300 MW Variable Speed Drives for Pump-Storage Plant Application Goldisthal

Aurélie Bocquel
Content

- Major benefits of the cyclo-converter driven doubly-fed induction machines
- Topology of the pump storage power station
- Cyclo-converter topology
- Mathematical model and simulation
- Power flow at constant torque in turbine and pump operation
- P/Q-diagram of the induction machine at different speeds and at the limits of the cyclo-converter
- Control structure of the doubly-fed induction machine with cyclo-converter
- Measurement results (torque steps, synchronisation, speed variation)
- Conclusions
Principle of a pump-storage plant

Goldisthal

Maximum dam level

Minimum level

Amount of exchanged water

Maximum dam level

Minimum level
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Major benefits of the cyclo-converter driven doubly-fed induction machines

- The efficiency of the turbine especially at partial loads can be increased by optimising the speed of operation.

- The converter only needs to supply about 30% of the total power of the machine; compared to a fully fed solution the installed power and the converter losses are reduced.

- The delivered power of the induction motor can be controlled with a high dynamic which is advantageous for grid stabilisation.

Single-line diagram of Goldisthal pump-storage station

- 4 turbines with a power of about 300 MVA each
- 2 of the electrical machines are designed as converter driven doubly-fed induction machines
- The converter feeding the rotor of the machine is with a power of 100 MVA one of the biggest cyclo-converters in the world
Machine cavern Goldisthal - different phases of the construction
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Machine cavern Goldisthal

Rotor of the induction motor under construction
Machine cavern Goldisthal

Assembly of the rotor of the induction machine, stator completed
4 turbines which can work in pumping and generating mode

2 turbines equipped with synchronous machines (331 MVA generative power each):
- classical excitement
- operation close to their rated power
- high efficiency
- fixed speed

2 turbines connected to doubly-fed induction machines (340.4 MVA generative power each):
- dynamic power control
- controlled with the cyclo converter
- speed range of −10% to +4% of rated speed
- optimisation of the efficiency varying the speed
- operation at partial loads efficient

2 start-up converters of 40 MW of rated power each:
- can start and stop the synchronous and induction machines
- each converter can be connected to each of the 4 machines
- during start up the cyclo converter excites the induction machine
- current source converters
- 24 pulse thyristor bridge on the line side
- 6 pulse thyristor bridge on the machine side
Cyclo-converter topology

100 MVA cyclo-converter for the doubly-fed induction machine

- Each phase of the rotor of the induction machine is fed by two anti-parallel 12 pulse thyristor bridges
- The anti parallel bridges drive circulating current to avoid overvoltages
- 3 parallel thyristor bridges carry the rated current

- 1 of these 3 is provided for redundancy (a failing bridge is disconnected via the pyrobreakers)
- Crow bars on the output protect the thyristors against overvoltages and can take over overcurrents generated by the machine

Cubicle carrying three independent 12 pulse thyristor bridges
(width/depth/height in mm: 3400 / 1400 / 2400)

DC choke (see next slide)

DC choke

rated current: 8970 A
rated voltage: 3716 V
DC chokes

The DC chokes driving the circulating current improve the protection of the converter

Rated current:  6365 A
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Mathematical model and simulation

- Detailed modelling of the cyclo-converter (72 Thyristors), the crow bars, the induction machine and the grid
- Simulation together with the drive control
- Importance of the simulation
  - design and verification of the power components and protection
  - design and verification of the converter control
  - calculation of the line distortions
Simulation results of a three-phase short circuit in the grid

- Due to the short circuit the rotor current rises quickly and reaches the overcurrent limit of the crow bars.
- The crow bar is triggered and the pulses of the cyclo-converter are shifted to the end position.
- The fired crow bar greatly reduces the voltage at the cyclo-converter and takes over the largest part of the rotor current.
Power flow at constant torque in turbine and pump operation 1/2
The doubly-fed induction machine can operate in a wide speed range related to the rating of the cyclo-converter.

Turbine operation: The mechanical power delivered from the turbine is converted into electrical active power generated in the stator \( P_s \) through the air gap of the machine and partly in the rotor \( P_r \).

Oversynchronous turbine operation: Thanks to the cyclo-converter, the active power in the rotor can be added to the stator power to generate the active grid power \( P_{\text{grid}} \).

Subsynchronous turbine operation: the cyclo-converter feeds the rotor with part of the active stator power necessary to generate the mechanical power.

Induction machine at synchronous speed:
- no active power is generated in the rotor
- \( P_s \) is equal to the mechanical power
- excitation by the cyclo-converter with constant current like a synchronous machine.

The reactive power of the induction machine can be controlled independently of the active power by the cyclo-converter.
At steady state operation the rotor flux amplitude and the magnetising current of the stator are constant.

With constant torque, the rotor current amplitude is constant and independent of the slip of the machine.

The rotor voltage amplitude varies linearly with the angular velocity of the rotor flux vector related to the rotor angle.
P/Q-diagram of the induction machine at different speeds and at the limits of the cyclo-converter

- Advantages of the doubly-fed induction machine:
  - Control of torque and flux with a high dynamic in all operation modes
  - Stable operation in all operation modes within the limits of the converter depicted by the P/Q circles
  Note: Operation of synchronous machines close to those power limits (e.g. with large rotor flux angles) can lead to instabilities

- The circles are determined by the maximum current of the cyclo-converter

- In the range of capacitive reactive power the power is limited by the maximum output voltage of the converter

stator voltage: 18 kV, grid frequency: 50 Hz, maximum rotor current and maximum rotor voltage
Flux oriented control based on a flux observer (extended Kalman filter) estimating the amplitude and angle of the flux in the machine.

Torque calculation using the estimated flux.

Synchronisation control:
- control of the flux of the machine with the cyclo-converter until electrical synchronisation between the stator voltage and the grid is reached
- synchronisation below the synchronous speed possible to reduce the start-up procedure duration
- the line breaker is closing with damped transient currents and resulting torque jerks
Current control structure of the cyclo-converter

- The reference rotor reactive current and torque generating current are transformed into rotor coordinates and compared to the calculated rotor current components $i_r$ by the rotor current controller.

- Using voltage feed-forward estimating the rotor voltage increases the dynamic of the current control.

- Circulating current controller is only activated if the rotor current is near zero.

*Reference values*
Simulation of a torque step from zero to the rated torque

This dynamic performance of the drive can be used to dampen active power oscillations in the grid.

Measurement of a torque step on site
(about 40% of rated torque)
At the end of the starting-up of the induction machine, the cyclo-converter is synchronising the stator voltage to the grid.

When electrical synchronisation is reached the line breaker at the stator of the machine is closed.

The transient currents and resulting torque jerks after closing the breaker are well dampened and disappear after about 500 ms.

Compared to a synchronous machine this drive can synchronise much faster to the grid.

The start-up time can be reduced by accelerating the rotor to only 92 % of the synchronous speed and synchronising to the grid with the cyclo-converter.

Measurement of the drive behaviour while closing the line breaker after synchronisation at almost 95 % of the synchronous speed.
Each of the 2 water pipes in Goldisthal is feeding 1 pair of turbines, consisting of one induction machine and one synchronous machine.

- The induction machine is running in turbine operation at about 300 MW (rated torque: 9000 kNm).
- The synchronous machine is taken out of operation and the water pressure of the turbine of the induction machine is changing drastically.
- The delivered power of the cyclo-converter driven induction machine is kept constant to 300 MW by changing the speed of the turbine.

Measurement of dynamical speed variations caused by a load rejection of the synchronous machine around the synchronous point (turbine operation with 300 MW)
advantages of the cyclo-converter driven induction machine drive compared to a synchronous machine drive

<table>
<thead>
<tr>
<th></th>
<th>Cyclo-converter Driven Induction Machine</th>
<th>Synchronous Machine with Standard Excitement</th>
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</thead>
<tbody>
<tr>
<td>Step response time (P, Q)</td>
<td>150 ms</td>
<td>several seconds</td>
</tr>
<tr>
<td>(zero to rated)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synchronisation time</td>
<td>10 s</td>
<td>20 s or more depending on mechanical load conditions</td>
</tr>
<tr>
<td>Synchronisation transient</td>
<td>damped after 500 ms</td>
<td>damped after several seconds</td>
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<tr>
<td>reactions</td>
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<tr>
<td>Average efficiency of the</td>
<td>80 %</td>
<td>70 %</td>
</tr>
<tr>
<td>whole storage unit (turbine +</td>
<td></td>
<td></td>
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<tr>
<td>drive)</td>
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A 300 MVA doubly-fed cyclo-converter driven induction machine drive for the pump-storage station Goldisthal was successfully put in operation.

The cyclo-converter only needs to drive a third of the total power of the machine at the most. The efficiency of the turbine is increased by varying the speed (−10% to 4%).

The high-dynamic flux oriented control (torque step response time <10 ms) can be employed for a very fast power control for the stabilisation of the grid.

Application of the drive system could also be advantageous for pump-storage stations with much less power (e.g. 50 to 100 MVA).