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RESEARCH ARTICLE

Impacts of Transactive Energy Trading on the Load Point Reliability Indices of LV Distribution System

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ABSTRACT The optimal allocation of renewable energy sources and energy storage systems in medium-voltage distribution grids to achieve several objectives was followed by low-voltage applications. However, the main obstacle against large-scale renewable penetration at low voltage grids has been found as a centralized energy market structure where it is almost impossible to achieve all the benefits of renewable energy sources. At this point, the transactive energy market, which enables selling the surplus energy of the distributed generation owners to a consumer in their neighborhood or reverse feeding the utility through intelligent metering devices, is an attractive option. This paper presents how the transactive energy market can improve renewable energy share and customer reliability in the low voltage distribution grid. The impact of the increase in the number of prosumers who prefer to participate in the market on load point reliability indices has been studied in detail. European low voltage Test Feeder is used as an application system with sun irradiation and PV generation in a specific geographical area in Turkey. Energy market prices and their estimated future are also based on Turkey's market prices. Reliability indices for a different number of prosumers in the network have been evaluated, and discussion has been provided regarding the network reaction to the increase in the number of prosumers. The results show that installing low voltage PV systems is an uncoordinated process, which requires a pre-simulation to estimate the economic benefits for the prospective prosumer locations, considering the consumer intentions on supply preferences.

INDEX TERMS Transactive energy market, peer to peer (P2P) energy trading, load point reliability indices.

I. INTRODUCTION

Distributed generation (DG) in medium voltage grids has been one of the hot topics of the power engineering community. Several formulations and solution methods were proposed to optimize them to achieve several objectives [1], [2], [3]. However, it was not an attractive issue among householders and other low-voltage (LV) consumers for a long time because of the high investment costs. Later, increased environmental awareness on not using fossil fuels, power quality, and reliability concerns, and potential benefits of demand response activities motivated small-scale consumers to utilize renewable energy sources (RES) and distributed generations of the low-voltage electricity grid worldwide. Consequently, Active (Low-voltage) Distribution Networks (ADN) have become a hot concern of network planners, which have to provide a flexible way out [4].

Technological improvement in using the internet and other information-communication technologies (ICTs) highlighted the need to meet the reliability expectations of the customers. This energy could be provided in rural areas using accessible energy resources. Distributed energy resources like PV panels and small-size wind turbines could be a good fit for the lack of energy transmission to rural areas [5]. However, increasing the capacity of small-scale PV systems causes several challenging problems for distribution companies (DisCos). DisCos have been looking to transfer the issues arising from the widespread use of rooftop PV generation

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into technical benefits and economic savings. Technical benefits include appropriate network design and operation. In contrast, the economic benefits related to decreased distribution costs and investment are due to shorter distances between the locations of generation and consumption points.

Considering environmental issues, among the most significant reasons for householders to use rooftop PV panels, in [6], the authors provided an intelligent energy trading platform with two main focuses. The first is providing a time-aware energy-sharing plan, and the second is reducing the network's total energy cost. Based on the traditional market structure, which did not let the low-voltage PV owners take full advantage of their investment, the payback duration increased with increasing PV unit size.

At this point, DG owners had two alternatives to get the full benefit of installed units: selling the surplus energy to the utility or directly to a nearby consumer. Based on the limits the distribution system operator (DSO) can put on DG units' allowable injected power to the network, it sells the surplus energy to the nearby consumer. The second transaction, selling the surplus energy to a neighbor, is more beneficial than selling to the utility. This energy transaction or sharing improved the balancing of the generated and consumed energies [7]. Such an energy trading system in which all the stakeholders on the grid can participate in the energy exchange and create a more efficient and reliable power transfer is known as the Transactive Energy (TE) Market [8]. Several studies regarding TE are summarized in the following paragraphs, mainly focusing on the market structures and effects.

In [9], a combination of trading between prosumers and consumers and Demand Response (DR) programs using Mixed-Integer Nonlinear Programming (MINLP) has been performed to decrease the whole power cost, reduction of switching operations, and power generation optimization. Gupta et al. presented a comparative study of several TE systems focusing on market structure, management, and architectural design. TE concepts improve with a focus on incidents from a local, distribution-level point of view. Also, these ideas have yet to be real-world implementation, It is crucial to create and use the right simulation platforms and tools to perform a detailed analysis of the obtained data. Each TE idea requires more effective design practices to improve the customer reliability, adaptability, and accuracy of the results [10].

In [11], a trading mechanism has been proposed in which household energy bill has been reduced, and prosumers get fair benefits simultaneously. Li et al., in the market clearing process using Nash bargaining theory, adjusted the interests of each agent [12]. As prosumers in LV distribution network mostly generate energy using PV cells, improper generation forecast could be a concern for the prosumers. Chen et al. prepared a transactive energy market platform in which prosumers and flexible loads could communicate, and the difference between realized and forecasted generation was compensated by the flexible loads [13].

Based on the centralized structure of the traditional market, only the consumers with high consumption, like DSOs or industrial companies, can participate in the market operation. The small players, like householders, are passive stakeholders without active participation in the grid operation. Such a structure makes the traditional market inefficient for prosumer-based clearing mechanisms. However, a transactive energy market is a sample of a decentralized platform that enables direct energy trading of the prosumers and consumers.

Unlike to a centralized, traditional market structure, decentralized architecture like Peer-to-peer (P2P) energy trading has several advantages, such as fault toleration, scalability, compatibility, and resiliency. On the other hand, maintenance and investment costs in a decentralized market can also be reduced or postponed [14].

Electric Energy Storage Systems (EESSs) can improve TEM benefits as electricity demand and PV generation are probabilistic and uncertain variables. EESS units can overcome the problems arising from the time differences between peak load duration and high power generation. EESS integration in the grid could result in peak load shaving by saving the prosumers' surplus generation in the off-peak period and injecting it back into the grid during peak load periods. This will reduce consumers' energy costs and utility infrastructural investments. EESSs could be considered alternative energy sources, especially in the case of islanding conditions due to switching processes [15], [16]. Islands with integrated EESSs can use the stored energy in an energy supply shortage, improving reliability indicators like the System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI). EESS installation becomes more vital when the network infrastructure installation or upgrade is more expensive because of the rural network's load dispersion and long overhead line feeders. However, network planners and operators must be careful about the optimum sizing of aggregator-owned central energy storage with respect to energy arbitrage and reliability improvement. In future rural feeders, an aggregator/retailer will likely purchase energy from both the main grid and prosumers at relevant times and sell it to the customers at other times [17].

Shahmohammadi et al. proposed a linearized model for the optimal design and operation of energy hubs to improve reliability [18]. Adequacy indices and maximum allowable loss of load probability are checked for single contingencies, and several reliability constraints are tested within the optimization process to satisfy the required reliability level for different load types. Considering the energy storage system (ESS) applications, a model was provided in [19] for ADN planning. An assessment of a long-term investment cost was prepared alongside a short-range operational condition. Authors exposed that by integrating ESS to 20 kV MV grid side, there would be an increase in supply reliability. In [20], the authors suggested a P2P energy transaction between Electrical vehicles and PV generation units with variable pricing terms.

AlSkaif et al. tested two different matching strategies between prosumers and consumers; the first was based on supply and demand equalities, and the second was based on the distance between TEM participants [21]. The study recommended the second strategy as it provided better conditions so that more householders participated in the P2P transaction process for more hours.

Reliability evaluation in an electrical network could be performed by applying direct analytical methods or simulation methods regarding the network characteristics and available data [22]. Creating the mathematical model of the network and then using numerical solutions for the model is the basic procedure of analytical methods for calculating the reliability indices. Depending upon the complexity level of the network, making some approximations is inevitable. Since these approximations may sometimes be the reason for low resolution in results, simulation methods are generally preferred for network reliability assessment [23]. These basic principles are also valid for LV distribution networks, and based on the number of elements, like nodes, branches, and busbars, simulation methods are mostly preferred for reliability calculations.

In [24], network reconfiguration was proposed using Modified Shark Smell Optimization (MSSO) to improve voltage profiles and reliability by minimizing network power losses. This reconfiguration resulted in more than 70% improvement in SAIFI, SAIDI, and Expected Energy Not Supply (EENS) values. To calculate the Mean Time to Repair (MTTR) and Mean Time Between Failures (MTBF), time sampling using Monte Carlo Simulation (MCS) was performed in [25].

Authors in [26] provided a P2P market strategy where the energy losses along the route between generation and consumption points have been considered in the pricing strategy. Two cases were studied: one with no local generation in the network and entirely relying on the utility grid, and the other with P2P trading among the three prosumers and the passive grid consumers. ENS, SAIDI, and SAIFI indices of the latter case were 20% better than the first case.

Most of the reliability studies in electrical power systems were focused on the HV or MV side of the grid. The limited LV distribution grid reliability studies have focused on assessing system-based or feeder-based indices. On the other hand, many customer interruptions originated from the LV network failures, compared to MV and HV networks. However, the failures in low-voltage networks affect a limited number of customers, and the reliability expectations of LV customers are generally load-dependent. In this context, unlike the MV networks, feeder-based reliability indices may not be the first concern of the end-users. Instead, they are more interested in the intended reliability improvements through transactive energy trading using small-scale prosumers in the LV grid. In this regard, this study concentrates on the load point reliability assessment in the LV distribution grid to account for the intentions of different load types.

This paper aims to fulfill the gaps mentioned above in the LV distribution grid for transactive market conditions by presenting a load point reliability assessment using the sequential MCS for the European LV test feeder given in Figure 1 for five case scenarios. The aim is to identify the appropriate number of PV installations using the reliability analysis of these five scenarios. The first case is assigned as the base case, where the grid does not include any prosumers, and the energy market operates as a traditional centralized market. In all other scenarios, a decentralized market using realistic market values of Turkey has been provided to check the supply of each load point.

In the first step, market analysis is performed for each case scenario. Then, load point reliability indices are calculated for the known reliability parameters of the grid components. The resulting reliability indices are finally compared to each other to state the performance of different operating scenarios and to identify the cost-effective number of prosumers for the test system.

The remainder of the paper is organized as follows. Section II describes the transactive energy market operation. Section III is devoted to LV distribution grid reliability assessment. Section IV defines the scope of the study based on the constraints and assumptions. Simulation results and their discussion are summarized in Section V. Finally, conclusions and prospective future studies are reported in Section VI.

II. TRANSACTIVE ENERGY MARKET

In this study, we deal only with residential loads. In this context, the end-users (customers) are categorized into two different groups;

- Passive end-users: These are passive loads without any generation facility. They are known as consumers.
- Proactive end-users: The loads in this category also have rooftop PV generation facilities. They will be called prosumers.

Prosumers prefer using their generation capacity as far as possible to meet their demand. However, they may have a surplus of energy depending upon the weather conditions and internal consumption. Based on traditional electricity market rules, prosumers can sell this surplus energy to the distribution grid according to the regulations prepared by the DSO authority. These restrictions put a cap on the maximum injected power to the grid and the selling price. It will discourage the customers from installing their own rooftop PV systems as it will extend the pay-back duration. However, selling the surplus energy to a non-centralized market, like TEM, will motivate the consumers to transform the prosumers, as far as financial conditions are appropriate. On the other hand, the customers of the surplus energy generated by the prosumers are generally their neighbors

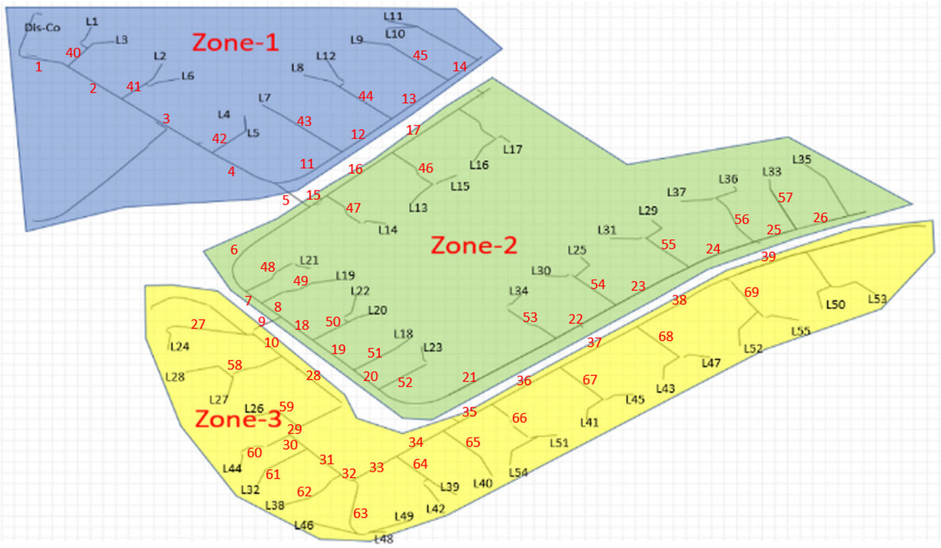

FIGURE 1. European LV test feeder.

in TEM. That is, while the main grid in the traditional market is the only alternative for the passive consumers to provide their energy needs, in TEM, they will have a choice to select their provider between different prosumers if it exists or the DSO. The main criterion in this selection is the energy price of prosumers or DSO bids in the market. However, some other determinants can affect the decisions made by consumers. As an example of these determinants, we can point out that environmental sensitivity issues increase the selection potential of the prosumers. On the other hand, there may be some emotional addiction or trust in supply reliability to the DSO because of long-term relationships with the customers. All these concerns affecting consumer preferences are included in the process using Loyalty Factors. Note that the loyalty factors are generally random and assigned to each consumer separately.

Two different types of tariffs are used in Turkish low-voltage distribution networks, and customers are free to choose either [27]. In a single-rate tariff, the prices are constant at each hour, whereas the three-rate tariff offers different prices for the three time slots in a day: daytime, peak time, and nighttime. On the other hand, each prosumer in the P2P market can offer different tariffs and prices for each consumer. Various factors impress this pricing mechanism, which will be formulated and described in this section.

Since the prosumers use the DSO low-voltage infrastructure for transferring their surplus energy to the other consumers in the grid, their energy prices are determined considering an additional distribution system usage charge (DSUC). There will be an energy loss along the route from the prosumer to the consumer, which is dependent on the type (cross-section) and length of the line segments. This energy loss also needed to be considered in the pricing process. In this regard, each prosumer in the grid provides a bidding price for each consumer using the following equations;

$$C_{pv} = C_{op} + C_{pf} \tag{1}$$

$$B_i = C_{pv} \cdot (1 + (C_{R_i}/100)) \tag{2}$$

In these formulas, C_{pv} [\$/kWh] represents the unit base price of the prosumers, which is composed of two components. The first one, C_{op} [\$/kWh], is the DSUC, which can be sampled using the transmission network DSUC value. The second one, C_{pf} [\$/kWh], is the price that will be paid to the prosumer by DSO in a traditional market [27]. B_i [\$/kWh] is the unit bidding price of i^{th} prosumer regardless of the demand point. C_{R_i} is the intended profit rate of the i^{th} prosumer, which is calculated considering the difference between the bidding price of the prosumer and the price that DSO offer to the prosumer (C_{pf}).

In order to calculate the line losses during transactive energy transfer from prosumers to consumers, an nxn loss coefficient matrix (**L**) can be constructed, where n is the number of end-users. An entry $l_{i,j}$ of this matrix denotes the percent active power losses along the route from prosumer-i to consumer-j for a 1 kW of power consumption. It can be calculated using the line lengths and line characteristics for a radial configuration. At any time-t, the comparison price ($CP_{i,j}$ [\$/kWh]) that prosumer-i offers to consumer-j, energy loss ($E_{lt,ij}$ [kWh] in the route between nodes i and j and the billing value ($BV_{t_{i,j}}$ [\$]) can be calculated for the transactive energy trading as follows.

$$\mathrm{CP}_{i,j} = B_i \cdot (1 + l_{i,j}) \tag{3}$$

$$E_{lt,ij} = E_{j,t} \cdot l_{i,j} \tag{4}$$

$$\mathrm{BV}_{t_{i,j}} = (E_{j,t} + E_{lt,ij}) \cdot B_i \tag{5}$$

Each consumer will prefer the lowest comparison price, $min\{CP_{i,j}, i = 1, 2, \ldots, n\}$, offered by the prosumers if, it is less than the DISCO retail price considering the loyalty factor.

Otherwise, the consumer will prefer to provide its energy from the distribution company. At the end of the billing period, based on the energy consumption, the consumer will pay the prosumer the following total amount expressed in (6).

$$\mathrm{BV}_{i,j} = \sum_{t=1}^{N_t} (E_{j,t} + E_{lt,ij}) \cdot B_i \tag{6}$$

The energy trading and corresponding prices are illustrated in Figure 2 for the traditional market and transactive energy market. The direction of the arrows shows the unit price paid by the relevant entity.

III. RELIABILITY

Most of the reliability analysis deals with costumer-based reliability indices like System Average Interruption Frequency Index (SAIFI) [interruption/year], System Average Interruption Duration Index (SAIDI) which is measured in units of time [hour], Customer Average Interruption Frequency Index (CAIFI), and Customer Average Interruption Duration Index (CAIDI) which is also measured in units of time[hour]. Although these indices provide valuable information about overall grid/feeder reliability, they do not express how the load points are affected by component failures or system improvements. On the other hand, low voltage distribution loads show customer-specific characteristics, and their supply sensitivities and reliability expectations may differ. In this regard, to account for different expectations, we calculated and compared the load point reliability indices like Average failure rate (λ [failure/year] which is also shown as [1/a]), average interruption duration (r [hour]), and average annual outage duration (U [hour/year]) for the base scenario and the other operating scenarios that will be defined in section VB.

It is clear that for a specific prosumer to supply the energy of the neighboring consumers, there should be sun radiation (daytime), and the amount of generated energy should be greater than the needs of the prosumer. Under these conditions, each prosumer supplies the needs of the consumers, which have bilateral contracts with the prosumer. In addition to this normal supply based on the bilateral contracts, prosumers also provide emergency supply for consumers who are in an electricity shortage because of a branch or main grid failure. However, emergency supply depends on the failure time (daytime or nighttime) and failure duration. Moreover, the location of the failure is also vital information for load point reliability calculations, especially for the cases with DG in the network to check the ability to provide energy to each consumer. Considering these situations, in case of a branch or main grid failure, feeder loads that are supposed to be supplied by the prosumers can be classified into the following categories,

- The loads that will experience an energy shortage during the failure duration: The main grid supplies these loads (they do not have any bilateral contracts with any prosumers), and the failed component is in the route between them and the main grid. Note that the loads with bilateral agreements are also included in this category if the failure simultaneously cuts all the paths between them and the main or the related prosumer.
- The loads that do not experience any energy shortage during the failure: Component failure does not cut the paths to the main feeder or the paths to the contracted prosumer, so the failure does not affect these loads. Note that the prosumer capacity should be sufficient enough to supply these nodes.
- The loads that experience an energy shortage during part of the failure duration: These are the prosumer-contracted consumers. However, they can not be supplied during part of the failure duration because of insufficient prosumer generation due to the lack of sunlight radiation. Note that the failure cuts their paths to the main grid

Load point reliability parameters are random parameters that can be computed by analytical methods or Monte Carlo Simulations (MCSs). The latter is preferred due to application simplicity [22], [23]. Unless otherwise specified, each network element in MCSs is considered a repairable two-state component. These states are in-service (operable) or out-of-service (failed) states, which are shown in Figure 3, where λ and μ denote constant failure and repair rates, respectively.

The load point reliability indices will be calculated based on the following steps [28], [29].

Step-1 Time to failure (TTF) and Time to repair (TTR) values for ith component in the grid are calculated using the following equations:

$$\mathrm{TTF}_{k,i} = \frac{-1}{\lambda_i} \times \mathrm{Ln}(R_{1k}) \tag{7}$$

$$\mathrm{TTR}_{k,i} = \frac{-1}{\mu_i} \times \mathrm{Ln}(R_{2k}) \tag{8}$$

$$\mu_i = \frac{1}{r_i} \tag{9}$$

where r$_i$ is the average repair duration of the ith component, λ_i and μ_i are the failure rate and repair rate values of the ith equipment, respectively. R$_{1k}$ and R$_{2k}$ are the random numbers within 0 and 1, k denotes the iteration count and Ln is the natural Logarithm.

Step-2 Costumers that will experience an energy shortage during the failure period of the ith component or at some part of it are identified with respect to their classification defined above.

Step-3 The life cycle of the ith element is calculated by summation of T$TF_{k,i}$ and T$TR_{k,i}$

Step-4 The previous three steps are repeated until the studied element's life cycle reaches a predefined value, MT. The MT value is selected in accordance with the grid size and the failure rate of network

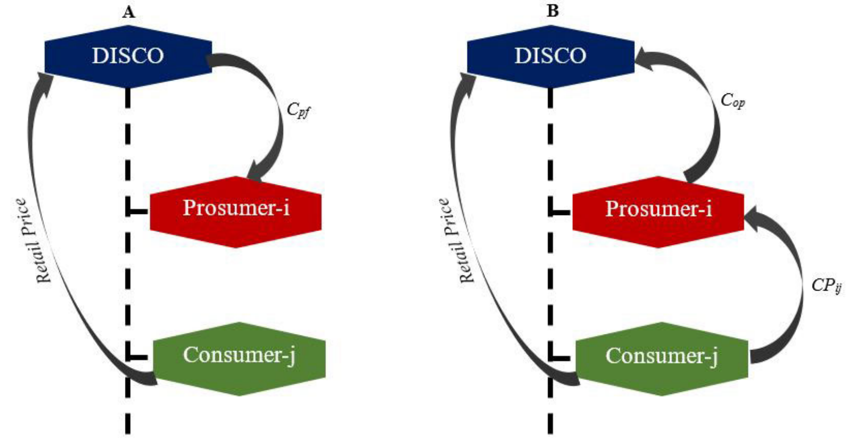

FIGURE 2. Unit price relations between DSO, prosumer-i and consumer-j in a traditional market (A), and in a Transactive energy market (B).

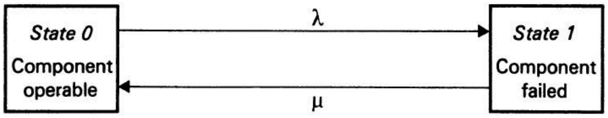

FIGURE 3. State-space diagram of a two-state unit.

elements so that each equipment or line segment can experience at least one failure in this duration.

Step-5 The previous five steps are repeated for all the other network elements, including the main grid.

Step-6 Load point reliability indices, namely, failure rate (λ), average outage duration (r), and average annual outage duration (U) are calculated for all the load points (customers).

Note that repair times longer than 1000 minutes are ignored and not included in the MCS process since such a long TTR value signifies a rare event and is generally crucial only for resiliency studies [30]. All the 6 step has been summarised in Figure 4, in this figure Max_i is the total number of branches in the network and value of Q is calculated from below equation:

$$Q = \sum \mathrm{TTF}_{i,k} + \sum \mathrm{TTR}_{i,k} \tag{10}$$

IV. CONSTRAINTS AND ASSUMPTIONS

There are some physical and logical constraints regarding the intended PV system and some assumptions therewithal. Based on the average generation capacity of photovoltaic (PV) cells and the average usable roof surface area in urban networks, PV unit capacity is considered 6 kW. Also, we assume that each LV customer can install only one PV unit. That is, if the number of prosumers is 2, it means there are two prosumers in the network located at two different load points in the system. As DSO or any other authority cannot force consumers to install PV units and participate in the P2P transactive market operation, the PV placement is a fully random process.

In all calculations and analyses, it is assumed that the power injected into the LV network by prosumers and the main grid is equal to the sum of the power consumption of the load points. In this study, no load-shedding scenarios have been considered. Therefore, in cases where a prosumer can provide only part of the energy required for a consumer, that consumer is assumed not to be supplied by that prosumer.

V. SIMULATION RESULTS AND DISCUSSION

A. TEST SYSTEM AND DATA

In this study, we use the European LV Test Feeder shown in Figure 1, as a test benchmark [31]. LV test feeder is a sample network from the LV grid in England. There are 55 load points in the feeder, which is connected to the 11 kV MV network through an MV/LV transformer with 800 kVA capacity. There are ten line types with different cross sections (different unit length losses) with an overall length of 1426.09 m in the feeder. As a common feeder in the European grid, this feeder is 3-phase, 50 Hz, with 416 V line voltage. The feeder is an entirely radial configuration with no close or open loops.

In order to facilitate the addressing of load points and enhance the comprehensibility of calculations, the LV test feeder is divided into three distinct zones, shown with different colors. This zoning is done with respect to the main feeder configuration, where the end users in these three zones are connected to the same main feeder with the same line type (cross-section of the main feeder). Note that the minimum number of zones for the given feeder configuration is three, where line-5 and line-9 serve as tie lines. However, the number of zones can be increased if desired. There is a total of 55 load points in the network, where 12 of these are in Zone-1, 20 in Zone-2, and 23 in Zone-3.

The details of 100 load profiles that contain 1440 data points, which correspond to one-minute data resolution, are illustrated in [31]. For each load point, load profiles are selected randomly with no repetitive characteristics. At this phase of the study, the average of the 55 load profiles shown in Figure 5 is used as the load profiles for all the loads.

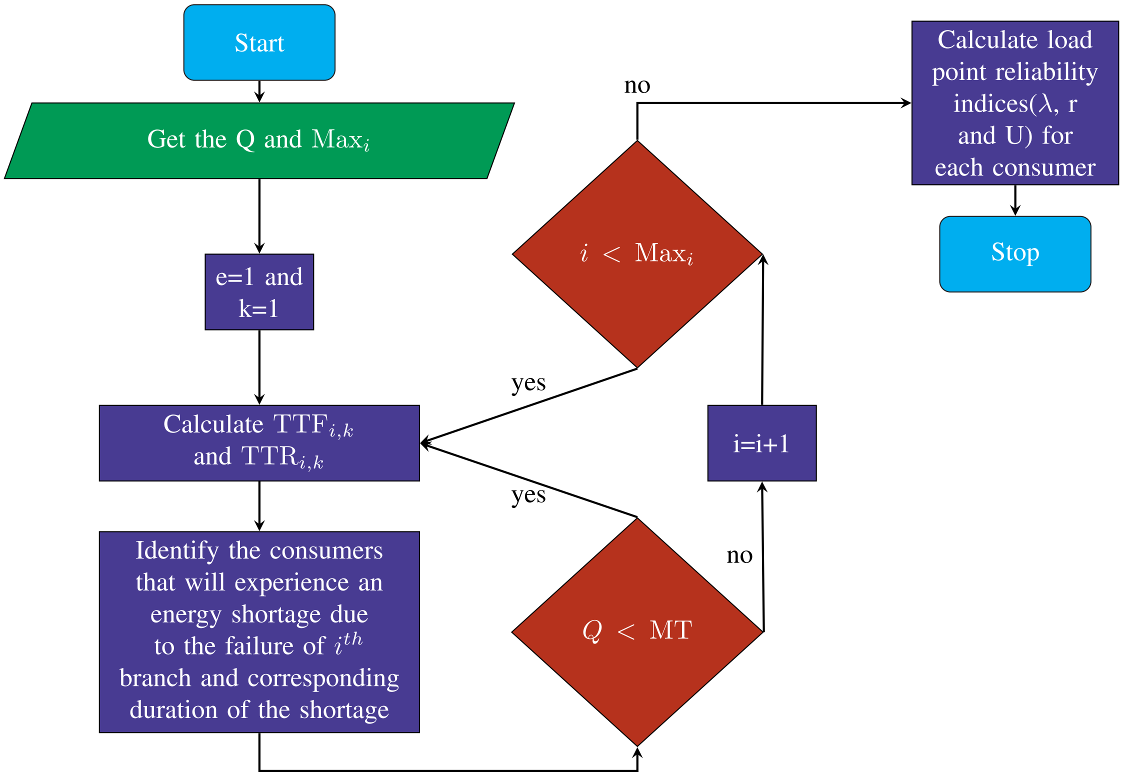

FIGURE 4. The flowchart of the reliability calculation process.

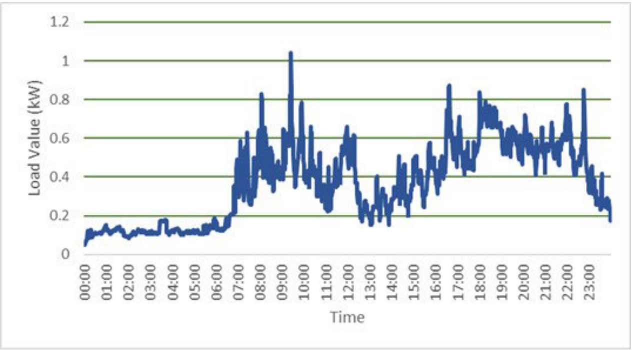

FIGURE 5. Average daily load profile.

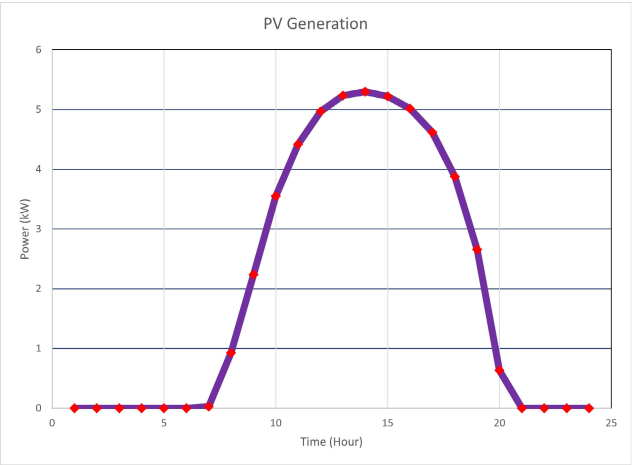

FIGURE 6. Hourly PV generation data for a sunny spring/autumn day.

Sun Irradiation data of a specific district in Turkey for a typical sunny spring or autumn day are used as the PV generation output [32]. Data is provided with an hourly resolution. To correlate the generation and consumption data of the network, the hourly value is used for the following 60 minutes. Based on [32], the output of the PV for a sunny spring/autumn day is given in Figure 6. Considering the generation output data and the average daily consumption given in Figure 5, prosumers are able to provide sufficient energy for internal usage from 8:00 to 20:00. They can share their surplus energy with neighbors through TEM from 10:00 to 17:00.

Low voltage lines and cables in this study are considered as the main feeder or branches, where the main feeder is the path starting from the LV side of the MV/LV transformer (line segment number 1 in Fig. 1 passing from all three zones and ends up with the line segment numbered as 39. Lateral branches are the line segments that connect the load points to the main feeder.

The failure rate and average repair duration for these line segments were selected in accordance with the report published annually by the distribution system operator of the Istanbul-Thrace district [28], as in Table 1. Note that the average repair duration of the lateral branches is half of the

TABLE 1. Reliability data of the LV distribution system.

	Failure Rate (failure/year.km)	Repair Time (hour)
Main Feeder	0.001	4
Branches	0.001	2
Main Supply	1	5

main feeder since the length of these branches is relatively shorter, which cause a shorter failure detection duration.

Finally, the reliability parameters of the main MV grid supply are also illustrated in the table, considering the outage rate and average outage duration of the MV network of the same report.

As explained above, a consumer's loyalty factor expresses a load's behavior dependency on the source type. It depends on the consumer's sensitivity to the energy source, CO2 emission, and the cost they must pay for their needed energy [33]. The loyalty factor for each load is assigned randomly between 0.5 and 0.85 and is illustrated in Figure 7.

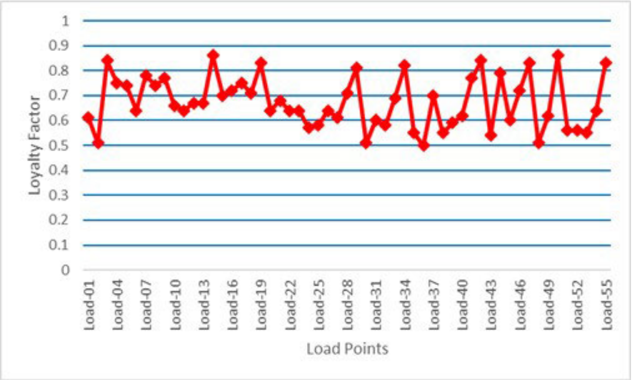

FIGURE 7. Randomly assigned load point loyalty factors.

All the PV units in this study are considered the same size and have the same characteristics since they are rooftop installations of similar houses. We have used the Turkish market for the pricing mechanism [27]. In this regard, DSO sells the electricity to the LV customers with a 3.37 \$Cent/kWh rate and buys electricity from the prosumers in the traditional market with $C_{pf} = 1.77$ \$Cent/kWh rate. The system operation fee for the prosumers is assumed to be the same as the transmission network rate, which is 0.10 \$Cent/kWh. On the other hand, prosumers are considered to sell their surplus electrical energy to the consumers with a constant profit rate of $C_{Rit} = 20\%$

B. ANALYSIS AND RESULTS

Theoretically, each of the 55 residential end-users can be a prosumer if it provides a financial and technical benefit. However, testing all the 55 scenarios where scenario-i corresponds to i prosumers would be time-consuming. Therefore, simulations are performed only for a limited four scenarios, each with a different number of prosumers at different zones, in addition to the base case scenario. The base case scenario refers to the operation without any prosumer in the network, and the network operates traditionally with a fully centralized configuration. The first scenario refers to the case of three prosumers, one prosumer for each of 18 end-users, each at a different zone. Since the rooftop PV installation is not a coordinated (pre-organized) process, they can be allocated at any load of the zones. Therefore, we assume that they are randomly allocated within the zone. Such a random assignment gave that the prosumer load points are L05 in Zone-1, L18 in Zone-2, and L42 in Zone-3.

The second scenario refers to the case where there are five prosumers, one prosumer for every 11 load points. The prosumer share of the zones is organized in parallel with the number of load points at each zone. The random distribution of the prosumers within the zone resulted in one prosumer in Zone-1, two in Zone-2, and two in Zone-3. For the sake of a fair comparison of the reliability indices of the scenarios, we only allocate the last two PV units, keeping the locations of the three PV units in the first scenario fixed. Again, random allocation of the two additional units shows that the fourth and the fifth PVs will be installed to L35 in Zone-2 and L24 in Zone-3, respectively.

The third scenario is based on the assumption of 1 PV unit for every seven load points, corresponding to 8 units. The distribution of the prosumers to the zones is two in Zone-1, three in Zone-2, and three in Zone-3. Keeping the locations of the prosumers of Scenario-2 fixed and randomly allocating the new units give us the following two prosumers in Zone-1, allocated at L05 and L11, three prosumers in Zone-2 allocated at L18, L35, and L15, and three prosumers in Zone-3 allocated at L42, L24, and L48.

The last scenario refers to the case where one prosumer is reserved for each of the five load points. This will give 11 prosumers distributed as; three prosumers in Zone-1, four prosumers in Zone-2, and four prosumers in Zone-3. Keeping the locations of Scenario-3 fixed, randomly assigned locations of the last three PV units are L-03 in Zone-1, L-16 in Zone-2, and L-53 in Zone-3. The prosumer locations are illustrated in Table 2.

TABLE 2. Prosumers location and data for each scenario.

Scenario	1	2	3	4
Zone-1	L05	L05	L05 L11	L05 L11 L03
Zone-2	L18	L18 L35	L18 L35 L15	L18 L35 L15 L16
Zone-3	L42	L42 L24	L42 L24 L48	L42 L24 L48 L53
Number of prosumers	3	5	8	11
Number of the loads feed by the prosumers	15	23	32	33

TABLE 3. The range of the load point reliability indices.

	Failure Rate, λ [f/year]		Average Annual Outage Time, U [hours]		Average Outage Duration, r [hours]	
	Min	Max	Min	Max	Min	Max
Base Case	0.9799	1.2739	4.2595	5.3756	4.1798	4.3467
Scenario#1	0.7479	1.2739	2.4506	5.3756	3.2395	4.3467
Scenario#2	0.7479	1.2605	2.4506	5.3305	3.2229	4.3467
Scenario#3	0.7244	1.2605	2.3882	5.3305	3.2229	4.3467
Scenario#4	0.7224	1.2390	2.3836	5.2139	3.2229	4.3467

Equations (1) to (4) are used for each scenario, considering the prices of the Turkish Market structure and the random loyalty factors explained above. The number of consumers that prosumers can supply, including their internal demand, is found to be 15 in Scenario-1, 23 in Scenario-2, 32 in Scenario-3, and 33 in Scenario-4 as far as sufficient sun radiations exist.

Steps 1 to 6, described in section III, are followed to perform reliability analysis. The MT value is considered as 5000 years for this test feeder, so each line segment will experience at least one failure based on the failure rate and repair duration values provided in Table 1.

All the line segments, including the main feeders and branches, and the load points are enumerated in Figure 1. The algorithm developed in this study considers this enumeration while identifying the unserved loads and the duration of the energy shortage in case of component failures. As declared previously, the partial supply, load shedding, and load priority are not considered in this study.

Load point reliability indices are calculated for each scenario. The indices vary for different loads for several reasons, such as the load point location in the network and the distance to the prosumers change the indicators dramatically. The range of the load point reliability indices for all load points in the network is summarized in Table 3.

For the sake of simplicity, case scenarios are compared with respect to their average load point reliability indices of 55 load points. The improvements of the reliability indices may refer to the base case or the special scenario case. Moreover, an increase in the number of consumers that the prosumers can supply also shows an improvement in quantity. However, we are mainly focused on reliability parameter improvements.

Figure 8 shows the average failure rates for the base case and four scenarios. Adding three prosumers to the network decreases the average failure rate by 6.91%. Additional two prosumers, Scenario-2, provide a further improvement of 4.25%, and the total improvement wrt the base case reaches 10.87%. The third scenario, which includes eight prosumers, will provide 4.75% additional improvement, and the total improvement, according to the base case, becomes 15.10%. The last case scenario with 11 prosumers in the network brings a relatively lower improvement of 0.81%, and the total improvement with respect to the base case reaches 15.79%. When the overall impact of additional prosumers on the average failure rate of the load points is analyzed, we can conclude that the marginal improvement of each additional PV unit decreases with the increasing PV numbers.

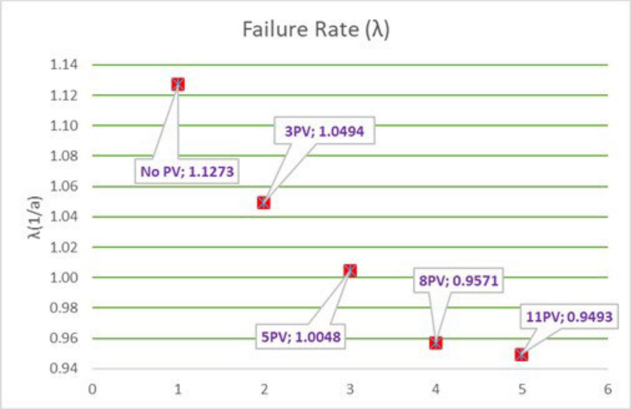

FIGURE 8. Average load point failure rates for each scenario.

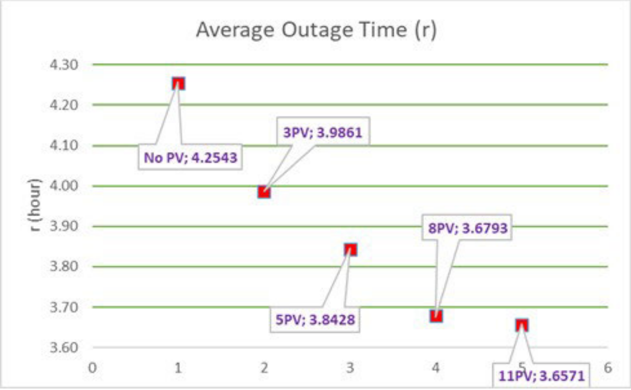

FIGURE 9. Average load point outage duration for each scenario.

Fig. 9 shows the average outage times for each scenario. The overall characteristics look like Fig.6. Average load point outage time improvements of Scenarios 1, 2, 3, and 4 with respect to the base case are 6.30%, 9.67%, 13.52%, and 14.04%, respectively.

Fig. 8 shows the average annual outage duration for each scenario. The overall characteristics look like Fig.6 and 7. However, the improvements are pretty much greater, as the annual outage duration is affected both by the failure rate and outage time. Average load point annual outage time. Average load point annual outage time improvements of Scenarios 1, 2, 3, and 4 are 11.52%, 18.02%, 25.0%, and 26.08%, respectively.

As stated earlier, the scenarios are designed according to the number of consumers without considering load priorities and size. At this point, zone-based evaluation of the load point reliability indices may play a crucial role. Therefore, the load point reliability indices of the three zones are illustrated in Table 4.

The average failure rate of Zone-1 is the lowest, and Zone-3 is the highest in base case operating conditions.

TABLE 4. Load point reliability indices of three zones.

		Base	1	2	3	4
Average Failure rate	**Zone-1**	1.0332	0.9224	0.9224	0.8516	0.8514
	Zone-2	1.1381	1.0668	0.9875	0.9456	0.9445
	Zone-3	1.1671	1.1007	1.0627	1.0223	1.0045
	All	1.1273	1.0494	1.0048	0.9571	0.9493
Average Outage Duration	**Zone-1**	4.2950	3.8754	3.8754	3.6154	3.6156
	Zone-2	4.2548	4.0123	3.7635	3.6128	3.6090
	Zone-3	4.2112	4.0211	3.8948	3.7704	3.7206
	All	4.2543	3.9861	3.8428	3.6793	3.6571
Average Annual Outage Duration	**Zone-1**	4.4363	3.6367	3.6367	3.1351	3.1347
	Zone-2	4.8405	4.3343	3.7846	3.4876	3.4812
	Zone-3	4.9392	4.4765	4.2087	3.9293	3.8112
	All	4.7936	4.2416	3.9297	3.5954	3.5436

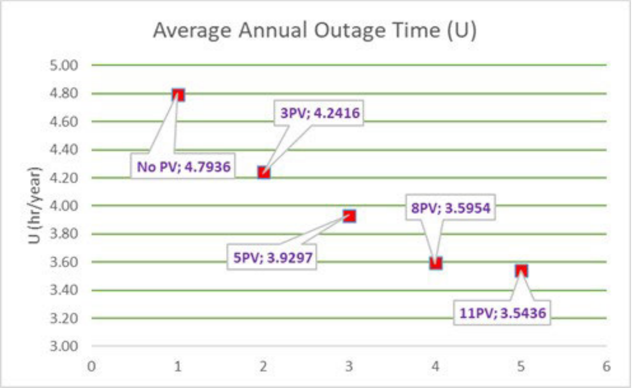

FIGURE 10. Average annual outage duration for each scenario.

The difference is about 13%. It is reasonable since the failure rate is related to the route length, and in this regard, Zone-1 and Zone-3 are the closest and farthest zones to the main supply, respectively. The second zone also shows a 10% higher average failure rate than the first. The outage duration for the three zones in the base case are almost the same because of the same root cause in all the zones: a failure in backbone lines or the literal lines and no alternative supply. The average annual duration for the three zones show similar characteristics with the average failure rates, as the average outage duration are almost constant.

The first scenario, comprising one prosumer in each zone, improves load point reliability indices in all three zones. Since the generation capacity of the prosumers in the three zones are equal, load point reliability indices are dominated by the number of load points and total load in each zone. In this regard, the most considerable improvements for the first zone are 10.7%, 9.8%, and 18.0% for the average failure rate, average outage duration, and average annual outage duration, respectively. The improvements for Zone-2 and Zone-3 are approximately 60% and 55% of the corresponding Zone-1 values.

The second scenario comprises two more prosumers than the first scenario, one for Zone-2 and one for Zone-3. These additional prosumers eventually increase the reliability indices of the second and third zones, while the Zone-1 and Zone-2 indices remain unchanged. Note that the improvements of the second zone indices are better than the third ones. The reason is related to the additional prosumer's location in Zone-2, which is the farthest location from the main supply (L35). On the other hand, the additional prosumer of Zone-3 is located by L24, and has a chance to win the price competition of the loads located in Zone-2 and Zone-3. That is, the additional prosumer in Zone-3 contributes to the reliability improvement of the two zones.

The third scenario is the extension of the second scenario with an additional prosumer at each zone. The additional prosumer in Zone-1 is allocated at the furthest end of the zone (L11) and, therefore, provides considerable improvement in zone reliability indices. On the other hand, the locations of the additional prosumers in Zone-2 and Zone-3 are not so good to provide the same relative improvements in these zones. Moreover, the incremental increase in prosumers in these zones is less than in Zone-1.

In the fourth scenario, the number of prosumers is one more than in Scenario-3. However, two of these new prosumers are the consumers who already have bilateral contracts with other prosumers in previous scenarios. Consumers who may prefer to provide their energy from their neighbors based on the loyalty factor are already fed in Scenario-3. Therefore, this scenario does not bring additional benefits in terms of reliability indices. In other words, beyond Scenario-3, adding new prosumers requires lowering the profit rates (energy prices). Since reducing the profit rate will increase the payback duration, Scenario-4 and further scenarios with more prosumers will not be profitable.

VI. CONCLUSION

Reliability expectations of LV customers are generally load-dependent, and unlike the MV networks, the traditional feeder-based reliability indices may not be the main concern of the end-users. Instead, LV customers are more interested in the intended reliability improvements through transactive energy trading using small-scale prosumers in the grid. In this regard, this paper has presented how the transactive energy market could improve renewable energy share and customer reliability in the LV distribution grid.

We used a European LV Test Feeder with sun irradiation and PV generation data from a specific geographical area in Turkey to validate the performance of the proposed approach. Energy market prices and their estimated future were also based on Turkey's market prices.

An economic analysis was first performed, and the load points participating in the P2P energy trading with the linked prosumers were identified for the four scenarios based on the pricing specifications. The random loyalty factors were also considered to account for the factors affecting consumer preferences. In the second step, the load point reliability indices were calculated using Monte Carlo Simulations for the base case operating conditions and the four transactive operating scenarios. They were then compared to the base values obtained for the traditional centralized market structure, where no prosumers existed.

The comparison of the load point reliability indices showed that an increase in the number of prosumers improved the reliability indices. However, the improvement rate was not constant. At first, the improvements for the low number of PV installations at appropriate locations were high, and the improvement rate remained relatively high to a certain number of prosumers. At this critical number of prosumers (eight for this test system), additional prosumers didn't bring satisfactory improvements because of network saturation. It was realized that, beyond this critical number of prosumers, all the consumers that might prefer using transactive energy had already contracted bilaterally with one of the available prosumers.

Reliability improvement rates of the prosumers depended on several parameters. First, installing a rooftop PV system in an LV grid is not a coordinated process. Therefore, the reliability improvement rates rely on random parameters, such as the number of prosumers, the prosumer share of the zones, and the prosumer locations in the zones.

When we analyzed the impact of the loyalty factors on transactive energy trading, we realized that the consumers showing high loyalty to the distribution company could only prefer the prosumer energy if the prosumers decreased their energy prices. However, such a price decrease caused an increase in the payback duration, preventing the increase in the number of prosumers. It is the responsibility of the distribution company to compensate for the loss of prosumers to have a more reliable network if reliability is one of the main concerns for the distribution company.

Finally, the results show that an uncoordinated LV PV installation may not provide the expected financial benefits. Based on the pre-simulation for the economic benefits, a feasibility study is required, considering the prospective prosumer locations and consumer intentions regarding their supply preferences. At this point, we must remember that all the results and conclusions are valid for the specified pricing conditions and reliability parameters. Moreover, to account for the practical implementations, the analysis will better be extended considering the energy storage units to minimize the volatility impacts of PV outputs.

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