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Modeling and Simulation of Advanced Reactive Compensation Systems in Renewable Energy Applications

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SUMMARY

This paper discusses modeling and simulation of advanced reactive compensation systems (RCSs) in renewable energy applications. Such RCSs are usually comprised of distributed static compensators (DSTATCOM) and switched shunt devices such as mechanically switched capacitors or reactors. The systems have various advanced control strategies with either voltage control, reactive (Q) control, power factor control as required by interconnection agreements or Grid Codes. Integrated systems where the DSTATCOM acts as an overall plant master control, with other controls in the renewable power plant receiving control commands from the master (or vice versa) are becoming more commonplace.

One of the major DSTATCOM applications is to mitigate the voltage impacts of large scale renewable energy integration, e.g., wind or solar power, on the power system and to provide reactive support for wind or solar plants to meet interconnection requirements and grid codes. This paper reviews two dynamic simulation models of the DTSTACOM (i.e., a major component in a RCS). Dynamic simulations showing both real and benchmark systems are presented to show that an RCS consisting of a DSTATCOM and mechanically switched capacitors can work and coordinate with wind turbine generators to comply with the voltage and reactive requirements of applicable grid codes. The reactive characteristics of the DSTATCOM are also presented and discussed. This paper contributes to the areas of advanced modeling approaches and integration of large scale renewables.

KEYWORDS

Wind power, solar power, wind turbine generator, grid code, low voltage ride-though, reactive compensation system, and static compensator.

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I. INTRODUCTION

Wind and solar generation plants are considered a clean and renewable energy resource. Among renewable energy sectors, wind and solar power have seen the fastest adoption rate and are installed in many large-scale commercial applications in the U.S. and elsewhere in the world.

The United States has witnessed a rapid wind power expansion in the past decade. According to the American Wind Energy Association (AWEA), the U.S. wind industry now totals 46,919 MW of cumulative wind capacity through the end of 2011 (Figure 1). The U.S. wind industry has added over 35% of all new generating capacity over the past 4 years, second only to natural gas, and more than nuclear and coal combined. Today, U.S. wind power capacity represents more than 20% of the world's installed wind power, the second largest wind power market after China in the world. By 2030, 20% of the U.S. electricity demand is targeted to be supplied by wind power. That would be approximately 300 GW of wind generation capacity.

Solar power is also experiencing a rapid expansion in the United States. According to the Solar Energy Industries Association (SEIA), developers in the U.S. installed 1,855 MW of photovoltaic (PV) solar systems in 2011, representing 109% growth over 2010 (Figure 2). In the fourth quarter of 2011, 776 MW of PV was installed, by far the most of any quarter in U.S. solar market history. It is forecasted that the U.S. installation is likely to reach 3 GW in 2012 and it could pass 10 GW in 2016 [1].

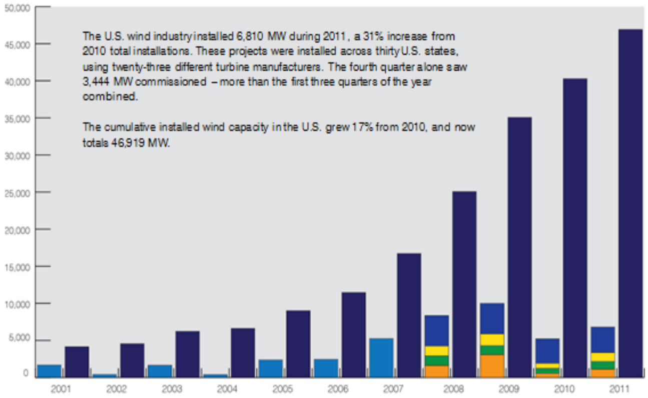

Figure 1: U.S. Annual and Cumulative Wind Power Capacity from 2001 to 2011[1]

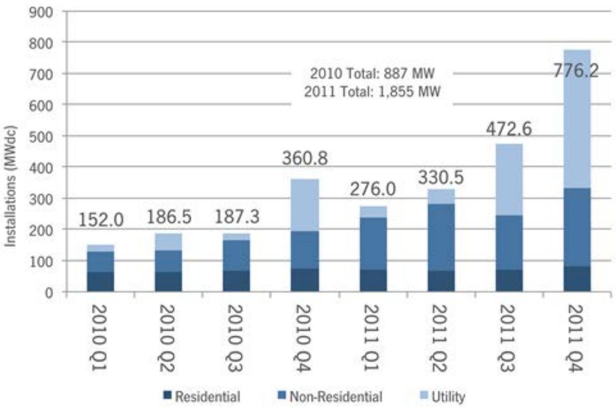

Figure 2: U.S. Annual Solar Power Capacity for 2010 and 2011[2]

As wind or solar power becomes a larger part of the total generation capacity in power systems in the U.S. and elsewhere in the world, there is an increasing concern over the impacts of wind or solar generation on power system operation and controls. Major impacts or issues related to integration of large scale wind or solar power include:

1. Transmission capacity to deliver wind or solar power
2. Issues on dispatch of wind or solar power with random characteristics
3. Reactive power capabilities of wind or solar plants
4. Thermal, voltage and stability impacts on the power grid
5. Power factor requirements from the power grid
6. Frequency and voltage ride-through capabilities
7. Short circuit effects
8. Harmonics and flicker effects

Advanced reactive compensation systems (RCSs) can help address issues in integrating wind and solar plants and in meeting interconnection requirements. Such RCSs are usually comprised of distributed static compensators (DSTATCOM) and switched shunt devices such as mechanically switched

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[1] Source: AWEA Public Market Report: "U.S. Wind Industry Fourth Quarter 2011 Market Report", January 2012

[2] Source: SEIA U.S.Solar Market Insight Report: " 2011 Year-In-Review | Executive Summary"

capacitors or reactors. Various advanced control strategies are applied including voltage control, reactive (Q) control, or power factor control at a local point defined as a Point of Interconnection (POI).

II. INTERCONNECTION REQUIREMENTS FOR RENEWABLES

The interconnection of large scale wind or solar generation with an existing power system requires compliance with grid codes, which are designed to address renewable integration issues as discussed above. Grid codes vary by country and also by region in a country. Grid codes in the U.S. are set forth by the North American Electric Reliability Corporation (NERC) and its regional reliability councils, Federal Energy Regulatory Commission (FERC), Regional Transmission Organizations (RTOs), Independent System Operators (ISOs), and transmission utilities or other concerned entities. These codes include voltage performance, reactive and power factor control and low voltage ride-through requirements for wind power interconnections, among other requirements. For instance, steady-state voltage at the point of interconnection (POI) of a wind plant is typically required to be controlled in the range of 95% to 105% of nominal value in base system and contingency operating conditions. FERC Order No. 661-A, which specifies Standards for Low Voltage Ride-Through (LVRT) Capability of a Wind Generating Plant [2], stipulates that wind generating plants are required to remain in-service during three-phase faults with normal clearing time (typically 4–9 cycles) and single-line-to-ground faults with delayed clearing time. A wind generating plant shall remain interconnected during such a fault on the transmission system for a voltage level as low as zero volts, as measured at the high voltage side of the wind plant step up transformer. This Order further stipulates that a wind generating plant shall maintain a power factor within the range of 0.95 leading to 0.95 lagging, measured at the POI, if the Transmission Provider’s System Impact Study shows that such a requirement is necessary to ensure safety or reliability. Some requirements for wind plants such as LVRT criteria are now also applied to solar generation by some regional interconnection entities [3].

III. REACTIVE CHARACTERISTICS AND MODELING OF DSTATCOM-BASED SYSTEMS

Most modern wind plants use either doubly fed induction generators (DFIG) or full converter wind turbine generators which may provide some reactive capability (one example would be ±0.95 power factor) or a reactive capability similar to synchronous generators. A solar photovoltaic (PV) plant has many similarities to a wind plant that uses full converter wind turbine generators. Reactive power requirements in the grid codes are generally met by either the reactive capability of the wind turbine generators (WTGs) or inverters in a solar PV plant, a collector substation based reactive compensation system (RCS), or a combination of both. Some grid codes require a specific power factor range of dynamic reactive power capability. This requirement can generally be met by WTGs or inverters in a solar PV plant, a DSTATCOM in the RCS, or a combination of both.

The S&C[3] PureWave® DSTATCOM Distributed Static Compensator provides reactive power to the power system for voltage support with a sub-cycle response time and continually adjusts to system operating conditions. In systems with wind or solar generation plants, the DSTATCOM can provide real-time fast voltage control, improve both power factor and system voltage profile, assist in voltage recovery after contingency events, and reduce the impact of wind or solar plant operation on the system voltage, as well as help meet grid codes such as LVRT requirements. Figure 3 shows a single line diagram of a typical DSTATCOM which uses IGBT-based dc-to-ac inverters. The inverters

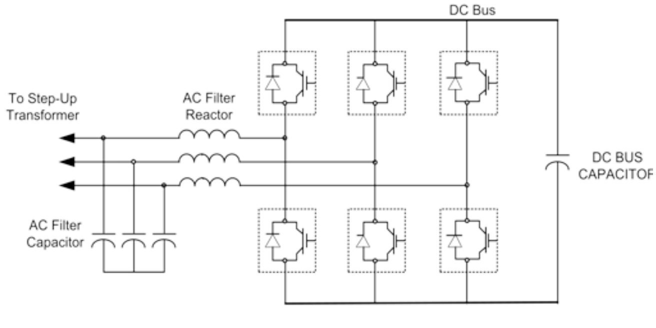

Figure 3: Single Line Diagram of a Typical DSTATCOM

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[3] S & C Electric Company

create an output ac voltage wave that is controlled in magnitude and phase angle to produce either leading or lagging reactive current. In the figure, the L-C filter reduces PWM (Pulse Width Modulation) harmonics and matches inverter output impedance to enable multiple parallel inverters to share current. When the output ac voltage is higher than the utility system voltage, it acts like a capacitor. When the output ac voltage is lower than the utility system voltage, it acts like an inductor. The DSTATCOM can also control and coordinate with switched shunt devices such as mechanically switched capacitors or reactors (MSCs/MSRs), creating RCSs that perform voltage regulation seamlessly over wide swings in utility system conditions and resulting in a lower-cost system simply considering the power electronics required.

The integration of large scale renewable generation requires system impact assessments that normally include steady state and dynamic analysis. For system impact studies involving renewable power plants, there are generally two dynamic simulation models of the DSTATCOM: 1) the generic model as shown in Figure 4, and 2) the specific model as developed by S&C and shown in Figure 5. The generic model includes such key components as voltage regulation (PI controller), coordinated switching logic for MSCs/MSRs, slow reset regulation, deadband control, slope/droop characteristics, regulation limits, overvoltage and undervoltage protection, and short-term rating capability. The specific model includes more control strategies such as reactive power control, power factor control, master-slave controls between the DSTATCOM and renewable plant controls, etc., in addition to those in the generic model. For renewable energy applications, parameters of the two models often need to be tuned based on a specific renewable project or the system to which the project is connected.

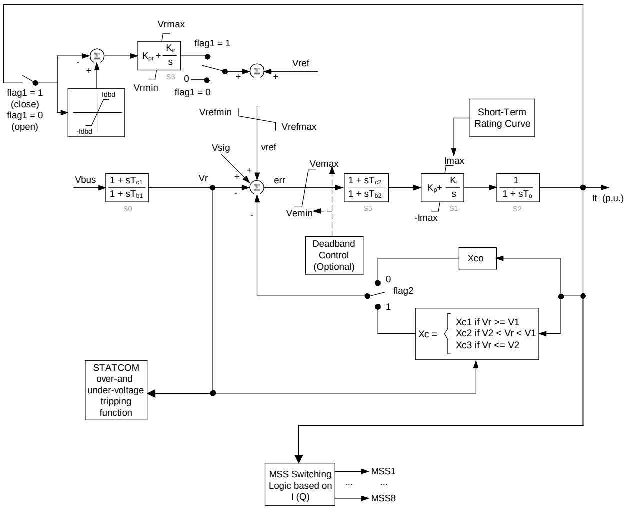

Figure 4: WECC Generic Model of DSTATCOM [4]

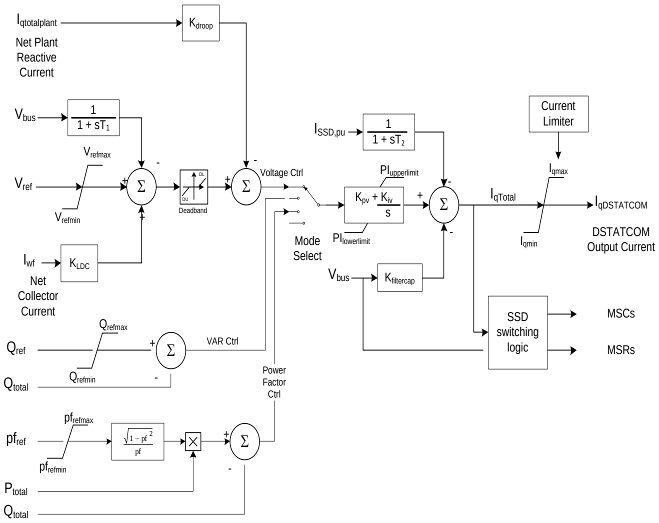

Figure 5: S&C Specific Model of DSTATCOM

Figure 6 shows a WECC generic model benchmark system [4] set up in a commercial simulation program [5] with the generic model tuned to represent the dynamic performance of the DSTATCOM. In this system, the DTSATCOM was modeled as a FACTS device with six MSCs/MSRs in the power flow model. Figure 7 shows a sample response generated from the aforementioned simulation program. The figure shows that the DSTATCOM output quickly increases up to its 264% short-term capacitive overload rating following the disturbance causing low voltage. Similarly, when the system voltage is elevated above nominal, the DSTATCOM output increases up to the inductive 264% overload rating. In fact, the DSTATCOM essentially becomes a constant current device outside its voltage control range to continue to support system voltage when it is at its limits, thus having a much better reactive capability to provide significant dynamic reactive compensation to maintain system voltage stability during contingency events, as compared to conventional SVCs.

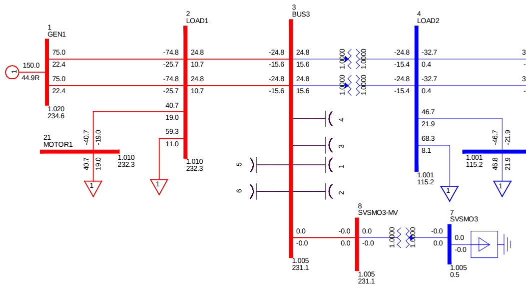

Figure 6: WECC Generic Model Benchmark System

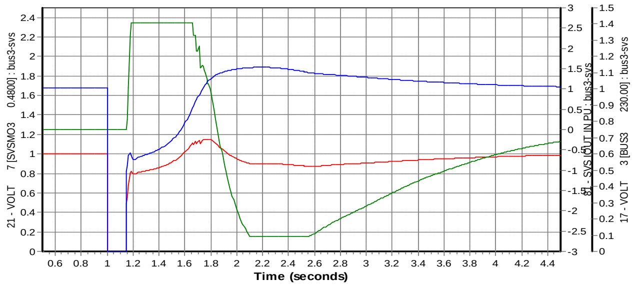

Figure 7: Response of the Generic Model for DSTATCOM (Green=DSTATCOM current; Blue=voltage at HV kV bus; Red=voltage at low voltage bus)

IV. CASE STUDIES

Figure 8 shows a control system configuration for a wind power plant connected to a transmission system in North America. The wind plant collector substation was configured into two sections with each having WTGs connected to a 34.5 kV collector bus through several feeders and producing a total maximum output through two substation transformers to the HV bus. In this plant, the wind power plant controller (PPC) was configured as the master control for both WTGs and the RCS which consists of one inverter based DSTATCOM and two MSCs connected to each collector bus section. The DSTATCOM control was configured to receive a Q-command from the master PPC controller and deliver what was requested without independent decision.

One applicable interconnection criterion for this plant is that the voltage regulation system must be calibrated such that a change in reactive power at the point of interconnection (POI) will achieve ninety five percent (95%) of its final value, no sooner than zero point one (0.1) seconds and no later than one (1) second following a step change in voltage. When the voltage regulation system requires the switching of a shunt capacitor or reactor, the switching operation must be delayed by ten (10) seconds.

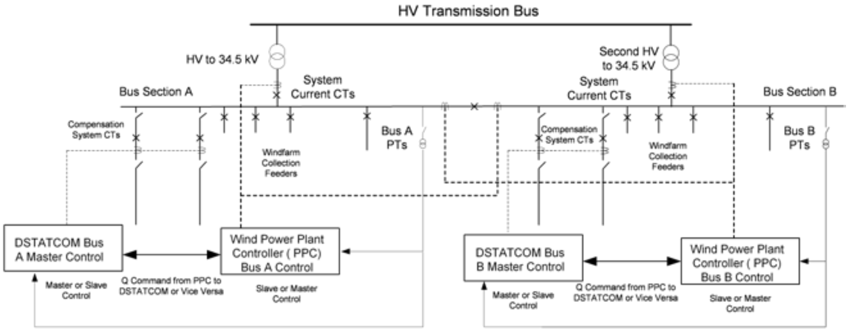

Figure 8: System Configuration of a Wind Power Plant with Master/Slave Controls

A system impact study was performed for the plant along with the RCS. For illustrative purposes, only the reactive power response and low voltage ride-through simulations were demonstrated here. Figure 9 shows the dynamic reactive power responses from the DSTATCOM and the WTG with a step change in master PPC controller voltage reference on one collector bus while the POI is maintained at 1.0 pu bus voltage. The simulation was performed using the aforementioned simulation program and the specific model of the DSTATCOM described in the previous section. The parameters of the DSTATCOM were tuned to represent its dynamic performance based on the system condition. The figure shows that the total reactive flow (capacitive) at the POI (i.e., the sum of reactive powers from the DSTATCOM and the WTGs) reaches about 52 MVAR between 0.1 and 1.0 seconds after a step change in PPC voltage reference, more than 95% (or 45 MVAR) of the required capacitive +48 MVar flow at the POI and thus meeting the criterion.

Figure 10 shows a simulation plot for the LVRT following a disturbance to drive voltage down to approximately 15% at the POI for 625 ms. The simulation indicates that the system response is stable, the wind plant stays on-line, and the voltage recovers to the pre-fault values and are well damped after the disturbance is cleared.

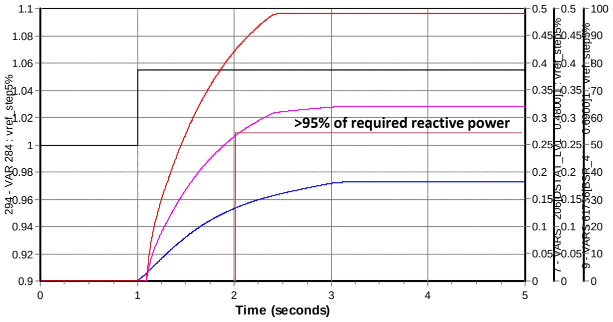

Figure 9: Reactive Power Responses to a Step Change in PPC Voltage Reference (Black=PPC Voltage Reference, Red=WTG Reactive Output, Blue=DSTATCOM Output, Pink=Total Reactive Flow at POI)

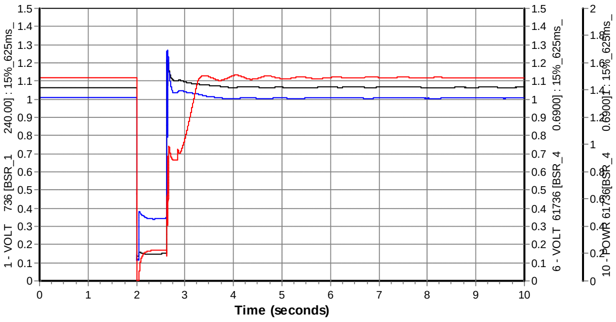

Figure 10: LVRT Simulation Plots for 15 % Voltage (Black=POI Bus Voltage, Blue=WTG Terminal Voltage, Red=Real Power)

V. CONCLUSIONS

A major DSTATCOM applications is mitigating the voltage impacts of large scale renewable energy integration, e.g., wind or solar power, on the power system and providing reactive support for wind or solar plants to meet interconnection requirements and grid codes. Dynamic simulations with real and benchmark systems show that a RCS consisting of DSTATCOMs and MSCs can be integrated with wind turbine generators in a wind power plant to comply with the voltage and reactive requirements of applicable grid codes.

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