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Zonal Day-Ahead Energy Market: A Modified Version of the IEEE 39-bus Test System

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***Abstract*— The increasing penetration of renewable energy resources (RES) in transmission system operating conditions require a suitable test system and a dataset to cope with current issues. RES penetration remarkably affects day-ahead market outcomes regarding zonal prices and dispatched generation levels. For this purpose, zonal day-ahead energy market models in the presence of RES in the generation mix need to be implemented. In this paper, the IEEE 39-bus system has been suitably modified to include solar and wind generation in the traditional generation mix. Hourly time series are used to define load profiles and wind and solar power generation. The zonal day-ahead market (ZDAM) resolution is simulated by solving a Linear Programming optimization problem employing Pyomo. Furthermore, steady-state nodal analysis is carried out using DIgSILENT PowerFactory, performed over a year horizon.**

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

I. INTRODUCTION

The majority of the modern power systems production and trading worldwide are *market-based*. In contrast, grid operations are strictly regulated by an independent body. The use of a power market ensures effective use of these resources with a reasonable electricity price. From this perspective, the progressive penetration of renewable energy resources (RES) affects the electricity price and the dispatched units. Nowadays, several steady-state transmission system studies are based on ZDAM solving, with a mixed generation installed of traditional thermal units and RES power plants, as in [1]-[2]. Moreover, studies on pricing criteria considering intra- and inter-zonal constraints have been evaluated in [3]. Electricity markets are auction markets, and they can be gathered into two main categories, energy and the ancillary service. The first aims at minimizing dispatching costs considering economic merit-order criterion; the latter provides the transmission system security during real-time operation. In a generalized European framework, depicted in Fig. 1, energy markets are composed of Day-Ahead Market (DAM) and Intraday Market (IDM) with a zonal network representation. In particular, DAM and IDM are daily markets with one hour of time resolution in which the first hosts the main electricity sale and purchase transactions for the day ahead. The IDM purpose is the adjustment of the supplying amount of energy to generators' technical limits and sudden weather variations to provide the correct amount of energy. In literature, one of the most used test systems is the well-known IEEE 39-bus system [3]; it has been used in many situations, especially to validate novel methods related to power system analysis (e.g. rotor angle stability, power system oscillations, etc.). Regarding the electricity markets, the authors of [5] tested the distributionally robust coordinated reserve scheduling model considering wind power uncertainty; however, having a test system to test concepts of electricity markets is still an issue.

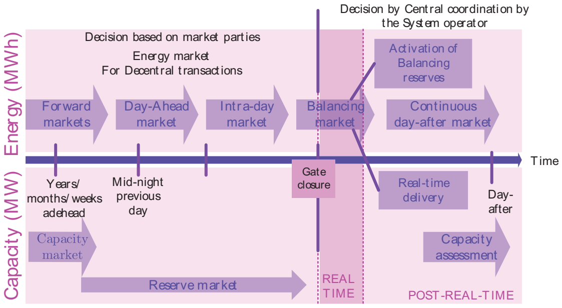

Fig. 1. Electricity markets general architecture inspired in EU markets

A chance-constrained optimal power flow with RES and load uncertainties is proposed in [6]. The reference [7] proposes a DAM with power-to-gas technology for typical winter and summer days. Further, in [8], a transmission and distribution system co-optimized economic dispatch method is applied to the IEEE 39-bus.

In this paper it is proposed a modified version of the IEEE 39-bus system, for the lacking a suitable dataset to validate novel methods in several network conditions (primarily related to electricity markets) for small test system. It includes a one-year dataset of loads, and traditional generators of the original IEEE 39-bus system [3] are replaced by solar, wind and several thermal power plant technologies. To evaluate the feasibility of the proposed version of the IEEE 39-bus system, techno-economic steady-state simulations have been developed. For economic purpose, thermal power plant marginal costs are defined, per each technology, to determine the merit order in ZDAM 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, technical simulations are carried out, by means of AC load flow routines, in which the network operating conditions are assessed considering the dispatched power provided by the ZDAM solution over the year. The results shown that the proposed modified version of IEEE 39-bus test system has been suitably designed.

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The article is structured as follows: Section II describes the methodology to evaluate the techno-economic power system behaviours. Section III explains the IEEE 39-bus system modified version. Section IV shows the results yielded by the ZDAM and load flow simulations. Finally, Section V includes concluding comments on the modified test system.

II. METHODOLOGY

In order to evaluate the power system behaviours, the procedure provides a two-fold analysis concerning the energy market and steady-state studies.

A. *Day-ahead energy market model*

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 represented by transmission lines, where generators as dispatched to provide N_S step bids. The day-ahead market is assumed to be evaluated over a specified time horizon which is discretized into N_T time steps (typically 1-hour resolution over a 24-hour horizon). For each time step, t_k ($k = 1, 2, \ldots, N_T$), the optimization problem of the zonal day-ahead energy market is solved. In this paper, a merit order analysis defines the dispatch priority of each generation unit (G_i, $i = 1, \ldots, N_G$) considering piecewise linear generation costs; and the load demand is assumed to be inelastic. With these suppositions, the ZDAM problem is formulated as an optimization problem, where the objective function is designed to minimize 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 moment t_k and C_g^s is the marginal cost of the s-th step of the g-th generator. The objective function presented in (1) is subject to six constraints: 1) Active power balance of the whole market, 2) Zonal active power balance, 3) Maximum limit of the generation units, 4) Clear bounds of the generators and 5) Bounds the zonal power flows, that are explained below. The solution of the optimization problem (1)-(8) yields the total dispatched power, as well as the cleared generators, the market-clearing price and the zonal power flows.

1) *Active power balance of the market*

The total power balance in the market is defined as:

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

where P_l^{tie} represents the power flow of the l-th interzonal transmission line, P_z^d is the total active power demand at the z-th zone.

2) *Zonal active power balance*

The zonal day-ahead market only transmission capacity limitations between the different biding zones are considered in the market-clearing process. Consequently, a constraint must be included to enforce the active power balance at each bidding zone (z = 1, 2…, N_Z):

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

where 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 if the l-th interzonal connection is entering the z-th zone, -1 if it is exiting, and 0 otherwise.

3) *Maximum limit of the generation units*

The generators are dimensioned to supply a maximum power, and to avoid an overload operating point, the sum of the accepted bid steps must be lower or equal to the rated power of each generator:

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

4) *Bid steps maximum power*

The energy supplier is enabled to offer multiple bid steps; each one is composed of a maximum power amount and suitable energy price. Therefore, a proper constrain enforcing the maximum step powers is required:

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

5) *The zonal Available Transfer Capacity (ATC) bounds*

The transmission lines interconnecting the bidding zones have physical ATC limits, set considering the classical N-1 security criterion, defined by the upper and lower limits (P_l^{ub} and P_l^{lb} , respectively) as:

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

B. *Steady-state analysis*

Solving the ZDAM, it is obtained the dispatched power of generation units, according to the economic merit order, summing the cleared power over the bid steps:

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

Considering a power system composed of N_{bus} buses, the steady-state condition of the power system can be defined by a set of equations representing the power balance of the system:

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

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

$$\begin{cases} P_k = \sum_{m=1}^{N_{g_k}} P_{G_m} - \sum_{m=1}^{N_{l_k}} P_m^d \\ Q_k = \sum_{m=1}^{N_{g_k}} Q_{G_m} - \sum_{m=1}^{N_{l_k}} Q_m^d \end{cases} \tag{11}$$

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

III. IEEE 39-BUS MODIFIED VERSION

The proposed test system is based on the classical IEEE 39-bus system; the modified version involves geographical location, load, and generation changes. Details of the proposed test system version are shown in the following sub-sections.

A. Geographical location

Using publicly available sources of old publications, the geographical coordinates of the major components of the test system have been defined using latitude and longitude. Fig. 2 shows the geo-references of the test system using DIgSILENT PowerFactory.

B. Load profiles

The test system is composed of 19 loads with a peak power equal to 6097.1 MW. The test system modified version takes advantage of the load modelling aspects included in DIgSILENT PowerFactory. These profile characteristics are obtained by a combination of Workday, Saturday, and Sunday behaviours during Winter, Crossing and Summer seasons. The load profiles are defined by peak load, which have three distinct trends based on the following characteristics: (i) L0: General commercial load, (ii) L1: Commercial weekdays load from 8:00 am to 6:00 pm and (iii) L2: Commercial evening load. The load profiles are created using fifteen minutes time resolution; Table I shows the leading statistic indicators: minimum, maximum, and average daily value, with the respective occurring time, for each characteristic of the three loads.

Considering the geo-references of Fig. 2, the previous load profiles are used to define three different behaviours in the system's demand required, according to the following criterion. (i) L0 is a load profile to be used at loads installed in the substation close to the city centres. (ii) L1 is the load profile found in suburban areas; therefore, this profile can be allocated to the loads outside the cities. (iii) L2 is supposed to be a load profile used at loads installed in the substations next to the ocean or the ones surrounded by the other load. Table II shows the active power peak load, the nominal power factor, the associated characteristic and the falling zone for each load, and Fig. 3 shows the yearly loads utilizing a boxplot. The peak and base loads are roughly 5587 MW and 758 MW, respectively, and the required annual load is 21.59 TWh.

C. Network market zones

Fig. 4 show the DIgSILENT PowerFactory one-line diagram of the zonal network considering the subdivision provided in [9]. The branch rated powers are set equal to 1000 MVA, according to [10]. The lines of Zone 3 (lines 01-39, 01-02, 39-08 and 08-09) have been doubled because the interconnection of Zone 3 with Zone 1 and Zone 2 are composed of one transmission line (01-02 and 08-09, respectively) and to consider an N-1 secure condition it is necessary to consider a doubling of the interconnection between the two zones to avoid the total disconnection. Moreover, line 02-03 interconnects two boundary lines between Zone 1 and Zone 2. Therefore, it is necessary to double this line as well in other to avoid overloads. Thus, the boundary between Zone 1 and Zone 2 (Boundary 1) has a total rated power of 3000 MVA, the boundaries between Zone 2 and Zone 3 (Boundary 2) and Zone 3 and Zone 1 (Boundary 3) of 2000 MVA.

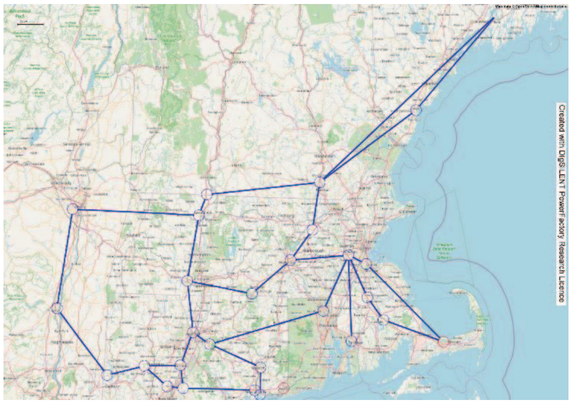

Fig. 2. DIgSILENT PowerFactory geographic diagram of the test system.

TABLE I. MAIN STATISTIC INDICATORS OF THE LOAD PROFILES.

Load Profile		**Main profile values**				
		Min	*Time*	*Max*	*Time*	*Avg*
L0	Summer Saturday	0.278	03:30	0.771	11:45	0.433
	Summer Sunday	0.191	06:00	0.350	21:00	0.268
	Summer Workday	0.221	03:15	0.872	11:45	0.511
	Crossing Saturday	0.279	03:15	0.812	11:45	0.452
	Crossing Summer	0.181	04:30	0.369	20:30	0.273
	Crossing Workday	0.225	03:15	0.924	11:45	0.530
	Winter Sunday	0.264	03:15	0.867	11:15	0.463
	Winter Saturday	0.174	04:30	0.394	19:45	0.270
	Winter Workday	0.198	03:00	1.000	11:45	0.556
L1	Summer Saturday	0.042	01:15	0.100	11:00	0.056
	Summer Sunday	0.038	08:30	0.050	13:00	0.045
	Summer Workday	0.042	03:30	0.697	09:30	0.266
	Crossing Saturday	0.038	02:30	0.128	09:45	0.065
	Crossing Summer	0.038	17:30	0.047	19:15	0.042
	Crossing Workday	0.037	04:30	0.811	11:00	0.309
	Winter Sunday	0.050	04:30	0.120	10:45	0.070
	Winter Saturday	0.050	04:30	0.074	19:00	0.060
	Winter Workday	0.048	04:30	1.000	09:30	0.371
L2	Summer Saturday	0.093	04:30	0.654	18:15	0.382
	Summer Sunday	0.089	04:30	0.581	19:45	0.329
	Summer Workday	0.104	02:30	0.725	20:15	0.413
	Crossing Saturday	0.093	05:30	0.779	18:30	0.444
	Crossing Summer	0.092	05:30	0.667	20:15	0.369
	Crossing Workday	0.104	05:30	0.850	20:30	0.467
	Winter Sunday	0.105	05:30	0.934	18:30	0.517
	Winter Saturday	0.114	05:30	0.802	20:00	0.439
	Winter Workday	0.105	05:30	1.000	18:30	0.532

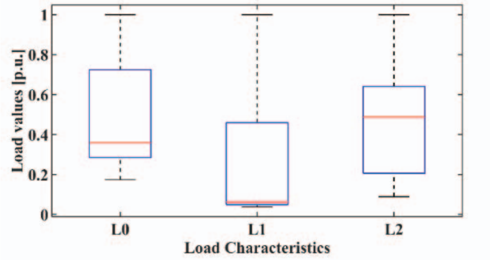

Fig. 3. Yearly load characteristic boxplots.

D. Generation Mix

The IEEE 39-bus system is composed of ten generators; the generator at Bus 39 represents the exchange connection with the rest of the transmission network; the remaining are nuclear, hydro or coal power plants. The latter are substituted by several generators of different technology, including RES, to increase the generation flexibility and competition in the electricity markets. For the sake of simplicity, the term "original" is referred to the IEEE 39-bus system, and "new" is referred to the modified version.

TABLE II. PROPOSED LOAD PROFILES AND INDICATORS FOR IEEE 39-BUS TEST SYSTEM.

Load name	Busbar	Active power [MW]	Power factor	Load characteristic	Zone
Load 03	Bus 03	322.0	0.99997	L2	Zone 1
Load 04	Bus 04	500.0	0.93847	L1	Zone 2
Load 07	Bus 07	233.8	0.94110	L0	Zone 2
Load 08	Bus 08	522.0	0.94759	L1	Zone 2
Load 12	Bus 12	7.5	0.08492	L2	Zone 2
Load 15	Bus 15	320.0	0.90218	L0	Zone 2
Load 16	Bus 16	329.0	0.99521	L0	Zone 2
Load 18	Bus 18	158.0	0.98245	L1	Zone 2
Load 20	Bus 20	628.0	0.98681	L2	Zone 2
Load 21	Bus 21	274.0	0.92208	L1	Zone 2
Load 23	Bus 23	247.5	0.94625	L0	Zone 2
Load 24	Bus 24	308.6	0.95815	L2	Zone 2
Load 25	Bus 25	224.0	0.97851	L0	Zone 1
Load 26	Bus 26	139.0	0.99260	L2	Zone 1
Load 27	Bus 27	281.0	0.96575	L1	Zone 1
Load 28	Bus 28	206.0	0.99114	L2	Zone 1
Load 29	Bus 29	283.5	0.99553	L0	Zone 1
Load 31	Bus 31	9.2	0.89443	L2	Zone 2
Load 39	Bus 39	1104.0	0.97531	L0	Zone 3

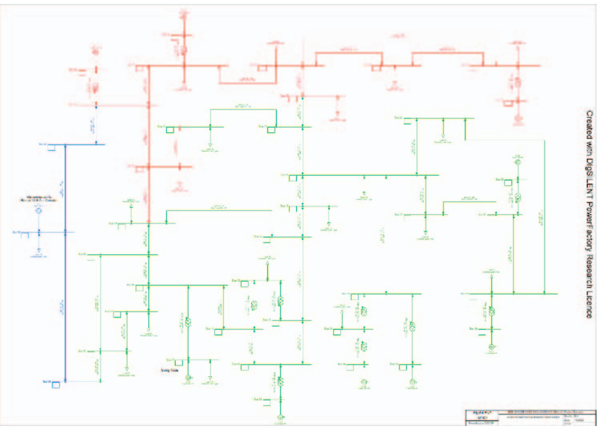

Fig. 4. One-line diagram of the IEEE 39-bus system in three zones. Zone 1: red, Zone 2: green, Zone 3: blue

The subdivision criterion is to keep the original generator rated power:

$$S_{n_j} = \sum_{i=1}^{N_j} S_{n_{i,j}} \quad j = 2, \ldots, N_j \tag{12}$$

where S_{n_j} is the rated power of the j-th generator of the original network, $S_{n_{i,j}}$ is the rated power of the *i*-th new generator to substitute the *j*-th generator, and N_j is the number of new generators of the *j*-th generator. Neglecting the external grid generator (G 01), the new test system presents 1500 MVA of wind turbines (WT), 2100 MVA of photovoltaic (PV), and 3300 MVA of several thermal power plants as generation capacity with a nominal power factor of 0.85. Fig. 5 shows the percentage installed capacity per each specific technology. It comprises roughly 52% of renewable energy sources (RES), and they are totally installed in Zone 2. The PV power plants' production is estimated according to the forecast weather by DIgSILENT PowerFactory. For the WTs it has been exploited the dataset of [11]-[12].

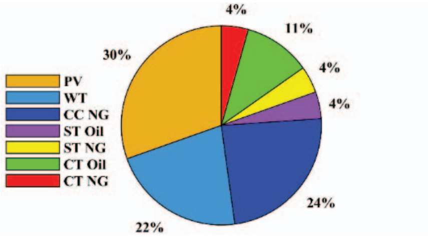

Fig. 5. Generation mix proposed for the modified version of the test system.

RES has a marginal price equal to 0.00 $/MWh to develop the energy markets. In contrast, the thermal generators have a marginal price varying according to the technology and the fuel. They are set according to the piecewise costs of [11]-[12] and reported in Table III with the respective breakpoints (BP). The BP represents the generator marginal cost changing power point. Gen Exchange 01 represents the equivalent exchange with the rest of the US/Canada transmission system. Therefore, its marginal price has been obtained as the average of all the marginal costs of the generators of [11]-[12], considering the first breakpoint RES as well. It is important to note that the dataset of [11]-[12] is appropriate for these purposes for two main reasons. On the one hand, both are transmission systems from the United States, making them the most reliable WT productions and marginal costs available online. Thermal power plant technologies presented in this work, on the other hand, are included in the NREL 118, and marginal prices are considered based on the respective rated power and technology.

TABLE III. PROPOSED GENERATION MARGINAL COSTS

Generator	**C_g^1 [\$/MWh]**	**BP_1 [MW]**	**C_g^2 [\$/MWh]**	**BP_2 [MW]**	**C_g^3 [\$/MWh]**	**BP_3 [MW]**
Gen Exchange 01	24.80	2833.00	56.22	5667.00	61.61	8500.00
Gen CC NG 01	35.04	204.00	36.84	293.25	39.56	382.50
Gen CT Oil 01	209.45	159.00	233.88	228.00	264.32	397.50
Gen CC NG 02	27.80	181.00	29.00	261.00	30.80	340.00
Gen ST NG 01	48.67	102.00	49.85	178.20	51.22	255.00
Gen CT NG 01	48.48	161.50	51.20	208.25	55.67	255.00
Gen ST NG 02	48.67	102.00	49.85	178.20	51.22	255.00
Gen CC NG 03	27.80	181.00	29.00	261.00	30.80	340.00
Gen CT Oil 02	218.65	136.00	234.19	195.50	257.97	255.00
Gen ST Coal 01	18.31	161.50	19.67	208.25	21.09	255.00
Gen CC NG 04	27.80	181.00	29.00	261.00	30.80	340.00

IV. RESULTS AND DISCUSSION

The ZDAM has been modelled and solved using the well-known python-based optimization library Pyomo [13]. The ATC values have been set to 1600 MW for Boundary 1 and 1000 MW for Boundary 2 and 3. The load is sampled each hour by the software. The zonal exchange constraints are bound for 1930 hours from Zone 3 to Zone 2, as seen from the duration curve of the interzonal bound percentage values (Fig. 6). Table IV shows the minimum, average and maximum zonal price during the year. Zone 3 is characterized by a lower zonal price due to the congestion among the other zones; therefore, each time it occurs, the market splitting implies clearing more expensive units installed in Zone 2 and Zone 1. Moreover, for 101 hours, the market-clearing price is equal to

0.00 $/MWh; this occurs when the RES production is sufficient to balance the demand load.

TABLE IV. 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

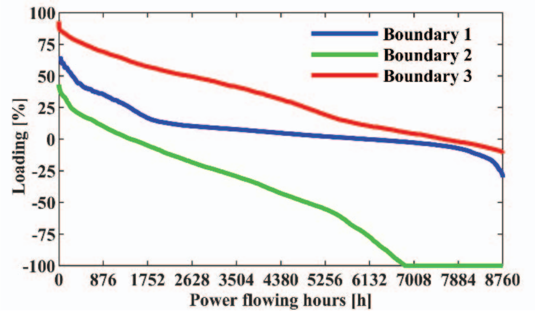

Fig. 6. Zonal boundaries power flow duration curve.

TABLE V. TEST SYSTEM LOAD FLOW LINE LOADING RESULTS.

Line	Minimum loading [%]	Maximum loading [%]	Average loading [%]
Line 01-02	4.5	54.5	21.7
Line 01-39	10.5	54.5	24.4
Line 02-03	5.0	55.3	20.6
Line 02-25	4.9	72.9	31.8
Line 03-04	11.2	49.6	19.5
Line 03-18	1.5	67.4	28.9
Line 04-05	6.0	59.5	27.7
Line 04-14	0.8	28.0	9.1
Line 05-06	0.3	40.8	19.3
Line 05-08	1.4	44.2	17.6
Line 06-07	0.8	32.9	13.4
Line 06-11	0.7	38.5	12.7
Line 07-08	4.7	46.9	20.3
Line 08-09	7.3	50.9	24.1
Line 09-39	8.7	50.9	24.6
Line 10-11	0.4	35.2	11.7
Line 10-13	4.7	59.0	26.0
Line 13-14	4.8	61.8	27.7
Line 14-15	9.8	75.3	31.9
Line 15-16	10.3	58.1	22.7
Line 16-17	1.2	92.5	26.3
Line 16-19	1.6	62.9	28.3
Line 16-21	6.8	30.8	13.4
Line 16-24	7.3	38.8	18.4
Line 17-18	0.8	64.9	25.0
Line 17-27	2.2	48.7	12.0
Line 21-22	4.5	37.8	12.5
Line 22-23	1.8	31.9	10.4
Line 23-24	4.3	21.6	10.3
Line 25-26	5.2	55.3	27.4
Line 26-27	1.4	70.0	12.1
Line 26-28	4.2	25.8	11.8
Line 26-29	5.3	26.1	11.3
Line 28-29	1.4	36.2	7.5

The steady-state performance of the proposed test system is performed using the power flow calculation command in DIgSILENT PowerFactory, setting the desired voltage of the busbar generators as in [3]. The total active power losses are 467.89 GWh, i.e. the 2.17% of the total yearly load. The minimum voltage value is reached at Bus 08 with 0.974 pu; the maximum occurs at Bus 26 with 1.071 pu. Regarding the line loading, Table 5 shows the minimum, maximum and average percentage values obtained during the yearly simulation, demonstrating the total feasibility of the proposed system.

V. CONCLUSIONS

This paper proposes a modified version of the IEEE 39-bus system specifically created to allow ZDAM simulations. It presents high penetration of RES and several thermal generation unit technologies installed among the three market zones. The new test system has been developed using DIgSILENT PowerFactory. Simulation results have shown that the geographical location plays an essential role as the power production of the PV power plants depends on the solar irradiation, the load profile is based on busbar surrounding (i.e., city centres, suburban areas or close to the ocean). The steady-state performance of the proposed test system has been assessed for the dispatched power of the ZDAM solution, proving the operating condition feasibility of the modified version of the test system over the one-year time horizon. The present work represents the basement for further studies related to the ancillary service market and reactive power re-dispatch, which will be investigated in additional pieces of research.

VI. REFERENCES

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