LBNL-59544

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February 2006

http://eetd.lbl.gov/ea/EMS/EMS_pubs.html

Published in the upcoming conference proceedings of the 2006 IEEE Power Engineering Society General Meeting.

This work described in this paper was funded by the Assistant Secretary of Energy Efficiency and Renewable Energy, Distributed Energy Program of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Disclaimer

Microgrids in the Evolving Electricity Generation and Delivery Infrastructure

Chris Marnay, *IEEE Member* and Giri Venkataramanan, *IEEE Member*

***Abstract*- The legacy paradigm for electricity service in most of the electrified world today is based on the centralized generation-transmission-distribution infrastructure that evolved under a regulated environment. More recently, a quest for effective economic investments, responsive markets, and sensitivity to the availability of resources, has led to various degrees of deregulation and unbundling of services. In this context, a new paradigm is emerging wherein electricity generation is intimately embedded with the load in microgrids. Development and decay of the familiar macrogrid is discussed. Three salient features of microgrids are examined to suggest that cohabitation of micro and macro grids is desirable, and that overall energy efficiency can be increased, while power is delivered to loads at appropriate levels of quality.**

***Index Terms*—distributed generation, power system operation, power system reliability, electric power quality, power system economics**

I. INTRODUCTION

THIS paper explores some of the issues surrounding the apparent ongoing reorganization of the power system into units employ distributed energy resources (DER) and that enjoy some measure of control independence from the traditional grid, entities that will here be referred to as *microgrids*. Symmetrically, *macrogrid* will be used to describe familiar traditional electricity supply involving large central station generation, long distance energy transmission over a network of high voltage lines, then distribution through medium voltage radial, or occasionally meshed, networks. Most industry analysts today agree that some form of less centralized supply and control is desirable and expected; however, the nature of locally controlled systems is far from determined, and indeed many forms of microgrids may emerge to meet their own local requirements, and such diversity is probably desirable. While addressing some of the wider issues, the main focus here is on three major benefits of microgrids internal to participants in it, namely 1. application of combined heat and power (CHP) technology, 2. opportunities to tailor the quality of power delivered to suit the requirements of enduses, here called heterogeneous power quality and reliability (PQR), and 3. the more favorable environment microgrids potentially establish for energy efficiency and small-scale renewable generation investments.

II. A SHORT HISTORY OF THE U.S. POWER SECTOR

A. The Industry's Roots

The historic progress of the electricity industry is here described in the context of the U.S.; however, parallels can likely be found in the histories of many countries. The industry began in the U.S. with a period of isolated systems, beginning when Thomas Edison opened Manhattan's Pearl Street station in 1882 [1]. Since early systems were naturally isolated, many microgrid enthusiasts suggest that microgrids are no more than a return to our engineering roots. While this is strictly true, the picture is clouded by two features of early power systems. First, they truly were isolated, whereas modern microgrid concepts generally incorporate an interruptible grid interconnection of some kind. Second, the era of independent systems was fairly short-lived. The birth of large interconnected systems was marked by the opening of the first remote alternating current (ac) system commissioned by Westinghouse in 1896 to serve Buffalo NY by a hydro station at Niagara Falls, about 35 km distant. In other words, the era of purely isolated systems lasted only a decade or two.

B. Unfettered Competition

Following was a chaotic period (1901-1932) of consolidation and growth led by privately owned utility companies that quickly resulted in the emergence of state regulation, beginning with the establishment of public service commissions in Georgia, New York, and Wisconsin in 1907. The availability of electricity grew spectacularly over this period, ultimately reaching two-thirds of all households. Total production increased 12 %/a on average, despite declines during the Great Depression at the end of the period, and prices fell by two-thirds. Centralized control over larger regions became increasingly practical and the electricity industry because a highly capital intensive pursuit.

C. New Deal Reform, the Golden Age, and Problems

The early frantic period was closed by various pieces of New Deal legislation intended to spread access to electricity service, develop the vast Federal dam projects, and limit the excesses of the private electricity utility sector. Increased Federal involvement and rapid expansion of electricity usage characterized the following era, and of equal importance,

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This work was supported in part by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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reliability improved significantly. The rapid demand growth of the World War II period continued into the golden post-war period, with residential sector applications and consumption growing most spectacularly. The Federal role was further expanded through encouragement of nuclear power beginning with the Atomic Energy Act of 1954.

The 1960's saw the industry reach its zenith, while at the same time, the first signs of problems were emerging. Demand grew as rapidly as ever, and yet environmental concerns, limits on efficiency improvements, and reliability concerns following the northeast blackout of 1965 signaled the coming end of the golden age. During the 1970's some problems became serious. Decades of falling costs reversed as a result of increased fossil fuel prices, all of which increased dramatically. Even domestically produced coal increased in cost by almost 16 %/a over the decade. Following the Three Mile Island Number 2 accident in 1979, the cost of nuclear generation also escalated, and no new reactors have been ordered since. This period also saw the beginnings of the philosophical questioning of large-scale systems that is now so familiar, especially large energy systems [2,3].

D. *Reversal*

Typical trends in the growth of per capita energy consumption in post industrial economies are illustrated by Fig. 1 [4]. While advanced economies become more electricity efficient, i.e. produce more income with less electrical energy, as shown by Fig. 2, prosperity and new uses for electricity consistently outstrip this improvement so per capita electricity use actually grows, substantially in some cases. The problems of centralized power supply make consideration of alternatives an imperative. In the U.S., perhaps 1979 was the actual tipping point because it was both the year that the utility share of generation peaked at 97 %, and it was also the year in which the Public Utility Regulatory Policies Act (PURPA) that revitalized independent generation was passed. Although competition in generation alone was contemplated and then only under limited circumstances at first, the process of decentralization accelerated dramatically in the mid 1990's with the establishment of independent system operators (ISO's) in various parts of the country during the years 1996-1998. This process of industry restructuring not only established competitive patterns of generation competition, but also contemplated retail competition in some cases. This process is still in motion, but at a much-reduced rate following the California market meltdown of 2000 and 2001, and restructuring has not progressed as far in the U.S. as in some other regions.

E. *Whither from here?*

This then is the starting point for this study. As asserted above, most in the industry see some merit in moving towards a more decentralized form of power system, but there is little consensus on the exact nature of that system. To be sure, the technical features of today's macrogrid reflect the legacy of centralized planning, operation and control. Even in the post-ISO controlled regions, a high degree of centralized decision-making is retained to ensure system adequacy, stability, security, and robustness, while accommodating contractual commitments between market entities. Also, rules extend well beyond the meter, for example, requiring generator shutdown during blackouts.

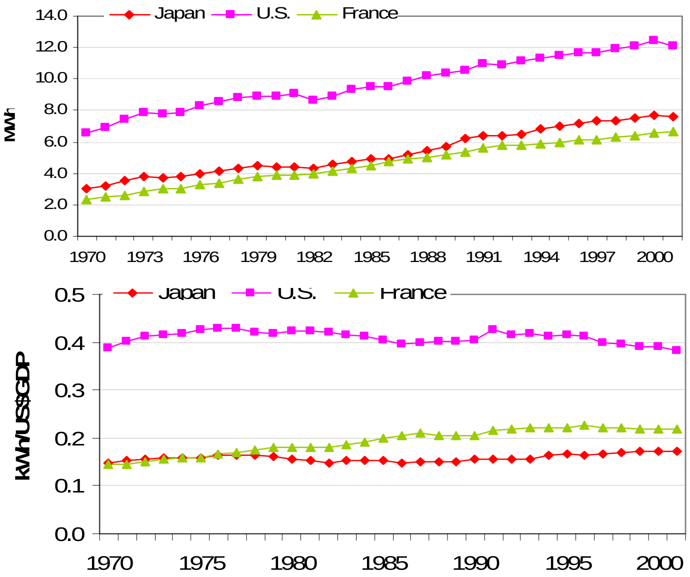

Fig. 2. Electricity Intensities of Three Developed Countries

III. DISADVANTAGES OF EXTREME CENTRALIZATION

Much has been said and written from many perspectives about the advantages of smaller scale generation and local control, but before addressing the key issues from that perspective, it is illustrative to consider the push towards microgrids, i.e. to consider what problems came along with the emergence of the familiar highly centralized grids of today.

Restrictions on power system expansion – Electricity demand continues to grow in the developed economies and the macrogrid may not be expandable to meet the requirement. In the U.S., demand is predicted to increase by about 50 % over the current quarter century. Siting all the necessary generating stations, transmission lines, substations, etc. to meet growing demand will pose a major political challenge.

Limitations of centralized power system planning – Even if growing demand can be met by the macrogrid, it is not clear that this can be achieved in a timely and organized way. In the U.S., investment in the grid has been falling behind demand growth for a quarter century, and investment in generating capacity has been erratic.

Risks of volatile bulk power markets – For some good economic reasons, establishing vigorous competitive whole-sale generating markets is a high priority, and yet they might prove to be counter to reliable supply.

Threats to an insecure system – Concerns about malicious attacks to the infrastructure haunt us, and unfortunately, the macrogrid poses a particularly attractive target.

Consequences of infrastructure interdependencies – The increasing interdependencies of our complex infrastructures may be recognized as a mistake. Modern communication systems typically fail in blackouts, and vice-versa utility operations are highly dependent on communications. And the interdependence extends to public transportation, water and sewage service, etc. Each of these services might be more dependable if it self-provided power independent of the grid.

Limits to the qualities of power delivered – Finally, the universal power quality paradigm of the macrogrid may be too costly to support, as described in more detail below.

IV. THREE ADVANTAGES OF MICROGRIDS

Much has been said and written about the many possible benefits of a distributed power system. See [6] for example. Here, the focus is on just three aspects of microgrids, combined heat and power, heterogeneous PQR, and the role of the microgrid decisionmaker.

A. CHP

CHP is likely to occur in microgrids, be it fired by renewable or non-renewable fuel. While the simple cycle efficiency of generation at modern central station power plants will normally exceed any likely competing technology available in small scales, CHP can change the overall efficiency competition considerably, potentially handing microgrids a lower overall carbon footprint. Since transporting electricity is much more convenient than transporting heat, placing generation where economically attractive heat sinks exist may be a desirable generation configuration, and one that suggests a high degree of dispersion. In fact, optimal dispersion might suggest generators be small and deeply embedded with demand, e.g. residential rooftop photovoltaics or thermal generation on multiple building floors collocated with heat loads such as domestic water heaters.

B. Heterogeneous PQR

Various indices for measuring power quality and power reliability are often used in quantifying levels of electrical service [7]. Outages may be scheduled for periodic maintenance operations on the electrical system, but unscheduled outages are generally much more disruptive and threatening to people and property. Outages effects include unavailability of certain services and processes, such as refrigeration, manufacturing, etc., plus dependence on on-site backup generation which is typically costly and environmentally damaging.

In contrast, deterioration in power quality has mixed and less dramatic effects. It is caused by deviations in the features of the electrical power delivered to the load such as voltage sags, swells, harmonics, imbalances, etc, which are triggered by periodic switching operations or by faults in the electrical systems due to weather-events, wildlife, user errors, etc. If power quality events do not lead to service loss, they become important only when they trigger degradation in the end-use service or equipment performance or durability. Thus, from an end-user perspective, power quality and reliability cause similar consequences and costs, while the scale and drama of events might be wildly different.

While the ideal is rarely achieved in practice, the prevailing macrogrid paradigm is to provide a universal level of PQR to every load in the network. Fig. 3 conceptually shows an approach to picking the optimum universal target PQR level for the economy to adopt.

The horizontal axis shows increasing service availability on a pseudo-log scale, with approximately the lowest reliability we can currently imagine as acceptable to the left and perfection to the right. The vertical axis shows societal cost of providing reliability. This cost has two components, the cost of providing reliability and the cost of the residual unreliability, i.e., of unserved requirements, with the sum representing the total societal cost. The optimum is clearly at the point of minimum total social cost, which in this case occurs to the left of the current U.S. target of about 99.99%. Developed economies have chosen to push reliability as far to the right in Fig 3. as possible, with relatively little consideration of the tradeoffs implicitly involved. Furthermore, the push to the right has resulted in system interdependency with possibly unnecessarily costly consequences when failures occur. One might also consider the effect of making systems more resilient to power outage, and local provision of electricity by DER is one potential method. It is pure speculation at this point what the net effect would be, but one possibility is that the societal optimal could be pulled leftwards.

While technical analysis of electricity service PQR can be highly sophisticated, by contrast analysis of the economics of the PQR of end uses is at best rudimentary. If the universal PQR is inadequate, backup or power conditioning provision is applied, and often backup is a code requirement, e.g., at hospitals, but otherwise the universal quality is accepted. Consider the pyramid shown in Fig 4, which illustrates how various electricity uses might be classified according to their PQR requirements. Some common loads are widely agreed to have low PQR requirements and appear at the bottom of the pyramid, and vice-versa. Other loads can be much harder to classify, e.g., refrigeration is re-schedulable in many applications, but might be critical in others, such as medication storage. At the top of the pyramid the exposed peak shows that not all requirements are currently met, i.e., a cut off exists.

Analysis of PQR in a form like the pyramid could potentially lead to the clustering of like PQR loads on certain circuits and the provision of electricity of appropriate quality to that circuit. At the same time, the effective provision of high PQR locally to sensitive loads could potentially lower the societal optimum for grid service, as mentioned above.

While space limitations preclude extensive consideration of the implications of power systems that deliver heterogeneous PQR, four observations are offered:

1. Little analysis or data collection has been done to establish the parameters of the pyramid shown in Fig. 4.
2. Matching the PQR delivered to the requirements of the end-use can potentially meet our goals at lower cost than universal PQR.
3. A wise approach would disaggregate loads such that the peak of the pyramid is as narrow as possible, and the base as wide because the former are the costly ones to serve.

4. Delivering heterogeneous PQR clearly poses some potential practical problems as well as benefits. All existing electrical equipment in the industrialized world is designed and manufactured with expectations of high and homogeneous PQR. Deviations from this norm will likely incur consequences and costs that are currently unknown. Likewise the consequences of disaggregating and segregating loads on various circuits of varying PQR are currently poorly understood.

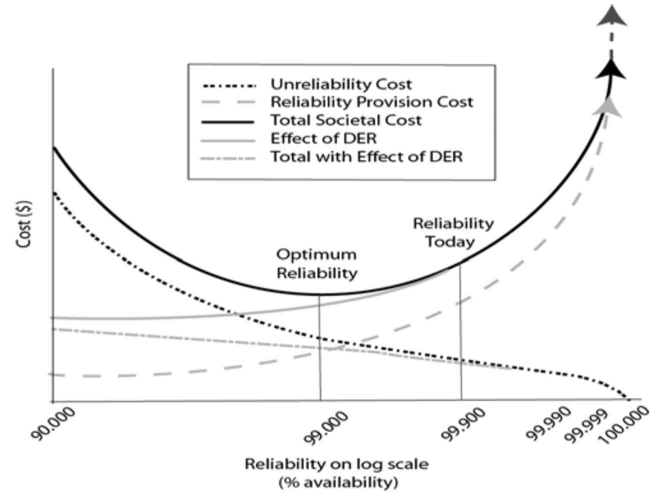

Fig. 3. Homogeneous Power Quality and Reliability

C. *Role of the Microgrid Decisionmaker*

Finally, a philosophical rather than technical point should be made. The decisionmaker in a microgrid offers a powerful opportunity to jump some of the hurdles we face in the macrogrid. As the purchaser of fuel inputs, electricity and other, the adopter of generating technologies, and also as possibly the selector of technologies on the demand side, he or she holds a unique vantage point that seems absent in the macrogrid. The alternatives on both demand and supply sides have a chance at being even handedly considered, and alternatives that have a hard time getting the attention of the macrogrid, such as diffuse renewables, perhaps have a better chance of being chosen.

V. CONCLUSIONS

Microgrids of various forms are a likely feature of the future electricity supply system, and they represent a radical departure from a long industry history of a heavy centralized and standardized macrogrid. There are reasons to believe both that the ability of the macrogrid to meet our growing needs for electrical energy of high PQR will be inadequate and environmentally and politically unacceptable, and that microgrids can deliver at least the three major benefits discussed. Nonetheless, the learning curve that must be climbed to capture these benefits currently appears steep indeed.

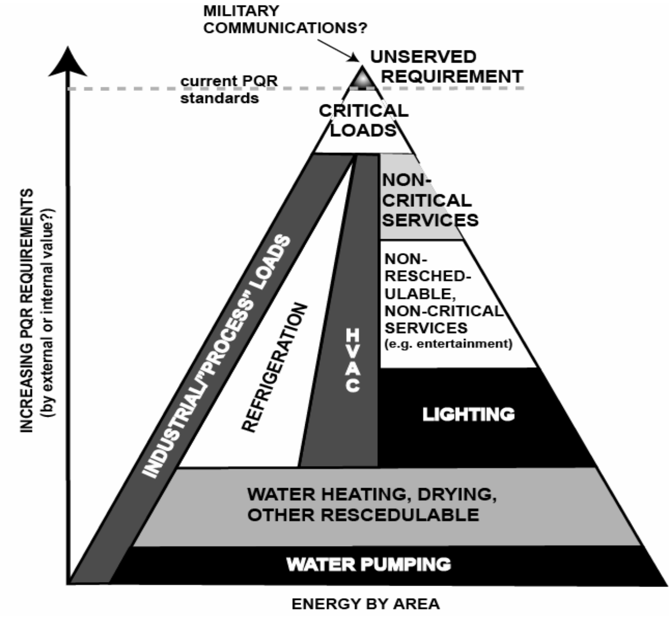

Fig. 4. Heterogeneous Power Quality and Reliability

VI. ACKNOWLEDGMENTS

This work described in this paper was funded by the Assistant Secretary of Energy Efficiency and Renewable Energy, Office of Distributed Energy of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Prior contributions to microgrid research by many colleagues at Berkeley Lab and within the Consortium for Electric Reliability Technology Solutions have provided much of the inspiration, and Kristina Hamachi LaCommare and Nan Zhou have provided research assistance with the preparation of the paper.

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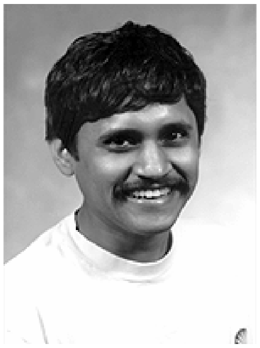
VIII. BIOGRAPHIES

Chris Marnay is a Staff Scientist in the Electricity Market Studies group within the Energy Environmental Technologies Division of Berkeley Lab. He leads work on modeling of restructured electricity markets, especially on problems concerning likely future adoption patterns of small scale DER, including fuel cells, microturbines, reciprocating engines, combined heat and power technologies, especially absorption cooling, and renewables, and the organization of small-scale generators into microgrids. He has an A.B. in Development Studies, an M.S. in Agricultural and Resource Economics, and a Ph.D. in Energy and Resources, all from the University of California, Berkeley. He has also studied at the London School of Economics and the University of Hawaii, and has worked at the University of Texas at Austin, and in various consulting capacities.



Giri Venkataramanan received the B.E. degree in electrical engineering from the Government College of Technology, Coimbatore, India, the M.S. degree from the California Institute of Technology, Pasadena, and the Ph.D. degree from the University of Wisconsin, Madison in the years 1986, 1987 and 1992 respectively. After teaching electrical engineering at Montana State University, Bozeman, he returned to the University of Wisconsin, Madison, as a faculty member in 1999, where he directs research in various areas of electronic power conversion as Associate Director of the Wisconsin Electric Machines and Power Electronics Consortium. He holds four U.S. patents and has published a number of technical papers. His interests are in modeling, design and control of power conversion systems, power quality improvement, and distributed generation systems.