Modelling Fractal-Structured Smart Microgrids

Exploring signals and protocols

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***Abstract*— This paper discusses some of the issues surrounding the interconnection of smart microgrids, with a focus on fractal structures, their implementation, management, operation, and potential effectiveness. It builds on a basic smart microgrid model which focuses on the property of localised energy balance, in order to mitigate the dependency on legacy-grid resources to accommodate short-term (hourly) and medium term (daily to monthly) imbalance. This model provides the basis for further development to allow connecting a group of such micro-grids into a network which externally presents identical structure and characteristics, so enabling the fractal-like interconnection of these micro-grids, or groups of microgrids. Such structures simplify the interconnection, management and operation of smart microgrids, and their connection to the legacy grid. They also intrinsically enable the notion of grid-edge trading. These characteristics have the potential not just to further enable and promote the effective utilisation of distributed generation and storage, but also to simplify and rationalise future backbone grid development.**

Keywords-fractal micro-grid; legacy grid; backbone grid; grid edge trading; localised temporal energy balance; autonomous microgrid.

I. INTRODUCTION

The rapid development of new renewable energy sources, typically with non-deterministic patterns of generation, provides significant challenges for the traditional, or *legacy*, grid [1]–[3]. Coupled with similarly rapidly developing storage technologies [4][5], and automation systems which enable effective and tolerable load matching and shifting [6], these technologies can facilitate a significant degree of distribution. Concerns with long-distance hierarchal/radial energy transfer and real-time load following from centralized generating systems, grow less and less relevant and appropriate when microgrids, with their highly distributed generation, storage, and load management, become more prevalent [2][6]–[10].

While the integration of centralized renewables into the legacy grid has been the subject of much research, discussion and debate [11][12], they typically require significant energy storage capacity for their contribution to be effective. Although a range of storage concepts have been explored, including V2G (Vehicle-to-grid) [13], when utilized with centralized renewable generation, the distributed nature of such storage in contrast to the generation, places increased energy transfer demands on the grid.

In this paper the microgrid concept is extended into networks of hierarchically interconnected microgrids, ultimately connected to the *backbone* grid, in a fractal-type structure [15]. The term *legacy grid* is well established, describing the centralized generation and distribution models of the past. Here, the term *backbone* is used to describe its evolution/successor where the centralized functionality begins to take on a new role, delegating aspects of control, balance and generation outwards from the center, depending to some extent on, and exploiting, the growth of localized balance, although elsewhere the term has been used to describe new major national and international transmission systems [8][14].

The protocols for the interconnection of the microgrids to the backbone grid, including potential grid-edge trading, are discussed, with an emphasis on overall system and communication simplicity, although there is no constraint on individual complexity within a single node [16]–[18]. This concept is not unlike that of the Internet, where the protocols are essentially simple, with any complexity residing in the individual terminal devices, and simple devices not ruled out [19].

This paper does focus on relatively small-scale consumption/generation nodes, typically those found in individual residential installations. However, the concepts could be extended to to larger commercial or industrial nodes, although some aspects may not scale so well.

The remainder of the paper is structured as follows. In Section II, a model to describe the characteristics of a smart microgrid is developed, and then in Section III, this is extended to enable multiple microgrids to be interconnected in fractal-type structures. Section IV then explores the way in which energy, and relevant information, might be exchanged within, and to and from, these structures, and the overall effectiveness of the approach. Section V summarizes the paper, and concludes that these techniques can lead to more effective utilisation of distributed generation, and simplify future backbone grid development.

II. MODELLING SMART MICROGRIDS

The notion of localised temporal energy balance within a microgrid, as a significant advancement of the *Net-Zero Energy Balance* concept [20][21], is well developed [22][23]. To minimize or completely remove grid dependency, balance conditions need to be calculated on a much shorter time scale than the annual balance used in the *Net-Zero* model. A household-level smart microgrid model, which enables these calculations, has been developed and is shown in Figure 1 [22] [23]. While the inclusion of the battery flows in both the *local consumption* and *local generation* totals may appear to account for the stored energy twice, this is necessary in order to examine flows over short time scales [22][23]. Typically, and usefully, balance calculations can be performed at hourly intervals over the year (as shown later in Figure 2).

For an example (New Zealand) household with an average daily consumption of 17.6 kWh, the energy balance plot of Figure 2 (taken from [22]) shows the actual hourly balance, based on the model of Figure 1, with solar PV chosen to exactly match the load over a year, and with 24 hours equivalent of battery storage (1.3 Tesla Powerwall 2s [5]). As can be seen, for this hourly energy balance plot, many of the 8760 hours lie on the diagonal, showing perfect balance.

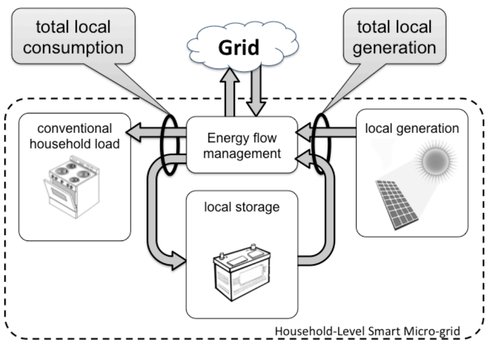

Figure 1. Energy flows within the smart microgrid, and the contextual definitions of local generation and local consumption.

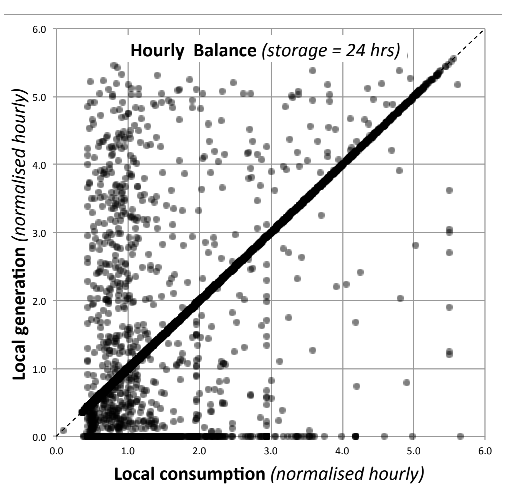

Figure 2. Energy balance at hourly intervals over a year for an example installation.

However, a substantial number fall below the diagonal, representing a net grid load for that interval, and a significant number lie above, representing excess generation. It is interesting to note that the *Net-Zero Energy Balance* model for this configuration would describe it as in perfect balance, which it is only if you consider generated and consumed energy over a whole year. The vertical stack of points towards the left of the graph represents times of high solar generation, often with low day-time load, as is experienced in most residential installations.

III. A Fractal Model for Networks of Smart Microgrids

The hourly balance plot of Figure 2 clearly shows the potential for networking such micro-grids, for example within a neighbourhood, to improve local energy balance. It is possible that when the example household of Figure 2 is in surplus, one of its neighbours may be in deficit, so providing the opportunity for local energy exchange, or grid-edge trading, and reducing the demand on the external backbone grid. Overall, this local exchange can only reduce the external demand, potentially reduce the network distribution capacity requirements, and make more effective local use of the distributed generation and storage, improving both the local and backbone efficiency.

The microgrid illustrated in Figure 1 represents just a single household. Several households in the same neighbourhood could be interconnected in a higher level microgrid, as suggested in Figure 3. Here, a number of households are connected to a higher level node, which bears very close resemblance to the household nodes themselves, and presents a similar face to the backbone/grid as the individual households previously did. In this model, the neighborhood node includes potential neighborhood load (e.g., community street lighting, electric vehicle charging), neighborhood storage, and neighborhood generation (perhaps in a school or other public building or space). A multi-level self-similar structure, such as this, can be defined as a fractal structure [15], and its utility in modelling and describing networks of smart-microgrids has been discussed [24].

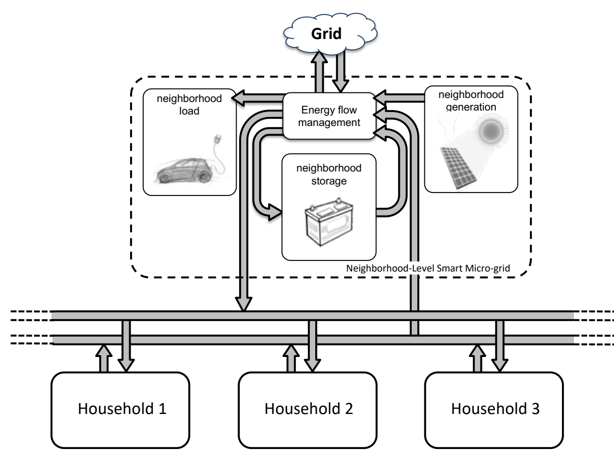

Figure 3. A collection of households grouped together in a neighborhood, using a fractal-like construction technique.

To support this fractal approach, closer examination of the neighbourhood grid of Figure 3, and the household grid of Figure 1, leads to the single generic microgrid model of Figure 4, which could represent a node at any level in a tree of microgrids; a household (leaf) node, or a neighbourhood, a suburb, or a township node, if appropriate. A leaf node would not have any connection to a lower level grid, and at any level, any component other than the energy flow management unit, could be omitted. In other words, some units could have no storage, some could have no generation, and some no load, or any combination of these.

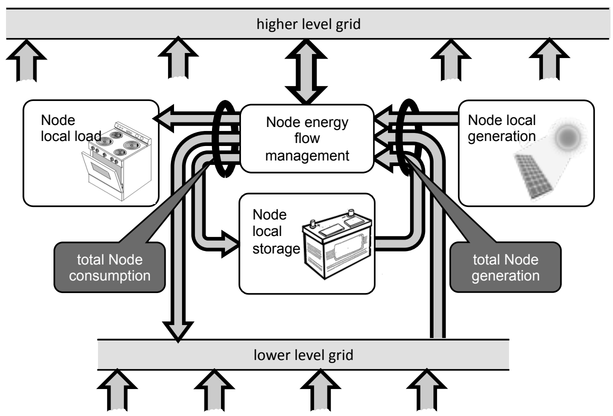

Figure 4. A fractal microgrid energy flow model.

IV. SIGNALS, PROTOCOLS, AND EFFECTIVENESS

For the purposes of this discussion, and our desire, alluded to in the introduction, to maintain simplicity in the communication between nodes, it is suggested that the only signal transmitted between nodes is one of price/need. This leads to the simplified generic node representation of Figure 5, with bidirectional energy flow and downward propagation of pricing signals. As suggested earlier, this simplicity is consistent with the end-to-end principle of smart system communication, fundamental, for example, to the Internet [19].

This simple model enables a non-smart (passive) node to pass on the incoming price signal downwards, to use/buy any available or offered energy it needs from above, and to propagate any surplus energy that it has upwards, to the higher level grid, if there is a demand for it. The more detailed model of Figure 4 implies that the lower level grid simply contributes additional load or additional generation.

Consider first a passive node such as this which is a leaf node, effectively more like the node of Figure 1. It would normally be in one of three possible states:

- *deficit*, when it is unable to meet its own demand from its own available generation and/or storage (i.e., when total node load exceeds total available node generation – Figure 1);
- *balance*, when it is able to provide for its own demand from local generation and/or storage, without any wasted generation (i.e., when total node generation can be adjusted to exactly meet total node load); and
- *surplus*, when it is unable to consume all of its available energy (i.e., when total node generation exceeds total node load, including battery charging – Figure 1)).

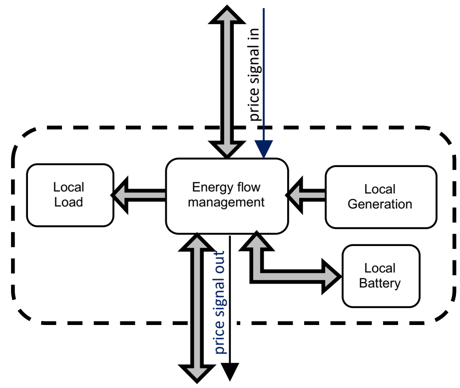

Figure 5. A simplified energy flow model for a fractal node.

For passive *non-leaf* nodes, consistent with the model of Figure 4, and for the purposes of the current discussion, the lower level grid is assumed to contribute to the node's generation and load, as mentioned earlier and suggested in the figure.

These three states just described are deterministic, and can be readily established, even for a passive node. However, as the "smart" nature of a node increases, the nature of these states may be modified by the energy flow management system, particularly in the *balance* state. For example, in this *balance* state, a smart node may decide, on the basis of history, current charging levels, future prediction, and price, to sell or buy energy from the upper grid. This is an attribute of the smart node alone, and has no impact on the topology and signals proposed in Figure 4 and Figure 5.

An individual smart node could potentially have a quite complex policy, perhaps to always sell when the price offered is at least 10% above the norm, and the battery is more than 80% charged. But it could also utilize factors such as expected

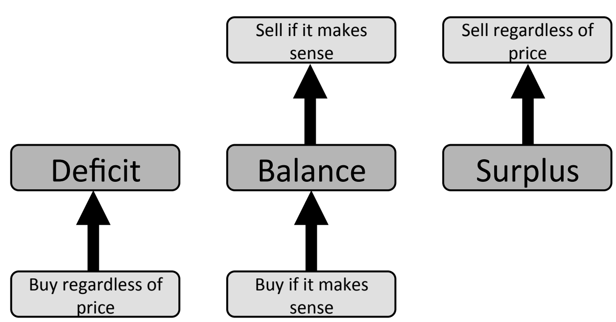

Figure 6. The three states of a fractal node such as Figure 5, with the addition of optional and imperative sell and buy.

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or predicted generation and load over the next period. The model here enables such policies to be implemented at the node level, and for smart nodes such as this to co-exist, and be networked, with more passive nodes such as that previously described. Figure 6 shows the original 3 states with the addition of the buying and selling imperatives (deficit and surplus), and options (balance). In the balance state, the decision to buy or sell is totally dependent on the policy employed by the node, and the price signal.

In general terms, we can represent the possible policy based decisions that could take place within a smart node to determine the “if it makes sense” modifier of Figure 6, with the decision tree shown in Figure 7.

Figure 7 still hides specific detail, but enables it at varying levels of complexity. For example, decision 1 “is there enough to last until next charging” could exploit history of daily load, time of day and solar characteristics, weather conditions now, and for the remainder of the day, amongst other factors.

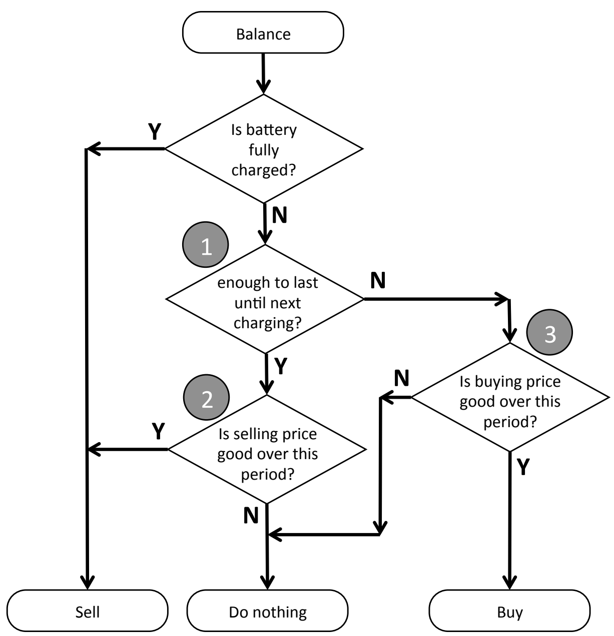

Figure 7. An energy flow management decision tree enabling flexible policy implementation, and levels of “smartness”, in any fractal node.

Decision 2, “is selling price good over this period”, suggests the node should look for the optimum time to sell during the time between now and the next charging. Decision 3, “is buying price good…” is really asking is the buying price likely to get lower before the battery runs out.

V. Conclusion

A model characterising a smart microgrid has been proposed, which allows for fractal structured interconnection. Individual nodes can be of any level of “smartness”, and totally passive nodes can be included without compromising the autonomy of others. The model is based on very simple signalling, consistent with the end-to-end approach successfully utilised, for example, in the Internet, which totally supports these notions of autonomy and participatory variety [19]. Without attempting to provide any technical implementation detail, the paper has demonstrated the potential utility of the approach.

Internally, the networked smart microgrid is no different in its configuration and operation when a part of a neighbourhood fractal network, than it is when it is a stand-alone backbone-grid connected microgrid. It is totally autonomous in its operation. Non-leaf nodes still retain this autonomy, although obviously the load and generation of the lower level nodes passes through them. Network transparency simplifies and facilitates individual interconnection, management, and operation of these microgrids.

Technically, grid-edge trading is implicit in the structure, although it is not explicitly represented. Contracting, accounting, charging for this at any level is not different from the situation on a regular grid with multiple generators and multiple consumers, but as described, it does fall short of enabling peer-to-peer contracting [17].

These features all potentially contribute to the notion that semi-self-reliant microgrids, can, without internal compromise, be connected into neighbourhood and local grids, which maximise the local consumption of local generation, and provide a basis for future backbone grid development, in terms of both generation and distribution capacity.

The model presented here is based purely on energy flows, and does not take into consideration the practical physical details of electricity networks, including voltage transitions, security, stability, etc. However, with the growth in distributed renewable energy, electronic frequency control, and the gradual decline of rotating generators, many of these issues must be regarded as volatile, as we move from the legacy grid model to the backbone plus fractal smart microgrids discussed here.

There are aspects of the model which may still subject to debate. For example:

- Should non-leaf nodes be able to modify the pricing information they propagate downwards?
- Should lower level nodes be able to signal their own selling price upwards?

If not specifically answered by the analysis, it is suggested that these considerations have been shown to be of little consequence, and unnecessary for effective operation of autonomous microgrids, although the model used here is based on effective and efficient energy utilisation, rather than being motivated by business opportunity.

Simulation studies of this model, utilising real household and neighbourhood consumption data, are currently underway.

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