The Cigré working group WG C4.601 on Power System Security Assessment was formed in August 2004, at the Cigré session 2004, and was given the charter to specifically look at the following needs in the industry:

1. The design of controls to enhance system security. This includes local device controls as well as system wide area controls and remedial action schemes.
2. Modeling of existing and new equipment required for power system analysis. (In this task it was felt that the most pertinent and timely activity was to look at the modeling and dynamic performance of wind generation systems.)
3. The design of monitoring systems for real time stability evaluation and control.
4. New analytical techniques for assessment of power system security. In addition to advances in computational methods, this includes the development of emerging approaches such as risk-based security assessment and the application of intelligent technologies.

To this end, all of the above subject matters were tackled by the Working Group. More specifically, of the more than one hundred members and contributors to the work, three ad hoc groups were developed within the Working Group, each given the task to address one of the first three subject matters above. The fourth task is one that the working group as a whole has presently started on, after having finished the other three tasks. The three completed tasks have resulted in the publication of three Cigré technical brochures. These are:

- Cigré technical brochure on Wide Area Monitoring and Control for Transmission Capability Enhancement (this effort was lead by C Relitanz)
- Cigré technical brochure on Modeling and Dynamic Behavior of Wind Generation as it Relates to Power System Control and Dynamic Performance (this effort was lead by P Pourbeik)
- Cigré technical brochure on Review of On-Line Dynamic Security Assessment Tools and Techniques (this effort was lead by K Morison)

During the course of the work, in addition to the formally elected WG members, a large number of others contributed significantly to these efforts. All have been properly acknowledged. The combined group of members and contributors constituted 125 experts from 25 countries. These included experts from equipment manufacturers, utility engineers, consultants and research organizations around the world. The work on the three technical brochures mentioned above was completed in December 2006, with final reviews and approvals before publication occurring in early 2007. Thus, the work took nearly two and a half years to complete.

Modeling and dynamic behavior of wind generation as it relates to power system control and dynamic performance

In the past five to ten years, due to the Kyoto Protocol signed in 1997 by 160 industrialized nations, there has been a focused increased in renewable energy sources in the global energy market. None has experienced a faster increase in penetration into the electrical power systems than wind turbine generator systems. This technical brochure is a comprehensive document focused at providing a single source of information for planning engineers in describing the characteristics and performance of wind turbine generators in both distributed and large scale wind farm applications. In addition, the document focuses on presenting recommendations on ways of modeling wind farms for both bulk power system studies and specialized studies. This includes:

- An overview of wind generation and the unique aspects of this type of renewable generation as opposed to more conventional fossil fuel generating plants.
- A description of the unique aspects of control and protection for wind turbine generators and the various types of wind generation technologies.
- A brief overview of the experience of various utilities from around the world with large penetration of wind generation in their system.
- A thorough, yet concise, discussion of the interconnection and operating issues that are unique to wind generation and how the latest generation of wind turbine

![Fig. 1: Doubly fed-asynchronous wind turbine generator.](source: ABB Motors & Drives, Finland)
generators are meeting these challenges (e.g., low-voltage ride-through).

- A discussion on the types of models available for system studies related to the interconnection of wind turbine generators to a utility grid and recommendations on appropriate level of modeling detail for power system analysis. Recommendations and discussion are given on improvements necessary in existing models.

- Discussions are also provided in the appendices, from manufacturers, on field and factory tests pertaining to model assessment and validation.

The document is divided into seven chapters and seven appendices.

Chapter 1: is a brief introduction.

Chapter 2: provides a thorough overview of the application and experience of some of the major utilities around the world with wind generation penetration into the power system. Discussion is provided on the technical performance issues experienced, methodologies employed to rectify these challenges and the future trends for wind generation penetration.

Chapter 3: gives a detailed account of the various wind turbine generator technologies (as well as some emerging ones, with some details differed to an appendix). This includes a comprehensive review of each technology, how they differ from one another, the unique dynamic performance (from a power systems perspective) that each of the technologies display, how the technical challenges (such as fault ride-through systems) are being addressed by manufacturers for each of these designs and what challenges remain.

Chapter 4: presents a full discussion of all the technical issues related to the interconnection of large (10 MW or larger) wind farms to the transmission system. This includes voltage-ride through, reactive power and power factor requirements, voltage control and regulation, controls interaction, harmonic, power quality and frequency control.

Chapter 5: discusses the key technical issues related to small wind farms on distribution systems.

Chapter 6: provides an in-depth overview of modeling of wind farms for both steady-state power flow and time domain dynamic simulations. In addition, recommended generic model structures are presented for all the main wind turbine generator types, including direct connected induction generators, doubly-fed asynchronous generators and units connected to the system through full-rated back-to-back frequency converters. The presentation in this chapter also deals with suitable methods to aggregate wind turbine generators in a wind farm into a simpler model of the collector system, but yet be able to develop a reasonable representation of the wind farm. Extensive discussion is provided on the modeling recommendations for various types of power system studies. This chapter is complemented by several appendices that provided further details on wind turbine generator modeling, including manufacturer specific models, models available in many commercial software programs, modeling wind turbine generators for small-signal rotor angle stability studies, emerging technologies such as the hydrodynamic gear driven wind turbine generator and discussion on model validation efforts by manufacturers.

![Fig. 2: Cross-section of the MWT-S2000 Mitsubishi wind turbine.](image)
Wind generation technology

Wind generation technology has matured over the past several decades into an economically viable and environmentally favorable source of energy. Today wind generation has become a significant portion of the generation mix in many countries around the world. This document has focused on describing the dynamic performance, behavior and modeling of this generation resource. In general, wind turbine generators tend to be quite different in both mechanical and electrical construction from traditional large thermal, nuclear and hydro power plants. A wind farm of comparable peak megawatt capacity to a large thermal power plant will consist of many tens to perhaps hundreds of wind turbine generators and span over many square kilometers of land or sea. Each wind turbine generator consists of the mechanical turbine, which typically has three rotor blades that can have a diameter in excess of 80 m that is connected to a small generator through a slender shaft, often with a gear box in between. There are presently four major concepts for the actual generator:

- A conventional, constant speed, induction generator,
- A variable speed induction generator unit with a variable, external, rotor resistance,
- A variable speed unit with a doubly-fed asynchronous generator, and
- A variable speed unit with a fully rated frequency converter connecting the generator to the electrical grid.

Each of these concepts, together with other emerging concepts such as the hydrodynamic gear drive train turbine, have been discussed and explained in detail in this document.

In the early years of wind turbine generator design, the units were mainly designed for application in distribution systems and as distributed resources. Thus, a typical requirement was for the wind turbine generators to disconnect from the system following a major system disturbance. Presently, most wind farms are of the tens to hundred megawatt range and are connected to major transmission systems. Thus, the expectation is for these generating units to help support the system during major disturbances. With the application of modern wind turbine generator technologies (and occasionally other supplemental devices such as static var compensators, etc.) it is possible to build wind farms capable of riding through voltage transients caused by typical transmission system faults and disturbances, and having adequate reactive reserves and automatic controls to provide voltage regulation at the point of interconnection.

Of course, the intermittent nature of the energy source (wind) is not controllable, thus this presently still constitutes the major challenge facing operating systems with large amounts of wind generation. Active power control systems have been proposed for wind generators that allow their contribution to frequency and/or tie-line regulation, but this is always at the expense of wasted wind power if no means of energy storage is available.

The exact amount of wind generation that may be incorporated into a system before the burden of operation becomes excessive (usually called maximum penetration of wind power) is highly system dependent, since it is affected by the weather patterns of the region, the type of installed generation capacity in the system, the available power transmission capacity of the system with its neighbors and the contractual obligations governing these interconnections. The unique and unambiguous determination of such penetration limits is still an open question.

Much progress has been made, particularly with research and development in the science of wind generation forecasting but significant additional work remains in this area as well as considerations related to the potential of marryng wind generation with energy storage technologies that could help with active power regulation as mentioned above.

Detailed discussion and generic models for modeling wind turbine generators have been provided in this document. From a modeling development perspective the key item that requires further work is model validation. Although, as documented here mainly in the Appendices, many of the manufacturer specific models have been validated by the respective manufacturers, work remains to be done to validate the generic types of models presented in Chapter 6 against field recordings of wind turbine generator response. Through such work, further refinements to the generic model structures may become evident and necessary, such as the behavior of certain doubly-fed asynchronous machine designs, which incorporate active crowbar controls during and immediately after system faults due to the rotor crowbar circuits being engaged and disengaged (this does not apply to all designs of doubly-fed units).

Further research on the participation of wind generation in primary frequency control, including methods for energy storage, as well as on standards to specify wind power penetration limits is in progress. These and other research subjects concerning the integration of wind farms into power systems can be found in the literature.

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