TAKING ADVANTAGE OF DISTRIBUTED GENERATION FOR VOLTAGE CONTROL

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ABSTRACT

Traditionally, power systems have been designed on the basis that power flows are from large generators, via the transmission network, through the distribution network to consumers. In the distribution system, the design assumed that all power was supplied from the bulk supply point and flowed radially outwards. Voltages throughout the distribution system were controlled by the on-load tap changers of the feeding transformers, assisted by booster transformers where necessary. Hence, the voltage to the consumers could be controlled within statutory limits. With the advent of distributed generation, the situation of all power flowing through voltage controlling transformers outwards towards customers does not always apply. Voltage control is therefore inherently more difficult and maintaining it within statutory limits is a major challenge for distribution network operators (DNOs).

DNOs generally require distributed generators to operate close to unity power factor in order to maximise the real power capability of the network. However, there is much to be gained by allowing generation which has the capability to contribute to voltage control to actively do so. Embedded synchronous generators are capable of altering their excitation so that they can contribute to voltage control. However, some form of controller is required so that the voltage can be maintained within tighter limits than required by the regulators. Such a target range is to within ±1.75% of the nominal value. This paper looks at how an embedded synchronous generator equipped with a suitable controller can contribute to voltage control within the standard IEEE 13-bus distribution system. This system is heavily loaded with unbalanced load and, without embedded generation, relies on a regulator transformer being fed from the sub-transmission network for voltage control. Fixed shunt capacitors provide some voltage support. Simulations will show the beneficial effects which result from inclusion of a synchronous generator which is allowed to contribute to voltage control rather than being constrained near to unity power factor regardless of the voltage of the busbar to which it is connected.

INTRODUCTION

Traditional distribution systems are designed for radial power flow outwards from the system bulk supply point (BSP). Where this is the case, voltage control can effectively be ceded to the transformers feeding the distribution system, sometimes assisted by technologies such as line drop compensation, booster transformers and power factor correction capacitors. Once distributed generation (DG) is introduced, this arrangement of voltage control equipment is no longer adequate. However, distributed generation is currently very important and will almost certainly be a part of power systems in the future [1].

Line drop compensation is generally set to control the voltage at some point distant from the feeding transformer. Even in the presence of distributed generation, the current in the feeding transformer is still correctly measured and the voltage drop in the line is correctly calculated so that the voltage at the controlled point is correct. Control of the on-load tap changer when distributed generation is connected results in there being a possibility of reverse power flow through the feeding transformer is discussed in ref [2]. However, line drop compensation can only control the voltage at one point and voltages in the system beyond the controlled point can no longer be assumed to fall as distance from the BSP increases. Generally, the voltage will increase close to a distributed generator which is contributing active power, so that a setting on the line drop compensation which provides for the voltage at the controlled point to be close to the maximum allowable is not appropriate.

CONTRIBUTION OF DISTRIBUTED GENERATION

Where significant amounts of distributed generation are present, it has been found necessary to implement rules designed to ensure that this generation contributes to voltage control on the system. Reference [3] reports that initially it was required that DG produced a level of reactive power at least 40% of the produced active power. Once the level of DG penetration and power production increased, this control regime was found to result in overvoltages. As a solution, it has been proposed that larger units are centrally dispatched and must be capable of providing voltage control. To achieve this on any system, some form of communications infrastructure is necessary and the cost of this would be significant for the distribution system operator or the distributed generator. In addition, the generator owner is entitled to compensation for providing this ancillary service and also for the loss of profit on the active power which he could have exported had the capacity of the generator not been taken up by the production or absorption of reactive power.

All of this effort to control the voltage within the distribution system in the presence of distributed generation ignores the possible contribution of distributed generation to voltage control. IEEE Standard 1547, clause 4.1.1 [4] demands that distributed generation does not actively contribute to voltage control. Despite this, reference [3] attempts to use the dispatching of distributed generation to both control voltage and also to optimise the input of distributed generation to minimise losses in the distribution system based on central dispatch, and hence acknowledges the possible positive contribution which this generation can make to voltage control. However, unless there are a number of larger generators in the distribution system, the cost of communications infrastructure is prohibitive, even if there is an attendant cost saving due to reduction of system losses. It is equally valid to note that, unless there are a number of distributed generators, preferably using various sources of energy, the generation can all be off-line simultaneously, and the utility must plan for this [5].

The idea of allowing distributed generation to contribute to voltage control within its own physical limits is interesting. It can be argued that such generation is relatively weak and is likely to spend much of its time either producing or absorbing its maximum rating of MVArs without having any significant impact on the network voltage. Where the network is strong, this may be accurate and it would not be beneficial or necessary for the distributed generation to contribute to voltage control. However, in other cases, typically where the generation is connected to a weak network, the distributed generation will be able to provide meaningful voltage support. Since distributed generation such as wind, tidal and wave generation are typically connected on the periphery of the power system, connection to a weak point is not unusual. This can also be true of synchronous generation installed by utility customers as back-up. Clearly, as the need to provide the capability to absorb or generate reactive power will impact on the capability of the generation to provide active power, some mechanism for the owner to receive payment for this ancillary service would have to be implemented.

TEST DISTRIBUTION SYSTEM

The standard IEEE 13-bus system of Figure 1 is a power distribution system which has been developed to be used for testing concepts [6] with the exception of the generator shown at Bus 680. This has been added here as a distributed generator so that the impact of such a generator can be examined. Various types of load, such as constant impedance, constant current, constant power and constant current, are used. The system is heavily loaded and load is poorly balanced between the phases. This raises the question of exactly what is meant by voltage control at a busbar where the voltages are significantly unbalanced. As a conventional synchronous machine can only generate positive sequence voltages and currents, it is reasonable that control of positive sequence voltage can be achieved. It is noted in reference [7] that voltage imbalance in the distribution system is principally the result of two factors i.e. unbalanced load at the distribution level and unbalanced voltage from the transmission system. These factors should ideally be dealt with outside of the distributed generation. The in-feed from the transmission system is via a three-

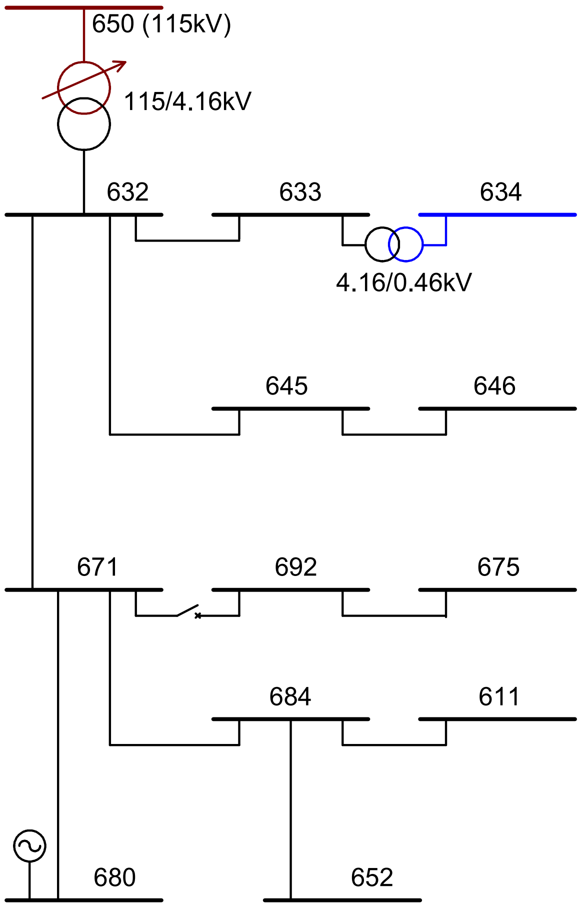

Figure 1 - IEEE 13-bus Distribution System

phase regulating transformer. A generator can be added at any of the busbars provided that the rating of the conductors of the system is respected. Due to the presence of single phase, two phase and three phase loads and feeders within the system, the voltage at all busbars is unbalanced. It is therefore necessary for the controller of a distributed generator to process the voltages measured on the three phases to determine the positive sequence voltage. This is calculated from:

$$V_1 = \frac{1}{3}(V_A + aV_B + a^2 V_C) \text{ where } a = -0.5 + j\frac{\sqrt{3}}{2}$$

It is the positive sequence voltage which must be controlled by the distributed generation if an improvement in voltage control is to be achieved.

The task of correcting the positive sequence voltage can be carried out by distributed generation. To look at the impact of the distributed generation, it is therefore necessary to calculate the positive sequence voltage at each of the busbars within the 13-bus system prior to the introduction of the generation. For simulations, the system has been modelled in Matlab using the SimPowerSystems toolbox. Verification of the model is provided by comparison with the published load flow solution prior to the addition of a generator at bus 680 [8].

In the 13-bus system, a number of the busbars are single phase or two phase. Only seven busbars of the 4.16kV system are supplied with all three phases. These are the busbars listed in Table 1. The supply busbar, busbar 650 is included in the results for completeness, but its voltage is primarily controlled by the transmission system.

	Without Generator		Generator Providing 0.7MW with pf = 0.85 leading		Generator Providing 0.7MW with pf = 1.0		Generator Providing 0.7MW with pf = 0.85 lagging	
Bus no.	Positive Sequence Voltage	pu	Positive Sequence Voltage	pu	Positive Sequence Voltage	pu	Positive Sequence Voltage	pu
632	2489.42	1.0236	2485.55	1.0349	2510.20	1.0451	2534.91	1.0554
633	2483.58	1.0212	2479.68	1.0324	2504.34	1.0427	2529.06	1.0530
650	2556.18	1.0510	2555.22	1.0639	2557.45	1.0648	2559.69	1.0657
671	2432.09	1.0000	2423.85	1.0092	2470.94	1.0288	2518.27	1.0485
675	2427.14	0.9980	2418.84	1.0071	2466.00	1.0267	2513.42	1.0465
680	2432.09	1.0000	2422.44	1.0086	2480.32	1.0327	2538.58	1.0570
692	2431.98	1.0000	2423.75	1.0091	2470.84	1.0288	2518.17	1.0485

Table 1 - Comparison of Positive Sequence Voltages

The impact of the distributed generator can be seen in Table 1, which shows the positive sequence voltages at the various busbars under steady state conditions. Only the busbars which are fed with all three phases are listed. With no generator present, all of the power is supplied from bus 650 of the transmission system. There is a voltage drop through the feeding transformer and a further significant voltage drop from bus 632 to bus 671 due to the high power flow along this feeder. There is effectively no voltage drop between bus 680 and bus 671 as bus 680 has no load connected to it. The high voltage at bus 650 is necessary if the voltages at the extremities of the distribution system are to be at adequate levels.

The remaining columns of Table 1 show the impact on the system voltages of a generator as its power factor is allowed to vary. In an unbalanced system, it is only possible to constrain the power factor in one phase to a particular value. The other two phases of the generated voltage will be 120º out of phase with each other while the busbar voltages will not be 120º out of phase with each other. The result is that, while one phase is constrained to a specific value of power factor, there will be a flow of reactive power in the other two phases which will not be of the same power factor. The magnitude of this flow will depend on how far from the expected 120º phase shift the actual angle of each phase of the system is.

It can be seen from the three sets of results in Table 1 with the generator present that varying the power factor will change the voltage of the busbar to which the generator is connected. A voltage drop appears between bus 680 and bus 671 due to the increased current flow in this feeder.

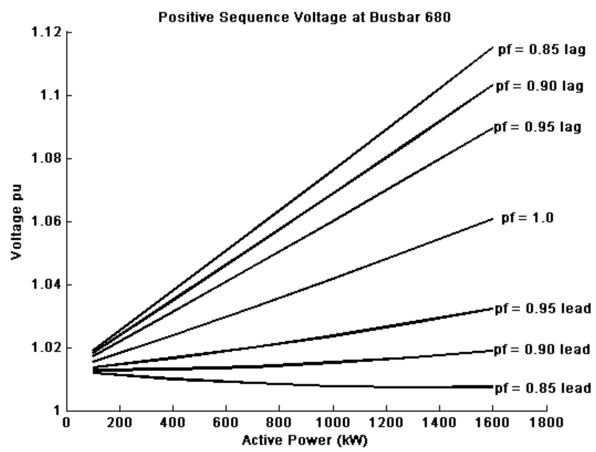

Figure 2 - Impact on Positive Sequence Voltage Of Active and Reactive Power Injection

Due to the presence of two sources, the distribution system is effectively composed of two areas of similar voltages. Close to bus 632, the voltage is principally controlled by the transmission system voltage at bus 650. Close to bus 680, the distributed generator is the more important factor in voltage control. This is evident from Table 1 where the generator is absorbing reactive power. The generator maintains the voltage in its vicinity to around 1.00pu while the transmission system infeed maintains voltages closer to 1.02pu. It can therefore be concluded that there is no longer any necessary for the voltage at bus 650 to remain so high. If a uniform voltage distribution of voltage throughout the distribution system is required, this can be achieved by either increasing the reactive power absorption of the distributed generator or reducing the voltage being provided at the secondary of the feeding transformer. The rightmost column of Table 1 illustrates the former approach.

Figure 2 illustrates the effect of the distributed generator at Busbar 680 on the busbar voltage. As the injection of real power increases, the voltage tends to rise. A synchronous generator is capable of either producing or absorbing reactive power. If it is equipped with a suitable controller, the level of reactive power can be altered by the controller to allow the positive sequence voltage at the busbar to be controlled.

Generator Providing 0.7MW with pf = 0.85 leading		
	Positive Sequence Voltage	pu
Bus632	2445.45	1.0182
Bus633	2439.59	1.0157
Bus650	2481.85	1.0333
Bus671	2417.54	1.0066
Bus675	2412.55	1.0045
Bus680	2432.69	1.0129
Bus692	2417.43	1.0065

Table 2 - Voltages due to Decreased Setting of Feeding Transformer Ratio

The results shown in
Table 2 illustrate that the voltages within the distribution system can be brought to within ±1.75% of each other. In this simulation, the ratio of the feeding transformer was reduced and the distributed generator supplied 0.7MW at a power factor of 0.95 leading.

CONCLUSIONS

The addition of generation to a distribution system results in the distribution system positive sequence voltage being improved, even in the case where the generator is constrained to operate at fixed power factor.

If the generator is allowed to participate in voltage control and is equipped with a controller suitable for this type of duty, the generator will be capable of responding to a wide range of changes in the voltage presented to it in such a way as to correct the voltage towards a set required value. Ideally, such a controller should operate entirely on the basis of local measurements of voltage and current to avoid the need for investment in a communications infrastructure. Optimum results can be achieved if the on-load tap changer of the feeding transformer is equipped with line drop compensation to assist with voltage control.

This paper has concentrated on the situation where there is only a single generator within the distribution system. Where a number of generators are present, voltage control is more likely to become an issue as these generators synchronise onto the system or disconnect from the system as they see fit. In this situation, assessment of the design of a controller would have to involve looking at whether controllers would interact with each other, possibly resulting in harmful oscillations.

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