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Fuel cells: A utilities perspective☆

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Abstract

Southern California Edison (SCE) is actively assessing how to maximize the benefits from fuel cell power systems and other distributed generation (DG) technologies deployed along existing distribution level circuits. From a utility perspective, the viability of DG fuel cell systems increase as the technology matures and more "value-added" features are incorporated. As the number of DG projects grows in SCE's service territory and optimism increases about the potential uses, so does the need to better understand the impact wide-scale deployment may have on the performance of California's energy system. Understanding how DG technologies affect distribution level circuits and devising effective deployment strategies is essential for the technology to gain widespread acceptance and become an integral part of SCE's Transmission and Distribution (T&D) system planning. Simulation results are presented in this paper that indicate fuel cell systems combined with electronically switched power inverters capable or providing reactive power (a.k.a. VAR) support are more advantageous than fuel cell systems without such inverter features. In fact, for the SCE circuit analyzed, a strategically placed 2.5 MW fuel cell system with VAR support capabilities has a greater affect on circuit performance than a 3 MW fuel cell system without VAR support. Even though the 2.5 MW fuel cell system with VAR support inverter possesses 16.7% less power rating than the 3 MW system without VAR support, it was more effective in reducing circuit current flows, reducing distribution line losses, and maintaining circuit voltage within ±5% of 12.47 kilovolts (kV).

Keywords: Fuel cells; DG operation; Utility circuits

1. Introduction

The purpose of this paper is to provide utility, industry, and government leaders a better understanding of how to effectively deploy fuel cells utilizing electronically switched power inverters, as distributed generation (DG) assets, into an existing electric grid. Extensive literature exists that addresses the requirements of DG operation and interconnection to the distribution system, but the effect fuel cells would have on a distribution level circuit are less understood. Computer-based simulation models were developed and exercised through basic "what if" scenarios that examined what types of benefits the utility could recognize if various size fuel cells with inverters were deployed along an existing distribution circuit.

This paper presents modeling and simulation results concerning the effect fuel cell systems would have on a "typical" Southern California Edison (SCE) 12 kV circuit. The circuit chosen to study was a circuit located in the San Bernardino Area. It was chosen for several reasons; the most important being that it represents the type of circuit, where SCE believes DG would be most helpful for the utility. The following will show the assumptions and reasoning that were used for this study, and provide a general understanding of the impacts on utility circuits. Specifically, this study will determine the size (MW) and placement of fuel cells with inverters may have on a distribution level circuit for the utility to realize necessary generation and VAR support benefits.

2. Problem and solution method

In order for fuel cells to be recognized as a utility asset rather than just another customer generation technology that must be accommodated, the basic operating principles and grid interactions must first be understood. Presented in this paper are analysis results for the fundamental characteristics of fuel cell interaction with the utilities distribution level circuits.

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The main tasks of the simulation were to: select a circuit in SCE's territory to study, model the loads associated with the selected circuit, develop equivalent circuits and models of the distribution circuits, conduct simulations, carry out sensitivity analysis of fuel cell effectiveness, identify the impact fuel cells, up to a total of 3 MW, have on the circuit, identify optimum placement, and identify the benefit of VAR support supplied by the fuel cell's power electronics inverter subsystem.

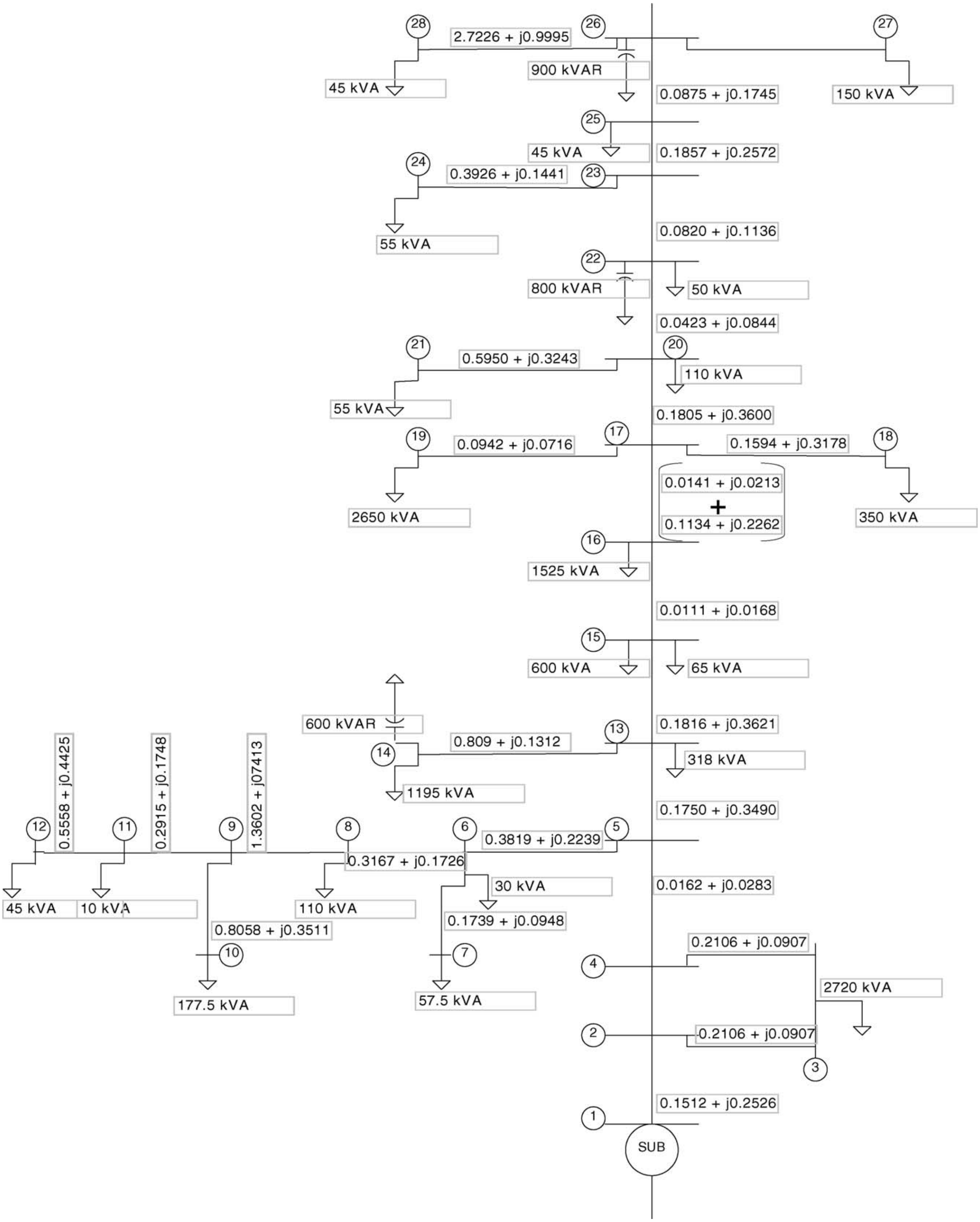

Fig. 1. Distribution circuit used to evaluate effects of fuel cell. Circuit loads given in kVA and the line impededence are given for nearest circuit node point.

For the circuit simulation GE Power Systems software called Positive Sequence Load Flow Program (PSLF) was used. PSLF, an industry standard simulation software, is known for comprehensive, accurate, and flexible power system modeling. The modeling techniques used in PSLF are known to lead to accurate results due to the direct use of nameplate data to minimize the errors that tend to arise in mathematical-based models. The ability to provide nameplate data for individual components is the primary reason PSLF was chosen for this simulation.

Fig. 1 shows a schematic diagram of the 12 kV distribution circuit used in the simulation. The impedances listed are taken from actual circuit maps, and the circuit loading levels are scaled and modeled based on a 600 A limit for the first leg of the circuit. A 600 A loading limit was chosen because 12 kV circuits are considered to be at risk when they reach 600 A.

An initial simulation was performed on the circuit with no generation or VAR support added to the circuit in order to determine the location, where generation is most needed. The voltages, kW losses, kVAR losses, and currents were examined in the simulation and the criteria that the voltage must be within ±5% of 12.47 kV on the primary side became the starting point to place generation along the circuit. Note that a SCE 12 kV line is actually operating at 12.47 kV. In order to maximize the use of the capacity or VARs provided by the added distributed generation (fuel cell) facility the first point evaluated is the lowest voltage point near the main line (point 17 in Fig. 1). This was done in order to evaluate the impact of generation at the lowest voltage and study the effects on the rest of the circuit. The following are the generation increments used at point 17:

1. 250 kW providing no VAR support;
2. 250 kW with 150 kVAR support;
3. 500 kW providing no VAR support;
4. 500 kW with 300 kVAR support;
5. 1000 kW providing no VAR support;
6. 1000 kW with 600 kVAR support;
7. 3000 kW providing no VAR support;
8. 3000 kW with 1800 kVAR support.

These generation increments were chosen because they represent common capacity values for installations or grouping of fuel cells, and understanding the effect of DG in this size range was of interest from SCE's perspective. Notice that the generation is simulated with and without VAR support. Here, we assumed a "black box" DG facility, which consists of a fuel cell and an inverter. We also assumed that the inverter could provide up to 0.6× (maximum power) VARs, while simultaneously providing maximum power output. These different scenarios were selected to show the impact of the differing generation capacity and VAR support on circuit voltage, power losses, and current.

Next for comparison, the generation was distributed in three different locations along the main line. Generation and VAR support was placed simultaneously at points 3, 17, and 25 in order to determine if distributing generation along the circuit has a greater impact than if generation is simply placed at the point of greatest need. The points were chosen because large loads are located at these points, and also because they represent points at the front, middle, and back of the circuit. In the following test cases, generators were placed at each of the three locations. For example, in case #1, a 250 kW generator was placed at point 3, another at point 17, and another at point 25. The following are the generator simulations that were performed:

1. 3–250 kW providing no VAR support;
2. 3–250 kW with 150 kVAR support provided by each generator;
3. 3–500 kW providing no VAR support;
4. 3–500 kW with 300 kVAR support provided by each generator;
5. 3–1000 kW providing no VAR support;
6. 3–1000 kW with 600 kVAR support provided by each generator.

In order to examine the effects of generation on a normally loaded circuit, the maximum current seen by the circuit was set to 400 A and the circuit was again analyzed in a similar manner as for the 600 A case. One thing to note here is that the largest generation used was 1000 kW. The reason for this is that the wire at the end of the circuit is not rated to accommodate the large currents produced by the larger generators. Below are the list of generators examined a point 17:

1. 250 kW providing no VAR support;
2. 250 kW with 150 kVAR support;
3. 500 kW providing no VAR support;
4. 500 kW with 300 kVAR support;
5. 1000 kW providing no VAR support;
6. 1000 kW with 600 kVAR support.

3. Assumptions

For this simulation, several assumptions were made in order to simplify the calculations and allow for accurate and easily understood results. The following are the assumptions used in this simulation:

- First the simulation will simulate a three-wire three-phase balanced circuit.
- Automated switches were not considered.
- The circuit being simulated was of radial design as depicted in Fig. 1.
- The circuit being simulated is an actual SCE circuit, but the loads used in the calculations were estimated.
- This "typical" 12 kV distribution circuit serves mostly residential loads.
- The power factor of 0.90 was assumed for the circuit uncorrected. Uncorrected power factor means the power factor that is not corrected by placing capacitors on the lines. The circuit's uncorrected power factor can range from 0.90 to 0.85 according to SCE's Field Engineering. Note that the power factor is determined at the substation because this is where watts and VARs can be measured. Load variation is not measured so that cannot be determined.

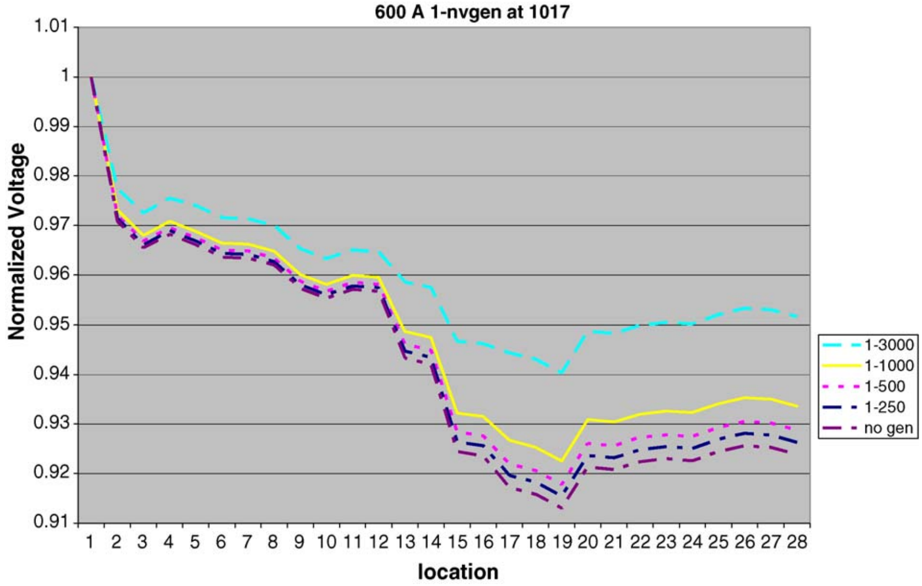

Fig. 2. The effects of various size fuel cells located at point 17 of Fig. 1 have on the voltage levels throughout the circuit. The generators are applied to a heavily loaded 600 A circuit and have no VAR support capabilities.

- The topology for the circuit was extracted from the circuit maps and facilities inventory maps (FIM) overhead and underground maps.
- The simulation includes the effect of fixed capacitor banks already present on the circuit. However, for simulation purposes the capacitor banks could be switched on and off.

In addition to the assumptions made above, a great deal of attention was paid to the resistance and impedance of the circuit wires. The length and size of wires was taken from the topology maps, and the conversion from wire sizes and wire lengths to resistance and impedance was done through Field Engineering's Flicker Short Circuit Duty (SCD) form. Simplification of the resistance and impedance model was done by adding lines together, where no significant load or branch circuits were attached to that part of the line.

Further simplification of the modeling process was done by aggregating the loads along the line and placing them at the end of the line if possible. The loads were added together by summing the total kVA of the transformers and then using the assumed power factor as a guide for determining the amount of kW and kVAR for the simulation. Aggregating the load in this manner allows a simpler model to be simulated and yet provides sufficiently accurate information.

As mentioned earlier, a total 600 A circuit load was picked because this is the current level at which the distribution circuit

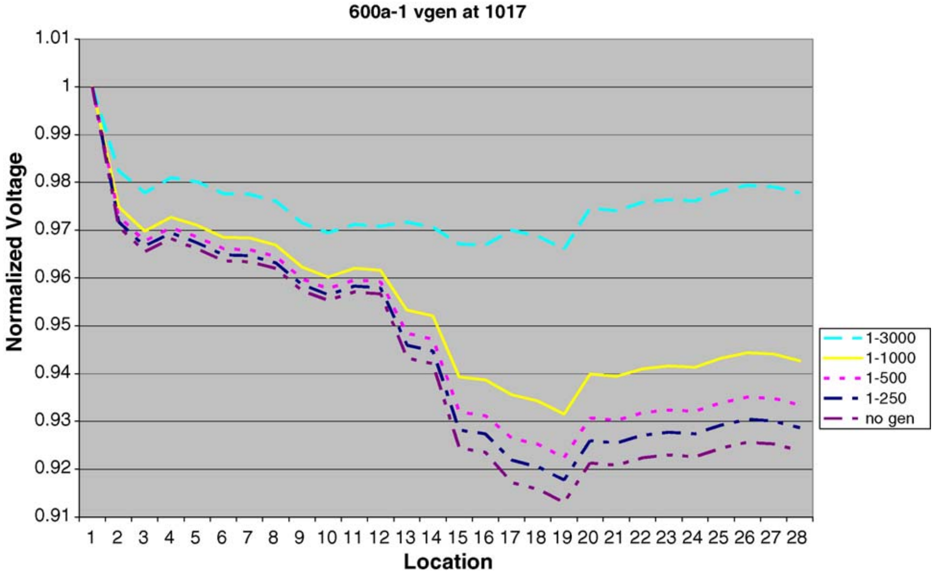

Fig. 3. The effects of various size fuel cells with VAR support capabilities located at point 17 of Fig. 1 have on the voltage levels at various points throughout the circuit. The circuit simulated is in a heavily loaded at 600 A.

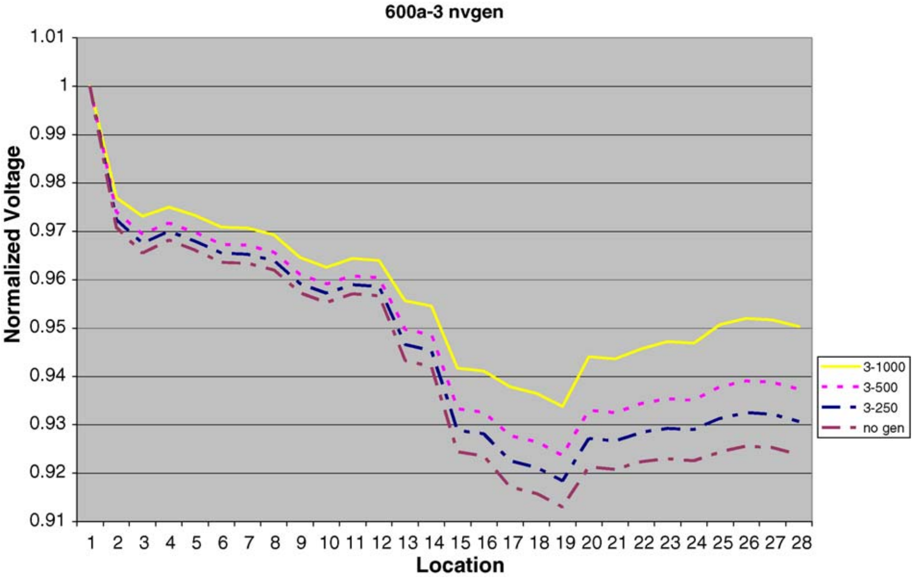

Fig. 4. Fuel cells located at points 3, 17, and 25 (all fuel cells the same size) with no VAR support capability are applied to the heavily loaded 600 A circuit. The voltage levels at various circuit locations are plotted.

becomes susceptible to problems. The loads in the circuit simulation were scaled so that the total current of the first leg of the circuit was at the desired 600 A while keeping the power factor at 0.9. This was done to mimic the heavy loading condition. The circuit was also scaled and modeled at 400 A in a similar manner. This loading level was picked as the typical low stress case meaning that the circuit is functioning at acceptable levels.

The generation added to the circuit is considered a “black box” that contains a fuel cell and an electronically switched power inverter. The main assumption here is that the fuel cell and inverter work independently. The fuel cell supplies the real power (kW), up to the maximum rated output, and the inverter acts as a reactive power (kVAR) source. Table 1 shows the kW and kVAR used for this study. It is also important to note that this combination of generation and VAR support calculates to a 0.86 leading power factor.

Table 1

Fuel cell rating (kW)	Inverter output at maximum generation (kVAR)
250	150
500	300
1000	600
3000	1800

One thing that needs to specifically be mentioned is that throughout the simulation, no attention was paid to protection schemes. This simulation is intended to determine the optimum deployment size and position of a fuel cell to provide the great-

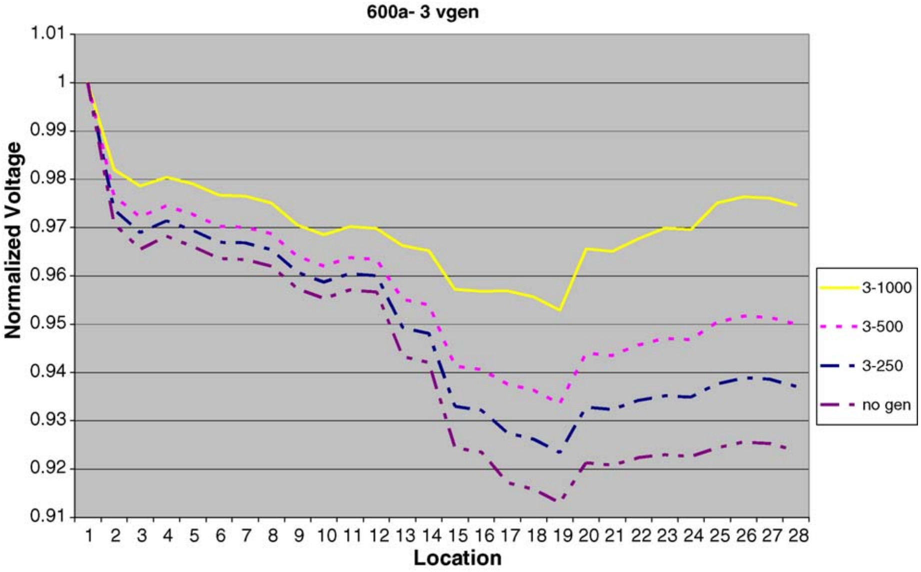

Fig. 5. Fuel cells located at points 3, 17, and 25 (all fuel cells the same size) with VAR support capability are applied to the heavily loaded 600 A circuit. The voltage levels at various circuit locations are plotted.

Fig. 6. The generator configuration is listed, where nv stands for no VAR capabilities and V stands for VAR support capabilities. The total Ploss and Qloss (real and reactive power loss, respectively) are then given for each configuration.

est amount of benefit from a utility perspective. The inclusion of protection schemes in the simulations is beyond the scope of this project.

4. Results

Fig. 2 shows what happens when one generator with no VAR support is placed at point 17 on the circuit simulation map. This is the heavily loaded circuit case (600 A) and point 17 is the location of the largest load. As can be seen from the graph none of the fuel cell sizes is capable of pulling the voltage above the necessary 0.95 V requirement. This is interesting because the total load on the line is approximately 10.5 MVA (MVA includes real and reactive power) and 3 MW of additional generation is a significant addition to a circuit of this size. Because of this result, it is necessary to consider fuel cells with VAR support capabilities. Fig. 3 is the same generation cases used in Fig. 2 except that the fuel cells include VAR support in the amounts listed in Table 1. Notice that the only case that is capable of keeping the voltage above 0.95 V at every point on the circuit is the 3 MW fuel cell with VAR support (equivalent to 3.5 MVA). Further simulations were able to show that 2.5 MW with VAR support (2.9 MVA) was the minimum amount needed to keep the voltage above the critical point. Notice that the total amount

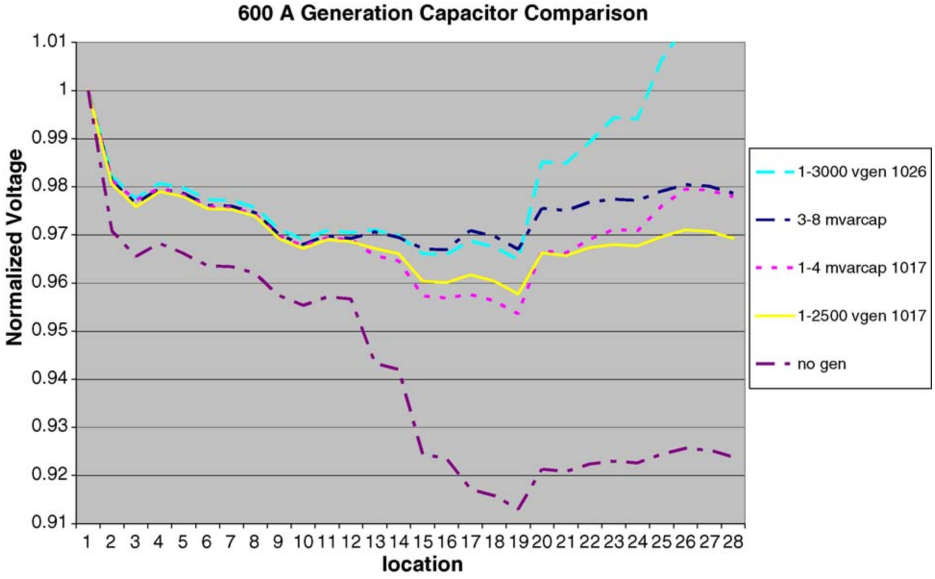

Fig. 7. The effects of several fuel cell and capacitor configurations have on the voltage at different locations throughout the heavily loaded 600 A circuit: 1–3000 vgen 1026 is one 3000 kW fuel cell with VAR support capabilities located at point 26 of Fig. 1; 3–8 mvarcap is 8 MVAR capacitors located at points 3, 17, and 25 of Fig. 1; 1–4 mvarcap 1017 is a 4 MVAR capacitor located at point 17 of Fig. 1; 1–2500 vgen 1017 is a 2500 kW fuel cell with VAR support capabilities located at point 17 of Fig. 1.

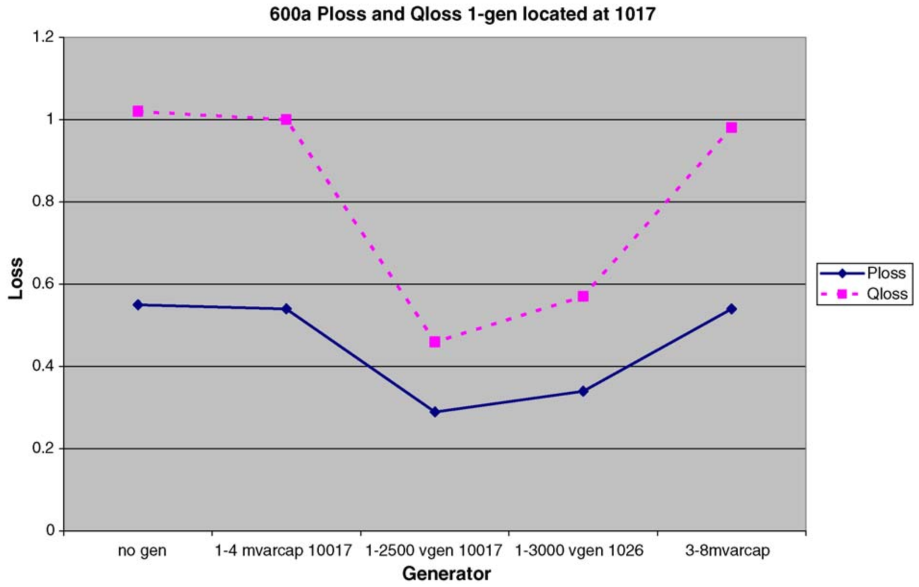

Fig. 8. The generators Ploss and Qloss (real and reactive power loss, respectively) for the configurations of Fig. 9.

of MVA supplied to the circuit by the 2.5 MW generator with VAR support is less than the 3 MW generator with no VAR support (3 MVA) and is still able to meet the required voltage level throughout the circuit. This shows that the circuit needs reactive power, not just the active megawatts supplied by the generator.

Figs. 4 and 5 are the cases that have three fuel cells deployed throughout the circuit (at points 3, 17, and 25). In the case of no VAR support (Fig. 3), the additional generation is not able to maintain the required voltage criteria. Notice that the 3 MW of multiple generation units are not as effective in maintaining the voltage as the case of one 3 MW generator placed at the location of the largest load. In Fig. 5 (VAR support included), we see that three 1 MW generators are needed to maintain the required voltage. It also shows that a full 3 MW of generation with VAR support is needed if distributed throughout the circuit. Again, the three 1 MW generators are supplying 3.5 MVA, which is the same as in the case with one 3 MW generator, however, with one 2.5 MW generator strategically located we achieve the same affect and have added only 2.9 MVA to the circuit. Note that by understanding distribution level circuits and intelligently placing generation at strategic locations on the circuit we can reduce the size of generator that is needed. The key lesson here is that SCE and other utilities can lessen capital costs and fuel

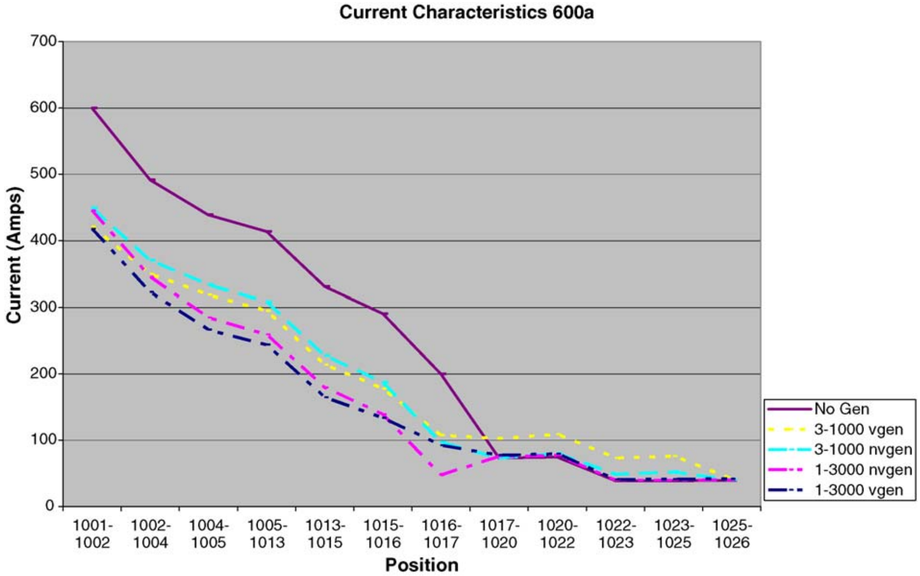

Fig. 9. The current levels between various locations in Fig. 1. For example, position 1001–1002 is the current level between node points 1 and 2. The cases plotted here are for a heavily loaded 600 A circuit with the following fuel cell configurations: 3–1000 vgen (1000 kW fuel cells with VAR support at points 3, 17, and 25 of Fig. 1), 3–1000 nvgen (1000 kW fuel cells with no VAR support at points 3, 17, and 25 of Fig. 1), 1–3000 nvgen (3000 kW fuel cell located at point 17 of Fig. 1 with no VAR support), and 1–3000 vgen (3000 kW fuel cell with VAR support located at point 17 of Fig. 1).

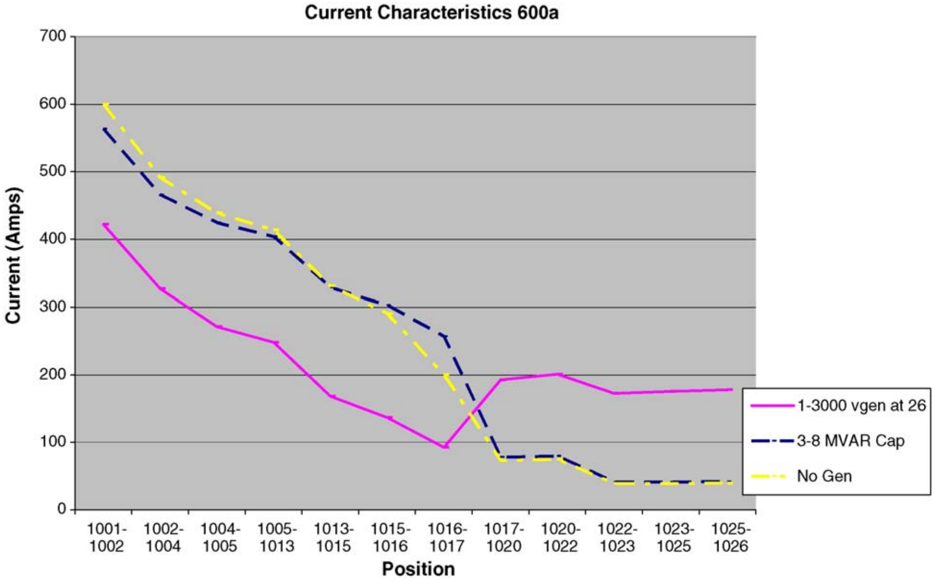

Fig. 10. The current levels between various location in Fig. 1. For example, position 1001–1002 is the current level between node points 1 and 2. The cases plotted here are for a heavily loaded 600 A circuit with the following fuel cell configurations: 1–3000 vgen at 26 (3000 kW fuel cells with VAR support point 26 of Fig. 1), 3–8 mvar Cap (8 MVAR capacitors points 3, 17, and 25 of Fig. 1).

consumption while maximizing benefits by better understanding how additional distributed generation will affect the circuit.

Another benefit can be acquired by "proper" placement of generation in the form of real and reactive power losses (Ploss and Qloss, respectively) shown in Fig. 6. As can be seen in Fig. 6, a 3 MW generator with VAR support located at point 17 results in the least amount of power loss for the system. Placing the generation close to the point of consumption reduces line losses, which in turn increases overall circuit efficiency. By placing generation in this position SCE would not only add generation to the circuit, but it would also reduce the amount of generation need because of the decreased line losses. For the case of three 1 MW generators dispersed along the circuit three 1 MW generators do not reduce the amount of losses as well as having one generator located at point 17 because the generation source is no longer near the point of consumption. Clearly, multiple and maximum benefits can be realized if fuel cells or other generation is wisely located based on such circuit analyses.

Previously, we have seen that adding generation alone is not enough to maintain the voltage on the heavily loaded 12 kV circuit, but what happens if only reactive power is added? This is an intriguing question because using capacitors to add the required reactive power is relatively inexpensive compared to generation

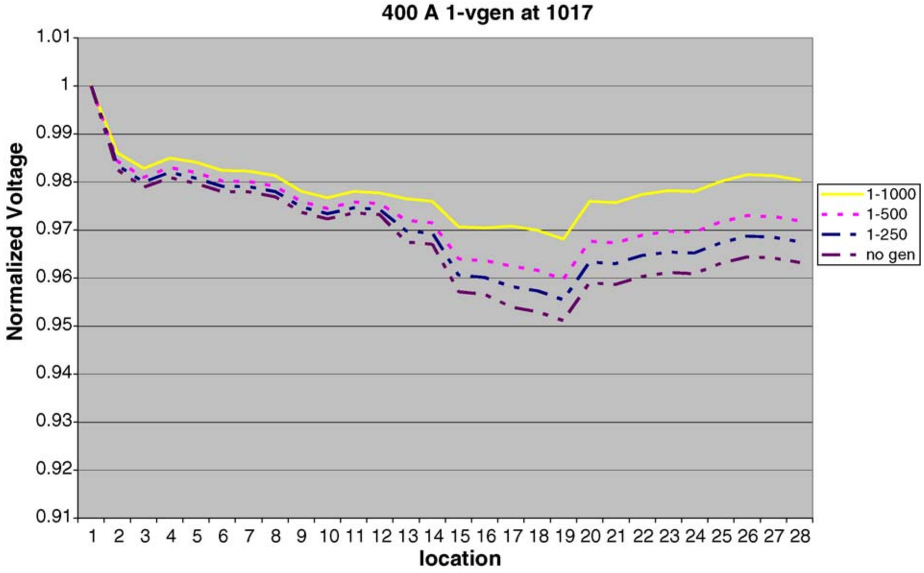

Fig. 11. The effects of various size fuel cells with VAR support capabilities located at point 17 of Fig. 1 have on the voltage levels at various points throughout the circuit. The circuit simulated is in a lightly loaded at 400 A.

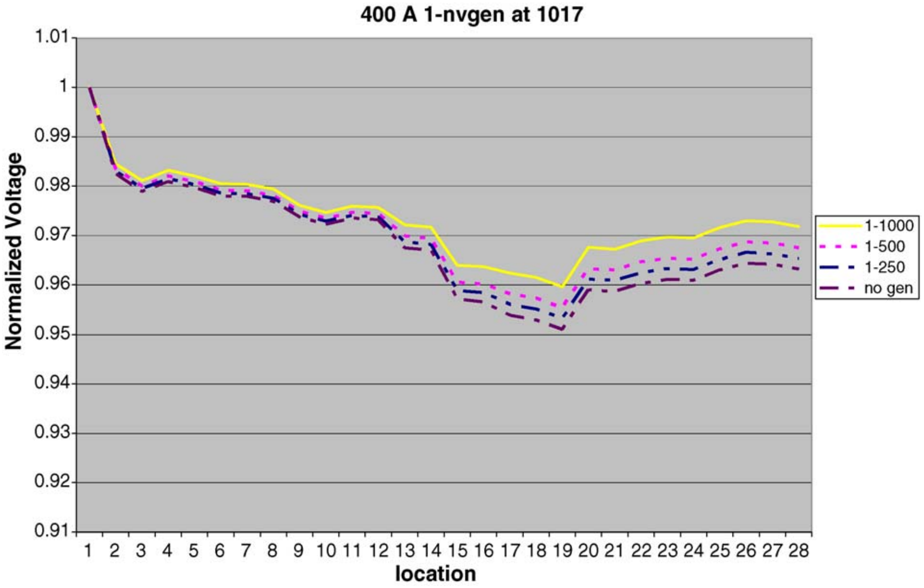

Fig. 12. The effects of various size fuel cells located at point 17 of Fig. 1 have on the voltage levels throughout the circuit. The generators are applied to a lightly loaded 400 A circuit and have no VAR support capabilities.

sources, such as fuel cells. Fig. 7 is interesting in that it shows what happens to the circuit for several different scenarios. If one 4 MVAR capacitor is placed on the circuit at point 17, the voltage can be maintained throughout the circuit as required. This seems like it would be the better solution, since it would lead to the least cost to SCE. However, there are other issues that need to be considered. Notice that placing this much capacitance on the circuit allows the utility to maintain the required voltage, but as Fig. 8 shows this does not help to reduce the real and reactive power losses in the circuit. In addition, notice the current levels along the main line shown in Figs. 9 and 10. As expected, the additional capacitance has done nothing to lower the current levels throughout the circuit. Remember that this is a heavily loaded circuit and even though the focus has been on maintaining proper voltage levels, it is also a goal to reduce the maximum current on the main line. Reducing the current level on the circuit to the light loading limit of 400 A eliminates the need for expensive upgrades, and allows the circuit components to operate in a low stress environment thereby increasing their lifetime and reducing costs for SCE.

For further comparison and demonstration as to the importance of astute fuel cell location, included in Fig. 7 is the condition, where a 3 MW generator with VAR support is now placed at the end of the circuit (point 26). As can be seen in Figs. 9 and 10,

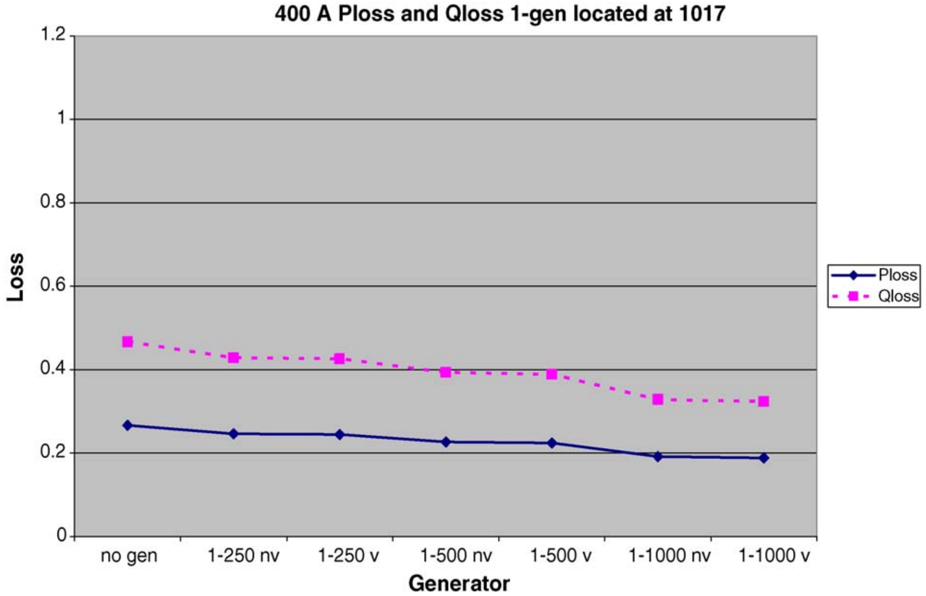

Fig. 13. The generator configuration is listed, where nv stands for no VAR capabilities and V stands for VAR support capabilities. All fuel cells configurations are listed by kW and are located at point 17 of Fig. 1. The total Ploss and Qloss (real and reactive power loss, respectively) are then given for each configuration.

this configuration is capable of reducing the current levels on the circuit, but it also increases the current at the end of the circuit. This is undesirable because the wires used at the end of the line tend to be smaller and are unable to handle the increase in current without affecting the voltage. If a generator were to be placed at this location, upgrades to the existing circuit would be required thereby reducing the benefits of the added generation. In addition, notice that in Fig. 7, the voltage is now well above the ±5% requirement. This result is a good demonstration that generation added to a circuit without analyzing the circuit impact may create a worse situation then if the generation were not added at all. Adding generation in the wrong location can have detrimental effects that would need to be planned for in order to maintain safe operation of the electrical system.

Figs. 11–13 are for the case of a normally loaded (400 A) case. The results are fairly uninteresting because the circuit is working properly before the generation is added. In essence, this is what was trying to be obtained in the case of a heavily loaded circuit with fuel cells and inverters added for generation and VAR support. In the case of the normally loaded circuit, the effects of the generation can be seen, but SCE does not obtain benefits because the added generation is inconsequential given the load status of the circuit. Thus, from a utility perspective, it is most beneficial to strategically deploy DG fuel cells with VAR support inverter technology on heavily loaded circuits. Something that should also be mentioned is that this simulation did not include the effect of load growth on the circuit. Circuits that are experiencing rapid load growth may benefit from tactically timed and strategically placed DG. Because of this, further simulations that include load growth, switching schemes, and protection schemes are needed to truly understand the benefits of placing DG on lightly loaded circuits.

5. Conclusion

Gathering all the data points of bus voltages, line losses, and current allows the authors to make the following “Rule of Thumb” observations. First, having the distributed generation closest to the largest load center increases voltage, decreases line losses, and decrease current flows. Second, the capacity of the generator should be a close match to the capacity required at the load center to prevent excessive export that might overload some lines due the decreasing sizes of wire as it is farther away from the substation. Third, from the two observations above, one would surmise (it is backed up by data) that having a large generator close to the load center would result in better circuit performance compared to generation distributed along the circuit that totals the large generator close to the load center. And finally, for the circuit being analyzed, the size of the generator has to be between 17 and 25% of the total load to make a noticeable impact on the circuit, and VAR support capabilities of fuel cell inverter systems greatly enhance circuit performance and allow SCE to recognize the most benefits.

The practice of meeting energy needs with DG is increasing in the U.S. and SCE intends on guiding technology leaders down the path that leads to the greatest benefits to technology leaders, utilities, and most of all the customers. As we have shown, the addition of fuel cells or other generating technologies with inverters can have beneficial or adverse affects on the distribution level circuit depending on the size, location, and VAR support capabilities of the units installed. One thing to consider is that all distribution level circuits are different. They differ in the length of lines, the current ratings, voltage levels, residential versus industrial loads, and the list goes on. When considering the addition of generation and VAR support to a circuit it is important to understand the circuit so an optimal placement can be found so as to increase the benefits the fuel cell units can provide.

We have shown that when appropriately sized and located, fuel cells can have considerable benefit to a utility, such as SCE when installed in heavily loaded distribution level circuits. SCE is aware that fuel cell technology is still maturing through various private, state, and federal research and development programs, and recognizes the potential and intends on contributing to the development of this exciting technology. Ultimately, this simulation is a “first step” towards understanding how to use “developing technologies”, such as fuel cells and VAR support inverters that are becoming available for SCE to consider during T&D planning. More in-depth studies are needed that include switching scenarios and protections schemes so that the effects fuel cells have on the bigger picture can be identified.