Transactive Energy in Electrical Power Systems with Virtual Power Plants

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***Abstract*—The energetic tendencies of self-production evident by the increase of microgrids, distributed energy resources, virtual power plants, among others, contribute in the development of mechanisms oriented to energy transactions. The present research proposes an heuristic method based on optimal DC power flows, that is used in minimization of costs by generation concept, for the analysis of the different forms of energy transactions, among which are the transactions by energy deviations, systems of transmission and power contracts. The analysis considers technical limitations, costs, energy balance, priority in renewable resources, pricing methods for transactions in the transmission system and the application of energy contracts; For optimization procedures, non-linear programming is used. The proposed algorithm is implemented in the IEEE test models of 4 and 118 buses.**

***Keywords*—Transactive energy,Energy markets,Optimal power flow, Renewable energy,Vitual power plant**

I. Introduction

The participation of Virtual Power Plants (VPPs) and microgrids (MGs) in the electric grid, along with the development of Distributed Energy Resources (DERs), Distributed Generation (DG), Renewable Energies (RE), and energy storage systems, brings forth several challenges and opportunities regarding the improvement of management, control, and operation strategies. These strategies aim to contribute to the enhancement of the electric service, primarily through the exploitation of renewable resources [1]–[3]. The transition to an energy system with a significant penetration of DERs also influences traditional energy market mechanisms [4], which has led to the emergence of the transactive energy (TE) model. This model focuses on coordinating the various agents involved in the electric system to achieve a dynamic balance between production, which takes on a decentralized nature, and consumption, with increased potential to act as a source of production as well [5], [6]. The interest in analyzing transactive energy models lies in the need to implement techniques that optimize network interconnection, operation, security, reliability, cost, among other factors [7], [8]. Research in the field of transactive energy proposes mechanisms focused on one or several of these aspects, primarily to determine energy trading strategies among the agents involved in a transactive environment [5]. In [6], a transactive control mechanism is proposed that considers the integration of electric vehicles into the grid, aiming to manage actions that minimize charging costs. In [7], an energy management system is designed, integrating requirements for energy generation, consumption, storage, and trading. In [8], the goal is to classify the costs and benefits of employing renewable energy sources within the framework of transactive energy. In [9], an algorithm is proposed that focuses on optimizing distributed energy sources in a microgrid by combining the optimal power flow model with evolutionary algorithms. In [10], a bilateral energy trading mechanism is integrated with optimal power flow techniques to increase the economic benefit of participants in the transactive market while ensuring the reliability and security of system operation.

From these examples, it can be observed how optimal power flows (OPF) are used for optimizing transactive energy models. OPF allows for the management and implementation of strategies based on different variables aimed at optimizing parameters such as security, quality, voltage profiles, reliability, cost, among others. Thus, the integration of OPF models into the field of energy transactions provides an interesting mechanism for proper energy management and cost minimization in the generation sector [11], [12].

With the intention of further analyzing the application of optimal power flows to transactive energy models, this research proposes a heuristic method based on the minimization of generation costs. It considers energy transactions resulting from power deviations, use of the transmission system, energy contracts, and the inclusion of photovoltaic generation systems.

Moving forward, this article is organized as follows: Section II presents relevant characteristics of transactive energy models and DC optimal power flows focused on cost minimization. Section III presents the problem formulation, describing the scope of applying optimal power flows to the transactive energy model, and introducing the algorithms used in the study. Section IV provides detailed results obtained from applying the optimization methodology to the IEEE 4-bus model. Finally, Section V presents the conclusions and future work.

II. Transactive Energy

In general, an energy transaction involves the participation of at least two agents. The first is responsible for specifying its energy requirements while the second takes responsibility for meeting the demand of the first agent. In addition, the

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parties involved may acquire the role of purchase or sale during the energy transaction according to their capabilities, infrastructure or availability [13]. From these aspects, the different types of transactions also arise, since depending on the resources available, a generation plant will be able to offer the energy produced, a consumer to publicize their energy requirements and the transmission system offer the means for energy transport [14].

A. Spot Transaction

A spot-type transaction is equivalent to real-time power trading or at least in short periods. Generally, this type of transaction is made by the presence of power deviations in consumption or production [15]. Example of this is any network-independent generation system, but with network connection capability; if it has production capacity above the demand to which it is supplied, it could inject it directly into the network, or at least offer it, which implies an immediate benefit to the generation system [16].

B. Transmission System

Node-to-node energy transactions necessarily involve the use of the transmission infrastructure, so it is natural the presence of costs for use and the right of connection to the electrical transmission system [17], [18]. However, the use of transmission infrastructure is not observable, insofar as it is difficult to determine the trajectory of the power injected or demanded by each agent individually; through power flows, the overall use that all agents involved exert on the transmission system can be estimated, but not in a particular way [19]. In this aspect arises the creation of several identification methodologies of the use and pricing, which seek to assign to each agent in an appropriate way, the charge corresponding to the impact of its transactive activity on electrical system [20]–[22].

One of the methods of transmission pricing is the so-called Postage Stamp, which assigns rates based on average costs and the power generated or consumed on a bus as the measurement of system usage. The pricing equation is (1):

$$R_t = TC\frac{P_t}{P_{Max}} \tag{1}$$

Where:
R_t: price for t transaction.
TC: total cost of transportation service.
P_t: maximum power supplied in transaction t.
P_{Max}: maximum power system.

This type of charging assigns to each agent that is participating in the electrical system, a charge proportional to the maximum circulating power through the network, it depending on the power injected or consumed by the agent; this, no matter what system nodes the transaction is performed on [22].

C. Energy Contracts

Energy contracts are medium or long-term agreements that involve some form of energy transaction according to the needs of the contracting agent. Transactions are usually made with start date and time, in addition to their duration [23].

III. Optimal Power Flow

In general, optimal power flows allows to find, for a given moment, the point of operation of the generation units that guarantee the dispatch of energy at the lowest cost while meeting various restrictions associated with the characteristics of the network, or for particular purposes such as line congestion analysis [24], contingencies [25], and security constraints [26]–[28].

A. Optimal DC Power Flow

The DC power flow solution adopts several simplifications, the line resistance is considerably lower than the line reactance, the difference in voltage angles on adjacent bus is small and the magnitude of voltages on each bus is one [29], [30], so the power Pi on a i bus is calculated with the equation (2):

$$P_i = \sum_{j=1}^{N} B_{ij}(\delta_i - \delta_j) \tag{2}$$

Where:
B_{ij}: susceptance of the line $i - j$.
$\delta i, \delta j$: bus angle i, j.
N: number of buses.

Taking into account the above simplifications, optimal DC power flows (DCOPFs) are a linearization that reduces the complexity of the optimization process [31], [32]. In DCOPF formulation, the target function is defined as (3), subject to power flow constraints by transmission lines (4), minimum and maximum capacity of transmission lines (5), minimum and maximum capacity of generation units (6) , and active power balance (7).

$$Min : OF = \sum_{i=1}^{N} P_{Gi}c_i \tag{3}$$

$$P_{ij} = (\delta_i - \delta_j)B_{ij} + R_{ij}(\delta_i - \delta_j)^2 \tag{4}$$

$$-P_{ij}^{max} \leq P_{ij} \leq P_{ij}^{max} \tag{5}$$

$$P_G^{min} \leq P_G \leq P_G^{max} \tag{6}$$

$$\sum P_g - P_d = \sum P_{ij} \tag{7}$$

Where:
P_{Gi}: power supplied by generation unit i.
c_{Gi}: cost of production of the generation unit i.
P_{ij}: power flow from i to j.
R_{ij}: resistance of the line i - j.
P_d: demand power.

IV. Problem Formulation

The progressive integration of VPPs into the power grid is expected to contribute representative amounts of power to the grid. This, coupled with self-production trends that implies a greater participation of several agents in the electrical system, result in energy transaction of various types. Hence the need to implement cost-minimizing-focused mechanisms that consider a transactive environment. Where, it will be required to supplement the total demand projections at the lowest cost, and from the perspective of producers, compliance energy contracts will be of vital importance even if there is a deficit in production, at which point it will be in the interest of the producer agent to supplement the energy contract through energy agreements with other producers at the lowest cost.

For this study, typical hourly production values obtained from photovoltaic panels are used. The production of these panels is scaled and in the study will fulfill the role of a VPP, which will have the capacity to supply only active power. In addition, certain assumptions are adopted. First, VPP can access price information and demand projections. Second, energy contracts are not intermittent, so the duration of the contract, the start time and power are specified, and during the transaction period the requested power must be delivered uninterruptedly. Third, the cost of the transaction C_{TE} is obtained by equation (8), applying the Postage Stamp pricing method to the assignment of the transmission cost.

$$C_{TE} = P_G c_G + R_t \tag{8}$$

The proposed methodology gives priority to the dispatch of renewable energy by allocating zero production costs to generation units of this type, this, for the global economic dispatch, since individually, the producer agent will assign the production cost to the generation units based on parameters such as operation, maintenance, and others. The same cost at which the producer offers its energy in the electricity market.

TABLE I
ALGORITHM 1

Algorithm 1: Energy transactions	
Step 1 :	Input → *Network topology parameters*
	$B_{ij}, c_{Gi}, P_{ij}^{max}, P_{Gi}^{min}, P_{Gi}^{max}, \Delta_{min}^{t}, T$
	Define → *Contract parameters*
	$h^{ini}, h^{end}, P^{TE}, a^{Prod}$
Step 2:	Demand and Generation Detours
	For $t = 1$ *in steps of* Δ_{min}^{t} *until* T
	If $P_{Gen}^{VPP} > P_{Dem}^{VPP}$
	$P_D^+ = [P_D^+; P_{Gen}^{VPP} - P_{Dem}^{VPP}]$
	$P_D^- = [P_D^-; 0]$
	Else
	$P_D^- = [P_D^-; P_{Dem}^{VPP} - P_{Gen}^{VPP}]$
	$P_D^+ = [P_D^+; 0]$
	End If
Step 3 :	Allocation of Powers during contracts
	For each contract in $t \,\epsilon\, [h^{ini} : h^{end}]$
	If $P_{Gen}^{VPP} > P^{TE}$
	Limits of $P_{Gi} = P^{TE}$
	Else
	Limit of $P_{Gi} = P_{Gen}^{VPP}$ → *Define Deficit*
	End If
Step 4 :	Cost-minimization dispatch
	O.F.:
	$Min \rightarrow OF = \sum_{i \epsilon \Omega_G} P_{Gi} c_i$
	Subject to:
	$-P_{ij}^{max} \leq P_{ij} \leq P_{ij}^{max}; \quad \forall ij \epsilon \Omega_{LT}$
	$P_{ij} = B_{ij}(\delta_i - \delta_j) + R(\delta_i - \delta_j)^2$
	$P_G^{min} \leq P_G \leq P_G^{max}; \quad \forall G \epsilon \Omega_G$
	$\sum_{i \epsilon \Omega G} P_{Gi}^t = \sum_{j \epsilon \Omega D} P_D^t$
	End For
Step 5 :	Find a producer agent if there is a deficit
	Calculate → *Transaction cost*
	$C_{TE} = P_G c_G + R_t; \forall\, a^{Prod}$
Step 6:	Show results

Algorithm 1 in table 1. sets out the methodology to the analysis of energy transactions including the model of cost minimisation by energy production. First, the characteristics and parameters associated with the network topology are identified, while defining the specific parameters of the energy contracts to be performed such as the start h^{ini} and end time of transaction h^{end} in addition to the contracted power P^{TE}. After that, power offsets are calculated. This section analyses exclusively the management of the generating units in the spot market, as these diversions indicate the degree of dependence of the network on the demand to which the VPP feeds. A positive diversion will represent a generation surplus that can be offered. Instead, a negative diversion will represent a generation deficit and thus the need for attention from another generation plant.

Subsequently, it works on energy contracts in which the generation limits of the DCOPF model are adjusted, it depending on the production of the agents and according to each contract,all this, within the period defined for the contract. Here, the ability of the producer agent to fulfil the contract by the specified power is analyzed. If during this procedure it is determined that the agent does not have the ability to maintain the contract under the specified parameters, it proceeds to calculate the deficit that will then allow to search for a second producer agent to assist the previous one with the compliance of the contract. What is done, by calculating the cost of the transaction for each of the agents, the lowest cost found will correspond to the producer agent with which the new contract should be made to handle energy deficit.

The procedure of setting parameters of the DCOPF model and applying it to define the energy clearance at the minimum cost is performed iteratively according to the specified minimum time interval Δ_{min}^{t} and until the total analysis time T is met.

The heuristic developed is applied in the- 4 bus test system in principle because of the simplicity of the system and the small number of variables of interest for the interpretation of the results. Fig. 1 shows the electrical system next to line reactance data, maximum powers, and generation costs. With regard to generation systems, one of them represents a traditional source of production and the other a deployed photovoltaic generation system, from which it was possible to obtain generation power metrics.

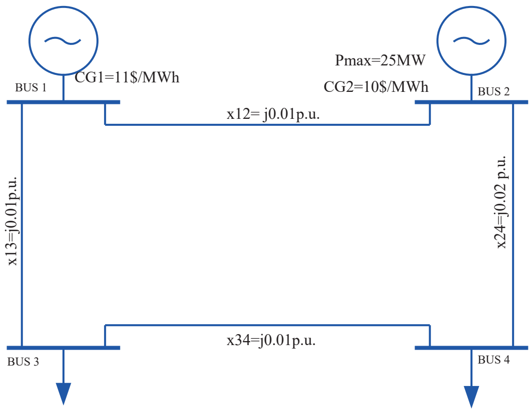

Fig. 1. Four bus electrical test system parameters.

V. Analysis of Results

The fig. 2 shows the energy dispatch at the lowest cost for the electrical system established considering spot transactions. It can be appreciated the contributions of each generator, the total demand, the demand to which the renewable generation plant supplies, in addition to the diversions between demand and generation. While the power generated by the VPP is less than the demand associated with it, the network assumes the power deficit, whereas when the power generated is higher than the load required, that power is injected directly into the network. Diversions of consumption and generation cause additional economic spending, which in turn benefits, from the predominant economic spending of the energy taken from the grid. In addition, over-generation can be observed representing a benefit, which although it is scarce, being considered with the reduction of the power dependence of the electric network, it is significantly beneficial at certain intervals.

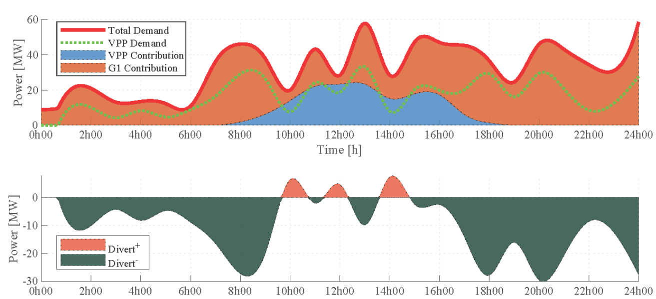

Fig. 2. Power contributions from the virtual power plant and the power grid alongside the deviations in spot-type transactions.

A second scenario considers an energy contract with a constant power supply for a period of 6 hours, in which the VPP assumes responsibility for supplying that power during the established period, as shown in the fig.3. In this period, the power injected by the renewable generation plant tries to adjust to the contracted power; however, there are specific points where the generation does not adapt to what was agreed. Although the energy dispatch developed allocates generation to assume the lack of production, it is not guaranteed to be at the lowest cost, as this involves the application of spot transactions, which are subject to demand uncertainty and may involve high costs. To do this, the methodology assigns a producer node with which an additional transaction can be made to cover the lack of power, looking for the lowest cost in the transaction. In the proposed system, since there are no more candidate generators, the methodology assigns the generator of bus 1 to carry out the new energy transaction.

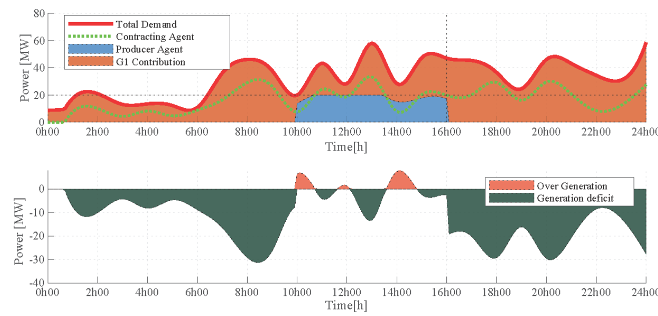

Fig. 3. Power contributions from the power plant and power grid in contract-type transaction.

Now, the methodology is implemented on the IEEE 118-bus test system, which has 179 transmission lines, 91 loads, and 54 generation units, of which 12 are renewable generation sources that play a role in the electrical system as producing agents with the ability to make energy contracts in energy supply fields. To each producer node are assigned particular parameters, i.e., different contracted periods and powers. The proposed algorithm identifies, as in the 4-bus test system, the producer nodes that cannot fulfill the contract in certain lapses, in which case the calculation of the costs that would involve a transaction with each of the generation units is carried out for a power equal to the maximum deficit presented during the transaction.

In Fig.4 shows the allocation of the producer agent and the generators with problems due to generation deficit and possible contract defaults. For the scenario used, generator 28, out of the 54 generators available in the electric system, would supply energy to the requesting generators, guaranteeing the lowest cost in the transaction. The sum of the contracted powers does not exceed the maximum power of the assigned generator, and furthermore, not all transactions would be carried out at the same time.

In Fig.5 shows the generation costs according to the energy demand at certain hours of the day, where it can be observed that the cost increases as the demand increases, for example, at 4:00 am the energy demand is 21 MW with a generation cost of 200 MW/day, while at 8:00 pm the energy demand is 49 MW with a generation cost of 550 MW/day.

VI. Conclusions

The methodology presented in this study broadens the perspective of optimal generation dispatch in an electricity market by incorporating criteria that address the various types of energy transactions present. The main focus lies in ensuring

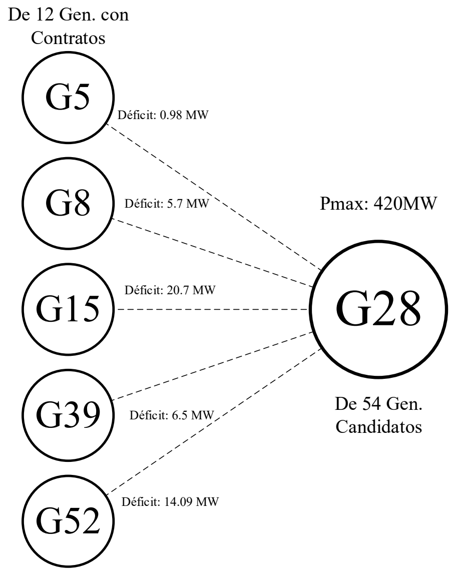

Fig. 4. Assignment of production agent for minimum-cost contract fulfillment.

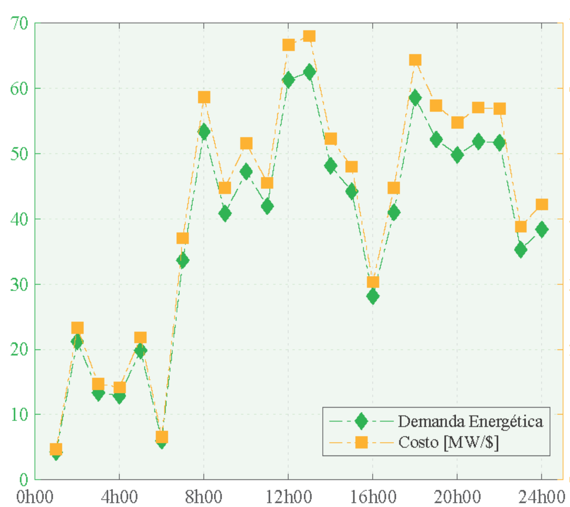

Fig. 5. Generation cost.

efficient management of these transactions, giving emphasis to both electricity contracts and spot transactions when there are no upstream contracts.

This proposal considers a variety of energy transactions with technical constraints, costs, power balancing, transmission losses and renewable generation considerations. Spot transactions, energy contracts and transmission line tariffs are analyzed in detail, with the objective of identifying the generation and allocation parameters of producing agents that comply with the energy agreements in the most economical way possible.

Highlighting the postage stamp pricing method, the aim is to quantify the impact of transactions in the system in relation to the maximum power available in the network. The choice of other pricing methods, which may approach impact measurement differently, influences the total costs of energy transactions. However, it is important to note that these changes do not alter the minimum cost associated with the allocation of producing agents.

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