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Towards a Hierarchical and Distributed Power Management Framework For SGs

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Abstract— **Escalating global power(energy) demands and the need to avail it in a reliable, efficient manner has led to the modernization of legacy and current power system grids into Smart Grid (SGs) equivalents his article proposes a hierarchical distributed arc. The paper mitigates the advantages of both hierarchical and distributed architectures in Smart Grid management and control. As is known, a hierarchical architecture of control and management will facilitate massive-scale data acquisition, exchanges, processing, and control for cooperative power exchanges between prosumers (end users), and the main power grid, via cloud computing. Such a distributed architecture affords autonomous decision-making capabilities with agent-based intelligence through edge/fog computing. Analytical results show substantial achievements of the proposed hierarchical and distributed SG/MG management framework based on an actual protocol and system implementation.**

Keywords—smart Grid, prosumers, OPEX and CAPEX, hierarchical, distributed generation, battery energy storage system (BESS).

I. INTRODUCTION

The key to successfully optimizing power dispatching in SGs would be to embark on a strategy that minimizes the OPEX and CAPEX associated with traditional and renewable generators, the transactional costs of the transmittable power, and maximizes the Utility's demand response benefits, concurrent with satisfying the load demand constraints.

This is achieved by effectively managing power generation, distribution, and usage in the SG or MG. Overall the primary objectives include the following:

- integrating renewable generation sources into the main power grid. These sources can be from individual households or PPPs.
- The real-time constant monitoring of electrical power consumption and its depletion in the SG.
- Acquisition of key grid measurements as well as billing-related data.
- Constant achievement of optimized balancing of demand and power energy consumption by end-users (Prosumers).
- Effecting regular interactions between end-users and Utility. An enabling ICT subsystem normally facilitates this.
- Constantly guarding and enforcing both privacy and security within the entire system.
- Enhancement of reliability by way of allowing degrees of autonomy in management.
- Ensuring the maximized efficiency in terms of assets used in the SG.

A vision of a future SG is shown in Fig. 1. Notably, a full-duplex ICT subsystem is incorporated to interlink the various entities communication-wise. In that way, end-users can trade effectively, e.g., maximize power trading with the Grid. This is because they would have acquired market-related information, as well as grid status, before trading any excess power to the Grid.

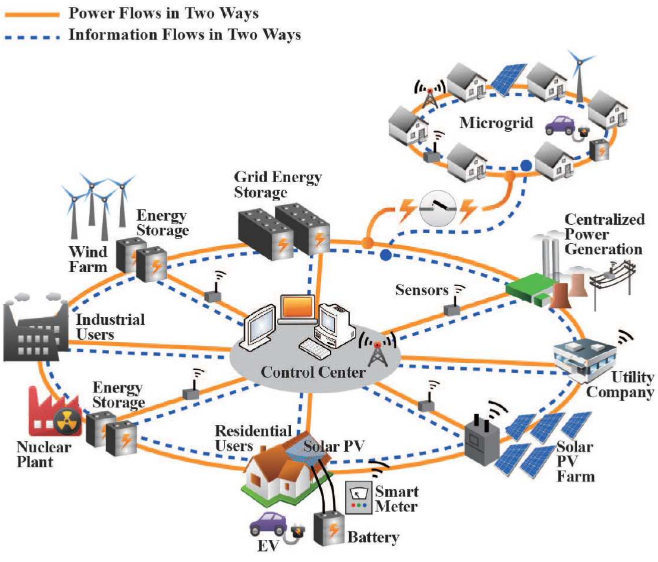

Fig. 1. An envisioned future Smart Grid system

At a functional level, the SG system encompasses various applications, and services, concurrently with advanced management and operation to ensure efficiency in balancing supply and demand. As such in the emerging distributed power systems of the future, demand-side management will play an important role in dealing with stochastic renewable power sources and loads. A near-unity load factor can be secured by employing Demand Response methods with storage systems and regulatory control mechanisms. Increasing the deployment of Renewable Energy generation

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and other forms of unconventional loads such as Plug-In Electric Vehicles will aid DR implementation with attendant better results for both prosumers and utilities. The central objective of DSM is to minimize PAR and energy costs by switching to cheaper RES and reducing CO_2 emissions. Overall, challenges that persist are a lack of real-time system controls, societal barriers to market deregulation, and insufficient time to avail consumers the time-varying pricing information. Load prediction and control state estimation can be employed to enhance observability in intelligent distribution networks using e.g., an agent-based control approach whose architecture derives from distributed control rather than a traditional centralized paradigm. The resultant DEG networks will have enhanced flexibility and adaptability of automation systems hence generally contributing to speeding the progress of Smart Grids. What is needed now is an effort to develop a standardized and integrated vision for SG. Electric vehicle technology will also in the future have a great impact on SG development. Consequently, there exists a vast potential for research both for backup and DSM as well as the provision of flexibilities for main grid management.

Consequently, based on this introductory review, this paper's contribution is as follows:

First, we briefly define and compare distributed and hierarchical power-dispatching configurations applicable to SGs.

II. DISTRIBUTED AND HIERARCHICAL-BASED POWER DISPATCHING

A): Hierarchical Agent-Based Control

Agents are local, and autonomous, yet decentralized to the extent that they can communicate with each other and make control decisions by themselves. The multi-agents [1], integrate to perform and accomplish certain tasks in a complex system. A hierarchical or distributed agent control method based on game theory architecture can capture the ability of self-organization and self-steering to realize individual goals typical of a consumer serviced by a specific microgrid. Multi-Agent-based technology has been successfully used to control micro-grids comprising PV plants, batteries, and adjustable loads [1].

A typical autonomous multi-agent system is designed and implemented in [2]. The agents can be sensitive to upstream outages and respond accordingly to allow islanded operation of micro-grids. Open source modeling and simulation tools for power systems such as GridLAB-D, UWPFLOW, TEFTS, MatPower, PST, InterPSS [3, 4] are available and help to integrate detailed grid systems and consumer models. These tools enable fast simulation and modeling as they are specifically tailored for MGs studies. Special cases of MG at the rural distribution level is considered in [5]. The results illustrate how SG technologies improve rural distribution systems management regarding energy management.

A functional SG would comprise three distinct levels namely, power generation and distribution, control and management, and lastly communications and security. The key to a reliant and efficient SG would be stabilized and economic control are two main factors to enable the reliable and efficient operation of microgrids. As can be recalled, since a typical SG comprises several interconnected and cooperative MGs, each with its own control, the interconnected structure will result in a distributed dispatch control architecture framework. Concerning a hierarchical structure, we have localized controllers that monitor and supervise each resource. This is followed by a supervisory controller at the individual MG level whose role is to oversee the entire MG domain. Furthermore, we will have a last-level controller that now interconnects all the MG supervisor controllers throughout the SG. We thus briefly describe and mitigate both hierarchical and distributed architecture to ascertain which would be an ideal choice for our proposed framework. Both types of control configurations will rely upon the provisioned ICT subsystem of the SG to achieve efficient as well as harmonious coordination among the various DERs (energy generators, be they renewable or otherwise). Fig. 2, illustrates the general control operations of an SG. As can be noted from the exact depiction, there are three levels, and both control information and data are afforded a duplex linking among the three levels. In that way, the SG's primary objectives of reliance, efficiency, and resilience are achieved.

The lowest-level controller regulates localized resources such as grid frequency (i.e. frequency sensors), whereas the top-level controller plays a supervisory role and is hence involved in key decision-making.

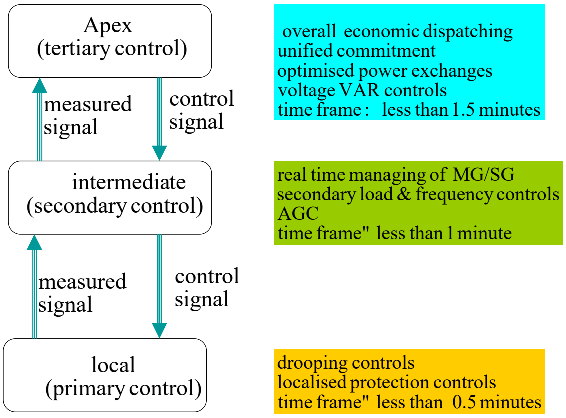

Fig. 2. Generalised SG control flow structure

Hierarchical Structure: Such a control structure thrives to achieve key objectives of an overall SG as cited earlier by employing a centralized controller at the apex(tertiary level) . The same level hierarchy will blend these objectives with operational constraints to ultimately define the base optimization problem. This level of control hierarchy must be efficient and reliable. Ultimately it integrates various homogeneous generating sources (DERs) and at the same time able to generate and cast real-time tariff signals to prosumers. In addition, it can forecast loads, Note that the key to achieving the projected objectives is having a reliable and efficient ICT subsystem via which it communicates with other entities within the SG domain.

The next level hierarchical control level (secondary control) addresses and ensures the overall system-level stability of the SG. Typically it is involved in near to real-time power

load management, frequency regulation as well as automized power generation control (APGC).
It is generally relied upon as a pacer or set pointer for primary level controllers in a dynamic fashion. Note that the voltage control problem is defined at this level of hierarchical control.

Distributed Control architecture: A distributed control structure relies on peer-to-peer communications in order to make informed decisions regarding the state and management of the overall SG..

Its flexibility in nature makes it relatively easy to add additional renewable generators, but not impacting on other already existing on lined system generators. A desirable turn around times for distributed control architectures would be no worse than in the order or 0.1 seconds. An failure in the system remains localised hence does not propagate and grind the entire SG grid to a halt. However note that such architectures rely on some sort of heuristics laws in executing control decisions and ultimately provide a suboptimal solution.

By comparison, we conclude the following:

- In terms of control system reliability and efficacy a hierarchical control architecture's top level failure will affect the entire system since coordination among the various controllers is lost, hence optimal operation not possible. However with a distributed control architecture, the fault's effects are localised.
- In terms of economics a hierarchical structure is optimal whereas its distributed equivalent is relatively suboptimal.
- With regards to design complexities, a distributed architecture is relatively easier to design.
- Scalability wise, a hierarchical structure shows more flexibility, whereas a distributed equivalent can only accommodate limited types of DERs.
- In terms of computational complexities, a hierarchical structure has a much relatively higher computational demand. This is because in the case of a distributed architecture, such loads are distributed throughout the participating peer controllers.
- Typically, a hierarchical controller (apex level) is implemented in the form of a high performance PC, whereas an embedded controller will suffice for aits distributed equivalent.
- Because of the absence of peer-to-peer communications, a hierarchical structure will generally operate at very low bandwidth, whereas its distributed equivalent will always require high bandwidth provisioning.

We thus conclude from this comparison that a hierarchical control configuration would be ideal for future generation SGs.

III. MODEL DESCRIPTION

In section we detail a distributed hierarchical based Dispatch Model framework model for energy generation supply, demand and trading. The first step is for us to specify the model's formulations.

A. Model Analysis

In this regard, we will assume a "look ahead policy" i.e. data pertaining to power usage in the past one day period (24 hours) is known apriori. This data included the following:

- 15 minutes interval power demand forecasting for the day ahead.
- 15 -60 minutes PV solar and wind generation potential forecasting;
- Approximated cost functions of the DERs, and other parameters such as maximum and minimum power generation limits.
- The state of the BESS, i.e. its initial charge levels.

The SG operates all its connected MGs in either one of the following modes:
Mode I: Standalone mode. In this case the MG is isolated from the main interconnecting Grid.
Mode II: connected mode: In this case the MG fully connects to the main interconnection grid and power trading may take place.

Mode I:
Given that in the SG, there exists different types of renewable and fossils generators whose cost functions differ, we thus can write:

$F_jP_j(t)) = b_jP_j(t) + c_j$ for an FC , and $F_jP_j(t)) = a_jP_j(t)^2 + b_jP_j(t) + c_j$ for a DE, where the constants a_j, b_j and c_j are parameters associated with the cost function; In this case, the power demands in a single isolated MG must match its generation capacity. The objective function therefore can be expressed as:

$$\min \sum_{i=1}^{n}\sum_{j=1}^{m} F_j(P_j(t)) * \tau_j(t) + s_j(t) \qquad (,1)$$

Subject to;

$$\tau_j(t) = \begin{cases} 1, & \text{if } \mathrm{j}^{\mathrm{th}} = ON \text{ at time } t \\ 0 & \text{otherwise (OFF)} \end{cases} \qquad (.2)$$

$$s_j(t) = \begin{cases} sc_j, & \text{if } \tau_{\mathrm{j}}(t) - \tau_j(t-1) = 1 \\ 0, & \text{otherwise} \end{cases} \qquad (3)$$

Where sc_j corresponds to costs associated with starting a selected generator j.

All this is subject to:

- $p_j^{\min} \le P_j(t) \le p_j^{\max}$, i.e., the power output of the j^{th} generator at arbitrary time t..

- $\sum_{j=1}^{m} P_j(t) = P_{load}(t) - P_{sources(t) - P_{BRSS}(t)}$, i.e., power balances between the total loads and aggregated generation.
- $p_{BESS}^{\min} \leq P_{BESS}(t) \leq p_{BESS}^{\max}(t)$. This relates to the BESS's stored power. Note that when $P_{BESS}(t) > 0$ the system is discharging; $P_{BESS}(t) < 0$ - the system is charging otherwise for $P_{BESS}(t) = 0$ there is no generation.

Mode II: the MG is connected to the main Grid

We recall that this mode is characterized by possible trading of power. This means either the MG can buy power from the primary Grid to sustain its current needs or vice versa, meaning its own excess generation can be traded with the Grid.

We distinguish a few scenarios as follows;

Scenario I: purchasing power from the interconnecting Grid;

In this case if the current tariff is $c_{grid}(t)$, then our objective function can be expressed as:

$$\min\left\{\sum_{t=1}^{n}(c_{grid}(t)P_{grid}(t) + \sum_{j=1}^{m} F_j(P_j(t) * \tau_j(t) + s_j(t)\right\} \quad (4)$$

$P_{grid}(t) > 0$, is the purchased power.

Hence the need to balance the equation;

$$\sum_{j=1}^{m} P_j(t) = P_{local}(t) - P_{wind}(t) - P_{pv}(t) - P_{BESS}(t) - P_{grid}(t) \quad (5)$$

Scenario II: Selling off power

We recall that this will mostly occur when the tariffs favor power generators (including end-users). In this case, the objective function is to maximize profits; hence we have;

$$\max \sum_{t=1}^{n}\left\{-c_{grd}(t)P_{grid}(t) - \sum_{j=1}^{m} F_j(P(t)) * \tau_j(t) + s_j(t)\right\} \quad (6)$$

Note that this time around, $P_{grid}(t) < 0$,

The equilibrium equation now becomes;

$$\sum_{j=1}^{m} P_j(t) = P_{load}(t) - P_{wind}(t) - P_{pv}(t) - P_{BESS}(t) - P_{grid}(t) \quad (7)$$

IV. EVALUATION

This section will use analytical and simulation approaches to evaluate the proposed hierarchical power dispatching framework. For certain aspects of the evaluation, we use the Plexim Simulation Platform. We have chosen 3-cooperative MGs that will be assumed to constitute a fully fletched SG. As part of our preliminaries, we provide a forecasted combined wind (WT) and solar (PV) generation capacity in [5]. Notably, as expected WT sources have the potential to generate power throughout a 24-hour cycle, whereas PV will optimally generate during mild sunny periods.

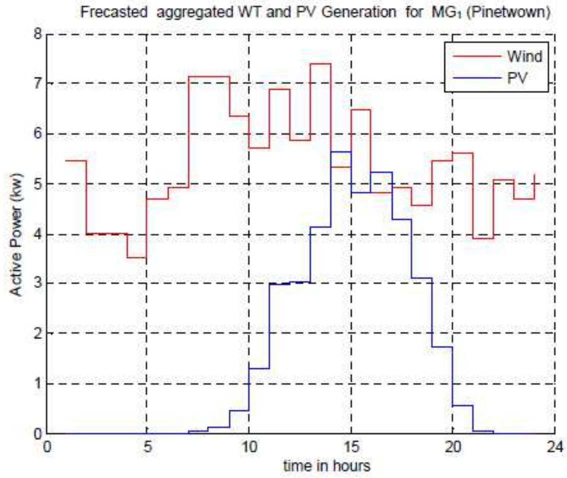

Fig. 3. Aggregated forecast Wind/PV generation for MG_i

Similarly, Fig. 4 exemplifies power demands by individual MGs. These are periodically availed (broadcast) to all prosumers so that the latter can decide when to trade.

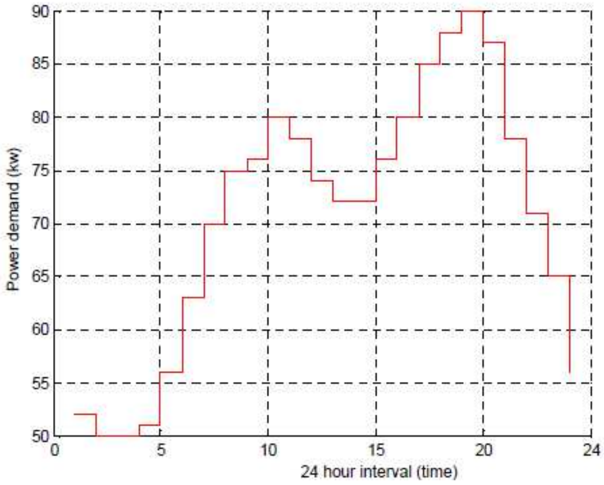

Fig. 4. Stand alone power demands in an MG

It is recalled that from the onset, we declared (defined) two modes of MG operations, one of which was in a standalone mode. In such a mode, the load demand will be consistently lower than aggregated actual (potential) generating capacity. In this scenario, the MG is disconnected from the Grid when power selling is not conducive in terms of current tariffs. However, as soon as tariffs improve, the system will connect should there be demand on the interconnecting Grid. The power demand variation is plotted in [4] comparison of MT, FC and BESS power generation variations and scheduling thereof over a 24-hour cycle is provided in Fig. 5.

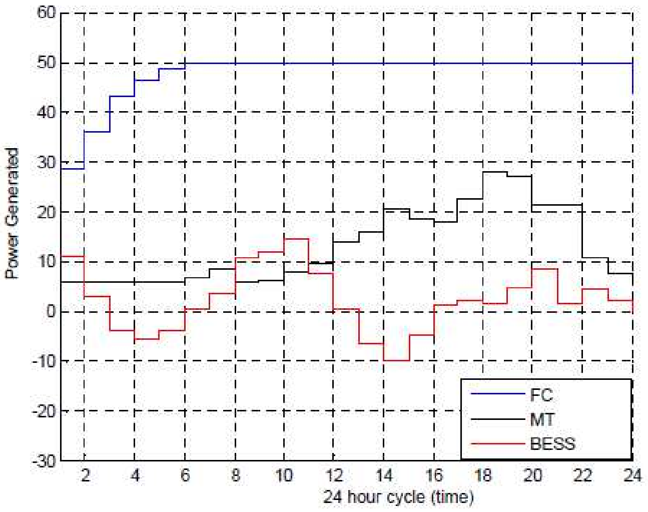

Fig. 5. Overall power scheduling over a 24 hour cycle for an MG in stand-alone mode

Note that the BESS will only start storing power (charging) when other sources are in a position to handle the current load demand, and the BESS itself is partially or critically depleted.

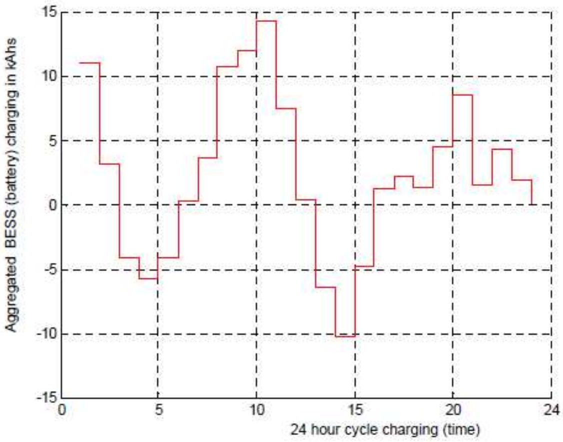

Fig. 6. Discharging and charging of the MG's BESS system

State of charge and discharging for a given MG (in this case MG 2) over a 24 hour cycle is plotted in Fig. 6. The charging/discharging curve mimics that of the power scheduling discussed earlier. Notably, when the MG is void of any power demands or is operating at p minimal loads, the BESS system is charging, while as the earlier attains near peak loading, the latter starts discharging to the local Grid to help support the demand response curve. Notably is also noted (though not shown) that the BESS system will charge mostly from PV/WT (renewable) power. Also, note that in our model framework, the BESS will also discharge to the local power bus, to reduce the dependence on DGs (diesel generators) as their OPEX in terms of fuel cost are pretty high.

According to the other mode of operation of the individual MGs constituting the SG, I in Grid non-isolated (connected) mode, power is being purchased to help sustain the local load in the affected MG.

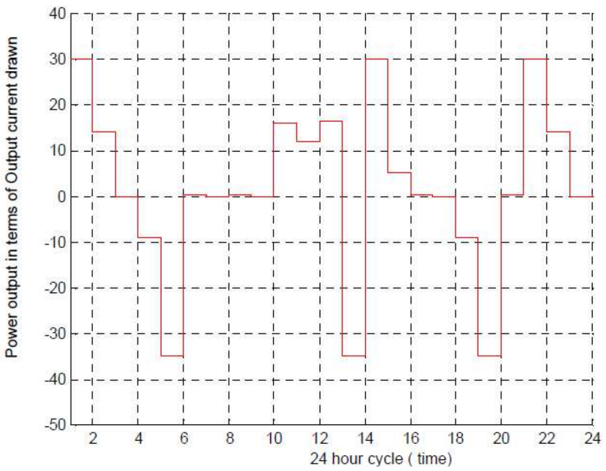

Fig. 7. Power derived from BESS

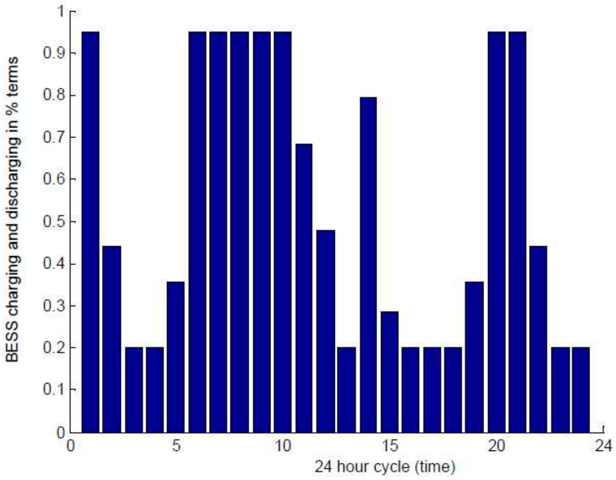

Fig.8. Charging and Discharging concurrent with power purchasing from the BESS

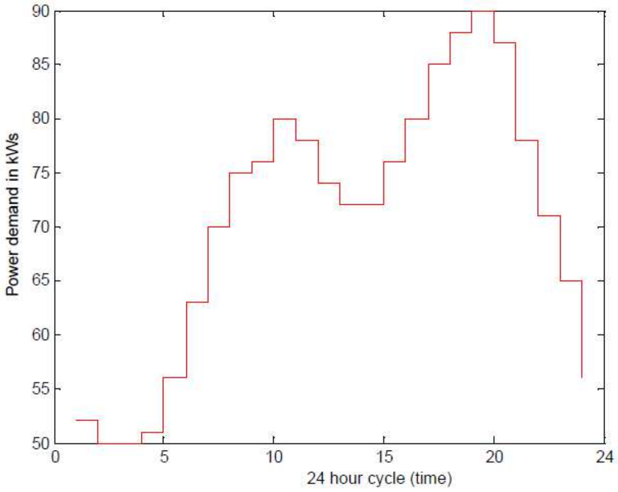

Fig. 9. Aggregated power demand for the MG in Grid-connected mode

In this case, the power derived from the BESS as plotted in Fig. 7 is wholly drawn towards supporting the current load demands.

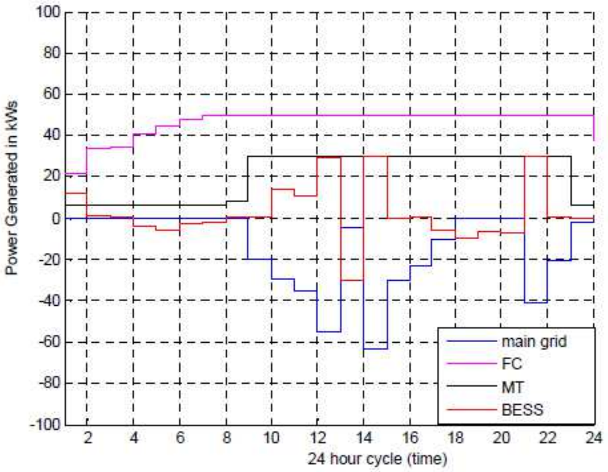

Fig. 10. Power scheduling concurrent with trading with the Grid when MG is trading(selling mode)

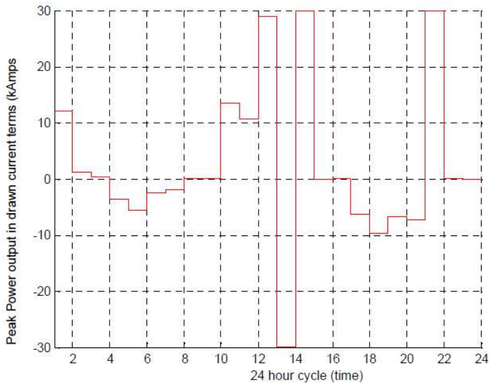

Fig. 11 State of charging and discharging when MG is trading (selling mode)

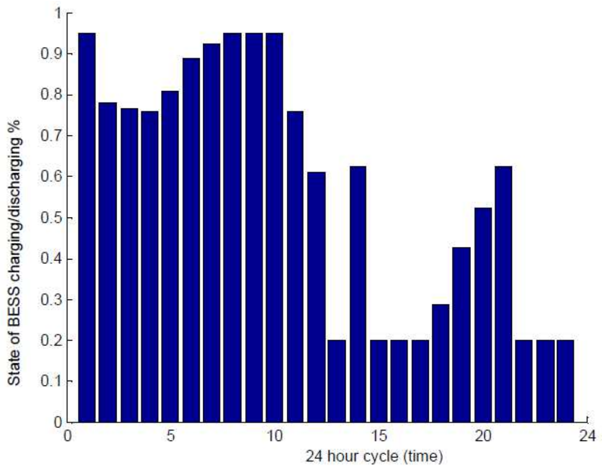

Fig.12. BESS discharging /charging when MG is trading(selling mode)

Figs 8 and 9, when inferred together, we note the following:

- That charging occurs when tariffs are relatively low, typically at dawn as well as in the early evening.
- Discharging to support the local MG occurs when tariffs are high and during peak hours.

We also consider a scenario of trading energy to the Grid, i.e., to support other MGs in distress.

Similarly, from the last three plots, i.e.Figs. 10, 11 and 12, we can infer the following:

- That once again, power storage in the BESS systems occurs when tariffs are low.
- During profitable trading for prosumers, power is discharged from the same BESS systems and sold to the Grid. In that way, prosumers maximize revenues.

V. CONCLUSION

The paper proposed and briefly analysed a hierarchical optimal dispatch framework that relies on several objectives in order to achieve the overall design goal of reliable and stable power supply, coupled with economic benefits to prosumers who elect to participate in power trading. Firstly, a mitigation on an appropriate dispatch control configuration was carried out. In our conclusion, we also note that such an architecture will provide interfaces and protocols, as well as a service infrastructure that supports third parties interested in developing energy management applications. The same architecture further enhanced by incorporating emerging technologies such as AI.

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