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# 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 Technology*
Delft, Netherland
J.L.RuedaTorres@tudelft.nl

*Abstract*— **Reaching net-zero emissions within 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 ancillary service markets. The first goal is to minimise dispatching costs by an economic merit-order criterion; the latter provides 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). Recently, 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].

One of the most exploited networks in literature is the IEEE 39-bus system [4], especially to validate novel methods through 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 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 network update 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.
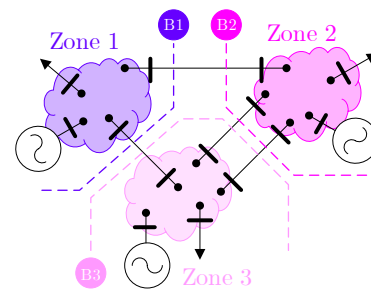


Fig. 1. Zonal network generalised architecture inspired by EU markets showing three zones.

In this paper, the test system described in [11] is further explained on network assumptions, and obtained results are described. Section II describes the methodology to evaluate the techno-economic power system behaviour. Section III presents 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 the 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 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 a 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:

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

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:

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

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

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

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

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

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, $\alpha_g^z$ 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 $\beta_l^z$ 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:

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

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 supposing $N$-1 security criterion for 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 to define a one-year dataset and 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).
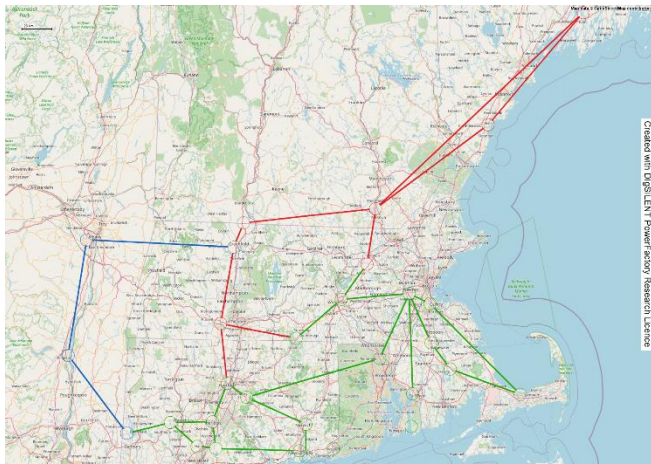


Fig. 2.   IEEE 39-bus system three zones geographic diagram.

### 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 the 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.
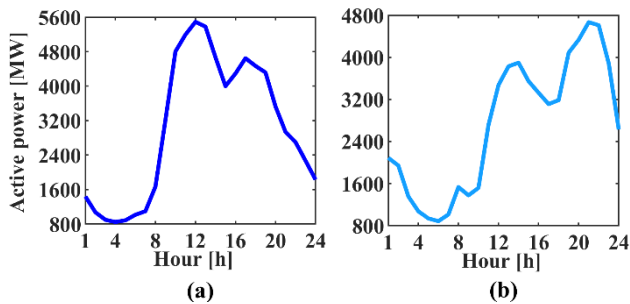


Fig. 3.   The system's total power demand considers a peak load day (a) and baseload day (b).

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.
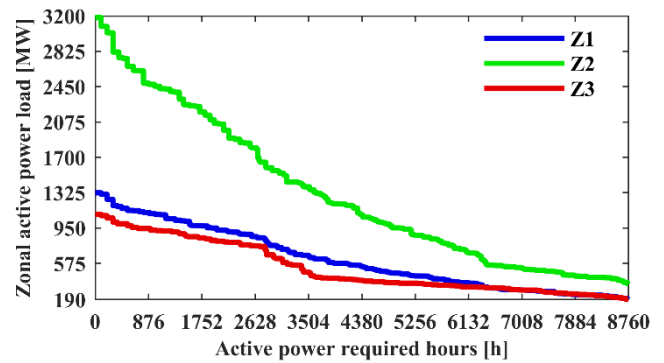


Fig. 4.   Zonal active power load duration curve.

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 ten 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, 31.8% wind, 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.
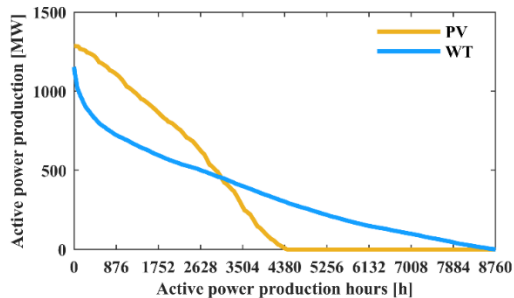


Fig. 5. Duration curve of the RES production of the modified test system.

## 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]. 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 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.
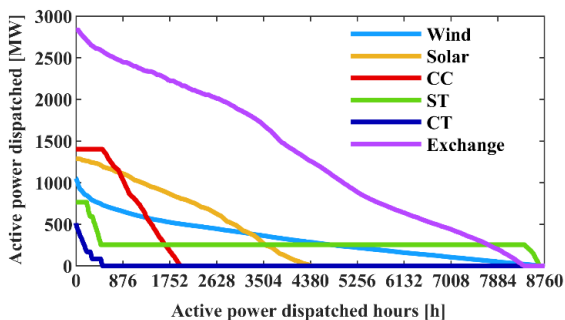


Fig. 6. Tecnologies' active power dispatched duration curve.

For 101 hours, the ZDAM market-clearing price is 0 $/MWh [9], meaning that the load is totally balanced by RES. It occurs during early morning hours, 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 hour, 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 *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 II, 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 II.    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 reached 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 III 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.
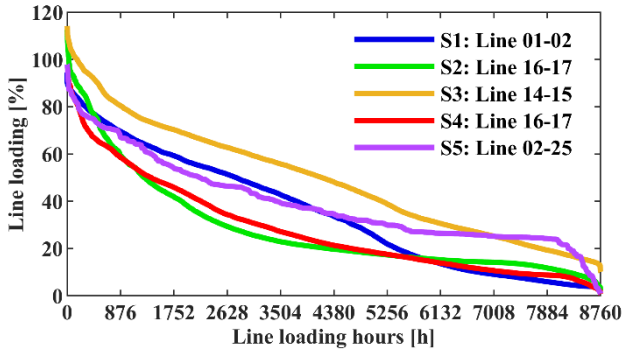
Fig. 7.   N-1 scenarios' most loaded lines duration curve.

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

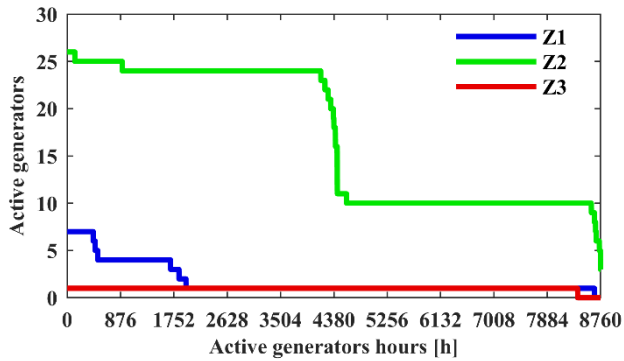| Scenario | Minimum voltage | | Maximum voltage | |
|---|---|---|---|---|
| | Bus | Value [p.u.] | Bus | Value [p.u.] |
| S1 | Bus 08 | 0.926 | Bus 28 | 1.098 |
| S2 | Bus 08 | 0.943 | Bus 28 | 1.112 |
| S3 | Bus 25 | 0.931 | Bus 28 | 1.103 |
| S4 | Bus 25 | 0.925 | Bus 28 | 1.097 |
| S5 | Bus 25 |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



Fig. 8.   Zonal active generators duration curve.

## 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 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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