A Review of Challenges to Real-Time Power Management of Microgrids

C.M. Colson, *Student Member, IEEE*, M.H. Nehrir, *Senior Member, IEEE*

***Abstract*—Microgrid systems show great promise for integrating large numbers of distributed energy resource (DER) systems into future power networks. This paper provides a brief overview of current microgrid technologies and issues associated with their implementation. The case is made for a real-time power management and control system that attempts to optimize microgrid systems based on multiple objectives, such as power demands, fuel consumption, environmental emissions, costs, dispatchable loads, etc. A multi-agent based control architecture that can ensure robust, stable, and optimal microgrid operation is also addressed. In addition to the discussion of power management and control topics, a qualitative classification tool has been proposed for assisting system planners in assessing the impact of microgrid systems on broader grid operations.**

***Index Terms*—Distributed generation, microgrid.**

I. Introduction

Global electricity generation is projected to increase 2.4% each year, from 16,424 billion kWh in 2004 to 30,364 billion kWh in 2030 [1]. Faced with expectations that global electricity demand will almost double by 2030 and concerns over new transmission line costs, omnipresent system stability issues, and the lack of power system flexibility in meeting localized demand, research efforts are rapidly progressing in areas that seek alternatives to stressed centralized power systems. A logical solution to these challenges is to deploy distributed generation systems, which are normally small in size (kW to a few MW capacity range), adaptable in structure, and installed close to customer load demand. Distributed energy resources (DERs), and specifically generation systems that utilize renewable sources of energy, provide an alternative means to derive electrical power without placing additional pressure on fossil fuel-based supplies. Alternative energy distributed generation (AEDG) technology promises to be part of the solution to meet a growing world's electricity needs and can provide power in a more customized, efficient, reliable, and clean manner.

Worldwide interest in DERs has inspired significant steady progress towards realizing these systems [2-6]. Most DER and microgrid research to date has focused on two broad areas: feasibility, system impact, and economic studies; and, conventional control and electronic implementation. Innovative computational techniques, including artificial intelligence and multi-agent networks, have been applied towards market penetration and participation, pricing, and other economic factors that will influence DER deployment and operations [7-13]. The effect of integrating distributed generation into the existing power grid has likewise been evaluated [14-16]. Primarily, post-processing algorithms, top-level hierarchical coordination protocols, and modern control methods have been explored for DER applications that fit within the conventional framework of the electrical infrastructure. Future microgrids will require new and innovative real-time control for internal coordination, as well as safe and stable external interconnection. In order for microgrid technology and systems to be widely accepted by customers and utility providers alike, significant research and development effort will be required into power management methods that are robust and autonomous. The operational challenges faced by the microgrid control architecture are uniquely different than those of conventional power systems. The authors of this paper intend to address a qualitative framework for the issues surrounding microgrid power management and likely control architecture designs. Power system protection or modifications to conventional reverse power protection necessary for microgrid implementation are not discussed. Without innovation for power management and control, critical pieces of microgrid system infrastructure, it will be very difficult, if not unlikely, for microgrids to achieve wider acceptance and implementation.

This paper is structured as follows: a description of DER technology and their integration into the power system through microgrids is discussed in Section II. Power management is reviewed in Section III, while Section IV presents the overall microgrid control architecture. Section V describes the multi-agent concept for microgrids, a power system planning tool for microgrid integration is presented in Section VI, and conclusions are given in Section VII.

II. DER Integration through Microgrids

A. DER systems

Emerging and existing DER technologies are primarily DC generation sources (e.g. photovoltaics, fuel cells), rectified high frequency AC sources (e.g. microturbines), some conventional generation sources, and storage systems (e.g. batteries). Clearly, these DC components can be coupled with inverter technology for interconnection with conventional

C.M. Colson (email: christopher.colson@myportal.montana.edu) and M.H. Nehrir (email: hnehrir@ece.montana.edu) are with the Electrical and Computer Engineering Department, Montana State University, Bozeman, MT 59717 USA.
This work was supported by NSF GRFP 2008065405.

978-1-4244-4241-6/09/$25.00 ©2009 IEEE

utility-regulated AC systems. Power electronics will be employed to interface microgrid DERs, storage, load, and the utility grid. Experience has shown that the impact of integrating a limited number of DERs onto the grid is not problematic [17]. Small DERs in limited deployment are too small in capacity to supply power back to the utility, also known as reverse powering. Additionally, with only one DER generator operating, its power management problem reduces to a trivial one. Newer research has investigated larger implementation of DERs and their benefits/drawbacks to overall system performance [18-21]. The authors intend to build on the body of work that indicates that uncontrolled connection of DER systems to the utility grid is undesirable and focus on the microgrid architecture as a means of achieving DER implementation goals. Additionally, the authors intend to show that with proper power management control, coupling multiple DERs, storage systems, and loads, within a microgrid framework that is capable of utility interconnection, can provide a safe and efficient operating alternative to current electricity delivery.

B. *Microgrids*

There are significant challenges to integrating increasing numbers of DERs onto the power system. The emerging focus on microgrids may offer a solution. While a standardized definition is difficult to establish, for the purpose of this paper a microgrid is described, similarly to [22], as: a small (several MW or less in scale) power system with three primary components: distributed generators with optional storage capacity, autonomous load centers, and system capability to operate interconnected with or islanded from the utility grid. Figs. 1 and 2 show examples of microgrid systems with several different AEDGs, split DC and AC busses, and centralized and decentralized control systems, respectively.

The microgrid is an infrastructure concept that allows more customizable power delivery in the form of DER assets nearer to the load demand. Not critical to their implementation, but worth consideration is the use of combined heat and power (CHP) systems with DER generators for added microgrid efficiency and service benefits. Interest in the microgrid concept, at the distribution level, with multiple DER sources has been increasing worldwide[4], mainly because the scalable generation sources connected to microgrids can be coordinated and controlled in a decentralized way. This operational mode allows diverse DER sources to provide their full benefits while potentially reducing the coordination and control burden on the utility grid. The primary goal of microgrid architectures is to significantly improve energy production and delivery to load customers, while facilitating a more stable electrical infrastructure with a measurable reduction in environmental emissions.

Microgrid deployment will not be without its own technological challenges. By distributing generation, continuity of power can improve for customers if microgrids are capable of operating in both interconnected with the utility or islanded. During normal operations interconnected with the utility grid, microgrids can provide excess real power and assist in voltage support. When separated from the utility

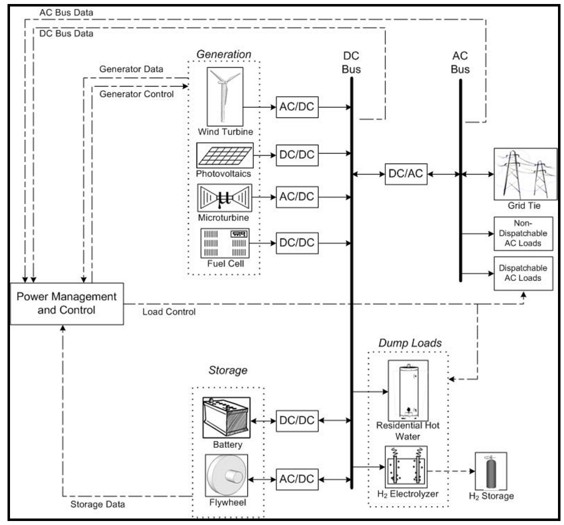

Fig. 1. Multiple-DER microgrid example (centralized control framework).

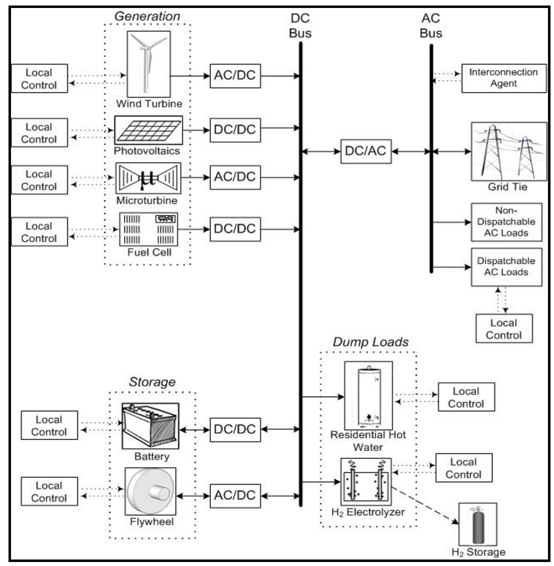

Fig. 2. Multiple-DER microgrid example (decentralized control framework).

due to abnormal grid conditions (e.g. grid fault, maintenance conditions) the microgrid must be able to regulate and sustain its own power delivery [23-26]. Interconnection standards for DERs do exist, although a key document, *IEEE Standard P1547.4* is currently under revision [22]. As highlighted in [27], a microgrid interconnected with the utility network must, at the very least, comply with grid rules and operate within power system specifications established for existing customers. Microgrid technology can add value for the customer and utility alike; meeting local demand for reliable electricity and reducing strain on utility resources. Ultimately, the economic concerns of customers and the utility will dictate the exchange of energy services between the microgrid and electrical grid.

C. *DER Systems with Combined Heat and Power*

Many DERs, such as high temperature fuel cells, show significant potential for hybrid operations [28]. Hybrid DER applications encompass combined cycle systems and

Combined Heat and Power (CHP) systems. In both categories of hybrid systems, high temperature process energy that would otherwise be rejected to the environment by the DER system are utilized for further energy extraction. Conventional CC systems are most commonly seen in gas turbine (GT) applications where the unutilized turbine exhaust heat is recovered in a heat recovery steam generator (HRSG). This steam then drives a secondary turbine-generator for additional electricity production. On the other hand, CHP systems, also known as cogeneration systems, do not typically generate additional electricity, but instead produce residential/ commercial heating or generate process steam. Similar to CC operations, CHP applications for DER systems can improve total system efficiencies. The microgrid infrastructure provides a means by which DER-CHP systems can be linked together to achieve maximum benefits for local energy needs.

III. Power Management

The primary goal of the microgrid power management architecture is to ensure stable delivery of electrical power to its local load customers, while optimizing energy production towards an assigned objective(s). The challenge for controlling real and reactive power on the microgrid is associated with the number of generation sources and loads. Proper power management control is achieved through either: a microgrid central controller, local distributed controllers, or a combination of the two. Numerous tradeoffs are present when approaching the microgrid power management control architecture, such as: necessary communication infrastructure, types and number of controllers, specificity of control algorithms, the interaction between controllers, etc. The balancing of multiple generators and load, the interaction of controllable and non-controllable components, and the dynamic characteristics of the microgrid system presents a daunting control problem. The scope of the microgrid control scheme should not be limited to simply meeting local power demands, but should encompass optimization techniques and address additional realistic constraints such as: emissions concerns, fuel availability and cost, weather conditions, the spot-market price of electricity, etc. To this end, the microgrid power management system must be capable of achieving a satisfactory, and hopefully optimum, solution to what is by definition a multi-objective combinational problem.

For typical multi-objective optimization problems, the goal is to seek an optimal solution for numerous competing objectives, simultaneously. In such problems, the satisfaction of the objective functions becomes a combination of vector "maximizations" or "minimizations". However, in most cases, a global maximum of any particular individual objective function may not be a satisfactory solution for the remaining objectives [29]. Because of this, we need to alter our concept of optimality for such problems. With similarity to economic systems, a Pareto optimum can be reached where the solution represents a state of "satisfaction" for one objective that cannot be raised further without lowering another objective's "satisfaction". Multiple formal mathematical techniques exist to derive Pareto solutions, but they can be computationally expensive [30]. The power management of a microgrid clearly fits into the broad field of multi-objective optimization problems of interest today and currently, such problems have not been proven to be solvable in strongly polynomial-time. This clearly complicates the design of an effective real-time microgrid power management control architecture that seeks proper stable and optimal solutions to its varying situation.

The formulation of the multi-objective, multi-constraint microgrid power management problem begins by identifying the attributes of the microgrid. These include the microgrid capability to operate in both grid-connected and islanded modes to:

- Meet consumer load demand within voltage and frequency limits.
- Reduce or defer distribution and transmission capacity additions.
- Reduce line losses, provide VAR support, and stimulate power market opportunities for trading ancillary services to the utility grid.
- Allow customization as load composition varies (e.g. urban, rural).
- Ensure stable and adaptable control system behavior for seamless "plug-and-play" implementation and sensible load control.
- Centralized or decentralized control necessitating what levels of communication infrastructure.

These attributes lead to the definition of the primary microgrid constraints:

- DER resource availability (i.e., solar insolation, wind energy, status of fuel, storage state-of-charge, etc.)
- Microgrid bus voltage and frequency levels; stability factors
- Real/reactive power demands from microgrid loads
- Status of interconnection

The primary objectives for the microgrid power management problem become:

- Minimize economic factors (e.g. fuel costs, operation and maintenance, etc.)
- Minimize environmental impact (e.g. emissions)
- Optimally dispatch dump/shedable loads
- Maximize delivery to utility grid (e.g. ancillary services, reserve margin, etc.)

The microgrid power management problem formulation outlines the difficulty of the control task. With competing objectives and rapidly changing parameters, the microgrid demands a real-time power management architecture that is both flexible and robust. Clearly, as a consequence of the complexity, classical control methods may not be adequate for a complete microgrid power management system design.

IV. Control

A. Existing systems and methods

The Consortium for Electric Reliability Solutions Testbed (CERTS) microgrid provides an example of an effective microgrid implementation. The CERTS microgrid is comprised of two primary components: a static switch and DERs [31]. The static switch serves as the gatekeeper for interconnection with the utility grid. The CERTS microgrid relies on a control scheme that is local to each DER, thus eliminating the possibility of catastrophic failure of a central coordinating controller. Additionally, this arrangement allows DERs to "plug and play" without requiring dynamic restructuring of the microgrid architecture, however, this capability would be feasible with a centralized controller, as well. Each local controller operates by sensing DER output voltage and current, converting these signals to real and reactive power quantities, and utilizing voltage versus reactive power (V-Q) and frequency versus real power (f-P) droop methods for appropriate control. The governing control principal for droop methodology is power balancing. While it has been shown to be very effective in the CERTS case, this scheme does not currently consider other competing objectives within its power management and control strategy.

Due to its desired flexibility in operation, the microgrid power management control scheme must encompass both grid interconnected and islanded modes of operation. Multiple concepts for the power management control necessary during proper utility interconnection are discussed in [32]. For unit power-control, the microgrid matches utility voltage at the connection point. Under this mode of control, the microgrid maintains its DERs at a common frequency at a set value slightly higher than feeder bus frequency to ensure a constant quantity of real power injected onto the feeder. This has the effect of minimizing loading fluctuations as seen by the microgrid DER generators. In feeder flow-control, the microgrid again regulates its voltage to match the connection point and adjusts its common frequency in response to load changes on the feeder. This has the effect of minimizing load fluctuations as seen by the utility. Under mixed-control, a combination of the unit power-control and feeder flow-control schemes is utilized. In addition to concepts in [32], cascaded control concepts are proposed in [26]. The goal for cascaded control is similar to unit power-control; microgrid DER generators modify their output of real power to adjust to changes in load thereby presenting a constant real power supply as seen by the utility grid. Although these are strong control schemes, they demonstrate only one part of the power management picture and do not take into account multiple objectives. It is proposed that these control concepts be integrated into a broader control architecture.

When presented with islanding conditions, the microgrid must be able to transition to a stand-alone configuration without causing a loss of power to microgrid loads. The power management system must evaluate other assigned objectives and control the overall microgrid system appropriately. It is expected that the physical interconnection, or point of common coupling (PCC), to the utility will consist of few simple components such as a static switch [33] or circuit breakers, a transformer, and sensors [34]. Upon islanding, a loss of synchronism will occur between the utility (when restored) and the microgrid. Under islanded conditions, common V-Q and f-P droop control methods, described in [32], could be used to properly meet demands of AC loads attached between the microgrid inverter and the PCC. Once conditions are satisfactory to restore interconnection, the microgrid must match voltage magnitude, frequency, and phase angle prior to physically connecting. It is noted that the phase sequence for three-phase connection is assumed to be unchanged during the grid outage.

The interconnection between the CERTS microgrid and the utility is maintained by a static switch. During abnormal events, the switch opens to sever the interconnection. When the tripping event clears, the islanded microgrid can be reconnected autonomously. This is achieved automatically by the static switch. While islanded, the microgrid loses synchronism with the utility and if the utility grid is restored to normal operation, the two will have differing operating frequencies. Given unique operating frequencies, periodically the utility grid and microgrid will rotate into phase. At that instant, the static switch shuts without electrical transients and reestablishes interconnection. As interconnection switching technology improves, it will provide microgrids a safe and effective means of autonomously achieving a "repairable" interconnection with the utility [36].

The islanded control strategies developed in [36] show that mode-specific control is achievable. However, mode-specific control strategies may have drawbacks. Power management and control while operating in one mode will be very different than another. For a synchronized system, the system frequency will either be dictated by the utility via the interconnection or by a DER generator attached to the islanded microgrid. The control of this frequency depends hugely on the mode of operation. Additionally, the real power injection by other DER generators will depend on their controlled variation with respect to system frequency. System voltage and reactive power injection requires similar control coordination. The transition from one mode-specific control scheme to another may cause instability and have undesired effects such as secondary protection events. Additionally, while traditional control methods for power and voltage control of DERs connected on the microgrid may not offer satisfactory flexibility when additional generation or load systems come on-line, or vice versa [37].

B. *Control Architecture*

A fundamental question that must be addressed prior to tackling the microgrid control architecture is how the microgrid will be physically configured. In addition, the hierarchical method of control is a key decision point to microgrid development. Given the diversity of microgrid component systems and the complexity of the multi-objective problem, the two primary areas for the formulation of a microgrid control architecture are discussed below.

Microgrid power management control is significantly different for DERs coupled on a common DC bus and utilizing a single voltage source inverter (VSI) for DC/AC conversion, than not establishing a common DC bus and each DER utilizing an independent inverter coupled on a common AC bus. In the CERTS case, the DERs are connected via the latter. Given that most DER resources are DC generation sources, it is logical to debate common coupling of sources on a DC bus for supply to a single microgrid inverter. The advantages are easier control of the DC/AC inverter, less complicated "plug-and-play" connection of on-coming or off-going DERs, and the direct connection of storage devices and dispatchable DC loads. On the other hand, doing away with a common DC bus and granting each DC source its own unidirectional inverter for connection to a common AC bus may simplify the inverter control scheme, but complicates the overall AC bus stability and synchronization. Additionally, the addition of storage, which is typically DC in nature, would require a more complicated bidirectional inverter setup.

In [34], a common DC bus and single microgrid inverter arrangement is discussed. It is suggested that the control architecture for each DER be decoupled from the inverter control scheme. This is because the lowest hierarchical level of the microgrid structure has generation and storage devices coupled on a common DC bus, and on a different hierarchical level, the inverter. In this arrangement, the proposed advantage is that only the flow of real power exists between the generation level and the AC bus, either unidirectionally or bidirectionally. This simplifies the power factor situation for the entire system and interconnection with the utility.

There are significant tradeoffs between implementing the microgrid control system with a centralized controller or distributing the control tasks to a lower hierarchical level. Clearly, a centralized controller has broader observability of microgrid operations. Although it brings greater knowledge for making control decisions, this comes at a cost in communication infrastructure and complexity of the centralized control supervisor. At a lower hierarchical level, simpler control systems with less knowledge about overall system parameters and that focus on more specific tasks are an alternative. As opposed to the centralized control case, an autonomous local controller needs only to take action to local events using local information. This may lead to more customized local control systems for uniquely different DER, storage, and load systems. For example, where fuel cells respond more slowly to fuel cell transients [38], a local controller could optimize the fuel cell response, deliberately controlling its output response to ensure a smooth transition to a new power level without the possibility of damage to the fuel cell. This customized local controller does not require additional knowledge about microgrid parameters to properly achieve this task. Although the need for communication infrastructure may be reduced, this comes at the cost of possible stability issues as controllers interact. In a decentralized control scheme, the failure of one control component should not fail the entire system wherein with a centralized scheme that depends heavily on extensive communication, this is a possibility.

V. Multi-Agent Concept

In order to achieve a robust integrated power management and control system for the microgrid, a collection of autonomous control agents that act towards a common goal is proposed. A multi-agent system (MAS) is a collection of autonomous computational entities (agents), which perform tasks based on goals. The agents are intelligent; they pursue their goals as to “optimize” given performance measures in an environment which can be hard to define analytically [39]. An agent, such as a software program, can act upon its environment as well as interact with other agents that may have conflicting goals towards an ultimate common goal. Agents can be imbued with limited or global perception of situational variables. The agents might propose to accept, reject, or counter-propose a course of action based on their communication with other agents.

The development of agent algorithms that converge rapidly to a Pareto optimal solution is a critical design step for the overall microgrid control architecture. Integral to the system-level design, however, is the design of control systems from the bottom-up as a MAS. For MAS architectures, autonomous agents work with a limited system-wide perspective. These local agents focus on their assigned tasks and pursue optimal solutions towards the achievement of their given goals. Each agent’s ability to affect the system environment is limited to the scope of their immediately controllable component. More broadly, agents are able to communicate information about their goal achievement to other independent agents comprising the MAS. Throughout operation, autonomous agents that make up the collective command structure work together to solve the intractably complex overall system optimization. In this way, the microgrid control problem is an ideal application of the MAS concept where a better self-organized and convergent system emerges from lower hierarchical agent intelligence.

The primary advantages of utilizing a MAS structure for microgrid control are: dynamic flexibility, asynchronous operation, system survivability, and lower communication overhead. Each local agent is given a level of intelligence that is consistent with its tasks. While these tasks are easily quantifiable, with rapidly changing system dynamics, the agents must be able to pursue their assigned goals such that they optimize given performance measures in an environment which is hard to define analytically. Additionally, this dynamic environment cannot rely on a synchronous structure as unanticipated events occur. By decentralizing the primary functions of control, agents are not dependent on communication traffic to carry out their tasks. For example, an agent could be designed to control the amount of real and reactive power a DER source provides to a bus. This agent’s algorithm would constantly take in sensor percepts and search for an optimal solution to the assigned problem. Despite a loss of communication with other agents within the MAS framework, an intelligent agent could continue to operate autonomously and dispatch its generator appropriate to perceived conditions. In this way, continuity of operations is maintained at a very high level and is not dependent on a central, monolithic controller. In another example, a simple agent would constantly monitor voltage and frequency on a bus. The agent’s assigned task may be to toggle non-critical loads based on bus conditions. The agent, in this case, serves two roles: it monitors the bus for its own task achievement and communicates this information to the broader MAS network. When bus conditions change unpredictably, the agent takes action to fulfill its goal without waiting for an exterior command. Consequently, the agent’s actions affect the system as a whole, without the need for explicit communication and other local agents with their own tasks/goals adjust based on conditions. In this way, asynchronous events and actions of distributed agents do not affect the operating survivability of the system.

Although MAS architectures typically use software agents, any collection of computational entities that contains independent agents with the ability to perceive and act upon their environment falls under this concept. Multi-agent systems have been shown to be effective in broad applications [40]. An example of a market-based microgrid MAS architecture implemented with the Java Agent Development framework (JADE) is shown in [7]. Characteristically, JADE agents can act upon their environment as well as interact with other agents to achieve a desired outcome. As is evident with multi-objective systems, these agents will often have conflicting goals but the system architecture facilitates progress towards an ultimate common goal. In pursuit of their localized goal, if agents must pass data between agents, the means and protocol of communication between them is important to the MAS implementation. It is expected that future multi-agent systems will capitalize on broadband infrastructure as an extremely effective means of microgrid multi-agent interaction. While the example cited in [40] describes an economics implementation of a MAS, the authors seek to expand the use of a MAS to the microgrid power management and control application.

VI. Microgrid Citizenship Tool

Adding a microgrid to a utility feeder introduces broad uncertainty for the bulk power system operator. Given that a microgrid can receive and supply electrical power, support and encumber voltage profile, and may act in an unpredictable manner (due to DER generation variability), how will a microgrid "appear" to the utility side of the PCC? From a planning perspective, the microgrid has a maximum aggregate generation capacity based on nameplate ratings of the installed DERs. The same is true for microgrid storage assets. However, the microgrid's actual ability supply real/reactive power at any given instant is impossible to predict due to the variable nature of some types of "green" DERs. Additionally, quantitative assessments of the aggregated load (dispatchable and non-controllable) attached to the microgrid can be made. The overall effect of is very different than a typical load termination on a feeder: an interconnected microgrid can act as a load at one instant (e.g. due to cloud cover, photovoltaic DER generation is low) and reverse power the utility the next (e.g. wind DER generation ramps up due to gusting). A desirable aspect of microgrids is the ability to act independently without a burdensome and vast communication infrastructure that shares information with the utility. In this way, the microgrid is an autonomous entity that accepts real and reactive power from the utility when it needs it, but will support the utility with real and reactive power when it can. In this view, the microgrid is sometimes a taker, sometimes giver, but always self-interested in meeting its local load demand. When interconnected, the utility is sometimes a giver, sometimes forced to accept, and in this way has a very different system relationship than to typical load centers.

Based on the key microgrid characteristics of nameplate generation capacity, installed storage, and load, a three-axis qualitative tool for judging the "grid citizenship" of a microgrid is presented in Fig. 3. Grid citizenship can be described as the way that an interconnected component interacts with the greater power system. Good "citizenship" is seen as contributing positively to the larger system by presenting a consistent profile. That profile may include dependable real/reactive power support, having adequate storage resources to mitigate power flow reversal across the interconnection, or appearing as a typical distribution load. Examples of poor "citizenship" can be seen as introducing large and intermittent power flow transients, frequent reversals, or causing a transient voltage profile on the feeder. Grid citizenship is defined in terms of the following ratios. The component ratio (CR):

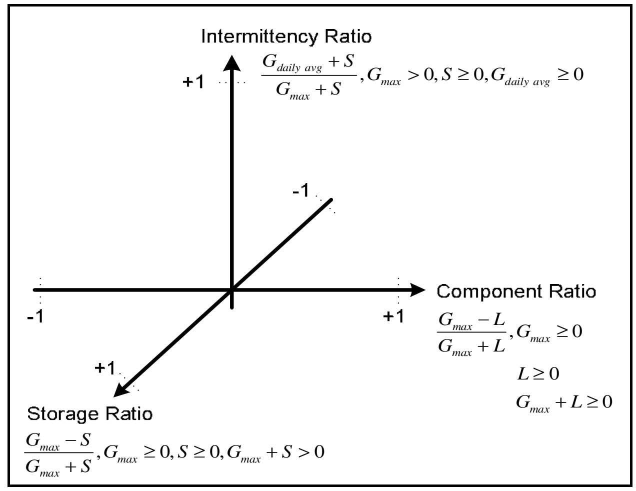

Fig. 3. Qualitative tool for judging microgrid "grid citizenship".

$$CR = \frac{G_{max}-L}{G_{max}+L}, G_{max}\geq 0, L\geq 0, G_{max}+L\geq 0 \tag{1}$$

where, G_{max} is the aggregated nameplate capacity of generation and L is the aggregated load, attached to the microgrid. The component ratio offers a qualitative scale (between -1 and +1) for the degree of generation-to-load. The storage ratio (SR):

$$SR = \frac{G_{max}-S}{G_{max}+S}, G_{max}\geq 0, S\geq 0, G_{max}+S>0 \tag{2}$$

where, S is the aggregated nameplate storage capacity attached to the microgrid. The storage ratio gives a measure of how well the installed microgrid generation is supported by its own storage. It is presumed that storage capacity will be far less than generation ($S << G_{max}$), but a zero or negative ratio indicates a significant storage resource. The intermittency ratio (IR):

$$IR = \frac{G_{daily\ avg}+S}{G_{max}+S}, G_{max}>0, S\geq 0, G_{daily\ avg}\geq 0 \tag{3}$$

where, $G_{daily\ avg}$ is a measure of the average amount of generated energy divided by the average number of hours the

DER was generating power per day. This ratio is intended to give a qualitative indication as to how “dependable” the microgrid is at supplying power. The intermittency ratio can vary between 0 and 1 (indicating constant availability of microgrid generation assets).

These ratios are meant to assist in high level power system planning. They offer a means of quickly classifying microgrids attached to the power system and qualifying them by their contributions to, or burden upon, the greater utility. Using Fig. 3, microgrid systems connected to a feeder can be displayed in such a way as to indicate qualitative measures of stability, power quality, and reliability. For example, given a rural radial medium-voltage (MV) feeder with a weak voltage profile (such as the case study example in [41]), power system planners can use the tool described above to assess the effect of adding one or more microgrid systems to the feeder. As an example, a system planner is presented with a single microgrid system with parameters specified in Table I for consideration.

TABLE I: EXAMPLE OF THE GRID CITIZENSHIP TOOL APPLIED TO A WEAK RURAL FEEDER

Parameter	Design Specification
Proposed Microgrid	
Installed Generation Mix	Photovoltaic / Wind
DC Bus Voltage (nominal)	400V
Installed Nameplate Capacity (G_{max})	5.0 MW
Daily average generation availability	22%
Installed Rated Load (*L*)	350 kW
Storage Rating (1-hr discharge rate)	225 A-hr
Storage Capacity (*S*, fully charged to discharged, 1.0 hr.)	90 kW
Calculated Ratios	
Component Ratio (CR)	0.869
Storage Ratio (SR)	0.965
Intermittency Ratio (IR)	0.234

This proposed microgrid has a high component ratio near 1.0 and a low intermittency ratio near zero. Using this information, the planner easily recognizes that this microgrid may not be a “good” grid citizen. Correspondingly, the planner could use this qualitative analysis to establish heuristics for evaluating attributes of the microgrid. One such heuristic is proposed in Fig. 4, where the planner might establish that an IR larger than +0.5 contributes to voltage support, while a IR less than +0.5 would adversely affect feeder voltage stability. Using simple heuristics and the plot of the ratios on a citizenship tool graph, the planner can quickly recognize that this proposed microgrid could cause large power reversals at the interconnection and contribute to a worse voltage profile on the weak feeder. However, a different microgrid system, or a combination of microgrids could yield aggregated ratios that would indicate to the system planner that they were better suited to supporting the weak feeder. In this way, the qualitative tool described above can assist in power system planning and analysis.

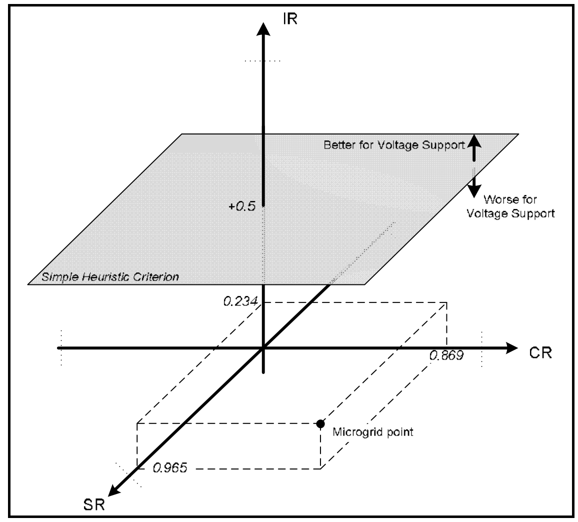

Fig.4. Plot of the ratios for the proposed microgrid and a sample heuristic criterion onto grid citizenship tool axes.

VII. CONCLUSION

Microgrid technology may be the strongest opportunity for integrated DER implementation in future power systems. This paper has presented the case for a real-time power management and control system that attempts to optimize microgrid systems based on multiple objectives, not only conventional real and reactive power dispatch. A review of the significant issues has been made, as well as demonstrating the need for continued research into multi-agent, decentralized control architectures that can ensure robust, stable, and optimal microgrid operation. Along with a discussion of power management and control topics, a qualitative classification tool has been proposed for assisting system planners in assessing the impact of a variety of diverse microgrids on grid operations.

REFERENCES

[1] United States Energy Information, “International Energy Outlook 2007 (IEO2007)”, Report #:DOE/EIA-0484, May 2007, available at: http://www.eia.doe.gov/oiaf/ieo/index.html.

[2] R. Lasseter, A. Abbas, C. Marnay, J. Stevens, J. Dagle, R. Guttromson, A. Sakis Meliopoulos, R. Yinger, & J. Eto, “Integration of distributed energy resources: The CERTS microgrid concept,” California Energy Commission, P500-03-089F, Oct. 2003.

[3] Y. Fujioka, H. Maejima, S. Nakamura, Y. Kojima, M. Okudera, and S. Uesaka, “Regional power grid with renewable energy resources: A demonstrative project in Hachinohe,” *CIGRE 2006*, Paris, August 2006.

[4] N. Hatziargyriou, H. Asano, R. Iravani, C. Marnay, “Microgrids”, *IEEE Power and Energy Magazine,* Vol. 5, Iss. 4, July - Aug. 2007.

[5] Directorate General for Research – Energy Production and Distribution Systems, “European SmartGrids technology platform: Vision and strategy for Europe’s electricity networks of the future”, April 2006, available at: http://ec.europa.eu/research/energy/pdf/smartgrids_en.pdf.

[6] O. Bailey, C. Creighton, R. Firestone, C. Marnay, and M. Stadler, “Distributed energy resources in practice: a case study analysis and validation of LBNL’s customer adoption model”, LBNL, Feb. 2003.

[7] A. Dimeas & N. Hatziargyriou, "Operation of a Multiagent System for Microgrid Control", *IEEE Transactions on Power Systems*, Vol. 20, No. 3, Aug. 2005.

[8] A.K. Basu, T.K. Panigrahi, S. Chowdhury, S.P. Chowdhury, N. Chakraborty, A. Sinha, Y.H. Song, "Key energy management issues of setting market clearing price (MCP) in micro-grid scenario", *Proceedings of the 42nd International Universities Power Engineering Conference*, 2007.

[9] H.A. Gil & G. Joos, "Models for quantifying the economic benefits of distributed generation", *IEEE Transactions on Power Systems*, Vol. 23, No. 2, May 2008.

[10] A.S. Siddiqui, & C. Marnay, "Distributed generation investment by a microgrid under uncertainty", *Energy*, Vol. 33, No. 12, Dec. 2008.

[11] H. Asano & S. Bando, "Economic evaluation of microgrids", *Proceedings of the IEEE Power and Energy Society 2008 General Meeting: Conversion and Delivery of Electrical Energy in the 21st Century*, 2008.

[12] A. Sinha, A.K. Basu, R.N. Lahiri, S. Chowdhury, S.P. Chowdhury, P.A Crossley, "Setting of market clearing price (MCP) in Microgrid power scenario", *Proceedings of IEEE Power & Energy Society 2008 General Meeting: Conversion & Delivery of Electrical Energy in the 21st Century*, 2008.

[13] C. Marnay, G. Venkataramanan, M. Stadler, A. Siddiqui, R. Firestone, B. Chandran, "Optimal Technology Selection and Operation of Commercial-Building Microgrids", *IEEE Transactions on Power Systems*, Vol. 23, Iss. 3, Aug. 2008.

[14] F.D. Kanellos & N.D. Hatziargyriou, "Control of variable speed wind turbines in islanded mode of operation", *IEEE Transactions on Energy Conversion*, Vol. 23, No. 2, June 2008.

[15] F. Blaabjerg, R. Teodorescu, M. Liserre, & A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems", *IEEE Transactions on Industrial Electronics*, Vol. 53, No. 5, Oct 2006.

[16] M.E. Baran & I.M. El-Markabi, "A multiagent-based dispatching scheme for distributed generators for voltage support on distribution feeders", *IEEE Transactions on Power Systems*, Vol. 22, No. 1, Feb. 2007.

[17] R.A. Walling, R. Saint, R.C. Dugan, J. Burke, L.A. Kojovic, "Summary of distributed resources impact on power delivery systems", *IEEE Transactions on Power Delivery*, Vol. 23, No. 3, July 2008.

[18] K. Sedghisigarchi & A. Feliachi, "Dynamic and Transient Analysis of Power Distribution Systems with Fuel Cells - Part II: Control and Stability Enhancement", *IEEE Transactions on Energy Conversion*, Vol. 19, No. 2, June 2004.

[19] E. A. DeMeo, W. Grant, M. R. Milligan, & M. J. Schuerger, "Wind Plant Integration", *IEEE Power and Energy Magazine*, Vol. 3, No. 6, Nov. 2005.

[20] C. Wang & M. H. Nehrir, "Short-time overloading capability and distributed generation applications of solid oxide fuel cells", *IEEE Transactions on Energy Conversion*, Vol. 22, No. 4, Dec. 2007.

[21] M. Thomson, & D.G. Infield, "Impact of widespread photovoltaics generation on distribution systems", *IET Renewable Power Generation*, Vol. 1, No. 1, 2007.

[22] B. Kroposki, T. Basso, & R. DeBlasio, "Microgrid standards and technologies", *Proceedings of IEEE Power & Energy Society 2008 General Meeting: Conversion & Delivery of Electrical Energy in the 21st Century*, 2008.

[23] M. K. Donnelly, J. E. Dagle, D. J. Trudnowski, and G. J. Rogers, "Impacts of the distributed utility on transmission system stability", IEEE Transactions on Power Systems, Vol. 11, No. 2, May 1996.

[24] T. Basso & R. DeBlasio, "IEEE 1547 series of standards: interconnection issues", *IEEE Transactions on Power Electronics*, Vol. 19, No. 5, Sept. 2004.

[25] G. Celli, F. Pilo, G. Pisano, V. Allegranza, R. Cicoria, and A. Iaria, "Meshed vs. Radial MV Distribution Network in Presence of Large Amount of DG", *Proceedings of the IEEE 2004 Power and Energy Society Power Systems Conference*, Vol. 2, Oct. 2004.

[26] K. Nishikawa, J. Baba, E. Shimoda, T. Kikuchi, Y. Itoh, T. Nitta, S. Numata, & E. Masada, "Design Methods and Integrated Control for Microgrid", *Proceedings of IEEE Power & Energy Society 2008 General Meeting - Conversion & Delivery of Electrical Energy in the 21st Century*, 2008.

[27] J. Zhenhua , R.A. Dougal, "Hierarchical microgrid paradigm for integration of distributed energy resources", *Proceedings of the IEEE Power and Energy Society 2008 General Meeting: Conversion and Delivery of Electrical Energy in the 21st Century*, 2008.

[28] C. Colson, M. Nehrir, M. Deibert, M. Amin, & C. Wang, "Efficiency Evaluation of Solid-Oxide Fuel Cells in Combined Cycle Operations", *ASME Journal of Fuel Cell Science and Technology*, to appear in 2009.

[29] Saul Gass, Linear Programming: Methods and Applications - 5th Edition, Dover Publications, Inc. 2003, pgs. 224-250.

[30] A. Osyczka, "Multicriteria optimization for engineering design", Design Optimization, edited by J. Gero, Academic Press Inc., 1985.

[31] P. Piagi, & R.H. Lasseter, "Autonomous control of microgrids", *Proceedings of IEEE Power & Energy Society 2006 General Meeting*, 2006.

[32] R.H. Lasseter, "Microgrids and distributed generation", *Journal of Energy Engineering*, Vol. 133, No. 3, 2007.

[33] R. H., Lasseter, "Extended CERTS microgrid", *Proceedings of the IEEE Power and Energy Society 2008 General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, 2008.

[34] J. Zhenhua , R.A. Dougal, "Hierarchical microgrid paradigm for integration of distributed energy resources", *Proceedings of the IEEE Power and Energy Society 2008 General Meeting: Conversion and Delivery of Electrical Energy in the 21st Century*, 2008.

[35] B. Kroposki, R. Lasseter, T. Ise, S. Morozumi, S. Papathanassiou, N. Hatziargyriou, "Making microgrids work", *IEEE Power and Energy Magazine*, Vol. 6, No. 3, May-June 2008.

[36] J.A. Pecas Lopes, C.L. Moreira, and A.G Madureira , "Defining control strategies for microgrids islanded operation", *IEEE Transactions on Power Systems*, Vol. 21, No. 2, May 2006.

[37] Z. Chen, Y. Hu, and F. Blaabjerg, "Control of Distributed Power Systems" *Proceedings from the CES/IEEE 5th International Power Electronics and Motion Control Conference, IPEMC '06*, Vol. 3, Aug. 2006.

[38] C. Wang & M.H. Nehrir, "Load transient mitigation for stand-alone fuel cell power generation systems", *IEEE Transactions on Energy Conversion*, Vol. 22, No. 4, Dec. 2007.

[39] Gerhard Weiss (Editor), Multiagent Systems, MIT Press, Cambridge, MA, 1999.

[40] N. Yu & C.C. Liu, "Multi-agent systems and electricity markets: State-of-the-art and the future", *Proceedings of the IEEE Power and Energy Society 2008 General Meeting: Conversion and Delivery of Electrical Energy in the 21st Century*, 2008.

[41] F. D. Kanellos & N. D. Hatziargyriou, "The Effect of Variable-Speed Wind Turbines on the Operation of Weak Distribution Networks *", IEEE Transactions on Energy Conversion*, Vol. 17, No. 4, Dec. 2002.