Renewable Energy Matching to Consumer Entities Based on a Maximum Flow Model

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Abstract. This paper designs a renewable energy assignment scheme based on maximum flow modeling for a microgrid containing distributed energy sources and consumption entities. Between the source and the sink node of a directed graph, mainly solar generators and consumption entities are interconnected via weighted links. Weights from the source to generators are decided by the amount of solar power production while weights from consumption entities to the sink by the amount of their energy demands. In addition, weights from generators to consumers correspond to the transmission line capacity connecting two objects, each from both parties. An additional node is defined to present the energy flow contracted with the main grid and its weight can be adjusted according to the additional energy purchase. The performance measurement result obtained from a prototype implementation shows that the renewable energy is stably distributed over multiple consumers until the energy generation reaches the maximum link capacity.

1. Introduction

In smart cities, many smart services are provided to the citizens, taking advantage of advanced information technologies and automated control mechanisms [1]. One of their most important targets is the smart power system, or smart grid, which pursues citywide energy efficiency [2]. Efficient algorithms, communication channels between diverse objects, sensor devices provide indispensable building blocks for smart grids [3]. In the modern power systems, the integration of renewable energies such as sunlight in addition to the appearance of complex power loads such as EVs (Electric Vehicles) makes it necessary to establish a more sophisticated control strategy [4]. Considering the unavoidable intermittent nature of renewable energy sources, it is desirable to consume as much energy as possible within an autonomous power subsystem called microgrid [5]. It is quite complicated and expensive to tightly control the flow of individual overproduced energy to the main grid.

Basically, microgrids are connected to the main grid to cope with the energy lack which takes place when the demand exceeds the embedded power generation capacity. In addition, a microgrid has a sort of renewable energy generators and energy storage equipment, trying to locally control the demand and supply with just minimized intervention of the main grid [6]. Renewable energy generators can send energy only to those consumers having direct cable connections. Here, every generator and consumption entity is not connected to the backbone power transmission network due to geographic constraints or economic reasons. That is, some consumer devices depend only on the renewable energy, risking the suspension of their operations. After all, the microgrid power network leads to a network flow graph, which allows us to develop an efficient energy allocation mechanism for the
microgrid. By this, it possible to maximize the amount of renewable energy consumed locally as well as to minimize the energy exchange with the main grid.

2. Renewable energy allocation

2.1. Network flow modeling

The energy consumption model can be represented by a directed graph from a source to a sink, while each generator and consumer entity is mapped to a node as shown in Figure 1. In the network flow graph, only those consumer entities receiving energy from at least one of renewable sources are included. It doesn’t matter whether they get energy also from the microgrid backbone. To begin with, there are links from the source to all respective generator nodes and also from all respective consumer entity nodes to the sink. Excluding the source and sink nodes, the graph consists of two parties, one for generators in the left column and the other for consumers in the right column. Links come from nodes in the generator group to nodes in the consumer group, according to the existence of transmission cable connection.

The energy demand of a consumer entity, such as $A$, $B$, or $C$ in Figure 1, is denoted by the weight of its link to the sink node. For a consumer entity, the sum of the weight for each input link must be larger than the weight of outgoing link to be able to meet its energy demand. Here, the electricity system is stable when the amount of actual flow is equal to the link weight which corresponds to the energy demand, for all consumer entity nodes. Exceptionally, node $A$ in Figure 1 takes energy only from a renewable energy generator, so it can fail in meeting the energy demand. The input link capacity can be less than the actual demand irrespective of the installed electricity transmission potential in case the energy generation condition is not good. In that case, $A$ will highly likely start discharging its battery, enter the energy-saving mode, or even stop its operation. On the contrary, $B$ and $C$ get energy from both the backbone and distributed sources, just trying to take from the latter as much as possible.

![Network flow model](image)

**Figure 1.** Network flow model.

The link weight from the source to a generator node, marked $S_1$, $S_2$, and $S_3$ in Figure 1, is the amount of electricity created in the generator, while the value is constrained by its maximum capacity. The generator capacity depends on the solar panels, battery chargers, and the like. The commonly available solar energy facility can produce tens or hundreds of kw. Particularly, $M$ is the node representing the energy flow from the backbone power system, while the link capacity from the source to $M$ is the amount of provisioned energy in the microgrid. Its electricity comes from the main grid or stable sources such as thermal power plants. The link weight from a power generator to a consumption entity is equal to the transmission cable capacity installed between both objects. Generated electricity can be distributed over the multiple consumers. On the contrary, a single consumer can receive from
multiple heterogeneous generators.

Based on this model, it is possible to make an energy supply plan by deciding the weight of each link [7]. The link weight is fixed for those links from solar energy generators to each consumption entity node, as they are hardware-dependent maximum amount of flow. The link weight from the source to a solar generator is the predicted value of power generation and the prediction much depends on the weather condition. In addition, the energy demand is also forecasted on each consumption entity based on the current consumption level and other factors just like in the frequency control mechanism. The link weight from the source to \( M \) is basically the amount of maximum energy flow contracted between the main grid and the microgrid. Usually, the link weight from \( M \) to a consumption node must be large enough to meet the consumer demand even in the absence of available renewable energy. For those links from the source to generator nodes, their link weights are limited by the generator capacity and the flow cannot exceed this limit.

The power demand in the consumer side keeps changing, however, the energy storage equipment can possibly absorb demand spikes, making the load flat for the most time interval and thus we can balance demand and supply based on the average demand level. Figure 2 shows an example in which \( S_1 \) generates 5 units of energy, while it can send to \( A \) up to 5 and to \( B \) up to 4. However, due to the actual demand and the allocation strategy, 2 units flow to \( A \) and \( B \), respectively. 1 unit, not consumed in \( S_1 \) can be discarded or sold to the main grid. The actual energy flow in Figure 2(b) cannot exceed the link capacity marked in Figure 2(a).

![Figure 2. Actual flow description.](image)

### 2.2. 2-pass assignment

Once the network flow model is built, particularly with the weight of each link, we can calculate the maximum amount of renewable energy for the microgrid to consume, taking advantage of the Ford-Fulkerson algorithm [8]. Then, it is also possible to know how much electricity should be assigned to respective consumers from each generator node. This scheme iterates the breadth or depth first search until there is no further path from source to sink. In each iteration finding a new path, the amount of feasible energy flow for a path is the minimum of the weights along the path. The weights of links on the path are decreased by this minimum value. Here, the process also increases the weight of every reverse link to allow potential selection canceling in finding the maximum flow, even though the reverse links are not explicitly shown in the network flow graph in Figure 1.

After all, we can know the total amount of energy flow and if this amount is smaller than the total demand in the microgrid (except for the demand which depends only on renewable sources), it is necessary to compensate for the insufficiency by purchasing additional energy from the main grid. How much to purchase more can be calculated by summing up the remaining weights in outlinks of consumer nodes. Now, it is necessary to increase the weight of the link from the source to \( M \). Next, the Ford-Fulkerson is run again to meet the energy demand and allocate the needed energy to each consumption entity. The remaining outlink weight for \( M \) becomes 0. After the secondary execution of the network flow process, it is possible that the link weight from a solar energy generator may still...
remain when it cannot be taken by any consumers. The amount of such energy is the sum of remaining weights in outlinks of generator nodes. Such electricity can be stored in the battery device (possibly including electric vehicles) or sold back to the main grid if connected [9].

3. Performance analysis

This section measures the performance of the proposed scheme via prototype implementation with Java programming. We select a microgrid having 5 solar energy generators and 10 consumption entities receiving energy from renewable sources. Without loss of generality, each consumption entity demands the same units of energy, namely, 20 units. Here, the unit is not explicitly specified, as it can be different by the energy consumption level of the facility. Each generator has connections to 3 out of 10 consumers, while the transmission capacity for all generator-to-consumer links is fixed to 10 units. In addition, 7 out of 10 consumers take energy also from the main grid with the link capacity of 20 units to cover the whole demand even without the renewable energy. The basic contract between the main grid and the target microgrid is set to 50 units. With this environment setting, we measure the effect of the amount of renewable energy produced in the generators.

The first experiment measures the amount of energy to additionally purchase from the main grid according to the increase in the per-generator solar energy creation. As almost all electricity is consumed in the microgrid, the energy purchase linearly decreases until 23 units as shown in Figure 3. Then, the energy is overproduced and there is no need to purchase any more. This result indicates that the network flow model can appropriately distribute electricity to respective consumers, calculating the amount of energy to purchase quite predictably. The maximum link weight from the source to \( M \) is assumed to be large enough to accommodate the demand in the microgrid. Otherwise, in case no renewable energy can be produced, the microgrid may undergo blackout.

![Figure 3. Purchased electricity](image)

Next experiment measures the unmet demand for those nodes taking energy only from solar generators. Actually, even if sufficient electricity is created, the demand cannot be met in case the link weight from generators is less than the demand. Figure 4 shows this situation. Even if the amount of renewable energy generation goes beyond 25 units, consumers suffer from energy insufficiency. Until then, the insufficiency decreases according to the increase in the generation. The sharp drop in the curve after 30 units indicates that more energy is assigned to the nodes solely connected to renewable sources.
4. Conclusions
In this paper, we have designed a renewable energy assignment scheme for a microgrid. Here, the network flow graph model is built to incorporate transmission cable connection, interaction with the main grid, distributed energy sources, and consumer demand. The two-pass maximum flow scheme first calculates the insufficiency in the microgrid and then the amount of surplus energy remaining after compensating for the lack. Here, the Ford-Fulkerson algorithm is exploited to obtain the maximum flow from renewable energy generators to respective consumer devices. Integration of intelligent computer algorithms in the smart city enriches smart services in our daily lives. As future work, we are planning to develop an elaborate solar energy forecast model to integrate into the network flow graph. This begins with the collection of weather information archive, solar energy generation history, and facility details including geographic records.

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