A Smart Grid Based Algorithm For Improving Energy Efficiency of Large Scale Cooperating Distributed Systems

Bakhe Nleya[1] Andrew Mutsvangwa[2]
Department of Electronic Engineering, DUT
Durban, South Africa
bmnleya@gmail.com[1]

Mendon Dewa
Department of Industrial Engineering,
Durban, South Africa

***Abstract*— A smart grid (SG) is a sophisticatedly integrated hybrid power generating system which allows bidirectional energy as well as management data exchanges. In this paper we look at improving energy efficiency in large scale cooperating power consuming as well as power generating systems. We discuss a clustered as well as hierarchical power scheduling algorithms that are geared towards optimizing the management of power tariffs, storage and distribution in a cooperative environment. From a generation perspective, solar intensity prediction is proposed for power generation forecasting and whereas from a power consumption perspective, we evaluate and model the power consumed by these distributed systems (consumers) and propose improving resource allocation, scheduling and network traffic management so as to make network and computing resources more power efficient**.

*Keywords— **energy management and demand response, hybrid power generating sources, power consuming systems, smart grid.***

I. INTRODUCTION

A Smart grid (SG)'s primary objective is to be responsive to utility and grid system loads. The legacy electrical power grids are generally focused on transmitting the generated electrical power from a few synchronized generating sources to multitudes of end users. On the other hand, a SG utilizes a duplex flow of both electrical energy and data control information to constitute a well controlled and managed distributed intelligent electrical power generation and delivery network system. The network is further enhanced with other modern information technologies so as to enable delivery of power to users or in a more efficient manner and at the same time managing system events almost in real time. For example, a SG is capable of responding to all events that occur within its domain (in the grid) , such as voltage/frequency drops, power generation, power transmission, power distribution, and power consumption, by adopting the necessary avoidance measures. It thus can be viewed as an integration of complementary devices, components, subsystems, functions, and services under the pervasive control of highly sophisticated control systems. Holistically the SG infrastructure can be decomposed into three sub-smart infrastructures or subsystem as follows: The smart information technology subsystem that is responsible for advanced information metering, monitoring, and management in the context of the SG. The smart energy subsystem that is responsible for electrical power generation, delivery, and consumption and lastly the critical smart communication subsystem that is responsible for facilitating an efficient communication platform for information transmission among systems, devices, and applications. Because the smart grid can provide flexibility and intelligence in electric power utility services, a reliable communication subsystem is key to achieving these objectives. In this regard both wired and wireless communication systems have been investigated and used in this context. However, issues related to reliable and effective communications achieved through standardization are continually being addressed. This sub-system should meet among other requirements, time synchronization, reliability, latency, authenticity and criticality of data delivery, as well as multicast support [2]. Interoperability in this subsystem of the smart grid is also crucial hence strides towards standardization of smart grid communications subsystems. Various bodies and organizations working on this include IEEE's IEEE C37.1 ,IEEE 1379 ,IEEE 1547 and IEEE. The International Electrotechnical Commission (IEC), defined standards that include IEC 60870, IEC 61968, IEC 61970,and IEC 62351. The National Institute of Standards and Technology (NIST) has published standards such as NIST 1108 and NIST[2]. Smart rid systems benefit users in the form of demand-side management in which the utility manages the user-side electrical loads through various incentives. Several demand-side management models including economic aspects based [3-5] and those that factor in grid-related issues such as frequency or voltage regulation [6] have been suggested. Lately, distributed generation (DG) is being promoted so as to facilitate incorporation of renewable and alternative energy systems [7]. In that way support electrical energy needs in remote and rural areas is addressed [8], where no main utility power grid exists or is unreliable. Microgrids (A microgrid is considered to be the building blocks of future smart grids) [9] will also be incorporated. Distributed generation of power facilitates as well as triggers the development of microgrids. A microgrid is regarded as one of the key cornerstones of the future SG [10]. A microgrid is a cluster of power energy generation systems, storages, and loads which under normal operation would connect with a traditional power grid (Macrogrid) so as to facilitate power transfer between the two should the need arise. Users within a microgrid domain can generate low voltage electrical power using distributed generation, such as wind turbines, solar panels ,bio-fuels and fuel cells. The connection point with the Macrogrid can be disconnected, thus enabling the microgrid operating autonomously [10]. It can now be regarded as islanded, in which users rely only on power generated within it. In this way, the islanded microgrid's ability to isolate itself from the rest of the power network leads to a reliable power supply within it, i.e. comparatively, this intentional islanding provide a higher local reliability than that provided by the power system as a whole [10]. The control paradigm can be centralized, distributed, or hybrid [11,12]. In a centralized approach, a designated microgrid central controller receives all measurements from a microgrid. In the distributed control paradigm, the measurement signals from energy sources are communicated to the respective local controllers. A distributed approach facilitates integration of the different energy sources [12]. Finally, the hybrid control paradigm combines the best features of the above two schemes, where distributed energy sources are organized in groups, and centralized control is applied in each group. Ensuring cyber security in a smart grid is quite a complex task mainly due to the diversity of the systems involved. Cyber security objectives include [13,14]:

- integrity, i.e. protecting against illegal modification or discarding of information.
- confidentiality which ensures protecting privacy and proprietary information by authorized restrictions on information access and disclosure.
- availability, i.e. ensuring reliable access to information and services whenever such a need arises.

Availability and integrity are the more in ensuring overall system reliability. However, due to the inevitable systems interactions with users, the importance of confidentiality is also growing in this two-way data communication system that interconnects the whole system including meters, collectors, communications network, and utility data centers. Overall ensuring cyber security in smart grid needs continuous monitoring so that any possible attack can be detected in time and appropriate actions can be taken quickly. [14]. Examples of approaches proposed so far to handle security issues include a public key infrastructure which is a mechanism that binds public keys with unique user identities by a certificate authority (CA)[15]. Anonymization [16], Privacy Preserving Smart Metering [14,16] , Distributed Data Aggregation for Billing and Collaborative Usage of Resources. In summary, we note that within the framework of SG, several operational as well as management goals, which have always been problematic as well as infeasible to practically solve in conventional power system grids, become easy and possible to solve.

So far we have found in this introductory review that most of the research the Smart Grid's operation management aim to improve energy efficiency in terms of demand and supply though sophisticated automation. In the process this is leading to an advanced enabling management infrastructure that will lead to a proliferation of extra functionalities hence more new management services and applications will emerge to further enhance grid efficiency. In the next section we discuss power distribution in an SG environment, followed in section III by a proposal for power scheduling that is geared towards optimally managing electrical power trading, distribution, as well as storage in a smart power grid with a Macrogrid and cooperating microgrids. Finally, we conclude the paper.

II. POWER GENERATING SYSTEMS

Primarily any electrical network aims to generate and supply power reliably and efficiently to all paying users. This requires considerable amount of engineering effort as well as monitoring of fluctuations in energy parameters such as voltage and frequency. Centralized power system architectures suffer from numerous technical, operational and economical limitations within their infrastructure and hence blackouts occur from time to time. These blackouts can be caused by various factors such as malfunctioning of power generating equipment, sudden unanticipated load demands, strong winds blowing pylons, flooding, e.tc. Earlier prediction of the occurrence of such events may ensure that the base load is adjusted to cope with the peak demand is always desirable [17]. A long term solution to ensuring energy efficiency is to replace current centralized power systems architectures with decentralized (distributed) ones. Distributed Generation (DG) incorporates generating sources such as wind turbines, micro turbines, photovoltaic systems, fuel cells, energy storage and the traditional synchronous generators to supply the needed power to distributed systems connected close to the consumers load, hence a solution offered by smart grids.

Overall, the technical, economic and environmental benefits of DG Integration in Smart Grids include, improvement of energy system reliability and flexibility, energy efficiency, optimization of electricity infrastructure replacement investment, facilitation of market interactions as well as access to products and services with choice, based on price and environmental concerns to users , affording the connection of widely distributed, renewable energy sources across the network, and more consumer interaction with the Smart Grid network. However the renewable energy sources will mostly be connected to the low voltage or medium voltage sections of the network [17]. Traditional power systems were not designed to incorporate low voltage power generation and storage at the distribution level. They are also not designed to allow the renewable energy sources to supply the power to the customers directly [18]. In an effort to enable efficient as well as real-time energy distribution in a smart grid system, a distribution control center (DCC) constantly collects real-time information from the three key components, i.e., the users, the grid, and the energy provider and utilizes it in making decisions on immediate and future electricity distribution and generation. Ultimately, it re-adjusts the operations of the associated key. Through the installed smart meters interface at the user side the DCC is able to encourage as well as enforce necessary measures during periods of grid constraints.

III. DISTRIBUTED POWER SCHEDULING ALGORITHM

Power demand scheduling is a way of avoiding chances of grid overload especially during peak power demand periods. In general, both centralized and distributed scheduling approaches have pros and cons. The earlier tend to achieve better solutions as the central controller has complete usage and related data for all the users even though this requires a complex communication infrastructure that facilitates each user sending required information directly to the central controller. On the contrary, distributed approaches require relatively cheaper communication connectivity infrastructure and hence are able to efficiently utilize the computing and processing power distributed at each end-user cluster or microgrid.

A: System Model Description

We start, this section by briefly describing a typical distributed power grid system model comprising a single Macrogrid and many microgrids (MGs) as illustrated in figure 1. As is known, a Macrogrid can supply a relatively stable and constant power whereas the DG in MGs can rarely achieve the same.

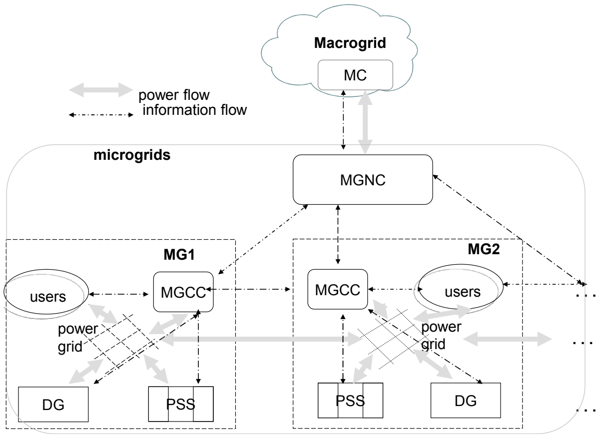

Figure 1. A Distributed Power Grid Model

However MGs can always inject their surplus power to the Macrogrid in a formal trading arrangement, hence the necessitation of taking into account key factors such as the power generation cost, power losses during transmissions, load smoothing and power storage facilities. Therefore, all these factors should be considered for both the Macrogrid and MGs. The Macrogrid is mostly equipped with the traditional power generating sources and mostly supplies power to its own set of users.

In the model depicted above, a dedicated Macrogrid controller (MC) aggregates data from the smart meters within the Macrogrid and uses it to ensure optimal power distribution to all its users. Likewise it trades power externally, i.e. with the microgrids (MGs) and other Macrogrids through the MG control center (MGCC).

The data flows are transmitted via a power line communication (PLC) system communications network infrastructure. Other forms of network can be provisioned as well to augment the PLC. Each MG is considered to be a basic building block of future smart grids [18] and typically may consists of several DG sources, an integrated power storage system (PSS), a smart infrastructure (typically smart meters, sensors and communication links), a set of users, and a single MGCC. All users within that MG can only demand power from it. The independent DGs within it support power demands within the MG. The PSS stores any excess power for discharging latter, should demand arise. It usually consists of a bank of deep cycle batteries as well as some Electric and plug-in hybrid vehicles (EVs/PHEVs). Each MG can also buy extra energy from the Macrogrid or other MGs and as such the MGCC will facilitate as one of its main functions. In this model, there is no direct data exchanges between the MC and MGCCs instead they interconnect via the MGNC hence only a single data connection point between the Macrogrid and the MGNC.

B: *Hierarchical* Power *Scheduling Algorithm*

A hierarchical power scheduling that assumes cooperation among users, microgrids as well as MGs (HPS_C) is described. The algorithm seeks to optimally distribute power in the Macrogrid as well as schedule power in cooperative DG MGs. We assume a discrete time slotted system numbered from 1 up to T .In other words in this system model we consider a time span of a single day subdivided into multiple time slots. Similarly the independent but cooperative power users are numbered from 1 to N , with each user demanding $d_i(t)$ amount of power at any time instant t . Note that each user may be a single stand alone family house, an unit in a block of apartments or an office building, etcetera. We also assume a total of M microgrids (MG) numbered from 1 to M . In each MG there are N_m users whose aggregated power demand is $d_m(t)$ at any given time slot t , whilst $p_m(t)$ is the power transfer either way between the Macrogrid and a given MG any given time slot t .

The power demand by each user in the network can be determined apriori acquiring usage parameters such as the arrival time of a power demand request(a_{ij}), time for completing the request(f_{ij}),the demand length(l_{ij}) and the power demand profile(p_{ij}). In this case the start time s_{ij} should satisfy the following scheduling constraint.

$a_{ij} \le s_{ij} \le f_{ij} - l_{ij}$.

The total electricity generation cost per day is $\sum_t C_t(P_t)$ where P_t is the total power consumed during slot t and C_t is its cost.

For the distributed power grid model in figure 1, we further define the following notations:

N - number of users in a MG.
M - number of MGs.
ψ - set of time slots from 1 to T.
$C_m(.)$ - transmission cost between Macrogrid and MG_m.
$d_j(t)$ - user i's total power usage within time slot t.
$p_m(t)$ -power between Macrogrid and MG_m.
$p_{m,\max}(t)$ -max. power between Macrogrid and $MG\,m$.
$C_{km}(.)$ - power transfer cost between two MGs(k and m).
$p_{km}(t)$ -power transmitted between MG k and m.
$g_{k,\max}(t)$ -maximum power generated in a MG k during timeslot t.
$C_{n,\min}(t)$ - $C_{n,\max}(t)$ -minimum and maximum power received in $MG\,m$ from other MGs respectively.
$s^*_m(t)$ -power to be stored in MG_m at time t.
$s_m(t)$ -the storage level in MG_m at time t.
- $\lambda_m(t)$ upper bound dual multiplier, and is periodically updated by a step-size $\delta \rightarrow \lambda_{m,t}(k)$.
$\in$ -terminating condition for updating $\lambda_{m,t}(k)$.
$\beta_m(t)$ -lower bound dual multiplier, and is periodically updated by a step-size $\tau \rightarrow \beta_{m,t}(k)$.
ε -terminating condition for updating $\beta_{m,t}(k)$
$\vec{(.)}$, $(.)^*$ offline and online optical solutions of $(.)$ respectively.

For the macrogrid, we assume that all power users are independent and adopt the following algorithm [22].

Algorithm A: Optimal Power Distribution (Macrogrid)

```
set $\hat{d}_i(0)$ and $\hat{p}_m$ for all $i \in N$ & $m \in M$ ;
while $i = 1:T$ do
$p_{m,\max}(t) \leftarrow$ MGNC
$p_{m,\max}(t) \xrightarrow{\text{solve}} p^*_m(t) \rightarrow$ MGNC
update $\hat{d}_i(t)$ and $p^*_m(t)$ for all $i \in N$ & $m \in M$ ;
exchange power $p^*_m(t)$ with MG for all $m \in M$
$\overset{*}{d}_i(t) \rightarrow$ to Macrogrid user $i$ , for all $i$ ;
end
```

Algorithm B1:Distributed Cooperation Power Scheduling Algorithm[22]

```
For $i = 1,2,3...,T$ , do
from $MG_m$ , $p_{m,\max}(t) \rightarrow$ MC, for all $m \in M$ ;
receive $p^*_m(t)$ from the MC and forward it to $MG_m$ , for all $m \in M$ ;
initialize $\vec{\lambda}_{M,t}(j)$ and $\vec{\beta}_{M,t}(0) \geq 0$ , and broadcast all MGs;
repeat
receive $p^*_{k,m,t}(j)$ from each MG;
update $\vec{\lambda}_{M,t}(j)$ and ;7 $\vec{\beta}_{M,t}(j)$
send to all MGs, for all $k, m \in M$ ;
until $(|\lambda_{m,t}(j+1) - \lambda_{m,t}(j)| < \varepsilon_{\mathrm{m}}$ and $|\beta_{m,t}(j+1) - \beta_{m,t}(j)| < \varepsilon_{\mathrm{m}})$ ;
broadcast $\vec{\lambda}^*_M(t)$ and $\vec{\beta}^*_M(t)$ to all the MGs;
end
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Algorithm B2:Distributed Cooperation Power Scheduling Algorithm[22]

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set $i = 1,2,3...,T$ do
estimate Macrogrid $\xrightarrow{p_{m,\max}(t)}$ MGNC;
receive $p^*_m(t)$ and compute constraints $C_{m,\min}(t)$ and $C_{m,\max}(t)$
repeat
receive $\vec{\lambda}_{M,t}(j)$ and $\vec{\beta}_{M,t}(j)$ ; solve for $p^*_{k,m,t}(j) \rightarrow$ MGNC;
for all $k, m \in M$ ;
till , $\vec{\lambda}_{M,t}(t)$ , $\vec{\beta}_{M,t}(t)$ are received;
compute $\grave{s}_m(t)$ then discharge/charge PSS for all $m \in M$ ;
$\xrightarrow{p^*_{k,m}(t)}$ $MG\,m$ & $\xrightarrow{p^*_m(t)}$ Macrogrid for all $k, m \in M$ ;
end
```

IV PERFORMANCE EVALUATION

We set up a simulation in which the number of time slots is set to 24 and vary the number of power requests. Note that a power request is defined as the power usage of an y electrical appliance for a defined period of time.

Table 1. Test case main parameters

Case	Users in MG/Macrogrid	Power requests per user
I	100/400	25
II	100/400	50
III	100/400	80
IV	100/400	75

We consider a SG comprising a single Macrogrid and two Microgrids. The Macrogrid supports 400 power users, while each MG supports 100 users. Power flows in MGs 2 are shown in figure 2.

The storage also plays an important role as a power buffer to enhance system stability and capacity. As a result,

with all the key factors considered, HPS_C is able to achieve a balance in the power system, maximize the Macrogrid user utilities, smooth the load of the Macrogrid, and minimize the cost in the cooperative MGs.

We also compare the HPS_C with other previously proposed algorithms namely:

- As soon as possible algorithm(AS_AP) in which each task is scheduled to commence at its instant of arrival.
- cooperative control (centralized algorithm) in which there is virtually no power scheduling at all.
- As late as possible algorithm (AL_AP) in which each task is scheduled such that it completes before the set deadline.

- Centralized distributed / online power distribution algorithm.

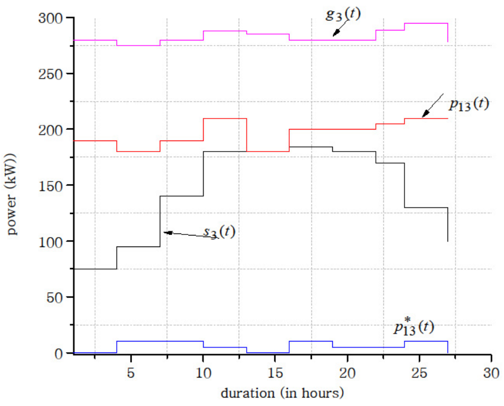

Figure 2. Power scheduling (MG 3)

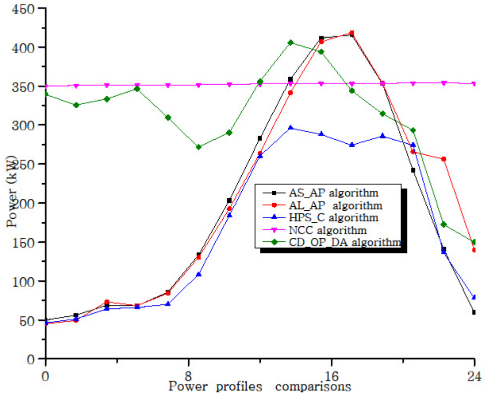

Figure 3. Power scheduling for different schemes

Shown in figure 3, is the power scheduling achieved by various schemes for case II. It can be seen from the graph that only the HPS_C algorithm achieves a fairly flat power demand during peak hours hence promoting efficiency.

IV. CONCLUSION

In this paper, we explored load demand scheduling of multiple cooperative end-users whose sole objective is to minimize the power generation costs. We compare several algorithms and only the HPS_C is able to achieve a fairly flat load demand scheduling.

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