Application of Generation in Distribution Systems

Computation and Modeling

For successful analysis of distribution systems containing generation, adequate analytical tools are essential. For accurate results, the computer model must incorporate all the items of plant needed to fully represent the actual system. Using approximate modeling methods cannot be justified since modern analytical methods are accurate and ensure credible results that build confidence in the model used.

Loadflow

The workhorse of analysis is the loadflow. This analysis computes all voltages, currents, and real and reactive power flows for any degree of unbalance in the system. This is important because distribution systems, by their very nature, include singe phase loads that result in unbalanced three-phase currents and voltages in the feeders and generators. The analysis is required to deal with a large number of load points and their corresponding distribution transformers.

The modeling of the load is probably the most difficult aspect of producing a viable system model. The accuracy of representation is important. Today, the option to use customer billing information is common. Individual customer data can be aggregated to provide distribution transformer loading to the model automatically, thus minimizing the data gathering effort to maintain an up-to-date model.

Regardless of any other considerations, a distribution system must be designed to ensure that the voltages and currents under peak and minimum loading conditions comply with regulations imposed to maintain industry standards.

Short Circuit

Short circuit analysis is essential to ensure that fault levels produced by faults do not result in damage to plant or endanger life. In addition, knowledge of fault currents and voltages are required for the proper application of protection coordination. A basic short circuit analysis provides the total fault currents for all standard types of fault at each point in the system. The results are used for comparing with the plant fault current withstand levels for all post-fault periods defined as sub-transient, transient, and steady state.

Synchronous Generator Application

When synchronous generation is connected at some point on a distribution feeder, the feeder voltage profile can vary considerably, depending upon the feeder loading, the generator real and reactive power loading, the feeder length and the location of the generator connection. Fault levels, feeder capacity, and regulatory requirements for supplying customers at acceptable voltages, are the principal constraints on generation in distribution systems. The limiting loading cases to be considered are:

- Full generation and peak feeder loading
- Full generation and minimum feeder loading
- No generation and peak feeder loading
- No generation and minimum feeder loading

Typical limits for allowable distribution voltage excursions are ±6% of nominal voltage, giving a 94% lower limit. It requires extensive loadflow analysis to ensure that voltage and other constraints are met for every loading condition.

A practical consideration arises in deciding what levels of voltage regulation are acceptable because allowance must be made for voltage drops at the customer secondary voltage, over and above those attributed to the primary. It is not uncommon for utilities to limit the maximum voltage excursions at distribution level to ± 2.5-3.5% to ensure satisfactory voltages at the customer point of supply.

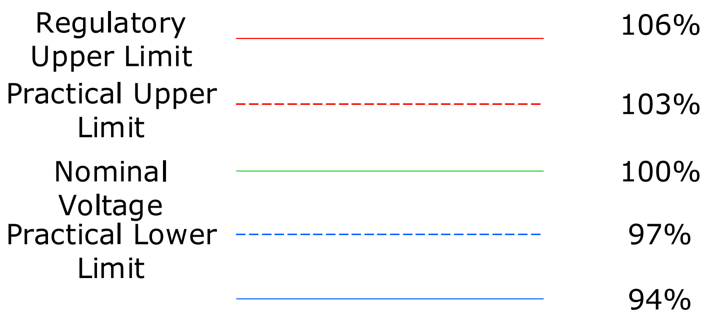

Figure 1: Voltage limits

Typical nominal regulatory and practical voltage limits are shown in Figure 1. This diagram below compares the voltage profile along a uniformly loaded feeder for different supply voltage levels with no generation present. Apart from the limit on the length of line imposed by the lowest voltage desired, these conditions can be met for a given peak load.

At minimum load, the supply voltage will rise, dependent upon the impedance between the substation and transmission source, assuming no form of voltage control at the substation. This rise must be contained within the upper voltage limit. These loading extremes determine the load magnitude and feeder length permissible.

In a practical situation, the conditions can be exacerbated if the bulk of the load is well away from the supply, as is the case for a so-called ‘express feeder’ designed for supplying the bulk of the load some distance from the substation. Then the voltage excursion at the end of the feeder is greater (see Figure 3). Even without generation, it is not possible to generalize in specifying feeder parameters and design voltage limits. Each case must be considered on it’s merits.

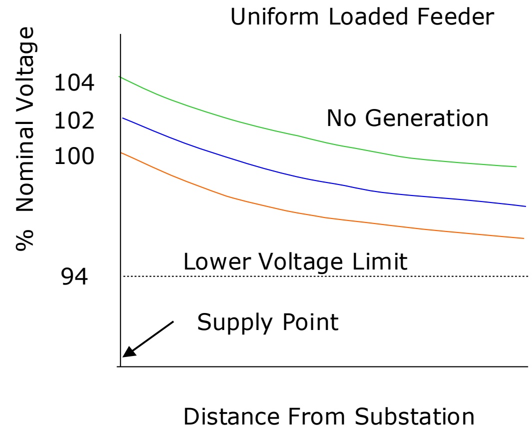

Figure 2: Voltage drop along a feeder

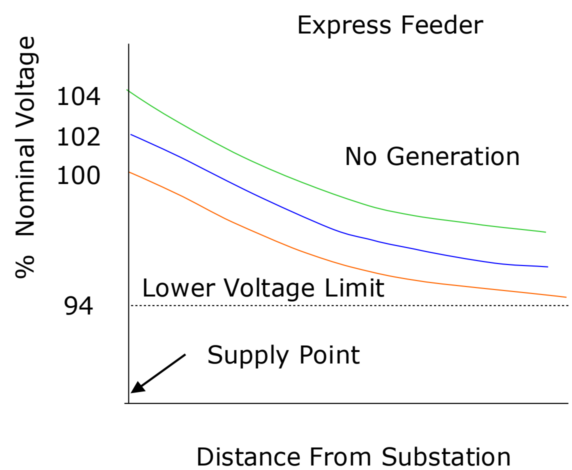

Figure 3: Express feeder voltage drop

If generation is connected part way along a feeder then the effect on the feeder voltage profile is more complicated. The generator can operate to generate (export) or absorb (import) reactive power. If importing, the machine must operate at a leading power factor and will be more susceptible to system disturbances affecting stable operation. If exporting, the magnitude of the export will determine if reactive power flows upstream towards the supply source from the generator or from the source to the generator. The voltage regulation for different sized generators is shown in Figure 4. As the size of machine is increased, the greater the difference between no load and full load voltage regulation.

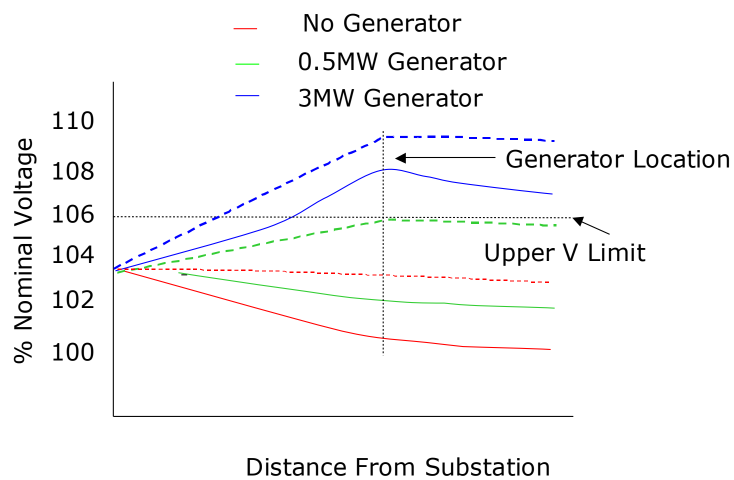

Figure 4: Feeder voltages with generation

The real power produced will determine if any reversal of real power flow occurs on the feeder and at what level of generation. Feeder losses are reduced if the generation reduces feeder flows upstream along the feeder. On the other hand, full output at minimum feeder load may give rise to conductor overloading in the reverse direction if conductor size is not adequate all along the feeder.

Assuming full generator output, the solid lines illustrates, qualitatively, the effect on the voltages of generating at maximum feeder loading for two different generator sizes. The chained lines show the corresponding voltages for minimum loading conditions. It is apparent that there is a maximum size of generator that can be connected at a given location. A machine greater than this size will result in excessive voltage ranges and unacceptable voltages for many customers. If the point of connection is fixed, there will be a finite limit on generator size, determined by the voltage rise at low load. Intuitively, the larger the generator, the closer it should be connected to the supply, or the stronger the feeder needed to supply it.

For every distribution voltage level at which generation is connected, there is usually a limit to the machine size that can be employed. For larger machine sizes, the closer to the substation busbars the connection, the less likely that feeder loading conditions will impose constraints on the generator loading. The higher distribution voltages allow more latitude on machine location.

The prime consideration is limitation of the voltage rise resulting from the real and reactive power injection of the synchronous generator. There are several options for easing these constraints:

1. Reduce supply voltage when generating
2. Allow the generator to absorb reactive power
3. Use regulators to boost and buck feeder voltages when necessary
4. Increase feeder conductor size
5. Limit generator output at low loads

Option 1 is limited by the practical limits imposed for voltage regulation purposes. Option 2 is limited by the reactive power absorption limits of the generator necessary to ensure stable operation.

For option 3, installing a voltage regulator at the start of the line to which the generator is connected is a practical measure that will give some relief to feeder voltages along part of the feeder at least. A regulator has the additional advantage of providing the flexibility to accommodate a range of generator sizes and the location where the generator is connected. However, introducing additional plant reduces reliability and increases cost and these factors must be taken into account.

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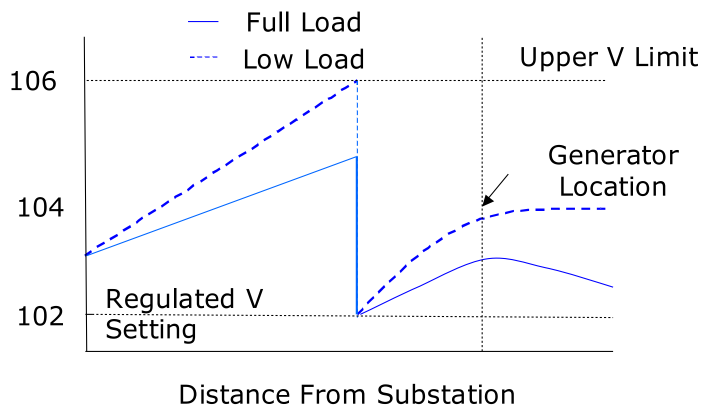


Figure 5: Feeder voltage with voltage regulator

A single regulator application is shown in Figure 5 where the regulator is applied upstream of the generator and the regulated voltage is set to ensure that the peak voltage on the regulator upstream node for light load conditions is within the prescribed limits. The voltage excursions are limited and can accommodate the full range of feeder and generator loading. More than one regulator may be necessary to ensure all voltages remain within limits for all feeder nodes on long feeders.

With option 4, change of conductor size is probably the simplest option in resolving voltage problems and depends upon the economics of increasing conductor size rather than on any technical constraint.

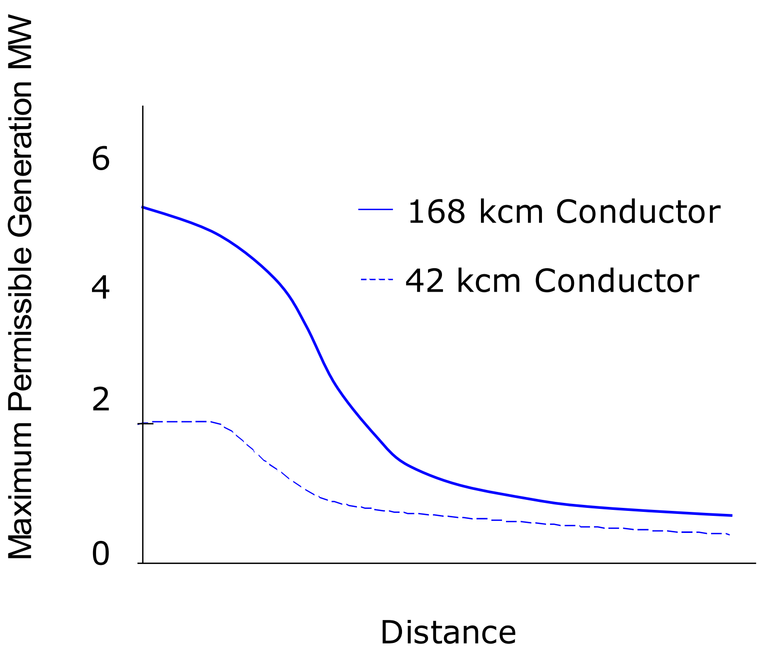


Figure 6: Generation limits for conductor sizes

Figure 6 shows the generator size-distance from substation relationships for two different sized feeder conductors. It shows that an increase in conductor size increases the size of generator that can be accommodated. It is apparent that the maximum size becomes significantly smaller further along a feeder. If a large generator is desired, it must be connected close to the substation.

For option 5, generation output reduction to control voltage is effective only if generator output can be reduced sufficiently during low load periods. The degree of flexibility in assigning load to the generator is a function of where the generator obtains its mechanical input. For example, in some industrial processes using back-pressure turbines, there may be limited freedom to change mechanical input. One particular application achieves variable input to a steam turbine-generator by bypassing the turbine steam supply and dumping the surplus steam in order to accommodate different generator loading levels for a constant steam supply. In others, the source of energy can be stored for short periods allowing generator output variations at will. In every case, the economic benefit of generator contribution is the primary factor in the decision to add generation to a feeder.

Regardless of the option chosen, there is no alternative to conducting a full set of loadflow analyses that cover a full range of operating condictions to determine if a given sized generator can be connected successfully at a particular location. Because of the range of voltages that must be accommodated with and without the generator present, the practical range of reactive power output possible is usually somewhat limited. It is not unusual to assign generator reactive power so that the machine supplies only the reactive power loss through the generator transformer if one is used, or at zero reactive power if direct connected. Again, only a careful analysis can determine what latitude is possible in assigning reactive power load.

Induction Generation Application

Conventional induction generators are often used instead of synchronous generators in distribution systems because:

- They are simple and robust compared with synchronous machines
- They require no excitation control
- Generally, they are not dispatched
- No synchronizing capability is required
- They are more economical

The main concern when connecting a conventional induction generator to a feeder is the reactive power demand of the generator, all of which has to be supplied through the feeder if no capacitive compensation is applied. The diagram shows the voltage conditions for full and low load for the relationship between the generator output and voltage drop along a uniformly loaded feeder. For peak load conditions, the voltage drop is significant and, if the generator were to be connected further along the feeder, this voltage drop is aggravated.

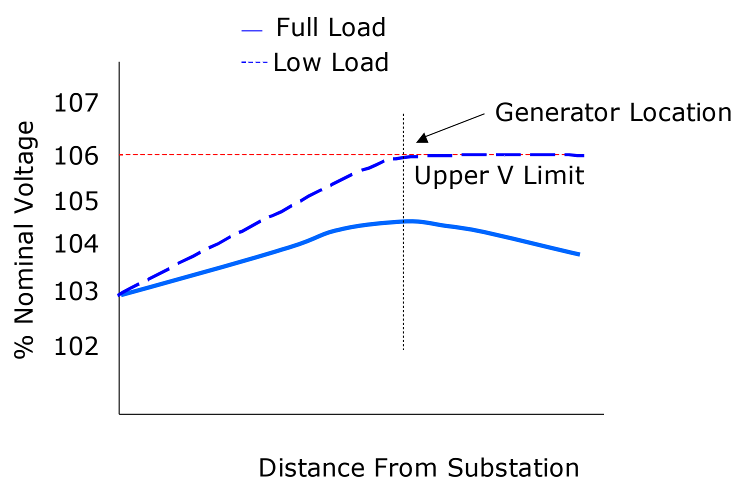


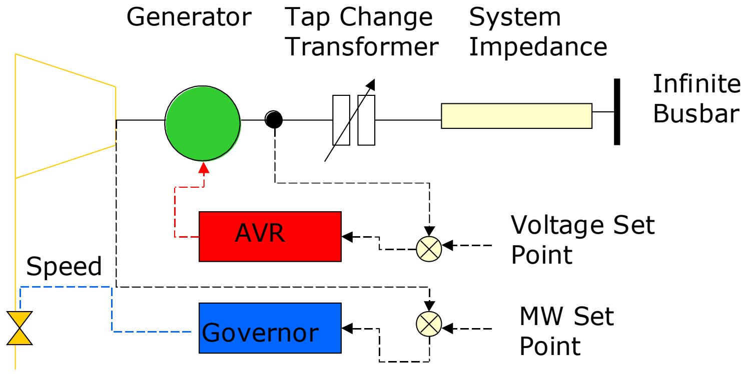
Figure 7: Feeder voltage with an induction generator

A solution, previously mentioned, is to compensate for the reactive demand by connecting capacitor compensation at the generator. This neutralizes the reactive power demand and makes the machine effectively reactive power neutral.

Note that double fed induction generators usually include the options of operating at a fixed lagging or leading power factor or in a voltage regulating capacity. The double-fed induction generator is frequently used in wind turbine installations and has the capability of controlling the reactive power output to provide fixed leading or lagging reactive power or a set power factor output. When required, the voltage at a selected point (usually the common point of connection to the power system in the case of a wind farm) can be regulated within the confines of the reactive power limits of the generator(s). This situation can be simulated within software to analyze the impact of one or more machines added to a feeder.

Tap Change Transformer

Synchronous or induction generators supplying a network may be connected through a step-up power transformer so that the optimum design voltage can be chosen for the size of generator. These transformers have tap changers with an assigned range of fixed tap positions. Analysis of the possible loading conditions arising on the feeder will determine the actual range of taps required to accommodate the voltage ranges for different reactive power flows. Failure to do so may prevent the machine delivering the required reactive power because of tap limitations when the voltage at the high voltage side of the transformer varies. Load tap changers provide additional flexibility but cost limitations often exclude their being used. The cost factor and the variability of the generated power precludes the use of load tap changers for wind generation.



Generation Impact Assessment

The presence of generation in a system requires that several different types of analysis be used to ensure that disturbances or the switching of loads or generation do not result in unacceptable situations that lead to abnormal currents and voltages which violate standards for operation.

It is usual to undertake a generation connection impact study when adding generation to a distribution system. If a generator is synchronous, the need to undergo the synchronizing process ensures that the moment of connection will have no impact on the system, that is, there will be no voltage or current surge. The normal procedure after synchronization is to permit gradual loading of the machine. Running load flows before and after adding a synchronous generator to a model determines the impact of real and reactive power flows on adding the generator. Generator reactive power flows can be adjusted as necessary to maintain voltage support. Simply running a load flow, removing the generator and running a second loadflow simulates loss of the generator for any set of loading conditions.

The effect of switching in an asynchronous generator depends upon a number of factors. An asynchronous machine that is part of a cogeneration scheme is typically gas or steam turbine driven and of the conventional induction type. The machine speed is brought up to near synchronous speed before the generator breaker is closed. On closing the breaker, the stator of the machine is energized from the supply and behaves initially like an induction motor; the duration of current inrush is limited since there is no torque required to accelerate the motor to normal speed. Upon reaching generating (super-synchronous) speed the generator will begin producing real power with the steady state reactive power supplied from the system according to generator loading.

If an asynchronous (induction) wind generator is connected to the system, the same process as above will occur if the generator speed is matched to system speed. A common alternative technique is to use a soft starting device consisting of controlled thyristors or transistors that limits the magnetizing inrush current, often to not much more than full load current. The same procedure in reverse takes place when the machine is unloaded prior to being disconnected. Such control minimizes transient torques applied to the turbine gearing, thus avoiding damage.

Asynchronous wind generators using double-fed wound rotor induction machines with frequency converters supplying the rotors allows up to 20% variation in operating speed. The mechanism for starting is akin to synchronizing and minimizes the magnitude of starting currents. One of the most onerous conditions arises when a fault has occurred, is cleared and the reactive power flows attempt to restore the system to steady state, especially if the machines are part of a wind farm. Rotors speed up when the fault voltage effectively removes load from the machines and the system supply source attempts to restore the excitation to the machines. Low voltage ride-through (LVRT) technology is available to span the the low voltage conditions due to faults and can mitigate the effect of abnormal conditions on the machine reactive power flows.

Another version of wind generation uses a full converter supplying both rotor and stator that gives precise control of the real and reactive power and, during a voltage dip due to a fault, it is possible to keep control of the current giving good performance during grid disturbances and full capability to ride-through faults. The generator can be synchronous or asynchronous for full converter fed types.

DESS can simulate the conditions valid for an impact assessment for asynchronous machines. Simply running a loadflow, with and without the generator, as for the synchronous case, simulates addition and loss of the machine. Assuming no soft-start device is used, direct starting of an asynchronous induction machine is simulated by using the motor starting feature of DESS. The resultant voltages and current flows represent the transient conditions. For double-fed asynchronous machines with voltage regulating capability, the effect of voltage regulation is simulated by using a synchronous machine model.

Short circuit conditions with generator present is modeled for synchronous or induction machines in the conventional manner. For double-fed asynchronous machines, the machine is simulated as a synchronous generator. Using transient impedances relevant for a conventional (squirrel cage) induction generator will provide the worst-case fault infeed condition for faults.