IMPACTS OF DISTRIBUTED GENERATORS ON THE OSCILLATORY STABILITY OF INTERCONNECTED POWER SYSTEMS

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ABSTRACT

Penetrations of distributed generation into interconnected power systems are gradually and continuously affecting the stability of these systems. In this paper, the impacts of distributed synchronous generators on the oscillatory stability of interconnected power systems are studied. Through computations of the feasibility boundaries corresponding to Hopf bifurcations of electromechanical oscillatory modes, operating limits for a stable operation of an interconnected system under small disturbances, such as predictable changes in loading conditions, are determined. The effects of distributed synchronous generators under different operating conditions are also investigated. Computer simulation studies presented show that the penetration of a distributed generator may cause local or inter-area oscillatory instabilities in the system.

I. INTRODUCTION

The necessity of higher energy efficiency and energy saving have motivated deregulation of electric utilities in some countries. Deregulation has encouraged the move toward distributed generation, where many smaller generating plants located close to the major loads, as opposed to a few large centrally located power stations, are penetrating into the interconnected system.

For many years, electric power systems have been operated within boundaries defined by conservative reliability criteria. And as higher efficiency is desired, especially as deregulation is encouraged, the operators are forced to operate the system very close to the operating limits.

With the new trend in the power market, intra-area (local) and inter-area transactions of electricity have been greatly proliferated. Typically, these transactions are of considerably shorter duration and larger variety than those vertically integrated utility structures, where utilities control power generation, transmission and distribution. Naturally, this leads to frequently changing operating points and load flow patterns that may cause stability problems. Therefore, stability analysis of a system under such transformation becomes more critical and difficult than it was before.

Stable operation of an interconnected power system under small disturbances such as predictable changes in loading conditions and power transfers involves small-signal stability analysis of the system's operating points. Following such changes, the characteristics of the oscillatory behaviour of the system depend on the local stability of the operating points. In this paper, oscillatory stability analysis has been studied within this frame.

Some examples for the studies on the impacts of the distributed generation on transient and voltage stability can be found in the literature, for example in [1]-[3]; whereas, in this paper, the impacts of distributed generators on the oscillatory stability are our main interest. Through calculations of the feasibility boundaries associated with Hopf bifurcations of oscillatory modes, we can determine the conditions for a stable operation of distributed synchronous generators in accordance with the rest of the network.

II. OSCILLATORY STABILITY AND FEASIBILITY BOUNDARIES

The quasi-stationary dynamics of large electric power systems can be modeled by parameter dependent differential-algebraic equations (DAE) of the form

$$\begin{aligned} \Sigma : \dot{x} &= f(x,y,p) \qquad f:\Re^{n+m+p} \rightarrow \Re^{n}, \\ 0 &= g(x,y,p) \qquad g:\Re^{n+m+p} \rightarrow \Re^{m}, \\ x \in X \subseteq \Re^{n}, &\quad y \in Y \subseteq \Re^{m}, \quad p \in P \subseteq \Re^{p}, \end{aligned} \tag{1}$$

where in the state space, $X \times Y$, dynamic state variables, x, and instantaneous state variables, y, are distinguished. The parameter space and its variables are denoted by P and p, respectively [4].

The feasibility region for the differential-algebraic model (1) of a power system has been introduced in [5] to distinguish the operating points of the system at which the system can be operated without loss of local stability. Within this region, the system operates at a locally stable equilibrium and can be driven to any point in the region by slow parametric variations without losing local stability.

Feasibility region and boundary [5] calculations are crucial to determine preventive measures against an occurrence of instability. Designing control schemes and determining operating conditions require careful assessments of the feasibility regions.

The feasibility boundary has been analyzed in Theorem 1 in [5] and it was shown that it corresponds to three zero-sets of functions which are related to the principal codimension one bifurcations, the saddle-node and Hopf-bifurcations, in case of a smooth induced dynamics and the singularity induced bifurcation in case of loss of stability along the singular set.

Essentially, the Hopf bifurcation related segments of the feasibility boundary occur as a simple pair of complex eigenvalues transversally crosses in complex plane from the negative in the positive half-plane [6]. This process is closely related to oscillatory instabilities as it generates (or diminishes) periodic orbits. An algorithm that calculates these segments has, for example, been considered in [7]. These algorithms involve a procedure to find equilibria which have eigenvalues on the imaginary axis. Essentially, they have two stages: the calculation of a single point on the feasibility boundary and then the calculation of the feasibility boundary segment which is near the point calculated ("continuation" techniques).

III. IMPACTS OF SYNCHRONOUS GENERATORS ON THE OSCILLATORY STABILITY

Penetrations of distributed synchronous generators can change the oscillatory stability of the whole system, depending on how they change the structure of the interconnected system and its operating point. From the mathematical point of view, a connection of a generator results in an expansion of the degrees of the parameter and state spaces, see (1). A new operating point is established and the stability of this point must be studied through the calculation of the feasibility boundaries.

Computation of the feasibility regions and their boundaries gives us important clues how the system must be operated without leading it to instability. In our studies, we select the parameter sub-spaces of load reference set points and speed droops of the governors to illustrate the feasibility regions. The calculation of the feasibility regions on the parameter sub-spaces of load reference set points directly shows the constraints on the real power transfers between the generator units and the other regions of the interconnected system.

The impact of distributed synchronous generators on the stability can be studied in two different conditions of interconnection:

1. The stability of the connection without any power transfer between the distributed generator and the rest of the system: If we think of a situation where no power transfer exists, we assume that the operating point concerning the rest of the system before the connection remains the same. But this does not necessarily mean that the stability of the interconnected system does not change, because the additional new parameters and states establish the new operating point and certainly change the stability of the operating point. This implies that the interconnected system might also lose its stability after a connection of a distributed generator even if there doesn't exist any power transfer between the generator and the rest of the system.

2. The stability of the connection under a power transfer between the distributed generator and the rest of the system: We can determine the oscillatory stability limits under different power transfer conditions through computations of feasibility boundaries calculated in parameter sub-spaces of load reference set points.

By a clustering method that uses coherency and modal analysis, we can identify the coherent groups of generators or buses which participate in different sets of oscillatory modes [8]. Thus, in a systematic way, we can approach the oscillatory stability problem caused by the penetration of a distributed synchronous generator. For example, an inter-area oscillatory instability caused by the connection of a distributed synchronous generator can be remedied by an area-wise control that includes the coherent group of participating generators to which the distributed generator belongs [9].

IV. SIMULATION OF CASE STUDIES

Here, we consider a system of two weakly connected areas to show the effect of a penetration of a distributed synchronous generator on the local and inter-area oscillatory stability of the system. In Figure-1, a synchronous generator (generator no.6) with a size quite smaller than the other generators is connected to the network with its local load. The system is represented by a model that involves its real-power-angle dynamics [4], since electromechanical oscillations and the stability associated with these oscillations are of interest. The generators equipped with speed governors and turbines are connected to the system with their local loads.

A connection of a synchronous generator to Area 1 increases the number of local oscillatory modes of the area by one. The electromechanical modes inherent to the system before the generator is connected and the additional mode (mode no.5) caused by the interconnection are listed in Table-1.

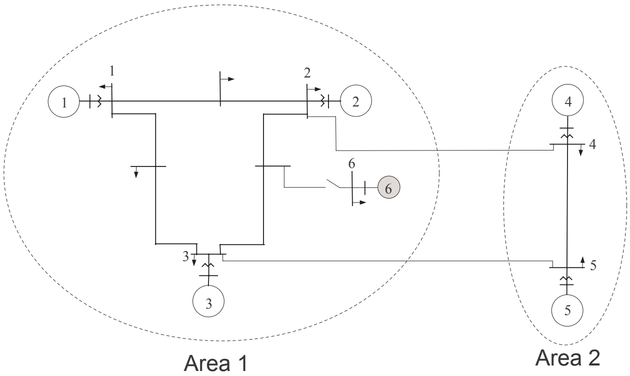

Figure 1. Penetration of a distributed generator in Area 1

The distributed generator can participate in some of the oscillatory modes at some extent. By coherency and modal analysis, we can distinguish the modes in which the distributed generator participates and the coherent groups of generators to which the generator will join with respect to these modes [8]. In this case, the distributed synchronous generator belongs to Area 1 with respect to the inter-area oscillatory mode (mode no. 1). That implies, under a disturbance which excites the inter-area mode, the distributed synchronous generator will start to oscillate coherently with the other generators in Area 1 against the generators in Area 2.

Table 1. Electromechanical oscillatory modes

Oscillatory Mode No.	Imaginary part of the corresponding eigenvalue
1	$\pm 4.1i$
2	$\pm 10.3i$
3	$\pm 12.8i$
4	$\pm 13.8i$
5	$\pm 34.6i$

A connection of a distributed generator, even without a power transfer between the generator and the rest of the system, may cause an oscillatory instability. To show this with an example, we compute the feasibility region and its boundary in the parameter sub-space $R_2 \times R_4$, where R_i is the speed droop of the governor [10] which belongs to the generator i, and we observe the location of the operating point before and after the connection. The feasibility boundary consists of Hopf bifurcation points associated with the inter-area mode and a local mode of Area 1.

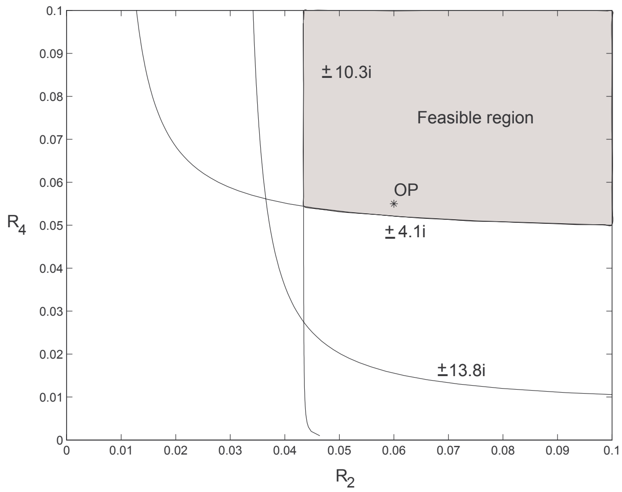

Figure 2. Feasibility region in $R_2 \times R_4$ before the connection of distributed synchronous generator

As can be seen from the figure, the operating point OP before the connection falls in the feasible region whereas after the connection, the same operating point falls in the infeasible region, see Figure-1 and Figure-2. The oscillatory instability in this case is associated with one of the local modes of Area 1. This instability mainly occurs as a result of improper control and the loading conditions of the additional distributed generator.

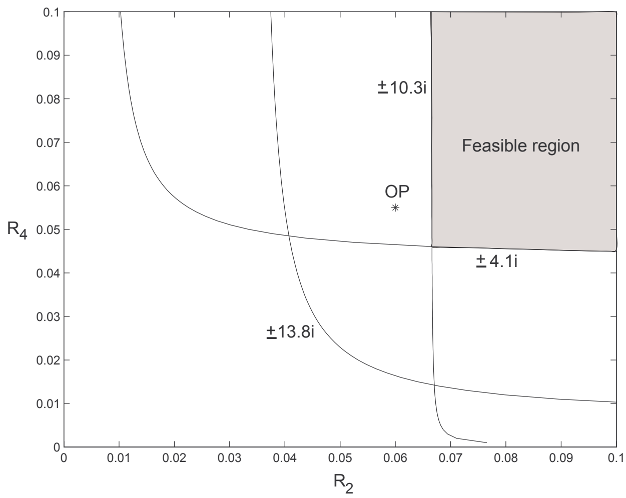

Figure 3. Feasibility region in $R_2 \times R_4$ after the connection of the distributed generator

Next, we consider the impact of a distributed generator on the oscillatory stability under the existence of a power transfer. In our case study, it is assumed that, for a period of time, the surplus generation at the location bus no. 6 will be used for the load increase in the region where normally fed by the generator no. 3 or vice versa.

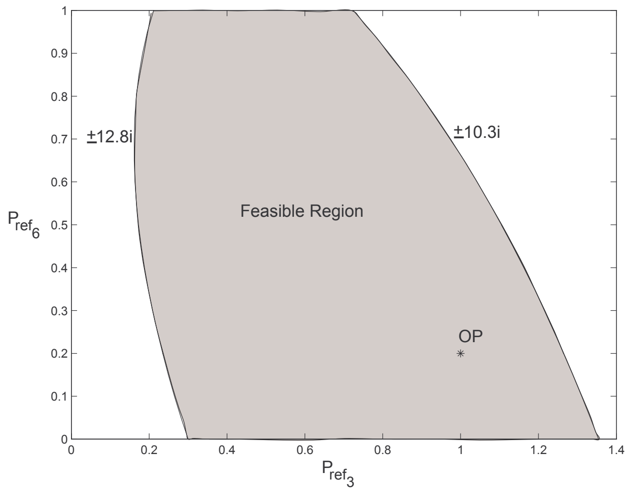

Figure 4. Feasibility region in $P_{ref_3} \times P_{ref_6}$ bounded by Hopf bifurcations of local oscillatory modes

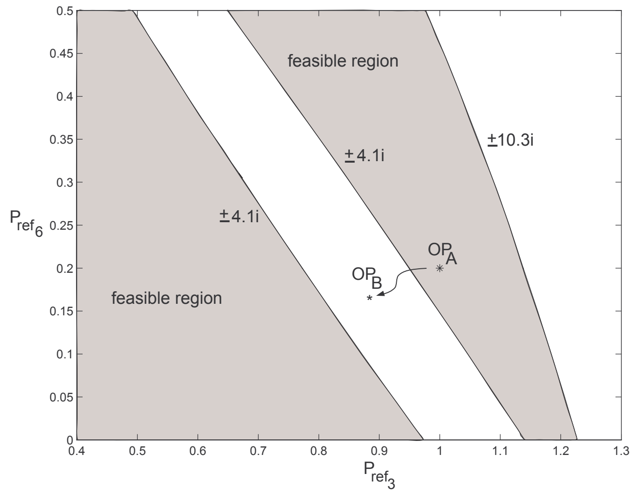

Figure 5. Feasibility region in $P_{ref_3} \times P_{ref_6}$ bounded by Hopf bifurcations of the inter-area oscillatory mode.

In Figure-4, the feasibility region is depicted in the parameter sub-space $P_{ref_3} \times P_{ref_6}$, P_{refi} is the load reference set point [10] for the generator i. The feasibility region is bounded by the Hopf bifurcation points associated with the local oscillatory modes of Area 1. The point OP corresponds to an operating point where no power exchange between no 3 and no. 6 is present. The load reference set points are changed to increase or decrease the generations at each site. Any slow variation in the generations and thereby in the power transfer within the feasible region do not change the stability of the system. In this region, after small disturbances, the system returns to its stable operating point. If the operating point passes through the feasibility boundary, depending on the type of the Hopf bifurcation, the system is led to an oscillatory instability. If the Hopf bifurcation is supercritical [6], there exist stable periodic solutions around the operating point and the solution approaches these limit cycles, thus resulting sustained oscillations. The amplitude of these oscillations depends on the closeness of the new operating point to the feasibility boundary. Under these circumstances, the stability and the normal operation of the system can be regained by driving the operating point back to the feasible region. If the Hopf bifurcation is subcritical [6], since there exist unstable periodic solution exist around the operating point, the system looses its stability and will be impossible to drive the operating point back to the feasible region after the region of attraction of a new properly selected operating point has been left.

As another possibility, we give an example of an operating condition for which the feasibility region is constrained by an inter-area oscillatory mode, see Figure-5.

As shown in the figure, a loading condition that changes and moves the operating point OP_A form feasible region into infeasible region can generate sustained oscillations between the generators. In this scenario, the penetration of a distributed generator causes sustained coherent oscillations between the two areas if the system is operated at the point OP_B in the figure. Hence, the sustained inter-area oscillations [9] due to distributed generations can be explained by supercritical Hopf bifurcations of inter-area modes. In Figure-6, sustained oscillations between the generator angles of generator no. 4 and no. 1, $\delta_4 - \delta_1$, are given after a small disturbance applied to the system that has been driven to an operating point in the infeasible region.

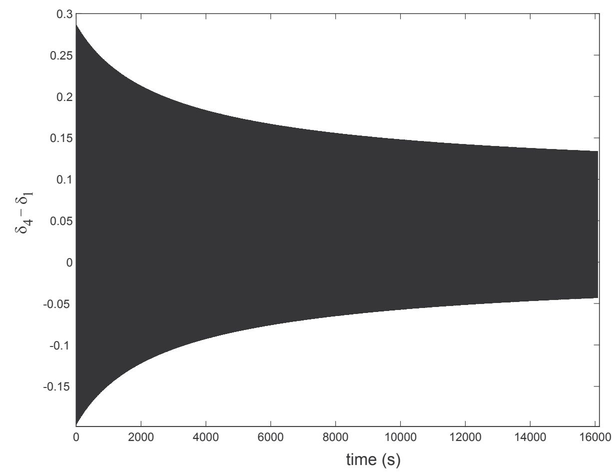

Figure 6. Generation of sustained oscillations as the solution of the system converges to a stable periodic orbit

V. CONCLUSION

In this paper, the impacts of distributed synchronous generators on the oscillatory stability in interconnected power systems are studied. For the investigation of the oscillatory stability, we propose a method, which is involved with the calculation of feasibility regions and their boundaries that are defined by the constraints due to Hopf bifurcations of electromechanical oscillatory modes. As expected, penetrations of distributed generations change the operating point and the topology of the system. A connection of a distributed generator may cause local or inter-area instabilities depending on many factors including the operating point intended, the location of the interconnection and the control parameters chosen. Some examples for these kinds of instabilities induced by the distributed generation have been demonstrated in the paper. For a safe operation in agreement with the integration of distributed generators, careful assessments of the feasibility regions and their boundaries that also include the possibilities of oscillatory instabilities due to distributed generation are necessary.

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