Distributed Generation: Voltage Stability Analysis

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Abstract—With the increasing use of distributed generation, which is usually connected to distribution or sub-transmission networks, the voltage stability phenomenon can be expected to occur when a system is operating with a high load. It is rarely mentioned in the literature that the problem can be associated with voltage-controlled buses or that voltage control can have the opposite effect to what is expected in generators. This study investigates voltage stability when a generator is connected to a distribution network. Using an analytical tool that can monitor voltage stability, this paper describes a case study of a 3-bus test system where the phenomenon is shown to occur. Then, using the IEEE 34-bus test system, tests are carried out to evaluate the impact of the connection of distributed generation on the voltage stability problem, active power loss and voltage profile.

***Index Terms*—distributed generation, distribution network, voltage stability**

I. INTRODUCTION

Figure 1 show a distributed generator connected to a network that is viewed as a voltage source in series with an impedance representing the transmission lines and transformers in the system. V_0 and V_1 are the voltages on each side of the impedance Z, and P_{GD} and Q_{GD} are the active and reactive power generated by the distributed generator connected to the network. There is a load represented by $P_1 + jQ_1$ at the point where the distributed generator is connected to the network.

The basic problem associated with connecting distributed generators to distribution networks is that the currents and power flows are modified by the impedance Z. In addition, the voltage drop across the impedance depends on the value of the impedance. If Z is large, V_1 will be strongly affected by variations in the current through Z due to the injection of power by the local generator. V_1 is given by:

$$V_1 = \left\{ -\frac{2a_1 - V_0^2}{2} + \left[\left(\frac{2a_1 - V_0^2}{3} \right)^2 - \left(a_1^2 + a_2^2 \right) \right]^{1/2} \right\}^{1/2} \qquad (1)$$

Where,

$$a_1 = -R(P_{GD} - P_1) - X(Q_{GD} - Q_1),$$

$$a_2 = -X(P_{GD} - P_1) + R(Q_{GD} - Q_1).$$

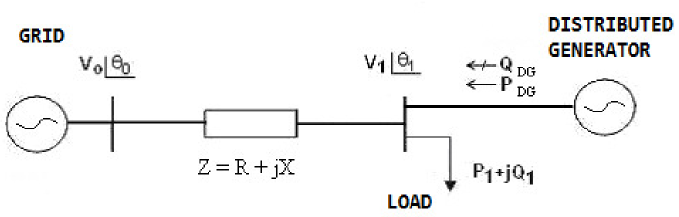

Figure 1. Connection of Distributed Generation to an Existing System

Using (1), it can be shown that the power generated by the distributed generator has an impact on voltage V_1 and that this is dependent on the local load and the impedance of the network.

The connection of generators to distribution networks modifies the radial design and structure of these networks, in which the flow is in a single direction, from the substation to the loads. Changing the flows changes the voltage profile.

II. SIMULATIONS

A. *Connection of a Generator on a 3 Bus Test System*

The single-line diagram used in the numerical tests is shown in Figure 2. Starting with the base case, the distributed generator is connected to bus 1. Different bus voltage-control configurations were considered.

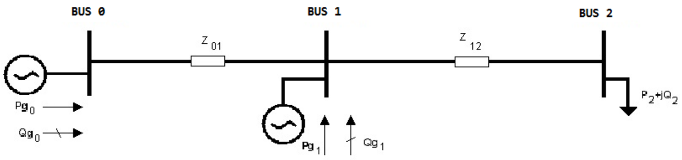

Figure 2. Single-Line Diagram of the 3-Bus Test System

The power flow problems for different system loadings with the distributed generator operating with and without voltage control were solved. For each operating point resulting from an increase in load, the voltage stability index was calculated.

The loading on the system is increased by increasing the load on bus 2. Different participation factors were considered, i.e. how each generator contributes to compensate for the active power imbalance caused by the increase in load.

In configuration (1) the distributed generator does not have any voltage control. Analysing the constant power factor curves (“nose curves”) for each participation factor, it can be inferred that the nearer the generation is to the load, the greater the power that can be transmitted to the load, as expected.

Analysis of the voltage stability index (the power margin to the maximum loading [1]) reveals that the power margin is reduced as the system loading increases. This indicates that progressively less power can be transmitted to bus 2 for the operating point being analysed. At the maximum point, the margin is zero. Onwards the system operates in the abnormal region as the margin becomes negative, indicating the value (expressed as a percentage of the load) that should be “removed’ from the load to reach the estimated maximum.

In configuration (2) the distributed generator is voltage controlled. Unlike in the previous test, the maximum loading does not depend on the participation factors for buses 0 and 1. The maximum power that can be transmitted to bus 2 is almost 66% greater than the maximum achieved for the best case in the test without any voltage control on bus 1. This is because of the smaller “electrical distance” between bus 2 and the next voltage-controlled bus, reducing the effort needed to transmit power to the load.

Analysis of the voltage stability index shows that for bus 1 it become negative after some load growth. This indicates that the generator on this bus is operating in the abnormal region and is starting to have difficulty injecting power into the system. The power margin on bus 2 then starts to deteriorate rapidly, and it becomes more difficult to transmit power to the load. Bus 2 reaches a maximum as the power margin approach zero. Onwards, bus 2 operates in the abnormal region, as indicated by the negative values for the power margin.

Configuration (3) represents the case where a synchronous compensator is connected to bus 2, as a result of which the voltage on the bus is constant and equal to the base case. Bus 2 therefore becomes a PV bus and bus 1 a PQ bus. The maximum power transmitted to the load is 68% higher than in configuration (2) and 874% higher than in configuration (1).

Although useful for understanding purposes, voltage values are well below the usual operational range.

B. Connection of Distributed Generation to a 34-Bus Test System

The test system used in this section is based on the IEEE 34-Bus Test System. The single-line diagram is shown in Figure 3.

Starting with the base case a distributed generator is connected to bus 23 and successive 1% increments in the system load are applied until the maximum is reached, when the power flow algorithm is unable to find any solution.

In these simulations the distributed generator has a participation factor of 100%, i.e., it is responsible for supplying the increased loading on the network. Two operating situations are analysed: the generator without voltage control (1) and with voltage control (2). In the first situation, the generator operates with a power factor of 1 and is therefore unable to generate/absorb reactive power or control the terminal voltage.

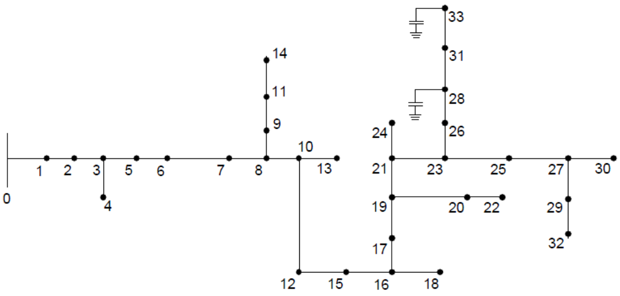

Figure 3. Single-Line Diagram of the 34-Bus Test System

Each load increment corresponds to a loading case. Near maximum loading—case 287—the system starts to operate in the abnormal operating region. From case 280 onwards, various buses have a negative power margin, as can be observed in Figure 4.

Under the test conditions, operation of the distributed generator would be limited by under voltage and increased losses (case 146). For this operating point, the active power generated on bus 23 is 1290.4 kW and the system load is 1536.4 + j1235.9 kVA, a 323.3% increase in relation to the base case. Voltage stability problems would not occur as the system only operates in the abnormal region from case 280 onwards. Figure 5 shows the voltage profiles for various loading cases.

Figure 6 shows how the active power losses change as the load increases. The losses for the last loading case before there is a voltage violation (case 146) are 133.1 kW. Compared with the base case (losses of 16.1 kW) this represents an increase of 727.4%. Higher loading values result in correspondingly higher losses, which reach 62.9% for case 287.

In operating situation (2), the generator terminal voltage is controlled. The simulation starts with the base case and uses the same assumptions as those used for operating situation (1). For each load increment, the active power balance is restored by the generator on bus 23 (100% participation factor) and the reactive power balance is the responsibility of the generators on buses 0 and 23, both of which have an infinite capacity to generate/absorb reactive power.

Analysing the voltage stability index, i.e. the power margin to the maximum loading, in Figure 7, none of the operating points lie in the lower part of the constant power factor curve. As a result, no voltage stability problems were observed for this simulation. Comparison of the voltage stability index for bus 23 reveals that in operating situation (2) the index for the operating points analysed are better. The smallest power margin is around 30% whereas in operating situation (1) it is less than 10% for loading cases close to the maximum (case 287).

For those cases where there is no voltage violation—case 254 in operating situation (2)— the index for bus 23 is M=34.6%. In operating situation (2) case 146, the most critical index for bus 23 is M=97.2%. However, these occur with a lower load.

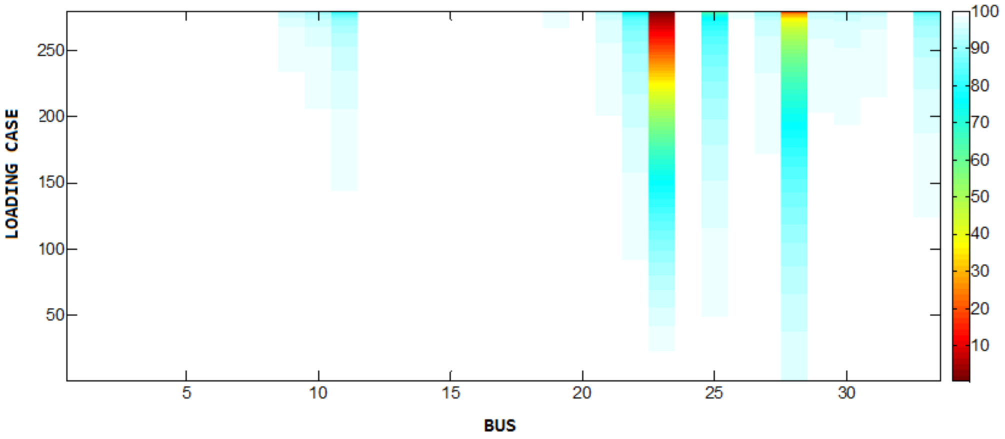

Figure 4. Voltage Stability Power Margin for Operating Situation (1)

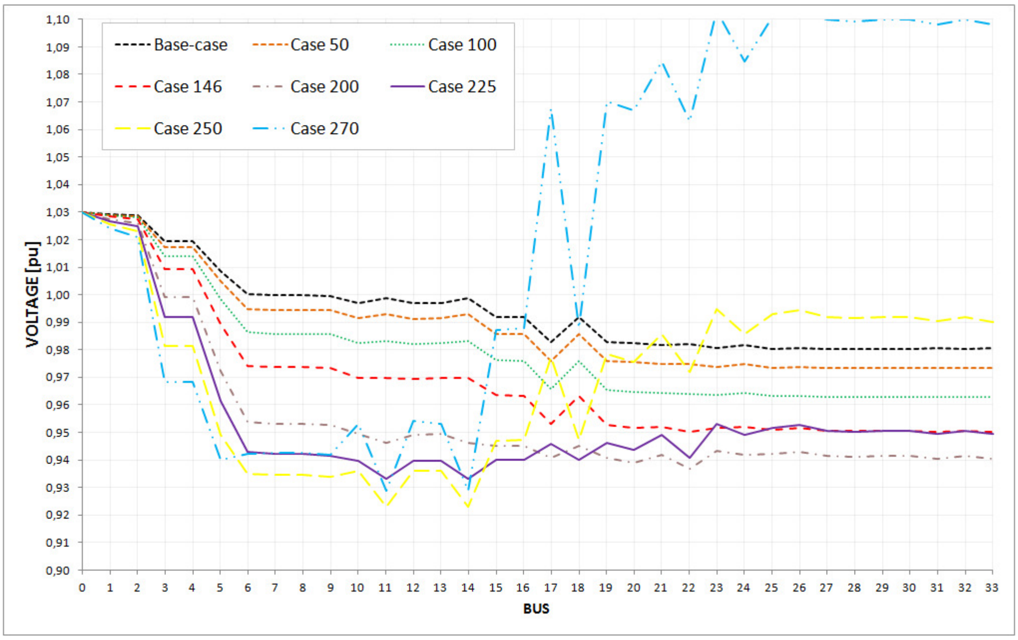

Figure 5. Voltage Profile for Operating Situation (1)

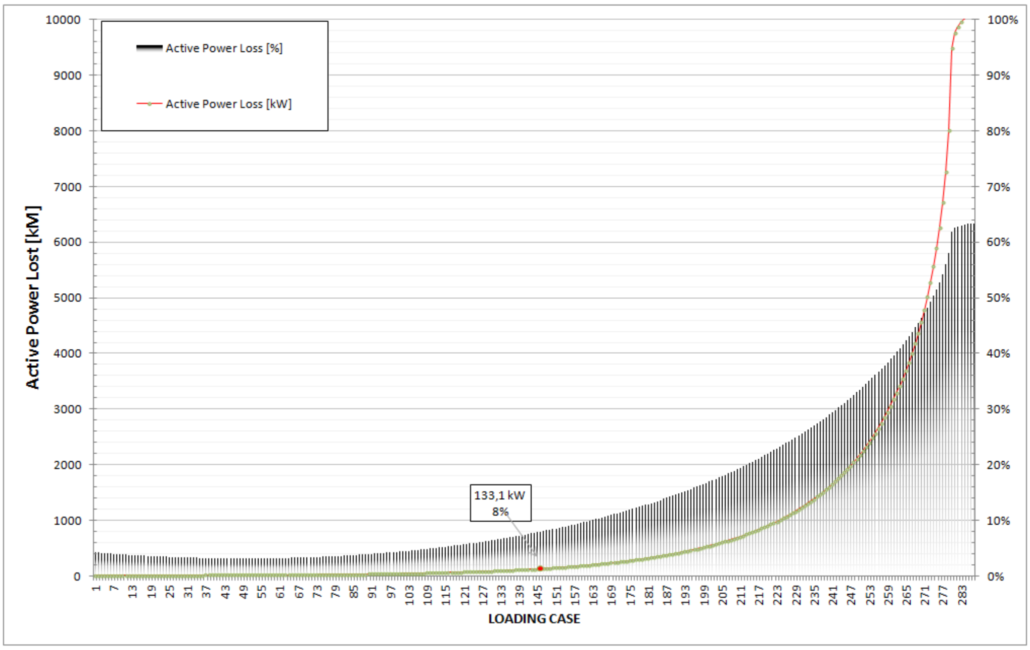

Figure 6. Change in Active Losses with Increasing Load for Operating Situation (1)

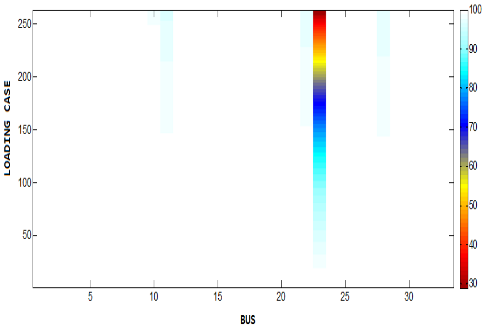

Figure 7. Voltage Stability Power Margin for Operating Situation (2)

Analysis of Figure 8 shows that the voltage remains around 0.98 p.u. for most of the buses close to the distributed generation bus and does not vary significantly as the loading changes. In contrast, although the voltage on bus 0 is also constant, the voltage in the region between buses 3 and 22 drops as the loading increases. Voltage violations below 0.95 p.u. occur from case 254 onwards.

Maximum active power generation on bus 23 is 5288.7 kW (case 263), when the system has a load of 4738.2 + j3811.4 kVA. However, considering only those operating points for which there are no voltage violations, the maximum generation is 4671.3 kW and the corresponding system load is 4500 + j3619.8 (case 254), representing a variation of 1139.7% in relation to the base case. Compared with situation (1), this represents a 262% increase in active power generation on bus 23 and a 192.9% increase in system load.

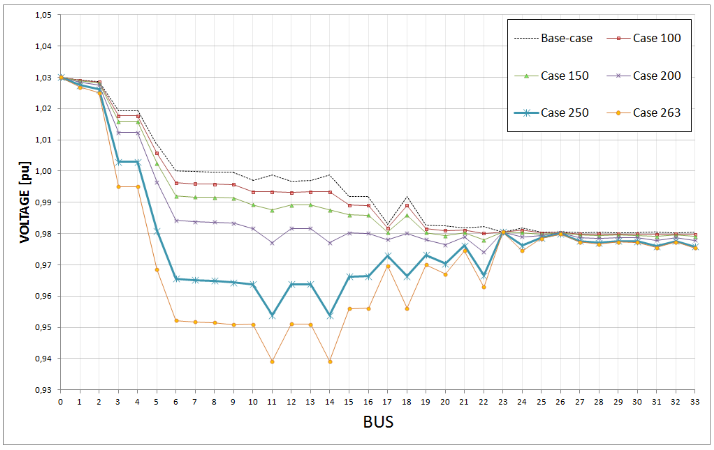

Figure 8. Voltage Profile for Operating Situation (2)

Figure 9 shows the change in active power losses in absolute values and as a percentage of total generation for each loading value. Considering those operating points where there are no voltage violations, the maximum active power loss is 550.4kW (case 254), representing 10.9% of system generation and an increase of 1139.7% in relation to the base case. With subsequent loadings there are not only voltage violations but also a considerable increase in losses. From case 254 to case 263 there is a 5.3% increase in load and a 68.9% increase in losses, ending with a 929.6 kW loss of active power.

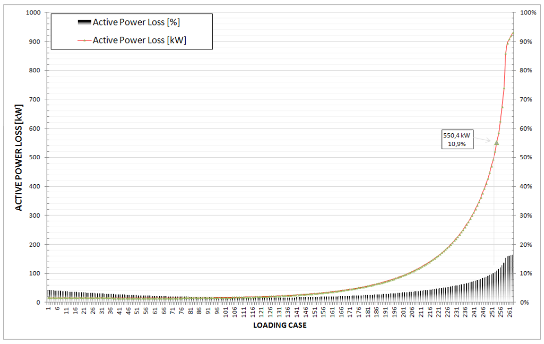

Figure 9. Active Losses for Operating Situation (2)

III. CONCLUSIONS

With the increasing use of distributed generation, which is usually connected to an existing distribution network at lower voltages, the voltage stability phenomenon can be expected.

A distributed generator was connected to a 3-bus system. Various operating modes were simulated. The operating points obtained in this way were evaluated according to their voltage stability index. It was found that there are operating points for which voltage control actions have the opposite effect to what is expected and that there is a maximum active power that can be generated by the distributed generator and transmitted to the load but with low voltages.

In another analysis, simulations were carried out using a 34-bus test system. A generator was connected to a bus with and without voltage control, and load increases were simulated for both of these operating situations. Voltage stability problems occurred, but in an operating region with large voltage violations and high active power losses. Therefore, voltage stability is not a constraint for distributed generation, as far as the performed tests are concerned.

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