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Feasibility Evaluation of Distributed Energy Generation and Storage for Cost and Reliability Using the 'Worth-Factor' Criterion

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ABSTRACT

The unprecedented growth in the electronic and semiconductor industries, process controlled industries like automobile, textile and paper, in addition to the growing domestic load over the past three decades has imposed severe operational, economic and maintenance constraints on the power utility companies. Service reliability and power quality are the key contributing factors imposing these constraints. Distributed technologies are a potential solution for the current problem but may not be the optimum solution when specific characteristics like the nature of load, desired level of performance, geographical location and the available energy resources at the time instance of operation are considered. This paper describes the feasibility of distributed resources in terms of the 'worth-factor,' a criterion that incorporates intangible benefits and translates them in terms of cost.

INTRODUCTION

DG (DG) has many benefits over central station power plants. Some of the principal benefits that are of interest to this paper are: [1,2]

1. *Size and scale of operation*

Central station power plants require large areas owing to their size and scale of operation thus making site selection and land procurement a challenging and expensive process. DG plants are easier to build and commission.

2. *Overall efficiency per unit size*

DG technologies incorporate advanced design technologies yielding improved process-cycle and overall efficiency. In addition, cutting-edge technologies in the areas of unit miniaturization, electrical insulation, heat conversion and computer/digital automation and control technologies have helped enhance the overall efficiency of the DG plants.

3. *T&D , substation & feeder costs*

DG is located at the load-demand center or close to the epicenter of the load, hence offering huge capital investment benefits for transmission lines, towers and auxiliaries, transmission substations, distribution substations, service and distribution transformers and feeders.

4. *Operating and maintenance costs*

The cost of operation and maintenance of the above mentioned equipment is avoided due to the proportional amount of reduction in electrical usage of this equipment. The frequency of faults owing to over-loading, temperature rise and heterogeneity of load are reduced provided external factors like ambient-temperature variations, weather changes and man-made errors occurring at the same instance of load-demand cause minimal detrimental impact.

5. *Electric and magnetic losses*

Transformers at different voltage levels from generation through distribution have inherent copper and core losses, in addition to the load-related losses. Similarly transmission lines, circuit-breakers, switches, isolators, control equipment, distribution feeders and associated auxiliary equipment add to the electrical losses. These losses and their related effects like magnetic interference, corona discharge and insulator flashover are minimized in terms of the occurrences and recovery time.

6. *Reliability and power quality*

DG with energy storage offers a high degree of reliability and power quality against grid-supplied power owing to better design and controllability with minimal losses. The power utility may be able to operate with a lower installed capacity and spinning reserves even under peak-load conditions and even during load-demand with low diversity factor.

7. *Expansion, modularity and environmental concerns*

DG avoids expansion costs of transmission and distribution networks owing to proximity to the load and ease of installation. DG units can be built and operated in clusters or modules providing the benefit of standard configuration and ease of maintenance with better reliability. DG technologies are not without environmental concerns but low emissions are achievable with minimal control and monitoring equipment.

ECONOMIC ANALYSIS

Literature surveys have shown that the opinion about the economic benefits of distributed resources has varied considerably among industry, utility and potential DG consumers/owners.

Central Power generating stations

The size range of most central power generation plants varies from 100-800 MW. With an overall plant efficiency of 35-40%, a thermal efficiency of 32-35%, and average nominal heat-rate of 3500 kcal/kWh, the generation cost is estimated at $450-$600 per kW. With annual operation and maintenance (O&M) costs of 20%, and a capacity factor of 5% the fixed costs for operation would be $205- $275 per MWh [3].

The transmission costs depend on cost per mile, topological conditions and the line termination cost associated with the substation at the other end. Costs range from $60,000/mile for a 46kV wooden pole sub-transmission line of 50 MVA capacity ($1.2 per kVA-mile) to over $1,000,000 per mile for a 500 kV double-circuit construction with 2000 MVA capacity ($.5/ kVA-mile) [4].

The substation costs depend on the type, capacity and local land costs. In rural areas, one a 69 kV substation with a 50 MVA transformer and a single incoming feeder could cost $90,000. If the substation serves a load of 4 MW, total substation cost would be $23/kW. The costs could go up to $33/kW in a suburban setting with two 40 MVA, 138/12.47 kV transformers fed by two incoming 138 kV feeders and four outgoing distribution feeders of 9 MVA capacity each.

The primary voltage feeder system and distribution costs vary from $10 to $15 per kW-mile for overhead to $30 to $100 per kW-mile for underground.

The service level costs depend on the pole-mounted service transformer cost and the number of households being fed by one service transformer. This cost is approximately $350 per customer household or $70 /kW of coincident load [5].

Distributed Technologies

The size range of distributed generators commercially available varies over a wide range depending on the type of the technology.

Microturbines: Non-recuperative and recuperative microturbines capacities range from 25-200 kW. With an average overall efficiency of 60-70% the total cost including that of the prime mover, generator, inverter and ancillary equipment is $700-$1000 per kW for non-recuperative and $900-$1300 per kW for recuperative versions. The installation costs vary from $200-$600 per kW. The cost per unit energy generated without cogeneration is estimated at 10-22 cents per kWh.

Fuel cells: Proton exchange membrane (PEM) fuel cells vary in size from 5-14 kW, while phosphoric acid fuel cells can vary in range from 150-200 kW. At an operating overall efficiency of 36-40%, the overall cost varies from $4000-$5000 per kW for PEM and $3000-$4000 per kW for phosphoric acid fuel cells. The installation costs for fuel cells are about $400 per kW. The cost per unit energy generated without cogeneration is estimated at 18.5-30 cents per kWh.

Photovoltaic: The size range commercially available is from 5 kW to 5 MW. The total overall cost is estimated at $4500-$11000 per kW, though the exact value depends on the configuration and the geographic location. Installation costs vary from $200-$350 per kW. The cost per unit energy generated varies from 17-38.6 cents per kWh [6, 7].

Wind turbine generators: Wind generator costs are highly variable based on the design, speed-reduction and auxiliary equipment needed, owing to varying wind velocities from place to place and time to time. The size ranges are from 5 kW-1 MW. The overall system costs are estimated as $1200-$3900 per kW, while the installation costs vary from $400-$5000 per kW. The cost per unit energy generated varies from 6-30 cents per kWh.

The total overall cost of every DG technology discussed above includes cost of the prime mover, cost of the generator and inverter and costs of ancillary equipment. However, these costs can vary based on size, duty-cycle and fuel.

Installation costs mentioned above can vary with utility interconnection requirements, labor rates, ease of installation and site-specific factors.

The cost per unit energy generated is calculated based on an average annual load-factor of 50%. This includes the average cost of fuel, O&M expenses and amortized capital charges.

DEFINITION OF THE PROBLEM

Economic analysis of distributed resources in most cases is based on total fixed system cost, installation cost, O&M expenses and cost of auxiliary equipment needed for reliability, power quality and emission control. This is not always true because the cost of a distributed source can increase or decrease based on the value of the energy generated for a specific application at a specific instance of time. The value benefit or loss offered by a standalone or grid-connected distributed generator with or without energy storage, for the application/process in question, cannot be modeled as a constant factor because the value factor is itself variable based on market prices, locally varying fuel prices, time instance of load-demand and available reliability of grid-supplied power.

CONCEPT OF WORTH-FACTOR

The worth-factor criterion is a simple and logical method to determine the cost-to-performance ratio. In order to apply the worth-factor criterion extensive research is needed on identifying the static and dynamic costs that are not tangible and have not been included in the economic analysis. This method enables interpretation of performance in terms of cost and explores the economic worthiness of a DG technology by qualitatively incorporating the intangible costs. Intangible costs are value-based expenditures based on the offered/desired performance level and the available resources at that particular point of time in the region or state under consideration.

FEASIBILITY ANALYSIS USING THE WORTH-FACTOR

The overall cost of a distributed generator unit with energy storage can change if one or more conditions exist at the time instance or during the operation of the unit. The following are some of the identified conditions that could possibly add or lower the overall cost of energy generated, based on the value of these conditions for cost-effective and qualitative operation of the application consuming the generated electric power.

Time Instance of Load Demand on the Hourly Load Duration Curve

Utility Perspective: DG is beneficial in peak-shaving applications as utilities need not install additional capacity to supply peak-loads or utilize spinning-reserves during peak-load conditions. Figure 1 shows a typical load duration curve for a residential area. The load-demand curve for an individual household shows brief, high, needle peak-loads. Refer to Figure 2 for the load distribution of one household.

For coincident loads the total peak load is less than the sum of the individual peak loads. With DG the peak loads can be further reduced, resulting in cost savings to the utility. The worth-factor of DG for the utility is hence an incremental reduction in the overall cost of generated power, enabling the energy rate to stay competitive, in addition to the increase in the available hours of operation of the generating reserves and a higher degree of reliability because of a slight increase in the redundancy factor.

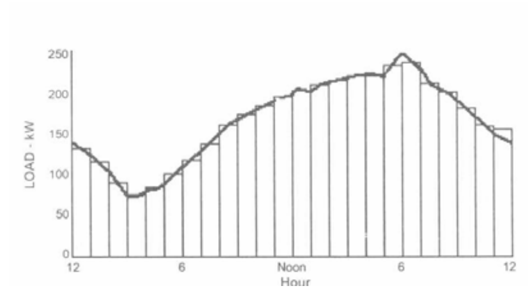

Figure 1. Hourly load duration curve for a residential area.

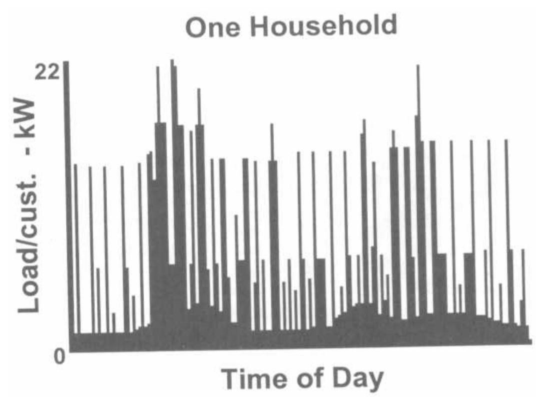

Figure 2.Load-duration curve for one household.

Consumer/Owner Perspective: There are two important categories of consumers and owners of DG, which will be called “A” and “B.”

Category A: Consumers needing high reliability and better quality of power supply, like manufacturing industries, process industries and the services industries, may be candidates for DG because the grid-supplied power under peak-load conditions is susceptible to momentary, instantaneous and/or temporary interruptions, and because of the potential risk of under-voltages, under-frequency events, and reactive power flows. In addition, the consumer may have to pay more for energy during peak-load hours, depending on the utility and the local rate structure. Hence the worth factor for this category of consumers is a combination of various factors and is appreciably higher.

Category B: Residential and some commercial customers can use grid-supplied power even under peak-load conditions because their operating processes can tolerate the risk of slightly lower reliability and reasonable contaminations in power supply. Worth-factor of DG for this category is zero.

Limiting conditions:

a. The consumer categories A and B do not need DG resources (even under peak-load) if there is surplus grid power resources and industrial loads are welldiversified, such as in states like Kansas, Missouri or Alabama.

b. The consumer category A needs DG and energy storage in spite of a excess grid resources because of a more erratic load demand pattern, such as in states like New York, Ohio, Illinois, Massachusetts or New Jersey.

c. The Consumer categories A and B both need DG and application-specific energy storage when the grid is impoverished and supplies a dense industrial load, such as in California, Washington and some parts of Arizona.

Markets and Deregulated Market conditions

The selection of a DG source is dependent on the wholesale and retail market structure in the region under consideration. A deregulated market adds to the complexity of decision-making about selection of DG with energy storage. Sustained demand and optimum supply volumes dictate the market prices at a given time. Under conditions when the wholesale and thus retail electricity prices are higher, DG offers a cost-effective alternative to consumers and owners. On the other hand, utilities suffer losses because if DG were not to be in place, economic gain margins would be higher.

This conclusion may not be justified in a deregulated market, because of the competitive pricing and the flexibility offered to the consumer in finding a utility allowing him to pay lesser per KWh than the overall cost per kWh from his own DG. Under such conditions, the economic value of DG can be assessed only from the market conditions, and the value is a dynamic variable, totally dependent on the market trends and indicators.

Desired Reliability

The degree of reliability desired by a consumer, as discussed earlier, is a dependent variable expressed as a function of the power supply requirement of the application/process [8]. Outages and interruptions are the main criteria for reliability evaluation. The frequency (how often occurring) and the duration (how long it lasts) both together or individually decide the extent of the outages' or the interruptions' impact on the application/process.

DG system design is particularly adaptive to reducing the frequency and duration of interruptions. Energy storage systems need to be selected and designed considering various factors like response time, fault-sensing and protection, rapid recovery and restoration and high reliability indices of the storage devices themselves.

Utility Perspective: Higher reliability requires more generating capacity, more redundancy in transmission and distribution equipment, and hence higher costs. The ability to incorporate higher reliability of power generated, transmitted and distributed depends mainly on one or more of the following prevalent conditions:

Type and size of connected-load: The nature of the load, load-demand and the duration of the connected-load decide the feasibility and extent of redundancy that the utilities build into their systems. If the connected load is mostly domestic, with most of the consumption for heating and illumination, reliability may not be as high because of the rate of return is lower. On the other hand, industrial loads with critical manufacturing and business needs, and who are willing to pay more, could be offered higher reliability. In addition, demand for reliable power supply over longer durations of time proves cost-effective and easily manageable for the utilities. Figure 3 shows the cost variation with demand duration. The quantity (magnitude of power) and the quality (reactive power flows, harmonic content) add operational and economic constraints on the supply-side.

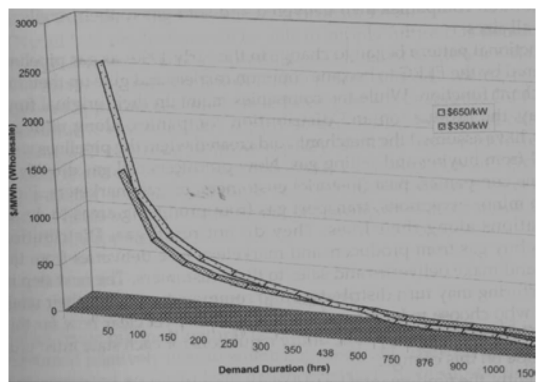

Figure 3. Cost of wholesale price drops as demand duration increases.

Location and coincidence profile of the connected load: The location of the connected loads is critical because the quality of service (reliability of service) demand from the consumer and that offered by the supplier varies on the type of the connected load. For example, if a medium-scale industrial consumer is located in a residential area, and needs a high reliability index, the supply-side costs increase considerably owing to the different values of reliability. To satisfy the needs of the industrial customer, the utility must make improvements to the feeder and the level of service to both categories, but the payments towards the higher reliability are received from only one consumer. Similar implications may exist for two industrial loads served by the same feeder, with only one industry needing high reliability, or only one willing to pay for it.

The issue of supply-side reliability gets more complex if the loads needing higher reliability occur at discrete time intervals and are widely separated by the occurrence interval on the load curve (low diversity factor). For bulk power demands, separated widely on the time axis, providing reliability for the utility is an enormous economic expense. On the other hand, coincident bulk power needs alleviate the problem of reliability to some extent but add to capital investments, in addition to higher O&M costs. Figure 4 shows coincident load for 2 households and 20 households. This additional cost is high as it needs to be distributed over a small spectrum of the consumer load.

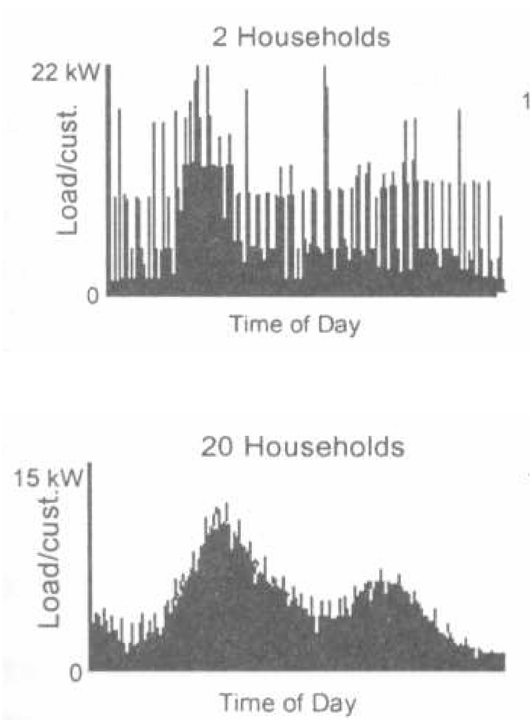

Figure 4. Typical demand for residential loads.

Hence the worth-factor of DG in such scenarios (utility perspective) is appreciably lower and utilities may be interested in encouraging DG installations, by way of subsidies in energy costs, installation, monitoring, and maintenance of interconnection equipment and remote energy-metering.

Consumer perspective: The importance of DG for consumers needing high reliability (Category A) depends on the revenue loss based on the inconvenience and disruption schedule, lost production and/or lost wages for personnel and rent/idle time of machinery, in the event of interruptions or outages. Startup time and recovery processes are overheads on top of the existing losses at that instance of time. Installation/ownership of DG by the consumer for higher reliability may be influenced by the following conditions.

Regulated Market: Regulated markets may not encourage energy prices that depend on the availability of abundant grid power. Under such conditions, category 'A' type consumers are encouraged to own DG and energy storage systems.

Stand-alone or Grid-connected: Based on the desired level of reliability for the process involved, availability, and cost of grid-power, the consumer may prefer grid-connected or stand-alone DG. For stand-alone systems the reliability expectations are higher and hence the design and performance of equipment including that of auxiliaries like voltage-regulators, inverters and fault-sensing devices need to be robust and optimal. The operational reliability of the DG equipment and auxiliaries is key to the overall reliability index. This increases the cost of design, operation and maintenance, owing to the need for skilled maintenance personnel and constrained operation schedules.

For grid-connected DG systems a robust design may not be required but selection of DG and energy storage equipment is critical for dual-mode operation. Other desirable characteristics include low response time, higher percent overloading capacity, discrimination against low-magnitude faults and a high degree of repeatability. Additionally, the design of the change-over control scheme needs better performance characteristics like rapid response time, sensitivity, stable-loop operation and intelligent control components.

Hence the worth of DG for consumers depends on the mode of operation and the prevalent market conditions.

Fuel Price, Quality and Availability

Installation and ownership of DG technologies like microturbines and fuel cells depend on the economics of operation and the efficiency of performance. Hence the quality and price of fuel are critical for feasibility analysis.

Fuel prices vary owing to various parameters – political factors, weather conditions, fuel supply and handling and outages in the distribution system. Under such circumstances the potential DG owners need to explore all options available on site and at the particular point of time. Other alternatives could be reliable power from the utility, microgrids, combined cycle DG plants and combined heating and cooling cycle plants to offset some fraction of the incurred costs. But each of these has its own merits and demerits that need careful analysis and examination in terms of economics and flexibility of operation.

The quality of fuel determines the heat content of fuel, and that in turn governs many functional parameters like input fuel pressure, heat-rate, thermal efficiency, electrical output, speed governor characteristics, rate of emissions, noise, aging of associated equipment and overhaul/maintenance requirements. With all the above parameters dependent on fuel quality the overall efficiency of a DG unit may not be the rated value and may vary from time to time, affecting economic calculations to an appreciable extent.

Thus to maintain a certain level of efficiency and thus a certain minimum cost of O&M, contractual agreements need to be made, so that the gas distribution and handling companies are made accountable to the quality of fuel they handle and supply. Tri-partite agreements between the DG owner, consumer and the fuel supply company, under the supervision and with the agreement of the appropriate governmental agencies, may be very useful.

Availability of fuel for 100% of the operation time is the primary requirement for any DG utilizing fossil fuels. Unlike domestic gas supplies for heating and cooking purposes, which can tolerate unavailability to some extent, DG requires uninterrupted fuel supply with the required flow rate and input pressure.

If microturbine and fuel cell generators using natural gas are installed at many locations or points within the gas distribution network, fuel supply requirements and input fuel pressure values may not be optimal, owing to the existing load on the gas distribution network. To alleviate this, existing capacities of the gas distribution lines may need upgrading, expanding the gas distribution network in all dimensions. The capacity upgrade of the existing fuel distribution network is very expensive and moreover dependent on local site factors.

The worth factor for the DG owner in this regard (fuel parameters) can be evaluated after extensive surveys and research on the long-term oil-pool prices nationally and internationally, on the existing gas supply network in the location of interest, the upgrade costs for the existing network, and the costs of procurement and maintenance associated with the auxiliary fuel handling, fuel regulating and fuel distribution equipment.

CONCLUSIONS

The research presented in this paper shows that the economic evaluation of DG and distributed energy storage involves many subtle, seemingly insignificant but interdependent parameters that cannot be modeled using existing economic and reliability models. In order to evaluate the feasibility of implementation and ownership of these upcoming technologies as realistically as possible, extensive research and value-estimation tools need to be used. The worth-factor criterion presented in this paper provides an insight into some of the value-based aspects that influence implementation and ownership of DG and distributed energy storage from both the utility and consumer perspectives. Value-based planning and modeling of DG and distributed energy storage is easier and more practical using the worth-factor criterion. Feasibility evaluation of the economics and reliability of DG and distributed energy storage, and value-based planning, are possible using the worth-factor criterion if the relevant data is available.

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