, from early ones based on the priority list and dynamic programming to the current most used ones based on mixed-integer programming [3]. Additionally, to obtain a feasible solution from the network perspective, the security-constrained UC (SCUC) problem has been defined to embed the network constraints in the optimisation problem [4]. Likewise, in the literature, the system network DC model is a well-known method to solve the SCUC more straightforward than the AC formulation [5]-[7]. The DC model is a linearisation of the full AC model, in which transmission losses and reactive power balance are neglected. Also, a value of 1.00 pu is supposed for the voltage magnitude of all buses [8]. But the DC model also has drawbacks due to its simplification can give us unrealistic results [9].

This paper proposes a bi-stage optimisation problem to develop a SCUC with economic dispatch (SCUCED) optimisation. In the first stage, a zonal day-ahead market (ZDAM) optimisation problem is solved, considering the interzonal flow bounds, aiming at minimising the generation supply. The dispatched power of the generators is exploited in the second stage to solve the SCUCED optimisation problem, in which the goal is to minimise the re-dispatching costs considering generators and network constraints. In this stage, an AC load flow is carried out to evaluate the overall operating condition of the system. The network constraints are included in the optimisation problem by means of linearised sensitivity factors to consider both active and reactive power network models, as well as the network losses. The approach is applied to a modified version of the IEEE 39-bus test system proposed by the authors in [10]-[11]. The simulation is carried out on the yearly peak load day, showing the effectiveness of the proposed method.

The authors are currently working on developing a simulation platform for power system operation considering economic aspects and uncertainty coming from RESs, so the modified version of IEEE 39-bus system is enhanced in this scientific paper to include the proposed methodology but also providing to the scientific a community a test system that would allow run more realistic simulations in terms of UC and economic dispatch. The final version of the modified version of the IEEE 39-bus system will be available at: https://github.com/fglongatt.

The following sections of this paper are organised as follows. Section II presents the proposed method for formulating the SCUCED. Section III presents the numerical results of the proposed methodology applied to the modified version of the IEEE 39-bus test system. Section IV shows and discusses the results yielded by the simulations, and finally, conclusions are mentioned in Section V.

II. PROPOSED METHOD

The framework of the proposed bi-stage method is shown in Fig. 1.

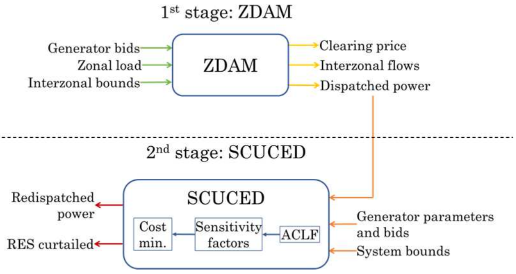

Fig. 1. Flow diagram showing the proposed SCUCED method.

The first stage consists in solving a merit-order criterium ZDAM in which the UC constraints are neglected. This formulation is based on the Pan European Single DAM in, which the cross-border constraints must fulfil [12]. In the second stage, the dispatched power obtained from the solution of the ZDAM is used to develop a SCUCED optimisation problem in order to fulfil generators and network constraints.

The main advantage in subdividing the methodology in two stages is represented by the UC and ED re-dispatch involving the AC network constraints in order to define generation scheduling fulfilling the network requirements. In the European framework, these operations are usually developed in the Intraday-Market keeping a zonal detail of the transmission network [13].

The SCUCED is carried out by solving AC load flow (ACLF) routines, and according to the operating conditions, sensitivity factors are evaluated in order to embed the linearised ACLF constraints in the problem constraints. Then, the re-dispatching cost minimisation is solved considering proper UC constraints, as well as the network ones. In the following two subsections, the two stages of the proposed method are described.

A. 1st stage: ZDAM model

The ZDAM optimisation problem is the same proposed in [10], and in the following, it is synthetically reported and described. Let us consider an electrical network with N_G generation units, installed among N_Z market zones, with N_L interzonal connections, where generators present N_S stepwise bids. The ZDAM is evaluated over a specified time horizon which is discretised into N_T time steps. For each time step, t_k ($k = 1, 2, \ldots, N_T$), the optimisation problem of the ZDAM is solved by a merit order analysis to dispatch each generation unit (G_i, $i = 1, \ldots, N_G$), assuming an inelastic load demand.

The ZDAM optimisation problem aims at minimising the total cost of generation (C_T) at one specific time period (t_k):

$$\min_{\mathbf{P_G}(t_k)} \left[C_T\left(t_k, \mathbf{P_G}\right) \right] \tag{1}$$

where the total active power dispatched at the moment t_k is:

$$\mathbf{P_G}\left(t_k\right) = \left[P_{G_1}\left(t_k\right) \quad P_{G_2}\left(t_k\right) \qquad P_{G_{N_G}}\left(t_k\right) \right]^T \tag{2}$$

And the total cost of generation at the moment t_k is:

$$C_T\left(t_k, \mathbf{P_G}\right) = \sum_{g=1}^{N_G} \sum_{s=1}^{N_S} C_g^s P_g^s\left(t_k\right) \tag{3}$$

where $P_g^s(t_k)$ represents the accepted active power of the s-th step of the g-th generator, and C_g^s is the marginal cost of the s-th bid step of the g-th generator. The objective function presented in (1) is subject to five constraints:

$$\sum_{g=1}^{N_G} \sum_{s=1}^{N_S} P_g^s\left(t_k\right) - \sum_{l=1}^{N_L} P_l^{tie}\left(t_k\right) = \sum_{z=1}^{N_Z} P_z^d\left(t_k\right) \tag{4}$$

$$\sum_{g=1}^{N_G} \sum_{s=1}^{N_S} \alpha_g^z P_g^s\left(t_k\right) - \sum_{l=1}^{N_L} \beta_l^z P_l^{tie}\left(t_k\right) = P_z^d\left(t_k\right) \tag{5}$$

$$0 \le \sum_{s=1}^{N_S} P_g^s\left(t_k\right) \le P_g^{\max} \qquad \forall g \in N_G \tag{6}$$

$$0 \le P_g^s\left(t_k\right) \le P_g^{s,max} \qquad \forall s \in N_S,\ \forall g \in N_G \tag{7}$$

$$P_l^{lb} \le P_l^{tie}\left(t_k\right) \le P_l^{ub} \quad \forall l \in N_L \tag{8}$$

in which (4) is the active power balance of the whole system, (5) is the zonal active power balance formulated of each zone ($z = 1, 2\ldots, N_Z$), (6) is the maximum limit of the generators, (7) represents the maximum power of each bid step of each generator and, finally, (8) is the available transfer capacity (ATC) bounds. In particular, P_l^{tie} represents the power flow on the l-th interzonal connection, P_z^d is the total active power demand of the z-th zone. Further, α_g^z is a binary parameter equal to 1 if the g-th generator belongs to the z-th zone and 0 otherwise. On the other hand, the binary parameter β_l^z indicates the direction of the l-th interzonal power flows, and it equals to 1 if the power flow is entering the z-th zone, -1 if it is exiting, and 0 otherwise. Finally, P_l^{ub} and P_l^{lb}, are the upper and lower bound of each zonal ATC, respectively, set considering the classical N-1 security criterion.

B. 2nd stage: SCUCED method

The objective function of the SCUCED aims at minimising thermal unit operating, re-dispatching and start-up costs and the cost of the RES curtailment. The objective function is subject to (i) Minimum up and downtime, (ii) generators' active and reactive power limits, (iii) bus voltage, and (iv) maximum branch loading.

The thermal unit operating costs are the unit marginal ones to perform in a perfect competition market, and, from a Transmission System Operator (TSO) perspective, a downward re-dispatch is an income, and vice versa for upward re-dispatch. A penalty fee is imposed on RES to avoid their curtailment (downward re-dispatch). Generators' limits involve the compliance of minimum and maximum power of both active and reactive power and the minimum up (MUT) and down time (MDT). Moreover, these generators' parameters, as well as the marginal costs, depend on the technology and the fuel of the power plant. The problem is solved considering the generator's active power dispatch and the RES curtailment as control variables.

III. MERIT-ORDER CRITERIUM ZDAM RESULTS

In this stage, the authors formulated and solved the problem as presented in [10]-[11]. The modified IEEE 39-bus test system has a high penetration of RES, and several thermal generation units (TGU) are installed among three market zones, called Z1, Z2 and Z3. The TGUs have a piecewise marginal price varying according to the technology and the fuel. The system's RES comprises 14 solar power plants and ten wind power plants, with a total installed capacity of 3600 MVA. The TGU technologies are combined cycle (CC), combustion turbines (CT) and steam turbines (ST), supplied by Natural Gas (NG), Coal or Oil with a total capacity of 3300 MVA among ten units.

TABLE I. GENERATORS TECHNICAL LIMITS AND START-UP COSTS

Generator	C_{SU} **[$]**	P_{MIN} **[MW]**	P_{MAX} **[MW]**	***MUT* [h]**	***MDT* [h]**
CC NG 01	31703.82	114.75	382.50	2	2
CC NG 02	28181.70	102.00	340.00	2	2
CC NG 03	28181.70	102.00	340.00	2	2
CC NG 04	28181.70	102.00	340.00	2	2
CT NG 01	27843.52	114.75	255.00	1	1
CT Oil 01	9461.38	89.25	297.50	2	2
CT Oil 02	8109.75	76.50	255.00	2	2
Exchange	0.00	0.00	8500.00	0	0
ST Coal 01	39737.8	114.75	255.00	24	48
ST NG 01	20274.21	25.50	255.00	8	12
ST NG 02	20274.21	25.50	255.00	8	12

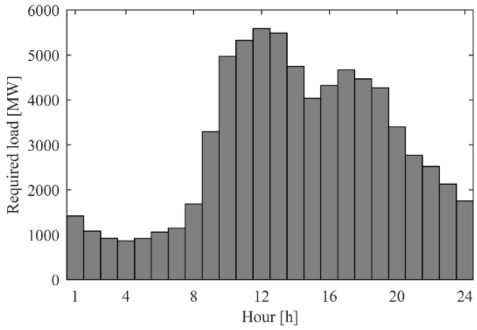

Fig. 2. Hourly load profile of the yearly peak load.

An equivalent 10000 MVA generator represents the interconnection exchange with the rest of the transmission network; for the sake of simplicity, it will be called "Exchange". Table 1 shows the active power limits, the start-up costs (CSU), and the MUT and MDT of the thermal generators. All the parameters, except the maximum power (PMAX), have been obtained, taking into account [14]-[15]. In particular, they are evaluated on each power plant's technology, fuel, and rated power. The Exchange is the only generator devoid of proper technical parameters and start-up costs, being an equivalent interconnection exchange. Marginal costs and breaking points of each generator's steps are the ones provided in [10].vThe ZDAM simulations are carried out on the yearly peak load day reported in Fig. 2. The load has an hourly resolution in which the minimum and maximum values are roughly equal to 869 and 5587 MW, respectively. The resulting dispatched generation is shown in Fig. 3, gathered by fuel.

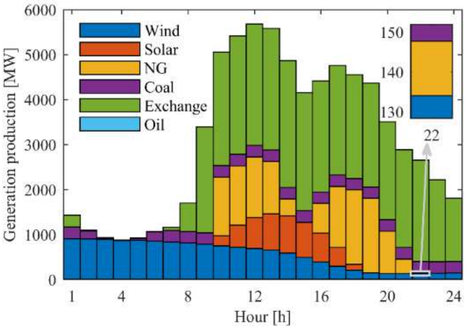

Fig. 3. Dispatched generation after the ZDAM solution per fuel.

It can be noticed that at 4:00, in which it occurs the minimum load, the wind production is sufficient to balance the load. The solar output subsists between 10:00 and 17:00, with a maximum output of approximately 833 MW at hour 14. Moreover, Fig. 3 shows that Coal generation is the cheapest unit, followed by the Exchange, NG, and Oil units. In particular, the last is never cleared because the more affordable units plus the RES are capable of supplying the required load. Finally, a detail of hour 22 shows that NG generation is the marginal one with roughly 14 MW.

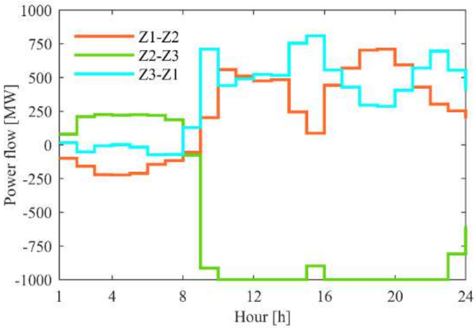

Fig. 4. Interzonal flows after the ZDAM solution.

Fig. 4 depicts the interzonal flow in which the bounds are respectively ±1600, ±1000 and ±1000 [MW] for Z1-Z2, Z2-Z3 and Z3-Z1. From 10:00 to 14:00 and from 16:00 to 22:00, Z2-Z3 reaches the lower bound, causing a market splitting of Z3. For this reason, the hourly energy price (Fig. 5) of Z3 is lower than the other zones during the market splitting hours.

IV. SCUCED RESULTS ANALYSES

The SCUCED optimisation problem is solved in the DIgSILENT PowerFactory environment by means of the module Unit Commitment and Dispatch Optimisation. The AC load flow simulations are performed by setting the voltage of the busbar generators as in the original version of the IEEE 39-bus test system [16]. The reference machine is the Exchange. Considering that the desired voltage of the generator connected to bus 36 is 1.0635 pu, in the optimisation, the voltage bounds are set ±7% of the rated voltage for all the busses. The maximum acceptable branch loading set in the problem, in percentage, is 100 %. The generation marginal costs and the line ratings are provided in [10] as well, whereas the start-up costs, as well as the generation parameters, are the ones reported in Table 1. The

RES penalty costs for curtailment are set at 150 \$/MWh. Considering the MUT and MDT of the generator ST Coal 01 and the time window of simulation, the optimisation is carried out without a rolling horizon subdivision, whereas the sensitivity factors are updated at each time step.

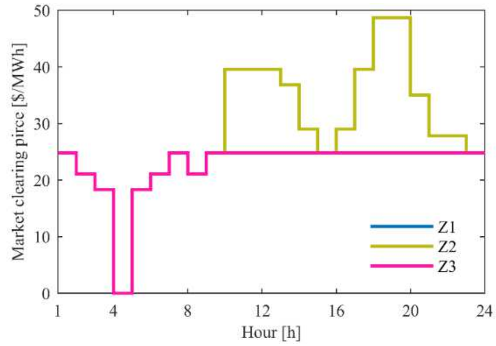

Fig. 5. Zonal market-clearing price.

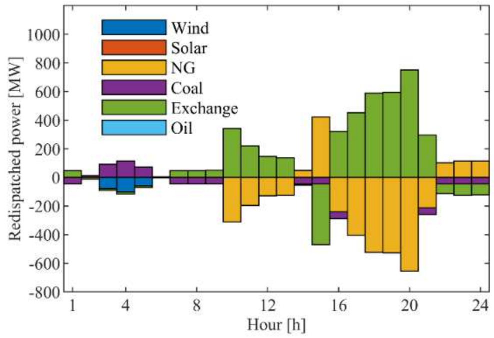

Fig. 6. Hourly net re-dispatched power per fuel.

Fig. 6 shows the net re-dispatched power after the SCUCED results gathered by fuel. Compared with the results of Fig. 3, it can be seen during hours 3:00-5:00 that the Coal generator is kept active at minimum power for the MUT constraint. In those hours, being a production lacking, only the reference machine re-dispatching (Exchange) and wind curtailment can allow the power balance keeping. It is important to pinpoint that the reference machine has the burden of loss compensation, even if it has not been dispatched after the ZDAM. In the market splitting hours, the Exchange is the most exploited generator for upward movement re-dispatching. It is due to the cost-benefit of the Exchange, it is the second cheaper unit after the Coal one, but the N-1 security criterium of the ZDAM boundaries limits its dispatching. Therefore, the full branch limits included in the SCUCED allow the increase in Exchange production, reducing the NG dispatched power, which is more expensive, during those hours. As it can be seen from Fig. 3, at hour 10, all the NG generators are started-up, and even if they are scheduled in the ZDAM, the software includes the start-up costs in the total dispatching cost reported in Fig. 7. For this reason, at hours 14:00 and 15:00 the NG is subject to an upper re-dispatch to avoid the start-up costs at hour 16:00.

At hour 22, as already said, one NG generator is the marginal one, and the software prefers to keep that generator active rather than turn it off in the remaining hours, and even it is more expensive. This occurs because the optimisation minimises the operating costs, and the NG generator is slightly lower, with 4.02 k\$/h, than the Coal one, that is 4.10 k\$/h from 22:00 to 24:00 as it can be seen in the detail of Fig. 8. The total net re-dispatched energy, considering both upward and downward movement, is approximately 10.65 GWh.

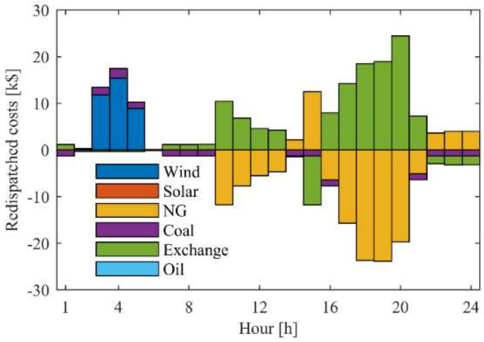

Fig. 7. Hourly total re-dispatching costs per fuel.

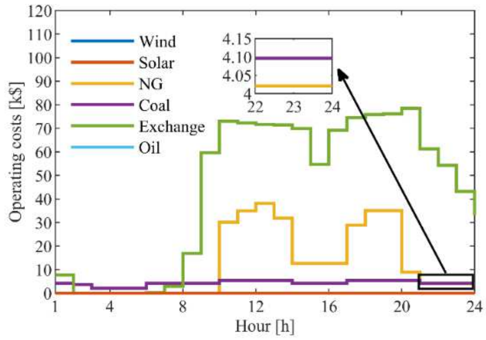

Fig. 8. Stepwise operating costs per fuel after the SCUCED.

Regarding the total re-dispatched costs reported in Fig. 7, the TSO pays the penalty costs in the hours in which the wind production is curtailed, and the total cost is 36.08 k\$. During the same hours, the Coal generator is kept active; for this reason, the start-up costs are not considered. On the contrary, at 10:00, four NG generators are started-up. Therefore, in addition to the re-dispatching costs, 116.2 k\$ of start-up costs have to be taken into account in the overall costs (Fig. 9).

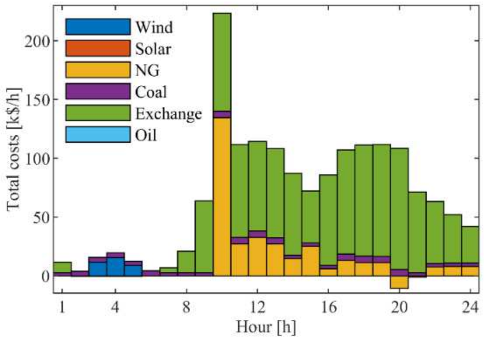

Fig. 9. Total hourly costs per fuel after the SCUCED.

Moreover, in Fig. 6, the NG production is reduced because their marginal costs are more significant than the Exchange ones. For this reason, from 10:00 to 13:00 and from 17:00 to 19:00, the total revenues from re-dispatching costs are higher than the expenses for the TSO, with a total profit of 14.94 k\$. In the remaining hours, the expenses exceed the revenues with a loss of 48.22 k\$. It is worth noting that the NG re-dispatching between 14:00 and 15:00 represents a significant cost saving for the TSO. Even if the re-dispatch costs 1.468 k\$, the actions taken during those hours saved a further 116.2 k\$ from being paid at hour 16:00 to start-up again the NG generators. Finally, Fig. 9 shows the sum of operating, re-dispatching and start-up costs. It can be seen that the Exchange represent the most expensive unit due to the power supply with a total daily cost equal to 1,171 k$. Then, there is the NG generation with a total daily cost of 315.1 k$. At hours 20 and 21, the downward re-dispatch costs are higher than the operating costs, and the sum is equal to -11.84 k$. Lastly, the daily cost of the Coal generator is 93.55 k$.

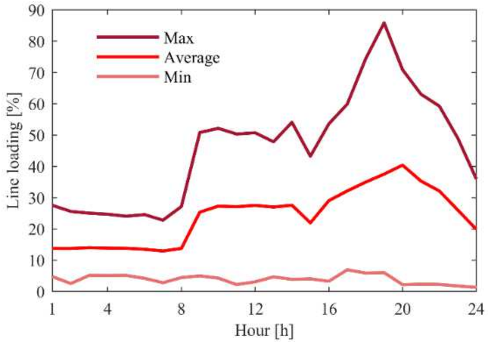

Fig. 10. Hourly maximum, mean and minimum line loadings.

Finally, Fig. 10 and Fig. 11 show the line loadings' maximum, mean and minimum values and the nodal voltages per hour. Both the results respect the constraint limits set in the optimisation. In particular, it can be seen that the maximum voltage is a constant value equal to 1.0635 pu. This is because it occurs on bus 36, where a must-run generator is set to provide reactive power to control the voltage [11].

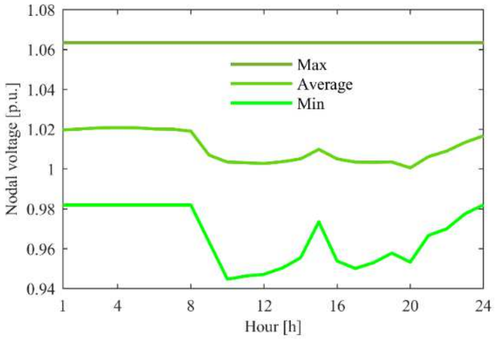

Fig. 11. Hourly maximum, mean and minimum nodal voltages.

V. CONCLUSIONS

In the present paper, a bi-stage SCUED is proposed. The main advantage of this approach is the simulation of SCUCED problems considering linearised AC load flow equations in the optimisation problem. Therefore, line loading and nodal voltage, as well as the UC, constraints are embedded in the proposed method. The method has been applied to a modified version of the IEEE 39-bus test system with high penetration of RES during the yearly peak hour.

The results show a suitable generation re-dispatching to fulfil both generation and network constraints set in the optimisation problem. The RES has been curtailed only in the hours with a low load required, in which only wind power plants are dispatched, to satisfy the MUT constraint of the Coal generator. Moreover, the tool minimises the costs in each hour, and in six hours, the revenues are more significant than the expenses. The main drawback of this tool is the addition of start-up costs for the dispatched power scheduled in the previous market; in this work, the ZDAM schedule. This behaviour affects the start-up or shutdown of the involved generators to avoid paying further costs (start-up costs). Further works will be developed, including ramps limit, shutdown costs, spinning reserve requirements, extending the time window to one year of simulations, and considering RES and load uncertainties.

VI. REFERENCES

[1] W. van Ackooij, I. Danti Lopez, A. Frangioni, F. Lacalandra, and M. Tahanan, “Large-scale unit commitment under uncertainty: an updated literature survey,” *Ann. Oper. Res.*, vol. 271, no. 1, pp. 11–85, 2018, doi: 10.1007/s10479-018-3003-z.

[2] I. Abdou and M. Tkiouat, “Unit commitment problem in electrical power system: A literature review,” *Int. J. Electr. Comput. Eng.*, vol. 8, no. 3, pp. 1357–1372, 2018, doi: 10.11591/ijece.v8i3.pp1357-1372.

[3] Q. P. Zheng, J. Wang, and A. L. Liu, “Stochastic Optimisation for Unit Commitment - A Review,” *IEEE Trans. Power Syst.*, vol. 30, no. 4, pp. 1913–1924, 2015, doi: 10.1109/TPWRS.2014.2355204.

[4] H. Ma and M. Shahidehpour, “Transmission constrained unit commitment based on benders decomposition,” *Electr. Power Energy Syst.*, vol. 20, no. 4, pp. 287–294, April 1998.

[5] D. Villanueva, A. E. Feijóo, and J. L. Pazos, “An analytical method to solve the probabilistic load flow considering load demand correlation using the DC load flow,” *Electr. Power Syst. Res.*, vol. 110, pp. 1–8, 2014, doi: 10.1016/j.epsr.2014.01.003.

[6] Q. Ploussard, L. Olmos, and A. Ramos, “A Search Space Reduction Method for Transmission Expansion Planning Using an Iterative Refinement of the DC Load Flow Model,” *IEEE Trans. Power Syst.*, vol. 35, no. 1, pp. 152–162, 2020, doi: 10.1109/TPWRS.2019.2930719.

[7] J. WANG, H. ZHONG, Q. XIA, and C. KANG, “Transmission network expansion planning with embedded constraints of short circuit currents and N-1 security,” *J. Mod. Power Syst. Clean Energy*, vol. 3, no. 3, pp. 312–320, 2015, doi: 10.1007/s40565-015-0137-8.

[8] M. A. Farrag, K. M. Ali, and S. Omran, “AC load flow based model for transmission expansion planning,” *Electr. Power Syst. Res.*, vol. 171, no. January, pp. 26–35, 2019, doi: 10.1016/j.epsr.2019.02.006.

[9] K. Purchala, L. Meeus, D. Van Dommelen, and R. Belmans, “Usefulness of DC power flow for active power flow analysis,” *2005 IEEE Power Eng. Soc. Gen. Meet.*, vol. 1, pp. 454–459, 2005, doi: 10.1109/pes.2005.1489581.

[10] G. Tricarico, R. Wagle, M. Dicorato, G. Forte, F. Gonzalez-Longatt, J. L. Rueda, “Zonal Day-Ahead Energy Market: A Modified Version of the IEEE 39-bus Test System”, submitted to IEEE ISGT Asia 2022.

[11] G. Tricarico, R. Wagle, M. Dicorato, G. Forte, F. Gonzalez-Longatt, J. L. Rueda, “A Modified Version of the IEEE 39-bus Test System for the Day-Ahead Market”, submitted to IEEE ISGT Europe 2022.

[12] ENTSO-E, “Single Day-Ahead Coupling (SDAC) “. Available online: https://www.entsoe.eu/network_codes/cacm/implementation/sdac/#:~:text=SDAC%20is%20an%20initiative%20between,power%20for%20the%20following%20day (accessed on May 15, 2022).

[13] ENTSO-E, “Single Intraday Coupling (SIDC)”. Available online: https://www.entsoe.eu/network_codes/cacm/implementation/sidc/ (accessed on May 15, 2022).

[14] An Extended IEEE 118-Bus Test System With High Renewable Penetration. Available online: https://item.bettergrids.org/handle/1001/120 (accessed on May 15, 2022).

[15] I. Peña, C. B. Martinez-Anido and B. Hodge, “An Extended IEEE 118-Bus Test System with High Renewable Penetration,” in IEEE Transactions on Power Systems, vol. 33, no. 1, pp. 281-289, Jan. 2018.

[16] Anantha Pai, Energy Function Analysis for Power System Stability. Springer, 1989.