Mitigating Brown-Outs: Fair Distribution of Locally Sourced Energy in Smart Grids

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***Abstract*—The introduction of more and more *local and distributed* energy resources (DER) into the current centralized electrical grid poses new challenges to energy distribution. DERs are significantly smaller in production capabilities than central power plants and their production is highly fluctuating. This means that their influence on the electrical grid is difficult to plan for, especially in brown-out situations, when there is not enough energy available to supply all consumers. This work focuses on the subproblem of fair electricity distribution in brown-out phases. Currently, network segments are switched on and off in a round-robin manner, regardless if there are local producers in these segments or not. However, enabling segments that include local producers more often would improve the overall amount of energy available during the brown-out phases, and thus, this measure would increase the number of supplied consumers. We propose new algorithms that leverage the power of local producers, but still keep a fair energy distribution for all consumers. Therefore, we evolve the current notion of fairness to improve the overall quality of service by taking into account equal supply times, as well as maximizing the number of supplied consumers. The proposed algorithms are compared to the current state of the art approach in the German electrical grid. Therefore, extensive simulations based on real-world low-voltage residential area networks were conducted. The results indicate an improved quality of service during brown-out phases. Moreover, the proposed method is not limited to low-voltage residential areas, but also applies to all hierarchy levels of the energy grid, ranging from the distribution grid down to future households implementing smart grid technologies.**

***Keywords*–Smart Grid;Micro Gird; Demand and Response; Fairness; Electrical Grid; Optimization.**

I. Introduction

The current electrical grid is already undergoing a change, which will accelerate even more in the future. Nowadays, the production architecture is based on large nuclear- and fossil-fuelled producers, which are located centrally in the grid. This concept will turn into an architecture that uses *local and distributed* energy resources (DER) in addition to a reduced number of central producers. DERs are based on renewable energy sources, amongst those, the most established ones are solar- and wind-energy. However, this increased amount of DERs in the electricity production introduces several new problems for the electrical grid. For instance, the flow of electricity can become bidirectional if the production of the DERs is high [1]. Furthermore, in contrast to the fossil-fuelled producers, the production of the DERs is highly fluctuating and thus, difficult to plan for [2]. Therefore, the establishment of an information and communication infrastructure (ICT) that provides monitoring and control capabilities becomes mandatory. If such a system is integrated into the electrical grid, the concept of a smart grid (SG) emerges.

A big step into the direction of increasing the share of renewable resources in the production of electricity was conducted recently in Germany. There, the *Renewable Energy Sources Act* (EEG) [3] was passed. This act states that, until the year 2025, Germany must generate 40%-45% of the electricity demand by renewable energy sources like solar panels and wind turbines. These changes, which the electrical grid is facing in terms of infrastructure, do not fit to the rules and network policies for maintaining controlled operation that are currently in use. A response to these changes, by adapting and establishing new policies and rules according to the new situation, is necessary. A subproblem concerning the outdated rules and policies, and the main focus of this work, is the demand and response (D&R) behaviour of the electrical grid in brown-out-scenarios. An energy grid enters a brown-out-state if the production capacities do not suffice to supply the demand of all consumers in the network. This also holds for the black-out-scenario, however, the complete absence of electricity introduces additional difficulties, like frequency synchronization.

The German state of the art procedure to cope with the problem of D&R in a brown-out-scenario works as follows: the network is logically divided into (preferred equally consuming) subnets. Each of these subnets has to be separable and reconnectable to the grid, such that these are allowed to either consume electricity or not. Subsequently, one after another of these subnets is separated from the grid in a round-robin based manner. After each separation of a subnet, the current network stability is measured. If the network has stabilized, the currently active consumers will be supplied for a certain amount of time, otherwise additional subnets are disconnected. The round-robin approach guarantees fairness in the brown-out-scenario. This is done by only allowing to disconnect the same subnet for a second time, after all other subnets have been disconnected at least once. In the very end, this method guarantees that each subnet is supplied, as well as disconnected for the same amount of time. Note that the very last round of the disconnection process might change the equality of supplied time for the latest supplied groups. However, this will be taken into account in case of further brown-out-cases, such that consumers with lower supplied time during the last incident will be preferred next time.

However, the procedure does not take the production capabilities of the subnets into account, but enforces equal supplied times for each consumer by deactivating the subnets in a round-robin based manner. This, however, will also deactivate the production capabilities, in terms of DERs, which are located in these subnets. Therefore, this attempt might even promote further destabilization of the network if the consumers are capable of producing high amounts of electricity. To face these challenges of the future energy grid it is important to develop new rules, policies and algorithms that take these DERs into account while concurrently providing fair electricity distribution.

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In this work, *fairness* is introduced as a measure for extending the definition of quality of supply in the electrical grid. Additionally, algorithms are presented that allow to use the production of DERs, to increase the number of subnets that can be supplied in the brown-out-scenario. However, there is no general definition of fairness. As of this, our fairness definition focuses the following two optimization goals: on the one hand, to provide equal supplied times for all consumers and, on the other hand, to maximize the number of supplied subnets in the grid.
As a use case, the introduced approach is tested in a simulation of a low-voltage distribution system of an residential area. It is, however, not limited to this scenario. The proposed approach can be used at all hierarchical levels of the electrical grid, ranging from the distribution grid to low-voltage areas. Moreover, with future technological progress, this approach can be applied to single consumers in the grid.
The remainder of this work is organized as follows. In Section II, an overview over scenarios in the domain of the electrical grid is provided, where fairness is an important goal. Section III describes a formal model for representing a micro grid in an undersupplied state and introduces a new fairness metric, which takes the equal distribution of electricity, as well as the average number of supplied busses into account. In Section IV, fair electricity distribution algorithms are presented. Followed by Section V, where the simulation process is described and the results are discussed. Finally, the paper concludes with Section VI.

II. Related Work

Fairness is a term discussed in many fields, most prominently in economics [4] and psychology [5]. However, fairness also became an important criterion in application of information technology [6] and especially in the area of scheduling algorithms [7] and resource allocation [8]. In this Section, a selection of work is presented that is concerned with the definitions and fields of application in the SG scenario. One of the most popular fields for applying fairness in the domain of SGs is the area of dynamic demand and response, where demand is dynamically adapted according to different strategies or algorithms to reach certain optimization goals. The approach of [9] uses a daily consumption schedule for the consumers in the network. The loads in this schedule are divided into two categories, namely fixed- and flexible-loads, where the latter can be moved within the schedule. In this work, consumers try to reduce their electricity bill by scheduling their flexible loads in such a way that the overall production cost for energy in the network is reduced. Hereby, fairness is achieved by charging users for electricity based on their contribution to minimize the production costs in the network. In [10], dynamic demand and response management is discussed in the environment of smart objects that can be activated and deactivated dynamically. In this scenario, fairness is introduced by using different scheduling approaches like round-robin or by assigning priorities for scheduling algorithms. The authors of [11] discuss fairness in the sense of a trade-off between the maximization of a consumers utility function (level of satisfaction dependant on the electricity consumption) and the minimization of production costs imposed to the energy provider. Another approach that defines the fairness of an algorithm as a matter of consumer satisfaction is presented in [12]. Hereby, the difference in starting time of so-called *soft loads* is used as a metric. A slightly different fairness notion is used by the authors of [13]; they present a day-ahead energy resource scheduling algorithm using DERs and Vehicle-to-Grid (V2G). To prevent unnecessary battery deterioration of the vehicles, the authors establish pricing levels, which are dependent on the power level of the batteries, to establish a fair remuneration scheme.
Another field of application is the planning of SG communication networks. The authors of [14] use equal quality of service as a fairness metric in their approach of planning wireless mesh neighbourhood area networks (NANs). They discuss fair placement of gateways to ensure an equal number of participants to be covered by each gateway.
Although there is a lot of ongoing work that uses fairness metrics in the SG scenario, the considered scenarios are mainly based on cases of normal operation. In contrast, this work considers the state of the art fairness metric and presents its drawbacks in the SG domain. Moreover, the presented algorithm aims to maximize the use of DERs while simultaneously maintaining fairness of electricity distribution among consumers.

III. System Model Definition

In this Section, a model to represent a microgrid in an undersupplied state is presented. In particular, the relevant parts of the microgrid are described and formalized. Subsequently, a formal definition of an undersupplied state is presented. The Section concludes with the introduction of assumptions about minimal provided supply and a presentation of the novel fairness metric.
The system considered in this work is a microgrid that encompasses multiple residential areas. This can be, for instance, the electrical network that connects several streets in a city. The microgrid is connected to the main grid (MG) through an adjustable transformer that handles incoming energy from the MG, as well as outgoing electricity into the MG. This transformer allows the measurement of electrical values for the different streets like phase voltage, phase angles, and ingoing and outgoing energy. Furthermore, this component provides the functionality of enabling and disabling incoming and outgoing connections, such that parts of the microgrid can be disconnected and reattached to the MG. In the following, a more formal definition of the system model will be provided.
Let the overall system be a set of street busses $ST = \{st_0, \ldots, st_n\}$, $n \in \mathbb{N}$. Each of these busses represents a prosumer, which is connected to the adjustable transformer (*tr*). This scenario is shown by Figure 1.

Each street bus st_i has a combined consumption and production, which is in general the sum of the consumption and production of all houses that are located in this street. The production capabilities of houses are non-zero if DERs are installed, otherwise they will be neglected (We will not go into further detail about production and consumption behaviour of the houses, but stay at the street abstraction level). Each prosumer can be a consumer or a producer at each specific point in time during the day. Let all prosumers be represented as a set C and the producers likewise as a set P. A prosumer is a consumer $c_j \in C$ if the consumption of electricity in the street is higher than the production provided by its local DERs. Whereas a prosumer is a producer $p_j \in P$ if the electricity provided by its local DERs exceeds the local demand. A more

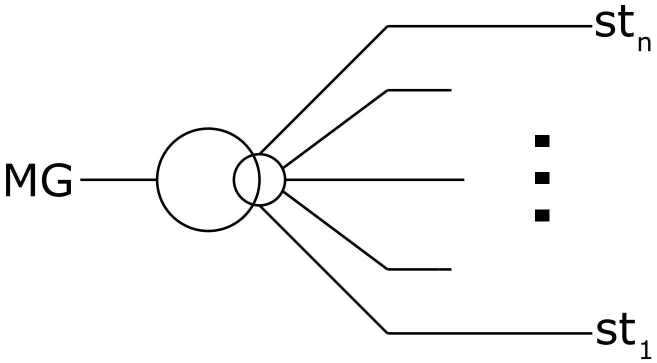

Figure 1. Representation of the considered scenario, where the street busses (st) are connected to the main grid (MG).

formal representation of these relations can be expressed as follows:

$$\forall t, i \; 0 \leq i \leq n \, \{st_i \in C \,|\, cons(st_i, t) > prod(st_i, t)\} \quad (1)$$

$$\forall t, i \; 0 \leq i \leq n \, \{st_i \in P \,|\, cons(st_i, t) \leq prod(st_i, t) \quad (2)$$

Parameter t represents a certain point in time during a time interval $[0, \ldots, T-1]$. The functions $cons(st_i, t)$ and $prod(st_i, t)$ provide the current consumption or respectively the production of electricity of street bus st_i at the time t. Equation 3 provides a formal description of the production function $prod(st_i, t)$ and, similarly, Equation 4 refers to function $cons(st_i, t)$.

$$prod(st_i, t) := \sum_{j=0}^{m} \int_{t}^{t+1} y_j(t) \mathrm{d}t \quad (3)$$

$$cons(st_i, t) := \sum_{j=0}^{m} \int_{t}^{t+1} x_j(t) \mathrm{d}t \quad (4)$$

The production and consumption of a street bus st_i at given point in time t is the sum of the integral of the production/consumption $y(t)/x(t)$ over the time step t for all the houses j connected to that bus. Without loss of generality it will be assumed for the remainder of the paper that the granularity of the time interval T is based on the hours of a day, such that $T = 24$. Any other time interval would be suitable too; especially smaller ones, when taking into account the volatile nature of SGs that include renewable energy sources like photovoltaic and wind power. With further technological progress, in the future it will be possible to refine this model by transitioning from the level of street busses to houses or even to the devices that are located in the houses.

In the following, a formal definition for an undersupplied state (brown-out) is provided. A microgrid is a part of the larger MG and either receives electricity from it or acts as a producer if the local production is high enough. However, since we are dealing with a situation of undersupplyment, we assume that the main grid can not provide enough energy to supply all street busses of the micro grid simultaneously. Moreover, we assume that this holds for at least one timestep during a day. The formal definition of an emergency state is as follows:

$$\exists t \, 0 \leq t < T \, prod(MG, t) < \sum_{i=0}^{n} cons(st_i, t) \quad (5)$$

Where $prod(MG, t)$ represents the amount of electricity the MG can provide for supplying the prosumers of the microgrid. As long as the production of the MG is high enough to partially supply the micro grid, the system is in a brown-out-state. However, if the MG does not provide electricity at all, the systems status changes to a black-out-state. Without loss of generality, this work focuses on an undersupplied state that is critical (brown-out), but not fatal (black-out) for the microgrid. In particular, this means that the amount of energy provided by the MG should at least cover the demand of some of the street busses located in the micro grid. A formal definition can be as follows:

$$prod(MG, t) \geq \max\{cons(st, t) | st \in ST\} \quad (6)$$

This definition guarantees that, for each point in time, the MG provides enough energy to supply a single street in the microgrid. Without this assumption we may have situations where the electricity is not enough to supply a single bus. This, however, represents a black-out-state in our model, and is not part of the current work. Note that in this case the model still holds considering future technological development and thus the possibility to transfer the problem recursively to individual streets. In addition to the electricity that is provided by the MG to supply the micro grid, the street busses contain local producers. Examples for such local producers are solar panels, wind turbines and similar, as well as batteries and alike. Thereby, solar panels and wind turbines are inherently volatile in availability and power output, while the availability of batteries and other energy storage systems is much easier to plan. In this paper, without loss of generality, we simulate local energy production with solar panels. If a bus is supplied, the local producers are active and increase the amount of available electricity. However, if a bus is not supplied the corresponding DERs are deactivated. To successfully supply a bus st_i at time t it is sufficient to provide the amount of electricity such that the sum of electricity provided by local DERs and the supply of the MG equal the demand of the bus. The formal definition is as follows:

$$cons(st_i, t) \leq prod(MG, t) + prod(st_i, t) \quad (7)$$

The function $prod(MG, t)$ hereby represents the amount of energy that is centrally provided by the MG. Changes of state, like from being supplied to being unsupplied or changing from being a consumer to being a producer, can be performed instantly in the digital representation of a system. However, the physical system consists of electrical and mechanical components that have time constraints for changing their state (e.g., electrical switches). To consider these constraints in the discrete simulation model, it is assumed that after a change of status has happened, this new status is kept for one timestep. To evaluate the fairness in the described model, in the following a new fairness metric is proposed. The currently used metric, which is based on equal supplied time, is not optimal anymore in the presence of future technological changes in the domain of the electricity grid. The transition from centralized to distributed production changes the way how the presence of prosumers influences the performance of the network. However, DERs can only contribute to the system if the corresponding bus, where they are located, is connected to the network. One part of the novel fairness metric is based on the assumption that strategies, which maximize the use of DERs, are able to supply more busses than other strategies. To represent this in the metric, the average number of supplied busses is used as a parameter. Furthermore, to include the fairness of handling the consumers, the sum of differences between the supplied time of all consumers is calculated. If an algorithm can supply a large number of busses, while minimizing the differences in the number of timesteps, in which consumers are supplied, the fairness metric is maximized. To achieve maximum performance of the DERs, prosumers that are producers are not taken into account. This is due to the benefit the network gets in terms of produced surplus electricity and thus, producers are allowed to stay connected. A more formal description of the fairness metric is as follows:

$$\forall i, j \in C \;\; f = \max \frac{\textit{avg\#ofsuppliedbusses}}{1 + \sum_{i,j \in C} |t_{sup,i} - t_{sup,j}|} \tag{8}$$

where $t_{sup,i}$ represents the number of supplied timesteps for consumer $i \in C$.

IV. Description of (fair) Algorithms

In this Section, several algorithms that aim to solve the resource allocation problem for the undersupplied state scenario, are presented. First, a slightly adapted version of the round-robin based approach, which is used in the German electrical grid, is introduced. Second, an iterative algorithm, which takes the DERs of the busses into account, is described. Finally, an algorithm that aims to maximize the use of DERs and, additionally, equalises the number of supplied time for each bus, is presented.

A. TRR - Traditional Round-Robin

This algorithm is a slightly extended version of the mechanism currently used in the German electrical grid. The Traditional Round-Robin algorithm, which is shown in Figure 2 works in a round-robin based manner and solves the problem of fair supply distribution as follows. The algorithm uses a list of busses and the information about the amount of production, which is centrally provided by the MG, to determine a subset of supplyable elements for the current timestep. Since the algorithm uses a round-robin approach, it is not allowed to activate a specific component for a second time before all other busses have been activated at least once. With this design it is ensured that each component stays active and inactive for an equal amount of time. An additional important remark is that this algorithm does not take the surplus electricity, which is provided by local DERs, and its influence on the network into account.

B. IIA - Improved Iterative Approach

The Improved Iterative Approach (IAA), which is shown in Figure 3, iteratively selects busses from its list and tries to supply them. In contrast to TRR 2 it takes the production of the local DERs on the busses and uses it for current production calculations. The algorithm provides a very rudimentary kind of fairness by indirectly favouring producers and consumers with a very low demand. The algorithm works as follows: first, if there still remains unused capacity, iteratively choose a street bus from the list of busses and check if the required demand can be met. If this is the case, then activate the bus and add the resulting production capabilities of its DERs to the overall production. If the selected bus cannot be supplied in this timestep mark it as unfit. After the algorithm terminates, it returns a list of busses that will stay active in this timestep and all remaining busses will be deactivated.

```
procedure TRR(production, timestep, busses)
    for i ← busses.length() do
        bus ← getLowestUptimeBus(busses);
        if bus == null then
            break;
        else
            if supplyable(bus) then
                activate(bus);
            end if
        end if
    end for
    return activeBusses;
end procedure
```

Figure 2. TRR - Traditional Round-Robin.

```
procedure IIA(production, timestep, busses)
    while consumption < production do
        bus ← getNextBus(busses);
        if supplyable(bus) then
            activate(bus);
            production += bus.getProduction();
        else
            markUnfit(bus);
            if AllBussesProcessed then
                return activeBusses;
            end if
        end if
    end while
end procedure
```

Figure 3. IIA - Improved Iterative Algorithm.

C. UEA - Uptime Equalizing Algorithm

The Uptime Equalizing Algorithm (UEA), which is shown in Figure 4 aims to maximize the use of DERs while maintaining equal supplied times for the busses. To achieve this, the algorithm distinguishes in a first step between consumers and producers. Second, all producers are supplied and their local production capabilities are added to the central production. This is possible as we are in the brown-out-scenario, where the central production provides at least enough electricity to supply a single bus each. After the activation of the bus, the local DERs are providing enough energy to sustain the bus. After all the producers are activated, the algorithm chooses a bus that is currently inactive and has a minimal amount of supplied time. In the next step, the algorithm checks if the selected bus can be supplied. If this is the case, the bus is activated, otherwise it is marked as unfit. After all busses are supplied or marked as unfit, the algorithm returns a list of busses that will stay active during this timestep and all remaining busses will be deactivated.

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```
procedure UEA(production, timestep, busses)
    while consumption < production do
        for all bus ∈ busses do
            if isSelfSustaining(bus) then
                activate(bus);
                production += bus.getProduction();
            end if
        end for
        bus ← getMinUptimeBus(busses);
        if supplyable(bus) then
            activate(bus);
        else
            markUnfit(bus);
        end if
        if AllBussesProcessed then
            return activeBusses
        end if
    end while
end procedure
```

Figure 4. UEA - Uptime Equalizing Algorithm.

V. Simulation of the Algorithms

In this Section, the conducted simulation is explained. The goal of this simulation is to evaluate the performance of the presented algorithms in a realistic scenario. Moreover, the simulation aims to evaluate the performance in the presence of our presented fairness metric. First, the general simulation setup is introduced. Second, the datasets that are used for demand and supply are described. Third, the simulation execution and corresponding results are presented. Finally, the results of the simulation are discussed.

A. Simulation Setup

The simulation framework was developed using the Java programming language. It implements the model described in Section III and is able to simulate a microgrid consisting of an arbitrary number of street busses. For the current simulation, a total number of five busses was chosen. Each bus has a combined consumption, as well as a combined production for each timestep. To generate a more realistic scenario the values for consumption and production are loaded from external datasets. For this setup, two different load profiles for street busses and one production curve of a solar panel are used. For simulating a brown-out scenario, the central production is derived using 6.

1) Load Set: For realistic load data of street busses in residential areas, real recordings of an adjustable transformer are used. This transformer is located in Saarland in Germany and it is connected to several streets containing housing areas. The real time data was monitored every second and the hourly average of the data is used for the simulation process. Two different load sets are used for simulation. One of the sets was generated by monitoring a larger street and represents a bus with a very high electricity demand, whereas the second set represents the consumption of a smaller street. Figure 5 shows the load curves of the busses for a day.

2) DER Production Set: For modeling realistic production behaviour, real-world solar panel production data is taken from Kronberg, Germany. The solar panel has a capacity of 4.51

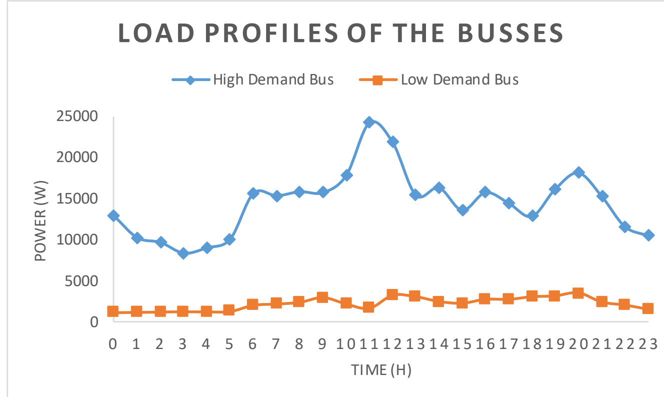

Figure 5. Load curves of the high/low demand busses connected to the adjustable transformer in Saarland (Germany).

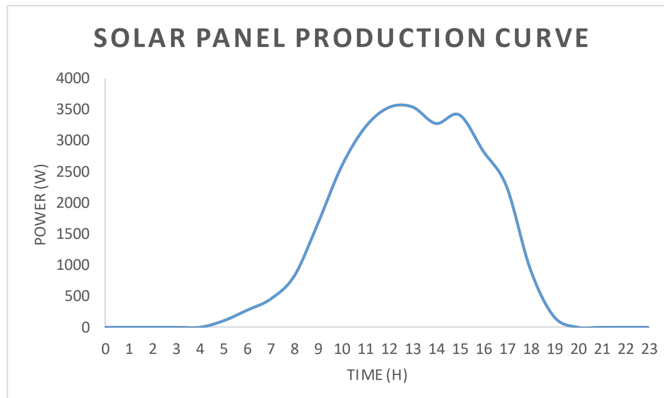

Figure 6. Production profile of a 4.51 kWp solar panel located in Kronberg Germany.

kWp and the recordings are provided in an hourly resolution. For the simulation, one of the previously mentioned solar panels is assigned to the low demand bus and three to the high demand bus. Figure 6 shows the production curve of the solar panel over a day.

B. Simulation and Results

The simulation consists of 1,000 iterations, where in each iteration, a new scenario is generated. In each iteration, the production and consumption values are allowed to randomly deviate by $\pm 10\%$ from the data set values to induce additional variation between the busses. During the simulation, each of the algorithms presented in Section IV is executed and compared in each run. The active busses in each run, are busses that stay online in the current timestep, either, because they are self-sustainable, or are supplied by the MG. Moreover, the full simulation process is conducted for both, the high demand set as well as for the low demand set.

1) Low Demand Bus Results: This Section presents the results for the simulation of the low demand dataset. Figure 7 shows the average results for 1,000 simulation runs with the data set of the low demand bus. From this set, five busses are generated and used for evaluation. Figure 7 shows the average number of supplied components during the corresponding time of the day for each of the algorithms.

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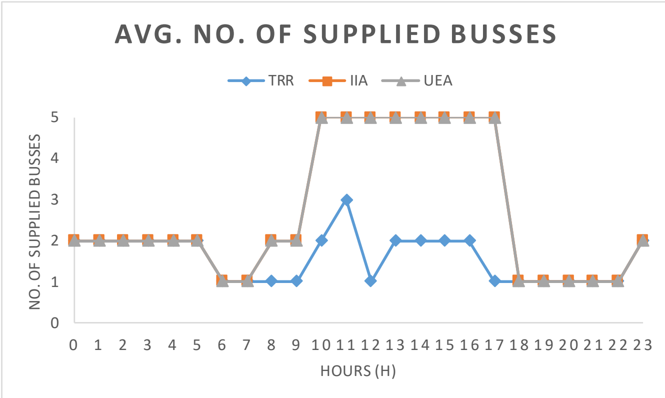

Figure 7. Average number of active low demand street busses during a time interval of 24 hours.

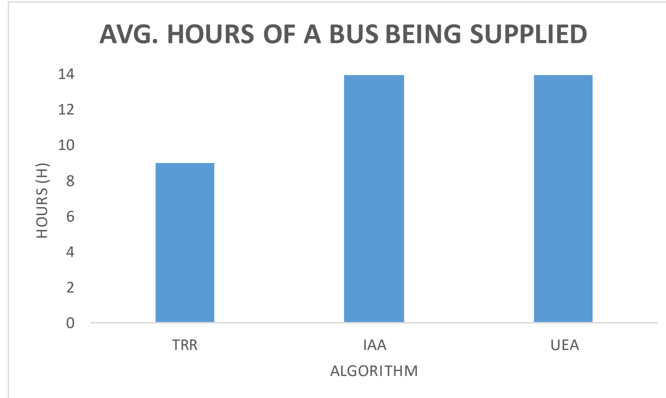

Figure 8. Total average number of how long busses were active during a day using the different algorithms in the low demand scenario.

The graph shows a significant performance drop of all algorithms starting from 5am in the morning. While the TRR algorithm can not really cope with this situation, IAA and UEA perform better. This is due to the consumption behaviour of the busses. While the overall production stays the same for TRR, the demand of the busses increases during the morning until about 12pm. As this gap grows with each timestep, busses must be deactivated to keep the consumption below the production provided by the MG. Most of the time, TRR is only able to supply between one and two busses while the rest remains deactivated.

IIA 3 and UEA 4 perform equally in this scenario as shown in Figure 7. Since both algorithms use the electricity provided by the solar panel located in the busses, the main difference is the way they choose the next candidate that should be supplied. IIA iteratively chooses the next element in its list of busses and its performance thus depends on the ordering of the busses, whereas UEA performs two steps: first, it activates all prosumers that are real producers in the current time step to uses their production for supplying additional busses. Second, it chooses the least supplied element out of the set of real consumers as a next candidate. The equality in performance of UEA and IIA, is due to the ratio between the required supply of the low demand busses and the provided electricity of the solar panels. The supply for the low demand bus deviates between 1,000Wh and 2,500Wh. In contrast, the solar panel is capable of producing 1,500Wh - 3,000Wh of electricity between 9am and 1pm. With this, the production of the solar panels highly likely exceeds the consumption of their individual busses during peak hours and the busses change from being consumers to being producers. Therefore, most of the prosumers in the low demand scenario become producers, and thus, the ordering of the busses for IIA does not influence the outcome anymore. Moreover, with the assumption provided in 6, each individual bus can be supplied and since most of them are producers, they are self sustaining. If every consumer becomes a producer, the iterative selection of elements equals the first activation step of UEA. This can be seen in Figure 7 at around 9am where IIA and UEA significantly increase the number of supplied components, as well as in the average uptime of busses shown in Figure 8. At about 6pm, the production of the solar panels can be omitted and, therefore, all algorithms perform equally.

The main difference between the algorithms becomes apparent if they are evaluated using the introduced fairness metric presented in 8. As mentioned before, a simple equality approach, like the one provided by the round-robin algorithm, is not suitable anymore for future distributed electricity production. Figure 9 shows the performance of the algorithms with regard to the fairness metric.

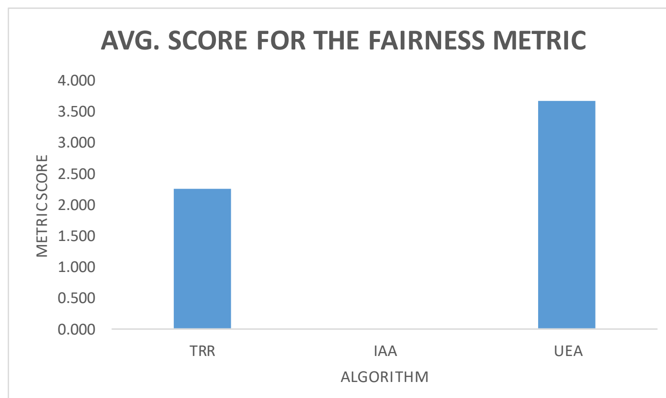

Figure 9. Average metric score of the algorithms in the low demand scenario.

As mentioned in Section III, this metric is based on the average performance of the algorithms while treating all consumers equally. TRR performs quite well, because it is purely based on a round-robin approach. This minimizes the denominator of the fraction in the metric. IIA scores a rounded value of 0. In spite of outperforming TRR with regard to the average supplied time of busses, IIA does not use any techniques to equalize the supplied times of busses. This, however, drastically increases the sum of differences in the metrics denominator and thus decreases the metric score. UEA on the one hand maximizes the use of real producers and, on the other hand, favours the bus with lowest supplied time. This leads to small differences between the supplied times, as well as it leads to a good performance with regard to average hours of supplied busses.

2) High Demand Bus Result: Figure 10 shows the average results of 1,000 simulation runs. For providing equal starting positions for both scenarios, again five different busses are derived from the dataset and their values are allowed to deviate from the original data by $\pm10\%$. However, since the demand of the bus is around ten times as high as the demand of the low demand scenario, the number of solar panels in each bus is set to three. If only one solar panel is located in each bus, they would not be able to influence the outcome of the simulation because the maximum production of the solar panel is significantly lower than the demand of a single bus. Therefore, it is assumed that, in a larger bus in a residential area with a high demand, the number of installed solar panels is higher than in a low demand area.

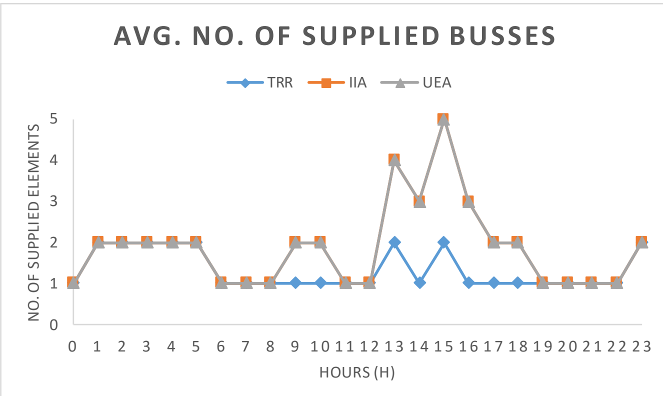

Figure 10. Average number of active high demand street busses during a time interval of 24 hours.

Most of the time TRR 2 is only able to supply between one and two busses. This is possible due to our assumption about the centrally provided energy and, additionally, due to the missing use of the surplus production of the DERs. The two algorithms that use the production of the DERs again perform equal in the simulation with regard to the average of supplied busses. The rapid changes in the performance of algorithms IIA 3 and UEA4 at 12pm is due to the demand spike that can be seen in Figure 5 at the same time. This is a moment, in which the electricity provided by the DERs simply did not suffice and additional busses had to be deactivated.

The application of the fairness metric in the high demand scenario shows similar results as in the low demand scenario. IIA and UEA perform equal with regard to the average uptime of the busses, whereas TRR performs worse due to the missing use of DERs. With regard to the fairness metric, the overall value decreased due to the smaller number of supplied busses, but still TRR and UEA perform better than IIA.

VI. CONCLUSION

The results of this work indicate that, with the introduction of a widespread monitoring infrastructure and the increasing installation of DERs in the electricity grid, traditional algorithms and their corresponding definition of fair electricity distribution are outdated. Traditional load shedding based on round-robin selection used in Germany, in case of brown-out phases, is compared to novel algorithms that use the electricity provided by local DERs to improve the quality of service. Therefore, a simulation of an electrical grid in a low-voltage residential area is conducted.

The presented method, however, is not limited to the low-voltage scenarios. Moreover, further technological progress will allow to apply our approach to all hierarchy levels of the energy grid, ranging from the distribution network to single consumers. Further development of smart meter technologies will even allow to apply the presented method to in-house appliances and, therefore, provide detailed regulation capabilities for distributing electricity.

While this paper had the German regulations in focus, future work will encompass and compare international laws and regulations. Our results indicate a lot of optimization potential in brown-out scenarios when local energy producers can be leveraged. In future, we intend to further explore this potential, especially with regards to volatile energy producers and local balancing of production and consumption, in order to reduce the influence of constantly changing energy levels on the transmission grid.

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