A Utility Maximized Demand-Side Management for Autonomous Microgrid

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***Abstract*—With the increase in renewable energy integration in the electrical power systems along with increase in the time-varying energy consumption by the users, it is imperative to regulate the load profile through pragmatic economical Demand-Side Management. Thus, the study carried out in this paper presents a real-time algorithm for cost optimization to achieve Demand-Side Management of a Renewable Energy Source integrated microgrid. The algorithm aims to achieve utility maximization and cost reduction for an optimal power scheduling in the presence of variable loads. The proposed approach mitigates the continuous changes in the variable loads that emulates the load profile found in residential, commercial and industrial users. The particular focus of this work is on developing a decentralized control scheme and a utility-oriented energy community, which provides user satisfaction based on energy management system, production units and load demand. Moreover, the paper presents utility maximization solutions on the combined energy profile of the microgrid targeting two main objectives, i.e., (1) minimizing the aggregate energy cost and (2) maximizing the provider's and user's satisfaction. Minimizing the aggregate energy cost aims to reduce the peak to average ratio of the aggregate energy profile of the microgrid using the cost function for energy cost minimization. The proposed technique is tested on microgrid which is coordinated in master-slave control topology. The implemented algorithm ensures a stable and efficient operation of the microgrid while minimizing the total cost of production.**

***Index Terms*—Distributed Generation (DG), Master-Slave Control, Demand-Side Management, cost optimization, Utility function.**

I. INTRODUCTION

Microgrids are the future of power systems and numerous studies are focused in improving the current structure to make them more economical, reliable and robust. The two-way flow of electricity and real-time monitoring of the grid are the distinguishing characteristics of the microgrid. These characteristics offer several benefits and flexibility to both utility providers and consumers [1]. For example, microgrid allows matching supply and demand in a timely manner along with enhancing the energy efficiency and grid stability. The microgrid integrated with renewable energy sources is expected to replace the traditional system and thus save consumer cost and reduce the global dependence on environment unfriendly fuels [2].

One of the main challenges that the utility planners tackle is meeting the generation with the time- varying load consumption especially with peaks in the load profile. One approach is demand response, which is an operating mechanism used to regulate user's electricity consumption in response to the supply conditions. The principal goal of demand response is to make the system more economical by cutting down on the generation cost of electricity by shaving the peak load or by shifting peak-hour demand to cheaper off-peak hours [3], [4].

Numerous studies in literature aim to optimize the Distributed Generation (DG) along with cost and a balanced load profile. In [5] Ahmed et al. proposed a utility-based optimal technique to achieve optimal power pricing for both the utility and the consumer. Their novel cost function showed superiority in being adaptive to different situations and offered better results to both the users and energy providers. This study was carried out by relying on a two-way communication infrastructure. In [6] Yang et al. introduced a parallel-distributed optimization framework in a microgrid employing renewable energy generation units. They divided the loads into base load, flexible load, and scheduled load. In addition, the users had the ability to optimize their own schedules as well. Their framework aimed at reducing information exchange by incorporating a simpler control technique, and more importantly reducing the peak power demand. However, their method didn't consider Demand-Side Management on the basis of prioritizing loads as a percentage of total load demand.

The study done in [7] introduces the cost reduction formula with a utility maximization algorithm on a microgrid that is connected to the main grid. In this paper, we aim to study the power cost reduction formula and utility maximization algorithm on an islanded microgrid employing renewable energy resources and energy storage systems.

The main contribution of our work is *to implement and*

TABLE I
PARAMETERS OF THE IMPLEMENTED MICROGRID

Parameter	**Value**
Rating of Master DG	75 kVA
Rating of Slave DG	11 kVA
Loads P1, P2, P3, P4, P5, P6	6+ j0.6 kVA
Line impedance N1, N2 , N3 , N4, N5	0.05+j 0.1 Ω

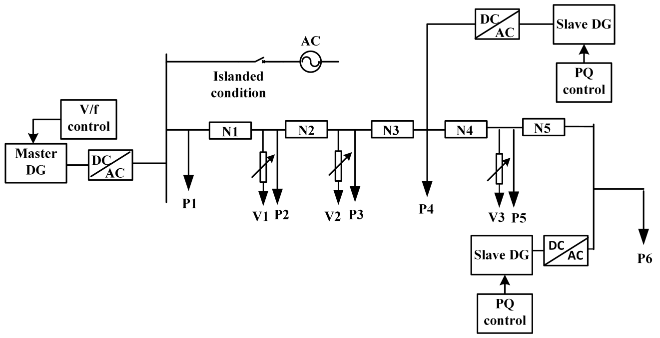

Fig. 1. Typical Microgrid Structure.

analyze the utility maximization function and cost reduction formula on a microgrid model equipped not only with conventional energy resources but also with variable load categories. The model of the microgrid is developed in PSCAD/EMTDC [8] software to capture a realistic behavior of the different components. The results show that the technique used is very promising in optimizing the schedule of power generation corresponding to varying load profiles and reducing generation cost while maintaining a stable and smooth operation. Moreover, the results ensure that the utility function based on load category is maximized, which usually relates to the higher customer satisfaction.

II. MICROGRID STRUCTURE

Fig. 1 shows the radial system which is a typical network topology found in distribution systems. The microgrid under study is integrated with dispatchable renewable energy source equipped with energy storage system. Table I gives the values of the parameters used in this system represented in Fig. 1. The variable load profiles V_1, V_2, V_3 of the industrial, commercial and residential loads respectively, is shown in Fig. 2. When the microgrid is operated in an islanded or autonomous mode, there are two main control schemes that are usually adopted for controlling coordination between the DGs. The two schemes are droop control and the master-slave control. In the droop-based control, the frequency and voltage of the system are a function of real and reactive power [9]–[11]. This results in fluctuation of these two parameters with varying load profile. To tackle this issue of changes in the voltage and the frequency of the system, and thus stabilizing the voltage profile and reducing the distribution and conversion losses in the microgrid, master-slave control is commonly implemented in V-f control mode (i.e voltage-frequency control mode). [12]–[14].

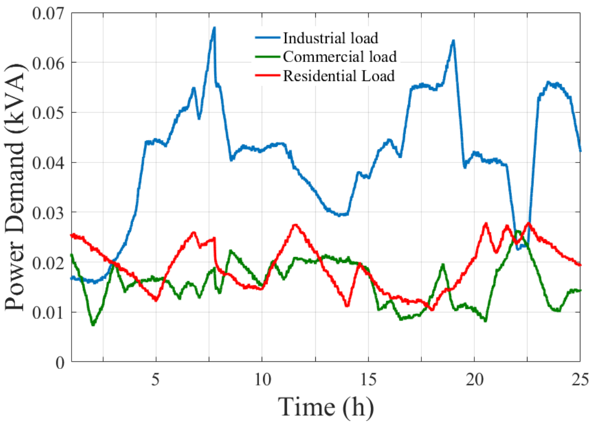

Fig. 2. Demand Profile of Variable Load.

Master-slave control comprises of a master DG, which is dedicated to voltage and frequency control. The master DG unit operates with the V-f control to stabilize the microgrid's voltage and frequency. It is responsible for generating set points for regulating these parameters by either operating in the P-Q control (in grid-connected operation) or V-F control (in islanded operation). Thus, the master DG contribute as controlled voltage sources. On the other hand, slave DG units operate with P-Q control injecting fixed real (or reactive) power following the voltage set point by the master DG. The slave DGs are controlled current sources that inject active and reactive power by being driven from voltage sources of either the grid (in grid-connected operation) or the master DG (in islanded operation). The master DG has sufficient storage in the form of higher rating to provide for any power mismatch in the loads and thus this system typically emulates a virtual grid-connected distribution network.

III. PROBLEM FORMULATION

In the system model of the microgrid distribution system, it is assumed that one energy provider relies on different energy resources to support the power usage of n users. The users could be residential, commercial or industrial consumers. It is important to explain that the utility function is a reflection of customer 's satisfaction and the sole purpose of the algorithm is to manage the load in order to maximize the utility function.

The users (residential, commercial, industrial) have their power consumption being monitored from smart meter (SM), which can also control the devices connected to it. All this information is being communicated to the Data Communication Centre (DCC) of the energy provider (Master DG). Thus, the exchange of information occurs at regular time intervals (t), and the updated control information is sent from the SM to DCC. The DCC then decides the power distribution among the loads connected according to the priority of the users, the total load, the cost and the generated power by the DGs. The real-time system information is managed to achieve an optimum solution for maximized user satisfaction at the most economical cost. We considered the following constraints when developing our algorithm for the cost function:

- Minimum load demand of the users have to be met at all times, which is a percentage of the total load called critical load. The percentage varies according to the load category. In this algorithm industrial load is given the highest percentage and 100% of the loads are critical. This is monitored using the priority set for each user denoted by $\omega_n(t)$
- The utility function is an increasing function and may get saturated over time.
- It is important to calculate real time prices for the changes in the cost function which can be used to control the power consumption of the load in the microgrid.

In the proposed algorithm, it is assumed that we have users that are independent and have their own profiles of power usage. For example, each user has a unique time schedule for using different electrical appliances. Weather consideration also play an important role in user demand for electrical power. Usually, the power consumption is relatively higher on a hot summer day or in winters in comparison to a mild day in the spring or autumn due to added energy consumption by air conditioner units.

Thus, it is difficult to characterize user preferences with an accurate mathematical model. In several studies, the user satisfaction is represented by the utility function [15]. The utility function can be described as function of power demand ($P_n(t)$ along with the priority of the user $\omega_n(t)$, thus $U(P_n(t), \omega_n(t))$ represents the satisfaction of user n on power consumption. For each user n, $\omega_n(t)$ of the utility function indicates the user's priority at time t. A larger $\omega_n(t)$ means higher priority. The value of $\omega_n(t)$ is sent to the DCC at each updating cycle by the smart meter.

For DGs providing power, when the total demand of the system is low, the generation cost increases slightly as the demand increases. The cost increases at a higher escalating rate when the load peak is near the grid capacity. Therefore, an increasing convex function is used to model the cost function for providing energy. Similar to [16], [17], a quadratic function models the provider's cost as follows:

$$C_p(t) = aP_n^2(t) + bP_n(t) + c \tag{1}$$

Where $a > 0, b > 0$ and $c \geq 0$ are constant values selected for the microgrid, $P_n(t)$ denotes the grid load, i.e., the total power consumption at a time t. It is assumed that the aim is to meet the load demand of each user under an acceptable cost constraint $C_p(t)$ at a time t, which should not be exceeded. Where $c(t)$ is the budget for the rest of this paper, which is the upper bound on the cost $C_p(t)$.

$$C_pt) \leq c(t), \forall t \in \{1, 2, ...T\} \tag{2}$$

Let $f(t)$ be the price function and $f(P_n(t))$ the price at time t. Therefore, it is assumed that $f(t)$ is an increasing convex function that maps the total load to a corresponding cost. Just like the utility function $U(t)$, the price function $f(t)$ also has a general form or determined by the provider. An online algorithm for Demand-Side Management for a microgrid is presented as follows:

$$max \sum U(P_n(t), \omega_n(t)) - f(\sum_{i \in N} C_p(t)P_n(t)) \tag{3}$$

subject to:

$$P_n(t) \geq P_{n,min}(t), \forall t \tag{4}$$

$$C(\sum_{n \in N} p_n(t)) \leq c(t), \forall t \tag{5}$$

In this paper, the aim is to maximize the customer satisfaction presented by $U(P_{ni}(t), \omega_n(t))$ versus minimizing the cost of the power set by the energy provider according to the load demand $\sum_{i \in N} C_p(t)P_n(t)$. It is assumed that the $C_p(t)$ values are previously set for each load demand taking into account the generation cost by the Master and Slave DGs. $P_{n,min}(t)$ is the minimum critical power demand which is unique for each user according to the priority.

Information exchange is an important element of the emerging microgrid which makes real-time Demand-Side Management possible. For real-time execution, it is critical to update the user's variable demand along with the maximum cost budget reflected in $C_p(t)$ in every decision period by the DCC [18]. The microgrid controllers used in the PSCAD continuously work to smooth the total power consumption of all users in the system, along with maintaining the grid stability. At each time instant t, the DCC sends the EP parameters such as load condition and capacity. Meanwhile, the users send their basic power demand to the DCC to request power for the time period. Also, the EP sends its cost limit to the DCC to get their energy provisioning cost controlled within an acceptable range [18].

Algorithm 1 summarizes the particular problem formulation of the proposed topology. The proposed technique is tested on microgrid which is coordinated in master-slave control topology inorder to model a virtual grid-connected system, However, it is a generalized formulation implementable for any Distributed Energy Source integrated microgrid.

IV. SIMULATION RESULTS AND DISCUSSION

In our model, we have three types of variable loads with different priorities for scheduling. During the peak load time the power deliverance for the industrial load has the highest priority level, while the residential loads and commercial loads has the second and last priority levels, respectively. The power deliverance is decided on the basis of the power cost function mentioned previously with the aim to achieve the highest customer satisfaction leading to maximizing the utility function. When the overall power demand is high then the power cost rises. In such a situation, the utility function decides to keep supplying power to the loads with the highest priority and reduces the power supply to the loads with the lower priority and in-turn controls the total power provided by the utility companies, which results in decreasing the power cost along with fluctuation in the power cost (elaborated later on in this paper). This method strives to decrease the power cost as well as the cost variance as shown later in the results. This study is built and formulated on PSCAD/EMTDC shown in Fig. 1.

Algorithm 1 Algorithm for Utility Maximization with Cost Optimization

```
Using the power consumption calculate Utility function
for each variable load
for Each variable obtain the utility function do
    $U_n(t) = P_n(t)\omega_n(t) - C_p(t) * P_n(t)$
    for Each variable load $n = 1, 2, 3$ do
        Compare the $U_n(t)$ to obtain $U_{max}$
        if $U_n(t) > U_{max}$ then
            $\omega^{\circ}_n(t) = \omega_n(t)$
            High Priority Load
            No changes in current injected
        else Restrict low Priority Load
            By applying current limiters to the
            variable load
        end if
    end for
    Update value of $U^{\circ}_n(t)$
end for
Obtain Cost profile
```

In addition to this, the main challenge that the microgrid operator tackles is providing power to variable loads (users). The information is gathered at each time slot and delivered to the various resources to inject power to the microgrid accordingly. The user's load information is monitored for the resources to respond to the changes made at the same time, the EP monitors the price of power accordingly. The utility function is involved to fulfill meeting the load demand of each user according to its priority and tries to minimize the power cost as shown in (3). The three loads (as mentioned earlier, industrial, residential, and commercial, with priorities in the same order) vary with time t and respond according to the generation units in the microgrid, as a result different values for the utility function and the cost function are obtained.

As can be seen from Fig. 3 that the average cost profile with and without implementing the algorithm differs. The average cost before introduction of the proposed technique is 0.70$/h and after introducing our technique it is 0.68 $/h, which corresponds to approximately 3% reduction in cost.

Variable loads connected to our microgrid follow a load profile shown in Fig. 2. After introducing the utility maximization and cost reduction formula the load profile changes to what is shown in Figure 4. From Fig. 4, it can be noted that the load that has the highest priority has been taking the power it needs at all times. The load that has lesser priority takes power depending on its power cost and are following the power cost reduction formula. This is due to the limitation imposed on the current injected to the three types of loads as per the load peaks, priorities and the power cost. If the industrial load is requesting a high amount of power, to decrease the cost, the current limiters built in the PSCAD model, would limit the current injected to residential and commercial load accordingly. The power scheduling method can be further observed when monitoring the total power supplied by the DGs. Fig 5 shows the total power generated by the DGs in the microgrid. It can be seen from Fig 5 that the total power provided without applying the proposed technique is higher than the total power provided after applying our proposed implementation. It can be noted that with the inclusion of the real-time algorithm the overall system runs smoothly with much less fluctuation resulting in less fluctuation in the cost.

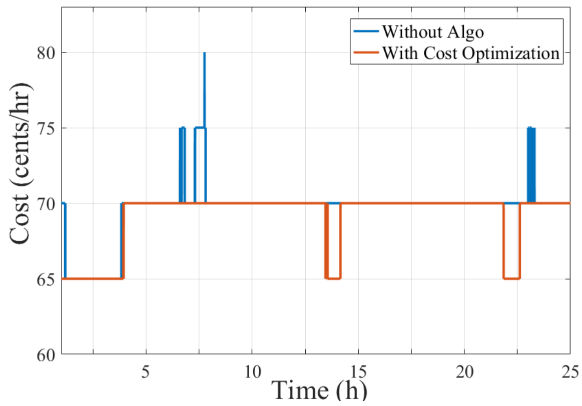

Fig. 3. The Cost before and after implementing the proposed algorithm.

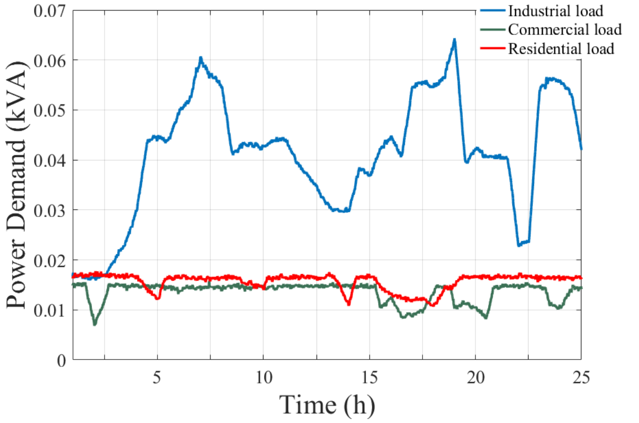

Fig. 4. Demand Profile of Variable Load after implementing the Algorithm.

Fig. 6 shows the total power demand before and after introducing the cost reduction and utility maximization formula. It can be observed the total power demand peaks after introducing the cost reduction and utility maximization formula are much lower than the total power demand peaks before introducing the algorithm and is equal to the results obtained in Fig. 5. Since the variance is less after implementing the algorithm, hence the Figures. 5 and 6 shows that the microgrid now has relatively higher stability with maximized utility.

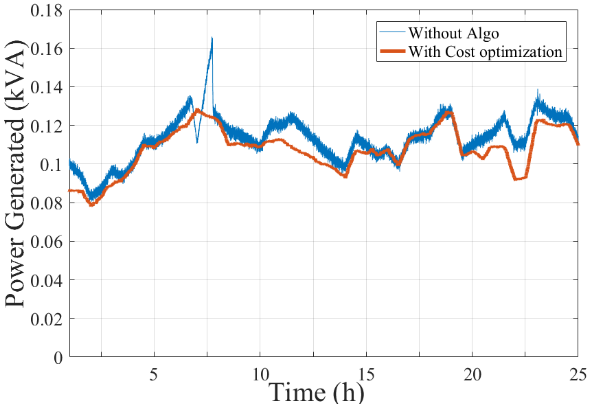

Fig. 5. The Power generated before and after implementing the proposed Algorithm.

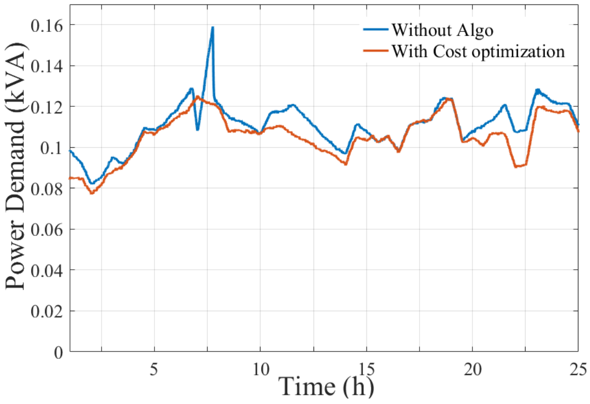

Fig. 6. The Power consumption of the loads before and after implementing the proposed Algorithm.

V. CONCLUSION

One of the most important objectives of the future microgrids is having the ability to adapt through real-time operation and pricing. Real-time operation helps in maintaining and improving microgrid stability through continuous matching of the load demand and the generation supply. In this paper, a real time algorithm based on utility maximization and cost reduction formula has been developed and implemented on a microgrid model controlled via Master-slave control topology. Power scheduling has been employed to mitigate the changes in the power demand. The proposed technique is simple to implement thus eliminating the complexity and computation time associated with the complex algorithms. The results confirm the effectiveness of the proposed algorithm reflected by a reduction of about 3% in the total cost corresponding to the demand of the simulated system. The proposed algorithm provides an efficient tool to the utility operators to implement a simple technique for Demand-Side Management which optimizes cost and maximizes user satisfaction.

VI. ACKNOWLEDGMENT

This work is supported by ICT Fund UAE, fund number 21N206 at UAE University, Al Ain, United Arab Emirates.

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