

# Potential Problems and Solutions Associated with Distributed Generation

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**Abstract**—This paper concerns possible technical problems which may arise as today’s electric power distribution systems begin to be utilized in very different ways from those for which they were designed. The main point of departure is a transformation of these systems into enablers of many new distributed generators (DGs) which are likely to be connected to the existing networks. The paper considers the interdependencies of electric power system objectives, such as low delivery losses, and the robustness of the future energy system whose dynamics are shaped by the properties of DGs and their dynamic interactions. It is highlighted that in order to reconcile these attributes it will be necessary to monitor, communicate, and control these systems more actively than at present. This will require technologies beyond current SCADA.

**Keywords:** Future Distributed Energy Systems, SCADA, AC Optimal Power Flow (OPF), Small-signal Instability, Voltage Dispatch, Smart Grids, Distributed Generation, Beyond SCADA.

## I. INTRODUCTION

Recent pressures for more sustainable energy have led to active efforts toward deploying smaller-scale power plants close to the end users. These plants are broadly referred to as distributed generation (DG) and their distinction from the large-scale central generation plants is often times blurry. For purposes of this paper we are only concerned with the small-scale generators located at the distribution side of the electric power grids. Such DG units offer potential advantages, for example, increased efficiency through waste heat recovery, loss power reduction and easier access to backup power during power shortages. Some DGs also fall under the category of renewable resources and are cleaner than the traditional large fossil fuel plants. Since deployment of renewable power is greatly encouraged through various state policies, it is likely that the penetration of at least renewable DGs will increase in the near future.

In order to provide sound support for integrating DGs seamlessly into the legacy distribution systems, it is essential to: (1) identify potential technical problems brought about by the DG deployment; (2) assess

current operating, maintenance and planning practices with respect to their ability to best integrate and utilize these new energy resources on behalf of the end users; and, (3) introduce technically innovative ways for sensing, monitoring, and coordinating future distribution systems in order to facilitate the best integration of DGs without creating reliability and safety problems. While these objectives are self-explanatory, in order to actually engage the technical effort of owners and operators of the electric power distribution systems, research must be done to make the case that this is indeed needed. This paper is a step in this direction, as it concerns questions 1) -3) and illustrates these issues on an example electric power distribution power system.

This paper starts by highlighting the evolution of multiple objectives as today’s distributed electric power systems transform into future distributed energy systems (Section II). As different candidate DG units request to be integrated, today’s electric power distribution system may be or may not be capable of accommodating their requests while at the same time ensuring that the objectives of the grid itself are met. Next, in Section III results of applying today’s criteria to selecting candidate locations of DGs are illustrated using the example network shown in Figure 1. In Section IV candidate locations for DGs obtained using today’s static decision making tools are analyzed for their robustness with respect to small signal perturbations. In Section V we point out the key role of high technologies in facilitating deployment of otherwise unacceptable candidate DGs because of their contribution to small signal instability. It is suggested that a careful coordination of the dynamics of candidate DGs within the system dynamics could overcome these problems. It is striking that such solutions conceptually eliminate the need for otherwise rigid exclusive tradeoff between efficiency and robustness. In the concluding Section VI we stress that the ideas in this paper deserve further major R&D effort if we are to fully transform today’s electric distribution systems into the highly efficient, flexible and robust future distributed energy systems. A currently taken approach of developing new

DG technologies as though they would be stand-alone resources falls short of fully integrating these novel resources to ultimately make the most out of them. The need for novel coherent policies capable of supporting value-based support of integrating DGs is described elsewhere [1].

## II. MULTIPLE OBJECTIVES IN FUTURE ENERGY DISTRIBUTION SYSTEMS

Historically, the electric power systems have evolved by building large-scale power plants to meet forecast system demand using integrated resource planning (IRP). The main objective of IRP has been to provide sufficiently diverse mix of large-scale generation capacity at a reasonable cost. Electric power transmission and distribution systems were built to ensure that power can be delivered to the end users even when some key equipment components are out of operation.

With the recent trend toward deploying smaller-scale energy resources closer to the end users, it is necessary to revisit the planning and operating practices of the electric power transmission and distribution systems. The MV/LV electric power distribution systems, in particular, are expected to enable integration and utilization of many unconventional small resources, generally referred here to as the DGs. Deployment of many of these DGs is initiated and requested by the end users and not by the utilities. Shown in Figure 1 is a schematics of such an evolving future energy distribution system. The electric power distribution system (shown in black) is supplied by the electric power source connected to bus 1. Typically this bus represents a point of connection between the transmission and distribution system and is generally modeled as an ideal slack source with constant voltage magnitude and phase angle for purposes of planning and operating the distribution systems.

For illustrative purposes, shown in grey are two small combustion plants connected to buses 13 and 14. In the future the same electric power distribution system may be expected to serve a small hydro plant (shown in blue) and/or small wind plant (shown in green). Such a typical future distributed energy system will have to rely on the distributed electric power system as the key enabler for integrating and utilizing new small DGs.

In this paper we consider the problem of integrating DGs into the existing electric power distribution systems in light of their transformation into the future distributed energy systems. In the future energy systems objectives of the electric power distribution system must be reconciled and coordinated with the objectives of many often unconventional technologies on the side of its end users (both DGs and customers). The main objective of a DG is to produce energy and make profit. Since most of the DGs have larger capacity than what is needed by the

local demand, a DG unit is better of being integrated in the local network.<sup>1</sup> However, this integration often requires extensive studies by the local utility to whose grid a DG wants to connect. In order to facilitate this process, there efforts are under way toward establishing standards for interconnecting DGs. Viewed strictly from the point of grid performance, one of the main criteria has been to design and operate the distribution systems with as little loss as possible. It is also critical to recognize that as an attempt is made to achieve such economies of systems in the future distributed energy systems, one may need to sense, communicate, and control the dynamics of such systems. This is in contrast with today's Supervisory Control and Data Acquisition (SCADA) which only samples and processes quasi-stationary data and not dynamic data.

## III. LOCATING DGs BASED ON STATIC UTILITY CRITERIA

In the past the only objective of the distributed electric power systems has been to optimize design and operations of the grid for the anticipated demand. Generation was assumed to be available and placed at the distribution substations, and as a rule, the utilities did not actively interact with the customers. As the industry transforms, utilities are likely to continue to use the same planning and operating criteria, unless technical and policy rules are designed to support their modifications. Therefore, using current criteria and viewing the objectives strictly from the point of grid performance, one of the main criteria has been to design and operate the distribution systems with as little loss as possible. In the past this was basically controllable by adding a large number of capacitors and by pre-programming to support power delivery according to the daily load curves. In the first part of this paper we summarize the recent results from [3] concerning the effects of DG locations on loss minimization. These results provide the basis for a simple quantifiable rule concerning monotonic dependence of DG locations and the resulting distribution losses.

In the second part of this section we recognize that some of the DGs may not be technically feasible because their presence leads to a non-convergent power flow solution. This has been recognized and has led to the recommendations to install DGs at the places of weak voltage support. It is unlikely that the deployment of DGs for supporting delivery of power from elsewhere can be made cost effective, unless the DGs are also used to produce real power. In particular, we suggest that, instead of building DGs with sole purpose of supporting voltage by producing reactive power only, it may be possible to dispatch existing DGs in order to ensure

<sup>1</sup>This is also very important for providing back-up power to the end users supplied by the DG in case this fails.

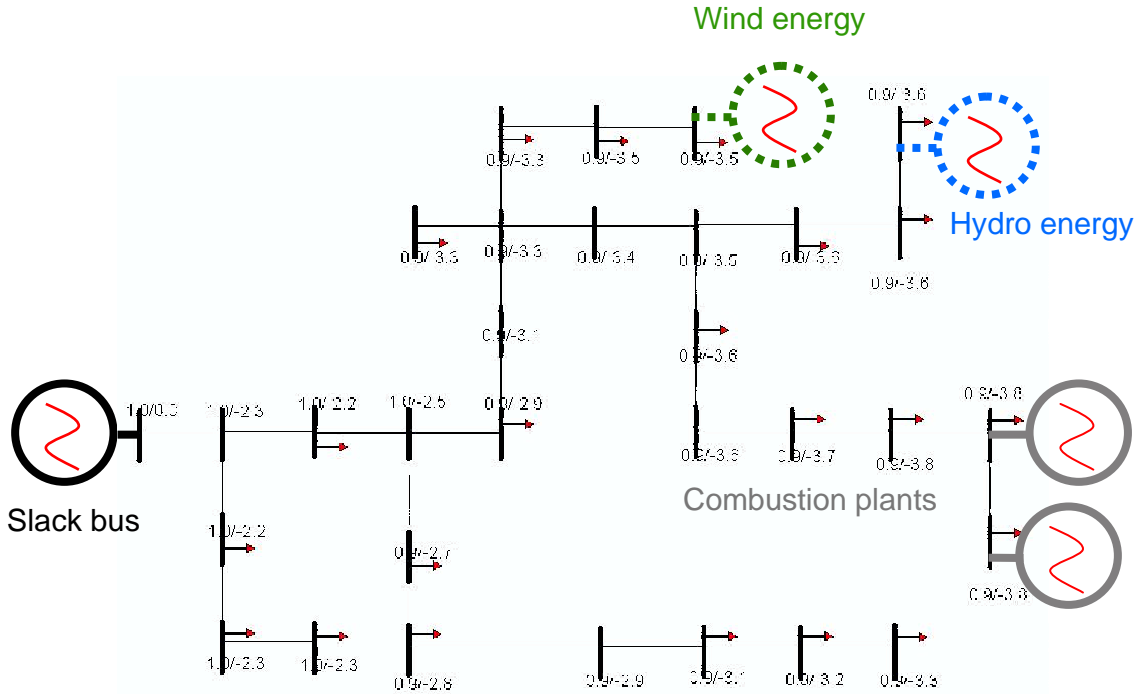


Fig. 1. A typical future distributed energy system

acceptable voltage profile to the end users. We therefore consider the need for voltage support for both optimizing distribution loss and for ensuring feasibility of the power flow and illustrate the results obtained using a test system chosen. The static interdependence of distribution losses and the voltage profile is influenced by both choosing the location of DGs and by the system-wide on-line voltage dispatch using, for example, an AC optimal power flow (OPF). As more and more distribution systems have SCADA, dispatching voltage on-line could become an inherent part of operating rules in future energy systems.

#### A. Optimal placement of DGs for loss minimization

Earlier methods for placing capacitor banks in order to minimize distribution losses in the electric distribution power systems will need to be enhanced by optimizing placement of candidate DGs. Because of this, it is important to establish guidelines for valuing various DGs for their relative impact on system-wide distribution losses. Here we summarize the results reported in [3] and illustrate them on the test system shown in Figure 1 for completeness. In particular, it was shown in this work that for radial distribution systems characterized by the unidirectional flows from the substation toward the end users, the larger electrical distance between the substation and the end users, the higher delivery losses. Based

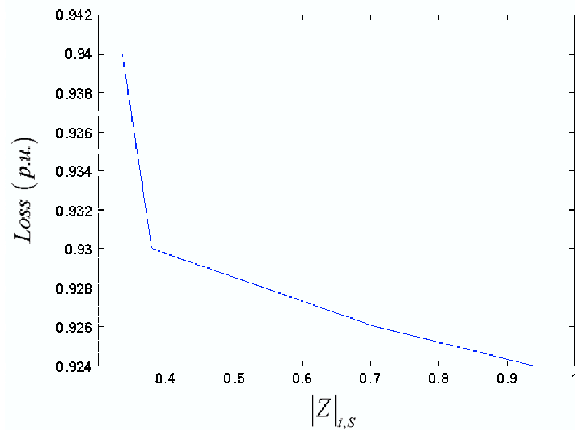


Fig. 2. Transmission Loss vs. Electrical Distance

on this intuitively appealing engineering observation, a guideline for placing DGs as far as possible from the substation was proposed. For the system shown in Figure 1 such an optimal placement of two combustion power plants of real and reactive power capacity  $0.7MW \leq P_{DG} \leq 0.8MW$  and  $-0.4MVar \leq Q_{DG} \leq 0.4MVar$ , respectively, was considered. According to [3], optimal locations for these DGs will be at buses 13 and 14.

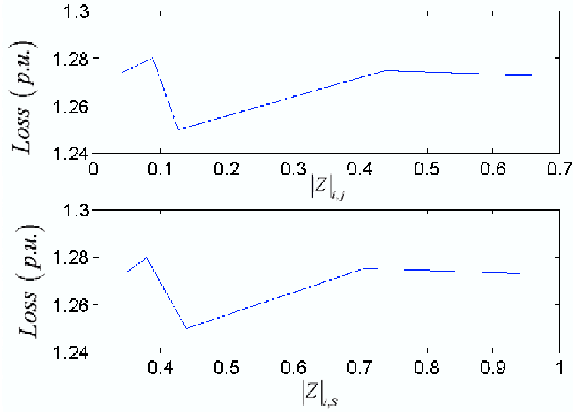


Fig. 3. The case of non-monotonic dependence of loss on the electrical distance

In order to further test this rule-based choice, an exhaustive assessment of all candidate locations was carried out using an AC OPF. The performance metrics used is total loss and the decision variables were both real power and voltages of the candidate DGs. The AC OPF confirmed the engineering based rule proposed in [3]. Shown in Figure 2 is a typical dependence of system loss on the electrical distance between the slack bus and one of the DGs. It can be seen that the further a DG is from the slack bus, the smaller system losses. This is the case for various combinations of interest, such as having:

- Two DGs close to the slack bus and close to each other;
- One DG close to the slack bus, and the second DG far from the slack bus;

The only anomaly found is when one DG is very close to the slack bus and the second DG also close or very close. This is shown in Figure 3 in which one can see that the system loss first decrease with the electrical distance between one DG and the slack bus ( $|Z_{i,s}|$  and the electrical distance between the two DGs ( $|Z_{i,j}|$  located close to the slack bus), reaches the minimum and then increases with the electrical distance. Based on these results, it would be possible to define guidelines for compensating DGs when they contribute to reduced delivery losses.

### B. Dependence of feasible locations for DGs on system-wide voltage profile

Here we assess the dependence of feasible candidate DG locations on the system-wide voltage support. In particular, we show a comparison between the results when the voltage is computed using an AC OPF-based and the basic power flow results which assume the

same voltage as without the DGs. It is essential to do this in order to make deployment of the future DGs at some future candidate locations feasible although these locations do not result in a feasible power flow. Not having a convergent power flow is often related to the problem of not being able to transport power from the locations of DGs where it is produced to the customers because of the insufficient voltage support. The first indication of this problem is that for some locations of DGs a power flow solution does not exist. We show here that for the system given in Figure 1 when optimizing voltage settings in a coordinated way in order to minimize total distribution losses by means of an AC OPF this technical problem goes away. Assuming that DGs participate in voltage dispatch within their available reactive power limits, much the same way as the other power plants, it is shown that while computing optimal voltage dispatch by assessing feasibility of candidate locations, all candidate locations for the two DG units of interest were feasible. On the other hand, exhaustive power flow computations using Graphical Interactive Power System Simulator (GIPSYS) have shown that many combinations of candidate DG locations were not feasible, in the sense of not being able to obtain a convergent power flow solution with the DG units added to the system, and modeled as any other power plants ("PV" units). On the other hand, relaxing the requirement for the DGs to support their voltage at the voltage value which existed at the candidate locations prior to adding the DGs resulted in feasible power flow solutions. The DG units were modeled as the "PQ" units in this case. A representative comparison of the voltage magnitudes and the line phase angle differences in two cases is shown in Figures 4 and 5, respectively. It can be seen that voltages are generally higher when optimized to minimize system loss, while phase angle differences are smaller than when not optimized to support integration of the candidate DG units. This result is straightforward to explain, since for the given power demand, the minimal loss is the result of smallest currents, and highest voltages.

Based on these results, it is straightforward to define quantifiable rules concerning integration of DGs into the existing distribution systems. If the utility does not have SCADA and does not optimize its voltage profile on-line, is more effective to relax the requirement for DGs to support voltage at their locations unconditionally. On the other hand, if the utility has the ability to dispatch voltage on-line by means of AC OPF, it is more beneficial to the system as a whole to have DG units participate in this dispatch.

In order to take advantage of AC OPF-based voltage dispatch to support such economies of system [2] which would otherwise not be possible, future distributed energy systems will need both SCADA and computer

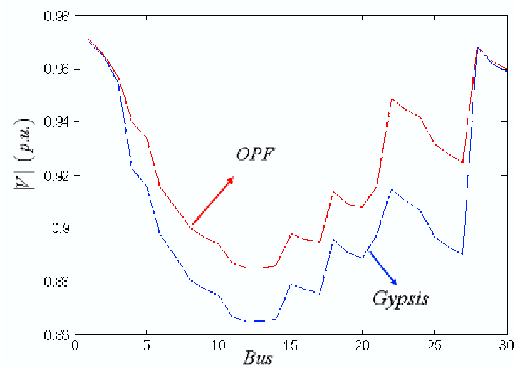


Fig. 4. Comparison of bus voltages for the cases of power flow (Gypsis) and AC OPF (OPF)

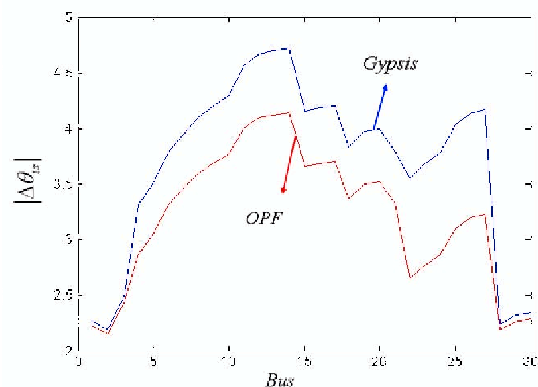


Fig. 5. Comparison of line phase angle differences for the cases of power flow (Gypsis) and AC OPF (OPF)

tools such as AC OPF for computing the on-line voltage adjustments. Given that today most of the distribution power systems do not rely on on-line monitoring and dispatch, it is essential to understand the potential of doing this in order to accommodate their transformation into the most effective enablers of future DGs. In order to give incentives to the power companies to install the SCADA in distribution systems and to actively utilize it for enabling the adaptation of the existing system to operate with DGs and other novel equipment, it is essential to design supporting policies. In [1] we introduce an approach for quantifying potential longer-term benefits brought about by deploying SCADA to support penetration of DGs and comparing these benefits to the cost of SCADA. This approach could be used in the future to design policies which encourage changes of current operating and planning practices toward active monitoring and on-line adaptation of available resources.

#### IV. POTENTIAL SMALL SIGNAL INSTABILITIES

In this section we analyze possible small signal instabilities caused by placing and operating new DG units within the existing distribution systems. We point out in this section that often even the most attractive solutions obtained using static optimization may not be robust with respect to small perturbations. The earlier work has already indicated that potential technical problems may be seen in frequency instabilities [4].

In this section we summarize the results of our extensive small signal stability studies for the system shown in Figure 1 above. In particular, we stress that it is possible to identify fundamental causes of potential instabilities, much the same way as one could explain fundamentals of selecting optimal locations of DGs for loss minimization. Of particular interest are relations between potentially optimal loss-based locations of the new DGs and their effect on the small-signal system stability. Using a small-signal dynamic model whose details are given in [5], it indeed turns out that the energy system with two combustion power plants located at buses 13 and 14 which result in the optimal loss is indeed small signal unstable. Since small-signal instability is one form of non-robustness, this is a clear indication that making the most out of the future energy systems may lead to other than static technical problems. This, in turn, requires further understanding of fundamental causes of such problems, and design of possible solutions.

As one step in this direction, our simulations have shown that loss minimization and system instability are not directly related. It is important to observe that the instability conditions, instead, depend qualitatively on the type of power plants, system characteristics and their locations. A detailed analysis of several types of small-signal instability is presented in [5] which suggests that major instabilities could arise by locating:

- *Case A*: DG units close to each other, but far away from the slack bus;
- *Case B*: one DG unit close to slack bus and the other far from it;
- *Case C*: both DG units close to the slack bus and close to each other; and,
- *Case D*: one DG unit very close to the slack bus, and the second DG also close to the slack bus. .

It is described in [5] how these cases are qualitatively different with respect to causes of instabilities and the effects of electrical distance. For mathematical models and analysis, see [5]. Here we summarize the qualitative findings of such modeling and analysis.

One example of *Case A* scenario is the system when two combustion plants are placed at the optimal loss locations 13 and 14. The state variables of both DGs contribute to the unstable eigenvalue of a dynamic

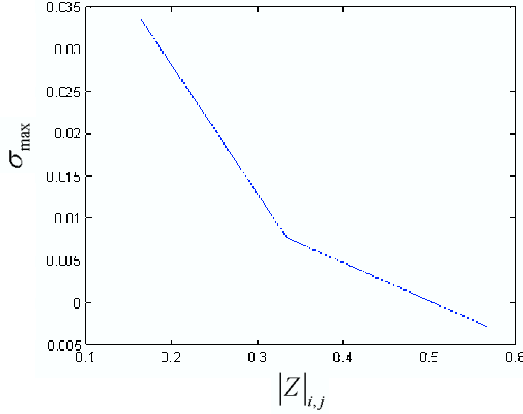


Fig. 6. Degree of instability as a function of electrical distance between the DGs

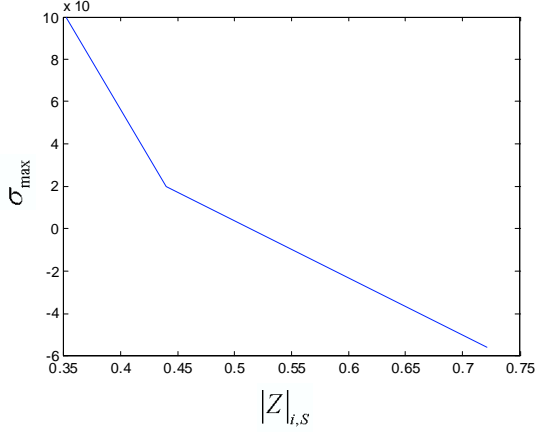


Fig. 7. Case B: Unstable interactions between the slack bus and one DG unit

system obtained when linearizing the nonlinear model around the AC OPF-based solution. The real part of the unstable eigenvalue  $\sigma_{max}$  is used as a possible measure of instability. Shown in Figure 6 is how this value becomes smaller as the distance between the two DGs increases (for example, for locations 13-12 and 13-11). The plot indicates that placing DGs further apart would make their interactions less unstable, although not fully stable before certain critical distance is reached. It was found experimentally that the critical distance between the two DGs is around .5p.u.

Cases B and C have similar qualitative behavior to Case A. Shown in Figure 7 is an example of Case B. Namely, the degree of instability (magnitude of  $\sigma_{max}$ ) decreases as the distance between the slack bus and the electrically close DG increases. This is as expected, because the interactions between these two plants are weakened. A participation factors-based analysis shows that the unstable eigenvalue is primarily contributed by the states of the DG which is electrically close to the slack bus.

In contrast with cases A, B and C, Case D is much

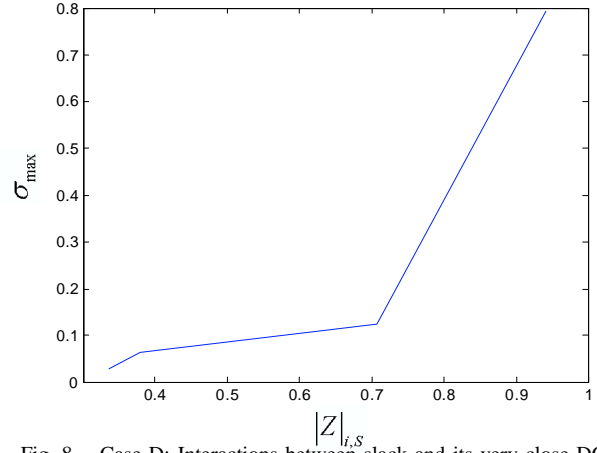


Fig. 8. Case D: Interactions between slack and its very close DG

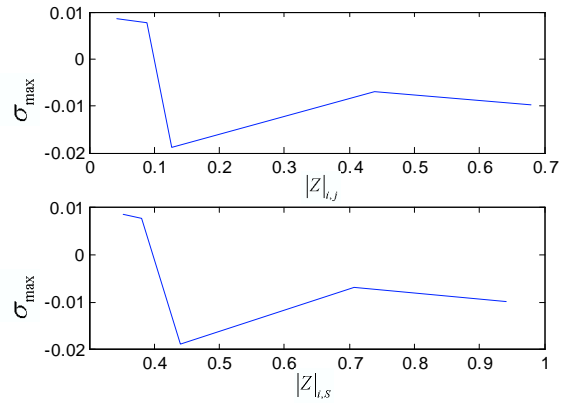


Fig. 9. Case D: Interactions between the slack bus and its very close DG units

more complex and not straightforward to predict without relying on the analysis of the dynamic models. The main contributing variables to the instability in this case are the coupling variables between a DG and the rest of the system. In the mathematical model used in [5] this coupling variable is real power generation of the DG. Extensive simulations show that if one DG is placed extremely close to the slack bus, the instability is more pronounced (larger  $\sigma_{max}$ ) and the degree of instability actually increases with the increase of electrical distance between two DGs, as shown in Figure 8. However, when the distance between the DGs decreases, the unstable eigenvalue becomes ultimately stable as shown in Figure 9.

A possible explanation for this phenomena is that the interactions between the DGs and the DG and the slack bus cancel each other if the DGs are sufficiently close to each other. Depending on the actual electrical distances, it is possible to also have an instability characterized by a small  $\sigma_{max}$  contributed mainly by the interactions of states associated with the DGs. In this case the oscillations between the individual DGs and the slack bus are in opposite directions and cancel each other,

but not completely. We have also found cases when the oscillations between the slack bus and the individual DGs are such that they result in combined high instability dynamics. The difference between these two cases can be identified by observing the direction of power generated by the two DGs (their coupling variables with the rest of the system [6]). When the two DGs produce power which is in the same direction the oscillations reduce, and, other way around, when the power generated by the two plants is in opposite direction, the oscillations are enhanced. These cases are described to point out that it may be possible to create guidelines for placing DGs which account for their effects on system robustness. However, these rules are much more complex than those concerning static optimization.

#### V. POTENTIAL ROBUSTNESS ENHANCEMENTS BY SENSING, COMMUNICATIONS, AND CONTROL

Based on the analysis above, it is critical to recognize that as an attempt is made to achieve economies of systems in future distributed energy systems, one may need to sense, communicate, and control the dynamics of such systems as well. This is in contrast with today's SCADA which only samples and processes quasi-stationary data and not dynamic data. Theoretical details for possible solutions using sensing, communications and control are presented in [5].

Here we briefly observe that, to start with, the system must be fully controllable and observable in order to stabilize initially unstable cases. It is assumed that each DG combustion plant is equipped with a governor control. It is straightforward to show that for the case of optimum loss placement (DGs at connected to buses 13 and 14), the system is fully controllable. Also, each DG is locally controllable and stabilizable.

The system-wide stabilization will depend on the characteristics of the system matrix as well as on the dynamics of the DGs themselves. The unstable cases analyzed above are only result of system matrix being affected by the coupling among the local dynamics. Qualitatively different instabilities may occur if the local DGs are intermittent and/or not equipped with local controllers. For example, it is well known that hydro plants are potentially unstable because of the non-minimum phase properties of their closed-loop transfer functions. The effect of large penetration of solar power on system robustness needs to also be studied in the future.

In this paper we have limited our small-signal stability analysis to future distributed energy systems with combustion plants only; these exhibit local stability, and the instabilities could occur due to unusual network interactions among the DGs. It is because of this that the location in the network is a determining factor to possible instabilities.

Due to space limitations questions concerning trade-offs between fast communications and more advanced control of DGs for stabilizing unstable cases is omitted here. A detailed treatment can be found in [5].

#### VI. CONCLUSIONS AND FUTURE WORK

This paper points out that, as the utility studies are carried out when considering new DGs, it is necessary to develop a systematic framework for assessing potential technical problems unique to the transformation of electric power systems into future energy systems. In particular, the grid objectives must be such that they reconcile the tradeoff between its performance and robustness. This points into the need for rule-based protocols when deploying and operating future distribution energy systems which go beyond today's scenario studies by the utilities and the reliance on current interconnection standards.

Since the electric power system was not planned for serving these new resources, it is important to develop systematic ways of enhancing the existing electric power grids according to well-defined and quantifiable performance objectives. This is a challenging task. In order to document the need for such enhancements, we describe in this paper possible interdependencies between the objectives of the grid, such as the feasibility of power flow, minimization of the distribution system losses and the robustness of the system with respect to small signal perturbations due to parameter, measurement and equipment status uncertainties. Systematic criteria for assessing potential of integrating DGs into the existing electric power distribution systems must account for these interdependencies. In particular, we stress that it is conceptually wrong to use one-size-fits-all criteria. The other extreme of doing excessive studies for each candidate DG is very complex and does not lend itself to justifying one choice over the other according to simple to grasp rules. The R&D challenge is, therefore, to develop a framework for transforming detailed engineering studies into a set of quantifiable rules which candidate DGs must meet in order to connect to the system. Furthermore, we suggest in the later part of this paper that if planning and operations of current electric power distribution systems are enhanced to transform the grid into an active enabler and coordinator of future energy distribution systems in which its end users (DGs and customers) are active decision makers, much can be gained as measured in terms of economies of systems. Recognizing this calls for non-traditional operation of electric power distribution systems with much sensing, actuation and communications. While this wave of "smart grids" has already begun under different initiatives, the fundamental challenge remains concerning rules for how much information should be

processed, why and how. Developing user friendly sensing, communications, and control tools to enable as high penetration of as many, often unconventional, distributed resources as possible is essential for future distributed energy systems with well quantifiable tradeoffs forms a major R&D challenge to our community.

Based on the technical results we have concluded that an effective integration and utilization of DGs requires planning procedures which involve assessment of possible technical problems and possible ways of eliminating these problems. More generally, we anticipate that near real-time coordinated monitoring and decision making will become essential for deploying large number of DGs without creating technical problems. This is currently not the practice, as most of the distribution systems are not equipped with any Supervisory Control and Data Acquisition (SCADA) systems. The results are illustrated and could be used to further establish guidelines for locating DGs in order to avoid such problems. Finally, future work is suggested to consider possible solutions to such dynamic problems and opening the possibility for wider deployment of DGs without losing robust system performance.

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