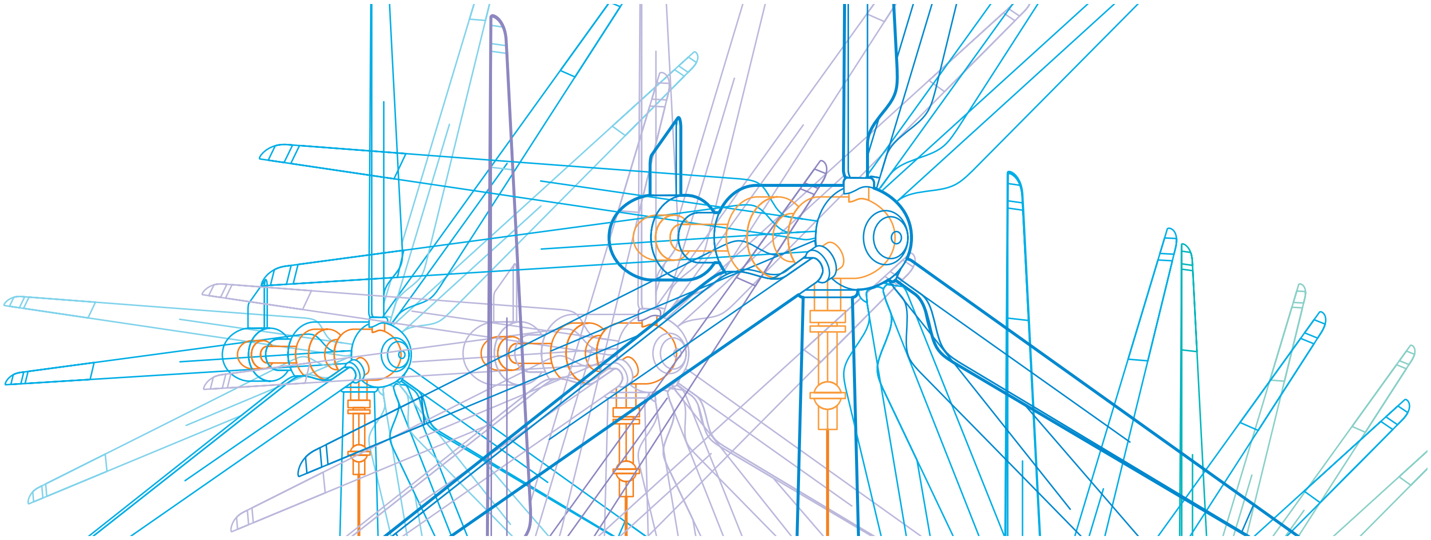
Renewable energy design considerations



Abstract

Renewable energy generation installations have noted a number of different design and performance issues that have not always been properly addressed during the development of the projects. These issues have included transient overvoltages, harmonic problems, transformer saturation, power factor, reactive power and voltage control.

ABB has been a major supplier of equipment for renewable power development for many years. Over these years we have observed a number of incidents and problems that resulted from an incomplete understanding of the requirements for designing and properly specifying the equipment.

Some examples include the following:

- Step-up transformers have failed at a number of wind farms and solar farms due to the total loading of the transformers being more than specified. This was particularly true concerning the lack of defining the harmonic loading on the transformers.
- Harmonics from the renewable generation have been amplified until the harmonic overvoltages failed arresters and damaged step-up transformers. These lower order resonant modes are due to the total capacitance of the extensive cable system and sometimes a combination of the cables and power factor correction shunt capacitor banks.
- Arresters and transformers have failed when faults have disconnected feeders with induction generators still connected and the ground reference has been lost. This results in high overvoltages on the un-faulted phases.
- High levels of harmonics have been measured when inverters for energy storage injected a low level of DC current into the transformer and saturated the transformer.
- Switching cable feeders with extensive cables or switching shunt capacitors on the collector system or on the near-by high voltage system can result in high transients being focused on some locations of a collector system resulting in repeated step-up transformers failing in the same location.

ABB has observed many cases of equipment failure due to the problems described above, but solutions are readily available. For example, eliminating the loading problems in Item 1 above is just a matter of properly specifying the transformers and specifying the k-factor or the harmonic loading. This is one of the areas being addressed by some of the wind turbine vendors who are now providing information on how to specify transformers for their wind turbine generators.

Harmonic loading, DC injection, voltage ripple, and voltage range of operation are key areas that influence the operation of the transformer. There is a trend in the industry now, widely seen in wind and starting in solar, to provide specification information for the transformers used for the particular technology being provided. ABB recommends specifications for transformers to withstand 110% of nominal voltage meaning that the transformers are expected to withstand 38kV for normal (34.5kV) operation.

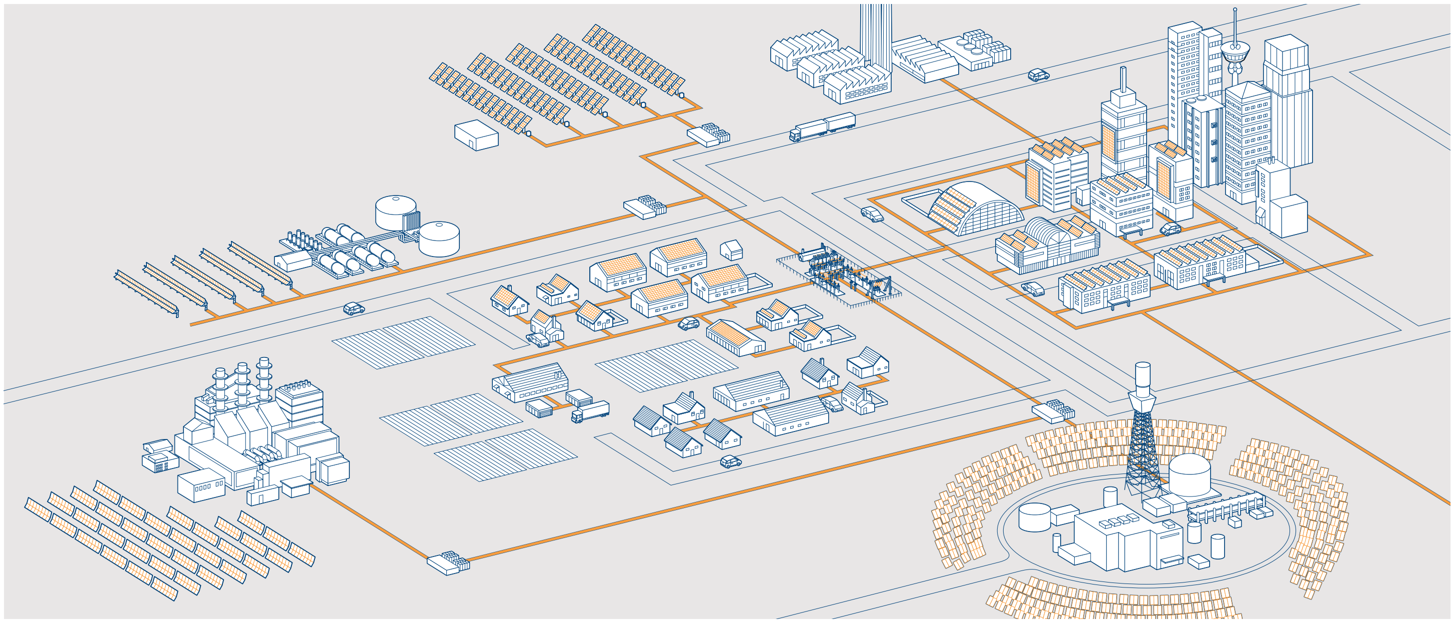
Typically, transformers designed per ANSI standards can handle up to 105% of the rated voltage; however the growing trend to overexcite the transformers to as much as 115% has been known to cause partial discharge, and even failure in some cases. These operating conditions and factors need to be specified to the manufacturer in advance so changes can be made to the design of the transformer to address them.

Harmonic problems mentioned in Item 2 are more of a challenge with some technologies than others. For example, in wind the full back-to-back conversion technology generates more harmonics than the doubly-fed induction generators with smaller converters, but in very weak systems even harmonics from doubly-fed induction generators may cause problems. The solution is to conduct harmonic studies for those technologies that have had harmonic problems and issues.

The one issue that is the “silent killer” of transformers is the transients discussed in Item 5 above. Most renewables systems will not experience this type of, but ABB has observed some step-up transformers fail due to this phenomenon. One configuration that can lead to amplification of transient voltages is the switching of shunt capacitor banks on the higher voltage system near the power transformers that connect the renewable collector system. Solutions may include synchronized closing of the shunt capacitor banks and adding additional arresters on the collector system.

As renewable generation continues to account for a larger part of total system generation, interconnection requirements are requesting renewable sources to provide some of the same services that conventional generation provides. Some of these requirements include low-voltage ride through, power ramp rates, and power response to system frequency disturbances.ABB has reviewed and studied many of these issues and they are summarized in this paper. The renewable energy sources that have been studied in the last few years include wind generation, solar photo voltaic (PV) generation, fly wheel energy storage, and sterling cycle solar generation. This paper discusses the issues by the type of problem or issue that has occurred.

As a manufacturer of majority of equipment and systems within utility scale renewable power plants, ABB has provided studies and evaluations for all of these problems in order to resolve past issues and prevent future failures and mis-operation of equipment. ABB also has the expertise to review interconnection requirements and help develop optimum solutions for meeting the requirements. The following sections explore several specific potential issues in more detail.



Introduction

Renewable energy generation installations have experienced various design and performance issues that have not always been properly addressed during the development of the projects. These issues have included transient overvoltages, harmonic problems, transformer saturation, power factor, reactive power and voltage control, power ramp rates, and response to system disturbances.

ABB studied many of these issues and they are summarized in this paper. The renewable energy sources studied in the last few years include wind generation, solar photo voltaic (PV) generation, fly wheel energy storage, and sterling cycle solar generation. This paper discusses the issues by the type of problem or issue observed.

Overvoltages

For the purpose of this paper, power system overvoltages are divided into three types:

- Transient Overvoltages (TOVs)
- Dynamic Overvoltages (DOVs)
- Harmonic Overvoltages (HOVs)

Transient overvoltages: These overvoltages are very high frequency and short term lasting from less than one cycle to several cycles. Generally their impact is within the first 30 milliseconds of the event that initiates the transients, and generally they are quickly damped in the system. TOVs can be caused by the following:

- Lightning strikes
- Transmission line switching
- Shunt capacitor bank switching
- Abnormal switching events
- Transformer and reactor switching

Generally, energizing a transformer or shunt reactor and ferro-resonance phenomena produce much lower frequency transients that last several cycles to many seconds, but these will also be addressed with the TOVs.

Dynamic overvoltages: These are typically fundamental frequency overvoltages. They can occur within a cycle, but they may remain on the system until some other action is taken to eliminate the overvoltage. Some of the typical causes of DOVs are:

- Transmission line and cable tripping
- Feeder tripping isolating generation on tripped feeder
- Load rejection
- Isolating shunt capacitors on a weak system
- Open-ended lines and cables

Harmonic overvoltages: These are typically overvoltages resulting from a harmonic resonance on the system. Resonant conditions occur when the shunt capacitance of a system parallels the system inductance, generally from the second to the fiftieth harmonic. This will be addressed in a separate section on harmonics in this paper.

Transient overvoltages

The main strategy to mitigate TOVs is the application of surge arresters. For some special conditions, an RC circuit (often called a “snubber circuit”) may be connected to damp high frequency transients and oscillations. For TOVs that are initiated by switching events, there are some methods of reducing the TOVs by special switching techniques. TOV mitigation techniques are discussed below for various types of transient events.

Lightning surges

Lightning overvoltages on transmission systems result from three possible causes in order of increasing severity:

- Induced voltages
- Shielding failures, that is, direct strikes to the conductor
- Backflashes

These three events only happen on overhead transmission or distribution lines. Since most collector systems for renewable energy generation are cable systems, lightning has not been a major problem. Renewable projects are usually connected to overhead transmission lines through a power transformer in a substation, but if the substation has proper surge protection these surges do not results in any significant TOVs on the collector systems.

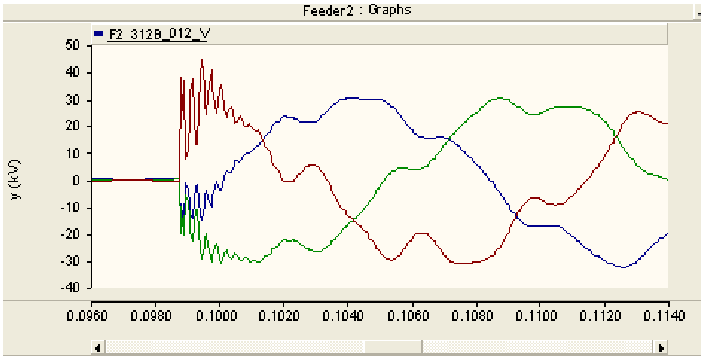


Figure 1 - Feeder Energized on 34.5-kV Collector System

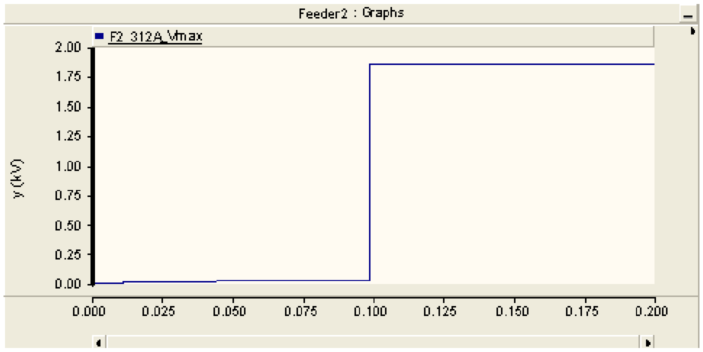


Figure 2 - Feeder Energized - maximum Peak Voltage of 1.85 pu on Feeder

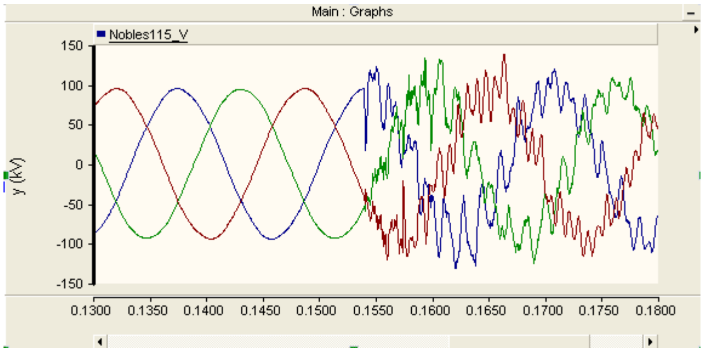


Figure 3 - Plot of 115-kV 40 MVAR Capacitor Switching Voltage on 115-kV Bus (Maximum Peak Voltage 1.44 pu)

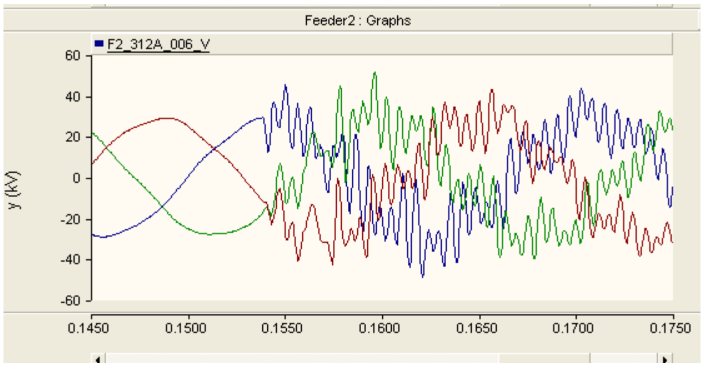


Figure 4 - Plot of 115-kV 40 MVAR Capacitor Switching Voltage on 34.5-kV Feeder

Transmission line and cable switching

The switching or energizing of the collector system cable feeders at wind and solar generating installations can result in significant transient overvoltages on the system. Figure 1 shows the voltage on the 34.5-kV feeder during an energizing simulation. Figure 2 is the plot of the maximum transient voltage on the feeder during the energization. The transient voltages during feeder energization are high but generally they can be limited by the arresters to an acceptable level.

Shunt capacitorbank switching

The shunt capacitor banks on the higher voltage system can cause voltage amplification on the renewable energy collector system. For example, the switching of a shunt capacitor bank on a 115-kV bus that connects to the collector system can result in the amplification of transient voltages on lower voltage systems that also have capacitance. The collector system cables provide significant capacitance on the 34.5-kV system. This amplification has been known to result in very high transient overvoltages. Figure 3 shows the voltage on the 115-kV bus for one of the capacitor energizing simulations. Figures 4 shows the results of that same simulation on the 34.5-kV system. Figure 3 is the 115-kV bus voltage on switching and Figure 4 is the voltage on the 34.5-kV system.

TOV mitigation methods

Surge arresters can reduce the TOV caused by transmission line or cable switching to more acceptable levels. Synchronized closing or pre-insertion resistors can minimize the TOV caused by shunt capacitor bank switching, and current limiting reactors can help minimize the outrush current during a fault.

Dynamic overvoltages

There are many different system disturbances that can result in dynamic overvoltages (DOVs), which are high 60 Hz voltages on a system. As defined, DOVs are typically fundamental frequency overvoltages. They can occur within a cycle, but they may remain on the system until some other action is taken. They normally result when an event leaves capacitance on the system that provides more reactive power than the system can use in its changed configuration. DOVs do not have as high peak voltages as TOVs, but their duration can result in equipment damage and failure if they are not reduced. In some case, DOVs reach the protective levels of the arresters which can quickly cause the arresters to fail.

Some of the typical causes of DOVs are:

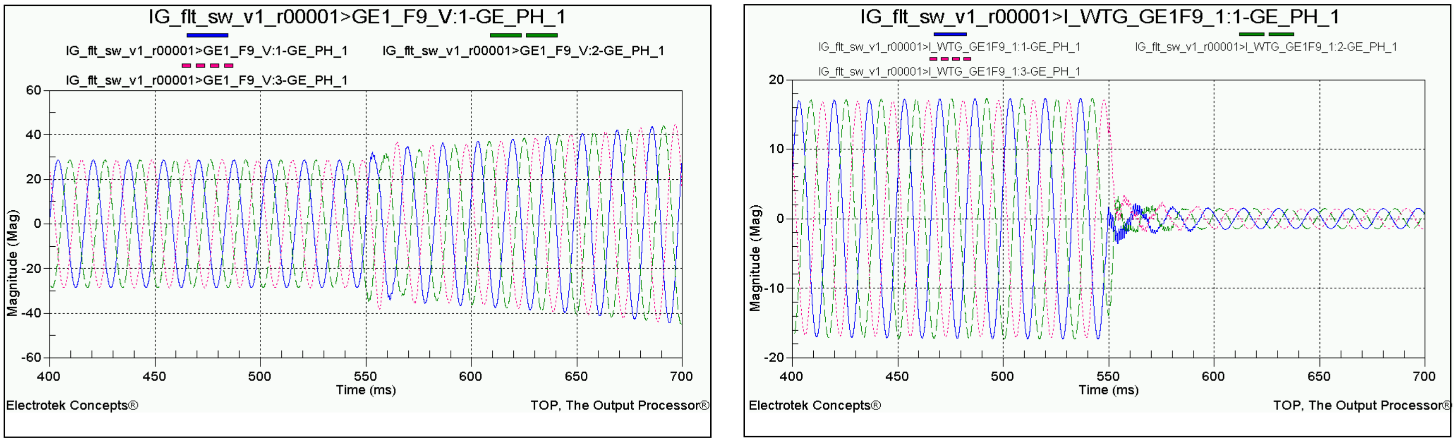
- Transmission line and cable tripping
- Load rejection or interruption
- Isolating shunt capacitors on a weak system
- Open-ended lines and cables

For renewable collector systems, the main event of concern for DOVs is the disconnection of a collector feeder with generation still connected and providing power to the feeder. Fortunately, for those systems that do not have a synchronous or asynchronous generator connected directly to the system but only have an inverter, the inverters will block power if the voltage goes too high, limiting the voltage rise.

Wind generation has several types of systems where the asynchronous (induction) generator is connected to the collector system. In this case, there are some special grounding requirements needed to minimize overvoltages during tripping of a feeder. Two different types feeder tripping are shown below, the normal cable feeder de-energization and fault-clearing scenarios. The significance of installing a grounding source (grounding transformer) for each 34.5-kV feeder is also shown. Figure 5 illustrates a feeder trip without a fault for a feeder with an asynchronous generation connected. It shows results for feeders with and without a grounding transformer. With or without out the grounding transformer, though, the voltage rises and may result in failure of arresters and sometimes damage to transformers and other equipment. The one method to mitigate the high voltage is to have a fast grounding switch to close and ground each phase immediately after opening the feeder.

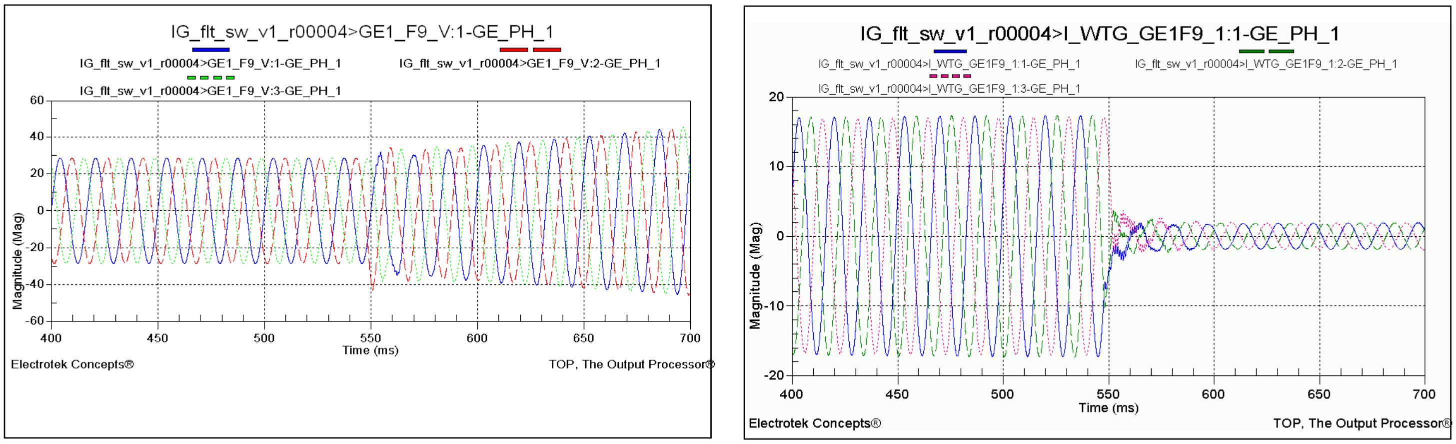
Figure 6 compares a feeder trip with a single-phase fault for a feeder with an asynchronous generation connected, again showing results with and without a grounding transformer on the feeder. Without out the grounding transformer the voltage rises and may result in failure of arresters and sometimes damage to transformers and other equipment; however, with a grounding transformer the overvoltages are limited.

Figure 5 - Asynchronous Generator: Normal Feeder De-energizing



(a) Feeder-Side Voltage at 34.5 kV Bus with a Grounding Transformer (kV)

(b) Currents of WTGs at Branch #1with a Grounding Transformer (kA)



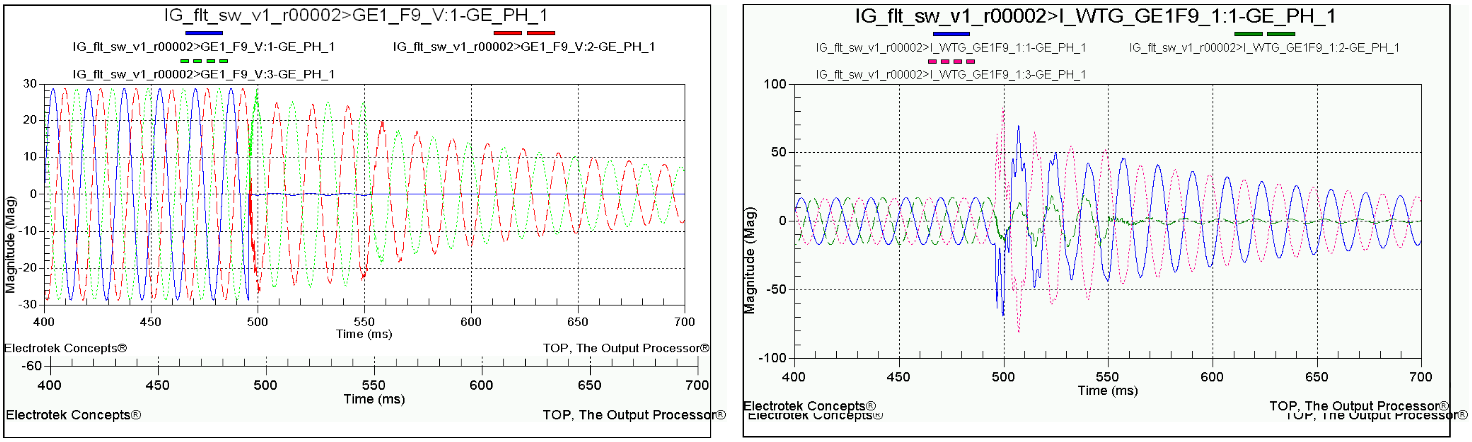
(c) Feeder-Side Voltage at 34.5 kV Bus without a Grounding Transformer (kV)

(d) Currents of WTGs at Branch #1 without a Grounding Transformer (kA)

DOV Mitigation Methods

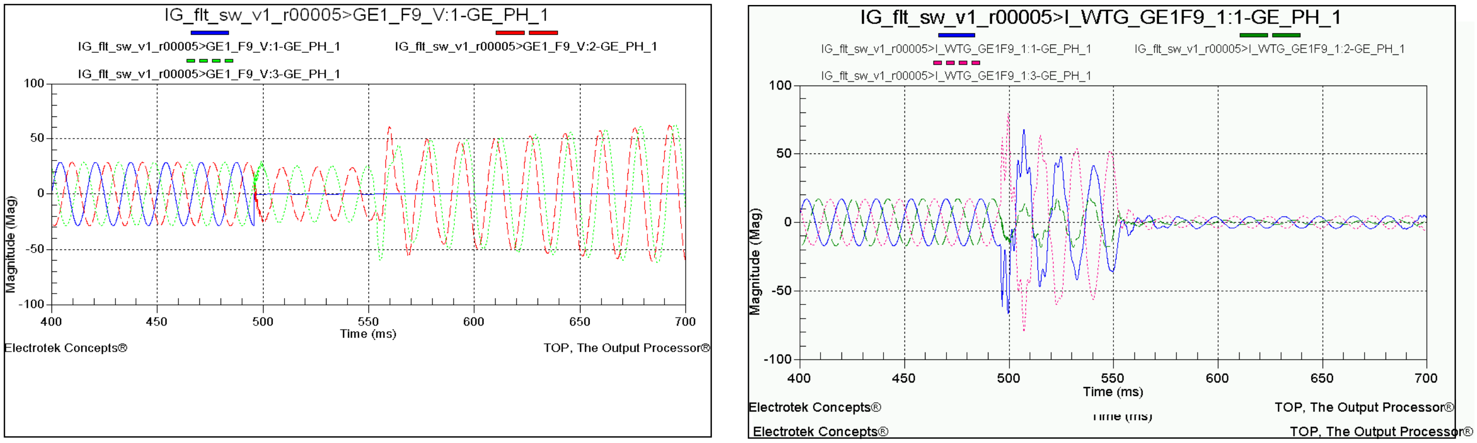
Installing a fast grounding switch to close and ground each phase immediately after opening the feeder can limit the DOV caused by an asynchronous wind turbine as explained in below example.

Figure 6 - Asynchronous Generator: Single-Line-To-Ground Fault at Station End



(a) Feeder-Side Voltage at 34.5 kV Bus with a Grounding Transformer (kV)

(b) Currents of WTGs at Branch #1 with a Grounding Transformer (kA)



(c) Feeder-Side Voltage at 34.5 kV Bus without a Grounding Transformer (kV)

(d) Currents of WTGs at Branch #1 without a Grounding Transformer (kA)

Harmonics

Harmonic Loading of Transformers

PV generation systems and many wind technologies use converters to provide 60Hz power to the collector system. These converters create harmonics of varying levels that result in harmonic currents flowing through the step-up transformers from the converters to the collector system. During the early development of these wind farms as converters started to replace simple inducton generators, transformer specifications for these converter technologies did not always consider the harmonic loading of the transformers. Some of the transformer failures of these early converer technologies were probably due at least in part to the harmonics.

Today, most wind turbine suppliers provide requirements for the step-up transformers that include the harmonic loading and power factor capabilities required of the transformers. It is important to include the harmonics for the proper transformer design.

Harmonic Overvoltages

Harmonic overvoltages are typically overvoltages resulting from a harmonic resonance on the system. Resonance is a naturally occuring phenomena on the power system. and occurs when the shunt capacitance of a system parallels the system inductance. These resonance conditions generally occur from the second to the fiftieth harmonic. It is when a resonance with minimal damping is excited by a harmonic source or by transient events that create harmonics on the system that high harmonic overvoltages can result.

Most harmonics on a transmission system are caused by loads being served from the system. The one major exceptions is when a transformer or line/cable reactor is energized. When this is done, especially with random closing, then a high level of unbalanced harmonic currents are injected into the system for a limited time.

Principles of System Resonance

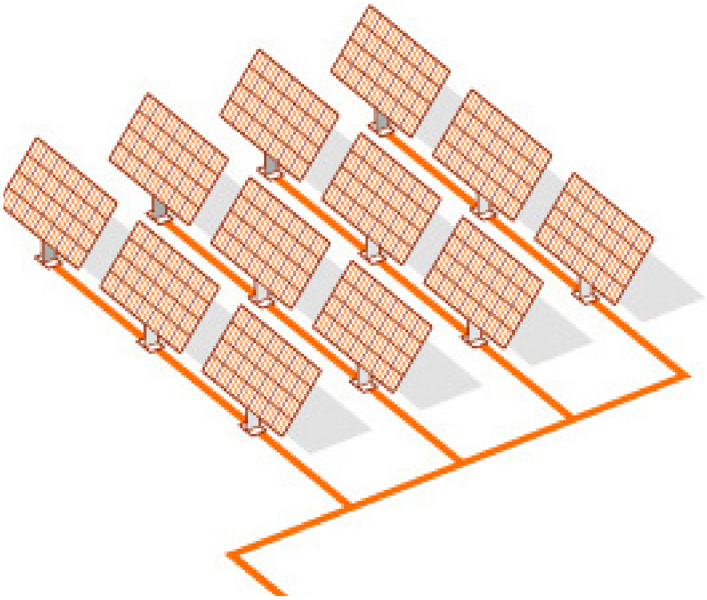
Shunt capacitors are commonly applied at all voltage levels on power systems. When shunt capacitor banks are connected to high-voltage and EHV systems, they create a characteristic resonance. It is important to note that they cause positive, negative, and zero sequence resonance. Generally the positive and negative resonance is almost identical, but the zero sequence may vary considerably from the positive and negative sequence. The same is true for cables or other equipment that have high capacitance to ground.

The odd harmonics are the characteristic harmonics on the power system. Balanced 3rd, 9th, 15th, etc. are considered zero sequence harmonics and they require a ground path since the harmonics on each phase are in phase. The other odd harmonics are positive or negative sequence. The zero sequence harmonics will see the zero sequence impedance and the positive and negative sequence harmonics will see the positive and negative sequence impedance. Therefore, it is important to look at both the positive and zero sequence impedance when analyzing a power system resonance and harmonic interactions. In general, a substation with generator step-up transformers and autotransformers (or three winding) with delta tertiary windings will provide a low impedance zero sequence path and the zero sequence resonance will be lower than the positive sequence. If there are no low impedance ground sources such as a switching station without transformers, then the zero impedance will be high and the zero sequence resonance will be higher than the positive sequence resonance.

An example of three shunt capacitor banks is shown below. These banks are installed at a 230-kV substation are shown with the characteristic resonance as each capacitor bank is added to the system. The resonance from these banks has not created any system problems and in general if there are no significant harmonics to excite the resonant points then no impact is expected.

Example of System Resonance: Three 230-kV Shunt Capacitor Banks

The zero (Ro, Xo) and positive (R+, X+) sequence plots of the frequency scans, with an increasing number the shunt capacitor banks, are shown in Figures 7 - 10.
Without any capacitance connected, there is no system parallel resonance which causes a high impedance peak. As more capacitance is added to the system, in this case as shunt capacitor banks, the system resonance peak occurs at lower frequencies.



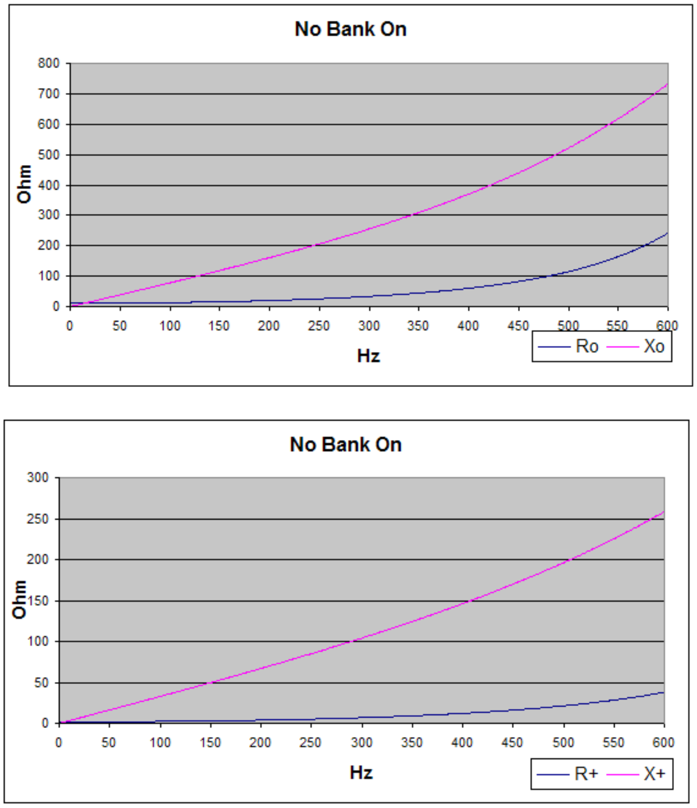


Figure 7 - Frequency Scan With All Capacitor Banks Off

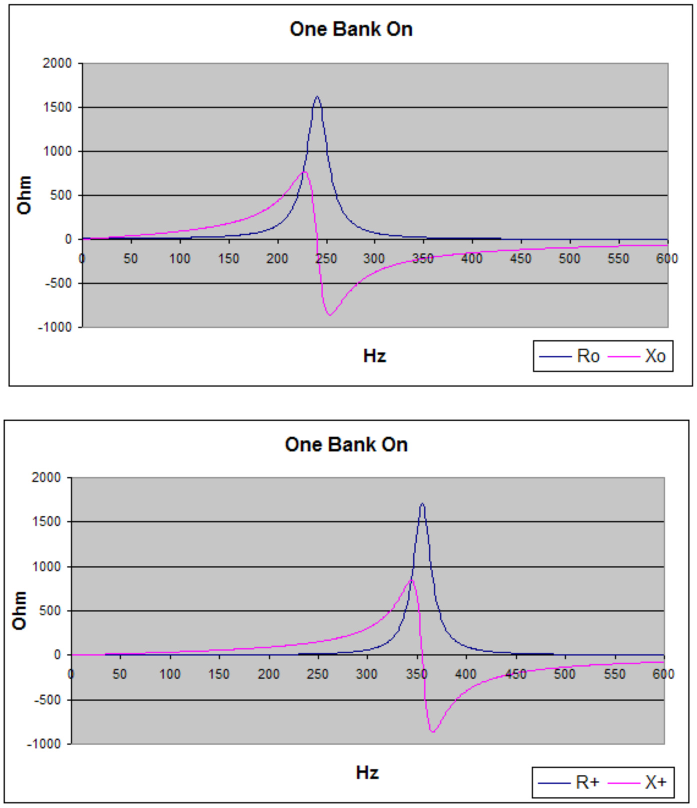


Figure 8 - Frequency Scan With One Capacitor Bank On

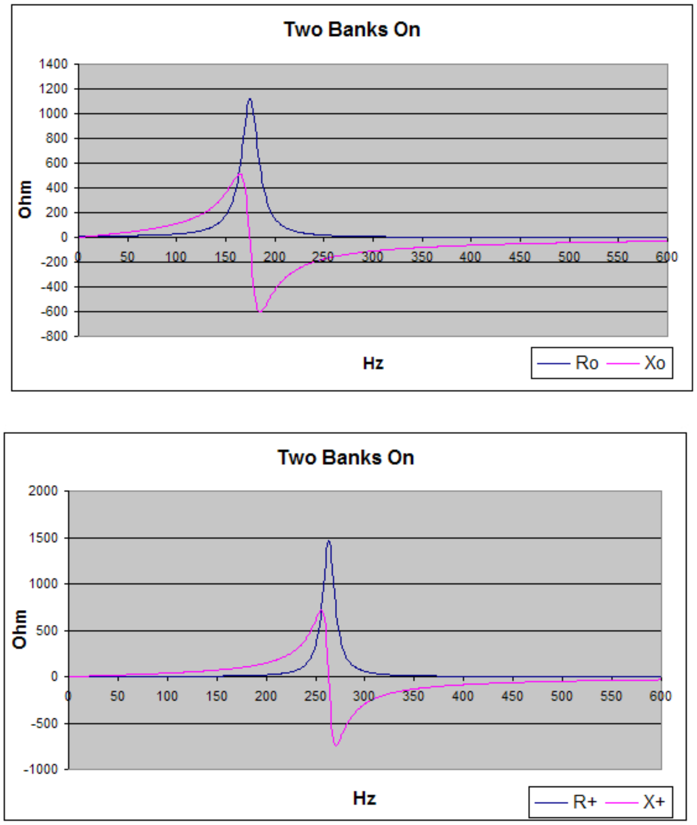


Figure 9 - Frequency Scan With two Capacitor Banks On

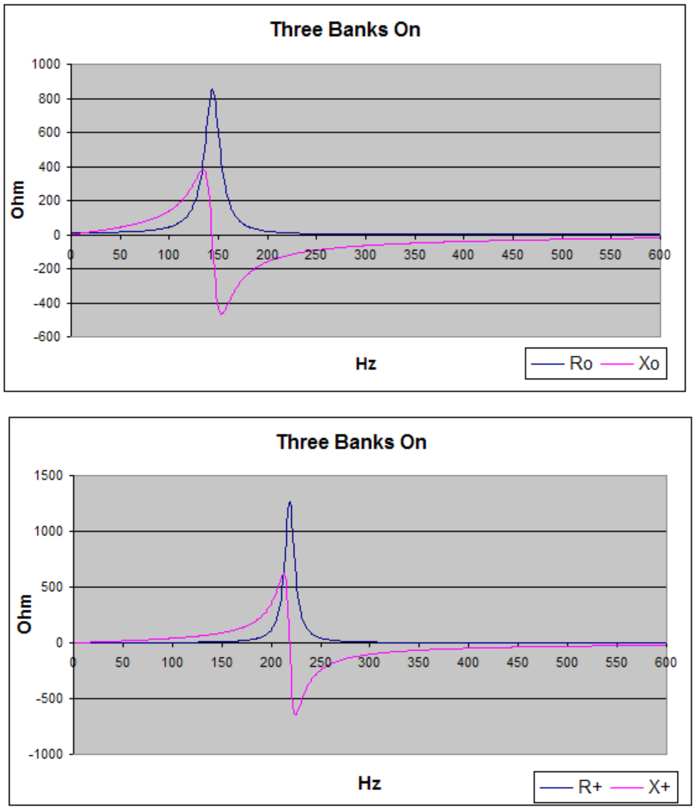


Figure 10 - Frequency Scan With All Capacitor Banks On

High harmonic impedance, by itself, is not an indication of a system problem. A problem only occurs if a source of harmonic current generated by a system component occurs at the resonance. With the high impedance it can result in high harmonic voltages. The harmonics can be amplified if they occur at a system resonance. As the system short circuit level changes, the parallel resonance will decrease for lower short circuit levels and increase for higher system short circuit levels.

Resonant conditions are part of the power system and a resonance by itself does not cause problems. However, the presence of significant harmonics can excite a resonance and this could result in problems for the power system.

Example of harmonic overvoltage: Wind Farm 34.5-kV Cable Collector System

The collector system for wind farms is typically underground 34.5-kV cables. As the wind farms have become larger and collector systems have 100 to 200 MW of generation connected, more extensive cable systems are required. The capacitance of the system can lower the resonance of the system into the range where it may amplify the harmonics. Figure 11 shows the frequency scan of a collector system where one of the parallel resonances is near the 5th harmonic.

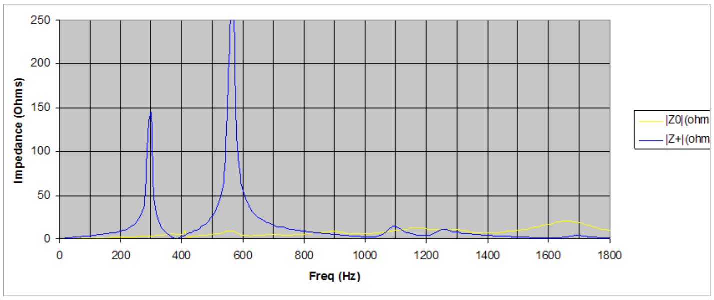


Figure 11 Collector System Frequency Scan

In figure 12 below, the wind turbines generated enough 5th harmonic currents to result in the harmonics being amplified.

These high harmonic voltages have failed arresters on collector systems and have also resulted in wind turbine step-up transformer failures. These types of harmonic problems are normally solved by adding a filter. Figure 13 below shows the 5th harmonic filter design for this system. Figure 14 shows the frequency scan with the filter added and Figure 15 shows the harmonic voltage distortion being significantly reduced.

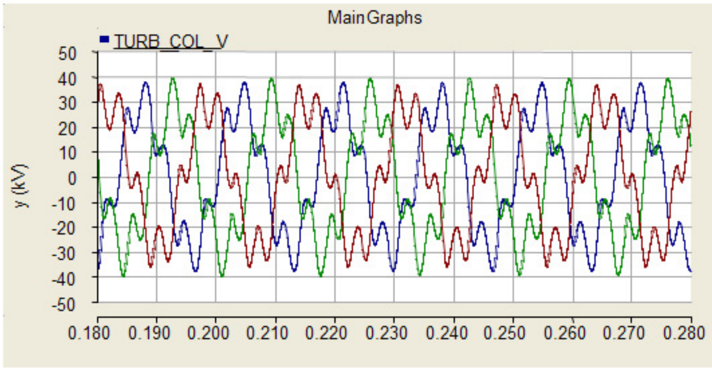


Figure 12 Harmonic Collector System Overvoltages from 5th Harmonic Wind Generation

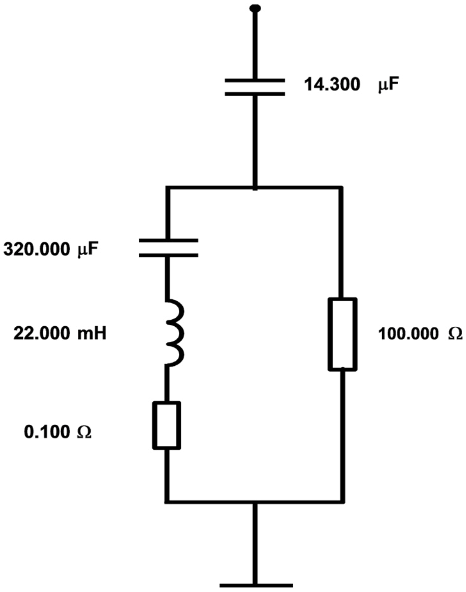


Figure 13 - 5th Harmonic Filter Design

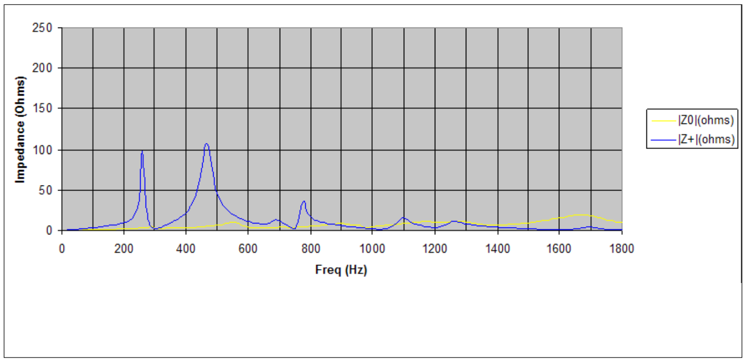


Figure 14 Collector System Frequency Scan with Filter

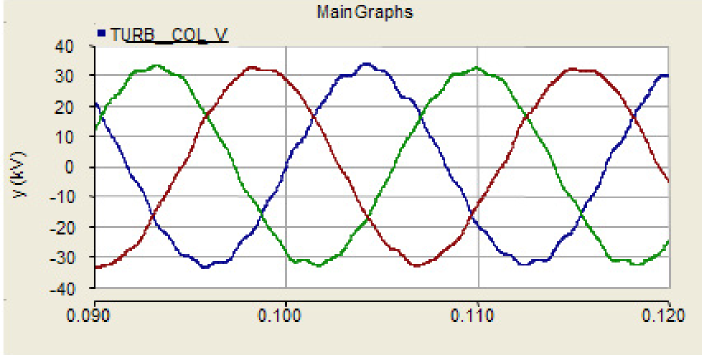


Figure 15 Collector System Voltages with 5th Harmonic Filter

HOV mitigation methods

In order to address the overvoltages and power quality issues caused by harmonics, a thorough harmonic analysis (harmonic load flow, frequency scan and a detailed harmonic analysis using harmonic sources specified by measured data or turbine manufacturer provided data) needs to be performed. Existing shunt capacitor banks can be detuned to system resonance frequency to avoid any potential HOVs. If the system produces harmonics, the equipment in the system must be rated to withstand the effects of harmonics along with the power quality at point of interconnection requirements. An important consideration is specifying the harmonic loading on the transformers so they can withstand these harmonics and the overheating caused by the harmonics. Most utilities follow IEEE 519 guidelines for voltage and current distortions limits at the point of interconnection. Addition of tuned harmonic filters can reduce the harmonic impedance at the resonance frequency thereby reducing the potential to cause HOV.

Transformer saturation

Transformer saturation is not normally an issue with renewable generation sources. However, the inverter technology used in one instance resulted in injecting small levels of DC current into the transformer and the resulting transformer saturation created significant harmonic currents. In the wake of this event, a study was done to evaluate transformer saturation.

The results of the study show that several amperes of DC current injection on the low side could easily cause transformer core saturation and result in very high levels of even harmonics (2nd and 4th) on the high side. If the DC current injection is reduced, the harmonic amplification is reduced. Once the DC current infection was reduced to 25% of the measured values, there was no longer any saturation causing amplification of harmonics on the high side.

Power factor and reactive power & voltage control

When renewable projects are connected to the utility's power grid, there are generally interconnection requirements for the power factor operating range and associated reactive power control and voltage control. This may be best demonstrated by the following example.

Reactive power requirements example and summary

The reactive power requirements for one solar power plant were analyzed. The system requirements for power factor at the point of interconnection called for available reactive power to be 33% rated power leading and lagging.

The design parameters and system assumptions were as follows:

- The 115/28-kV power transformer has a +/- 15% LTC, 8% impedance on 20 MVA, and continuous rating of 33 MVA
- Inverter step-up transformers are 5.6% on 1 MVA
- The generation is 30 MW
- Inverter bus maximum voltage is 1.1 pu
- Inverter bus minimum voltage is 0.9 pu

The power factor calculation requirements at the point of interconnection based on the above assumptions for a total of 30 MW are:

Lagging requirements:

30 MW gen X .33 = 10 MVAr

A 10% margin is added due to the uncertainties of the final system impedances:

10 MVARS + 10% = 11 MVARS

Leading requirements:

30 MW gen X .33 = 10 MVAr

A 10% margin is added due to the uncertainties of the final system impedances:
10 MVARS + 10% = 11 MVARS

The reactive requirements at the point of interconnection (POI) calculated above are:

For leading power factor: 11 MVArs at the POI
For lagging power factor: 11 MVArs at the POI

To meet the power factor at the POI and to supply the reactive power losses in the transformers and system, the reactive power capability of the inverters must be 0.80 power factor.

Figure 16 below shows the system with the inverters at the maximum 0.95 lagging power factor. Figure 17 shows that an inverter power factor of 0.85 will meet the system lagging power factor at the point of interconnection with a 1 MVAr margin. Figure 18 shows that an inverter with a power factor of 0.95 requires an additional 8 MVArs to meet the system lagging power factor at the point of interconnection. Figure 19 shows that an inverter power factor of 0.95 is sufficient to meet the system leading power factor at the point of interconnection.

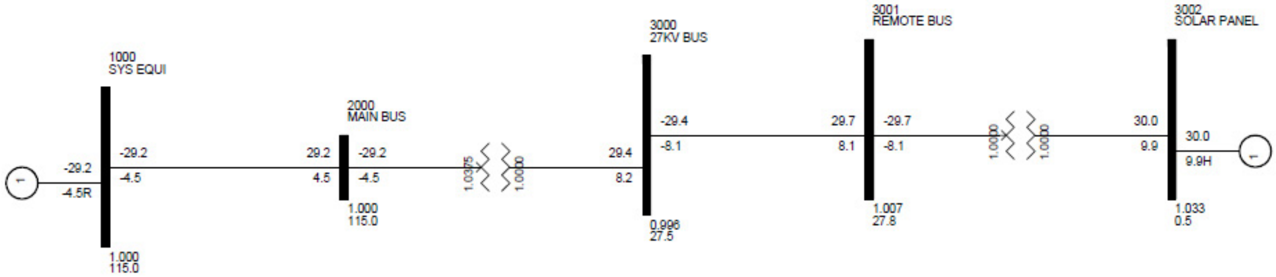


Figure 16 – Inverters at 0.95 Lag Power Factor (Additional 6.5 MVArs Needed at POI)

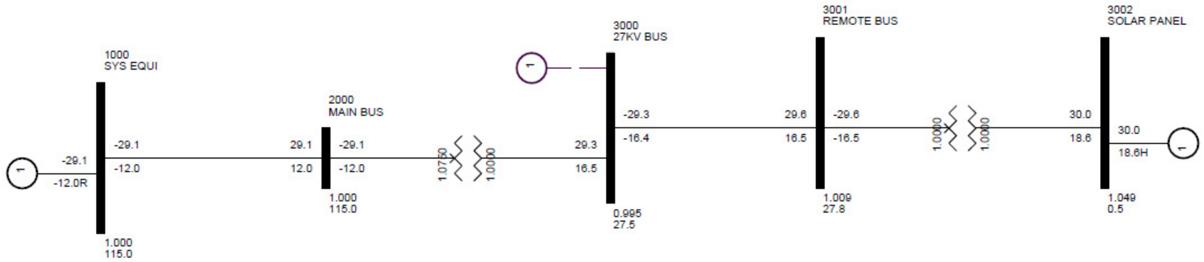


Figure 17 – Inverters at 0.85 Lag Power Factor (No Additional MVArs Needed at POI)

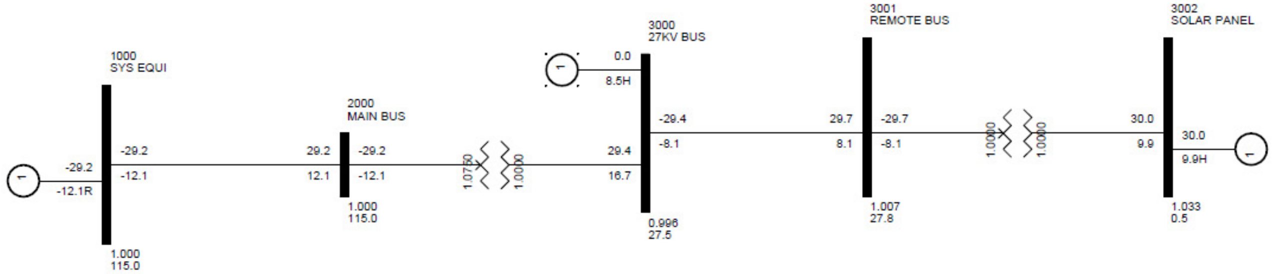


Figure 18 Collector System Frequency Scan with Filter

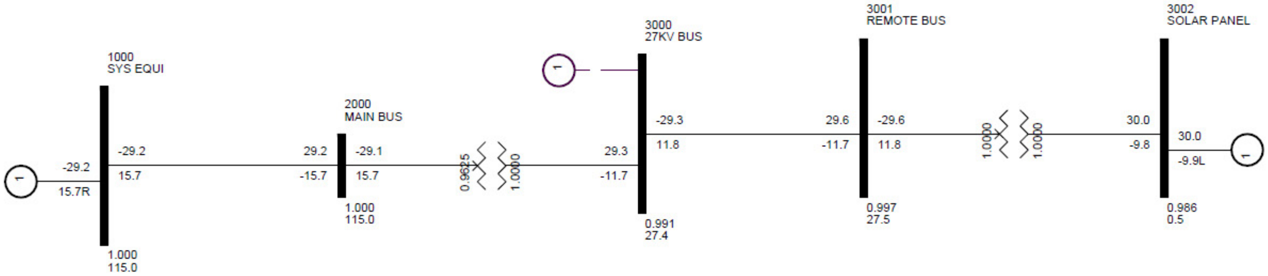


Figure 19 – Inverters at 0.95 Lead Power Factor (No Additional MVArs Needed at POI)

Some of the results from power factor studies can be summarized as follows:

- In more compact collector systems such as solar, for peak loads there are overall reactive power losses in the system so they absorb MVArs
- In large wind systems with extensive cable systems, the cable charging provides some compensation to reactive power and may even supply a few MVArs
- The above items must be considered when evaluating the capability of the inverters to meet the system power factor requirements at the point of interconnection. However, in general the system will absorb reactive power at peak load.
- With some inverter technologies, filters may be required and these will supply reactive power to the system.
- Wind turbine generator vendors can provide a specified power factor for the operation of their units.
- Solar generation vendors can often provide or absorb more reactive power by sizing the inverters larger than the maximum PV capability, which allows for reactive power control. This also means that at lower power levels more reactive power is available than at maximum power output.
- For generation that does not have the capability to operate through the required power factor range, shunt capacitors or shunt reactor banks may be needed to help meet the reactive power requirements. As an alternative for providing dynamic and continuous reactive power, SVC or STATCOM technologies provide controllable reactive power sources.

Voltage control

Besides meeting power factor requirement, sometimes there are also voltage control requirements. Many vendors of renewable generation provide a control system to monitor the voltage at the point of interconnection and adjust the generation voltage to maintain a desired voltage level. For wind generation this system has a somewhat slow response; however, each wind unit can quickly respond to maintain its terminal voltage which is important in system recovery from disturbances.

Power ramp rate limits

Some interconnection requirements, especially for smaller isolated systems, have a maximum rate at which the power from renewable generation can be increased and a maximum rate at which it can be decreased. In addition, there may be a requirement to respond to frequency variation on the power system. If the generation cannot meet these requirements then some type of energy storage system is required to temporarily absorb or supply the energy to limit the rate of power change. Examples of when energy storage could be needed for wind would be when a front with very high winds moves in and the wind velocity becomes higher than acceptable, in which case the generation is shut down. For solar, and example would be when a cloud comes over the PV and significantly reduces the generation output.

The two items that will determine how much energy storage is required are the ramp rate control or limit and the required generation for frequency response and regulation.

Ramp rate control

An example of meeting a ramp rate of 10% of peak generation per minute for PV generation is outlined below. The ramp rate control must limit the increase and decrease in power to 10% of the maximum rating of the PV generation. This means that if the PV were at maximum output and a cloud suddenly obscured the sun, the PV output would go to a reduced level assumed to be 30% for this example. An energy storage system such as a battery energy storage system (BESS) will need to be sized for at least the maximum PV generation in order to pick up the lost power and ramp it down to 30%. Since the ramp can be 10% per minute it can be ramped down in 7 minutes. The MWh of storage for a 10 MW PV is calculated by:

$$\text{Energy} = 70\%\ \text{Max Power in MW} \times (7\ \text{min.} / 2) \times (1\ \text{Hr} / 60\ \text{min.})$$
$$= 0.408\ \text{MWh}$$

The same energy may be required to be absorbed when the clouds no longer obscure the sun and the PV can go to full power.

Frequency response and regulation

The frequency response requires the PV generation to be able to increase or decrease the generation output by 10% of the maximum generation for large frequency deviations in order to help the system respond to these deviations. The PV system must maintain the 10% response for 9 minutes and then it is allowed to ramp down at the defined ramp rate limit of 10% of maximum power per minute.

For an underfrequency event, the BESS would need to respond by providing the extra 10% power for 9 minutes. This would require the following energy storage for a 10 MW PV:

Energy output = (0.10 x Max Power in MW) x (9 min.) x (1 Hr / 60 min.)
= 0.15 MWh

For an overfrequency event, the BESS would need to respond by absorbing the extra 10% power for 9 minutes. This would require the following energy storage:

Energy input = (0.10 x Max Power in MW) x (9 min.) x (1 Hr / 60 min.)
= 0.15 MWh

Total energy storage

The total energy storage capability of the system needed to respond to all of these events is based on the following assumptions:

- 0.15 MWh of storage will need to be reserved to absorb energy for an overfrequency event.
- 0.15 MWh of storage will be needed to meet the underfrequency event plus 0.408 MWh of storage to ramp down after nine minutes.
- This always assumes that a ramp up will always follow a ramp down so the battery will be mostly discharged when the PV needs to be ramped up.

Based on these assumptions, we can establish the following:

- The range of energy storage for the BESS in this example will need to be 0.558 MWh.
- The power rating of the BESS will need to be rated to absorb or supply the 70% PV generation.
- The BESS can also provide the reactive power requirements. If the BESS is not at its maximum output it will be able to provide fast voltage control except for the short time it may be at maximum output before ramping down. The slope can be adjusted to coordinate with other reactive power sources in the area. This will allow the PV inverters to operate near unity power factor and not be required to supply reactive power.
- The maximum charging and discharging rate for the batteries will be 10% of the maximum PV generation per minute.

Voltage and frequency performance

Standards have been adopted by many system operators requiring renewable generation to ride through certain levels of low voltage and high voltage. This requirement specifically has identified the low voltage ride-through conditions. Also frequency ride-through has also been specified. Both of these are discussed below

Low voltage ride-through and overvoltage tripping

Figure 20 below shows some of the curves that have been used to define the low and high voltage ride-through capabilities required for renewable generation. More recently these requirements have been to require some zero voltage ride-through as shown by the green line plotted below. The plots show the low voltage levels at which the generation is expected to stay on-line and return to full output when the voltage recovers. The high voltage line shows the voltage level that the generation must accept before tripping. Above the high voltage line or below the low voltage line the units may be tripped.

Many of the renewable generation suppliers have designs to meet these requirements although there are still many models available that do not meet these requirements or at least the more stringent requirements. These requirements are being applied to all types of renewables so it is important to know what the interconnection requirements are so the proper units are provided.

Frequency deviation ride-through

Figure 21 below shows typical frequency ride-through requirements. Most converter technologies can operate in a wide range of frequency so for many of the technologies this is not an issue, but there are some products that do not have the capability provided to operate with large frequency deviations. This curve indicates the generation must operate at 57 Hz for 3.3 seconds then ramping up to 59 Hz over 5 minutes.

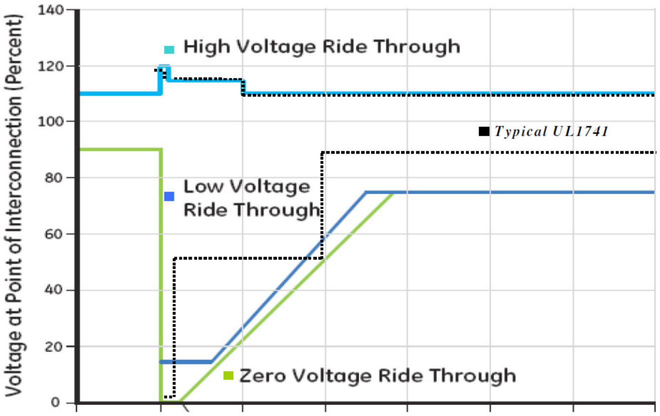
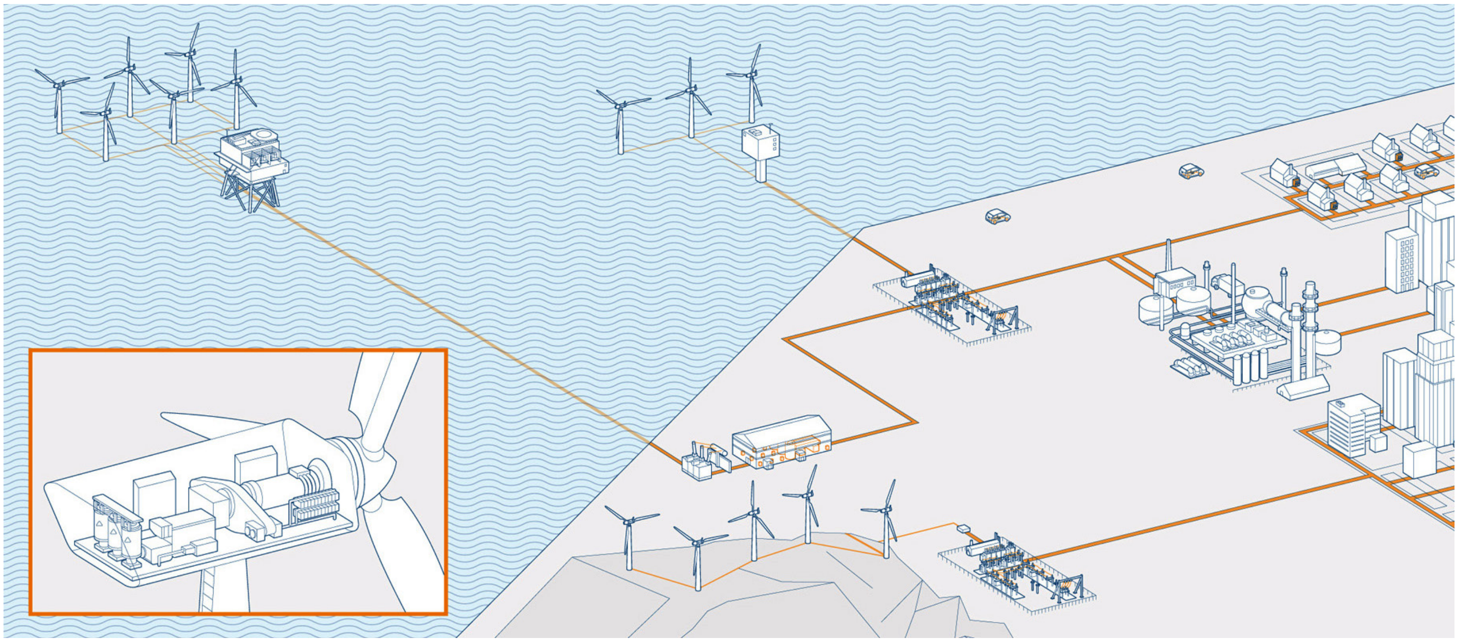


Figure 21 Typical Frequency Ride-Through Requirements



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Continuous capabilities have been defined as low frequency from 59 Hz to 5.4 Hz and high frequency from 61 Hz to 60.6 Hz. Most inverters have the capability to operate in a much wider range.

Conclusion

As more renewable energy sources come online, they will take on greater and greater importance in the overall generation mix. It is therefore vital to build our understanding of the engineering challenges these installations present. In this paper, we have outlined some of the most common sources of system disturbances and equipment failure in renewable facilities: overvoltages; harmonics; transformer saturation; power factor, reactive power and voltage control; power ramp rate limits; and voltage and frequency performance.

ABB has had the opportunity to examine the causes behind many failures that have occurred within renewable energy facilities, and we have drawn on that experience here to identify technical solutions to these challenges. In many cases, avoiding later problems comes down to taking a more holistic view of the renewable plant and specifying equipment with the particular characteristics of these installations in mind. In other instances, performing up-front studies (e.g., on harmonic load flows) can yield valuable insights that can then be used to inform system and component design. In any event, it is increasingly clear that the owners and operators of renewable energy facilities can benefit from the experience of their peers as well as qualified service providers with a view to the overall health of the system.

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