

New application of voltage source converter (VSC) HVDC to be installed on the gas platform Troll A

by

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Summary

Voltage source converter (VSC) HVDC and cable wound high voltage motor (High Voltage Motor) are novel technologies that enable powering of offshore installations with electrical power from shore. On the gas platform Troll A in the North Sea 65 km west of Bergen, Norway, the world's first HVDC transmission system, which will be designed to operate as an electric drive system based on these technologies, will be installed. Gas production capacity will thereby be maintained and expanded on Troll A – economically and environmentally friendly as more gas turbines can be avoided.. The system in Troll A includes a voltage source converter (VSC) on shore and dc cables for transmission of power to the platform. On the Troll A platform, another VSC is directly connected, i.e. in a unit connection, to a cable wound high voltage motor acting as a variable-speed synchronous machine. The motor drives a gas compressor. As the compressor speed is variable, the machine is supplied with variable frequency and variable voltage, from zero to max speed, including smooth starting and acceleration. By means of modest filters on the output of the converter, the motor winding stress is kept at a safe level. This paper describes design aspects of the electrical drive system for Troll A.

Design aspects include:

- Weight and volume limitations on an offshore platform.
- Integration of voltage source converter VSC HVDC and cable wound high voltage motor in a unit connection.
- Adoption of a voltage source converter VSC HVDC transmission to a long distance variable speed drive.

The control system for the offshore converter designed for voltage source transmission applications has been adapted and extensively tested to perform state of the art motor speed and torque control. Measurements of motor currents and voltages as well as rotor position are used together with an advanced model of the machine electromagnetic parameters to calculate converter switching pulses in much the same way as is done in smaller industrial variable-speed drives. The converter station on shore, including the controls, operates on the other hand identically to a normal voltage source (VSC) HVDC transmission system.

Space and weight capacity are very expensive and scarce resources on an offshore installation. Particularly in the light of these constraints, the voltage source converter (VSC) HVDC and cable wound high voltage motor concepts offer important advantages. The voltage source converter technology requires smaller filters than conventional HVDC, and no synchronous condenser is required. With the cable wound high voltage motor, no transformer is required.

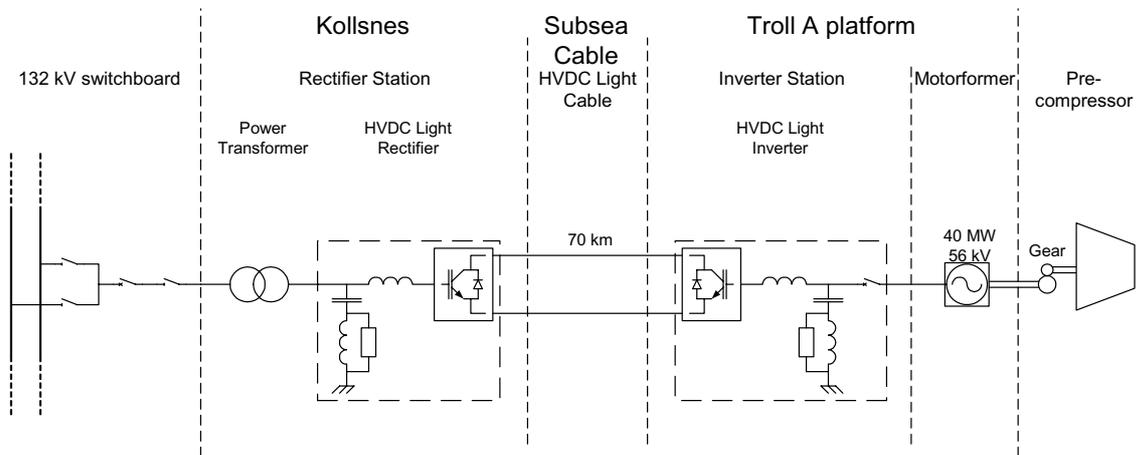


Figure 1 Simple single line diagram

1. Reducing costs and emissions with power from shore

On most offshore installations, power supply generators and large compressors are driven by onboard gas turbines or diesel engines. Many of these have total efficiencies as low as 20-25 % under the best of conditions. The result is emission of large amounts of CO₂ emission and unnecessary high fuel consumption. The Kyoto Protocol supports trading of greenhouse gas emissions. CO₂ emissions can therefore represent a cost. On the Norwegian shelf, CO₂ taxation already today in effect makes emissions costly even without such trading.

If electrical power can be supplied from shore – for power supply as well as compressor drivers – CO₂ emissions from offshore installations are eliminated. This leads to a significant cost savings for oil companies. In addition, transmission of electrical energy from shore involves less maintenance, longer lifetime and higher availability than gas turbines and diesel engines. If the transmission equipment can be located on decommissioned installations offshore, the postponed removal cost for the installation can be an important factor as well.

In addition, the environment can no doubt be saved from considerable amounts of greenhouse gas emissions if the electrical energy can be produced on shore instead of in low-efficiency power stations offshore. A land based Combined Cycle gas power plant from which waste heat is utilized can have efficiency up to 75-80 %.

Even with up to 10 % losses in a long transmission to an offshore installation, the savings will be significant for most installations.

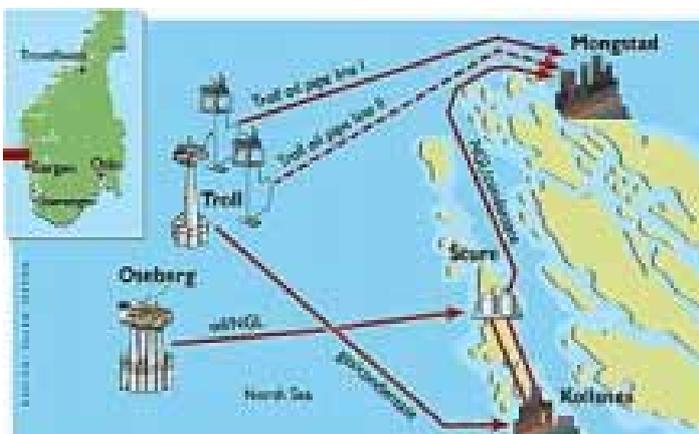


Figure 2 Gas pipelines in the nordsee

2 VSC HVDC and High Voltage Motor push gas to shore

Troll A is the largest gas production platform on the Norwegian shelf. Annually producing about 40 % of the total Norwegian gas production, Troll A can produce up to 100 million cubic meters of gas per day. Today, the reservoir pressure drives the gas to the onshore processing plant at Kollsnes. At

Kollsnes, the condensate, water and gas are separated and the gas is compressed and transported through pipelines to the European continent.

As gas is being taken out of the reservoir, the pressure decreases. In order to maintain production capacity, offshore pre-compression of the gas will eventually become necessary.

Conventional systems would use gas turbines for driving the compressors. It is estimated that for this project, annual emissions of some 230,000 tonnes of CO₂ and 230 tonnes of NO_x would result. Avoidance of such emissions is a relief for the environment, and with the CO₂ taxation in effect on the Norwegian shelf, such emissions would also impose a significant operating cost.

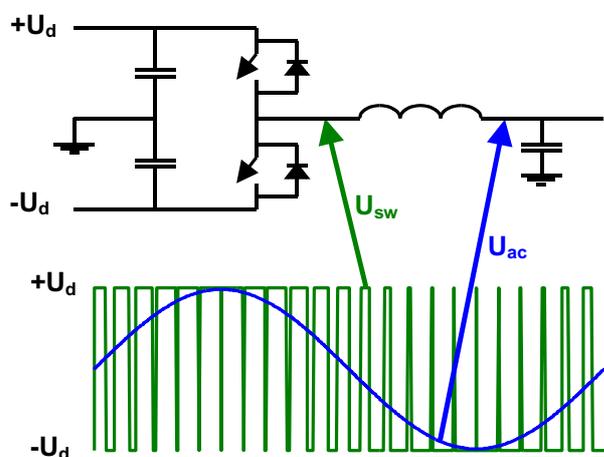
Together with Statoil – the operator of Troll A – ABB developed the alternative system illustrated in Figure 1. The system is based on ABB's novel technologies VSC HVDC and High Voltage Motor. The two technologies have been successfully employed on shore since 1997 and 1998, respectively, but never before on an offshore installation and not together operating as an electric drive system. The system uses power from the onshore electrical grid to drive the compressors on the platform, thus avoiding greenhouse gas emissions from the platform. The system gives the following advantages:

- High availability 99 %
- Increased life length 30 years
- Increased efficiency
- Reduction of CO₂ by 65 %
- Reduction of SO_x and NO_x
- Less maintenance and shorter maintenance shutdowns

Two identical compressor and drive systems will be installed in the first phase, which is planned to go into operation in the fall of 2005. Phases 2 and 3, with one additional compressor and drive system in each phase, are envisaged to be taken into operation approximately 2010 and 2020, respectively.

3 VSC HVDC – rectifying, inverting and controlling

With VSC HVDC, the use of series-connected power transistors has allowed connecting voltage-source converters to networks – at voltage levels hitherto beyond reach. This can be used for power transmission, for reactive power compensation and for harmonic/flicker compensation. With fast “vector control”, this converter offers the ability to control active and reactive power independently while imposing low levels of harmonics, even in weak grids. The powerful and robust Industrial HVDC Control, MACH 2, proven in multiple VSC HVDC and SVC installations to date, governs the converters.



In VSC HVDC, Pulse Width Modulation (PWM) is used for generation of the fundamental voltage. Using PWM, the magnitude and phase of the voltage can be controlled freely and almost instantaneously within certain limits. This allows independent and very fast control of active and reactive power flows. PWM VSC is therefore a close to ideal component in the transmission network. From a system point of view, it acts as a zero-inertia motor or generator that can control active and reactive power almost instantaneously. Furthermore, it does not contribute to the short-circuit power, as the AC current can be controlled.

Figure 3: Principle of pulse width modulation

On the Troll A platform, the VSC HVDC converter feeds the variable-speed synchronous machine, by conversion of the incoming dc voltage from the sub sea cables. As the desired compressor speed is variable, the machine is supplied with variable frequency and variable voltage, from zero to max speed (0-63 Hz) and from zero to max voltage (0-56 kV), including smooth starting, acceleration and braking. The drive system operates equally well at 0.5 Hz as at 50 Hz. By means of modest filters on the output of the converter, the motor winding stress is kept at a safe and low level.

There is no communication between the rectifier control on land and the motor control on the platform – the only quantity that needs to be detected in both ends of the transmission is the dc-link voltage. With little energy storage in the dc-link, the motor control system is designed such that it can follow even rapid changes in the power flow at the opposite end, without disturbances to the motor operation. Robust control means reducing nuisance tripping.

The VSC HVDC converter design for Troll is based on two-level bridge, midpoint capacitor grounded. The design philosophy enables operation both steady state and dynamic, with extremely low levels of induced ground currents. This feature is one of the critical factors for implementing an HVDC system in an offshore environment. There is no need for any cathode protection in conjunction with the installation.

Operation with variable frequency in one end and fixed grid frequency in the other does not require main circuit equipment that differs from the normal design. The design principles adopted for normal transmission system applications also applies for an electrical drive system. The same offshore design could therefore also be used to feed a local ac network.

4 VSC HVDC Cable – transporting the power

The VSC HVDC concept includes another development: The VSC HVDC Cable. It is an extruded polymer cable. For High Voltage AC, there has been a technology shift from paper insulated to extruded polymer cables. The corresponding development to produce an extruded HVDC cable has resulted in a flexible and cost effective cable that is an important part of the VSC HVDC concept.

The cable is designed with a 300-mm²-copper conductor surrounded by a polymeric insulating material, which is very strong and robust. The water sealing of the cable is designed with a seamless layer of extruded lead and finally two layers of armouring steel wire in counter helix for the mechanical properties of the cable. The strength and the flexibility make the VSC HVDC cables well suited for severe installation conditions and deep waters in the North Sea.

5 High Voltage Motor – driving the compressor



The launch of an innovative cable technology in 1998 raised the prospect of increasing motor voltage ratings to radically higher levels. The innovation was the use of HV cables as the windings of electrical machines [4].

The HV cable-winding concept was first applied to an electric generator [5]. A number of these generators have already entered service. The concept has now been applied to motors, with the development of a synchronous machine. The first High Voltage Motor was installed at an air separation plant in Sweden in November 2001 [6].

Figure 4 Sketch of the High Voltage Motor

The new HV technology promises a number of benefits, including the following:

- Reduced and simplified system due to elimination of the transformer and related switchgear
- A substantial reduction in system losses, mainly due to the elimination of the transformer and related equipment. Losses could be reduced by up to 25%.
- Other environmental benefit, e.g. the new motor is epoxy-free and therefore easy to recycle.
- Reduced costs for service, maintenance and spares
- Improved reliability and availability of the system, due to the elimination of the transformer and auxiliary equipment.

The High Voltage Motor features conventional rotor, exciter, control and protection technologies. Most of the stator technology is also conventional with exception for the winding. The cable slot is designed for low electrical losses, proper cable clamping, efficient cooling and simple installation. The key to success for cable-wound machines is the slot design. Four-pole rotor design implies smaller machine size, lower weight, lower noise levels, and higher cost-effectiveness when comparing with a two-pole design.

Because of the hazardous area a brushless exciter is necessary. The exciter is design to give close to full torque at start. The distance between the motor and converter can be fairly long since the current is relatively small, in this case approximately 100 m. In order not to have high voltage exposure in the area around the motor the winding and supply cables are connected by use of cable jointing. High voltage exposure to air is therefore only present in the converter module.

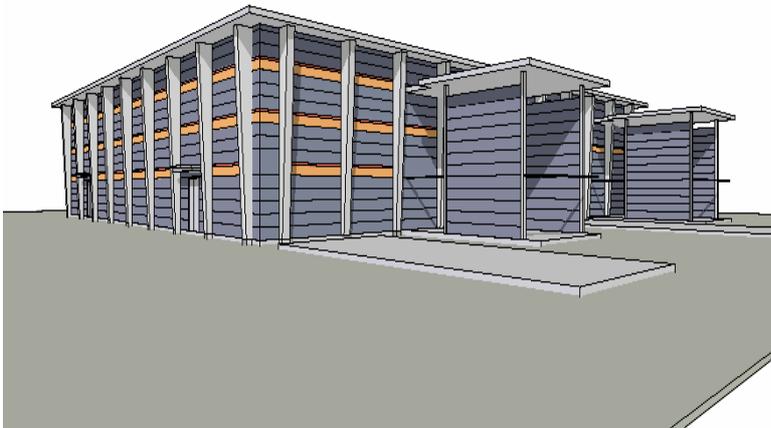
Important factors to consider when designing a motor for VSC converter drive system are the voltage and current harmonics and du/dt . The current harmonics give extra losses in the stator cable winding and also on the rotor poles. The du/dt affects the outer semi-conducting layer of the cable. A great effort has been made to secure the earthing of the cable to reduce the induced current and voltage transient

The current harmonics is considerable lower than for Load commutating inverter (LCI) drives, which is used for conventional motors at this power levels.

To make the machine more compact and with less weight has the stator a direct water-cooling system.

6. Demands on HVDC offshore

Space and weight are scarce resources on offshore installations. Particularly in the light of these constraints, the VSC HVDC concept offers important advantages: Since the filters are small, VSC HVDC can be made compact and lightweight compared to other solutions.



The compactness of VSC HVDC is illustrated in by comparing the size of the installation onshore and offshore as shown in Figures 5 and 6 above. The volume for two systems is:

- For onshore (W x L x H)
45.6 x 49.7 x 8.4 m
- For offshore (W x L x H)
18.5 x 19 x 15 m

Figure 5 Two 40 MW land-based VSC HVDC stations.

Apart from the obvious needs to make the converter station compact and lightweight, the Troll A offshore environment places a number of other demands on the converter station and equipment. Examples include:

- Safety for personnel as well as for equipment in a gas (hydrocarbons), from production and processing, environment.
- The offshore environment is very tough. Salt and humid air imposes severe requirements on the choice of materials and surface treatment.
- Integration of the control system towards the process control and shut down systems on the platform.



Figure 6: Sketch of two 40 MW VSC HVDC offshore module excluding the motor located on the platform deck.

The high voltage equipment has been installed inside a module offshore and indoor building onshore. The ventilation system in the module/building has been designed to protect the high-voltage equipment and the electronics from salt and humid air. The main circuit equipment is therefore exposed to lower environmental requirements than a normal outdoor installation. Which allows for a more compact design.

The ventilation also has to take care of the airborne losses. An advantage of being offshore in the North Sea is of course that cold (5-11 °C) water for cooling is readily available. Another requirement on the ventilation system comes from possible presence of gas in the area. Both the installation onshore as well

as the offshore has been over pressurized to ensure that no gas can enter high voltage areas. In case gas is detected, the system is tripped and deenergized directly. A conclusion is that there are no additional requirements on main circuit equipment when installed in an offshore environment.

Adaptation of the control system towards the platform process control introduces another dimension in reliability compared to normal transmission systems. In an area exposed to gas, safe and guaranteed tripping is more important than continuous operation. The control system has therefore been complemented with fail-safe circuits for external tripping from systems such as.

- Process shut downs
- Emergency shut down (gas and fire detection)
- High Integrity Pressure Protection System (HIPPS)

The objective of the HIPPS is to serve as a back up protection, with specific security requirements, to protect against overpressure in the pipelines downstream of the compressor. This could for instance occur if a valve on the high-pressure side is closed and the motor and compressor continues to operate. The HIPPS system together with its connection to the VSC HVDC has been designed and verified to meet the Safety Integrity Level 3 (SIL 3) requirements.

7. Electrical Drive System, unit connection.

The inverter control software is adapted to perform motor speed and torque control – while the control hardware is identical for rectifier and motor converters. Measurements of motor currents and voltages and rotor position are used together with an advanced model of the machine electromagnetic parameters to calculate converter switching pulses in much the same way as is done in smaller industrial variable-speed drives (e.g., ABB's ACS600/ACS1000/ACS6000). Over the entire motor

operating range, unity power factor and low harmonics are assured, while sufficiently high dynamic response is always maintained. Protection and monitoring of converter and machine are also included in the same controller. Even the excitation converter, supplying the synchronous machine field winding, is in the MACH 2 control system.

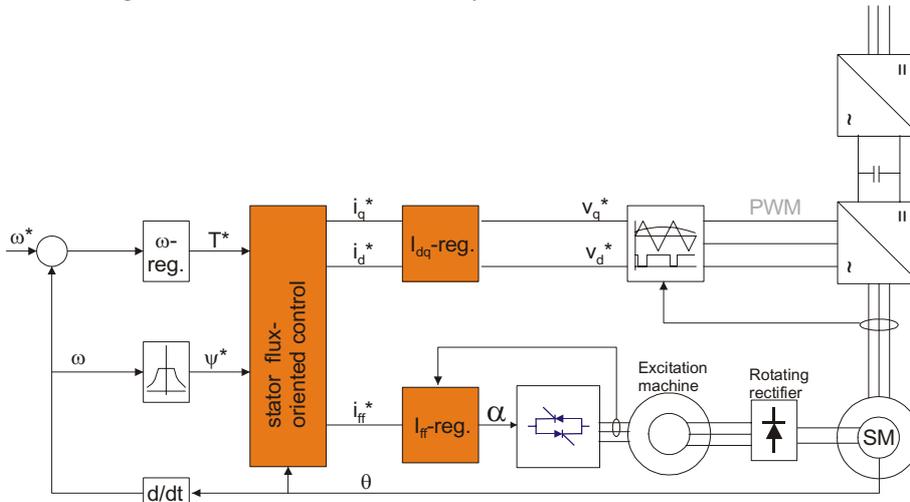


Figure 7 Electrical drive system control

One of the differences between conventional drive systems is the distance between rectifier and inverter and the very long dc cable (70 km). Therefore, one important design aspect is that keeping dc voltage at a constant value is essential for controllability as well as ensuring that there is no unnecessary over voltage stress on the dc system. This is however identical to the design of

a transmission system where one station, in this case the onshore, controls the dc voltage while the offshore controls the active power through motor Torque and speed controls. A back-up control is implemented to override the drive system control in case voltage control capability in the onshore station is lost, for instance during temporary ac disturbances. The control coordination of the stations is made without the use of telecommunication system.

7.1. Factory testing

Factory testing of the complete electrical drive system (VSC HVDC, dc cable and High Voltage Motor) was not practically possible due to power, size, cost and time constraints.

An extensive test program was therefore set up to verify that the modification of the VSC HVDC transmission system including the MACH 2 controls could be used as a complete drive system. Furthermore the control modifications needed for the adaptation were identified. The test set up used a 120 kW synchronous machine representing the motor and a dc machine representing the compressor load. The excitation system and speed sensors were emulated to ensure that the interface to MACH 2 was identical to the real system. A model of the VSC HVDC was also set up in order to get a complete true-to-scale system as possible.

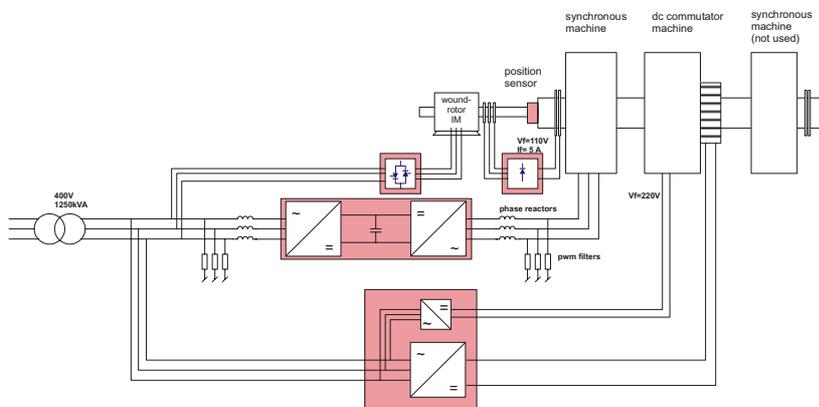


Figure 8 Low scale test set up

With this system it was possible to verify:

- Normal start / stop.
- Load and reference variations
- Encoder and excitation malfunction
- AC system disturbances, i.e. ride through
- The machine models used in the digital simulations.
- Operator training and demonstrations

7.2. Unit connection

An important weight and space saving is due to the direct connection of the motor to the converter without the use of a transformer. The optimum design in respect to voltage and current for a given power level (40 MW) for the High Voltage Motor matched very well the optimum for a VSC HVDC transmission system.

One of the important issues during the design of the electrical drive system has been the harmonics ranging from low order harmonics up to very high frequency. The desire to have low weight on an offshore platform gives the optimum solution that the High Voltage Motor should not be designed for excessive harmonics. The design philosophy has therefore been to install filters with the same filtering capacity that is normally required in a high voltage installation and not allow for large harmonics to be absorbed by the High Voltage Motor. The harmonic generation from a VSC HVDC converter is primarily at the switching frequency (2 kHz) and above while there is almost no generation of harmonics in the low frequency range (5, 7, 11 and 13:th harmonic), which is common in a normal thyristor control drive. One of the consequences of installing ac-filters in a system with a variable frequency is that there will always be a risk that the resonance that occurs between the capacitance in the filter and reactance in the motor and converter could match one of the low order harmonics. Even though the voltage generation arising from primarily imperfection in the motor windings as well as from the VSC HVDC converter is very small, the resonance may give large harmonic currents. A low order harmonic controller has therefore been implemented into the VSC HVDC controls with the purpose to generate counter voltage with the same phase and amplitude as the motor low order harmonics and thereby eliminating any undesired low order harmonic current.

8. Conclusions

In most cases, power supply to offshore installations from shore has been difficult or even impossible as long as the alternatives have been AC cables or classic line-commutated HVDC systems. VSC technology has enabled development of HVDC systems with converter stations that require smaller filters and no local generation or synchronous condensers, and with control properties far superior to those of classic HVDC. The technology using VSC HVDC now makes it possible to supply electric power from shore to offshore installations.

Placing high voltage equipment on offshore installations poses some challenges, size and weight constraints are important. The module can handle the special safety considerations and the harsh offshore environment therefore standard, or even lower rated, electrical high voltage components can be used. The same design can also be used to feed local ac network offshore.

Using a VSC HVDC transmission system as a long distance electrical drive system and adapting it to special requirements arising from offshore gas production has shown to be possible.

9. References

- [1] Asplund, Eriksson, Jiang, Lindberg, Pålsson, Svensson: DC transmission based on voltage source converters, Cigré SC14 Session, Paris,
- [2] 1998. Axelsson U, Holm A, Liljegren C, Åberg M, Eriksson K, Tollerz O.: The Gotland HVDC Light project – experiences from trial and commercial operation; CIRED 2001, Amsterdam, Netherlands, June 2001.
- [3] Hörle N, Eriksson K, Maeland A, Nestli T.: Electrical supply for offshore installations made possible by use of VSC technology.
- [4] M. Leijon et al., "Breaking conventions in electrical power plants", in CIGRE Session Report, 11/37-03, Paris, 30 August - 5 September, 1998.
- [5] M. Leijon, "Powerformer - A radically new rotating machine", ABB Review, no. 2, 1998, pp. 21-26.
- [6] T. Trumbo, O. Forsell, J. O. Lamell, G. L.F. Porsby, C. Sundström, "42 kV Compressor Motor for Air Separation Plant in Sweden", PCIC-2002-32.