A Modified Version of the IEEE 39-bus Test System for the Day-Ahead Market

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

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

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

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

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

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

***Abstract*— Reaching net-zero emissions inside the proposed time requires an enormous effort from the energy sector, and it is even more challenging for the electricity infrastructure. This article offers a modified version of the IEEE 39-bus system specifically created to allow zonal day-ahead market (ZDAM) simulations. The system representation is based on the original version of the IEEE 39-bus system but considers the integration of renewable energy resources (RES) in the generation mix: solar and wind. Hourly time series are used to define load profiles and wind and solar power generation. The zonal day-ahead energy market information has been created by solving the optimisation problem. Numerical results of the proposed power test system are provided for the yearly ZDAM and steady-state performance, in N and N-1 conditions, respectively, through Pyomo and DIgSILENT PowerFactory features.**

***Index Terms*-- Day-Ahead Market, IEEE 39-bus system, DIgSILENT PowerFactory, Renewable Energy Resources.**

I. Introduction

Electricity auction markets include two main categories: energy and the ancillary service markets. The first goal is to minimise dispatching costs by an economic merit-order criterion; instead, the latter provides the power re-dispatching to ensure transmission system security during real-time operation. In the European framework, energy markets are composed of Day-Ahead Market (DAM) and Intraday Market (IDM). In the last years, a pan-European cross zonal continuous-trading DAM and IDM have been developed to increase resource sharing and reduce price volatility [1]-[2], and Fig. 1 shows a generalised zonal market representation. However, the influence of intra- and inter-zonal formulation on pricing criterion has been considered [3].

In literature, one of the most exploited networks is the IEEE 39-bus system [4], especially to validate novel methods by means of the small test system. For example, the authors of [5] tested the distributionally robust coordinated reserve scheduling model considering wind power uncertainty regarding the electricity markets.

A chance-constrained optimal power flow with renewable energy sources (RES) and load uncertainties is proposed in [6]. Furthermore, the authors of [7] propose a day-ahead market (DAM) with power-to-gas technology for typical winter and summer days. Further, in [8], a medium- and long-term electricity trading approach considering RES uncertainty has been evaluated on the IEEE 39-bus system. The traditional IEEE test systems were developed several decades ago and represent a fundamental tool to validate research in the power system field because they provide standard public data. However, the progressive penetration increase of RES requires a network updating to cope with the current power system issues. In particular, the influence of RES in electricity markets and transmission evolution planning has been developed in [11]-[12]. The lack of a suitable dataset to validate novel methods in several network conditions leads to the definition in [9] of the modified version of the IEEE 39-bus system with a one-year dataset of loads and RES. The RES is composed of wind and solar power plants, and the loads are commercial with three different behaviours. In particular, the traditional generators of [4] are replaced by solar, wind and several thermal power plant technologies. For the latter, marginal costs per each typology are defined to determine the dispatched active power through DAM solving. In contrast, solar production and load profile are defined according to the geographical location of the IEEE 39-bus system busbars and the features embedded in DIgSILENT PowerFactory software. Finally, steady-state simulations are carried out to assess the network operating condition for each time step, considering the dispatched power provided by the DAM solution.

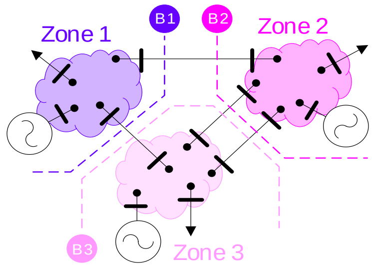

Fig. 1. Zonal network framework generalised architecture inspired by EU markets showing three zones.

In this paper, the test system described in [9] is further explained on network assumptions, and obtained results are described. The article structure is Section II describes the methodology to evaluate the techno-economic power system behaviour. Section III explains the IEEE 39-bus system modified version adjustments applied to obtain a yearly dataset to develop a two-fold analysis regarding the market and network outcomes. Section IV shows the results yielded by a zonal DAM (ZDAM) and load flow simulations. Finally, concluding comments are provided in Section V.

II. Methodology

The modified version of the IEEE 39-bus network has been developed to suit a two-fold analysis concerning the energy market and steady-state studies in N and N-1 topology conditions, explained in the following sub-sections. Further insights regarding ZDAM results are described in [9].

A. ZDAM model

Let us consider an electric power system with N_G generation units, installed inside a total of N_Z bidding zones inside the market, with N_L interzonal connections, where generators as dispatched to provide N_S step bids. The ZDAM is evaluated over a specified time horizon discretised into N_T time steps (typically 1-hour resolution over a 24-hour horizon). For each time step, t_k (k = 1, 2, …, N_T), the optimisation problem of the ZDAM is solved. In this paper, merit order analysis defines the dispatch of each generation unit (G_i, i = 1, …, N_G) considering piecewise linear bids; the load demand is assumed to be inelastic.

The ZDAM problem is formulated as an optimisation problem, where the objective function is designed to minimise 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 $P_g^s\left(t_k\right)$ represents the cleared active power of the s-th step of the g-th generator at the timestep t_k 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: Active power balance of the whole system (4), Zonal active power balance (5), formulated of each zone (z = 1, 2…, N_Z), Maximum limit of the generators (6), Maximum power of the bid steps (7) and Available Transfer Capacity (ATC) bounds (8). They are formulated as follows:

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

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

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

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

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

where P_l^{tie} represents the power flow on the l-th interzonal connection, P_z^d is the total active power demand at 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 is introduced to add directionally to the inter-tie power flows, and it equals to 1 is the l-th interzonal connection 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.

The solution of the optimisation problem (1)-(8) yields the total dispatched power, as well as the cleared generators, the market-clearing price and the interzonal power flows. Solving the ZDAM, the dispatched power of generation units is obtained by summing the cleared power over the bid steps:

$$P_g\left(t_k\right) = \sum_{s=1}^{N_S} P_g^s\left(t_k\right) \qquad \forall g \in N_G \tag{9}$$

B. Load flow simulation

Considering a power system composed of N_{bus} buses, the load flow analysis is carried out by solving a set of non-linear equations representing the power balance of the system:

$$\begin{cases} P_k = \mathrm{Re}\left(V_k^* \left(V_k Y_{kk} + \sum_{\substack{j=1 \\ j\neq k}}^{n} Y_{kj} V_j \right)\right) \\ Q_k = \mathrm{Im}\left(V_k^* \left(V_k Y_{kk} + \sum_{\substack{j=1 \\ j\neq k}}^{n} Y_{kj} V_j \right)\right) \end{cases}, \ k = 1, \ldots, N_{bus} \tag{10}$$

where P_k and Q_k represent the total active and reactive power injection at the k-th bus and are defined as:

$$\begin{cases} P_k = \sum_{m=1}^{N_{g_k}} P_{G_m} - \sum_{m=1}^{N_{l_k}} P_m^d \\ Q_k = \sum_{m=1}^{N_{g_k}} Q_{G_m} - \sum_{m=1}^{N_{l_k}} Q_m^d \end{cases} \tag{9}$$

where N_{g_k} and represent N_{d_k} the number of generation units and load demand connected to the k-th busbar.

The steady-state simulations are evaluated in the base case scenario and consider several N-1 topology condition scenarios. In particular, for the latter, it has been supposed the outage of one boundary branch per time to verify the proper modelling of ZDAM ensuring N-1 secure condition on the ATC bounds.

III. IEEE 39-BUS MODIFIED VERSION

The proposed test system is based on the IEEE 39-bus system in which generation and load are suitably adjusted in order to define one-year dataset do develop market and steady-state simulations. This section contains more information about the modified version of the IEEE 39-bus systems described in [9].

A. Geographical location and zonal subdivision

The IEEE 39-bus system is well known as the ten machines New-England Power System. It represents a simplified transmission network of several Westcoast United States of America. Using publicly available sources of old publication, the geographical coordinates of the major components of the test system is defined using latitude and longitude. Moreover, the zonal subdivision proposed in [10] is used to define three market zones for the modified version of the IEEE 39-bus test system. Fig. 2 shows the geo-reference for each bus, with the zonal subdivision. In particular, in red, there is Zone 1 (Z1), in green Zone 2 (Z2) and in blue Zone 3 (Z3).

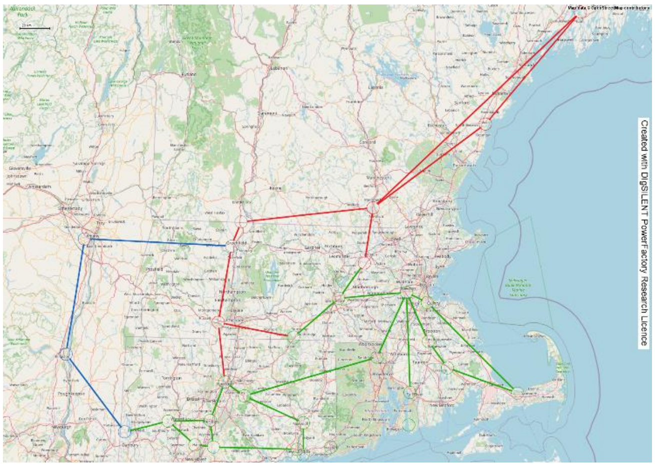

Fig. 2. IEEE 39-bus system geographic diagram with the three market zones.

B. Load profiles

The original test system is composed of 19 loads with maximum peak power equal to 6097.1 MW. In [9] the behaviours of three DIgSILENT PowerFactory load profiles are described (typical commercial load, daylight working day commercial load and evening commercial load), and they are distributed on IEEE 39-bus test system according to the geographical location of the connected busbar and considering different daily curves according to the weekday and the season.

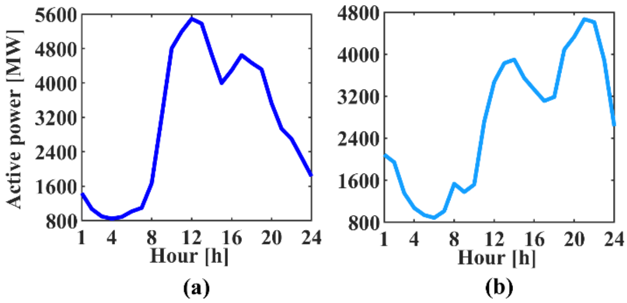

Fig. 3. The system's total power demand considers the peak load day (a) and the minimum load day (b) of the year.

For the sake of completeness, Fig. 3 shows the trend of a peak load day (a) and a baseload day (b). The peak load is equal to 5587 MW; it occurs 97 times during the year, i.e. during each Winter working day, whereas the minimum load is equal to 758 MW, and it appears 18 times, i.e. on the Crossing Sundays with total energy required equal to 21.59 TWh. Furthermore, Fig. 4 depicts the yearly zonal load duration curve. Z1 and Z3 have similar behaviours, with a zonal peak load of 1323 and 1094 MW and a minimum load of 197 and 193 MW. On the other hand, Z2 is the most energy-consuming zone during the entire year, with a peak of 3182 MW and a minimum load of 389 MW.

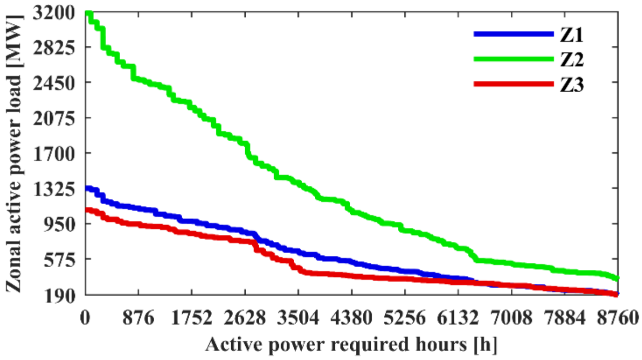

Fig. 4. Zonal required load duration curve.

TABLE I. ORIGINAL AND REPLACING GENERATION RATED POWER AND ZONE BELONGING.

Original Generators		Replacing Generators		Zone
Gen name	***Rated power [MVA]***	***Gen name***	***Rated power [MVA]***	
G 01	10000	Gen Exchange 01	10000	Z3
G 02 (Nuclear)	700	Gen Solar 01	150	Z2
		Gen Solar 02	90	
		Gen Solar 03	60	

		Gen Solar 04	100	
		Gen Solar 05	180	
		Gen Solar 06	120	
G 03 (Nuclear)	800	Gen Wind 01	150	Z2
		Gen Wind 02	200	
		Gen Wind 03	90	
		Gen Wind 04	200	
		Gen Wind 05	160	
G 04 (Coal)	800	Gen Solar 07	150	Z2
		Gen Solar 08	60	
		Gen Solar 09	100	
		Gen Solar 10	180	
		Gen Solar 11	120	
		Gen Solar 12	190	
G 05 (Coal)	600	Gen Solar 13	220	Z2
		Gen Solar 14	380	
G 06 (Nuclear)	800	Gen CC NG 01	450	Z2
		Gen CT Oil 01	350	
G 07 (Coal)	700	Gen Wind 06	120	Z2
		Gen Wind 07	180	
		Gen Wind 08	200	
		Gen Wind 09	120	
		Gen Wind 10	80	
G 08 (Nuclear)	700	Gen CC NG 02	400	Z1
		Gen ST NG 01	300	
G 09 (Nuclear)	1000	Gen CT NG 01	300	Z1
		Gen ST NG 02	300	
		Gen CC NG 03	400	
G 10 (Hydro)	1000	Gen CT Oil 02	300	Z1
		Gen ST Coal 01	300	
		Gen CC NG 04	400	

C. Generation Mix

The original IEEE 39-bus system is composed of 10 generators; the generator G01 connected to the Bus 39 represents the exchange connection with the rest of the transmission network; the remaining are nuclear, hydro or coal power plants. In [9], the criterion to substitute the original generation with the new mix of solar, wind and several types of thermal power plants is explained. For each thermal generator technology, the marginal costs are provided as well. Table I reports the rated power of the original and modified version of the IEEE 39-bus system, including the zone, of each generator.

Z1's installed capacity is 2700 MVA, of which 44.5% is a combined cycle (CC), 33.3% is a steam turbine (ST), and 22.2% is a combustion turbine (CT). At the same time, Z2 has 4400 MVA of installed generation with 50% solar (PV), 31.8% wind (WT), 10.2% CC, and 8% CT. Finally, Z3 presents only the exchange generator with a rated power of 10000 MVA. The yearly solar production is estimated according to the forecast weather by DIgSILENT PowerFactory in relation to the bus geo-references, whereas [14]-[15] are used to define the yearly wind profiles. Fig. 5 shows the annual duration curve obtained from the RES production.

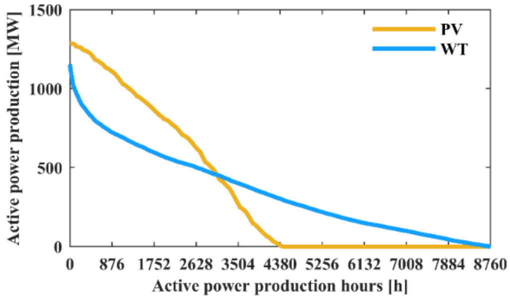

Fig. 5. Duration curve of the modified test system RES production.

IV. RESULTS AND DISCUSSION

The optimisation problem related to the energy market is modelled and solved using the well-known python-based optimisation library Pyomo [16], employing GLPK as solver. The results related to the pricing and zonal flow have been discussed in [9]. The active power dispatched per technology is reported as a duration curve in Fig. 6. Gen Exchange 01, with a dispatched energy of 11.52 TWh, provided the main annual energy amount. RES supply amounts to 3.08 TWh by solar and 2.84 TWh by the wind. Downstream there is the ST and CC production with 2.35 TWh and 1.70 TWh, respectively. Finally, CT has high bid costs, and it provides for 0.10 TWh during the peak.

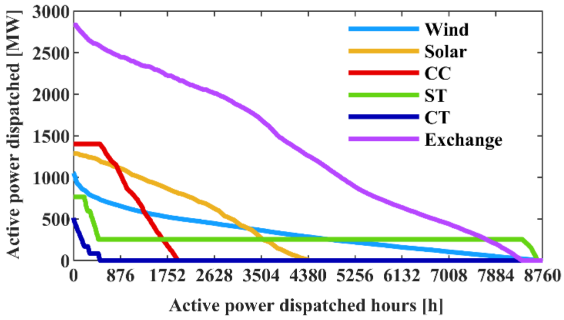

Fig. 6. Tecnologies' dispatched power duration curve.

TABLE II. MAIN INDICATORS OF THE OBTAINED ZONAL PRICES.

Zonal prices	**Minimum [$/MWh]**	**Average [$/MWh]**	**Maximum [$/MWh]**
Zone 1	0.00	29.12	233.88
Zone 2	0.00	29.12	233.88
Zone 3	0.00	24.30	29.00

As reported in Table II the minimum market-clearing price is 0 $/MWh, meaning that the load is totally balanced by RES. It occurs for 101 hours, during early morning, with a low required load, in which only wind power plants are dispatched. Furthermore, the wind production forecast is higher than the required load during that hours, causing a total energy production curtailment of 11.28 GWh.

The AC load flows performance of the proposed test system is performed using the software DIgSILENT PowerFactory, setting the desired voltage of the busbar generators as in [4]. The reference machine is the *Gen Exchange 01*, and *Gen CC NG 03* and *04* are set as must run machines to provide reactive power to control the voltage in Z1.

In addition to the line results obtained in [9], voltage results are reported in Table III, showing minimum, maximum and average values of the load busbars. The minimum value is reached at Bus 08 with 0.974 pu, whereas the maximum occurs at Bus 26 with 1.071 pu, keeping the variation between ±7.1% of rated voltage.

TABLE III. TEST SYSTEM LOAD FLOW VOLTAGES RESULTS.

Busbar	**Minimum voltage [p.u.]**	**Maximum voltage [p.u.]**	**Average voltage [p.u.]**
Bus 01	0.984	1.049	1.035
Bus 02	1.027	1.049	1.042
Bus 03	0.991	1.042	1.027
Bus 04	0.963	1.016	1.000
Bus 05	0.962	1.000	0.988
Bus 06	0.968	0.996	0.986
Bus 07	0.945	1.001	0.984
Bus 08	0.939	1.004	0.985
Bus 09	0.954	1.031	1.011
Bus 10	0.978	0.992	0.987
Bus 11	0.974	0.993	0.986
Bus 12	0.963	1.000	0.985
Bus 13	0.975	0.998	0.990
Bus 14	0.972	1.014	1.000
Bus 15	0.982	1.037	1.017
Bus 16	1.002	1.047	1.032
Bus 17	0.996	1.050	1.033
Bus 18	0.992	1.048	1.031
Bus 19	1.002	1.037	1.024
Bus 20	0.977	0.998	0.990
Bus 21	1.015	1.052	1.040
Bus 22	1.042	1.054	1.050
Bus 23	1.049	1.060	1.056
Bus 24	1.012	1.050	1.038
Bus 25	1.001	1.041	1.027
Bus 26	1.011	1.059	1.042
Bus 27	0.994	1.057	1.038
Bus 28	1.019	1.047	1.037
Bus 29	1.021	1.035	1.031

The *N*-1 conditions are evaluated by building five scenarios considering the outage of one of the boundary lines per time: 01-02 (S1), 03-04 (S2), 03-18 (S3), 08-09 (S4), 17-27 (S5). Fig. 7 shows the duration curve of the most overload line for each condition. In S2 and S3, overloads occur, respectively, at lines 16-17 and line 14-15. The first reach a maximum overload of

112.6 % with 25 hours of overloading; the second overload is up to 114.2 % with 164 overloading hours. The most loaded line is below the rated power in the remaining scenarios. Line overloads during contingency can be allowed up to a certain threshold, e.g. the author of [17] supposed a margin of 25% higher than the nominal limits. As a result, the system line loading during contingency operation of the above-mentioned lines is met by the boundary limits set in the ZDAM, according to the *N*-1 security criterion.

Finally, the minimum and maximum nodal voltage values are reported in Table IV in the N-1 scenarios. The results show an increase in voltage range variation in each scenario. In particular, on Bus 28 occurs, the maximum voltage varies from 1.097 pu in S4 to 1.139 pu in S5. In S3, S4, and S5 bus 25 is subject to the lowest voltage value. Both the buses belong to Z1, and their excursion is related to the low number of active generators to control the voltage in that market zone, as shown in Fig. 8. In S1 and S2 the lowest voltage value occurs on Bus 08, as in the base case scenario without boundary line outage.

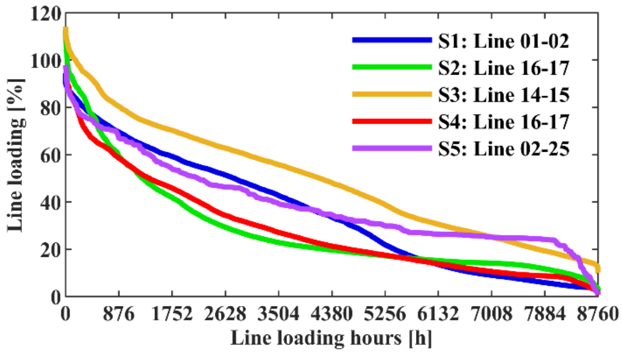

Fig. 7. N-1 scenarios' duration curve of the most loaded lines.

TABLE IV. MAXIMUM AND MINIMUM VOLTAGE VALUES IN N-1 CONTIGENCY SCENARIOS.

Scenario	Minimum voltage		Maximum voltage	
	Bus	***Value [p.u.]***	***Bus***	***Value [p.u.]***
S1	Bus 08	0.926	Bus 28	1.098
S2	Bus 08	0.943	Bus 28	1.112
S3	Bus 25	0.931	Bus 28	1.103
S4	Bus 25	0.925	Bus 28	1.097
S5	Bus 25	0.937	Bus 28	1.139

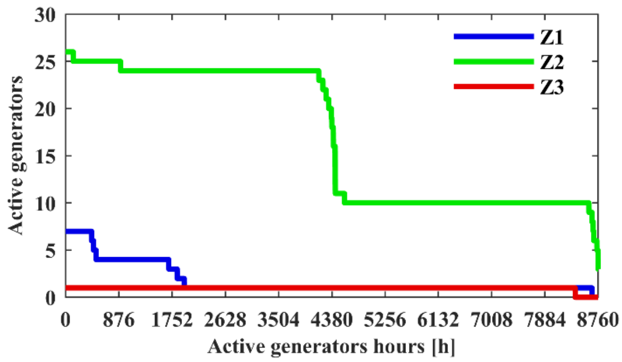

Fig. 8. Active generators duration curve for each market zone.

V. CONCLUSIONS

In this paper, the authors proposed a modified version of the IEEE 39-bus system with high penetration of RES specifically created to allow ZDAM simulations. The test system consists of 35 generators installed among three market zones. The ZDAM is solved by considering a merit-order criterion, in which fossil fuel generators present proper marginal costs and ATC is based on *N*-1 security contingency. The transmission system topology has kept the original IEEE 39-bus topology as much as possible. It has been developed using DIgSILENT PowerFactory, embedding time series of solar and wind power and power demand for an entire year considering the one-hour resolution.

The steady-state performance of the proposed test system is based on the dispatched power of the ZDAM solution in both base case and *N*-1 boundary conditions. Moreover, two generators of Z1 are set must run in order to control the zonal voltage. The results show that the base case scenario, with the hypothesis mentioned above, is feasible in terms of operational conditions. Furthermore, the results obtained during *N*-1 scenarios are suitable for line loading. In contrast, the voltage excursions in S2, S3 and S5 are higher by 10% of the nominal voltage due to a lack of active generators to control the voltage in Z1. This means that during the contingency operating conditions, it could be necessary to activate other generators in Z1 to control the voltage.

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