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Decentralized Demand Response Power Management System for Smart Grids

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***Abstract*—According to the rapidly growing demand for electricity, as well as the emergence of various types of participants inside a Smart Grid (SG), it is necessary to develop a universal approach to ensure the beneficial interaction of all participants within a SG, thereby reducing the demand for electricity from the Utility Grid (UG). First, we introduce a universal approach to designing SGs of various structures, thereby aiming at the total benefit for all participants. Secondly, an algorithm for implementing a profitable pricing policy within a SG is implemented, as well as penal mechanisms are implemented. Moreover, a decentralized scheme of interaction between participants within a SG using blockchain technology is implemented. Finally, the effectiveness of the approach is checked taking into account various indicators, including a different number of participants and a time interval.**

***Index Terms*—Demand Response, Smart Grid, Blockchain**

I. INTRODUCTION

Every year, the demand for electricity grows worldwide [1] and in light of the current global scenarios, most countries are preparing to meet this increasing demand by growing their green energy production capacity. Some countries are targeting to have as much as 80% of their power generated through these means [2]. Green energy which is also referred to as renewable energy sources bring with themselves a number of limitation, among which one is the huge variation in production capacity. For instance, wind energy completely depends upon the speed of wind and this parameter can vary heavily thus affecting the production capability. In order to adjust to such variation, the Smart Grid technology is used.

A conventional smart grid comprises of the three broadly defined actors. The power generators, aggregator and consumer. The generator produces power which is then bought in the form of bundles by the power aggregator. This power is then sold to power consumers based on their requirement. With the recent technological advancement and the introduction of low cost PV cells along with the increasing use of Electric Vehicles, consumers can also participate in the SG by supplying power back to the aggregator, thus making them prosumers. The introduction of prosumers adds an extra layer of risk. The random power generation pattern of prosumers results in a random change in available power at the aggregator. This as a result leaves the aggregator in a dilemma, of either to be over conscious and buy a larger power bundle from the conventional generators so that he can fulfil the power requirement in worst case scenario or to estimate and than hope that the prosumers would continue their production patterns and buy less energy from conventional generators. In the former scenario, the consumer pays more for power as the aggregator has to balance out his overall cost across all the consumed power. Whereas, on the other hand, the aggregator ends up looking for more power when it is needed. In a conventional power distribution network, requesting more power from a conventional generator might not be possible as generators can only produce some certain amount of power and increasing production on the fly is not much viable. One way of mitigating this issue is to form a central hub that monitors and manages all the power requirements and ensures that everyone gets the power that is needed. This requires every generator and every aggregator to contact a central command centre, which evidently becomes a single point of failure in the SG.

In order to overcome these issues, researchers have proposed multiple approaches in the past. The authors of [3] developed an IDR (integrated demand response) program, which consists of two parts (Supplier Side Model, Customer Side Model). By using a distributed algorithm, utility companies and EH (Energy Hubs) communicate automatically and determine their optimal behavior thus ensuring that the aggregators buy the right amount of energy. In [4], the authors propose a price optimization model based on the ratio of production and consumption levels within microgrids. This approach assumes the introduction of a coordinator (Energy Sharing Provider) to ensure the operation of the algorithm. The model can be applied for the day-ahead or hour-ahead market. In [5], a combined approach is used, which includes a real-time price model and a stimulating model. To manage the energy consumption of end users, the concept of "i-Energy" is used. The exchange of information between the Utility Grid and end-users takes place directly. In [6], the biobjective optimization approach is applied taking into account customer's satisfaction and the cost of energy consumption. In this approach, consumers can actively participate in the system, changing their level of consumption to reduce cost. One of the indicators that affect the operation of SG is the parameter of consumer willingness to shift loads. We cannot know about this in advance, however, some works [4], [6] address these issues. Most of the aforementioned approaches work well in a three actor SG model but the unpredictability of a prosumer becomes an issue for most of them. This has been addressed by the introduction of a Blockchain based distributed ledger technology into the SG architecture.

In [7] the authors propose a blockchain based model for distributed management in SG, and a Smart Contract in order to control DR events within the SG, which are introduced to increase reliability of a system, and to store all the data in a secured and tamper proof manner. In [8], the authors propose using three separate blockchains (BlockPRI, BlockSEC, and BlockTST), where BlockPRI stores privacy settings, BlockSEC stores users' data, and BlockTST stores information regarding electricity trading. The authors of [9] describe different use cases of using blockchain in SGs. The issue of using blockchain for peer-to-peer electricity trading, and the issue of security and privacy in smart grids are considered. In [10], the authors considered the problem of single point of failure, and developed a blockchain-based secure energy trading scheme for SGs, which is called "EnergyChain". The security issues regarding SG are considered in [11] and [12]. In this work, the authors consider blockchain technology as an alternative to current solutions, which will ensure reliable and secure exchange of information within SG.

The main contributions of this paper are:

- We introduce a universal template, which is called SGN (Smart Grid Node), in order to be able to design SGs of various structures based on this template.
- To ensure profitable terms of interaction within the SG, an efficient pricing model, based on [4], with the refinement of incentive and penalty mechanisms was implemented.
- In order to exclude such a concept as a single point of failure, as well as to ensure the confidentiality of SG participants and a secure way of interaction, we adapted and implemented the pricing model in a decentralized manner, designing it in the form of a Smart Contract.

The rest of the paper is organized as follows. In Section II, the question of determining a universal template for designing SGs of various structures is considered. Section III discusses the implementation of the internal price optimization algorithm. Section IV describes a decentralized approach for the interaction of participants within the SG. In Section V, the performance of the proposed approach is evaluated through simulations. The conclusion is drawn in Section VI.

II. THE UNIVERSAL DESIGN APPROACH

The complexity of energy systems grows continuously, which leads to a wide variety of approaches, structures and solutions [13], [14].

Given the constant development and complexity of power grids' structure (including SGs), an approach is needed that will simplify the representation of power grids.

In order to simplify the schematic representation of the SG, and to get away from the infinitely growing number of different entities, it is necessary to define a template element that can represent an entity of any type.

In actuality, consumers buy energy from the aggregators, aggregators buy energy from generators and sell it to consumers, generators sell electricity. Prosumers on the other hand, are special types of consumers. They can buy electricity from aggregators and can also sell it back to them when they have it in abundance. They atain their abundant energy by employing power generation approaches such as a solar power plant or a small wind power plant.

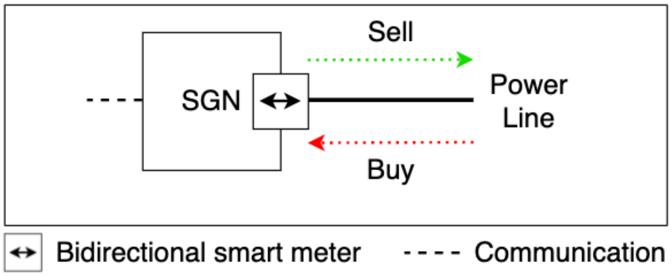

Fig. 1: Smart Grid Node

Using the aforementioned definitions, here we introduce the concept of SGN (Smart Grid Node) (Figure 1). By using this entity, we can represent any element within the SG. For example, a consumer is a SGN, which has a zero production level, and a generator is a SGN, which does not consume electricity. All entities within the SG have a communication channel, which is necessary for interaction with other SGNs.

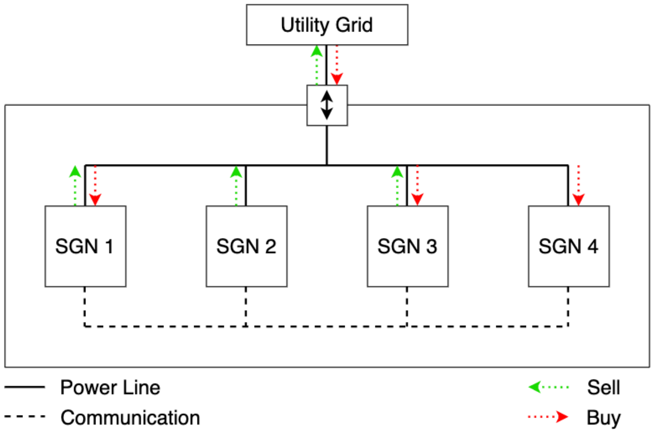

Fig. 2: Smart Grid designed with SGNs

Figure 2 shows the simplest SG, which is designed with SGNs. In this scheme, there are only four SGNs (participants), two of which can buy and sell electricity (SGN 1, SGN 3). SGN 2 only sells, it can be a prosumer who only sells, or it can be an aggregator, or a generator. SGN 4 only buys electricity, it can be a prosumer, or maybe an aggregator that does not sell (does not supply) electricity. From our point of view, it is not important who exactly is SGN, since our goal is to ensure a balance within the SG. Moreover, the SG has a point of communication with the Utility Grid, through which electricity can be sold and bought.

In order to be able to represent any SG using SGNs, we replace the concept of ”Utility Grid” with ”External Grid”. We also propose to consider the SGN as a hierarchical structure. As we can see, the structure of the simplest SG and the structure of the SGN are identical. SG and SGN have points of interaction with an external network, as well as communication channels. In Figure 3 we present a universal representation of the SG.

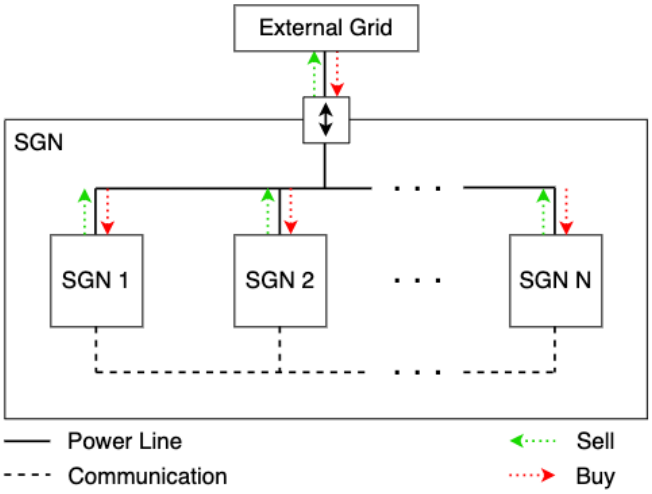

Fig. 3: Universal Smart Grid Design

In our approach, any participant in the SG is represented as a SGN, in addition, any SGN can represent a hierarchical structure. Thus, we can say that the SG is a ”grid of grids”, in which all participants have the same rights. In this implementation, the main goal is the beneficial interaction between all participants and it does not matter which entity SGN represents. Moreover, this approach allows us to abstract from the real structure of the SG and concentrate on developing an algorithm for interaction between participants.

III. PRICE MODEL

In this section, we consider the algorithm for optimizing the internal price for the SG. As a basis, we took the algorithm, which is described in [4].

Each SGN_i, at each time slot h has its levels of electricity production P_i^h and consumption TP_i^h. Some SGN have zero levels of electricity production or consumption (for example, a consumer and a generator). In order to develop a more universal approach, we consider such SGNs as participants with zero levels of consumption or production (in a time slot h).

Each SGN at each time slot h has a parameter of the net power (NP_i^h). Based on this indicator, we determine the action of the SGN in a certain time slot. If SGN produces more than it consumes, then the excess energy will be sold to the SG. On the other hand, if SGN consumes more than it produces, we understand that in a particular time slot h, the SGN will buy electricity from the SG.

Based on the net power indicators of all SGNs, we have two other indicators for the whole SG - TSP^h (Total Selling Power) and TBP^h (Total Buying Power). In the same way as in the case of a separate SGN, we can calculate the net power of the whole SG. Based on this indicator, we know the status of the system in a specific time slot h. If the SG produces more electricity than it consumes, this means that excess electricity can be sold to the external network.

It is worth noting that the calculation of the net power parameter for the whole system and for an individual SGN is identical in both cases. In order to operate with only one parameter for determining the status of the system, the SDR parameter is used - the ratio of the total selling power by the total buying power (in time slot h). Based on this parameter, the price optimization algorithm inside the SG works. Figure 4 shows price options for the interaction of the SGN within the SG, as well as interaction with the Utility Grid.

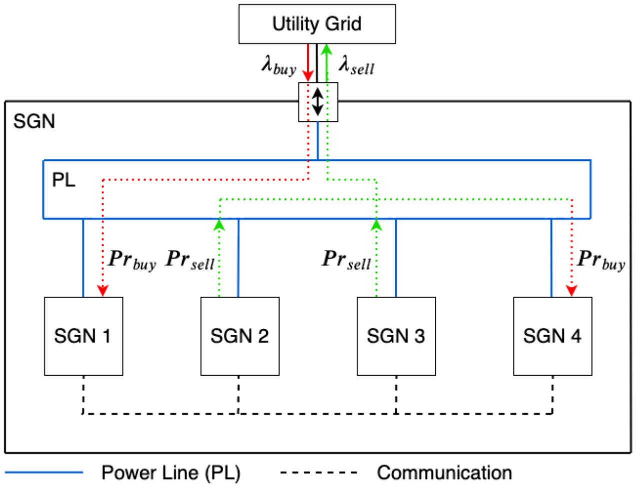

Fig. 4: Prices within the SG

In this example, SGN2 and SGN3 sell excess electricity to the SG at the price Pr_{sell}, while SGN4 buys electricity from the SG at the price Pr_{buy}. Also, SGN can sell electricity to the SG at the price Pr_{sell}, which will then be sold to the Utility Grid at the price λ_{sell}. If there is a lack of electricity inside the SG, it is necessary to buy it from the Utility Grid at the price λ_{buy} and then sell to the SGN at the price Pr_{buy}. It is worth noting that the price λ_{buy} is the buying price of electricity only from the UG, λ_{sell} is the selling price of electricity only to the

UG. Within the SG, a single pricing policy (Pr_{sell}, Pr_{buy}) is applied.

The meaning of the price optimization algorithm is that the purchase price of electricity from the SG (Pr_{buy}) should be less than the purchase price from the Utility Grid (λ_{buy}), and the sale price of electricity to the SG (Pr_{sell}) should be higher than the sale price to the Utility Grid (λ_{sell}). Therefore, SGNs are motivated to work with each other. If some SGN has some excess electricity, it is more profitable for him to sell it to the SG at the price (Pr_{sell}), which is higher than the sale price to the UG (λ_{sell}).

Next, we determine the main actions in the system. For the convenience of the SG participants, the purchase and sale prices will be optimized at the beginning of a new day. Thus, the first action is to optimize prices within the SG. As a next step, SGNs change (optimize) supply and consumption patterns taking into account new prices. Over a new day, SGNs can change their patterns, they only need to understand that this will entail changes in the entire SG, therefore, with critical changes that greatly violate the approved patterns at the beginning of the day, SGNs will be fined. The next day we need to start the process again taking into account the supply and demand patterns from last n days (in this work n = 1).

In addition to optimizing prices, we consider price changes (the use of a fine) in case the SGN changes its level of consumption or production, which was agreed in advance. Note that we are interested in cases when the level of production decreases, or the level of consumption increases. In both cases, SGNs can act both as a seller and a buyer, so different prices can change (Pr_{sell} or Pr_{buy}). The logic of the formation of fines is described in more detail in Appendix A.

IV. BLOCKCHAIN

In this section, we consider the application of blockchain technology in SGs as a method of interaction between all SGNs. Firstly, the introduction of such a technology allows us to exclude unnecessary participants (regulatory bodies) from SGs, which are used to ensure the operation of the algorithm [4]. Secondly, the use of blockchain allows us to solve the problems of security and privacy in SGs.

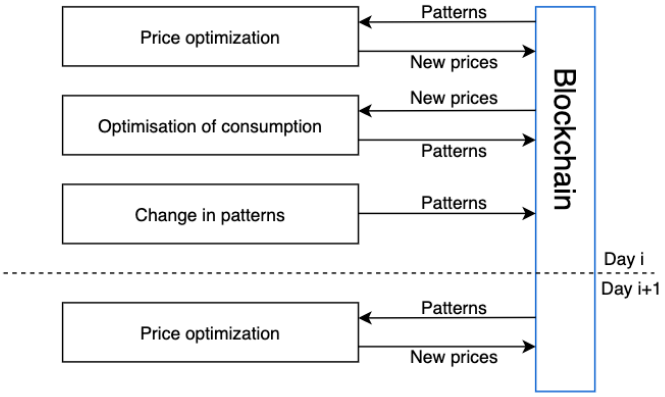

Fig. 5: Interactions within a blockchain

At the beginning of a new day, we optimize the sale and purchase prices of electricity for the entire SG, so we have a transaction and send it to the blockchain. The next step is to optimize the levels of electricity consumption on the side of SGNs. After SGN determined that a new block appeared, in which new prices are indicated, it optimizes the level of electricity consumption for a day in advance. If for some reason SGN did not update (optimize) its consumption level, this means that it agrees to work in the previous mode, taking into account the updated prices. Updated consumption patterns form transactions that are also sent to the blockchain. During the day, SGNs can also change levels of consumption and production, which will also lead to the creation of new transactions. Then we return to the beginning and everything starts again, namely with the optimization of purchase and sale prices (Figure 5).

V. THE RESULTS

To run the simulation, we randomly generate consumption patterns (0-2 kWh) and production patterns (0-3 kWh). The prices of purchase λ_{buy} and sale λ_{sell} of electricity for the Utility Grid were taken from sources [15], [16].

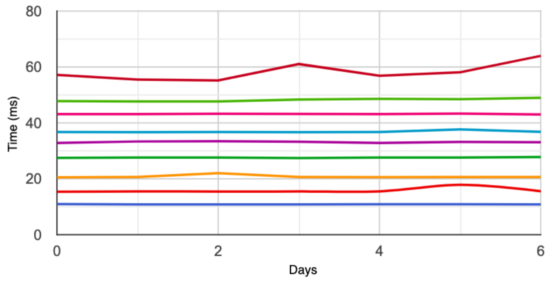

Fig. 6: Price optimization time

Initially, an algorithm to optimize the purchase and sale prices of electricity for the SG was implemented. Figure 6 shows the time (ms) to find a solution for a different number of SGNs over a period of 7 days. If we consider a period of 7 days, this means that the price optimization was performed 7 times (at the beginning of each new day). As we can see from the graph, the time for a solution does not exceed 100ms, even taking into account the different number of SGNs.

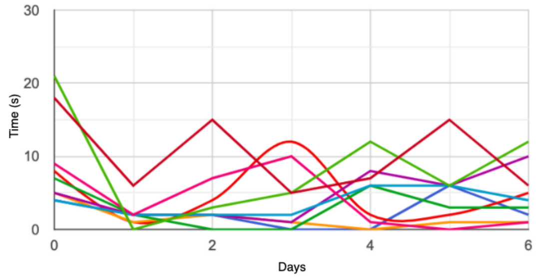

Fig. 7: Mining time

One of the indicators that we estimated is the block mining time over time. For a more realistic simulation, the maximum number of transactions in a block is determined as $rand(2, n)$, where n is the number of SGNs.

Figure 7 shows the total time required to mine the blocks within one day (during the period of 7 days). When testing the time required to optimize consumption patterns, the results showed that the time did not exceed 20 seconds.

TABLE I: SGN #2 daily economy

Day	Base cost	Opt. cost	Economy
1	2.01	1.49	0.52
2	1.72	1.24	0.48
3	1.72	1.43	0.29
4	1.72	1.21	0.52
5	1.72	1.29	0.43
6	2.01	1.48	0.53
7	2.01	1.6	0.41
Total	12.91	9.74	3.18

The next test case was to check the value of the savings indicator for a randomly taken SGN. As we can see in Table I, which shows the value of daily savings, the total savings for a SGN #2 was 3.18 pounds for 7 days. The results of testing the algorithm for 10 SGNs over 30 days also showed that the cost for SGNs was always less than when interacting directly with the Utility Grid.

VI. CONCLUSION

In this paper, an algorithm for determining internal prices inside a SG was implemented, and issues of imposing penalties were also considered. We conducted testing taking into account the different number of SGNs, emulating their interaction for 7 (and 30) days. Testing results showed that SGNs in the Smart Grid can reduce the cost of using electricity, taking into account possible penalties and changes in the levels of consumption and production.

APPENDIX

SGNs can change their levels of electricity consumption and production during the trading day. If SGN increased its level of electricity consumption, it can act both as a buyer or a seller, therefore, it is additionally necessary to consider the role of SGN after the changes.

Suppose that the SGN increased its level of consumption, but still continued to participate in the role of a seller, in which case the selling price of electricity from this SGN to the SG is calculated in accordance with Algorithm 1.

Algorithm 1

```
if ($SDR_{old} \geqslant 1$) then
    if ($SDR_{new} \geqslant 1$) then
        $Pr_{sell(new)} = Pr_{sell(base)} - \beta$
    else
        $Pr_{sell(new)} = \lambda_{sell} - \gamma$
    end if
else
    $Pr_{sell(new)} = Pr_{sell(base)} - \gamma$
end if
```

Thus, we determine how the change in the level of consumption influences the whole system. If SG acted as a seller and continued to work as a seller, then we consider such a change to be non-critical. Otherwise, if the SG acted as a seller, and then changed the status to the buyer, then we consider this change to be critical. Therefore, for different situations, we use different penalty values: β - a slight effect on the system, γ - a significant effect on the system.

Thus, if SG continues to act as a seller, we impose a small fine of β, if the system becomes a buyer after the change, we impose a large fine (we make the sale price lower than the λ_{sell} price), because this situation is undesirable in the SG. If the SG acted as a buyer, and after the change increased the volume of purchased electricity, in this case a large fine is also imposed (from the selling price optimized at the beginning of the dayPr_{sell}), since we cannot infinitely load the Utility Grid, increasing demand. If the penalty is imposed on the optimized price, then it is imposed once a day, and the price does not change anymore (for the worse for the SGN).

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