AN EVALUATION OF ALTERNATIVE VOLTAGE CONTROL METHODS ENABLING INCREASED DISTRIBUTED GENERATION CONNECTION CAPACITY

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ABSTRACT

The paper reports on work carried out under the Strategic Technology Programme; a collaborative programme between the UK distribution system operators. A radial and an interconnected example network are used. The impact and increased connection capacity of operating generators in constant voltage rather than at a constant power factor is investigated. From the results, a new approach for planners considering the operation of generators in a constant voltage mode is devised. The regulatory and commercial issues are discussed.

INTRODUCTION

The Strategic Technology Programme is a collaborative programme between the UK distribution system operators (DSO) run by EA Technology. Module 5 'Networks for Distributed Energy Resources' commissioned a project to study innovative active voltage control techniques. The work investigates the impact of generators operating in different voltage control modes. Two networks are used; radial and interconnected, each with generation connected. For each network, there are two situations, one with weak and one with strong line parameters. The limits of the capacity of the system are studied using single load flows and then the behaviour over a time period of minutes in one second time steps to evaluate the interaction of the network to different methods of control. These studies are carried out using a tool specially developed at EA Technology and use a series of single load flow calculations using the IPSA load flow engine. Each load flow uses values from generator and load profiles, generator control parameters (entered by the user) and the outputs from the previous load flow as inputs. The interaction of generators with different voltage control methods and their impact on transformers and reactive power in the network is investigated.

Network models

The radial network is illustrated in Figure 1. One feeder is modelled in detail and a single load represents the other feeders connected to the 11kV bar. Table 1 gives the loads and generator values.

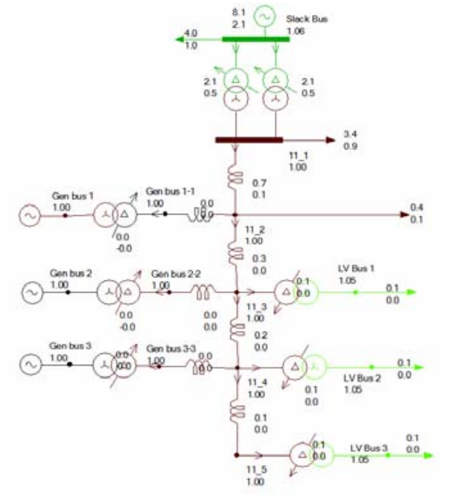

Figure 1 - Radial network

Loads/ generation	Weak		Strong	
	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
33kV	40	10	40	10
11kV	19.4	4.9	34	0.14
LVbus1,2,3	0.6	0.085	1.0	0.1
Gen bus 1	2	variable	1.5	variable
Gen bus 2	3	variable	2.25	variable
Gen bus 3	2	variable	1.5	variable

Table 1 Loads and generators on the radial network

The LV taps on the 11/0.4kV transformers are set so that at minimum load (taken as 10% of maximum load) and zero generation, the LV busbar voltage is at or just below the statutory limit of 1.06 per unit. Taps on generator transformers are fixed at nominal.

The interconnected network forms a ring through the 132kV and 33kV circuit (see Figure 2). A hydro plant is connected to one of the 33kV circuits and a windfarm to the 132kV circuit.

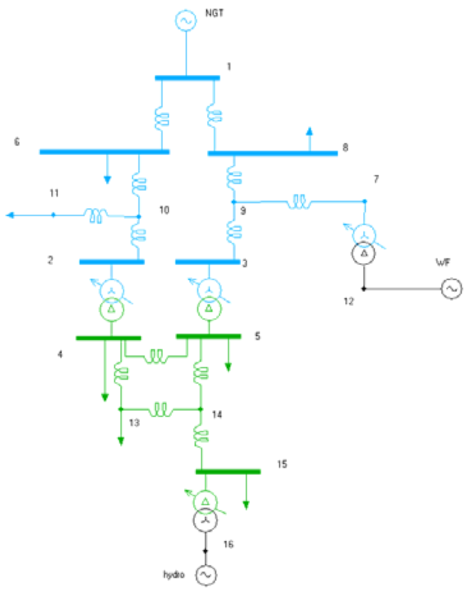

Figure 2 Interconnected network

	Weak		Strong	
Loads	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
33kV	20	5	15	3.8
132kV	50/100	7/14	25/50	3.5/7.0

Table 2 Loads and generators on the interconnected network

On both networks, the impedances of the strong and weak network take into account the fact that the weak network is long overhead lines and the strong network is short cables. The minimum load is 10% of maximum. Two methods of operating the generators were studied:

1. Constant power factor (pq mode).
2. pv mode with limits. This allows operation at a fixed power factor (normally unity) whilst the terminal voltage is within set limits. If the voltage moves outside these limits the power factor changes to hold the terminal voltage at the limit.

On the radial network the second mode of operation is investigated with the same voltage limits for all three generators and with different voltage limits.

RESULTS

Figure 3 to Figure 5 show the voltage profile at the 3 LV load feeders on the radial network with different generators operating in pq mode, in pv mode with the same voltage limits for each generator (an upper limit of 1.00 per unit) and in pv mode with upper voltage limits of the second and third generators increased to 1.01. The LV voltage profile is smoothest with the different generator voltage limits.

To keep the voltage within limits, in pq mode generator 1, 2 and 3 must operate at power factors of 0.912, 0.931 and 0.886 respectively each importing reactive power. In pv mode they only need to operate at these poor power factors for a small proportion of the time. Overall the amount of reactive power absorbed or exported by the generators and in total on the network is reduced by the generators operating in pv mode. Changing the voltage limits of the generators reduces the reactive power further and changes the proportion of reactive power absorbed by the three generators. Operating in pv mode can also prevent breeches of voltage limits before tap changers have time to operate.

Operation in pv mode holds the voltage at the nearest generator busbar constant. This may not however prevent voltage breaches at other nodes. The voltage limits of the generators can be reduced to keep voltages at other nodes within limits however there is a limit to the power factor at which a generator can operate.

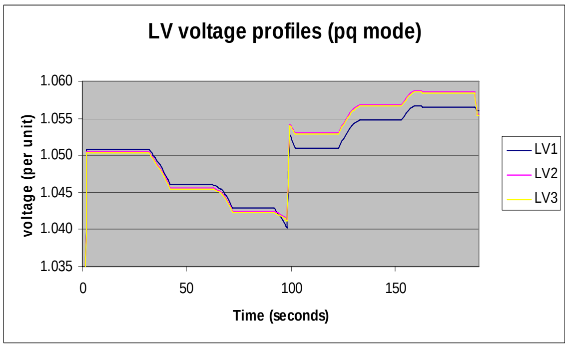

Figure 3 Voltage profile of the 3 LV load feeders with the generators operating in pq mode.

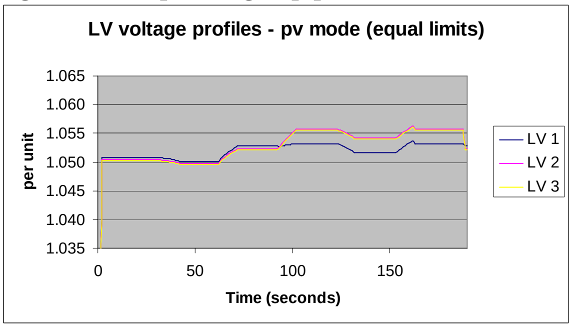

Figure 4 Voltage profile of the 3 LV load feeders with generators operating in pv mode (with equal limits).

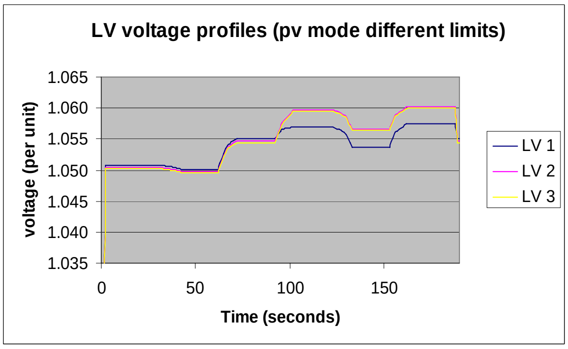

Figure 5 Voltage profile of the 3 LV load feeders with generators operating in pv mode (with different limits).

With the generators operating in pv mode with voltage limits of 0.94 and 1.001 per unit, the generators' power factors are significantly different especially when operating at different outputs. In general they have a lower power factor when operating at part load. Generator 3 at the end of the feeder has the lowest power factor in all situations. A very small change to the generators' upper voltage limits to 1.001, 1.004 and 1.007 for generators 1, 2 and 3 respectively brings the power factors of the three generators much closer together and under certain combinations of output generator 3 has the highest power factor. A small change in generator voltage limit can therefore have significant effect on power factors.

With the generators operating at full output, the loads on the LV feeders are changed so that they do not have the same demand. On the strong network the largest generator remained at unity power factor indicating that the size of generator had a significant influence, the position of the generator had an impact on the weak network indicating that the impedance was also significant.

Similarly the results of both the strong and the weak interconnected networks demonstrate that the generating export capacity of the hydro and wind farm can be maximised by varying the power factor depending on the load conditions on the network. Operation in a pv mode can allow generation to be connected to the interconnected network where voltage is the constraining factor if the generators operate a pq mode. In addition pv mode can prevent voltage limit breaches before the transformers have tapped.

Table 3 shows that on the strong network at unity power factor the wind farm can generate 87MW at maximum load but only 10MW at minimum load (a negative indicates a leading power factor). By changing the power factor at minimum load to 0.99 leading the wind farm can continue to generate 80MW. At maximum load the hydro can also increase its output by 4 MW (this does however increase the reactive power flow in the line directly connecting busbars 33_1 and 33_2). If the wind speed will not permit the wind farm to generate at full capacity, it must operate at a reduced power factor however this is preferable to reducing the output to 10MW or 20MW to maintain a power factor of unity or 0.99 leading.

Wind P MW	Wind Q MVAr	Wind S	Wind pf	Hydro P MW	Hydro Q MVAr	load
80	-10.5	80.78	-0.992	20	0.2	min
65	-9	65.62	-0.991	20	0.2	min
50	-8.5	50.72	-0.986	20	0.2	min
30	-6	30.60	-0.981	20	0.2	min
20	-2.5	20.16	-0.992	20	0.2	min
10	0	10	1	20	0.2	min
87	0	87	1	20	0.2	max
87	0	87	1	24	0	max

Table 3 Power factors and reactive power needed for different loads on the strong interconnected network

Interaction between the generators can occur, on the strong network the hydro plant's reactive power output mirrors the wind farm's real output and as a result the transformer tap does not change as the generator keeps the voltage within limits. The hydro plant therefore operates at a worse power factor than necessary if the tap changed. On the weak network although the wind farm has an impact on the 33kV voltage, the hydro plant remains in pq mode.

IMPLICATIONS

From the results it is clear that in some circumstances operating generators in pv mode is beneficial. The following gives a new approach for network planners to calculate settings for generator connections in pv mode. Assuming one generator is already connected the voltage headroom available is shown in Figure 6:

V_{g2} is the maximum voltage rise that can be caused by generator 2.

If $V_{g2}=I_{g2}Z$ where I_{g2} is the generator current and the Z is the impedance of the line then

$V_{g2}/Z = I_{g2}$

$S= I_{g2}V_{g2}$ where S is the maximum power rating of generator 2.

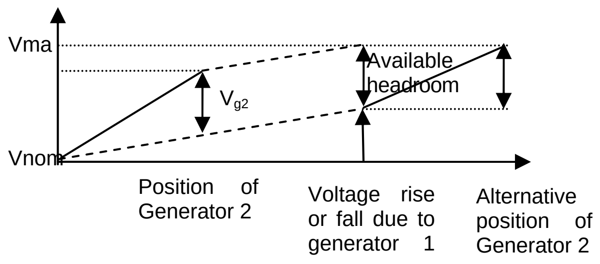

Figure 6 Diagram of the voltage headroom available for 2 generators

From this the headroom can be plotted as in Figure 7**.** If the generators are operated in pv mode such that at a particular power factor (for example 0.95) the maximum voltage rise is maintained under the worst case minimum load, maximum generation scenario, under all other conditions the generator can operate at a better power factor. If existing generators are operating at a fixed power factor (pq mode), this power factor is used to calculate the voltage rise they cause.

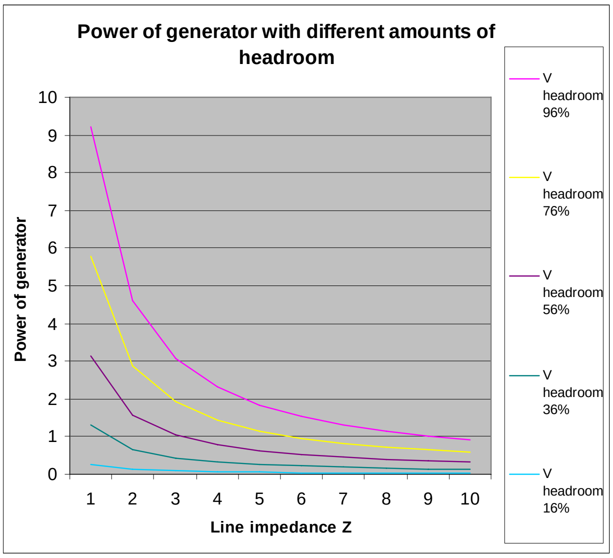

Figure 7 Graph showing the change in maximum power capacity for different amounts of voltage headroom and line impedance

A DSO may decide to operate generators in pv mode but not allow the first generator to take up all the voltage headroom available in the expectation that other generators will want to connect closer to the busbar in the future. Figure 7 shows that generators closer to the busbar can have a greater power capacity for the same voltage rise therefore overall more generation will be able to connect. Figure 7 is for illustrative purposes only, the appropriate impedances and voltages would need to be used for the particular feeder in question.

Generators could connect a slightly higher capacity than the worst case scenario would allow assuming that the worst case scenario will only happen for a small amount of the time. Alternatively additional capacity may be included on the assumption that additional generation will either not connect or that the additional capacity will have paid for itself by the time it connects.

It is likely that limits to voltage rise that are smaller than the maximum possible would only be negotiable for smaller generator developments at 11kV. Large windfarms or other generators at 33kV and above will want to maximise their capacity and take all the voltage headroom available.

Once the voltage headroom has been selected.

1. The cases of minimum load, maximum generation and maximum load, minimum generation must be checked to ensure that there are no current or voltage limits are exceeded. The generator voltage limits and transformer target voltage may need to be adjusted.
2. The voltage on other feeders without generation must be checked to ensure that it does not breach voltage limits (other measures such as in-line voltage regulators may need to be considered if this is the case).
3. The interaction of the generation must be studied to ensure that the generators do not aversely 'follow' each other.

With different combinations of generator outputs and demand, a range of power factors or voltage limits may be agreed in which the generators must be able to operate. With more than one generator on a feeder, generator voltage limits may be adjusted to the pattern of behaviour required – i.e. all the same voltage or minimum variation in power factor between the generators. This may result in a range of voltage limits to be included in the generator connection agreement so that adjustments can be made in the future.

Regulatory and Commercial Issues

The regulatory and commercial framework in the UK was designed for a network with very little distributed generation operating in pq mode. If the generators operate in pv mode they may be contributing to maintaining the network voltage when operating. The DSO may want to be satisfied that if the generator fails to maintain its terminal voltage at the agreed level that the generator will disconnect and that network voltages can be maintained without the generator.

In order to facilitate the connection of future distributed generation, the DSO may wish to specify a range of operating limits at which the generator may be asked to operate; none of which give a power factor that is impractically low. This would allow the DSO flexibility to connect more generation or load but this would be a departure from the standard connection agreement used today.

CONCLUSIONS

Although care must be taken to ensure the generators do not interact in an adverse manner, in general operating generators in a pv mode increases the connection capacity of the network and improves voltage control capability. From the results of network studies on an interconnected and radial network this paper offers a new approach to planners considering allowing generators to operate in a pv mode.

ACKNOWLEDGEMENTS

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