Title
Effects of Distributed Generation on Voltage Levels in a Radial Distribution Network Without Communication

Journal
Journal of Electrochemical Energy Conversion and Storage, 7(6)

ISSN
1550-624X

Authors
Auld, Allie E
Brouwer, Jack
Smedley, Keyue M
et al.

Publication Date
2010-12-01

DOI
10.1115/1.4001050

Effects of Distributed Generation on Voltage Levels in a Radial Distribution Network Without Communication

Allie E. Auld

Jack Brouwer[1]

Keyue M. Smedley

Scott Samuelsen

Advanced Power and Energy Program,
University of California Irvine,
Irvine, CA 92697

The challenges associated with incorporating a large amount of distributed generation (DG), including fuel cells, into a radial distribution feeder are examined using a dynamic MATLAB/SIMULINK™ model. Two generic distribution feeder models are used to investigate possible scenarios where voltage problems may occur. Modern inverter topologies make ancillary services, such as on-demand reactive power generation/consumption economical to include, which expands the design space across which DG can function in the distribution system. The simulation platform enables testing of the following local control goals: DG connected with unity power factor, DG and load connected with unity power factor, DG connected with local voltage regulation (LVR), and DG connected with real power curtailment. Both the LVR and curtailment strategies can regulate the voltage of the simple circuit case, but the circuit utilizing a substation with load drop compensation has no universal solution. Even DG with a penetration level around 10% of rated circuit power can cause overvoltage problems with load drop compensation. The real power curtailment control strategy creates the best overall circuit efficiency, while all other control strategies result in low light load efficiency at high DG penetrations. The lack of a universal solution implies that some degree of communication will be needed to reliably install a large amount of DG on a distribution circuit. [DOI: 10.1115/1.4001050]

Keywords: distributed generation, distribution system, dynamic model, electric utility, fuel cell, inverter, voltage regulation

1 Introduction

New advancements in inverter-based decentralized electrical energy technologies, which include everything from plug-in electric vehicles, solar photovoltaic panels, to combined heat and power (CHP) with fuel cells and microturbine generators, have the potential to change the premises upon which electric power is generated, transmitted, distributed, and consumed [1]. Whether the proliferation of these energy resources is driven by energy economics or environmental concerns, the existing distribution system is not designed to be flexible enough to accommodate these resources, even provided that the necessary accommodations were well known. Previous work has shown that voltage regulation can become a major concern when large penetrations of distributed generators significantly change the distribution feeder characteristics [2–4]. The IEEE 1547 standard for interconnecting distributed generation (DG) states that the generator may neither actively regulate any voltage nor cause any voltage on the system to go beyond specified requirements [5]. This clause alone will limit the penetration of DG allowed in many existing distribution scenarios. Thus, independent of the difficulties in economically installing fuel cells and other DG systems, producing a large percentage of power on-site may be an ambitious goal from the other side of the point of common coupling (PCC): the electricity distribution system.

Recent interest and investment in smart grid technology promises to make the distribution system more intelligent in the long term, by enabling communication and control between load meters, voltage regulators, field capacitors, d-FACTS, smart substation elements, and even other circuits [6]. In this scenario, DG will play a major role, due to its ability to change power output and power angle, in meeting the needs of the distribution system and the greater utility network. However, waiting for these widespread intelligent circuit upgrades will create a major barrier to installation and deployment of a high penetration of DG. It is thus critical to the near-term deployment of DG to understand what converter behavior is desirable and most compatible with the current system, and then to construct and deploy such converters to be upgradeable, so that in the future, as smart grid circuits become available, the asset is further optimized and incorporated into the system.

The goal of this paper is to explore four different control methods, where each rely purely on locally measured parameters: DG with unity power factor (baseline control), DG and local load with unity power factor (power factor correction), DG with local voltage regulation (LVR), and DG with real power curtailment (RPC). These control strategies are evaluated based on whether they cause the generator to create (1) over- or undervoltages on the circuit, or (2) undesirable utility conditions such as an excessive reactive power demand. A DG control that successfully improves the voltage regulation and power flow in the circuit is labeled as a "model citizen." A poor citizen DG control creates major problems in the circuit, and a good citizen has a neutral effect [7]. These four control strategies are added to a variety of generic feeder models and the resulting behavior is analyzed and classified to determine whether locally controlled distributed generators can become a model citizen of the grid. Finally, the circuit efficiency of each scenario is also calculated, analyzed, and compared, providing an additional facet of the impacts of DG on the circuit.

[1]Corresponding author.

Contributed by the Heat Transfer Division of ASME for publication in the JOURNAL OF FUEL CELL SCIENCE AND TECHNOLOGY. Manuscript received October 19, 2009; final manuscript received November 25, 2009; published online August 24, 2010. Editor: Nigel M. Sammes.

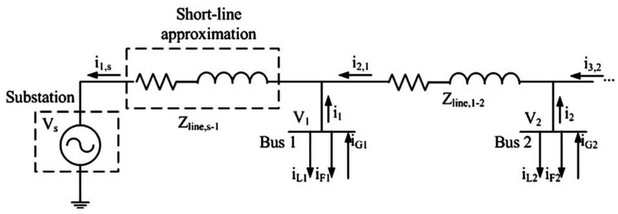

Fig. 1 Circuit schematic of distribution model

2 Background

At present, addition of DG to distribution circuits is tightly limited and regulated to prevent any possible problems. The IEEE-1547 standard is developed as a guideline for this implementation [5]. This standard states that a DG installation may neither cause any voltage on the system to go outside of set limits, nor actively regulate the local voltage. It recommends that a generator either operates with a power factor of 1 or provide a power factor compensation for the local load to the realistic limits of 0.9, leading to lagging.

ANSI C84.1 defines the allowable voltage rating at the customer entrance for Range A, which encompasses most DG locations, is from 114 V to 126 V (0.95–1.05 per unit). To allow for transformer and secondary line losses, a study into this issue by GE, under contract by NREL, defines the acceptable per-unit (p.u.) voltage at the distribution transformer primary as 0.98–1.05 p.u. [4] The per-unit value is the actual value normalized to a set base value, and is used here for both voltage and power.

This same study looked at all combinations for six different DG levels on each of eight different base circuits, with two control strategies, two load growth scenarios, four DG locations, and two load levels. For each case, the maximum and minimum voltage across both are recorded and used to understand voltage behavior of the circuit, due to the addition of DG. All cases are designed to have no steady-state voltage problems when no DG is implemented. Many of these cases resulted in either under- or overvoltages on the circuit, which would preclude the DG installation and realize the problems associated with installing generators on a distribution feeder [4].

The current work takes a subset of the circuits from the GE/NREL work and focuses on how the DG-grid interface could be controlled to avoid voltage problems. As a premise, it is assumed that the generator real power output can be curtailed on demand. An example of a generator that is curtailable, though not controllable, would be a photovoltaic (PV) array [8]. It is also assumed that the inverter connection can provide either a leading or lagging power factor. A variety of cases that span different DG locations, penetrations, and load power are simulated for different control strategies. All the control strategies try to execute control using purely local information such as local load reactive power or local bus voltage, which represents the current manner in which DG is introduced.

3 Assumptions and Approach

3.1 Model Development. The set of models used to explore these circuits are developed in MATLAB/SIMULINK™, according to a modified version of the ladder iterative technique from Ref. [9]. The models are built and solved entirely in the time domain, and provide voltage and current waveforms as outputs. A circuit schematic of the simulated radial distribution model is presented in Fig. 1. The time-based data are run through a postprocessing MATLAB code to produce voltage magnitudes, angles, and real and reactive power flow. This method lacks the optimization of a more commonly used load flow analysis software, but it has a major advantage in providing flexibility for the design of an interface between the DG and the grid, as well as control and communication throughout the feeder.

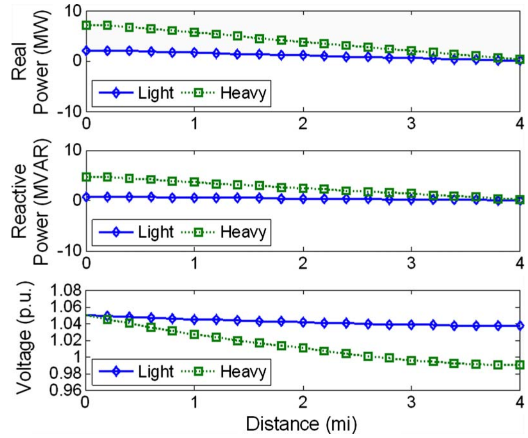

Fig. 2 Real/reactive power flow and voltage profile for Circuit A without DG at light and heavy load

3.2 Circuit Models. This work explores two generic feeder models: Circuits A and B.

3.2.1 Circuit A: Simple Model. The first circuit explored has 20 load buses, evenly spaced along a 4-mile feeder, with a substation "source" bus set at 1.05 p.u. voltage, assuming a 12.47 kV base. There are no transformers modeled and no capacitors on the line. The first half of the line has an impedance of $0.5+j1.0\ \Omega$, and the second half has an impedance of $0.8+j1.4\ \Omega$. The base power is 7 MW, and the load is evenly distributed among the 20 load buses. Light load means a total power of 0.3 p.u. with a power factor of 0.95; and heavy load means a total power of 1.0 p.u. with a power factor of 0.85. Spanning light and heavy load conditions represent a temporal variation in the loading of a distribution feeder. Circuit A approximates a simple, densely loaded urban circuit. The real/reactive power flows and voltage profile are shown in Fig. 2 for the case without DG. Distance is measured as the distance from the substation. Power flow is defined as positive when going from the substation toward the circuit loads. As there is no generation of real or reactive power on the circuit, all power flows are positive and monotonically decreasing along the length of the circuit. This corresponds to a voltage profile that always decreases with increasing distance from the substation. The heavy load case causes a larger voltage drop, but both load cases result in acceptable voltages at all locations on the circuit.

3.2.2 Circuit B: Voltage Control Model. The second circuit is similar to Circuit A, except that this circuit is 8 miles in length with four fixed capacitor banks, rated at 1200 kVAR, and evenly distributed at bus 4, 8, 12, and 16. The longer line now has a first half line impedance of $1.0+j2.0\ \Omega$ and the second half impedance of $1.6+j2.8\ \Omega$. Also, there is an automatic voltage regulating (AVR) autotransformer at the substation with load drop compensation (LDC). LDC uses a compensation parameter and a local power flow to approximate the line drop, and compensate for this by changing the output voltage. Essentially, this will increase the substation voltage during heavily loaded times, and decrease it at light load to prevent overvoltage. The compensation parameter assumed here is $0.6+j1.1\ \Omega$ with a voltage set-point of 1.02 p.u. and a maximum voltage of 1.05 p.u. A characteristic voltage profile of the circuit without DG at both light and heavy load times is shown below in Fig. 3. The operation of the AVR with LDC is indicated by the high substation voltage, indicated by the y-intercept, for the heavy load case, and lower voltage for the light load case. Figure 3 also shows the real and reactive power flows for Circuit B without the presence of DG. The fixed capacitor banks result in substantial reactive power flowing from the circuit to the substation, which causes the voltage profile of the light load case to rise with increasing distance from the substation.

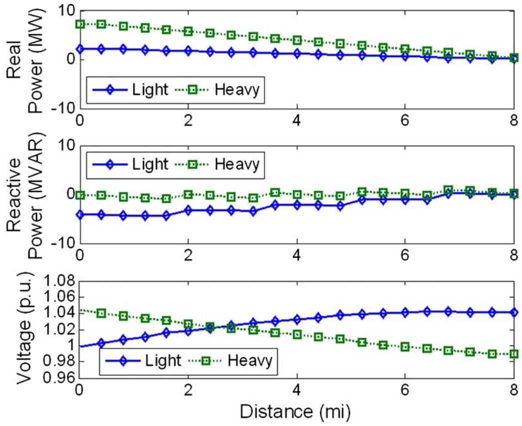

Fig. 3 Real/reactive power flow and voltage profile for Circuit B without DG at light and heavy load

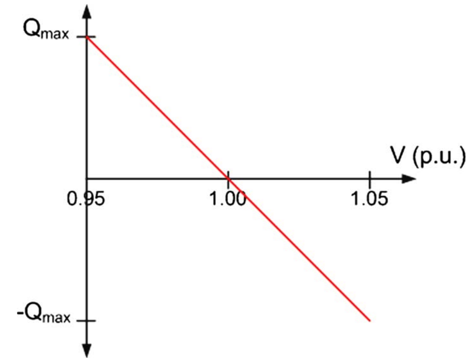

Fig. 4 Diagram of reactive power consumption by local voltage regulation control

For model verification, a sample four-bus system is created with a base voltage of 10 MVA and a base voltage of 12 kV. Values for the line and load impedance are chosen to be arbitrary, but realistic. For simplicity of hand calculation, the loads are all assumed to be at constant impedance with overhead distribution lines, which means capacitance can be neglected. The MATLAB/SIMULINK™ model is then compared with the same four-bus system in both POWERWORLD, which is a conventional load flow simulation program, and to hand calculations for the same bus. The comparison of bus voltages and angles are shown below in Tables 1 and 2, and the close agreement between results of all three methods indicates that MATLAB/SIMULINK™ method is a valid way to simulate load flow in a three-phase power system. A comparison of line power flow shows similar agreement, and an additional comparison between MATLAB/SIMULINK™ and POWERWORLD for constant power loads is consistent, indicating that both constant power and impedance loads are represented realistically by the MATLAB/SIMULINK™ model.

3.3 Control Strategies. Four different local control strategies are described and explored herein.

3.3.1 Baseline. The baseline case control strategy is to set the generator to run at full real power capacity all the time and to produce no reactive power. This simple control strategy most closely resembles how most DG units today operate, particularly high temperature fuel cells, which have exhibited little load-following capability [10].

3.3.2 Power Factor Correction. An alternative DG control strategy is to operate at full real power capacity, and to create an overall power factor of 1, as seen by the distribution primary. This requires the DG to compensate for the consumption/generation of reactive power by generating/consuming it locally. This strategy assumes that the generator has limits of 0.9 leading to 0.9 lagging power factor, as referred to the generator output capacity, and it cannot compensate outside of this range.

Table 1 Bus voltage comparisons in p.u.

	Theoretical	POWERWORLD	SIMULINK
Bus 1	0.969	0.97	0.969
Bus 2	0.953	0.95	0.953
Bus 3	0.946	0.95	0.946

Table 2 Bus angle comparisons in degrees

	Theoretical	POWERWORLD	SIMULINK
Bus 1	−2.85	−2.85	−2.85
Bus 2	−4.55	−4.56	−4.55
Bus 3	−5.50	−5.51	−5.50

3.3.3 LVR. A control strategy for regulating the generator bus voltage is to use reactive power injection to directly affect the local bus voltage. This is investigated in Refs. [4,11]. The generator sinks the reactive power if the voltage is too high, and sources it when the voltage is low. Here, the limits of 0.9 leading and lagging are used, along with a 5% voltage droop. A diagram of the associated reactive power is shown in Fig. 4.

3.3.4 RPC. All previous methods assume that DG real power is independent of the utility desires and feeder condition. This assumption infers that either the owner controls its operation, or that the output is intermittent due to natural causes. The real power curtailment strategy assumes that the voltage will be adequately regulated in the feeder with no DG, and thus, irregular voltages must be due to excess DG real power. The real power curtailment method is derived from Ref. [8] and generalized to all generators in the circuit. If the local voltage exceeds 1.05 p.u., the output power is reduced until the voltage falls below 1.05 p.u. Between 1.04 and 1.05, the previous output power is maintained, and if the voltage falls below 1.04 p.u., the output power will be increased if it was being curtailed.

3.4 Analysis Parameters. The output parameters of interest across the various studies include maximum/minimum voltage and substation real/reactive power input. The voltage extremes must be between the 0.98 p.u. and 1.05 p.u. boundaries set on the power system. Ideally, the voltages will be within a narrow band at the lower end of the acceptable range. This is because lower voltage will reduce the power requirement for constant current and constant impedance loads, and indirectly provide an efficiency benefit. The real and reactive power should have an export/import pattern that is more desirable than without DG. For real power, this is assumed to be within the confines of load-leveling: power import at heavy load is less than or equal to that without DG, and power import at light loads is greater than or equal to the nominal power on the circuit. Similar conditions are also applied to reactive power consumption, as it is assumed that this resource is added with switched capacitor banks. At present, one-third of utility capacitor banks are fixed and the other two-thirds switched to meet changing load requirements. A reduced swing in the reactive power usage would reduce the number of switches and extend the component lifetime. The reactive power usage should not extend outside of the range, as adding reactive power need would directly equate to an increase in infrastructure investment, and a reduced reactive power load might recede below the permanent demand met by the base 1/3 of nonswitched capacitors. The basic comparison metrics are summarized in Table 3.

Table 3 Analysis metrics for comparing control strategies

	Model citizen	Good citizen	Poor citizen
Voltage max	$V_{max} < 1.05$	$V_{max} \leq 1.05$	$V > 1.05$
Voltage min	$V_{min} = 0.98$	$V_{min} \geq 0.98$	$V < 0.98$
Real power	Load leveling	$P_{dem} \leq P_{dem,max}$	$P_{dem} > P_{dem,max}$
Reactive power	Load leveling	$Q_{dem} \leq Q_{dem,max}$	$Q_{dem} > Q_{dem,max}$

4 Results

4.1 Circuit A

4.1.1 Baseline Case. The simple feeder baseline case shows overvoltages for penetrations above 0.2 for generators located at the end, and above 0.3 for generators located at the middle, as presented in Fig. 5. The overvoltages occur during light load, when a net export of DG power creates a voltage rise in the circuit. An example illustrating this effect is shown in Fig. 6 for a DG penetration of 100% located at the middle. The discontinuity in power flow at 2 miles is due to the injection of 7 MW real power. In the light load case, this injection results in a substantial negative real power flow that corresponds to a voltage rise from the substation to the circuit midpoint. The overvoltage problem is not present in the heavy load case because the voltage drop, caused by a large reactive power demand, dominates the voltage increase due to reversed real power flow. The real power import to the circuit (Fig. 7) decreases linearly with penetration, and the reactive power import (Fig. 8) is insensitive to DG because it does not generate reactive power. There are no voltage problems associated with citing DG at the beginning of the circuit.

4.1.2 Alternate Control Strategies. Adding the power factor correction control to the generator does not correct the overvoltage problem, and in fact, exacerbates it slightly by reducing the voltage drop, due to the reactive power flow in the circuit. The local voltage regulation control succeeds in eliminating the overvoltage problem, but it creates new problems in the real and reactive power flows. This control strategy works by assuming that reactive power flow through a line impedance will change the voltage. This is true for a remote bus, but a bus near to the substation is considered a stiff voltage source and no amount of reactive power flow will change this. As a result, when the generator is located at the beginning, the voltage regulation control causes a sharp increase in the reactive power demand of the system both at light loads (model) and at heavy loads (poor). The reactive power flow change for the LVR case is presented in Fig. 9. It should be noted that there was never a voltage regulation problem in these cases where the DG is at the beginning. Thus, voltage regulation is not a universal solution and will sometimes create new problems while trying to solve a problem that did not exist.

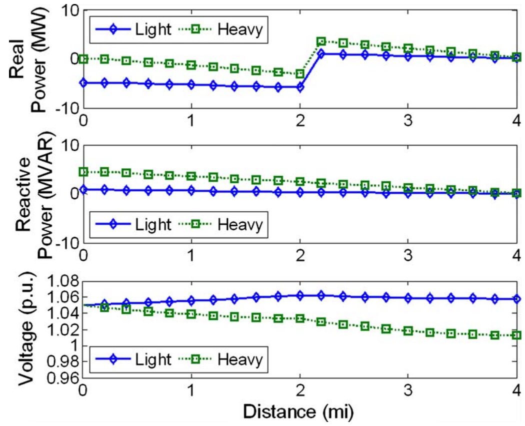

Fig. 6 Real/reactive power flow and voltage profile for Circuit A with 100% DG penetration at middle

The load curtailment control strategy does not affect the circuit during heavy load conditions when overvoltage is not a problem. In the light load cases, the generator real power output is decreased and the resulting substation power is shown in Fig. 10. This control action eliminates the overvoltage problem, as shown along with the other control strategies in Fig. 5. An advantage of the curtailment method is that most overvoltage problems occur during light load conditions. This period typically coincides with night and low electricity rates—a time when DG users may want to reduce real power output, and thus, fuel consumption. This type of control would naturally turn DG units into peaker units, and level the grid tie-line power flow. However, this reduction in output will be detrimental to the circuit performance if it occurs during high load, when the power is most critical. Additionally, combined heat and power (CHP) installations associated with many applications (e.g., manufacturing) may not have the flexibility to be turned down by the utility.

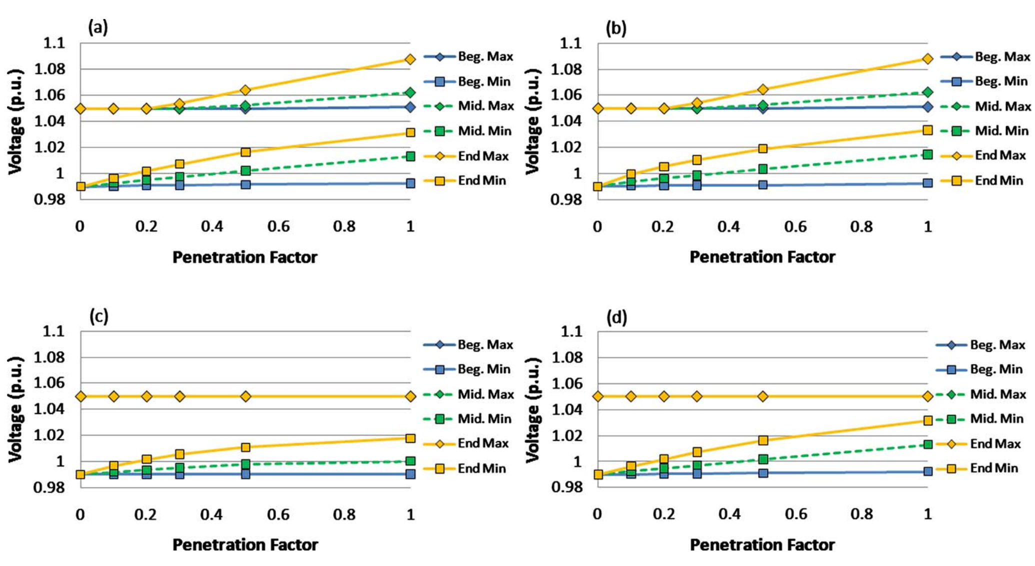

Fig. 5 Voltage regulation cases for Circuit A: (*a*) baseline, (*b*) PFC, (*c*) LVR, and (*d*) curtailment

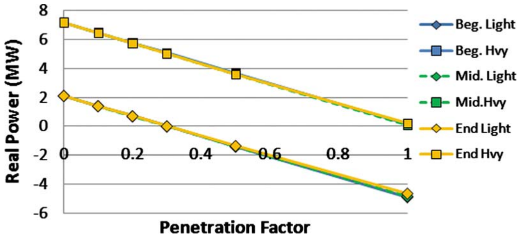

Fig. 7 Circuit A, substation real power flow for baseline

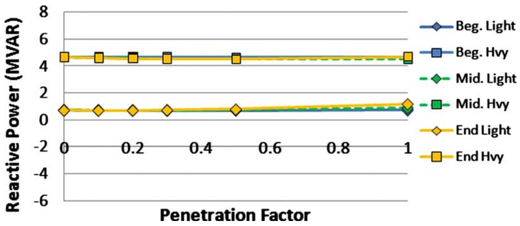

Fig. 8 Circuit A, substation reactive power flow for baseline

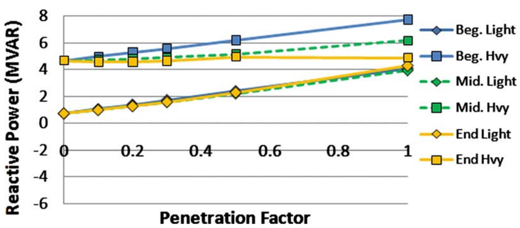

Fig. 9 Circuit A, substation reactive power flow for LVR control

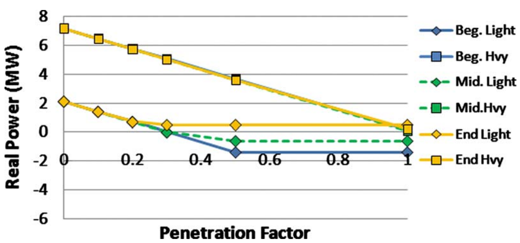

Fig. 10 Circuit A, substation real power flow for curtailment control

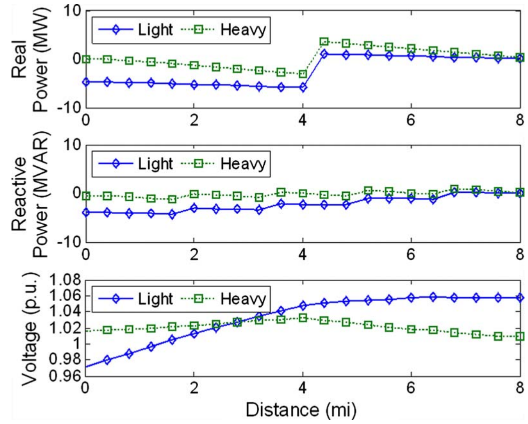

Fig. 12 Real/reactive power flow and voltage profile for Circuit B with 100% DG penetration at middle

4.2 Circuit B

4.2.1 Baseline Case. In Circuit B, the LDC changes the substation voltage in proportion to the substation real and reactive power flows. The addition of DG now not only alters the power flow on the circuit, but also the substation voltage. The voltage extremes for each case of Circuit B are presented in Fig. 11. Without LDC, locating the DG by the substation did not change the power flow in the rest of the circuit, and this location was relatively safe. With LDC, the generator reduces real power flow, which causes a low voltage problem and results in undervoltages at penetrations greater than 0.3. The DG-at-middle case exhibits a combination of problems: the same overvoltage as from Circuit A for penetrations above 0.3, and a new undervoltage problem that begins occurring at penetrations above 0.5. When DG is at the end, there is an overvoltage for any penetration above 0.1, and an additional undervoltage for penetrations above 0.5. The detailed behavior of Circuit B with a 1.0 penetration of DG at the middle is presented in Fig. 12. The substation undervoltage occurs for the light load case due to considerable exportation of both real and reactive power. Yet, even this undervoltage is insufficient to compensate for the voltage rise in the circuit, and the furthest circuit locations experience overvoltages. The real power import is identical to that of the baseline control case for Circuit A (Fig. 13). The reactive power import is still insensitive to DG penetration,

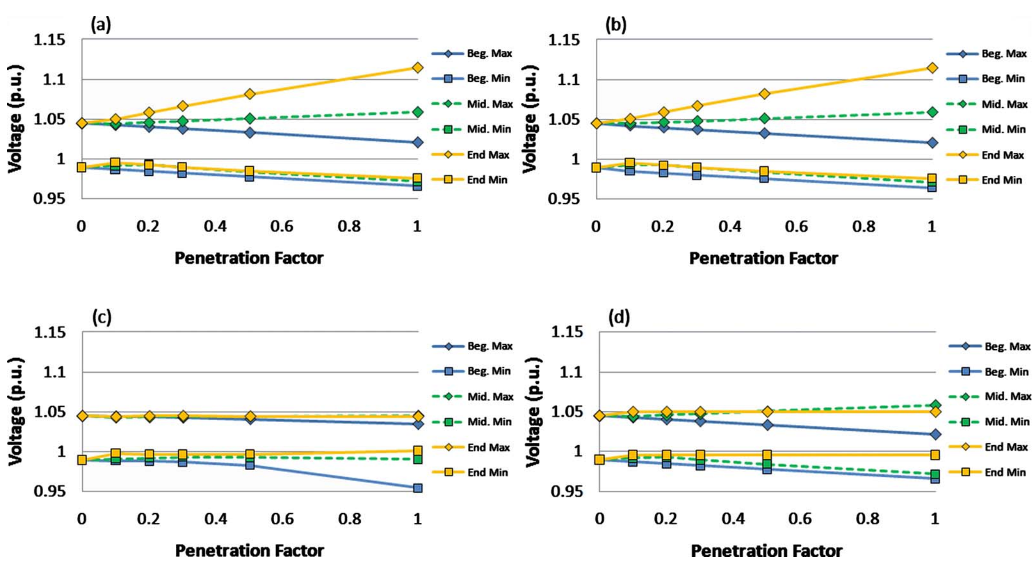

Fig. 11 Voltage regulation for Circuit B: (*a*) baseline, (*b*) PFC, (*c*) LVR, and (*d*) curtailment

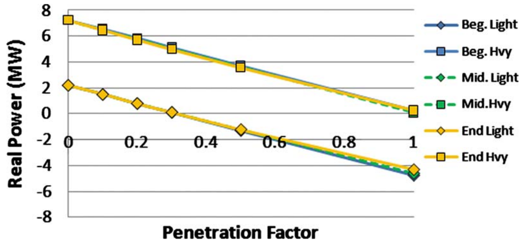

Fig. 13 Circuit B, substation real power flow for baseline

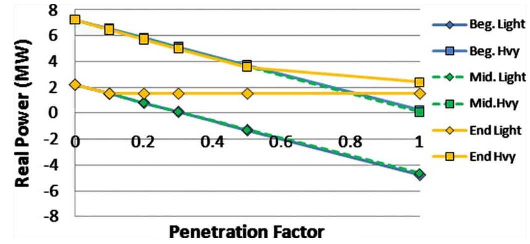

Fig. 16 Circuit B, substation real power flow for curtailment control

but the addition of fixed capacitors on Circuit B results in a reactive power import that is either near-zero or negative, which means the circuit is exporting reactive power (Fig. 14).

4.2.2 Alternate Control Strategies. Again, power factor correction is completely ineffective in addressing voltage regulation problems. LVR can effectively eliminate all overvoltages, but there is still an undervoltage problem associated with adding DG to the beginning of the circuit, as presented in Fig. 11. The LVR control still causes a poor reactive power demand profile, as shown in Fig. 15. Not only does LVR control increase the demand for reactive power at heavy loads, but it also increases the importation of reactive power during light load when the generator is located at the beginning. This is another problematic consequence of installing generators with LVR control.

Results from the curtailment method are mixed and are highly location dependent. When the DG is at the end of the circuit, the power curtailment eliminates both over- and undervoltages throughout the circuit. However, when the DG is located at the middle or beginning, the location of the voltage problems do not coincide with the generator, and the output power is not curtailed—thus, the middle and beginning cases show the same behavior as cases without control. In addition, the 1.0 penetration DG-at-end case invoked power curtailment for both light and heavy loads, which is shown in Fig. 16. A 7 MW DG installation would never function above 4.7 MW, which adds another undesirable constraint to the installation. The conditions for over- and undervoltage are summarized in Table 4, along with the effectiveness of the LVR and curtailment regulation strategies.

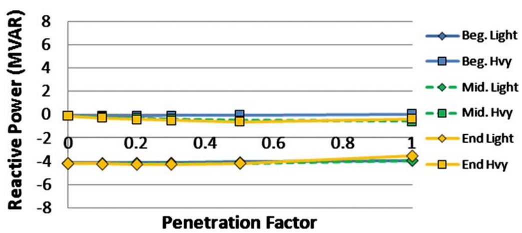

Fig. 14 Circuit B, substation reactive power flow for baseline

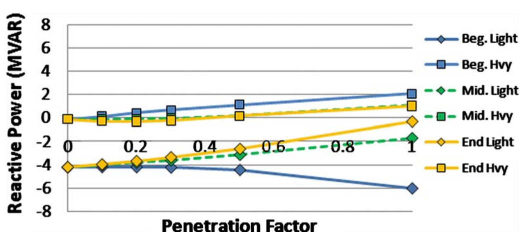

Fig. 15 Circuit B, substation reactive power flow for LVR control

5 Circuit Efficiency

In addition to affecting voltage, power flow through the distribution circuit consumes real power and causes line efficiency losses. As a result, the circuit efficiency will depend strongly on the same factors that affect voltage, which include DG placement, penetration level, and control strategy. The circuit efficiency is defined as the fraction of real power input that is consumed at the load

$$\eta_{\text{circuit}} = \frac{P_{\text{load}}}{P_{\text{substation}} + P_{\text{DG}}}$$

As this definition does not account for transmission or substation/distribution transformer losses, it is not intended to absolutely quantify the effects of DGs on power delivery. It instead provides a simple and useful measure for comparing the variations in distribution line losses attributable to DG parameters.

5.1 Circuit A. The efficiencies of Circuit A with the baseline control are presented in Fig. 17. When the DG is located at the beginning, the efficiency is roughly independent of penetration because the impedance between the generator and the substation is minimal. For the light load cases, both middle and end locations have an initial increase in efficiency with penetration that is followed by a sharp efficiency loss for penetrations above 0.3. At these high DG levels, excess real power flows directly from the DG to the substation and creates additional line losses throughout the circuit. When these circuits are loaded heavily, the DG power is instead consumed locally and the efficiencies remain high.

The LVR control strategy creates an efficiency profile that is similar to that of the baseline control, except that the efficiency losses at light load/high penetration are exacerbated by the increase in reactive power flow as well. All efficiencies for the

Table 4 Summary of voltage problems with Circuit B and the effect of LVR and real power curtailment strategies

	Threshold	LVR	Curtailment
Overvoltage	Mid (50%+)	Fixes	No effect
	End (10%+)	Fixes	Fixes
Undervoltage	Bed. (30%+)	Worse	No effect
	Mid (50–100%+)	Fixes	No effect
	End (50–100%+)	Fixes	Fixes

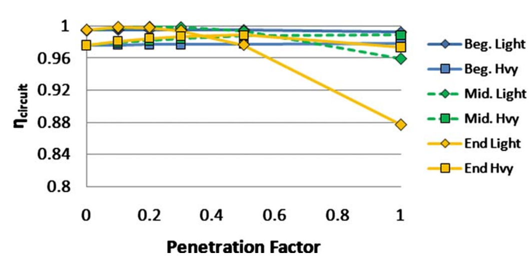

Fig. 17 Circuit A, circuit efficiency for baseline control

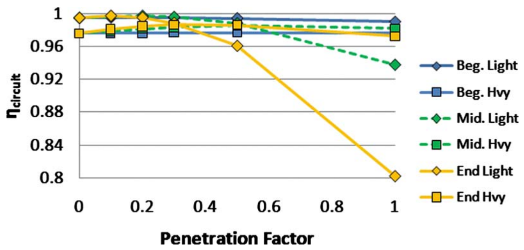

Fig. 18 Circuit A, circuit efficiency for LVR control

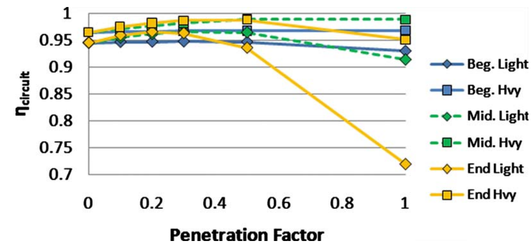

Fig. 21 Circuit B, circuit efficiency for local voltage regulation

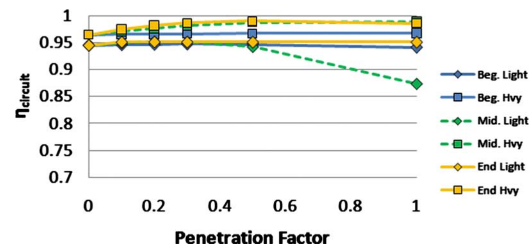

Fig. 22 Circuit B, circuit efficiency for curtailment control

circuit with LVR control are presented in Fig. 18. In contrast to baseline control, the real power curtailment control eliminates the DG-to-substation bulk power transfer that is the source of this efficiency loss. Curtailment control allows the efficiency to remain high for all DG scenarios, as shown in Fig. 19. This efficiency analysis shows that compensating for voltage rise with reactive power consumption not only increases stress on the external electric power system, but it also compromises the efficiency as well. Providing the model citizen load-following behavior instead improves the efficiency associated with installing generators at the middle and end of the circuit, and thus enhances the benefit locally.

5.2 Circuit B. The baseline efficiencies of Circuit B, presented in Fig. 20, demonstrate trends similar to those of Circuit A. One notable difference between the two circuits is that Circuit B has higher efficiency for heavy load than light load, while Circuit A showed the opposite trend. The capacitors installed in Circuit B cause this difference because during light load they generate excess reactive power that is exported through the substation. In the heavy load condition, this reactive power is consumed in the circuit and not subjected to traveling long distances as it does in Circuit A. The same high penetration/low efficiency trends from Circuit A are still observed in Circuit B, although the longer line of Circuit B results in lower numbers overall.

The local voltage regulation control strategy again continues to closely follow the efficiency trends of the baseline case, as presented in Fig. 21. The light load DG-at-middle efficiency is improved with LVR because the reactive power draw of the DG prevents reactive power export in the light load condition. However, the DG-at-end 1.0 penetration case has an even worse efficiency because the reactive power must travel farther than in the DG-at-middle case, and the line impedance is higher on the latter half of the line.

Figure 22 presents the real power curtailment strategy, which generates an excellent efficiency profile for all penetrations when the DG is located at the end, due to the same load-following effect observed in Circuit A. The beginning and middle DG locations are unchanged from the baseline control, due to the lack of corrective action by the DG controller during these situations.

6 Conclusions

The distribution system functions by making assumptions about the circuit that DG installation, including most current fuel cell systems, invalidates and thereby creates problems with maintaining proper voltage. In addition to a baseline case where the generator produces a rated real power output, three alternative control strategies are investigated: power factor correction, local voltage regulation, and real power curtailment. All of these strategies rely only on locally measured information and do not assume communications in the circuit, which is the usual case today. The power factor correction strategy is found to be ineffective at preventing overvoltages and shows poor citizen behavior whenever the baseline control strategy does. The local voltage regulation and real power curtailment have varying effectiveness depending upon DG installation and operating conditions. Local voltage regulation can exhibit model citizen behavior when implemented with DG installations far from the substation, but it can also act as a poor citizen when located near the substation. Real power curtailment may not always work, but it is always better than an interconnection strategy without any control. The efficiency of the circuit also changes with various DG penetrations and locations. In general, the real power curtailment control strategy was most effective at consistently maintaining high circuit efficiencies when it could provide corrective action. This is due to the reduced import and/or export of real and reactive power that results from this strategy, and implies that the "model citizen" load-following behavior for the rest of the electric utility provides localized benefits as well. As no control strategy elicited model citizen behavior in all cases, the results imply that some degree of communication and control on the circuit is needed to allow high DG penetration. Sufficient communication and control may be as simple as a priori knowledge of DG location relative to the substation and other loads, and choosing a proper control strategy accordingly.

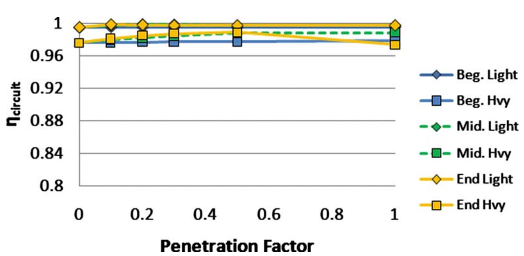

Fig. 19 Circuit A, circuit efficiency for curtailment control

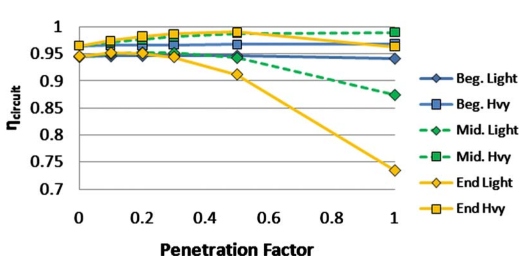

Fig. 20 Circuit B, circuit efficiency for baseline control

Acknowledgment

The current work was partially supported by the Engineer Research and Development Center of the U.S. Army Corps of Engineers under Contract No. W9132T-08-C-0003 with the Construction Engineering Research Laboratory. The authors thank Frank Holcomb and Nick Josefik for their technical and administrative support.

References

[1] Walling, R. A., Saint, R., Dugan, R. C., Burke, J., and Kojovic, L. A., 2008, "Summary of Distributed Resources Impact of Power Delivery Systems," IEEE Trans. Power Deliv., **23**(3), pp. 1636–1644.

[2] Conti, S., Raiti, S., Tina, G., and Vagliasindi, U., 2001, "Study of the Impact of PV Generation on Voltage Profile in LV Distribution Networks," *Proceedings of the 2001 IEEE Porto Power Tech*.

[3] UMIST, 2002, "Integration of Operation of Embedded Generation and Distribution Networks," Report No. K/EL/00262/REP.

[4] GE Corporate Research and Development, 2003, "DG Power Quality, Protection and Reliability Case Studies Report," Report No. NREL/SR 560-34635.

[5] SCC21, 2003, "1547 IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems."

[6] Amin, S. M., and Wollenberg, B. F., 2005, "Toward a Smart Grid," IEEE Power and Energy Magazine, pp. 34–41.

[7] Marnay, C., and Bailey, O. C., 2004, *The CERTS Microgrid and the Future of the Macrogrid*, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA.

[8] Conti, S., Greco, A., Messina, N., and Raiti, S., 2006, "Local Voltage Regulation in LV Distribution Networks With PV Distributed Generation," *Proceedings of the SPEEDAM 2006, Internation Symposium on Power Electronics, Electrical Drives, Automation and Motion*.

[9] Grigsby, L. L., 2007, "Electric Power Generation, Transmission, and Distribution," *Electric Power Engineering Handbook*, 2nd ed., CRC, New York.

[10] Mueller, F., Jabbari, F., Gaynor, R., and Brouwer, J., 2007, "Novel Solid Oxide Fuel Cell System Controller for Rapid Load Following," J. Power Sources, **172**(1), pp. 308–323.

[11] Lasseter, R. H., 2007, "Microgrids and Distributed Generation," J. Energy Eng., **133**(3), pp. 144–149.