Marginal Cost of Reactive Power Capability in a 1 MW Distributed Energy Resource

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***Abstract*—Distributed Energy Resources (DER) are generally connected to the utility distribution network. Many DER technologies employ inverters that can provide dynamic control of real and reactive power. Dynamic reactive power in distribution systems can yield improvements in efficiency, reliability, and reduction in demand charges for "behind the meter" installations. In order to determine the appropriate reactive power ratings for DER systems, developers and entrepreneurs must be able to calculate both the value of reactive power to customers and the marginal cost of adding or subtracting an increment of reactive power rating to a product. This study examines the marginal cost of various reactive power ratings for a 1 MW DER product presently under development by Rolls-Royce Fuel Cell Systems.**

I. INTRODUCTION

Fuel cells are but one of a large number of Distributed Energy Resource (DER) technologies under intensive development and early deployment on utility distribution networks. Many DER technologies (e.g. fuel cells, microturbines, photovoltaics, wind,) employ solid-state inverters as the interface between the DER prime mover and the distribution network. Inverters with modern digital signal processor-based control systems offer an economical, highly flexible means to control both real and reactive power flows under normal, transient, and fault conditions.

Dynamic control of reactive power in distribution networks is valuable to both the network owner/operator and the customer. Commercial and industrial customers are typically assessed a demand charge that is based on the maximum current supplied over any 15-minute period during the billing cycle. Some utilities impose "ratchet" terms that assess fees based on maximum current supplied during the prior 3, 6, or 12 months. Dynamic reactive power control allows the customer to keep the power factor at the meter close to unity, which minimizes the demand charges. Demand charges and the savings associated with avoiding them can be substantial. MTechnology, Inc. (MTech) operated a "microgrid" demonstration project that included 2 fuel cells rated 200 kW / 235 kVA. Reactive power was dispatched via a serial interface port at any power factor between 0.85 leading and 0.85 lagging. MTech monitored the real and reactive power flows at the utility meter connection, and dispatched reactive power from the fuel cells to maintain a near-unity power factor. This resulted in savings averaging $1,200 per month, approximately 5% of the facility's electric power charges.

Distribution network operators have additional reasons to value dynamic control of reactive power. Keeping power factor close to unity keeps current flows near minimum, and since resistive losses scale as current squared, minimum current flow reduces losses and improves system efficiency. Dynamic reactive power also offers the ability to better control and maintain service voltage levels and power flows. Local supply of reactive power is a key element in fast voltage collapse. Appropriately controlled reactive power can improve network reliability and reduces aging of equipment due to excessive current flow. The market value of these services is not as easy to calculate as reduced demand charges, but network operators are certainly aware of the issues. There are multiple efforts to further define and quantify[1] [2] [3] [4] [5] the benefits for both DER in general and DER supply of dynamic reactive power in particular.

II. DESCRIPTION OF THE 1 MW DER

Rolls-Royce Fuel Cell Systems Ltd. is presently developing a 1 MW stationary fuel cell power plant based on solid oxide fuel cell (SOFC) technology. The system is a hybrid, using a combination of SOFC and microturbine technology. The power plant is configured as 4 generator modules each rated at 250 kW. Sub-systems such as fuel processing, controls and auxiliaries support all generator modules.

Each generator module will include an inverter rated to supply 240 kW to a standard 480 VAC North American low-voltage distribution system. The inverter control system will include functionality to regulate both real and reactive power.

The development effort is focused on producing a product that can compete with well-established internal combustion engine

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(ICE) technology on the basis of price, while providing benefits of higher efficiency and greatly reduced emissions. This is an aggressive target as existing fuel cell power plants are priced at a premium of 2 to 5 times the price of ICE products with similar power ratings.

DER applications of ICEs generally utilize synchronous machines and governors to maintain the prime mover at an appropriate speed. These machines can also produce both real and reactive power by controlling the excitation of the synchronous machine. The response of the excitation circuit is generally much slower than solid-state inverters, and the dynamics of synchronous machine interaction with the utility network can be quite complex. Synchronous machines in DER applications are generally rated to produce maximum reactive power corresponding to a 0.8 power factor at rated real power.

III. CANDIDATE REACTIVE POWER RATINGS

The Rolls-Royce Fuel Cell Systems design philosophy is to leverage the advanced state of development, mass production, and low cost of industrial variable speed motor drives (VSDs) to meet the cost and price targets required for a competitive fuel cell power plant. VSDs are designed to operate AC motors, but with modest changes to the control system will function as utility interface inverters. The concept of modifying VSDs for use in distributed generation applications has been partially demonstrated in projects funded by the National Renewable Energy Laboratory [6] and elsewhere.

One advantage of utilizing commercially available components is the ease of predicting price as a function of performance. The development program must determine appropriate ratings for both real and reactive power, efficiency, size, weight, and many other parameters. Determination of the appropriate reactive power rating of the final product requires knowledge of two parameters: the value customers will place on the capability, and the marginal cost of adding (or subtracting) reactive power capability. Quantitative market valuation of reactive power is a complex subject beyond the scope of this study. The use of standard (as opposed to custom-developed) components to implement the inverters allows a straightforward evaluation of marginal costs.

Several assumptions and simplifications are necessary to perform the marginal cost study.

1) We assume that the changes required in the DER product to accommodate different reactive power ratings are confined to the inverter current rating and associated AC circuit breaker ratings. Specifically, we neglect the effects of increased reactive power ratings on the DC bus that is ultimately connected to the fuel cell, microturbine, PV array, wind turbine, or other DER prime mover. Some of these technologies are sensitive to disturbances on the DC bus. Changing the reactive power rating may require changes in the energy storage and/or filter network used to isolate the DER prime mover from fluctuations arising from load imbalances, load steps, load rejections, or other disturbances.

2) We ignore the contribution of the microturbine to the reactive power output of the DER. Typical hybrid fuel cell / microturbine DER products derive 10-20% of the total real power from the microturbine. There are no commercially successful products at present, and the optimal ratio has not been demonstrated in the marketplace. Many DER technologies do not utilize hybrid systems. This simplification keeps the results of the study applicable to a wide range of DER technologies.

3) We do not account for any additional equipment or changes in fees that may be required to interconnect the DER product to the utility distribution network. The requirements and practices vary widely and are developing rapidly.

4) We ignore the effects of providing reactive power to the distribution system. System impedance varies substantially, and while injecting reactive power generally increases the local voltage, we do not account for these effects in this study.

5) We do not consider the ability to supply reactive power at less than full load. Variable speed drives and other inverters are frequently operated at less than maximum real power. Under these conditions it can be possible to produce substantial quantities of reactive power.[7] We confine our study to the ability of the DER system to supply a given reactive power while operating at or near rated real power.

Each of the four inverters in the fuel cell power plant must supply 240 kW of real power. (The microturbines are assumed to contribute 10 kW each. Actual power output from turbines is a strong function of atmospheric pressure, temperature, and humidity.) Competing ICE-based DER products typically offer reactive power capability equivalent to operation at a power factor (PF) of 0.8 leading or lagging. Matching this capability is an appropriate basis for comparison. The reactive power required to deliver 240 kW at 0.8 PF is 180 kVAR, with apparent power 300 kVA.

Current rating for the inverter is determined by operation at “low line” conditions. Interconnection standards allow voltages at the point of common coupling to vary +/- 10% from the nominal 480 VAC. Providing 300 kVA into a low line voltage of 432 VAC requires 401 Amps (hereafter rounded to 400 Amps.) Reducing the reactive power rating of the converter to zero reduces the inverter current rating at low line conditions to 321 Amps.

Utilizing standard industrial motor drives means that we are not free to select any current rating. Drive manufacturers have developed standard products. Several manufacturers offer drives with ratings of 300, 400, and 600 Amps. The 400 Amp drives satisfy the 0.8 PF case. The 300 Amp drive is slightly undersized for the zero reactive power case.

Drive current ratings are ultimately determined by the ability to cool the equipment, particularly the semiconductors. We can utilize the 300 Amp drive to serve a 240 kW requirement by reducing the maximum ambient temperature rating (typically 40°C) during low-line conditions, or by limiting the drive output power from 240 to 225 kW under low-line conditions. This effectively cuts a corner from the operating envelope of the unity PF case. Our use of a slightly underrated drive results in a slightly higher estimate of the savings associated with eliminating reactive power capabilities from the inverters.

A 600 Amp drive can deliver 445 kVA, 240 kW and 375 kVAR, into a 432 volt low line, with a resultant power factor of 0.54.

The changes in inverter current rating require changes in the protective AC circuit breakers used to connect the inverter output to the distribution network. Each inverter is protected by its own circuit breaker, and the power plant is protected by a main circuit breaker. Electrical codes and standards require safety factors in the application of circuit breakers. Circuit breakers come in standard frame sizes and ratings. Changes in the size of the circuit breakers may result in changes to the connecting bus and to the panels that house the equipment.

Table 1, shown below, summarizes the inverter, inverter circuit breaker, and power plant main circuit breaker rating for reactive power ratings of 1, 0.8, and 0.54 PF.

Inverter Power Factor	**1**	**0.8**	**0.54**
Inverter Min. Current Rating	321	400	595
Standard VSD Current Rating	300	400	600
Inverter Circuit Breaker	400	600	800
Main Circuit Breaker	1600	2000	3000

Table 1: Equipment Rating for 3 Reactive Power Ratings

IV. MARGINAL COST OF REACTIVE POWER RATING

A one-line diagram and bill of material was submitted to a local representative of industrial motor drives and their associated electrical packaging business. They produced cost quotations for purchase of a complete, commercially packaged power system for the 1 MW power plant. The quotation included both the 4 main fuel cell inverters and an estimate for the interface to the microturbines, all electrical connections, circuit breakers, bus, panels, and enclosures. The results are shown in the table below.

PF	1	0.8	0.54
kVAR	0	720	1500
Cost	$280k	$320k	$420k
% change	-	14%	50%
$/kVAR	-	$56	$93

Table 2: Marginal Cost of Reactive Power Capability

Table 2 shows that the marginal cost of reactive power for this particular configuration of a 1 MW power plant is in the range of $56 to $93 per kVAR, and that the marginal cost per kVAR increases as the reactive power capability is increased. This result is not unexpected. The trigonometric relationship between real, reactive, and apparent power means that the inverter minimum current rating increased only about 25% for the first 720 kVAR, but reaching 1500 kVAR requires a 85% increase in current rating over a unit with no reactive power capability.

The incremental costs of adding reactive power capabilities to a DER product appear favorable when compared to the $50 per kVAR[8] to $100 per kVAR[9] costs associated with competing static VAR compensator technologies. These systems are typically much larger and enjoy economies of scale. The fact that 720 kVAR can be procured for as little as $56 per kVAR indicates that adding reactive power capability to DER inverters merits further investigation.

It is tempting to compare the cost per kVAR with costs associated with switched capacitor banks. The cost of switched capacitors is roughly proportional to the installed kVAR rating, unlike our results that show an increasing cost per kVAR as reactive power is increased.

Utilities and large building owners know from experience that switched capacitors represent a very different set of capabilities and cost structures. Every switching operation on a capacitor bank exacts a toll in terms of reduced lifetime for the switch and the capacitors. This adds a depreciation term to the economic calculation that is different from inverters. Unlike solid-state inverters, maintenance and inspection costs for the switch and the capacitors are not trivial and must be included in any budgetary exercise.

Finally, the capabilities of switched capacitor banks to respond to rapidly changing conditions is quite limited and set by fundamental electrical laws. The kVARs supplied by capacitors is a function of system voltage, and falls as square of the voltage decrease. Falling network voltages are often associated with conditions where reactive power is needed most. Reactive power provided by inverters can be controlled to remain constant, to increase as voltage decreases, or to produce any desired behavior within the current and voltage limitations of the equipment.

The regulated and unregulated markets are in the process of determining the prices willing buyers will pay for each set of capabilities: those provided by fixed and switched capacitors, and those provided by inverters and other sources of dynamic reactive power. We will refrain from direct comparisons until the time that market clearing prices for each set of capabilities are well established.

V. SUMMARY

The marginal cost of adding reactive power capabilities to a particular DER product rated 1 MW is determined to lie between $56 and $93 per kVAR. Unlike switched capacitor banks, the marginal cost per installed kVAR increases as the reactive power capability is increased.

These figures are representative of an early stage in the development of the final product. There is ample opportunity for better matching of plant ratings to available components, negotiations with competing vendors for better pricing, and changes in the architecture of the system. All of these actions may reduce costs and significantly alter the marginal cost of adding reactive power capability.

Our assumption regarding no changes to the filter network between the inverters and the prime mover must be carefully examined for each DER technology considered.

Adding reactive power capability to a DER product results in significant increases in the cost of the power conversion system. The question of whether these costs are justified will ultimately be settled by the value willing buyers place on dynamic reactive power capabilities.

ENDNOTES

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