Optimized Scheduling of Power in an Islanded Microgrid with Renewables and Stored Energy

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Abstract—The conception of the Smart Grid (SG) paradigm is to offer many benefits to the transmission, distribution, and consumption of energy. One catalyzer ingredient of the SG repertoire of changes is the idea of microgrids. As a new low voltage distribution subsystem, microgrids are expected to improve reliability, help integrate distributed resources, isolate power disturbances, and ameliorate load and supply balance. In this paper, we study a microgrid power scheduling problem with renewable sources and energy storage where five different classes of appliances are prioritized by smart meters. A novel formulation and solution based on mixed integer programming are proposed. Preliminary simulations show the efficacy of the optimization to schedule power among users and appliances of a microgrid in terms of the total power consumed and the number of power usage requests accepted by the system.

I. INTRODUCTION

Smart Grid (SG) is a term generally used to refer to an enhancement of the traditional power grid, especially, in terms of the computing and communications technologies. The existing power grid is currently used to carry power from a few central generators to a vast number of consumers through a transmission and distribution network. On the other hand, SG uses two-way flows of electricity and information to create an automated, secure and distributed advanced energy delivery network. Smarter generation, transmission, distribution and consumption of electricity are essential to achieve a reliable, clean, safe, resilient, secure, efficient, and sustainable power system [1].

The developments in the SG technologies introduce a new paradigm called microgrid to augment and improve the current grid [2]-[5]. A microgrid is a low voltage distribution network that is enhanced with Distributed Generation (DG), Combined Heat and Power (CHP), an energy storage subsystem, and/or a degree of autonomy to operate in intentional or accidental islanding mode. DG component of the microgrid might contain conventional as well as the renewable sources. Microturbines, fuel cells, photovoltaic panels, wind turbines are some of the examples of the DG in the microgrid. Main benefits [4], [6] are improved reliability, integration of the distributed resources, isolation of power disturbances, and improving load and supply balance.

In order to utilize the microgrid functionalities efficiently and get the maximum benefit from such a structure, it is crucial to manage the distributed generation and consumption within the microgrid via a control center, which is referred to as a Microgrid Control Center (MGCC). Automatic Meter Reading (AMR) and Automatic Metering Infrastructure (AMI) systems are smart metering technologies which are key for linking MGCC to homes and appliances in the grid [7], [8]. While AMR provides only from-user-to-grid data, AMI establishes a bidirectional communication that enables both monitoring and controlling of appliances by the grid [1]. Transition from AMR to AMI systems is expected to bring improved utilization of techniques, such as Demand-Side Management (DSM), load-shedding, smart power scheduling and optimal resource allocation in microgrid.

In this paper, we propose a system under the assumption of the existence of a smarter grid consisting of microgrids equipped with AMI systems, smarter appliances, renewable resources and stored energy. A system model to allocate the available resources among the loads in accordance with various Quality-of-Service (QoS) requirements, as determined by prioritization weight and minimum required total energy, and different time and power transference or shiftability profiles within an islanded microgrid are studied. Our solution involves a novel Mixed Integer Programming (MIP) model that maximizes weighted energy utilization with the help of an energy consumption scheduler.

To the best of our knowledge, our paper is the first to model an islanded microgrid with renewable resources and stored energy in order to optimize the energy usage among the constituent appliances with respect to priority specifications. Our taxonomy of the appliances in terms their temporal and power adaptability characteristics are also novel and unique.
The remainder of this paper is organized as follows: Related work is covered in Section III. Section IV provides the problem definition, system model and MIP formulations. Performance evaluation results based on our MIP model are presented in Section V. Section VI includes the concluding remarks and discussion for future work.

II. BACKGROUND ON SMART GRID AND MICROGRID

Some of the noteworthy standardization efforts, high-level conceptual reference models and roadmaps for SG are given by NIST Framework and Roadmap for Smart Grid Interoperability Standards [9], IEC Smart Grid Standardization Roadmap [10], CEN/CENELEC/ETSI Joint Working Group on Standards for Smart Grids [11], and IEEE P2030 [12]. A conceptual view of the NIST’s SG reference model is depicted in Figure 1. Note the bidirectional electric and information flow and the integration of the renewables.

An important enabler of the Smart Grid initiative is put forward under a general term of microgrids, as briefly stated in Section I. Microgrid control may be centralized, distributed or decentralized, or a hybrid of the former two [13], [5]. In terms of the layout, possibilities are radial (tree) or networked [14]. Well known microgrid testbeds include CERTS [15], [16], NEDO [17], NTUA [18]. For a comprehensive review of the microgrid testbeds, refer to [19].

A leading standardization is carried out under IEEE 1547.4 [6] that uses the term Distributed Resource Island System (DRIS) to refer to the microgrid. IEEE 1547.4 envisions four modes of operations for microgrid: (1) normal parallel mode, (2) transition-to-island mode, (3) island mode, and (4) reconnection mode. The microgrid can function autonomously in the case that a single point of common coupling with the macrogrid is disconnected (forced islanding) or in the case that the local resources of the microgrid are forecast as sufficient to power microgrid loads (intentional islanding). Both trigger an islanded microgrid. The generators in the islanded microgrid continue to supply power to loads without getting power from the macrogrid, which can provide a higher local reliability, high penetration of renewable sources, self-healing, active load control, and improved efficiencies [20]. Our work in this work mainly focuses on islanded operation of microgrids of the future grid.

III. RELATED WORK

Without any loss of generality, to include renewable sources, a wind tribune is chosen as a power generator of the microgrid. The power curve in Fig. 2 illustrates a typical power output of wind tribunes.

DSM is one of the most important components of the grid of the future [22]. The overarching goal of DSM is to improve the efficiency and effectiveness of the grid by means of reducing the Peak-to-Average Ratio (PAR), cost, etc. DSM tries to shift and/or reduce the load to achieve its objective. As part of the DSM approach, several energy consumption scheduling algorithms have been studied for different design objectives [23]-[27]. In [23], energy-cost and PAR minimization are performed with the help of an energy consumption scheduler and a Linear Programming (LP) formulation. Joint energy payment and waiting time minimization are studied in [25]. A game theoretic approach is proposed to maximize the utility function in [24]. In [28], a consumption scheduling algorithm based on integer linear programming (ILP) and game theory is applied to minimize load.

Contrary to the current grid, one of the key features of the future grid is to adjust loads dynamically, turning them on or off as needed. This is called load shedding. In an islanded microgrid, load shedding may be used to
maintain the system reliability. In [29], an optimization framework has been proposed to find the minimum amount of load to shed while satisfying load balance and shedding constraints. Dynamic load shedding schemes have been studied in the presence of large disturbances accounting system dynamics [30]-[32]. [33] presents a two-step algorithm for the optimal load shedding in an intentional island. In the first step, the transient stability problem is solved via generalized reduced gradient method. In the second step, the post-fault steady state analysis by using an ILP framework.

Another important concept of the future grid is the incorporation of renewable sources. Renewable sources may provide decentralized power generation to facilitate forced islanding upon system failures. On the other hand, the intermittent nature of these sources makes them unreliable. Therefore, it is vital to correctly model these sources as part of the SG initiatives. In order to accommodate these intermittent renewable resources in problem formulations, there have been efforts to model their behavior [34], [35]. Generation scheduling of an islanded microgrid is investigated in [34] with renewable resources and batteries. [36] studies a self-healing problem formulation so as to reallocate and reroute power after failure. A decentralized Virtual Power Plant-based Energy Management System to manage a microgrid with renewable sources is proposed in [37].

Our approach differs from the aforementioned studies as follows: (1) Our model deals with the energy consumption, not generation, (2) We consider a prioritization scheme for deploying resources to appliances, (3) We include both renewable and stored energy as part of our microgrid model, (4) A unique classification of appliances is an intrinsic part of our formulation in terms of temporal and power adaptability dimensions.

A. Preliminaries

A system with multiple users and a MicroGrid Control Center (MGCC) is considered. It is assumed that each user is equipped with a smart meter that has energy consumption control or scheduling capabilities. Smart meters are able to establish a bidirectional communication with the MGCC. The block diagram of the system is shown in Fig. 3.

We consider a microgrid scenario where users’ appliances cover five groups of appliances. These groups are power and time shiftable (PS/TS), power non-shiftable and time shiftable (PnS/TS), power shiftable and partly time non-shiftable (PS/TnSp), power shiftable and full time non-shiftable (PS/TnSf) and power non-shiftable and full time non-shiftable (PnS/TnSf), shown in Fig. 4. The first and the second groups contain the smart devices each of which can be scheduled in time via smart meters. The smart devices are building blocks of the Smart Grid and are projected to become commonplace in the future. Although the third group also includes time-shiftable appliances, this group models appliances which are in need of continuous service for some blocks of time. The fourth and the fifth groups stand for old-fashioned time non-shiftable appliances. These groups are included to provide backward compatibility in our optimization model. Power shiftable is adopted to model appliances which can work at different power levels, such as refrigerators, hot water boilers etc. Before presenting our model, we define the following sets for user $u_i$’s appliance $a_j$ using the notation provided in Table I:

$$S_1 = \{(i,j)|u_i \in U, a_j \in A \text{ and } a_j \text{ is PS/TS}\}$$
$$S_2 = \{(i,j)|u_i \in U, a_j \in A \text{ and } a_j \text{ is PnS/TS}\}$$
$$S_3 = \{(i,j)|u_i \in U, a_j \in A \text{ and } a_j \text{ is PS/TnSp}\}$$
$$S_4 = \{(i,j)|u_i \in U, a_j \in A \text{ and } a_j \text{ is PS/TnSf}\}$$
$$S_5 = \{(i,j)|u_i \in U, a_j \in A \text{ and } a_j \text{ is PnS/TnSf}\}$$

and $S = S_1 \cup S_2 \cup S_3 \cup S_4 \cup S_5$.

B. Problem Definition

Given a set of users, $U$, and a set of appliances for each user, $A$, under discrete timing of $K$ time slots with a
set of appliances, \( U \), available power generated by a renewable source at time slot \( t \), power consumption of user \( u \), maximum available energy stored in the system, and weighted usage time of the appliances.

### C. The MIP Model

All system variables with their acronyms and descriptions are presented in Table I. Note that the power levels in Table I, \( p_{ij}^l, l = 1, \ldots, |L| \), is assigned to be

\[
p_{ij}^l = \frac{|L| - l + 1}{|L|} p_{ij}^1, \quad \forall i \in U, \forall j \in A
\]

where \( p_{ij}^1 \) denotes the maximum power of user \( u_i \)’s appliance \( a_j \).

In the following, we consider three cases. The first is our novel modeling and the other two are comparative schemes to be used in performance evaluations in Section V where no optimization takes place.

1) Case 1: In this case, we introduce our novel MIP model as presented in Figure 5. Note that, it is possible to allocate \( E_s \) over all time slots. The objective is the maximization of the weighted usage time (i.e., weighted energy utilization) while satisfying the constraints. Equation (11) states that energy utilization is a binary variable (i.e., whether a slot is used or not). Equation (7) puts an upper limits on the total power utilization at each time slot. Equation (8) states that there is a limit on the minimum amount of energy provided at the end of time slots to user \( u_i \)’s appliance \( a_j \). We note that this constraint works as a Quality of Service (QoS) parameter for users and different QoS requirements can be satisfied by allocating different minimum energy requirements to different appliances. Additionally, for user \( u_i \)’s appliance \( a_j \), \( E_{min}^i = 0 \) indicates that this appliance can be shed completely. Equation (9) is used to ensure that each power appliance works at one power level at a time when it is turned on.

2) Case 2: We consider a scenario in which all appliances are turned on in the first time slot and continue to run as long as there is enough power supplied to the system. In other words, there is no stored energy optimization over the time slots. We assume the stored energy is depleted at the end of the first \( K_1 \) time slots. Note that, after time slot \( K_1 \), the appliances rely only on the renewable power supply. To obtain this case, Equation (7) in the MIP model in Figure 5 should be replaced with Equation (12)

\[
\sum_{i \in U} \sum_{j \in A} \sum_{l \in L} p_{ij}^l t_{ij}^l \leq P^r(k) + P^s(k) \forall k \in K
\]

and Equation (13) should be added as a constraint, where \( K' = \{1, \ldots, K_1 \} \).

3) Case 3: This case models the existing power grid. Similar to the second scenario, all appliances start to run in the first time slot and continue to operate until there is enough power supplied to the system. Yet, the major difference from Case 2 is that, there are no appliance classes or weights for the appliances. Available power in each time slot is allocated among the appliances randomly. As a result, there is no guarantee that minimum

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**Table I: Notation Table for our formulation.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{ij}^k )</td>
<td>user ( u_i )’s appliance ( a_j ) is utilized in time slot ( k ) at power level ( l ) if ( t_{ij}^k = 1 ), and is not utilized if ( t_{ij}^k = 0 )</td>
</tr>
<tr>
<td>( U )</td>
<td>Set of users, ( U = u_1, u_2, \ldots, u_{</td>
</tr>
<tr>
<td>( A )</td>
<td>Set of appliances, ( A = a_1, a_2, \ldots, a_{</td>
</tr>
<tr>
<td>( K )</td>
<td>Set of time slots, ( K = k_1, k_2, \ldots, k_{</td>
</tr>
<tr>
<td>( L )</td>
<td>Set of power levels, ( L = l_1, l_2, \ldots, l_{</td>
</tr>
<tr>
<td>( P^r(k) )</td>
<td>Available power generated by a renewable source at time slot ( k )</td>
</tr>
<tr>
<td>( P^s(k) )</td>
<td>Available power stored in the system at time slot ( k )</td>
</tr>
<tr>
<td>( E_s )</td>
<td>Maximum available energy stored in the system</td>
</tr>
<tr>
<td>( p_{ij}^l )</td>
<td>Power consumption of user ( u_i )’s appliance ( a_j ) at level ( l ) in a time slot</td>
</tr>
<tr>
<td>( w_{ij}^l )</td>
<td>Weight of user ( u_i )’s appliance ( a_j ) at level ( l )</td>
</tr>
<tr>
<td>( E_{min}^i )</td>
<td>Minimum required total energy for user ( u_i )’s appliance ( a_j )</td>
</tr>
</tbody>
</table>

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**Maximize** \( \sum_{i \in U} \sum_{j \in A} \sum_{l \in L} \sum_{k \in K} w_{ij}^l t_{ij}^kl_{ij}^l \)

**Subject to:**

\[
\sum_{i \in U} \sum_{j \in A} \sum_{l \in L} p_{ij}^l t_{ij}^k \leq P^r(k) + P^s(k) \forall k \in K
\]

\[
\sum_{k \in K} \sum_{l \in L} p_{ij}^l t_{ij}^k \geq E_{min}^i \forall i \in U, j \in A
\]

\[
\sum_{l \in L} t_{ij}^l \leq 1 \forall i \in U, j \in A, k \in K
\]

\[
\sum_{k \in K} P^s(k) = E_s
\]

**Fig. 5:** The MIP model for the first scenario.
required energy for an appliance is supplied. In other words, there is no scheduling and this case establishes a lower bound for the proposed cases.

V. PERFORMANCE EVALUATION

We used GAMS for solving the MIP model [38]. In all three cases from Section IV-C, the total stored energy, $E_s$, is set to 1000 MW where $|A| = 50$, $|U| = 5$, $|K| = 24$. In Fig. 6a total reward (weighted usage time) vs. percentage of TS appliances (PS/TS and PnS/TS) for Case 1 and Case 2 is shown. The numbers of PS/TS and PnS/TS appliances are equal and 50% of all TS appliances can be shifted. It is clearly shown that the total reward increases when more TS appliances are introduced to the system. In addition, increasing the number of power levels ($|L|$) also provides more reward. Case 1 outperforms Case 2 to corroborate the intuitive expectation that adding some level of smartness (in our formulation, smarter distribution of power consumption) to the grid yields favorable results.

In Fig. 6b total consumed power in each hour for no optimization case and the proposed scheduler for various power level numbers along with the power generation profile of the wind tribune in [21] are plotted. 60% of the appliances belong to TS classes. Number of TS appliances are divided into PS and PnS types equally. Both Case 2 and Case 3 consume the total stored energy in the first few slots and then power consumption is limited by the amount of power from the intermittent renewable sources. On the other hand, our proposed scheduler (Case 1) smoothens the power consumption pattern as compared to the latter two cases. The Peak to Average Power Ratio (PAPR) is of Case 2 and Case 3 were 2.19dB while our proposed scheduler (Case 1) reduces PAPR down to 0.70dB. It is concluded that the proposed scheduler both maximizes the total weighted usage time and decreases PAPR.

Fig. 6c plots the percentage of appliances whose power requests are satisfied as a function of time. Case 2 and Case 3 supply electricity to all users in the first few slots until they deplete the storage. After the stored energy is depleted, Case 2 schedules the generated power among the appliances according to their weights and requirements while Case 3 randomly selects the appliances to be turned on. Even though the total consumed power for Case 2 and Case 3 is same as it is seen from Fig. 6b, Case 2 supplies more appliances than Case 3. Case 1 for $|L| = 3$ can always serve around 75% of appliances where Case 3 can only serve half of the appliances after the stored energy is consumed. Fig. 6c shows that increasing the number of power levels from 1 to 3 brings about 5% more appliances that can be served.

VI. CONCLUSION

In this paper, we have investigated the problem of islanded microgrid operation where a subset of the power grid is designed to operate completely disconnected from the rest of the power grid. Our goal is to make this mode of operation for the microgrid more sustainable by intelligently allocating power among the users and their appliances in accordance with priority levels as configured in the smart meters. To the best of our knowledge, such a modeling of a microgrid power usage optimization with renewable sources and stored energy is the first in the literature. Our model also includes a novel taxonomy of the energy usage by appliances in terms of time and power level adaptability. Our contributions are in the problem formulation and solution approach as well as in the comparative performance evaluations that show clear advantages of using intelligent power allocation as compared to the current system.

As part of the future work, we are planning to evaluate our problem formulations in terms of other objective functions, such as cost minimization or PAPR minimization, and to extend the model with multiple microgrids especially to assess scalability and potentially complex inter-microgrid power transfer.