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An Integrated Transactive Energy Market and Distribution Grid Analysis Platform

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SUMMARY

Through the increased implementation of distributed energy resources (DERs) into the power system, the need for improved grid control at the distribution-level is becoming necessary. Furthermore, in recent years, the study of transactive energy between customers and small producers (prosumers) has gained traction. Within this new environment of higher DER penetration and the potential for prosumer enabled electricity markets, the voltage stability and economic impacts on electric power distribution grids need to be analysed. This article describes approaches and results on our endeavour to develop an integrated transactive energy market and distribution grid analysis prototype system named Transactive Prototype Application (TPA). The prototype application described in this article enables researchers and utilities to initiate transaction intents and analyse their impact on the distribution system power flow. The power flow results are used to calculate distribution locational marginal prices (DLMPs) while integrating grid constraints. Finally, the tool enables/disables the transaction intents based on their feasibility and priority.

KEYWORDS

Transactive energy, transactive control, trading platform, prosumers, smart grid, Distribution Locational Marginal Pricing

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INTRODUCTION

The adoption of consumer-level electric energy production and storage and smart consumer appliances is accelerating. Examples of technologies leading this adoption are photovoltaic (PV) generation, small wind turbines, electric vehicles, and smart appliances. Within such a new prosumer (producer-consumer) enabled Smart Grid, allowing the managed, safe, and secure distribution and sharing of electric power between prosumers, or between prosumers and the utility, with utility oversight, may incentivize the increased adoption of renewable distributed energy resources.

However, the increased adoption of distributed energy resources and the enabling of such transactive energy markets brings several unsolved challenges to utilities concerning their safe and secure operation. These challenges present several research questions, such as economic dispatch and generation and the grid's stability. Tools that enable the co-simulation and analysis of the power grid state in the presence of distributed energy resources and transactive energy markets are much needed to help adequately answer such questions.

The transaction control techniques discussed in the literature as "Transactive Energy" use a prosumer-enabled smart grid. Transaction control techniques are applied to optimize the use of DERs, electric vehicles (EVs), smart buildings, and other assets to ensure the grid's stability. As defined in [1] and [2], transactive energy necessitates pricing algorithms and control mechanisms to operate the grid in a resilient and economical fashion. Recently, laboratories, utilities, and other research institutes such as Pacific Northwest National Laboratory (PNNL) [3]-[4], National Grid, and Omega Grid, have conducted pilot programs to investigate the application of transactive energy. The Pacific Northwest Smart Grid Demonstration (PNWSGD) [5] used peer-to-peer negotiation based on consensus principles to coordinate the operation of DERs. The Olympic Peninsula GridWise Demonstration [6]-[7] was the first proof-of-concept demonstration project in the US that used a double-auction market for congestion management. Building upon the Olympic Peninsula Demonstration, the American Electric Power (AEP) gridSMART® demonstration [8] project used a 5-minute double auction market to dispatch responsive residential loads on four local feeders holding approximately 200 participating households. These households' responsive loads included heating, ventilation, and air conditioning, with input preferences from the household customers. Flexibility curves were developed and employed to create a market-clearing engine to form a price-sensitive demand curve for the distribution circuit. This demand curve was used to calculate the clearing price and supply bids to generate a locational marginal price for electricity.

The Campus for Research Excellence and Technological Enterprise program (CREATE) under the Singapore national research foundation has described the requirements and software architecture of the software framework for simulating distribution grid operation. The proposed software by CREATE is the Flexible Distribution Grid Demonstrator (FLEDGE) [9]. This simulation tool allows for the integration of flexible resources into the distribution grid. Optimization techniques are then suggested for the flexible resources such as flexible loads and battery energy storage systems (BESSs).

In the Netherlands, a living smart grid community was opened through a demonstration project called PowerMatching city [10, 11] that used a double-auction market to balance supply and demand. This demonstration used simultaneous optimization for energy trade and active distribution management. The PowerMatcher software was created to operate the PowerMatching city through various residential appliances, electric vehicles, and wind turbines. An electronic exchange market was used to determine the supply or demand amount for each device agent through a bidding system.

In this article, we describe a prototype software system that enables researchers and utilities to: (a) manually initiate hourly transaction intents between prosumers, both for additional load and distributed photovoltaic generation, (b) programmatically merge the load and PV generation resulting from the transaction intents with known stored load and generation profiles, (c) automatically generate

OpenDSS input models and data and run unbalanced power flows, (d) programmatically bring power flow results into the transactive market tool for each and all buses or nodes and transaction intents to calculate a distribution locational marginal price, (e) use resulting bus voltages, and DLMP price to enable or disable hourly transactions based on their feasibility and priority. Customers can purchase power at the DLMP rate of their specific node on the system, improving the grid social welfare.

This article is organized as follows: An enhanced 13-bus distribution system model and its simulation in OpenDSS are described in Section 2. Section 3 presents the theory and implementation of the distribution locational marginal pricing algorithm. Section 4 introduces the web-based management interface module of the integrated TPA prototype system. Section 5 discusses the communications manager module and the database data model. Section 6 provides the simulation results. Finally, section 7 concludes the paper.

II. DISTRIBUTION SYSTEM MODEL

The IEEE 13-bus distribution system was enhanced to model the small-generation electrical behavior, such as home solar panels. PV and Load profiles were generated based on real data [12]. The 13 -bus power system model with the load and generation profiles was fully implemented in the simulation tool OpenDSS [13]. OpenDSS was selected since it is adapted to unbalanced systems and the simplicity of connecting it to the web application. A three-phase power flow analysis was conducted for calculating the state, i.e., voltage phasors, to evaluate voltage stability. The power flow calculations were performed using OpenDSS. When a case is executed, OpenDSS calculates the power flow and exports the metered data for data analytics. With metered data collected at each prosumer site, the application monitors the voltages at the customer meter point for transaction feasibility determination. If the voltage level at a consumer location exceeds a per unit (p.u.) threshold (for example, 1.05) during the transaction time, then that transaction will be disabled.

II.A. PROSUMER ENHANCED 13-BUS MODEL

The IEEE 13-bus system is at a 4.16kV voltage level with relatively short line distances. The base system is a small distribution network but has a significant load that provides flexibility in generating analytics scenarios. The lines are modeled as overhead (OH) and underground (UG) lines, with the availability of a shunt capacitor and regulating transformer.

The IEEE 13-bus system was enhanced to include photovoltaics at every customer site location, as shown in Fig. 1. Prosumers were aggregated such that a group of houses or subdivisions represents a single customer site. The 13-bus system has unbalanced loads on a single-phase feeder, providing additional realistic complexity with unbalanced power flows. Additionally, there is an industrial load connected to Bus 671. Within each prosumer location, it is possible to consume and produce power injected back into the grid. The ratings of the PVs were designed to match the load values. Tables 1 and 2 list the power ratings and other characteristics for each load (Consumer Site) and PV (Producer Site) in our resulting prosumer enhanced 13-bus model. The net effect is that our power system model and resulting scenarios can model a single medium voltage distribution feeder connected to one substation. Groups of prosumer sites, each with loads and PV generation, are connected to three-phase and single-phase bus nodes. End-of-line step-down transformers found close to utility customer sites, such as center-tapped transformers, were not modeled.

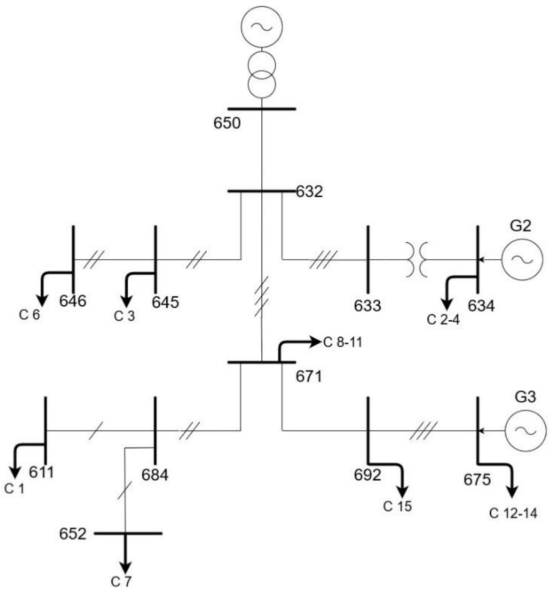

Figure 1. Line Diagram of the Prosumer Enhanced IEEE 13-bus System

Table 1. Load Description of the Enhanced IEEE 13-bus System

Customer #	P (kW)	Q (kVAR)	Bus	Phases
1	170	80	611	1
2	160	110	634a	1
3	120	90	634b	1
4	120	90	634c	1
5	170	125	645	1
6	230	132	646	2
7	128	86	652	1
8	17	10	670a	1
9	66	38	670b	1
10	117	68	670c	1
11	1155	660	671	3
12	485	190	675a	1
13	68	60	675b	1
14	290	212	675c	1
15	170	151	692	2

Table 2. PV Panel Power Generation Details

Customer #	P (kW)	Bus #	Phases
1	170	611	1
2	160	634a	1
3	120	634b	1
4	120	634c	1
5	170	645	1
6	230	646	2
7	128	652	1
8	17	670a	1
9	66	670b	1
10	117	670c	1
11	1155	671	3
12	485	675a	1
13	68	675b	1
14	290	675c	1
15	170	692	2

II.B PV GENERATION AND LOAD PROFILES

As discussed, synthetic load profiles were used to simulate industrial and residential loads in the application's calculations. These loads were implemented as recurring dynamic and static loads throughout a 24-hr profile. The load values varied over 24 hours and changed with a granularity of one load value per hour. The residential load profile is shown in Fig. 1 and is used for all loads except for consumer site 7. The consumer at site 7 is an industrial load and is constant throughout the day.

Data was gathered from the National Solar Radiation Database [14] and used to create generation profiles for photovoltaics to model a realistic distribution system with prosumers. The data under consideration was recorded in July 2010 at the Spokane airport [14]. In OpenDSS, the PV model uses a power profile with per unit measurements. A power profile over a whole year was considered. The maximum iridescence value for the year was used to normalize the data. Fig. 2 shows the generated normalized PV profile over one week in July 2010. A week's worth of data was then used for the test model to simulate the variability of real PV profiles that the customers may experience, comprising cloud impacts and rain.

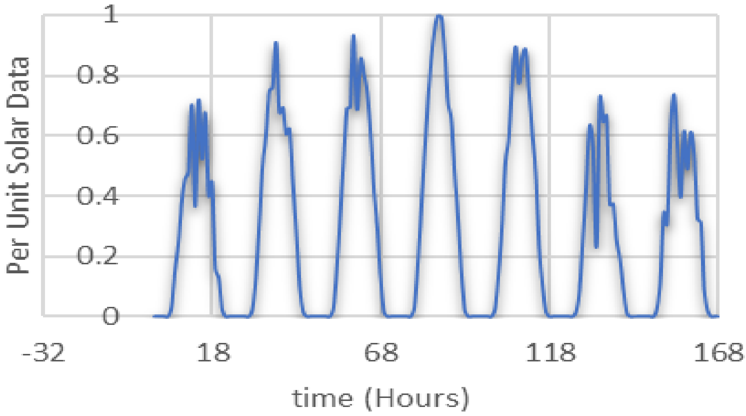

Figure 2. One Week of PV Data Power Output During July 2010

III. DISTRIBUTION LOCATIONAL MARGINAL PRICING

With the increased renewable distributed generation integrated into the distribution system, the trend towards a more open competitive market will impact the grid operation and the needed control by the distribution system operators (DSO). The general economic and social welfare can be maximized by considering distribution locational marginal pricing, representing the price of incremental power injected or consumed at different locations. In practice, locational marginal pricing are considered for power transmission markets [2,3].

DLMPs are proposed in the research community and calculated by executing a constrained optimization of a cost function that depends on the procurement and price of real and reactive power from distributed generation (DG) and possibly flexible loads (FL). The objective is to minimize the total cost while ensuring the system constraints and boundaries are satisfied. Equality constraints translate the need for real and reactive power consumption and supply balances within the distribution system. The inequality constraints represent the limits of the distributed generation capability, lines' and transformers' capacity limits, voltage constraints at different buses. The cost function is then minimized using semi-definite programming that provides the total optimized cost and the DLMPs at the nodes. The obtained DLMPs can be classified into real power DLMPs and reactive power DLMPs. As proposed in [3,4,15], DLMP values provide a standpoint of the distribution grid conditions to the wholesale energy market or cleared price for the energy market. The impact of the LMP from the transmission system was included at the distribution feeder. DLMP prices were evaluated and calculated down the feeder, and the obtained fluctuations of the DLMP price relate to the grid.

With the addition of distributed generation into the distribution system, the distribution system operator has the ability to incorporate a new market. In this market, the social welfare of its prosumers can be evaluated and prices can be calculated with respect to location. In literature and every day operation, this locational marginal pricing [2] has been the backbone of transmission companies market structure and dispatch. This application can also be applied to the distribution system such as a distribution locational marginal price. Through metering, this social welfare can be applied to a supply and bid function similar to the LMP and provides the following optimization welfare function (1), where p^{fl}, p^{g}, q^{g} are the procurement of real and reactive power from distributed generation and flexible loads.

$$maximize\ w(p^{fl}, p^{g}, q^{g}) := w_p(p^{fl}, p^{q}) + w_p(q^{g}) \quad (1)$$

In order to maximize this optimization problem, constraints and boundaries are set to calculate the DLMP price. Where the real and reactive power losses p^{l} and q^{l} are represented by p^{l} and q^{l} respectively. Equation (2) denotes the voltage limits. The real and reactive power of the distributed generation is constrained in (3)-(5), where dg is the dispatchable generation and fl is flexible loads if present.

$$V_L^{-} \leq V_L \leq V_L^{+} \quad (2)$$
$$p^{dg-} \leq p^{dg} \leq p^{dg+} \quad (3)$$
$$q^{dg-} \leq q^{dg} \leq q^{dg+} \quad (4)$$
$$p^{fl-} \leq p^{fl} \leq p^{fl+} \quad (5)$$

Once the constraints have been set, the DLMP values can be determined and optimized through semi-definite programming. The overall representation of the DLMP values can be found in the real power DLMP and reactive power DLMP as proposed in [15]. Each DLMP contains four price components that are added together to provide the nodal price. The four elements of a DLMP are injected energy, loss, congestion, and voltage price terms. Indeed, the final nodal price represents the impact of loads and generation at that node on the distribution grid, considering the value of losses, energy cost, and congestion components. Further details regarding the DLMP program at hand is shown in [4].

IV. TPA MANAGEMENT INTERFACE

The architecture of TPA consists of four modules:

1. OpenDSS Simulator.
2. Management Interface (Web Application)
3. Database Management System (MySQL)
4. Communications Manager
5. DLMP Program

Fig. 3 presents a high-level representation of TPA's system architecture and the flow of data. The Management Interface is the module that is intended to enable the management and administration of all data within the TPA system. Managed data include customers, producer sites, consumer sites, power system model elements, and transactions. The management interface module, in turn, interfaces with the database engine to populate transactions and entity profile data. The entity profiles simulate real-life PV generation or consumer loads.

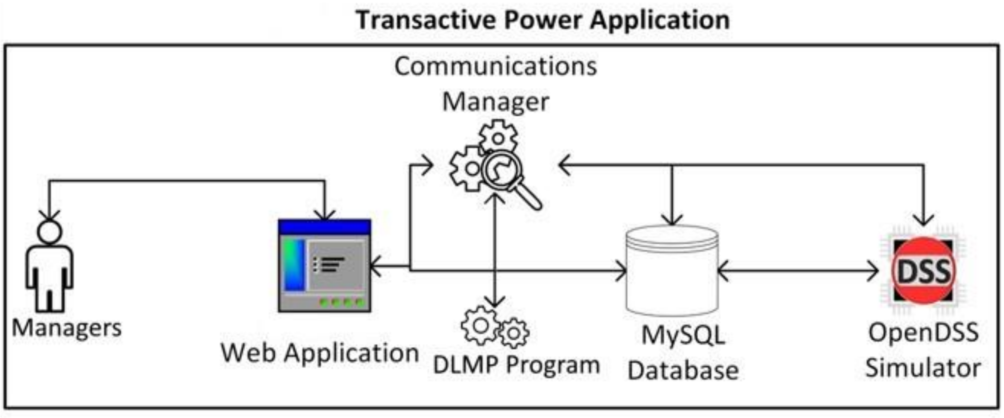

Figure 3. TPA System Architecture and High-Level Data Flow

Fig. 4 depicts the TPA's management interface main menu, which is divided into three sections: Dashboard, Management, and Administration. The main menu also provides search functionality. The web-based management portal can be accessed by clicking on the logon icon on the top right corner of the web application homepage. Within Fig. 4, the management tab was expanded to show its contents. This menu contains entries named Transaction Management, Customer Management, Site Management, Profile Management, and Power System Model Management. Due to article page length limitations, not all implemented interfaces are shown.

Figure 4. Management Menu of the TPA Management Interface

IV.A MANAGEMENT INTERFACE: TRANSACTION MANAGEMENT

Within the Transaction Management menu option, there is a menu option named Transaction Agreement Manager. Fig. 5 shows the Transaction Agreement Manager screen. This screen contains fields for the transaction agreement ID number, the transaction start datetime, the transaction end datetime, the transaction overvoltage indicator checkbox, a checkbox which indicates if the transaction price criteria has been met, a checkbox indicating if the transaction is supported by the system, the 'Producer Site Name' text field and the 'Consumer Site Name' text field.

Under the Management Menu, there is the Customer Management sub-menu, which contains a link to the customer. Each customer has multiple column fields. These fields consist of an ID number, a name, and the state of residence. All the customer column field values can be edited by an TPA administrator.

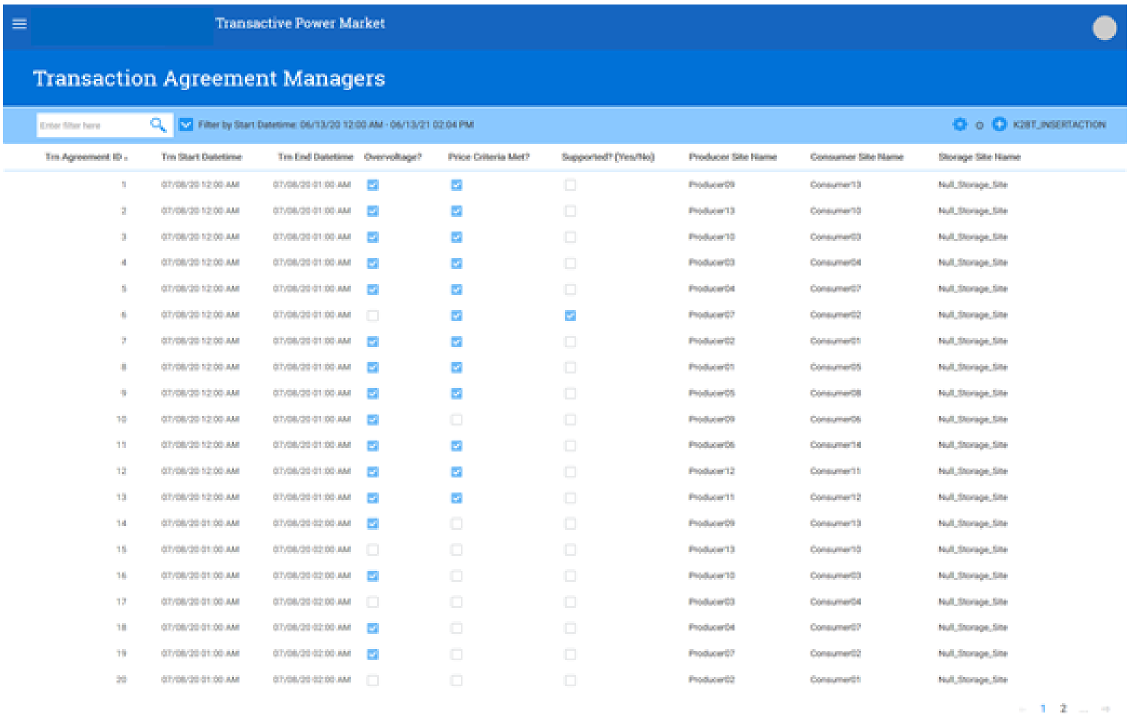

Figure 5. Transaction Agreement Manager Screen

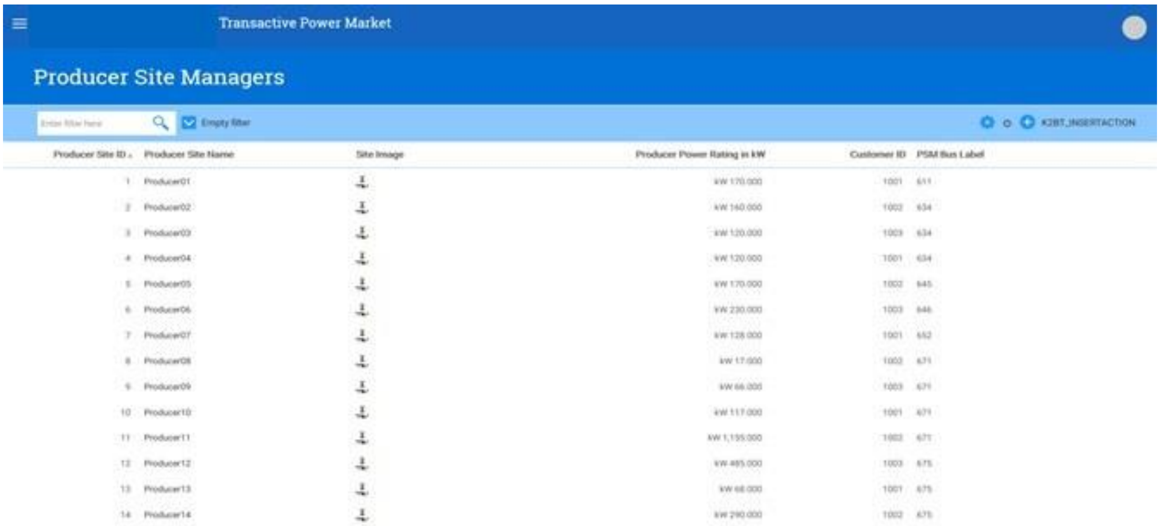

Figure 6. Producer Site Manager Screen

IV.B MANAGEMENT INTERFACE: PROFILE MANAGEMENT

Under the Management Menu is the Profile Management sub-menu. This sub-menu contains a link to the Manage: Producer Site Generation Profile – One Year, Hourly screen. Each producer profile has two column fields, which designate the ID of the profile, as well as its name.

A link to the Manager: Consumer Site Load Profile – One Year, Hourly screen can also be found within the Profile Management sub-menu of the Management Menu. Each consumer profile has two column fields, designating the ID and name of the profiles.

IV.C MANAGEMENT INTERFACE : BUS MANAGEMENT

The Management Menu contains the PSM Management sub-menu, which has a link to the PSM Bus Manager screen. This screen lists all the buses and their respective nodes and phases available in the

TPA's database. Each bus has multiple column fields, which include: the bus label, the number of phases on the bus, the voltage base, and a checkbox indicating if it is enabled or not. The bus labels currently used by TPA correspond to the bus object codes used by OpenDSS, which can be found in the OpenDSS reference guide [14]. The buses available in the database can be edited, and new buses can be added to the system.

IV.D MANAGEMENT INTERFACE : LINE MANAGEMENT

Under Management Menu, there is the PSM Management sub-menu. This sub-menu contains a link to the PSM Line Manager screen. All the lines available in TPA's database are listed on this screen. Each line has multiple data values associated with it. These values include the line label, name of the line, number of phases, then the length of the line in meters, and a checkbox that indicates if the line is enabled among other line characteristics as modeled by OpenDSS. The lines available in the database can be edited, and new lines can be created. Lines are composed of wires which are attached to bus nodes at each end.

IV.E MANAGEMENT INTERFACE : LINE TYPE MANAGEMENT

The PSM Management sub-menu in the Management Menu has a link to the PSM Line Type Manager screen. This screen lists all the line types contained in the TPA's database. Each line has several data values. These values include: the ID number for the line type, the name of the type, and the number of phases of the line. The line type IDs correspond to the line type ID object codes used found in the reference guide for OpenDSS [13]. The values for the available line types already in the database can be edited, and new line types can be added as well.

V. COMMUNICATION MANAGER AND DATABASE

In this section, we describe the design of the Communications Manager component of the TPA prototype and the database data model.

V.A DATABASE MODEL AND ENGINES

A simplified entity-relationship diagram of the database data model is shown in Fig. 8. The database stores data records and their relationships for Customers, Consumer Sites, Producer Sites, Transaction Agreements, Buses, and their Nodes, Lines and Line Types, Profiles for all Sites. Storage Sites are supported by the data model and web application but not used in our analysis at this time. The MySQL database engine is currently used to store the data.

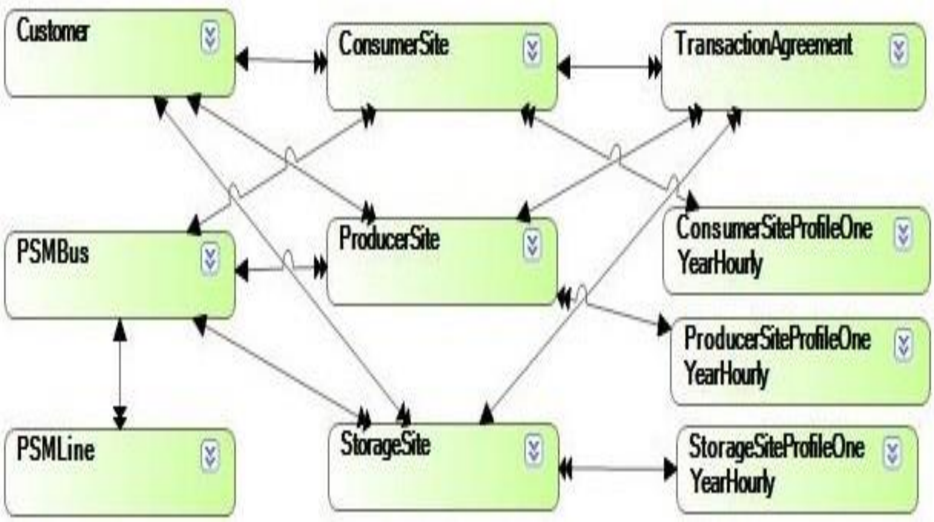

Figure 7. An Entity-Relationship Diagram for the TPA's Database

V.B COMMUNCIATION MANAGER MODULE

The TPA's Communications Manager module is a set of scripts written in the Python programming language. The communications manager processes the power system model and transaction intent data from a specified time window. The specified time window consists of individual time-steps with a granularity of one hour per step. This means that the specified time window must be of a given length in whole hours. The communications manager processes only one time-step per iteration of a large looping procedure, shown in Fig. 9.

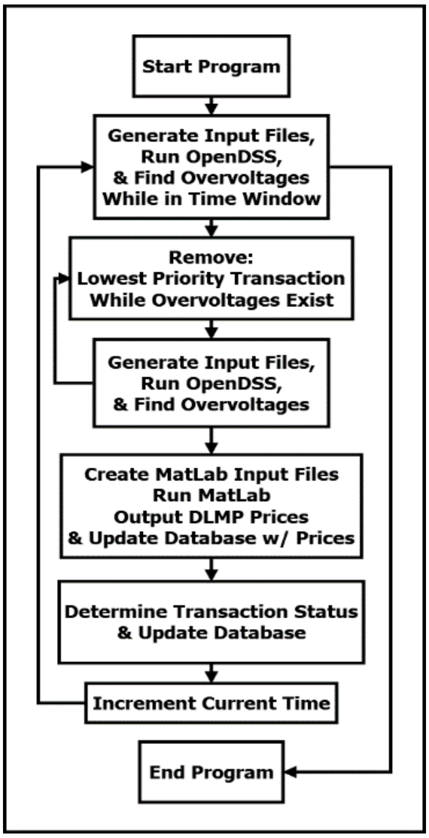

Figure 8. Workflow of the Communication Manager/ TPA Backend

In each time-step iteration of the main looping procedure, the data acquired from the database is used to generate three sets of input data files. One set of files consists of the OpenDSS power system model. A second set consists of transaction-related files for each hour-long time-step of the specified time window. The final set of files are inputs into the DLMP program. By generating these three sets of files, the TPA backend can rely solely on the information in the database instead of using existing hard-coded file assets. This allows the input to OpenDSS and the DLMP program to change dynamically instead of being purely static. Having access to a dynamically changing model will enable researchers to test different scenarios, depending on what infrastructure elements are enabled in the database.

The output data that results from running OpenDSS with the previously generated model and transaction-related input files is used in a sub-process that detects any transactions that would cause an overvoltage in the system. These overvoltages are detected in a set of 'monitor' files that are generated by OpenDSS. These monitor files contain the calculated voltage and currents for each Bus and Node in the system and are placed in a new 'output' directory, created for each run of the backend script. If the voltage level of a Bus reaches above a given threshold, e.g., 1.05 per unit, then the transactions will lead to an overvoltage. If overvoltage transactions are detected, they are eliminated one at a time in a sub-loop. After each overvoltage transaction is removed, the transaction-related input files are regenerated using the reduced set of transaction intents as input. OpenDSS is then re-run to verify whether there are additional overvoltage transactions. This sub-process continues until all the overvoltages are eliminated.

To determine which transactions causing overvoltage should be eliminated, all the transactions under consideration are set in a specific order following an assigned 'priority value' from the database. This priority value is currently arbitrary, but a future version of the TPA application could include a mechanism by which customers could purchase 'priority points' from the utility. Alternatively, the utility itself could assign priority values to specific transactions, given a set of fair pre-determined criteria. With each transaction now having a priority value, all the transactions in a specified time-step can be ordered such that transactions with the highest values are given higher priorities to avoid being disabled when overvoltages occur, and transactions with lower values are eliminated from consideration first.

Once all the overvoltages in the given time step are eliminated, the communications manager generates the DLMP program input files. These files allow the DLMP program to calculate price values for that specific time step. These price values are then written into the database and are used to update the status of the transaction intents on the database for the given time step. If a transaction intent does not result in overvoltage and it meets the DLMP pricing criteria, it is accepted. If a transaction is eliminated due to an overvoltage for the associated bus or node, or it does not meet the DLMP pricing criteria, then the transaction intent is denied. This updated transaction status is then written into the database and is displayed by the Web application. Finally, the current time step is incremented, and the entire process repeats until all the time steps in the specified time window have been processed. The communications manager then commits its findings to a log file, and the script/ program terminates.

VI. SYSTEM OPERATION AND SIMULATIONS

The current operational workflow of the TPA system prototype is as follows: Once the transaction data has been entered manually, this data is programmatically merged with the load and PV profile information. Based on the results of that transaction and profile data merging, for both loads and PV generation, a set of OpenDSS input files is generated. The structure of the power system model for OpenDSS is also programmatically generated. Then OpenDSS is run to determine the power flows and the expected voltages and currents at each bus for that hour. Based on the voltage at each bus, the system decides to either accept or reject a transaction, and this information is stored on the database and shown on the Web interface. Fig. 5 depicts the Transaction Agreement Manager screen showing that all but four transactions in our evaluation scenario have been rejected due to overvoltage.

During our simulations on the enhanced IEEE 13-bus model, the value 1.05 per unit voltage was used as a threshold to test the application for approving or denying transactions. An example of testing this threshold can be noted in Fig. 9, where the voltage over a 24-hour period is shown for Customers 1 to 5. In this figure, the maximum voltage is 1.042 PU located at customer 2, and the minimum was 0.9688 PU located at customer 1. Due to the voltages not reaching the threshold, all transactions over the 24-hour period were accepted.

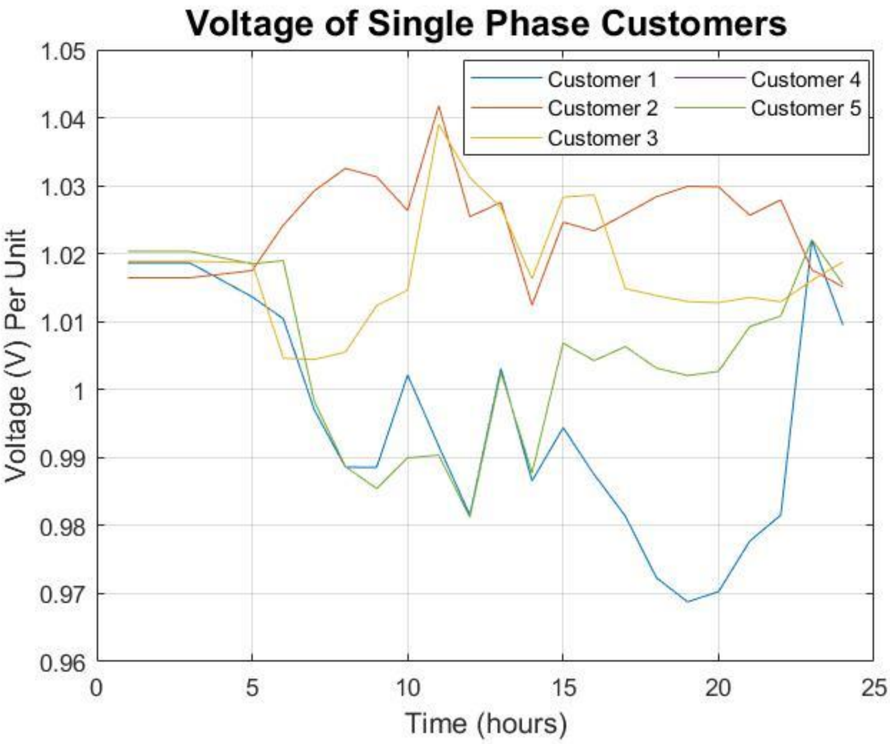

Figure 9. Customers 1 Through 5 Voltage (V) over a 24-hour Period In Per Unit

VI.A ENHANCED 13-BUS SYSTEM CASE STUDY

One case study, based on a renewable enhanced IEEE 13-bus model is shown in this section. Scenarios include a full distribution system model (IEEE 13-bus), classic and renewable distributed generation, different hourly generation and loads profiles, and example transaction intents.

VI.B SCENARIO 1: NO PV GENERATION INCLUDED

The first scenario is based upon the original IEEE 13-bus scenario with the loading of the system at its original values. This scenario was used as a baseline for DLMP analysis where photovoltaic generation was not included in the system. This baseline system is used to show congested lines and elevated prices due to the maximum loading as shown in Fig. 10 and Fig. 11. It can be noticed that the resulting congestion point is inherently bus 671, due to this congestion, the price increases past this bus for the real power DLMP. Reversely, due to a negative reactive power flow, the price has been reduced past bus 671 for reactive power DLMP. The respective dispatched generation is located in Table 3 and the customer power usage is noted in Table 4.

Table 3. Generator Dispatch Full Load Scenario

Generator Location	kW	kVAR
632.A	231.61	3.621
632.B	210.55	167.86
632.C	270.67	134.04
634.A	50	0
634.B	50	0
634.C	50	0
675.A	250	0
675.B	250	0
675.C	250	0

Table 4. Customer Load Full Load Scenario

Customer	kW	kVAR
C1	170	20

C2	160	115
C3	120	109
C4	120	240
C5	170	125
C6	0	0
C7	128	68
C8	8.5	5
C9	33	19
C10	58.5	34
C11	0	0
C12	485	-10
C13	68	-140
C14	290	12

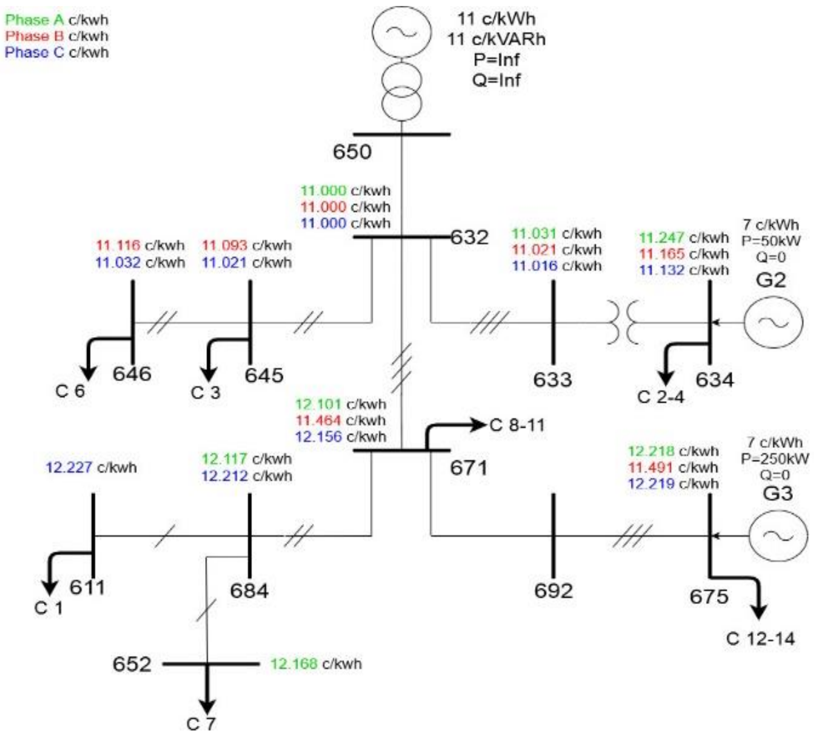

Figure 10. Real power DLMP at different buses of the IEEE 13 bus system

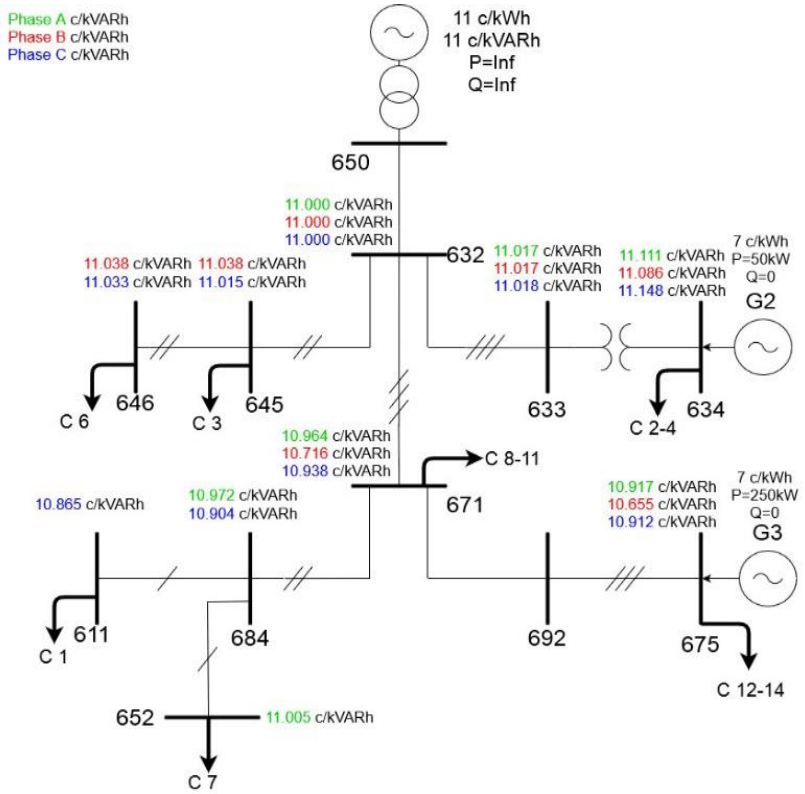

Figure 11. Reactive power DLMP at different buses of the IEEE 13 bus system.

VI.C SCENARIO 2: PV GENERATION INCLUDED IN THE IEEE 13 BUS SYSTEM

The second case considers the use of photovoltaic generation in the IEEE 13-bus system. The PV rooftop generation is assumed to be installed in residential areas to produce real power. The total power penetration of PV was set to 60% of the residential loads. The industrial load at bus 675 (C11-13) is at full load. A total of 512 kW PV generation was added to the system. Thus, the total load supplied by the classical dispatchable generation reduces from 1811 kW to 1290 kW. With this amount of generated PV power, Table 5 shows that generator 632 on phase A is no longer producing any real power. This primarily means that, in phase A, real power is not purchased from the substation feeder. The PV and dispatchable generation fully cover the consumed power within phase A.

Table 5. Dispatchable generation with 60% PV generation

Generator	kW	kVAR
632.A	0	46.758
632.B	78.487	182.46
632.C	225.17	160.78
634.A	28.441	0
634.B	50	0
634.C	50	0
675.A	250	0
675.B	250	0
675.C	250	0

Table 6. Customer Load with 60% PV generation.

Customer	kW	kVAR
C1	68	20
C2	64	115
C3	48	109
C4	48	240
C5	68	125
C6	0	0
C7	51.2	86
C8	8.5	5
C9	33	19
C10	58.5	34
C11	0	0
C12	485	-10
C13	68	-140
C14	290	12

Fig. 12 displays the real power DLMPs in all three phases which are around the same cost as the dispatchable generation. A notable example is on bus 652, where the price has reduced from the case one price is 11.005 c/kWh to 7.034 c/kWh. Resulting in a reduced price of energy for customers on bus 652. Fig. 13 indicates the reactive DLMPs where the PVs are assumed to provide only real power. The DLMPs values are close to the cost of reactive power at the feeder 11 c/kVARh.

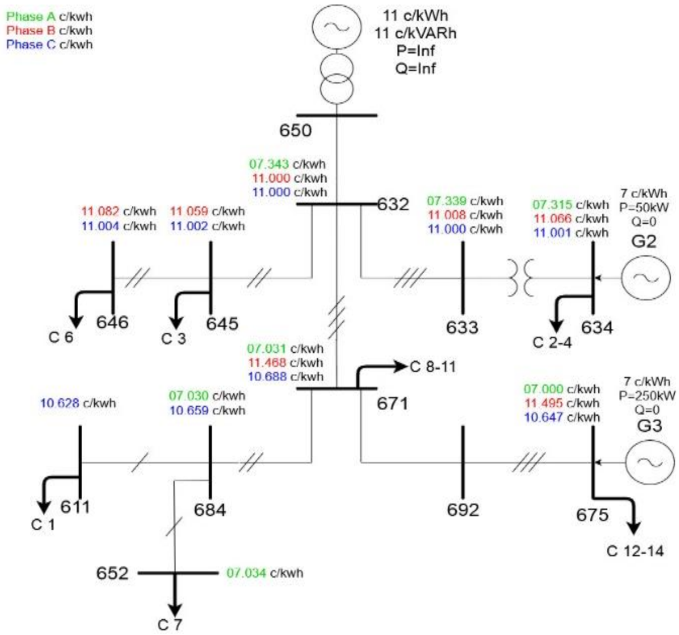

Figure 12. Real power DLMP at different buses of the IEEE 13 bus system with 60% PV.

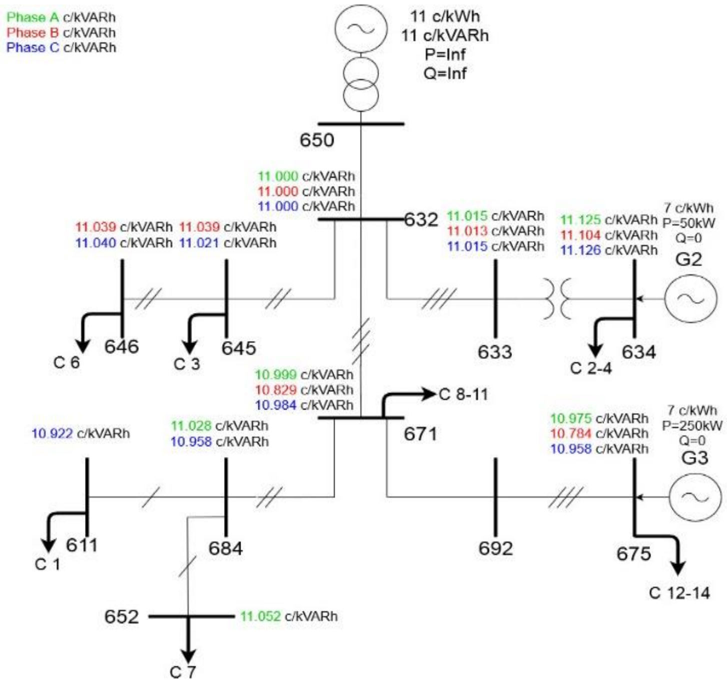

Figure 13. Reactive power DLMP at different buses of the IEEE 13 bus system with 60% PV.

VII. CONCLUSION

This article describes the architecture, design, implementation, and evaluation of an integrated transactive energy market prototype called TPA. This system enables researchers and engineers to analyze the effects of distributed energy resources and transactive energy markets on the electric power distribution grid. TPA resulted from the successful integration of modern web-application technologies, Python-based processing, and the OpenDSS unbalanced power systems analysis software. The current prototype of TPA supports the modeling and modification of an electric power distribution system model, load and generation profiles, and prosumer-initiated transactions. It provides a web-based management interface for managing all data models and transaction prioritization. The transaction prioritization and nodal pricing algorithms are based on DLMPs. The goal is to maximize the economic benefit, welfare, security, and availability of the electric power grid in the presence of prosumers. Scenarios considering different conditions of the IEEE 13-bus distribution systems were illustrated.

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