Adjustable speed drive with a single 100-MW synchronous motor

The aging fan drive system of the NTF wind tunnel at NASA's Langley Research Center in Virginia, USA, was recently replaced by a new adjustable speed drive (ASD) from ABB. Its single 100-MW (135,000-HP) synchronous motor makes the NTF ASD the world's largest adjustable speed drive system. HVDC and traditional ASD technology, as well as large rotating machinery design and manufacturing techniques, contributed to the new drive.

NASA's National Transonic Facility (NTF) **1** in Hampton, Virginia, is a closed-circuit, high Reynolds number, pressurized, cryogenic wind tunnel, widely used by the aircraft industry for its ability to accurately simulate the full-scale, in-flight performance characteristics of large transport aircraft at transonic speeds. NTF is unique because, in addition to matching the flight Mach number, it can also simulate the high in-flight Reynolds number, typically between 50 million and 100 million, associated with these aircraft. Aircraft designs can be optimized when this flight parameter is matched. When not matched, the uncertainties associated with data extrapolation have forced aircraft designs to be overly conservative, making them costly and degrading the expected performance [1]. Only a few of the world's wind tunnels are able to achieve Reynolds numbers above 10 million, and of these NTF is the only tunnel that can simulate Reynolds numbers in excess of 100 million.

To meet the high-volume, high-quality developmental testing needs of the aircraft industry, NASA has initiated several projects to improve productivity at the NTF. Of these, the most significant involves the replacement of the existing fan drive system with a new state-of-the-art drive system and new synchronous motor. The new system improves tunnel productivity in several areas:

- Tunnel operation time is increased by the new independent drive system, which replaces a drive that shared its control system with another tunnel.
- Facility downtime is minimized by replacement of the aging Kramer control system and the complex three-motor, two-gearbox drive line, which often were a cause of breakdowns in the past.
- Testing capability is improved through the elimination of operational limitations imposed by the gearboxes and acceleration/deceleration limitation of the control system.
- Operating costs are reduced by the improved drive efficiency and the smaller number of personnel required to operate and maintain the drive line.

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General data of the NTF wind tunnel

Type:
Fan-driven, closed-loop, continuous-flow, pressurized wind tunnel

Fan:
Fixed-pitch, single-stage, axial-flow type with variable inlet guide vanes, driven by 100-MW synchronous motor

Dimensions:
Test section: 2.5 x 2.5 x 7.63 m (8.2 × 8.2 × 25 ft), with slotted walls
Tunnel circuit length: 151 m (497 ft)
Tunnel volume: approx. 6,513 m^3 (230,000 cubic ft)

Operating characteristics:
Speed range: Mach 0.2 to 1.2
Reynolds no: 120 million at Mach 1.0
Pressure range: 100 – 900 kPa (15 to 130 psi)
Temperature range: –195 °C to 65 °C (–320 °F to 150 °F)
Test media: air, nitrogen

Wind tunnel at NASA's National Transonic Facility in Virginia, USA **1**

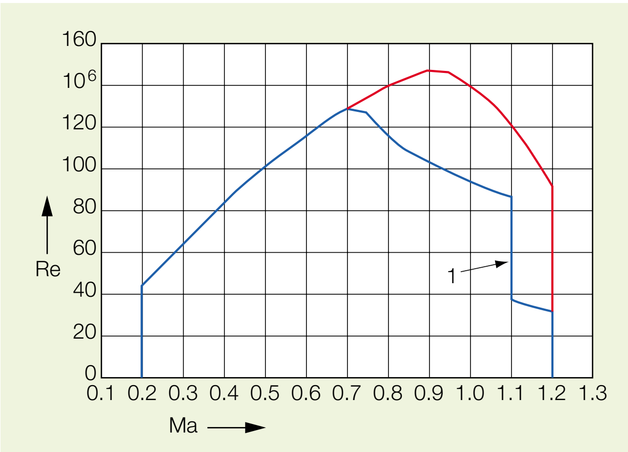
2 compares the performance curve of the new drive system with that of the previous drive. (See box on previous page for full NTF wind tunnel data).

Background

Having established the need to replace the existing fan drive system, NASA undertook an evaluation study of the technology currently available on the market. The study concluded that an all-new adjustable speed drive system with a single 100-MW motor was feasible. The

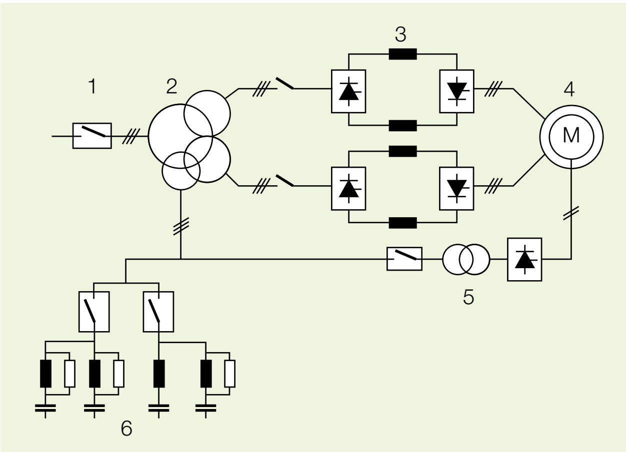
Mach number versus Reynolds number performance curves for NASA's NTF wind tunnel **2**

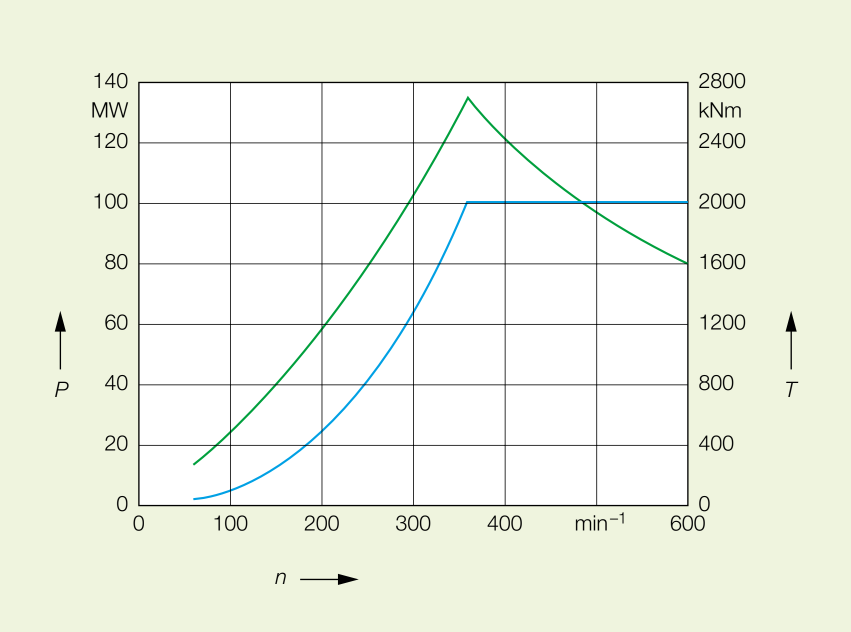
Ma	*Mach number*
Re	*Reynolds number*
Blue	*Previous drive*
Red	*New drive system*
1	*Gearset limitation*



Single line diagram of the chosen ASD system configuration **3**

1 *Supply system*
2 *Transformer*
3 *Converter*
4 *Motor*
5 *Excitation system*
6 *Filter*





NTF wind tunnel requirements **4**

Blue *Shaft power*
Green *Torque*

P *Power*
T *Torque*
n *Speed*

advantages of the single motor solution are:

- Simple shaft line-up (replaces aging Kramer control, 3 motors, 2 gearboxes, liquid rheostat)
- Simple system controls
- High efficiency
- Reduced maintenance
- State-of-the-art monitoring and diagnostics

New 100-MW (135,000-HP) synchronous motor used to operate the NTF wind tunnel **5**

ABB teamed up with a construction company, Raytheon Engineers and Constructors (REC), to offer an 'Integrated Systems Turnkey Project' solution to NASA. The proposal presented elaborate schedule details to minimize the NTF shutdown. After a thorough evaluation of the proposal, NASA awarded the contract to ABB in August 1995.

Although this size of ASD had never been built before (at the time the world's largest ASD was rated at 65 MW), ABB was able to successfully demonstrate all of the capabilities (technology, engineering and manufacturing resources, references) required to successfully build and install such a drive [2]. Despite the fact that the system concept for this very large drive system represents a standard load commutated inverter, the system design draws on expertise from several other areas:

- The converter makes use of technology adapted from converters used in HVDC transmission.
- The synchronous motor is based on hydropower generator design technology.
- The transformer is a specialty, rectifier-duty type used in HVDC transmission.
- The excitation system is a standard product normally used with large turbogenerators.

ASD system design

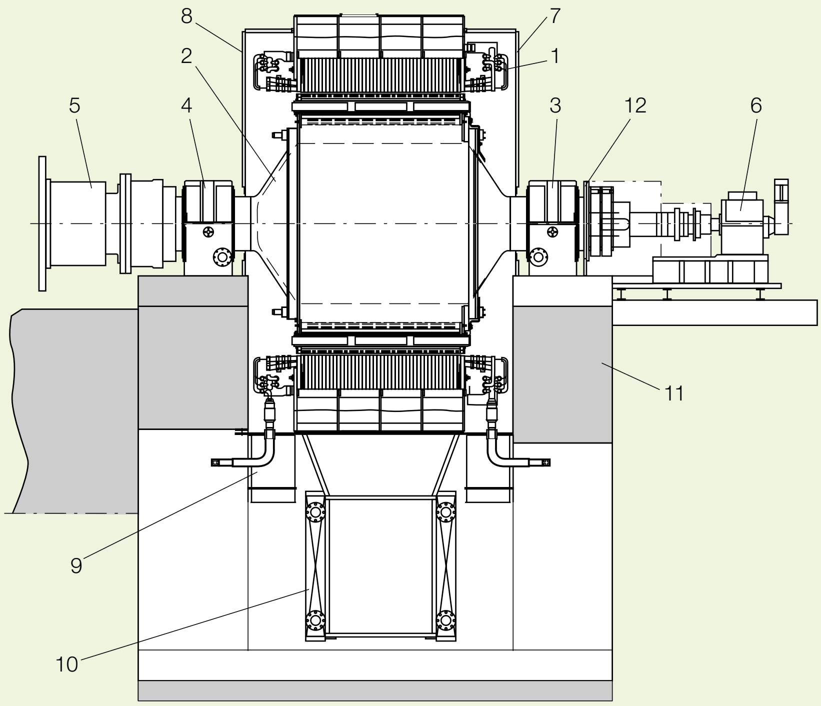
The configuration and components of the ASD system were designed to meet all NASA requirements for this special application [3] and at the same time minimize the harmonic distortion produced in the supply system and reduce the machine airgap pulsating torques.

The high shaft-power requirement of 135,000 HP, as well as constant power at speeds between 360 and 600 rev/min, called for a synchronous motor fed by a load commutated inverter (LCI). In the ASD system configuration that was chosen, an LCI in two-channel 12/12-pulse connection feeds two separate motor stator windings **3**.

The LCI takes power from the supply network at constant voltage and frequency, and converts it to variable voltage and frequency for the adjustable speed synchronous motor. The synchronous machine can be accelerated (motor mode) and decelerated (generator mode) at any speed within the operating speed range of the NTF fan **4**.

The main components of the ASD are:

- Synchronous motor
- LCI (power electronics and control system)
- Converter transformer
- Harmonic filter



General layout of the synchronous motor **6**

1	*Stator winding*	7, 8	*Stator covers*
2	*Rotor shaft ends*	9	*Motor-driven fans*
3	*NDE bearing*	10	*Air-to-water heat-exchanger*
4	*DE bearing*	11	*Foundation frame*
5	*Torque-limiting device*	12	*Sliprings*
6	*Turning gear device*		

Motor

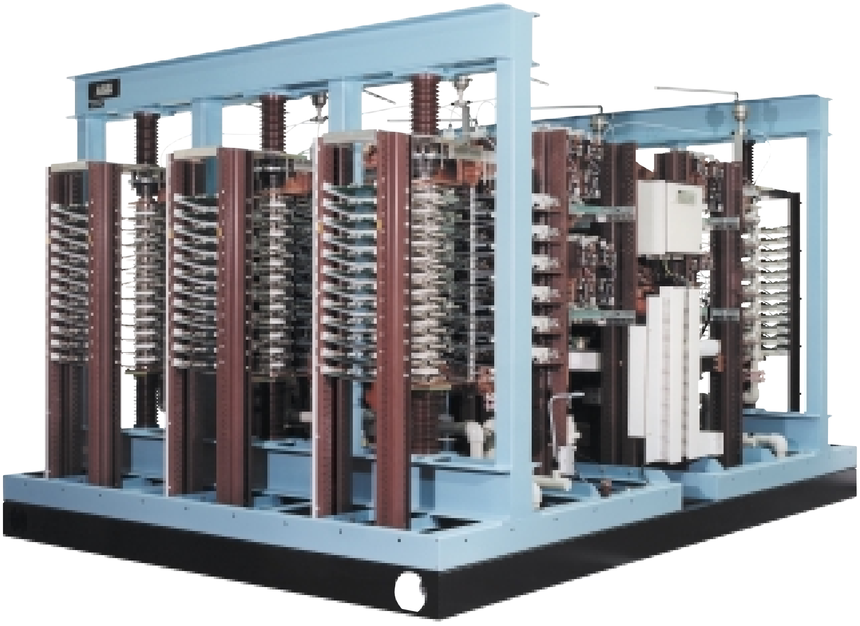
The synchronous motor **5**, **6** is a 12-pulse type with two stator winding systems. Due to the 30° electrical phase-shift between the two stator systems, the pulsating torques are reduced and less mechanical stress acts on the shaft train. The maximum possible machine power factor is achieved for every load condition by firing the machine-side thyristors with the maximum delay angle allowed by the recovery time of the thyristors. The machine power factor at full load varies between 0.85 and 0.93 (*Table 1*). Current harmonics have been taken into account in the design of the stator windings.

LCI

The power section of the LCI **7** consists of two independent 6/6-pulse channels, resulting in a total of 4 identical three-phase bridges. Each bridge has 6 branches with 12 series-connected thyristors; each thyristor is rated at 5200 V repetitive reverse/direct voltage; one thyristor per branch is redundant (n+1). The ASD is able to run continuously at full load even in the event of one thyristor per branch failing. Both the line-side and the motor-side converter can operate as a rectifier or inverter, allowing the machine to function as a motor (driving mode) or generator (braking mode). The thyristors are cooled by an internal deionized-water

Table 1:
Operating data of the new ASD motor

Shaft power [MW]	*Speed* [rev/min]	*Voltage* [V]	*Current* [A_{rms}]	*Power factor* [pu]
18.6	180	5,800	1,050	0.95
37.2	240	7,700	1,550	0.94
64	300	9,500	2,130	0.94
100	360	11,500	2,800	0.93
100	480	12,000	2,780	0.90
100	600	12,500	2,810	0.85



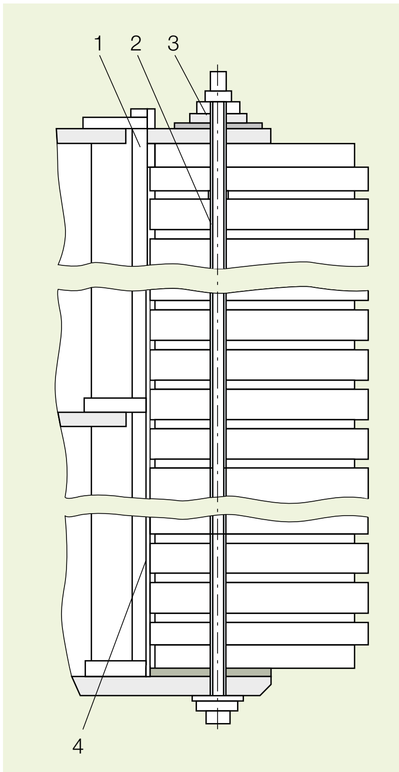
Load commutated inverter with 4 identical three-phase bridges **7**

Motor design

The synchronous motor **5** is of the salient pole type, with two independent stator windings shifted 30° electrical. The duty point of full power at base speed (360 rev/min) defines the size of the machine, ie the maximum flux densities and the maximum stator currents. The maximum flux density in the air gap is 1.1 T. Between 360 rev/min and 600 rev/min the machine operates with field weakening. At 600 rev/min the airgap flux density is reduced to 0.7 T. Since it was re-used, the existing motor foundation had to be taken into account in the mechanical design of the motor baseframe. The chosen motor

Stator core clamping system **8**

1 *No axial connection between core and frame, resulting in no axial forces acting on frame*
2 *Bolts are insulated over full length*
3 *Insulating disc and Belleville spring*
4 *Stator back dovetails for torque transfer*



circuit. The converter efficiency at full load is better than 99%.

The main tasks of the LCI control system are to adjust the speed of the machine to the desired value and to ensure the correct function of the LCI. The open and closed loop control functions are processed by the programmable high-speed controller (PSR). Firing and monitoring of the 288 LCI thyristors is via fiber optic cables. UNITROL® P, ABB's PSR-based excitation system [5] is installed.

All units of the LCI power section and control system have been used for many years in ABB large industrial drives, HVDC systems, static var compensators, large rectifier plants and static excitation equipment. The use of proven systems ensures high reliability and performance. All operational and safety requirements are also met.

Transformer

The 136-MVA converter transformer connected to the 115-kV grid has two secondary windings for the rectifiers and a tertiary winding for the harmonic filter. The values chosen for the winding impedances optimize the operation of the LCI and harmonic filter. These design values were guaranteed by means of finite element analysis and special manufacturing techniques. Factory testing has indicated only a very small variation between the winding impedances and their design values.

Harmonic filter

A harmonic filter **3** was installed to ensure that NASA requirements for line power factor and harmonic distortion were met in full. The filter is connected to the tertiary winding of the converter transformer with a fundamental power of 50 MVAr and is split into four series-resonant circuits tuned to the 3rd, 5th, 11th and 13th harmonic frequencies. The power factor and harmonic distortion remain within the recommended THD limits under all NTF operating conditions (*Table 2*).

design is very similar to the design normally used for applications in hydropower plants.

Table 2:
Voltage distortion at 115 kV PCC[1)]

Shaft power [MW]	*Speed* [rev/min]	*THD* [%]	*Limit as per IEEE 519 [4]* [%]
18.6	180	1.4	2.5
37.2	240	1.7	2.5
64	300	1.3	2.5
100	360	1.1	2.5
100	480	1.1	2.5
100	600	1.1	2.5

1) Point of common coupling to the power utility

Stator

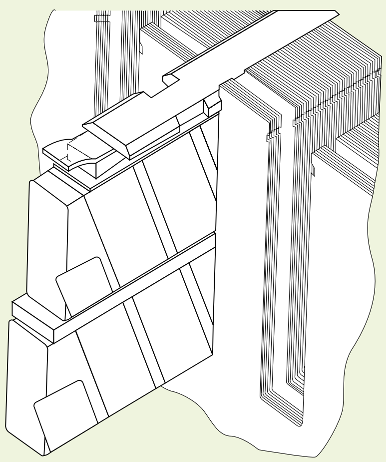
The stator has a welded frame, designed specifically to meet the requirements of the existing foundation. The stator core is built up of low-loss silicon alloyed magnetic steel sheets with a thickness of 0.5 mm and a loss coefficient of 2.7 W/kg at 1.5 Tesla. The stator core is clamped together by through-bolts that distribute the pressure as required and cause no unwanted reaction in the stator frame **8**.

The stator winding is a two-layer Roebel bar winding, placed in 144 slots and insulated for a maximum voltage of 22.5 kV, which corresponds to the electrical stress on the windings due to the two 12.5 kV systems in the stator. The insulation system is based on mica and glass tape impregnated with epoxy resin. Impregnation takes place under vacuum and pressure (VPI system) and every single bar is tested at a voltage of 90 kV before being placed in the stator core. The current density in the bars is 3.56 A/mm^2 at full load. The stator bars are secured laterally using the round-packing method, which ensures excellent mechanical and electrical performance under all operating conditions. The bars are held in place by double-tapered wedges and a ripple spring **9**.

Rotor

The rotor **10** is a forged hub with conical shaft ends designed especially for this application. This allows the hub to expand without creating any excessive stresses in the forgings. The poles are built up of laser-cut steel plates and copper excitation coils. Instead of solid end plates, cylindrical coil supports are used to reduce pole shoe surface losses and provide the necessary radial support. The design of the rotor takes into account the influence of harmonic torques in normal operation as well as the effect of short-circuit currents on the stator. The rotor coils consist of rectangular copper sections; there are 38 turns per coil. The maximum current density in the rotor circuit is 3.15 A/mm^2.

Fixation of stator bars in the slot by means of the round-packing method, with semiconductive foil and silicon compound, double tapered wedges and a ripple spring **9**



Cooling

The machine is cooled by a closed air circuit, in which 10 motor-driven fans provide the forced ventilation. Operation of the fans is controlled according to the motor load. At 360 rev/min and 100 MW, 6 fans provide an air flow of 42 m^3/s. At 600 rev/min and 100 MW all the fans run together to provide an air flow of 70 m^3/s.

Bearings

The bearings are of the tilting pad type and feature pressure oil injection at low speeds. They are mounted on the same foundation frame as the stator.

Coupling

A torque-limiting device is integrated in the coupling to limit the mechanical stress in the existing shaft line. It releases at an overtorque value of 4,500 kNm (maximum operating torque transferred to the fan: 2,680 kNm).

Tests and commissioning

All components of the ASD were fully tested in accordance with standard test procedures. Based on ABB's experience, this level of testing adequately demonstrates the system design per-

Rotor of the new, 100-MW (135,000-HP) synchronous motor **10**

formance. No factory system tests were carried out. However, an integrated controls system function test was performed.

Both the LCI and the motor were assembled on site. The commissioning procedure was designed to meet NASA's and ABB's requirements and to bring the drive system on line in a safe and orderly sequence. Acceptance tests included air mode as well as cryogenic full-load tests.

The NTF wind tunnel with the new drive system was tested and officially accepted by NASA in December 1997, when it achieved a new world record by running with a power output of 100 MW at a nominal speed of 600 rev/min.

The measured motor efficiency at 600 rev/min and 100 MW is 98.36 % (versus 98.17 guaranteed). The measured motor characteristics and temperature rises are in close agreement with the calculated values. A 120-Hz vibration that occurred in a cover panel of the stator frame at 600 rev/min could be corrected during commissioning, lowering the noise level of the motor to the required value of 90 dBA.

The technology utilized in the NTF project can also be considered for other applications requiring very large adjustable speed drives.

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