Design Studies for a Wind Farm Collector System

Jenny Z. Zhou and Robert S. Burton

***Abstract*--This paper discusses the insulation coordination and transient overvoltage of a 75 MW wind farm collector system with a point of interconnection at a 230 kV substation. The switching overvoltages were determined by simulation of a three-phase model of the system in the electromagnetic transient program PSCAD/EMTDC. A generic back-to-back power converter wind generator model was used to investigate the transient overvoltage due to fault and switching events. The purpose of the design studies was to determine the appropriate feeder cable voltage rating and to determine whether additional grounding transformers or surge arresters are required.**

***Keywords*: Switching transient, Full converter, Wind turbine generator, Collector system, Cable, PSCAD/EMTDC.**

I. Introduction

When designing a large wind farm and its collector system, detailed electrical system studies are required to specify equipment ratings, optimize the design, and identify/mitigate any undesirable interactions with generators or nearby electrical systems. This paper discusses the insulation coordination and transient overvoltage of a 75 MW wind farm collector system with a point of interconnection at a 230 kV substation. The wind energy will be delivered to the load serving area via an HVDC transmission line and an interconnected ac system. The HVDC converter station is directly connected to the 230 kV substation. This study assesses the impact of transient overvoltage during fault and switching events and provides the requirements and specifications for arrestor sizing and location. The collector system design includes a single point ground provided by the delta-wye 230/34.5 kV transformer at the main wind farm substation. The transient behavior and equipment overvoltage stresses that occur when the collector system feeder breaker trips during normal and faulted conditions are major concerns. The purpose of the design studies is to determine the appropriate feeder cable voltage rating and if additional grounding transformers or surge arresters are required.

The switching overvoltages were ascertained by simulation of a three-phase model of the system in the electromagnetic transient program PSCAD/EMTDC. The wind farm units and the collector system were modeled. The model included a detailed representation of each wind turbine generator, each 34.5 kV/690 V generator step-up transformer, the feeder cables, and the arresters. The collector substation will consist of one 230/34.5 kV transformer and four low-side 34.5 kV breakers. The substation will be connected to a 230 kV substation by approximately 23 miles of 230 kV overhead transmission line.

II. System Description

The base case load flow in PSS/E format was used to generate wind farm collector system surrounding equivalents. The system modeled consists of surrounding 230 kV and 345 kV equivalent sources. All transmission lines were represented by frequency dependent distributed parameters in the study model. The HVDC system was modeled as an equivalent load. Fig. 1 shows the wind farm collector surrounding equivalent.

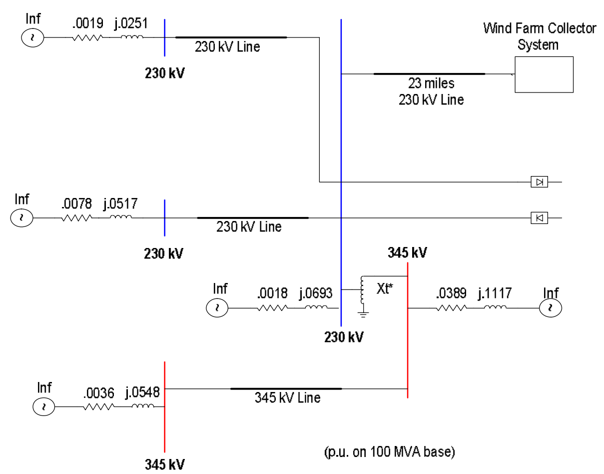

Fig. 1. Wind farm collector surrounding equivalent

A. Wind Generators

The wind farm will use variable-speed wind turbine-generators. Each wind turbine-generator unit has a rated power output of 2.3 MW. The electrical drive train of each unit consists of an induction generator coupled to the grid via a back-to-back power converter. Fig. 2 shows the basic single-line diagram of the wind turbine generator.

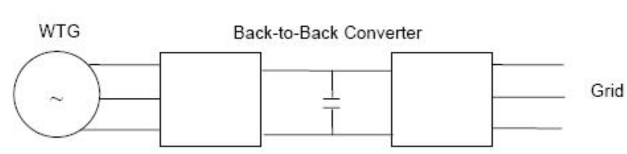

Fig. 2. Single-line diagram of wind turbine generator

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The converter allows generator operation at variable speed, frequency, and voltage, while supplying power to the grid at a constant frequency and voltage. The converter is capable of delivering MWs and delivering or absorbing Mvars both to and from the grid.

A generic wind generator model was used to investigate the transient overvoltage due to fault and switching events. The basic configuration of the generic 2.3MW full converter wind turbine generator had a conventional synchronous generator connected to the turbine. The wind turbine had pitch control to regulate overspeed. The three-phase output of the synchronous generator at 1150 V was connected to a thyristor rectifier consisting of a 6-pulse thyristor valve group. It normally operated as a diode bridge, but the pulses were removed for overvoltage protection of the dc circuit. The ac side converter was a synthesized current modulated inverter that generated a 0.69 kV, three-phase ac waveshape with a high pass, 0.48 Mvar ac filter.

Three control modes, ac voltage control, constant reactive power control, and constant power factor control were implemented in the model. Protections with adjustable settings were included in the model: overspeed protection, ac undervoltage protection with LVRT settings according to FERC order No.661-A [2], and dc undervoltage protection. The wind turbine generator was designed to block and trip if the protection settings were exceeded.

The voltage at the wind turbine-generator (WTG) terminals (the voltage at the coupling between the back-to-back converter and the grid) was 690 V and was stepped up to a collector system voltage of 34.5 kV through a generator step-up transformer (GSU). Each GSU was rated at 2.5 MVA with Delta/Y grounded 34.5 kV/690 V at 6% impedance. The wind farm had a 34.5 kV collector system network to collect the power output from the individual wind turbine generators.

B. Wind Farm Collector System

The collector substation consisted of one transformer (150 MVA Delta/Y grounded 230/34.5 kV at 8.5% impedance) and four low-side 34.5 kV breakers.

The collector system consisted of four radial feeders, each having between seven and nine wind turbines. All feeders were underground, and each consisted of the following conductor sizes: 1/0, 4/0, 750 MCM, and 1000 MCM 345 Mil EPR, each with a concentric neutral. The cable that ran between the turbines was approximately three-quarters of a mile long. The four feeders were named circuits 800 (7 WTGs), circuit 801 (8 WTGs), circuit 802 (9 WTGs), and circuit 803 (9 WTGs). Fig. 3 shows feeder circuit 803 of the collection system in which only one wind turbine generator model is represented. The other feeders are of a similar design. Feeder circuit 803 has one switch cabinet that connects to three sub feeders.

Coupled PI sections with correct impedance and line charging were used to represent each underground cable. A 34.5 kV ABB XPS metal oxide arrester with a 27 kV rating and 22 kV MCOV was selected for this study [3].

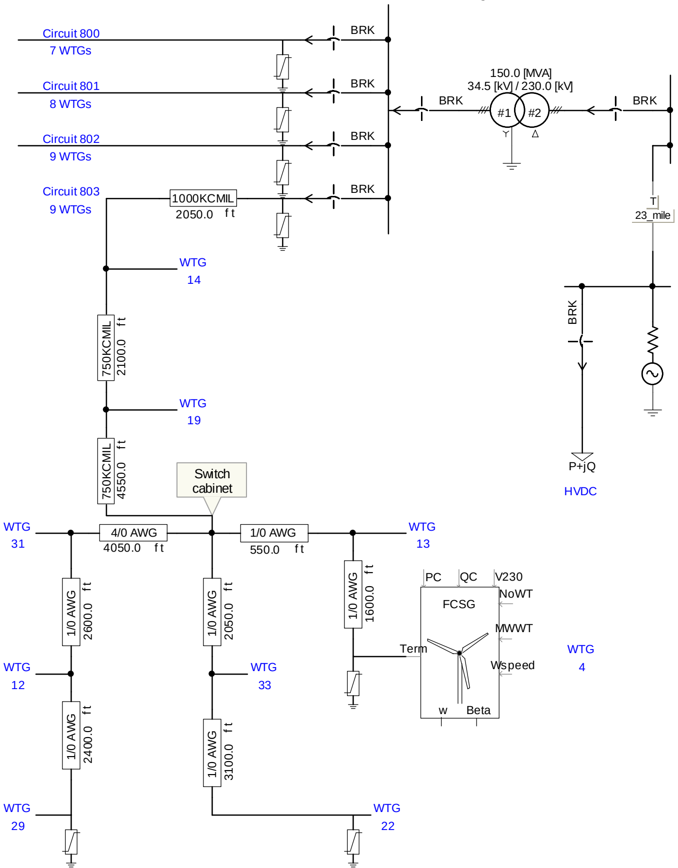

Fig. 3. One feeder of the wind farm collector system

III. Study Results

The cable switching surge depends upon several factors, such as time of breaker closing and opening, the breaker pole span, the fault type, the fault location, the connected network, the amount of charge on the cable, and other tower and conductor related parameters. Simulations were carried out for various feeder and wind generator configurations for different types and locations of disturbance. Feeder cable energization overvoltages from the system under trapped charge were studied for each feeder cable. The fault clearing overvoltages were evaluated for each feeder cable. During the simulations, the maximum voltages at each WTG terminal, along the cables and switch cabinets, at the 34.5 kV breakers, and at the cable terminations were recorded. The worst case scenarios in terms of maximum voltage were identified during the simulations. The results from the study were analyzed to identify the locations most electrically suited for surge arresters. The arrester rating and the arrester duty were determined.

A. Feeder Cable Energization Overvoltage

Feeder cable energization overvoltage from the system under a trapped charge was studied for each feeder cable. For each energization case, the 34.5 kV feeder breakers in the substation were closed and then opened prior to the energization operation by point-on-wave to simulate the maximum trapped charge on the cable. For each energization case, a 5-cycle protection delay was applied before closing the breaker and 20 random breaker closings were simulated with a breaker pole span of 8 ms. During the simulations, the phase "A" breaker was closed at random angles between 270° and 360° of the phase "A" voltage, and the phase "B" and "C" breakers were closed randomly within ±4 ms from the closing of the phase "A" breaker. The closings of phases "B" and "C" were selected independent of each other.

Arresters at the feeder/sub-feeder end and at the connection to the substation 34.5 kV bus for each feeder were studied when the arresters were out of service and when the arresters were in service.

Based on experience and current industry practice, and as per IEEE Std 1313.2-1999 [1], the typical phase-to-ground switching overvoltage is 1.8 to 2.0 pu with reference to the maximum system line-to-ground voltage. In this study, a base voltage of 28.17 kV was used, which is the peak phase to ground voltage of 34.5 kV. The calculated maximum voltage at various locations along the cables and switch cabinets for each feeder were recorded. The maximum energy absorption of each arrester was also recorded.

The results show the worst energization overvoltage under a trapped charge was 2.87 pu without arresters in service. The overvoltage was reduced to 1.84 pu with both arresters at the feeder end and at the connection to the substation 34.5 kV bus in service. Fig. 4 shows the waveforms of the voltage at WTG #23 of feeder circuit 800, the arrester energy absorption and the arrester discharge currents. The energy absorption under this situation was about 1.6 kJ. The duration of the switching impulse was less than a quarter cycle. For the 22 kV MCOV arrester, the energy discharged is 1.6/22 = 0.07 kJ/kV of MCOV.

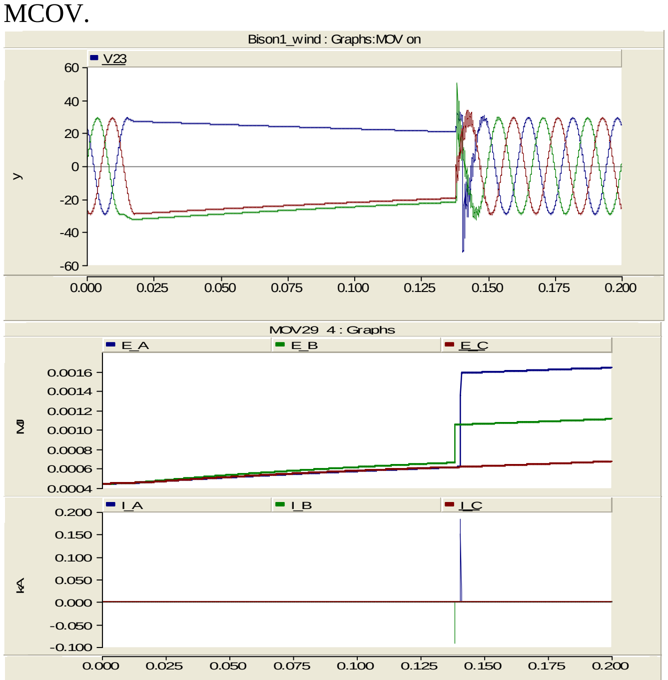

Fig. 4. Feeder800 WTG#23 energization overvoltage and arrester energy duty

B. Clearing Fault Overvoltages

Three types of faults (single-phase-ground, two-phase-ground, and three-phase-ground) and three fault resistances, (0.01 ohm, 1 ohm, and 10 ohms), were studied. Various faults were applied at five fault locations: at the middle of the feeder cable, at the both sides of the 34.5/230 kV step-up transformer, on the line end connected to the HVDC system, at the feeder far end, and at the end nearest to the substation WTG terminals. For each fault clearing case, faults were applied between 270° and 360° of the phase "A" voltage at 19 points on the wave 5 degrees apart. For each of these 19 faults, a 5-cycle protection delay was applied before opening the respective breakers to clear the fault. During simulation, the maximum voltages at each wind turbine terminal and switch cabinet were monitored.

The fault clearing overvoltages were evaluated for each feeder cable. Different types of fault at the different locations were applied under the following system configurations:

- One 2.3 MW WTG at the far end of each feeder
- One 2.3 MW WTG at the nearest end to the substation of each feeder
- Two WTGs, each with 2.3 MW at the far end and at the nearest end to the substation of each feeder
- All WTGs, each with 2.3 MW at each feeder

When two arresters, one at the end of the feeder and one at the connection point of the feeder to the substation 34.5 kV bus were in service, the worst clearing fault overvoltage was around 1.9 pu, which occurred when clearing faults at the cable or at both sides of the 34.5 kV/230 kV step-up transformer. With only one arrester at the connection point of the feeder to the substation 34.5 kV bus in service, the worst clearing fault overvoltage was over 2.0 pu, in the vicinity of the far end of the cable. The results show that it is required to install an arrester at the end of each feeder to prevent switching overvoltage. It is also required to install an arrester at the end of each sub-feeder in case the sub-feeder, which has an arrester installed, is switched off.

Fig. 5 shows the waveforms of the voltage nearest to the substation at feeder circuit 803, the arrester energy absorption and the arrester discharge currents when clearing a single-phase-ground fault with 0.01 ohm fault resistance at the low-voltage side of the 34.5/230 kV transformer when all WTGs connected to this feeder are in service. The maximum energy absorption is about 41 kJ and the duration of the switching impulse is less than a quarter cycle. For the 22 kV MCOV arrester, the energy discharged is 41/22 = 1.86 kJ/kV of MCOV.

The study also shows when the arrester is installed at the feeder cable side of the 34.5 kV breaker, the floating grounding from tripping breakers is prevented and an additional grounding transformer is not required.

Fig. 6 and Fig. 7 show the waveforms of the voltage nearest to the substation at feeder circuit 803 when clearing a single-phase-ground fault with 0.01 ohm fault resistance at the middle of the feeder cable with and without a surge arrester at the feeder cable side of the 34.5 kV breaker in service. In Fig. 7 it can be seen that when the feeder 34.5 kV breaker trips, the ground source of the substation step up transformer is lost and the floating grounding imposes high transient overvoltage to the feeder cable. While Fig. 6 shows that with an arrester installed at the feeder side of the 34.5 kV breaker the floating grounding is prevented.

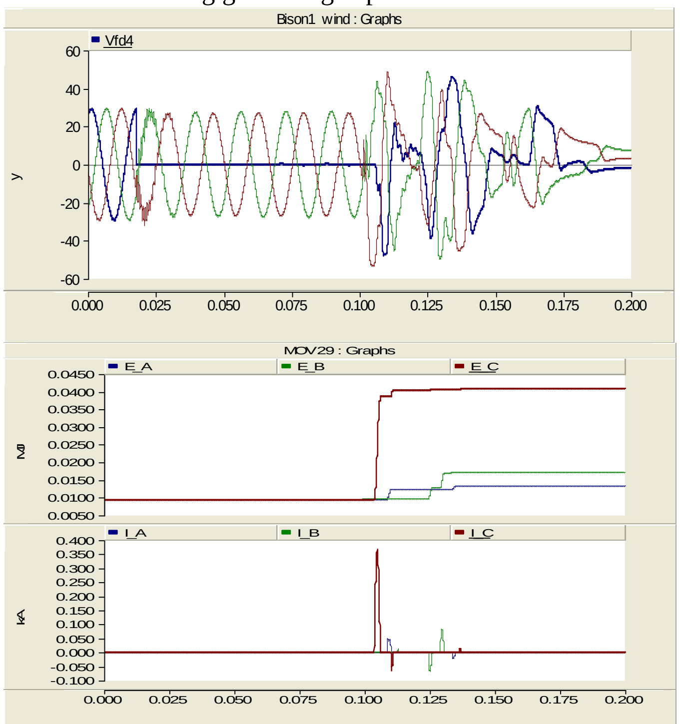

Fig. 5. All WTG@ Feeder803, Fault overvoltage and arrester energy duty

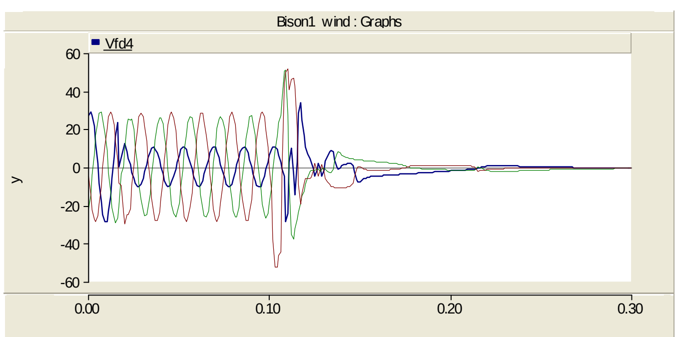

Fig. 6. All WTG@ Feeder803, Fault overvoltage with arrester in service

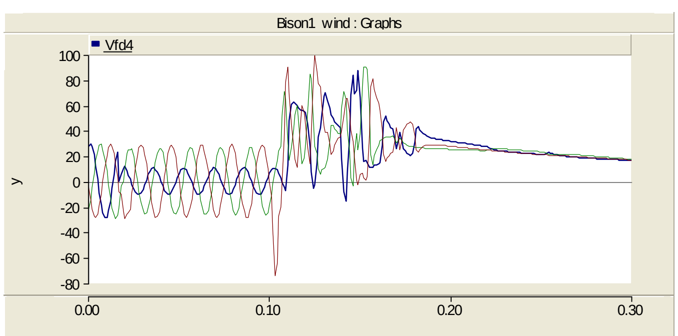

Fig. 7. All WTG@ Feeder803, Fault overvoltage without arrester in service

IV. Conclusions

Transient behavior and equipment overvoltage stresses that occur when the collector system feeder breaker trips during normal and faulted conditions are major concerns when designing a wind farm collector system.

This paper investigates the insulation coordination and transient overvoltage of a 75 MW wind farm collector system with a point of interconnection at a 230 kV substation to determine the appropriate feeder cable voltage rating for the system and to determine whether additional grounding transformers or surge arresters are required to prevent transient overvoltages. The wind farm collector system used in the study included a single point ground provided by the delta-wye 230/34.5 kV transformer at the main wind farm substation.

The switching overvoltages were determined by simulating a three-phase model of the system in an electromagnetic transient program. The wind farm units and the collector system were modeled in detail. A generic 2.3 MW full converter wind turbine generator model was used to investigate the transient overvoltage due to faults and switching events. Simulations were developed and conducted for the energization of the feeder cable under a trapped charge and for the clearing of various fault events. The following conclusions were derived from this study:

- Arresters at the end of the feeder cable and the sub-feeder cable and an arrester at the connection to the substation 34.5 kV bus of each feeder are adequate for limiting transient overvoltage. A 34.5 kV ABB XPS metal oxide arrester with a 27 kV rating and 22 kV MCOV was selected for this collector system.
- To prevent floating grounding from tripping breakers, arresters should be installed at the feeder cable side of the 34.5 kV breakers. Additional grounding transformers on each feeder cable are not required to protect the feeder from overvoltage.
- With arresters in service, the energization overvoltage was below 2 pu, the worst clearing faults overvoltage was around 1.9 pu. The maximum energy absorption of the arrester under fault conditions was around 41 kJ and the energy discharged was 1.86 kJ/kV of MCOV and the duration of the switching impulse was less than a quarter cycle, which are within the energy capability of the selected surge arrester.

V. Acknowledgment

The authors gratefully acknowledge Dennis Woodford for his work on the generic wind turbine modeling and for his review of this document.

VI. References

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