

Renewable Energy Transmission by HVDC Across the Continent: System Challenges and Opportunities

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Abstract—Rapid development of renewable energy in China is driving a major shift in the characteristics and control requirements of the electricity grid. Since the best renewable energy resources are far away from load centers in the east and southeast, transmission over long distances is required. Over 20 high-voltage DC (HVDC) transmission lines, with a combined capacity exceeding 150 GW, are in operation or are currently under construction. This rapid expansion of new generation and transmission capacities based on power electronics starts to change the characteristics of the grid, especially in areas where they concentrate, creating new stability problems and operational challenges. New system theories and technologies are required to support the development and operation of a future grid that relies more and more on power electronics. This paper highlights the characteristics of power electronics as used in renewable energy generation and HVDC transmission systems, discusses the impacts of these power-electronics-based assets on grid stability and operational requirements, and identifies opportunities for the development of both new system theories and system technologies to support a national energy policy that emphasizes the use of clean energy.

Index Terms—Grid code, high-voltage DC transmission, renewable energy, system resonance, system stability.

I. INTRODUCTION

MOTIVATED by the need to combat air pollution and reduce reliance on fossil fuels while meeting the rising energy demand driven by the rapid industrialization and urbanization of its over 1.3 billion people, China has adopted an aggressive national policy to develop renewable energy, including PV, wind and hydropower. By the end of 2016, the total installed PV and wind power generation capacity in China reached 77.42 GW and 168.69 GW, respectively, accounting for over 30% of the world's 790 GW total installed PV and wind power generation capacities [1]. China has also established itself as a global leader in hydropower development. In 2016, the total installed hydropower capacity increased to

330 GW, including 26.7 GW pumped hydro and representing more than a quarter of the world's total. The national goal is to grow total installed solar, wind and hydropower generation capacity to 110 GW, 210 GW and 350 GW, respectively, by 2020 [2], [3]. These solar and wind energy development targets also include 5 GW solar-thermal power plants and 5 GW offshore wind energy systems.

While electricity generation from renewable sources still represents a relatively small portion of China's total electricity consumption, the high concentration of available renewable resources has already created some unique challenges for the design and operation of the grid. Since most of the population and industry are in the east and southeast parts of the country but the best PV and wind resources are in the north and northwest, long-distance transmission (over 2000 km in many cases) is required for most large-scale PV and wind power plants. High voltage DC (HVDC) is preferred and often the only viable solution for such long-distance transmission. The situation is similar for hydropower generation plants, which are concentrated in the east-central and southwest regions.

Fig. 1 shows the HVDC transmission lines that are already in operation or currently under construction/development in China.¹ There are a total of 20 HVDC lines, 11 connected to large solar and wind energy development areas in the north and northwest and 9 for transmission of hydropower from the south and southwest. All 20 lines are based on line commutated converter (LCC) technologies. The majority of these lines are rated at ± 800 kV, except two that are at ± 500 kV and one (from Changji, Xinjiang to Xuancheng, Anhui, under development) at ± 1100 kV. Almost all lines that are currently in operation were developed after 2010. The combined capacity of these HVDC transmission systems reaches 153.2 GW, and the total length of the lines combined exceeds 32,900 km, an average of 1650 km per line, with the longest line exceeding 3300 km.

The rapid development of renewable energy generation and HVDC transmission is driving a major shift in the characteristics and control requirements of the electricity grid. Power electronics is a key enabling technology for both renewable energy generation and HVDC transmission, but also has im-

Manuscript received November 20, 2017; revised December 3, 2017; accepted December 5, 2017. Date of publication December 30, 2017; Date of current version December 6, 2017. This work was supported in part by the State Grid Science and Technology Project "Impedance-Based Modeling and Control of Distributed Generation Systems" (NYB1720170218).

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DOI: 10.17775/CSEEJPES.2017.01200

¹Fig. 1 and the discussion that follows do not include the Luxi back-to-back HVDC link in Yunnan Province that uses a hybrid of LCC (line commutated converter, 2 GW) and VSC (voltage source converter, 1 GW) technologies, and three smaller (1 GW or less) VSC-based point-to-point or multi-terminal HVDC projects in Guangdong, Fujian and Zhejiang Province. A new 9 GW, four-terminal HVDC system based on MMC technology is planned by the State Grid and will be discussed in Section V.

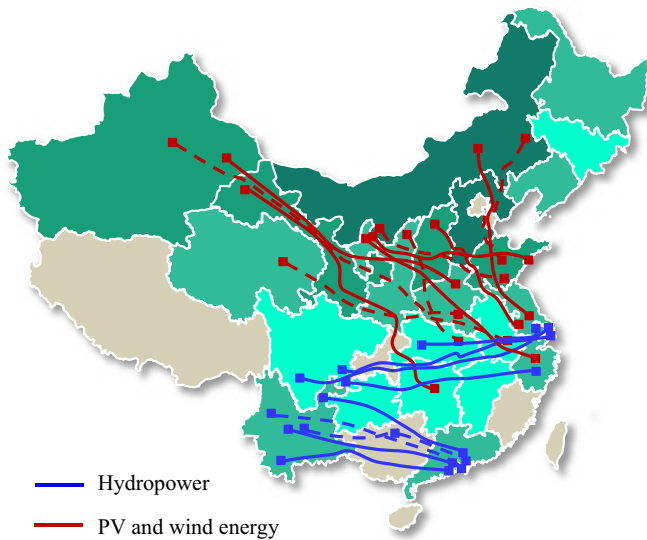


Fig. 1. HVDC transmission lines for transfer of renewable energy across China (solid lines: already in operation; dashed lines: currently under construction and to be completed by 2020).

portant new impacts on grid stability and power quality because of its fast control and sensitivity to fault and other abnormal conditions of the grid. If not properly designed and managed, these assets may have detrimental effects on grid control and stability. On the other hand, the fast control and flexibility of modern power electronics also creates new opportunities to enhance grid stability, improve power quality and increase grid resiliency, in addition to enabling a greener and more efficient electricity supply system.

High-power and high-voltage power electronics have advanced rapidly in China over the last decade. A strong domestic manufacturing industry has emerged that is capable of supplying virtually all types of power electronics equipment for PV, wind, as well as HVDC applications, including HVDC converters based on both LCC and MMC technologies and DC circuit breakers for multi-terminal HVDC systems [4]–[7]. However, compared to the rapid advance in equipment technologies and manufacturing/engineering capabilities, there has been a lag in the development of system control and stability theories that integrate power electronics and in preparing the grid for large-scale integration of renewable energy and HVDC transmission. As a result, there is a growing gap between power electronics equipment design capabilities and grid system technologies, which challenges grid operation and stability and threatens to hinder further development and application of renewable energy in China.

This paper identifies system challenges and opportunities for the development of a future grid in support of China's national energy policy that emphasizes the use of clean energy. We will start by highlighting the fundamental characteristics of power electronics as used in renewable energy generation and HVDC transmission systems, discuss the impacts of these power-electronics-based assets on grid stability and control and identify the needs and opportunities for the development of both new system theories and system technologies. The rest of the paper is organized as follows: Section II reviews

the characteristics of power electronics from the grid system point of view and the implications of these characteristics for grid system stability and control. Section III provides an overview of modeling and analysis methods capable of capturing fast controls and dynamics of power electronics. Section IV presents a case study to illustrate the nature of new system problems related to the use of power electronics and the application of new small-signal methods in the analysis and mitigation of such problems. Section V discusses possible new system technologies to improve grid stability and to support future expansion of renewable energy generation.

II. RENEWABLE AND HVDC IMPACTS ON GRID SYSTEMS

A. Characteristics of Power Electronics

Power electronics is the underlying technology and enabler for renewable energy generation and HVDC transmission. Compared to synchronous generators and transformers, power-electronics-based generation and transmission assets have very different characteristics dictated by the nature of power semiconductor devices and their controls. From the grid system point of view, the most important characteristics are 1) fast control and dynamics; 2) limited overloading capabilities.

- 1) *Fast Control and Dynamics*: The development of modern power electronics is characterized by steadily increasing operation (switching) frequency through improvement in semiconductor power devices and innovation in circuit design. High switching frequency not only helps to increase control speed and improves control performance, but also reduces the use of materials (in transformers as well as filter inductors and capacitors), thereby reducing volume, weight and cost.² While the switching frequency in high-power and high-voltage designs is limited by device technologies, operating at several kHz is possible and common for PV and wind inverters (and 1–2 kHz for VSC and MMC-based HVDC converters). Accordingly, the bandwidth of most control functions used in typical grid-connected converters is close to or higher than the fundamental frequency, as illustrated in Fig. 2 [8]. Such fast control creates complex dynamics in the upper subsynchronous as well as supersynchronous frequency range, as indicated by the circle in Fig. 2, that do not exist in traditional power systems. This leads to new high-frequency stability and resonance problems [8], [9], as will be discussed in the following subsections.
- 2) *Limited Overloading Capabilities*: Traditional generators, transformers and other electromechanical and electromagnetic energy conversion devices can endure significant overvoltage stress and overcurrent that may be several times the nominal rating for many cycles (of the fundamental frequency). In contrast, semiconductors have very limited overloading capabilities and may be permanently damaged within microseconds, when subjected to overcurrent or overvoltage. Fast-acting pro-

²It is worth reminding ourselves that these features also represent the advantages of power electronics over conventional electromechanical and electromagnetic energy conversion technologies and are the reasons to develop and use power electronics.

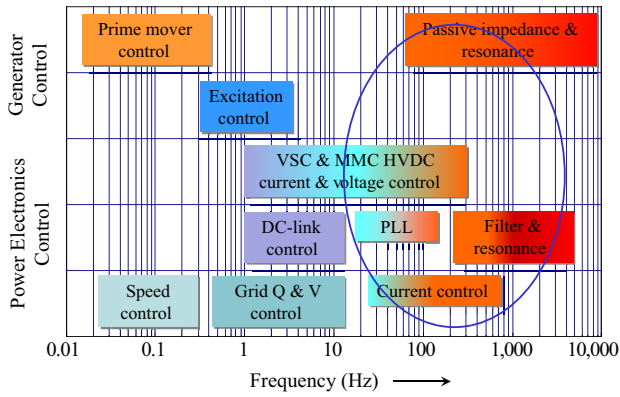


Fig. 2. Speed of control of synchronous generators vs. power electronics for renewable energy and HVDC applications [8].

tection is therefore essential for the safe operation of any power converter. Once in the protection mode, a converter behaves very differently and may become non-functional. This makes the behavior of power electronics very sensitive to grid conditions and highly variable under grid fault and other abnormal conditions. While a converter can be over-designed by using more semiconductor devices to increase its overloading capability, doing so will increase the cost and is against the spirit of power electronics.

These characteristics, dictated by semiconductor physics, complement each other, in the sense that small overloading capabilities lead to fast responses that enable fast control and fast control in turn makes it possible to protect against overloading. However, each of them conflicts with certain aspects of today's grid system control and operational requirements and creates new system challenges, as discussed below. In general, fast control and dynamics changes system small-signal behavior and stability at high frequencies, while the behavior under fault impacts transient stability.

B. Wind Turbines and PV Inverters

One of the problems caused by fast control and dynamics of power electronics is harmonics and high-frequency resonances in large wind and PV farms, especially those connected to the grid through long transmission/distribution lines (*weak grid*) or HVDC converters [10], [11]. The consequences of such harmonic and resonance problems may range from poor power quality to frequent tripping of turbines and PV inverters, and to physical damages of sensitive components. Many such incidents have gone unreported in the past, but several major incidents in the last few years have brought the problems to the surface and caught international attention [12].

In conventional power system studies, harmonics are considered steady-state power quality problems, caused primarily by the nonlinearity of loads. Accordingly, modeling and mitigation of harmonic-related problems have focused on identifying and limiting harmonic emission from devices that generate harmonics due to nonlinearity. Wind turbines and other converter-based generation units have been treated as such sources of harmonics due to their switching operations and imperfect control. The resulting harmonic emission are

usually at frequencies that can be expressed as $mf_1 + nf_s$, where f_1 is the grid fundamental frequency, f_s is the switching frequency and m and n each is an integer. Existing grid code compliance tests also focus on such characteristic harmonics and impose a limit on individual harmonics as well as the total harmonic distortion from turbines and PV inverters. However, these harmonics are usually well attenuated through converter design and cannot explain the excessive amount (as high as 40% of the fundamental) and unusual frequency (which cannot be expressed as $mf_1 + nf_s$) of harmonics measured in many practical harmonic events in wind and PV power plants.

The impedance-based stability theory presented in [13] associates this new harmonic and resonance problem with the fast control of power electronics. According to the theory, a grid-connected converter can be modeled as a current source with output impedance. The output impedance depends on converter control and is usually "active," with small or even negative damping over a wide frequency range in which the converter excises control. An under-damped series resonance in the converter output impedance may amplify harmonics in the grid voltage, if the harmonic frequency coincides with the resonance frequency. More critically, the converter output impedance may form a new series resonance with the grid impedance, leading to a sustained harmonic oscillation when such a system resonance is not sufficiently damped.³ In the worst case, the resonance may be unstable, causing growing harmonic oscillation that will eventually trip protection, or cause physical damage if there is no proper protection.

Large wind and PV farms in north and northwest China are particularly vulnerable to such harmonic and resonance problems due to their high concentration and the relatively weak AC grid in the area. A common problem is resonance in the 100–300 Hz frequency range caused by the high (inductive) impedance of long transmission and distribution lines and the capacitive output impedance of type-IV turbines and PV inverters within their current control bandwidth [14]. Such high-frequency harmonics are responsible for tripping of turbines and PV inverters in many cases, and may cause damages to filter components and transformers. Another common problem is subsynchronous resonance between type-III wind turbines with series-compensated lines [15]–[19]. Subsynchronous resonances may also occur in both type-III and type-IV wind turbines connected to a grid that uses no series compensation [20], [21]. Such subsynchronous resonances and supersynchronous resonances in the 50–100 Hz range are of special concerns for the grid system as they may excite mechanical resonance modes of nearby synchronous generators and trip their protection. The case study presented in Section IV will show such an incident.

Harmonics used to be considered local power quality problems that cannot travel far in the grid. However, that is not the case for resonance-induced harmonics, which can spread over hundreds of kilometers, hence are truly system problems.

The strength of a grid can be characterized by the short

³Strictly speaking, they should not be called harmonics, as the frequency is not related to the fundamental and can assume any value. However, for the lack of a better term to use, we will refer to them as "harmonics," with the understanding that they can be at any frequency.

circuit ratio (SCR) at the interconnect point of a wind or PV farm. By industry norms, a grid with SCR higher than 4 is considered strong and should not post a problem for the operation and stability of wind turbines and PV inverters. Special considerations and careful tuning of controls are required when the SCR drops below 4. In many wind and PV development areas in north and northwest China, the equivalent SCR is less than 2 when calculated on the basis of the full renewable generation capacity. Such low SCR translates into high impedance of the grid seen by individual turbines and PV inverters, which can easily lead to resonance problems. More careful design of the transmission and distribution network can improve the SCR by e.g. reducing the number of voltage levels and transformers, but will not fundamentally solve the problem. The ultimate solution rests on advanced control of turbines and PV inverters to improve their ability to work with weak grids. Section V will discuss some possible solutions.

C. HVDC Converters and Transmission Systems

Use of HVDC transmission has additional effects on wind and PV power generation plants in the north and northwest of China. Because of the high voltage level required to transfer multi-GW power over long distances, all HVDC transmission lines shown in Fig. 1 are based on line-commutated converter technologies. Using LCC HVDC to transmit power generated largely from wind and PV power plants is unique to China. LCC-based HVDC transmission was considered for offshore wind farms in Europe several years ago, and the proposed solution included the use of STATCOM rated at about 50% of the transmission capacity to enable a black start as well as to provide voltage support for the offshore AC collection system [22], [23]. Siemens had also proposed the use of uncontrolled diode rectifiers for HVDC transmission of offshore wind [24]. However, no such system has been built and all HVDC transmission systems that are currently in operation or being planned for offshore wind farms in the world use VSC or MMC technologies.

The effects of LCC-based HVDC may be insignificant in a strong grid dominated by synchronous generators and where the HVDC transmission capacity is relatively small. That is not the case, for most HVDC systems built in the north and northwest of China either in many areas, the HVDC transmission capacity far exceeds the capacity of local synchronous generators and the power is primarily fed from renewable sources. This impacts the operation of wind/PV power plants as well as the stability of the grid:

- 1) *Small-signal Stability*: Impedance of the HVDC converter may become an important part of the equivalent grid impedance seen by wind and PV power plants, especially those in close proximity to the HVDC station. Since the HVDC converter is another power electronics device with active control (albeit relatively slow for an LCC), its impedance is significantly different from the relatively simple inductive impedance of overhead transmission and distribution lines, which may lead to new and more complex resonance and other small-signal stability problems. The consequences of such a problem may also be more far-reaching than what have been

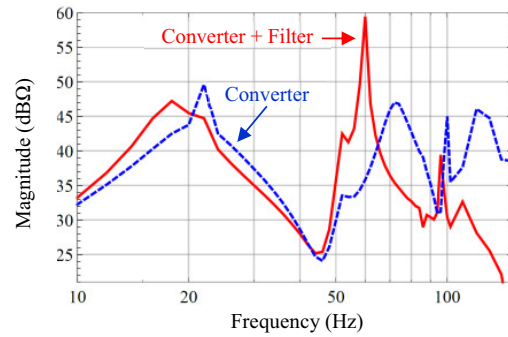


Fig. 3. Impedance scans of an LCC HVDC converter showing more complex behavior than overhead transmission lines.

observed, as it may affect the HVDC converter and ripple through the HVDC line to the receiving network. As an example, Fig. 3 shows the impedance scans of an LCC HVDC converter obtained from a detailed EMT simulation.

- 2) *Transient Stability*: A common problem with LCC-based HVDC transmission is commutation failure at the receiving terminal. When this happens, active power flow instantly drops to zero, causing a large transient in the HVDC link as well as the AC network at the sending end. One consequence is that the sending network voltage rises rapidly and causes wind turbines and PV inverters to trip because of overvoltage protection. Simulation of the Jiuquan-Hunan HVDC line, of which the sending-terminal network is depicted in Fig. 4, indicates that the network voltage may rise above 1.4 pu after three consecutive commutation failures, causing almost all wind turbines in the area to trip. In addition to the impact on the receiving network as discussed below, the instant loss of large generation capacity would also pose a risk for the stability of the regional AC network. Equipping turbines and PV inverters with high-voltage

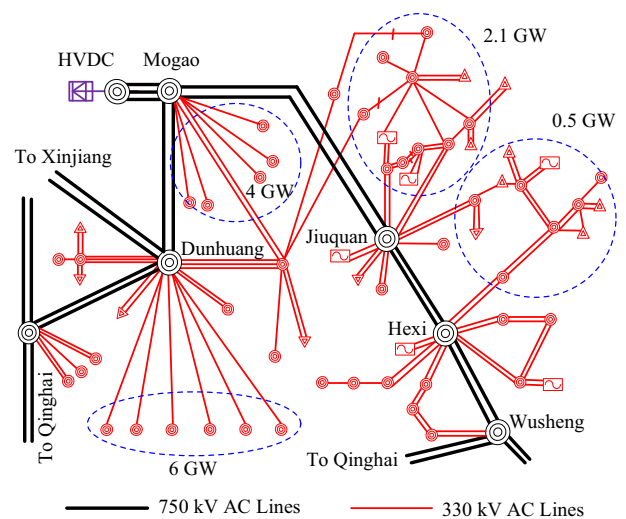


Fig. 4. Sending-terminal network of the Jiuquan-Hunan HVDC line that was simulated to show the effects of HVDC commutation failure. The four circled areas and the number next to each indicate major wind power plants and the combined capacity in each area. The HVDC is rated at ± 800 kV, with a full transmission capacity of 8 GW.

ride-through (HVRT) capabilities would help to reduce the potential for overvoltage tripping, but is unlikely to solve the problem.

- 3) *Frequency Response*: The immediate effect of a commutation failure on the receiving network is the large variation of reactive power and possible voltage stability problems. However, loss of renewable generation at the sending terminal due to overvoltage tripping can amplify the effects and lead to frequency regulation and frequency stability problems as the system loses large amounts of active power infeed for a prolonged period of time. The large voltage transient caused by commutation failure of one HVDC station could also be coupled to other nearby HVDC stations, causing cascading commutation failures and further amplifying the impacts on the receiving network. In the worst case, the grid may lose frequency stability and disintegrate. The sending network will have a similar problem (and is more susceptible to it.)

The problems discussed above are related to the highly nonlinear and largely uncontrollable behavior of the LCC during a large transient. Compared to the LCC, voltage-source converters and modular multilevel converters offer controllable and linear behavior over a wide range of operations, including the ability to operate in all four quadrants on the PQ plane and to ride through large transients of the system without losing linearity and controllability. MMC-based HVDC technologies have been successfully used in the German North Sea offshore wind farms. MMC-based HVDC transmission capacity is presently limited to ± 320 kV/1 GW. A new four-terminal, MMC-based HVDC project planned by the State Grid for transferring renewable energy to the sites of the 2022 Winter Olympics and the City of Beijing (see Fig. 5) will push the technology to ± 500 kV/3 GW. As MMC technology continues to improve, it can be expected to soon match the voltage and power transmission capabilities of LCC HVDC, providing new opportunities to improve HVDC and renewable energy system stability. Section V will discuss some such opportunities. On the other hand, MMC may introduce resonance and stability problems at even higher frequencies (> 1 kHz) [25]. Such high-frequency resonance problems have to be considered from the beginning in MMC control and system development.

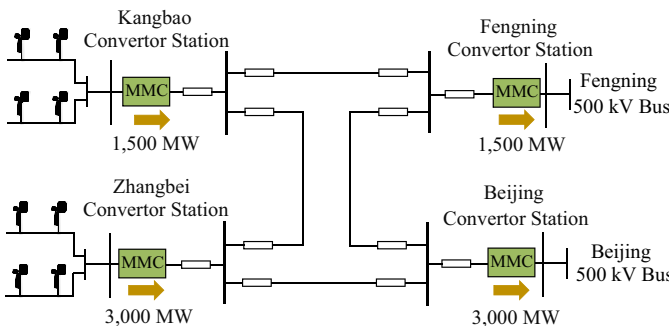


Fig. 5. A four-terminal MMC-based, ± 500 kV HVDC network under development for transferring renewable energy to 2020 Winter Olympics site and Beijing.

III. SYSTEM MODELING AND ANALYSIS METHODS

Referring back to Fig. 2, control and dynamics in traditional power systems are slow, usually falling far below the fundamental frequency. Phasor (rms-value) models are adequate for describing such systems and for their stability analysis. The new problems associated with power electronics as discussed in the last section fall in the electromagnetic transient (EMT) frequency range and necessitate the use of EMT models for system modeling, stability analysis, and control development. Recognizing this, the State Grid has invested in new EMT simulation capabilities at the China Electric Power Research Institute. The simulation system currently under development will be able to simulate systems with up to 2000 substations and 31 HVDC lines. However, EMT simulation has several limitations and it alone is inadequate for addressing the problems identified in the previous section:

- 1) EMT simulation can confirm the existence and quantify the behavior of a problem that has been identified, or reproduce a problem that has already happened, but is ineffective in uncovering unknown problems, especially new problems that are not well understood.
- 2) EMT simulation can serve as a tool to verify the performance of a design or the effectiveness of solutions to a known problem, but is inadequate as a design tool, as numerical responses provide very limited insights that are often essential for developing a design or solution.
- 3) EMT simulation has to compromise between accuracy and size of the system and is prone to numerical convergence and other computational problems when dynamics at many different time scales are simulated together.
- 4) EMT simulation requires detailed models that may be very difficult to obtain, especially when it has to include different power electronics products, as their models are diverse and contain design details that manufacturers are usually unwilling to share.

Small-signal analysis complements numerical simulation and has been widely used in power system stability studies and control development. A fundamental challenge for small-signal analysis in the EMT frequency range, which is necessary for dealing with new high-frequency stability problems discussed in Section II, is the linearization of nonlinear power electronics converter and control models. Linearization is usually performed by Taylor expansion about a fixed operation point. This is straightforward for a DC system because a fixed operation point can be identified once the system is in steady state. This also works for AC systems described using phasor (rms-value) models, as the variables (complex phasors or amplitudes and phases) involved in such models also become constant (fixed) in steady state. Indeed this is how small-signal analysis has been performed in existing power system small-signal stability studies. However, phasor models cannot be used to study new resonance and stability problems in the EMT frequency range.

One way to eliminate the time-varying behavior at the fundamental frequency, thereby permitting linearization for small-signal analysis, is to transform a three-phase converter model into a dq reference frame that rotates at the fundamental frequency. In such a rotating reference frame, balanced three-

phase quantities become constant, such that linearization can be performed in the same manner as for DC systems. The commonly used three-phase to dq transformation is given below in (1). For the transformed model to be meaningful and useful, the angle θ should be set to the angle of the voltage at the terminal of the converter.

$$\sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \cos \left(\theta - \frac{2\pi}{3} \right) & \cos \left(\theta + \frac{2\pi}{3} \right) \\ -\sin \theta & -\sin \left(\theta - \frac{2\pi}{3} \right) & -\sin \left(\theta + \frac{2\pi}{3} \right) \end{bmatrix} \quad (1)$$

The linearized dq-frame model can be put in a state-space form for small-signal stability analysis using time-domain techniques, such as eigenvalue and modal analysis. Alternatively, dq-frame impedances can be defined based on the linearized dq-frame model and be used in conjunction with the generalized Nyquist stability criterion to determine system stability [26]–[28]. The review paper [29] pointed out several limitations of the dq-frame impedance method in comparison with the sequence impedance method discussed below. An additional limitation was recently identified in [30] based on the fact that the transformed dq-frame model is synchronized to the terminal voltage of the converter being modeled, as indicated by (1). This implies that, for a system involving multiple converters (wind turbines, PV inverters, or HVDC converters), each converter would be modeled in its own dq frame and different converter models would have to be converted into a common reference frame in order to form a coherent system model. The conversion of the reference frame can be performed by a constant rotation matrix similar to that used to link different synchronous generator models in the dq-frame. However, such a constant rotation matrix is based on the assumption that the dynamics of the transmission/distribution line can be ignored, which cannot be accepted in the EMT frequency range. Considering these, small-signal modeling in the dq reference frame is deemed impractical for EMT transient and stability analysis of multi-converter systems.

A direct method to linearize EMT models and develop small-signal frequency-domain models was reviewed in [29] and used to develop *small-signal sequence impedance models* for two-level VSC (for application in type-IV turbines, HVDC transmission, or as PV inverters) in [14], type-III turbines in [16], LCC in [22] and MMC in [31]. The resulting sequence impedance models can be used in conjunction with the impedance-based stability theory presented in [13] to study resonance and instability problems from subsynchronous to supersynchronous frequency ranges. Case studies presented in [14], [15], [21], [22] and [32] demonstrated that different resonance problems involving wind turbines and PV inverters as reviewed in II.B, or different HVDC transmission systems can be analyzed using this method and solved by reshaping the impedance through active control. Table I summarizes the features of this method and compares it with EMT simulation and the dq-frame impedance method reviewed before.

The SISO (single input single output) system impedance model presented in [13] is easy to use and effective when one resonance mode dominates, such that the system can be represented by two impedances forming a single loop. The

TABLE I
COMPARISON OF DIFFERENT SYSTEM ANALYSIS METHODS

Criteria & Considerations	Time Domain	Frequency Domain	
	EMT Simulation	DQ-Frame Impedance	Sequence Impedance
Valid at high frequency	✓	✓	✓
Appl. to different converters	✓	×/✓	✓
Protect supplier design info	×	✓	✓
Intuitive, easy to obtain	×/✓	×	✓
Easy to build system model	✓/×	×	✓
Easy to perform system analysis	×	×	✓
Predict stability margin	×	×	✓
Serve as a tool for designers	×/✓	×	✓
Analysis points to solutions	×	×	✓
Scalable to large systems	×	×	✓

case study presented in the next section shows that even very complex systems can be reduced to this form. MIMO (multiple input multiple output) models could be developed based on sequence impedances for more complex systems, such as a multi-terminal HVDC network, where multiple resonance modes may coexist and have to be analyzed together. The method could also serve as the basis for small-signal analysis of hybrid AC-DC systems discussed in Section V.

IV. A CASE STUDY

This section presents the resonance incidents encountered in the Hami wind energy collection system in Xinjiang Province during 2015–2016 as a practical case study to demonstrate the nature and complexity of this new type of system stability problem, the application of the sequence impedance method reviewed in the last section in a step-by-step manner to isolate the problem and identify key factors that contribute to the problem, as well as the development of a simple solution based on the analysis by modifying the control of one wind turbine products.

A. Background

Xinjiang is rich in both wind and PV energy resources. Consequently, renewable energy development has been a priority in the region and a major driver for economic development in recent years. By the end of 2016, the province had installed 18.8 GW wind and 6 GW PV power generation capacities, concentrated in eight geographical areas. The largest concentration is in the Hami area – with a 9.24 GW wind and 2 GW PV installed capacity. This area also includes 5 GW coal-fired power plants. To transfer this large amount of power, a ± 800 kV, 8 GW HVDC line connecting from Hami to Zhengzhou in Henan Province was developed and put into operation in January 2014. This 2192 km HVDC line was among the first HVDC projects that were developed primarily for the transmission of renewable energy from the north and northwest to load centers in the east.

On July 1, 2015, a harmonic incident in the area was recorded and caused activation of the TSR (torsional stress relay) of the synchronous generators in the coal-fired power plants, consequently shutting down three generators. An active power oscillation at about 30 Hz was recorded during the incident, which correlates with one of the torsional modes of

the generators that were shut down. Between September 2015 and January 2016, 70 more incidents were recorded during which the TSRs were activated 8 times. The problem stopped in late January 2016 when a new 750 kV AC transmission line between the Santanghu and Hami substations was put into operation. However, the problem came back again in late March 2016 after more wind turbines were installed and put into operation in the Wangyangtai area.

B. Subsynchronous or Supersynchronous Resonance

Since the incidents involved activation of the TSR, the initial conclusion was that the problem was due to subsynchronous resonances. PMU data also showed significant subsynchronous harmonic currents in the 20–40 Hz frequency range flowing in the transmission lines connected to the synchronous generators. Further analyses, however, showed that a supersynchronous harmonic between 50 and 100 Hz played a more important role. The harmonic spectra presented in Fig. 6, which was recorded during a subsequent resonance event, is representative and shows two harmonic symmetrical about the fundamental frequency. The supersynchronous harmonic, at about 75 Hz, is about 1.5 times the subsynchronous harmonic at ~25 Hz. The ratio between the dominant supersynchronous and subsynchronous harmonics was as high as 10 in some other recorded events.

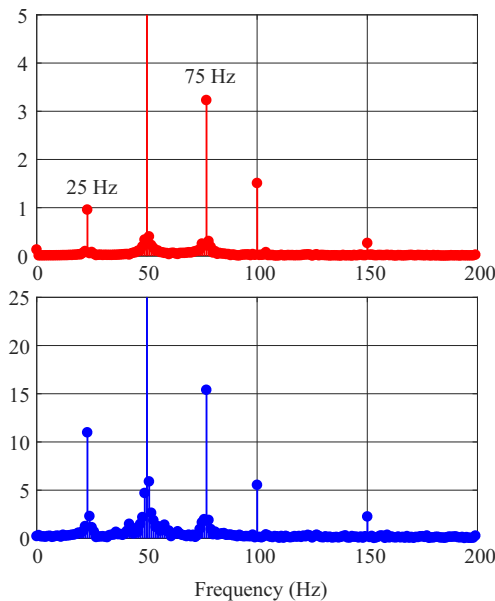


Fig. 6. Grid voltage (upper) and current (lower) harmonics recorded during a resonance incident in the Hami area.

The TSR was tuned to protect the generator against possible torsional oscillation at any of the mechanical modes, which are all below 40 Hz. The mechanism for a supersynchronous harmonic to trigger the TSR can be explained using the waveforms illustrated in Fig. 7. The 50 Hz signals at the top represent the voltage at a generator terminal. The two harmonics underneath, one at 19.5 Hz and the other at 80.5 Hz, are symmetric around the fundamental and each represents a harmonic current flowing into the generator. When multiplied with the fundamental voltage, each harmonic current produces

an active power that fluctuates at a frequency equal to the difference between the fundamental and the harmonic frequency, which is 30.5 Hz and is the same for both current harmonics, as indicated by the waveforms on the bottom in Fig. 7. Therefore, both harmonics create a subsynchronous torsional excitation on the generator. When this excitation frequency coincides with any of the mechanical modes of the generator, the TSR will be triggered. Based on this analysis and the fact that the supersynchronous harmonic was much higher than the subsynchronous harmonic, a conclusion was reached that it was a supersynchronous resonance problem.

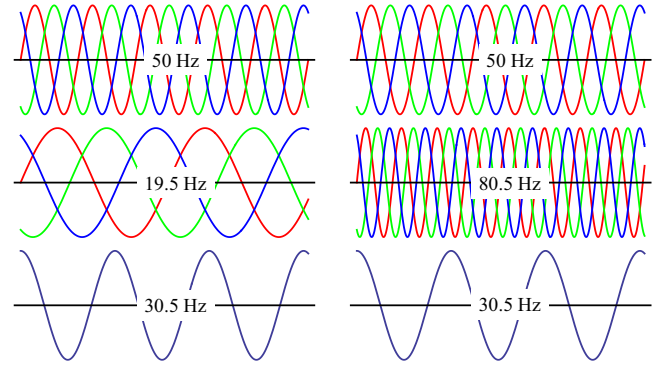


Fig. 7. Subsynchronous power variation produced by a subsynchronous (left) or supersynchronous (right) harmonic current.

C. System Modeling and Analysis

Based on the assessment presented above, the focus of analysis shifted to electrical resonance in the 50–100 Hz range in order to identify the root cause of the problem and develop a solution. The sequence impedance method reviewed in Section III provides an effective tool for this propose. Building a complete system impedance model, however, would require impedance models of all components, which turned out to be a major challenge because of the complexity of the system: The system involves more than a dozen different type-III and type-IV turbine products produced by 7 domestic turbine manufacturers, using converters made by 10 other companies, in addition to the thermal power plants and HVDC converter. To compound the challenges, most of the turbine products did not even have basic simulation models at that time, let alone impedance models.

A step-by-step engineering approach was taken to tackle this complexity problem, with a focus on finding the root cause and developing a practical solution as soon as possible. As the first step, impedance responses of the HVDC converter and the generators were scanned based on a numerical simulation of their EMT models. Detailed network models were also built to determine the equivalent “grid” impedance seen by wind farms in different areas. This analysis led to the conclusion that the impedance of the HVDC converter and generators, when viewed from wind power plants, is shielded by the high network impedance in the frequency range of interest and the resonance was primarily between wind power plants and the network impedance. As an example, Fig. 8 presents a simplified system impedance model for wind farms in the East Wangyangtai area that had frequent resonance problems after

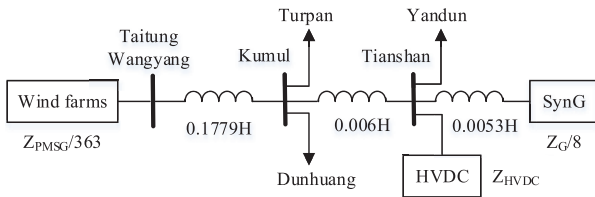


Fig. 8. Simplified system model for wind farms in the Wangyangtai area.

March 2016. The 0.1779 H inductor represents the impedance of the transmission lines and transformers connecting the wind farms to the HVDC station in Hami.

Type-III turbine output impedance is normally inductive in the low frequency range due to the dominant effects of the induction generator [16]. Such inductive impedance would not form resonance with the inductive grid impedance indicated in Fig. 8. Based on this, type-III turbines were excluded in further analyses of the system, and the focus narrowed down to type-IV turbines.

D. Type-IV Turbine Impedance Modeling

The affected type-IV turbine design was licensed from a foreign company and the manufacturer did not have full access to the control algorithms. Without the design details, it was impossible to develop analytical impedance models or to build a simulation model for numerical scan of impedance responses. To get around this problem, a solution based on control hardware-in-the-loop (CHIL) simulation was developed [33]. In this approach, the turbine mechanical system, generator, and converter main circuits are modeled in an electromagnetic transient (EMT) simulator and simulated in real time. Turbine control functions are performed by the actual control hardware and software that exchanges signals with the real-time simulator. The method, illustrated in Fig. 9, can be considered a hybrid between a pure numerical simulation and the direct measurement of impedance. Reference [33] presented details about the setup and procedure to perform such a simulation.

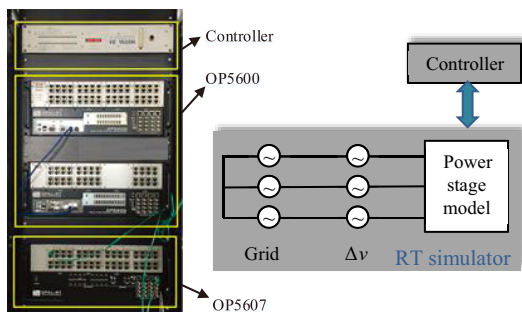


Fig. 9. CHIL simulation to scan wind turbine impedance responses.

The dashed (red) curves in Fig. 10 show the scanned impedance responses of the affected type-IV turbine under one operational condition. To understand the cause for system resonance, the equivalent grid impedance seen by each turbine is calculated based on the simplified system model given in Fig. 8. The solid straight lines represent the responses of this equivalent grid impedance. Since only

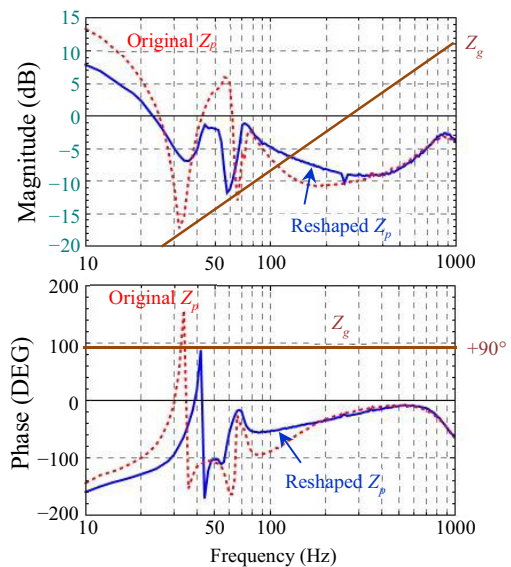


Fig. 10. Impedance responses of the type-IV wind turbine used in Hami area.

positive-sequence control is used in the turbine, the negative-sequence impedance does not have the complexity of the positive-sequence impedance below 100 Hz and will not form a resonance with the grid, hence is not included in Fig. 10.

The impedance responses in Fig. 10 indicate a large dipping at two frequencies that are symmetrical about 50 Hz. Both have the potential to intersect with the grid impedance, but the one at 60–80 Hz is more critical: the lower than -90° phase in this frequency range signifies capacitive impedance with negative damping, which would cause an unstable resonance with the inductive grid when the impedances intersect in this frequency range. This was identified as the reason for the observed supersynchronous harmonics. Through dynamic coupling in the turbine small-signal responses, as modeled in [34], [35], the resonance-induced supersynchronous harmonic would also induce a subsynchronous harmonic at a frequency symmetrical about the fundamental. The sporadic nature and variable frequency of harmonics observed from measurements during different incidents can be explained by the dependency of the impedance intersection point on the number of turbines that were actually in operation and their power output.

E. Damping of Resonance

The impedance analysis in the last subsection also pointed to a solution to the problem: to damp the resonance by shaping the type-IV turbine output impedance through modification of its control. No detailed design information of the turbine was available, but several control parameters could be adjusted externally. Based on the understanding of how turbine impedance is affected by different control functions in general [14], emphasis was put on the PLL as well as current control, but the grid voltage feedforward gain was also examined. With each set of new control parameters, CHIL simulation was run to determine the effects on the impedance, with the goal to reduce the dipping while boosting the phase response especially in the 60–80 Hz range. The solid blue curves in Fig. 10 represent the

reshaped turbine impedance responses after many rounds of optimization, and show that the dipping at both frequencies is reduced. More importantly, the phase in the 60–100 Hz range is significantly boosted such that no under-damped resonance would form even if the network and farm impedances intersect in this frequency range.

Field tests were conducted in June 2016 and showed reduced harmonics from turbines with the modified control during system resonance, which confirmed the expected effects in reducing dipping in the turbine output impedance. The CHIL simulation platform was also used to test the time-domain performance of the turbine to make sure the modified control meets other grid code requirements, including low-voltage ride-through. The changes were then recommended to the manufacturer and were subsequently implemented on ~2000 affected turbines between July and October 2016. No new resonances involving these turbines have occurred since then.

The incidents in the Hami area (and in the German North Sea [12]) served as a wake-up call for the industry and demonstrated that the problems discussed in Section II are real and their impacts can be far reaching. The industry is also taking steps to incorporate sequence impedance modeling and analysis in new products and project development [33], [36], and to develop new grid codes [36]–[38] that include requirements for sequence impedance modeling and analysis. However, more development and new system technologies are required in order to address the broad challenges identified in Section II. The next section highlights some possible approaches and opportunities for future development.

As pointed out in Section II, “weak grid” is a common challenge for renewable energy development in the north and northwest. This can be seen from the simplified system model in Fig. 8. There were 363 type-IV turbines in the wind farm area indicated in the figure. Based on the capacity of these turbines, the SCR of the equivalent grid each turbine sees was calculated to be 1.6 by just considering the 0.1779 H inductance from the wind farm to the 750 kV bus. It is also worth noting that the connection from each turbine to the 750 kV bus involves three transformers (690 V to 35 kV, 35 kV to 110 kV, and 110 kV to 750 kV) and they contribute more than 60% of the 0.1779 H inductance. Optimizing the distribution and transmission network design to reduce the number of voltage levels and transformers can help to reduce the grid impedance.

V. FUTURE OPPORTUNITIES

As pointed out in Section II, two fundamental characteristics of modern power electronics are *fast control* and *limited overloading capabilities*. They complement each other at the device and converter level, but each conflicts with certain aspects of how existing power systems are designed and operated: Fast control introduces high-frequency transients and stability problems not considered in existing system theory and stability analysis, while the need to protect a converter itself against overvoltage and overcurrent creates highly nonlinear behavior during large system transients, pushing converter

operation into a space that may be detrimental to system stability when support of system stability is most needed. The limited controllability and highly nonlinear behavior of the LCC also creates the potential to amplify system transients and couple system dynamics across different time scales. These can be seen as the fundamental challenges behind the different problems discussed in Section II.

Since the challenges are interrelated, a system approach is required and should include:

- 1) Power electronics controls that support the system;
- 2) System design that takes advantage of power electronics;
- 3) System modeling, control and stability theory that includes power electronics as an integral part.

A. Power Electronics Control

Control defines how a power converter behaves. Like in the development of any new technology, many companies entered the wind and PV business by having their own, proprietary controls that are *better* in some aspects than their competing products. As a result, the market is filled with wind turbine and PV inverter products that use different designs and have very different characteristics, especially in aspects that are not yet regulated by the grid code, such as impedance and other frequency-domain characteristics. This creates a major challenge for grid system design and analysis, as the case study in the previous section demonstrated.

With the successful application of the sequence impedance method as a framework to identify and solve system resonance problems, there have been suggestions to develop *standards* for wind turbine and PV inverter impedance responses that would avoid resonance problems altogether. This is, however, very difficult, if possible at all, because of the broad frequency range in which system resonance may occur, the complex relationship between control and impedance, and possibly conflicting requirements between impedance response and time-domain behavior (such as LVRT). Similar concepts have been proposed for other industries (e.g. in the space and aircraft industry) and have all failed for similar reasons.

A possible approach to standardizing wind turbine and PV inverter behavior and to ultimately solve their grid integration problems is to harmonize their controls. With the evolution of technology, the lessons learned in recent years, and new models to fully characterize controls, it is possible now to develop and make available to the industry *reference controls* for wind turbines and PV inverters that combine the best practices of the industry, are thoroughly characterized and have well-defined (and known) behavior under different grid conditions. Such a standardization process usually would occur naturally as the technology matures, as has happened to synchronous generators and other technologies, but could take many years. A coordinated R&D effort would accelerate the process and remove a major barrier for grid integration and operation of large renewable energy power plants.

In addition to impedance and other dynamic characteristics, harmonization of power electronics controls should also define behavior under abnormal conditions, including operations under faults, in a way that supports system stability. It is also important to consider the fundamental characteristics of power

electronics – fast control and limited overloading capabilities – from the beginning of any such development. Concepts that ignore or work against these characteristics will have unexpected consequences or not work at all in practice.

For example, controlling a converter to emulate the behavior of a synchronous generator, a concept that attracted some interest in recent years, involves removing the fast current control loop so the converter behaves like a voltage source. While this is possible in steady state and by small-signal measurement, the converter still has to be protected against overcurrent. Without active current control, the converter current would double even for a small (e.g. 10%–20%) change in the grid voltage and the converter would instantly enter overcurrent protection mode, which has no resemblances to synchronous machine behavior. The consequence is that the emulated synchronous generator behavior is completely lost when such behavior is most needed for supporting system stability. Even worse, when overcurrent protection takes the place of the active current control that can otherwise maintain a linear and well-defined current response down to even 0% grid voltage, the converter behavior becomes highly nonlinear over a much wider range of grid voltage, which will have other unintended and negative consequences. It is important to consider such unintended consequences such that the solution to one problem does not lead to new and greater problems.

B. System Design

Most of the challenges discussed in II.C are related to the limitations of LCC HVDC technology, namely, limited controllability and highly nonlinear behavior. MMC-based HVDC technology overcomes these limitations by virtue of faster control and better controllability over a wide range of operation. In addition to being used to develop new HVDC transmission lines in the future, MMC technology may also be used to enhance existing LCC-based HVDC systems, as illustrated in Fig. 11 for the HVDC line A.

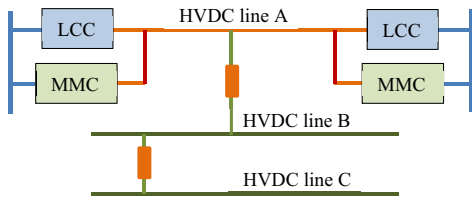


Fig. 11. Use power electronics to enhance HVDC transmission system.

Initially, the MMC can function as STATCOM to support reactive control and improve voltage stability at both sending and receiving terminals. This function does not require the MMC to be in parallel with the LCC at the DC terminal, such that it does not have to have the same voltage rating as the LCC. Compared to synchronous condensers that can also provide reactive support, MMC can provide more dynamic response and faster voltage regulation. At the sending terminal, this will help to provide a more stable grid for renewable energy integration and improve power quality for local loads. Through proper control, the MMC may also provide active damping to possible resonances in renewable power plants

over a wide frequency range [39]. In the receiving network, MMC-based STATCOM will help to reduce the potential of LCC commutation failure and to contain the impact of such failure to prevent the cascading effects discussed in II.C.

When connected in parallel with the LCC at both AC and DC terminals, as indicated in Fig. 11, the MMC can continue to perform STATCOM functions to the AC network while also increasing transmission capacity of the HVDC line. It could also help to improve the stability and reliability of the DC link. However, detailed studies are needed to prove the feasibility of such parallel operations between the voltage-source (MMC) and current-source (LCC) converters and to develop necessary controls to enable, as well as to maximize the benefits of such parallel and hybrid configurations.

Future advances in power electronics would also open the door for other applications to improve the stability and reliability of the HVDC transmission system and the AC grid. For example, different HVDC lines may be connected together by using power electronic devices, as illustrated in Fig. 11. The device connecting two HVDC lines can be a DC circuit breaker that acts as a DC intertie, or a DC-DC converter that can fully control power flow. As can be seen from Fig. 1, many of the HVDC lines are in close proximity or even cross each other, such that the additional lines connecting them will be short. Ultimately, all HVDC transmission lines could be connected together to form a multi-terminal HVDC network as an additional backbone for the national electricity grid [40], [41]. This creates many opportunities but also presents multiple challenges for the industry and the research community. Development of the four-terminal HVDC system depicted in Fig. 5 will provide valuable experience for such a hybrid AC-DC system.

C. System Modeling and Control

The review of new small-signal modeling and analysis methods and stability theory in Section III has focused on renewable energy systems that already use high-frequency power electronics and fast controls. As MMC-based HVDC transmission and other applications enter the grid, there needs to be similar broadband small-signal modeling and analysis methods that can be applied to study high-frequency dynamics and intercoupling in complex networks, including hybrid AC-DC grids. EMT simulation of a large system with dynamics (and possible stability problems) that extend into several kHz will become more difficult, making the development of small-signal methods and tools more critical [42]. New control architectures and technologies are also required in order to effectively deal with the multitude of control functions that may be tightly coupled over a wide frequency range. The four-terminal MMC-based HVDC system in the Zhangbei area again provides a unique opportunity to understand the challenges and to test new theories and methods.

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