ABB Review Article

Bremen´s 100-MW static frequency link

Issue-No: 9,10/96 (pp.4-17), M420

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Static frequency converters are today the equipment of choice for the links that exchange energy between railway power supplies and national electricity grids. At 100 MW, the 'Bremen' static frequency link in Germany is currently the world´s highest rated installation of its kind to employ GTO thyristor technology. Further development of the GTO thyristors, which are connected in series, plus a new type of gate unit, made the high rating and good economy of the link - between a 16 2/3-Hz and a 50 Hz system - possible. The advantages of the new installation over earlier links include high availability and a considerably better efficiency over the full power range.

For historical reasons, traction power supplies in many countries have frequencies which are different to the frequency of the national grid or, alternatively, are operated with direct current [1, 2, 3]. Although the railways have their own power plants, the strong fluctuation in power demand often makes it necessary for the supply systems to also be connected to the national grid. In Germany, for example, ties exist between the traction power supply and the national grid at about 40 locations. Besides meeting about a quarter of the railways' total power demand, these ties also allow the traction power supplies to be stabilized. Also, since most of them can be used to exchange energy in both directions (ie, from the 50-Hz to the 16 2/3-Hz system, and vice versa), traction power generation can be scheduled in a more economical way.

Operation of the frequency link and environmental protection

Blast-furnace gas - a byproduct of pig iron production at the German steel company Stahlwerke Bremen GmbH - is supplied by pipelines with a diameter of up to 1.8 m to the Mittelsbüren power plant, which is located near the steelworks. The electric utility Stadtwerke Bremen AG, which owns the power plant, burns the gas in turbines to generate electrical power for German Railway. This collaboration, which began in 1964, is of considerable ecological importance as it saves coal which would otherwise have to be burnt in other power plants to meet demand. CO_2 emissions are substantially reduced as a result.

The drop in traction power demand at weekends made it necessary in the past to burn off a certain amount of the blast-furnace gas. Since the static 100-MW frequency link has been operating in Mittelsbüren, the blast-furnace gas can be utilized more efficiently as Stadtwerke Bremen can convert the traction power into three-phase AC power, and vice versa. In the future, it will be possible to use almost all of the gas to generate electrical power. Also, any power which German Railway does not want can be converted and fed into the power system of Stadtwerke Bremen.

Hitherto, the environmental benefit accruing from the cooperation between the steelworks, railway authorities and electric utility has been equivalent to about 750,000 t of CO_2 per year, this being the amount that other power plants would otherwise have emitted. With the new converter, an additional reduction of 150,000 t of CO_2 will be achieved each year.

The static frequency link for exchanging energy between the 16 2/3-Hz system and the 50-Hz system also helps to secure a more reliable supply of power in the two networks, since a power shortfall in one of the systems can be compensated for by the other.

With the help of the new system tie, the traction power units of the Mittelsbüren plant can be included in the three-phase AC power generation (or power from the 50-Hz system supplied to the 16 2/3-Hz system in an economical way) when less or even no blast-furnace gas is available, or when the full power plant rating is not at disposal for other reasons. This not only ensures good matching of the power plant capacity to the actual supply, fuel and cost situation, but also makes sure that the contractual obligations to German Railway are met independently of the supply of blast-furnace gas.

From rotary to static converters

Traditionally, converter stations linking traction power supplies with national grids have had rotary converters installed in them. In recent decades, the increasing reliability of power semiconductor devices, and particularly the successful introduction of gate turn-off (GTO) thyristors, has made static converter installations the preferred option. The benefits they offer are as follows:

- An improvement in efficiency of about 5 percent over the entire power range [2]

- Lower first-time costs due to the elimination of the costly foundations for rotating installations
- Longer intervals between maintenance, plus shorter downtimes, resulting in higher availability
- Modular design of the components, making the equipment easier to service

Static traction power links built in the past have featured converter units with a rating no higher than about 15 MVA. ABB recently took a first step towards higher ratings with the 2 x 25-MVA installation for Swiss Federal Railway's converter station at Giubiasco, in southern Switzerland. This installation was placed in commercial operation in 1994 [1, 3].

A single converter with high rating for Bremen

In 1991, Stadtwerke Bremen AG awarded ABB Power Generation and ABB Industrie AG a contract to study the feasibility of building a high-power converter for exchanging electrical energy between a 16 2/3-Hz and 50-Hz system; the converter was to be built with GTO thyristors in series connection and have a transmission rating of up to 100 MW in both directions. The feasibility study showed that further development of the GTO thyristors, their series connection and use of an innovative hard driven gate unit [4], would allow an economical static frequency link to be built that satisfies these conditions.

The main technical data of the Bremen frequency link are given in Table 1. The installation consists of a single converter rated at 100 MW/MVA. This tremendous leap in power rating was made possible by several innovations in GTO thyristor technology that guarantee highest reliability.

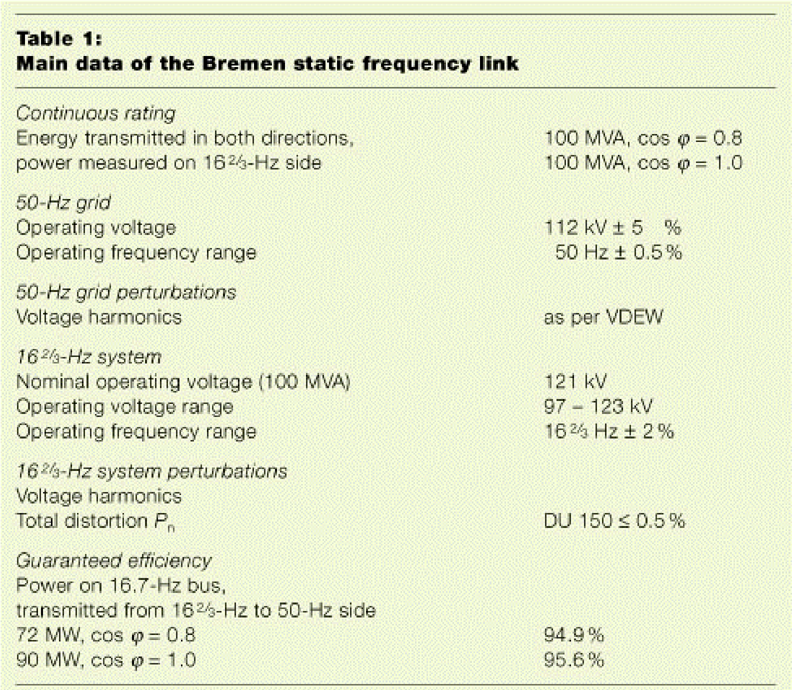


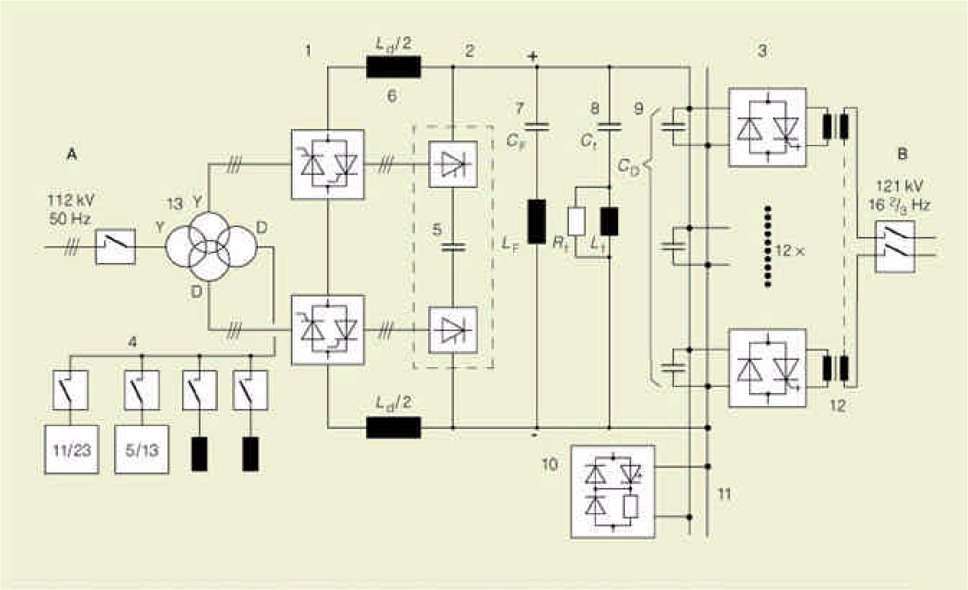
Table 1:
Main data of the Bremen static frequency link

Continuous rating	
Energy transmitted in both directions,	100 MVA, $\cos\varphi = 0.8$
power measured on 16⅔-Hz side	100 MVA, $\cos\varphi = 1.0$
50-Hz grid	
Operating voltage	112 kV ± 5 %
Operating frequency range	50 Hz ± 0.5 %
50-Hz grid perturbations	
Voltage harmonics	as per VDEW
16⅔-Hz system	
Nominal operating voltage (100 MVA)	121 kV
Operating voltage range	97 – 123 kV
Operating frequency range	16⅔ Hz ± 2 %
16⅔-Hz system perturbations	
Voltage harmonics	
Total distortion P_n	DU 150 ≤ 0.5 %
Guaranteed efficiency	
Power on 16.7-Hz bus,	
transmitted from 16⅔-Hz to 50-Hz side	
72 MW, $\cos\varphi = 0.8$	94.9 %
90 MW, $\cos\varphi = 1.0$	95.6 %

A single converter unit which is capable of the full power rating offers higher efficiency than converters made up of multiple units. In addition, the smaller number of components automatically improves the reliability, while investment and running costs are also lower. It is worth noting, too, that in Bremen all of the necessary redundancy is integrated in the converter itself.

Frequency link circuit and configuration

The main power circuit of the Bremen frequency link consists primarily of the thyristor converter on the three-phase AC side, the DC voltage link, the GTO converter on the 16 2/3-Hz side, and the converter transformers. Also shown in Image 1 is the filter and compensation equipment for the three-phase AC network and the DC link, plus the main overvoltage protection gear and the equipment for protecting the station in the event of 'shoot-through'. The voltage and frequency of the power system operated by Stadtwerke Bremen AG remain practically constant. In the traction power supply, on the other hand, both the voltage (97-123 kV) and the frequency (16.3-17.0 Hz) fluctuate considerably in normal operation. The nominal voltage and nominal current of the DC link are 10 kV and 10.5 kA, respectively.

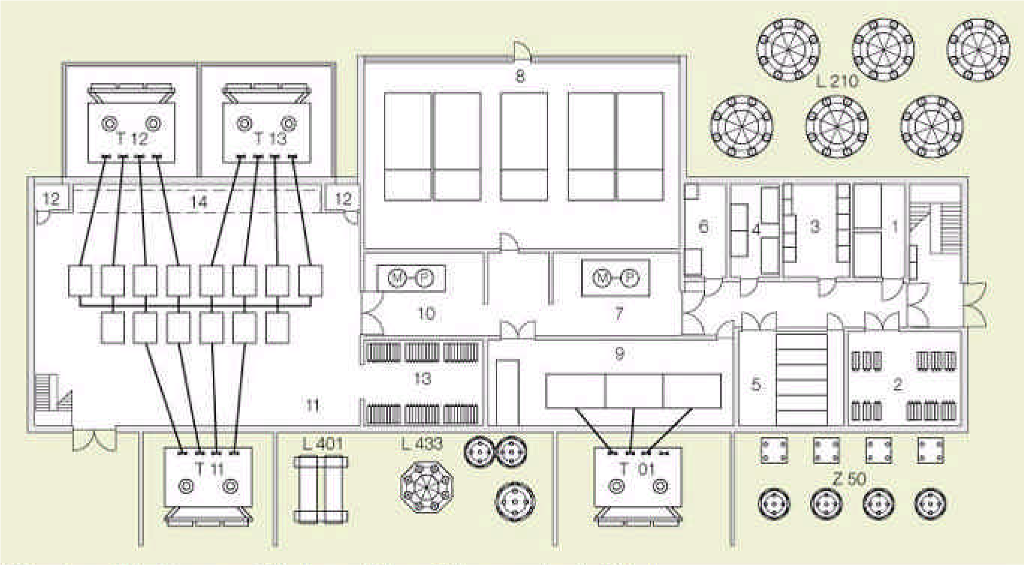


Basic circuit diagram of the 100-MW static frequency link of Stadtwerke Bremen

A Three-phase AC power system
B Traction power supply

1 Thyristor converter
2 DC voltage link
3 GTO thyristor converter
4 Filter (11/23, 5/13) and compensating equipment
5 Common turn-off circuit
6 Smoothing reactor
7 33-Hz filter
8 Highpass filter
9 DC link capacitors
10 Voltage limiter
11 DC link buses
12 Summation transformer, 16⅔ Hz
13 Converter transformer, 50 Hz

1



Plan view of the frequency link (ground floor of the converter building)

1 Auxiliary transformer
2 50-Hz filter
3 UPS and AC distribution
4 Battery
5 20-kV switchgear
6 DC distribution
7 Cooling plant, 50 Hz
8 Water/air heat-exchangers
9 Converter room, 50 Hz, with common turn-off circuit
10 Cooling plant, 16⅔ Hz
11 Converter room, 16⅔ Hz
12 Ventilation
13 Capacitors, 33-Hz filter
14 Ventilation ducts
T11–T13 Transformers, 16⅔ Hz
T01 Transformer, 50 Hz
L210 PF correction equipment, 50 Hz
L401 Smoothing reactor
L433 Reactor, 33-Hz filter

2

The new installation is located directly behind the 110-kV substation of Stadtwerke Bremen AG and immediately next to German Railway's 110-kV substation. The converter and the control and monitoring equipment are accommodated in a two-floor building. All the capacitor banks are also located in this building to protect them from pollution caused by the steelworks and from salinity in the air, a consequence of the installation's site, which is close to Germany's North Sea coastline. The transformers, compensating coils, smoothing reactors and filter coils are installed in front of the building.

100-MW frequency static link of Stadtwerke Bremen

1 Converter building 2 PF correction reactors 3 Water/air heat-exchangers 4 16⅔-Hz transformers

3

The layout of the rooms in the 54 m by 15 m large building is practically the same on the ground and upper floors, since the main components (both converter units, the DC link capacitors and the common turn-off circuits) are evenly divided between the two floors and arranged identically. The chosen configuration ensures that the connecting buses are kept as short as possible.

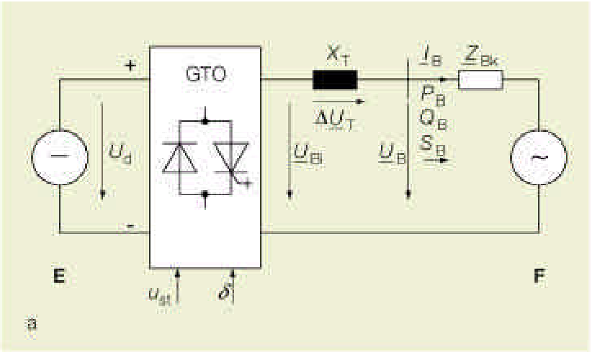
Transparency and good access to the station components was given a high priority during the planning. In this respect, the installation benefits in full from the inherent advantages of the converter's modular design: ease of maintenance, low service costs, short repair times in the event of equipment failure, all of which add up to high availability. The room in which the converter on the 16 2/3-Hz side is installed has been dimensioned to ensure good access to all the components. Half of the converter modules and the voltage-limiting modules are on each floor of the building.

The control system cubicles are situated on the top floor, in a central position to ensure short cables to the power components. Also on the top floor is the MMI station for local control.

The transformers as well as the compensation, filter and smoothing reactors are all located outside of the building, but close to their associated power components.

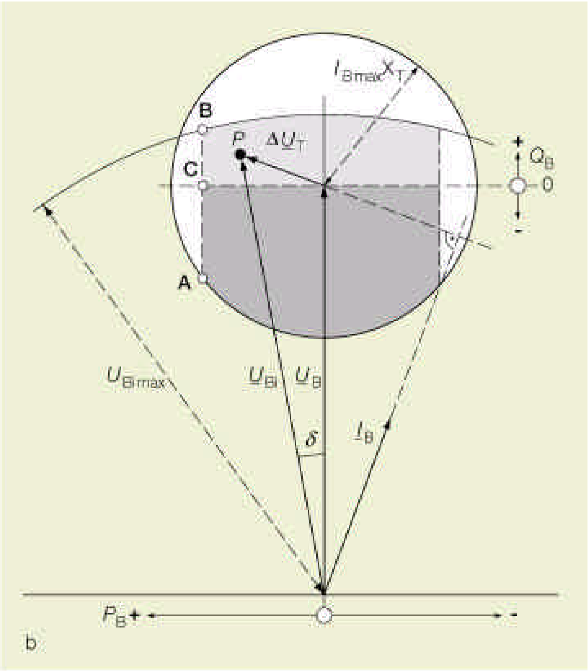
Principle of operation and equipment layout on the 16 2/3-Hz side

The direct voltage of the DC link is kept constant by the converter on the three-phase AC side. The GTO thyristor converter generates an internal voltage with freely adjustable amplitude and phase and a frequency which is determined by the interconnected operation. The reference quantities for the manipulated variables of the converter are the voltage and phase relation at the tie to the traction power supply.



Principle of operation of the GTO thyristor converter

a	*Equivalent circuit*
E	*DC voltage link*
F	*Traction power supply*
U_d	*DC voltage*
U_{Bi}	*Internal converter voltage*
X_T	*Short-circuit reactance of 16⅔-Hz transformer*
ΔU_T	*Voltage drop across X_T*
U_B	*Traction power supply voltage at connecting point*
Z_{Bk}	*Short-circuit impedance of traction power supply*
P_B, Q_B, S_B	*Power fed into 16⅔-Hz system*
I_B	*Output current of GTO thyristor converter*
u_{st}, δ	*Output variables of control system*



b	*Simplified vector diagram of GTO thyristor converter*
A, B, C	*Defined operating points*

4a,b

The vector diagram in (Image 4b) illustrates the principle of operation of the converter with GTO thyristors. A key role is played by the short-circuit reactance X_T of the single-phase converter transformer (Image 4a). The internal converter voltage U_{Bi} can be freely chosen within certain limits (grey area). This defines the voltage drop DU_T and with it the amplitude and phase of the current I_B.

The availability of reactive power is limited by the maximum internal voltage that can be set. This is defined by the direct voltage of the DC link and the converter control procedure described in the following. In connection with this, it should be noted that the restrictions on the switching time do not allow the full control voltage u_{st} to be utilized (the maximum control voltage factor is 0.96).

The apparent power S_B is limited by the maximum current I_B that can be conducted by the GTO converter and the converter transformer (small circle in Image 4b). Whereas in the case of the transformer this limit has only thermal origins, in the case of the converter consideration also has to be given to the turn-off capability. In addition, the active power limits (the perpendicular borders of the grey area) depend on the design of the infeed circuit (thyristor converter, etc) on the three-phase AC side.

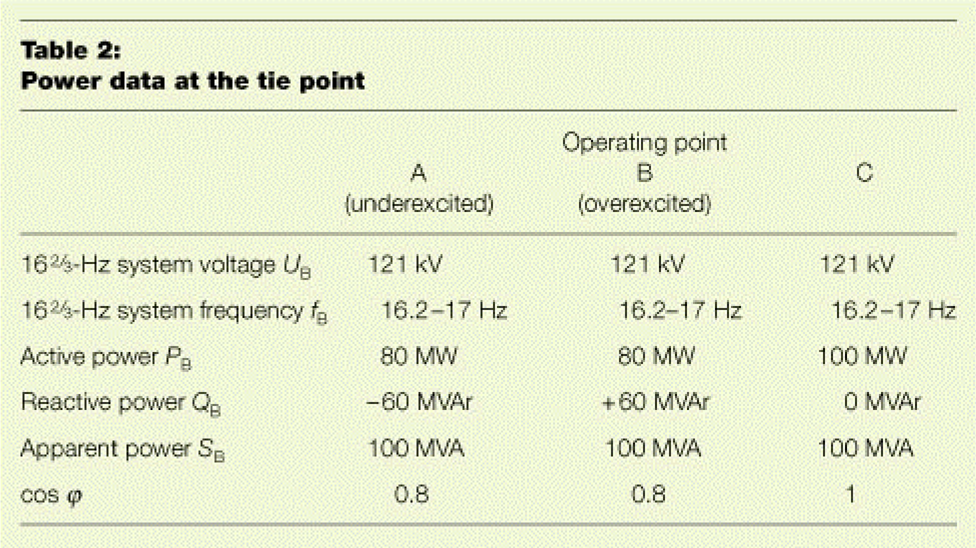
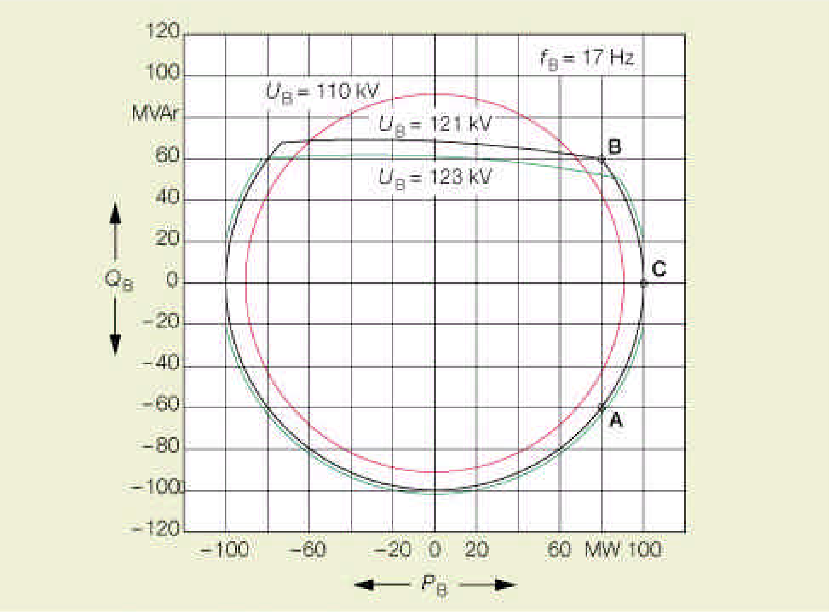


Table 2:
Power data at the tie point

	Operating point A (underexcited)	B (overexcited)	C
16⅔-Hz system voltage U_B	121 kV	121 kV	121 kV
16⅔-Hz system frequency f_B	16.2–17 Hz	16.2–17 Hz	16.2–17 Hz
Active power P_B	80 MW	80 MW	100 MW
Reactive power Q_B	−60 MVAr	+60 MVAr	0 MVAr
Apparent power S_B	100 MVA	100 MVA	100 MVA
cos φ	0.8	0.8	1

The PQ diagram representing the 16 2/3-Hz side corresponds to the defined power data (Table 2). The circle for $U_B = 121$kV includes the three specified operating points A, B and C, and corresponds to the maximum current allowed for the GTO thyristor converter. This also determines the maximum power at a lower railway network voltage. In the overexcited range, the power limit is defined at point B by the maximum possible converter voltage.

Since an additional antiparallel thyristor converter with the same power rating is installed, the symmetrical operating points A', B', C' are valid for the energy flow from the 16 2/3-Hz side to the 50-Hz side.

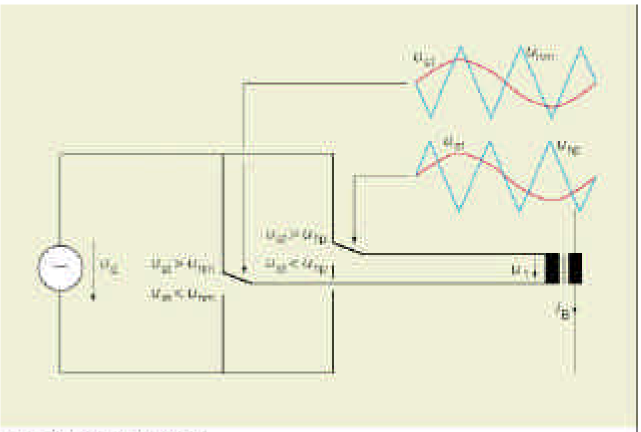


PQ diagram for the 16⅔-Hz side

P_B	Active power, positive when energy flows from 50-Hz to 16⅔-Hz side
Q_B	Reactive power, positive during overexcitation
U_B	Traction power supply voltage at connecting point
f_B	Frequency of traction power supply voltage
A, B, C	Specified operating points

5

Control method and output voltage



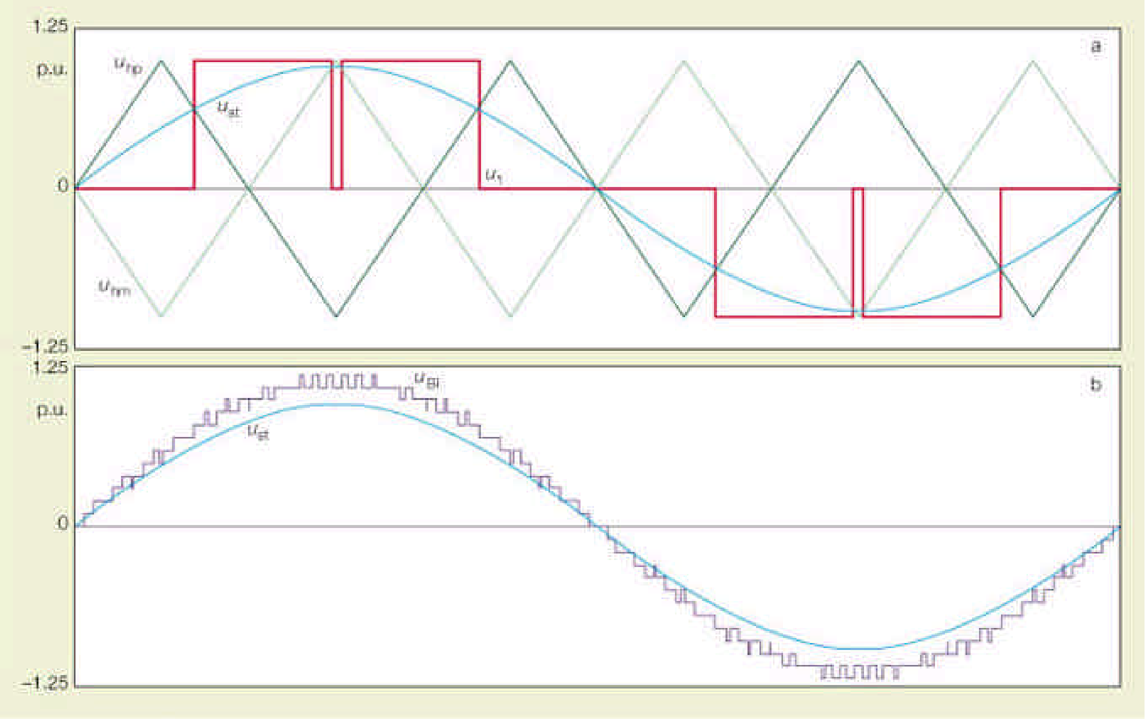
Principle of PWM control

u_d	*DC voltage*
u_{st}	*Control voltage*
u_{hm}, u_{hp}	*Auxiliary control voltages*
u_1	*Output voltage of one stage*
i_B	*Output current of GTO thyristor converter*

6

The proven PWM (pulse width modulation) method was chosen for the control, this method being used widely today for drive systems. The switching commands for the individual phase modules (U-modules) are generated on the basis of a comparison of the instantaneous values of the sinusoidal control voltage u_{st} with the triangular carrier voltages (auxiliary control voltages u_{hm} and u_{hp}). The carrier frequency corresponds to three times the traction power system frequency. Each GTO thyristor therefore performs three switching cycles for every period on the 16 2/3-Hz side.

All twelve GTO thyristor bridges are controlled using the PWM method; the carrier signals of two adjacent stages are displaced electrically by 15 ° (180 °/12, referred to the carrier period). Because of this there are 12 mutually displaced step voltages. The summation of these step voltages, which takes place due to the series connection of the high-voltage windings in the 16 2/3-Hz transformer, results in an approximately sinusoidal output voltage with a very low harmonic content. No additional filters are necessary.



Voltage formation, GTO thyristor converter

a *Characteristic of voltage u_1 (one stage)*

b *Resultant internal converter voltage u_{Bi} at summation transformer output, for control voltage of $u_{st} = 0.9$*

u_{hm}, u_{hp} *Auxiliary control voltages*

7

The output voltage is controlled by means of adjustment of the amplitude of the control voltage u_{st} and its phase relation d, referred to the traction system voltage U_B at the point where the frequency link is connected.

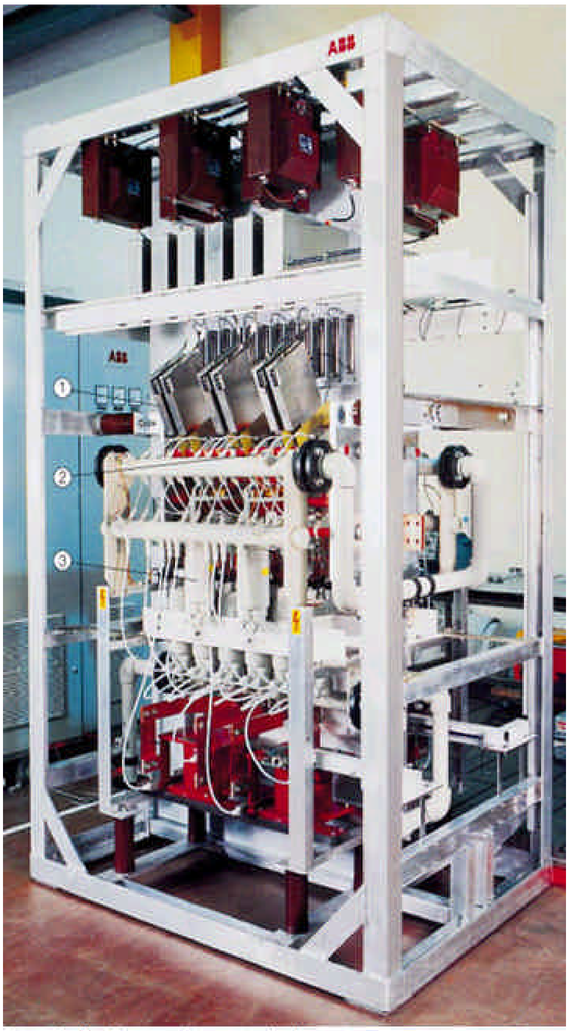
Converter on the 16 2/3-Hz side

The high power rating of Bremen's frequency link was made possible in the first place by key technological advances that are incorporated in the GTO thyristors used in the converter on the 16 2/3-Hz side. This converter consists of (Image 1):

- Twelve H-bridges, each with two phase modules, connected in parallel with the DC voltage link
- Four voltage limiters in the DC voltage link
- The DC voltage link, coupled direct and consisting of a low-inductance busbar and capacitors
- The valve base electronics

Low-inductance phase modules

Each of the phase modules has six GTO thyristors connected in series. The phase module with the DC link bus and the directly connected capacitors is designed with a very low inductance to ensure that only minimal energy is stored in the leakage inductance, thereby minimizing the voltage stress during switching.



Low-inductance phase module
1 Gate unit 2 Semiconductor stack 3 Snubber circuit **8**

Very low-inductance HV capacitors (200 nH per 10-kV unit) are used for the DC voltage link. The capacitor elements are built using self-healing, dry technology. In the event of an internal defect in the insulation, evaporation of the metal layer is restricted to the immediate locality, and no short-circuit occurs.

The power semiconductors, resistors in the snubber circuits and current-limiting reactors are cooled with deionized water. The reliability of the converter is also increased by this (no fans for forced-air cooling).

Series connection and redundancy

The series connection of the GTO thyristors calls for precise timing of the switching, with all of the series-connected GTO thyristors capable of being switched within 200 ns. To this end, ABB developed the so-called hard driven gate unit, which features a much higher rate of rise and amplitude than conventional gate drives [4]. To achieve this, the inductance of the gate unit had to be reduced by a factor of about 100, requiring a completely new design in which the GTO thyristor and gate unit are united in a single, compact module.

The nominal direct voltage of the DC link is 10 kV. Four GTO thyristors connected in series in each branch of the bridge are sufficient for this rating. With six GTO thyristors connected in series, one semiconductor device could fail without causing the installation to perform at less than its full level.

If a second thyristor in the same branch should fail, controlled shut-down of the installation is initiated. The incorporation of redundant semiconductor devices reduces the voltage stress level of all of the components and significantly improves their mean lifetime.

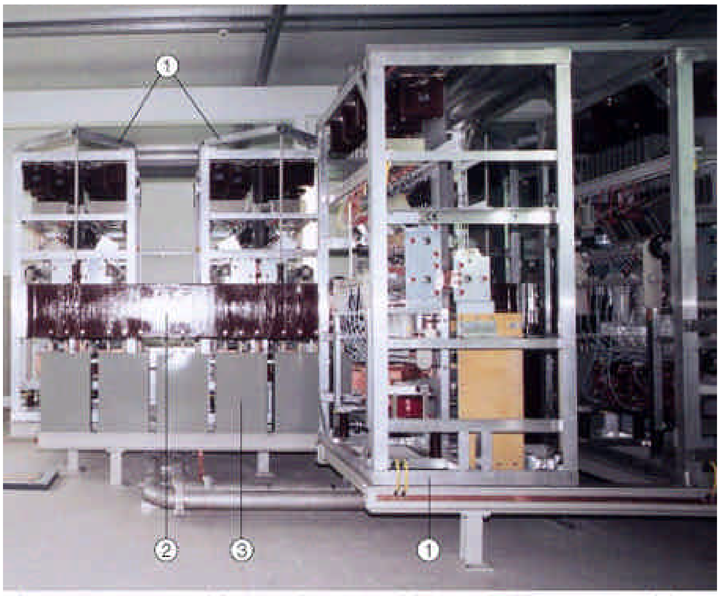
Calculations based on field data show that a converter with GTO thyristors connected in series and with integrated redundancy will, on average, suffer a total breakdown just once in seven years. This figure presupposes annual maintenance, during which any defective redundant components identified during operation are replaced. The availability can be significantly improved by replacing these components at shorter intervals.

DC link bus connections

The low-inductance design principle also applies to those parts of the DC link that are closely tied electrically to the converter. The voltage link conductors therefore consist of two flat bars running parallel to each other with just a layer of MICADUR® insulation separating them. Since internal short-circuits could cause considerable mechanical stress, the structure has been designed to withstand every conceivable fault event. After being calculated and simulated, the stress withstand capability was also tested in ABB's high power laboratory.

Voltage limiter

Fast-acting control circuits ensure that the DC voltage is kept constant by the infeed thyristor converter. Nevertheless, disturbances in either of the two power systems can cause transient over voltages. To protect the converter, a voltage limiter has been integrated which connects a load resistor into the DC link the moment the permitted voltage limit is reached. The voltage limiter consists of four parallel GTO thyristor switches with load resistors. These are, in effect, four slightly modified branches of the phase module of the GTO thyristor converter to which a resistor and freewheeling diodes have been added.



Converter modules (1) with DC link bus (2) and DC link capacitors (3)

9

Protection

The three-stage protection concept comprises prevention, protection firing, and damage containment in emergency situations. The overriding philosophy is that everything has to be done to prevent fault situations from occurring in the first place. This end is served by redundant GTO thyristors as well as controlled shut-down in the event of failure of a second thyristor in the same branch. In addition, the two branches of a GTO thyristor phase are interlocked to prevent them from becoming conductive simultaneously.

If the preventive measures fail, shoot-through is detected within just a few microseconds by a measuring device (also provided in redundant mode). To relieve the defective GTO thyristor phase, all the other phases of the converter are turned on (protection firing). The design of the converter ensures such that this causes no damage. Besides, the integrated preventive measures ensure that protection firing occurs on only very rare occasions.

The GTO thyristor converter has also been designed to withstand faults in the event of failure of the protection system. Although all of the semiconductor devices (GTO thyristors and diodes) in a defective phase can be destroyed by the full fault current flowing through a central fault location, there will be neither mechanical nor thermal secondary damage as a result of this. No plasma is formed and no components will explode.

Verification

Since the GTO thyristor converter in Bremen is the first of its kind and features largely new technologies, special importance was attached to the verification of the components and subassemblies used in it. This was carried out by simulation with highly sophisticated models and by laboratory testing of the different parts of the installation.

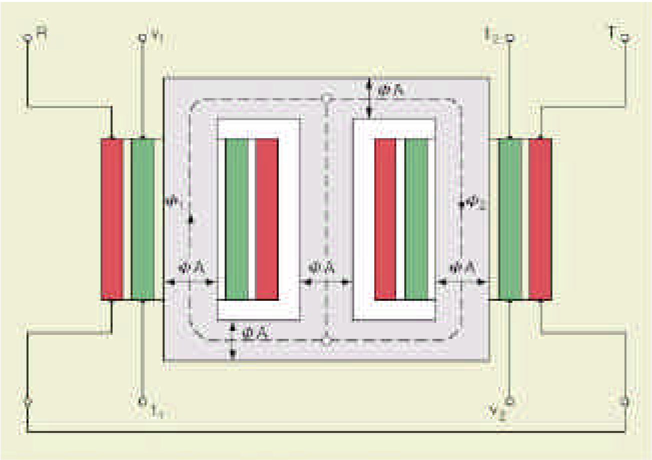
The program used for the simulation was a new one with improved models of the power semiconductors. The parameters were obtained from special measurements carried out on the hardware. In this way it was possible, for example, to verify the shoot-through and protection firing within the context of the overall installation and the power systems. In addition, the influence of the component tolerances could be clarified and worst-case tests could be carried out.

Besides the type-tests, which were performed in accordance with the standards, several other tests were carried out. These included:

- Tests to determine what happens in the high-frequency range during transient faults in the traction power system.
- Impulse current tests to verify that no mechanical damage is caused to the components in the event of all the protection stages failing.
- Further impulse current tests to verify that the characteristic data of the semiconductor devices do not change even after as many as 100 instances of protection firing.
- An endurance test lasting longer than 100 h under the following conditions: 150 percent rated current, 120 percent rated voltage, 150 percent nominal frequency and zero redundancy [4].

Transformers on the 16 2/3-Hz side

The summation transformer on the traction power side consists of six two-phase units with yoke. Since the two phases are decoupled magnetically by the yoke, they act as individual transformers. The secondary windings of the two phases receive power from adjacently modulated GTO thyristor bridges. Although their fundamental components are in phase, the harmonics are phase-shifted due to the displaced pulse pattern, resulting in a magnetic flux in the yoke equal to approximately 10 percent of the main flux in the wound yoke during steady-state operation. Despite this, the return limb's cross-section has the same dimensions as the main limb to allow temporary (eg, during power system faults), virtually independent switching of the two GTO thyristor bridges without any risk of the transformer becoming saturated.



Schematic diagram of one unit of the summation transformer
R, T Phases Φ Magnetic flux

10

A conventional three-phase AC transformer core made of grain-oriented magnetic sheet steel and with windings on just the outer yokes was therefore used for the two-phase unit. Each yoke carries one primary (16 2/3-Hz side) and one secondary winding in a concentric arrangement. All the primary windings are insulated for the full test voltage. Two two-phase units share a common tank.

Special attention was paid to the open-circuit leakage impedance of the individual phase systems. The spread of these impedances had to be limited as much as possible as it determines how the traction power system voltage is divided between the transformers (and therefore among the GTO thyristor bridges) when the thyristor valves are non-conducting. A very uneven distribution could lead to the amplitude of the alternating voltage in the bridges with the largest share of the voltage being higher than the DC link voltage. This would cause overloading of the DC link via the diodes in the H-bridges.

Another recognized problem involves the DC voltage components that appear in the output voltage of the thyristor bridges when the timing of the switching is not optimal. Even a relatively small proportion of these components can lead to signs of transformer saturation or load the bridges with magnetizing current, and even make operation impossible. The problem grows with the size of the installation and is further intensified by the series connection of the GTO thyristors. In the Bremen link, a constant error of just 1 µs per phase would lead to a DC voltage component of 33 mV, causing a magnetic bias of approximately 1.4 T. By comparison, the operational induction with a maximum output voltage is 1.55 T. To make sure that any DC voltage component that might occur is limited, an innovative system was developed which promptly detects such components and lowers their value to an acceptable level.

Design of the DC link

The main purpose of the DC voltage link is to de-couple the three-phase AC power system from the traction power supply. It has to ensure that the GTO thyristor converter is supplied with a constant direct voltage and at the same time prevent harmonics on the 16 2/3-Hz side from reaching the 50-Hz circuit. Also important, for protection reasons, is the minimization of the distributed capacitance C_D, which is hard-wired to the converter.

One result of the traction power supply being a single-phase system is that power oscillation with double the traction power frequency occurs. A tuned 33-Hz filter therefore has to be incorporated in the DC link. The link rating is defined by the ripple in the direct voltage that can be tolerated under the assumption of maximum frequency deviation in the traction power supply and worst-case filter detuning.

The traction power converter must also be capable of trouble-free operation in cases of relatively strong distortion of the traction power supply voltage. The 3rd and 5th harmonics, in particular, can reach high values. To achieve the necessary insensitivity to these harmonics, a damped highpass filter is integrated in the DC link in addition to the 33-Hz filter.

50-Hz-side converter and compensation equipment

Power is fed into the system from the Stadtwerke Bremen grid via a line-commutated 12-pulse thyristor converter, this being more economical than a self-commutated converter.

The high level of grid cabling results in excessive reactive power, which has to be compensated for during low-load periods by reactors. The reactance coils can also be connected into circuit whenever the frequency link is not in operation. Filters and reactors are switched mechanically to obtain the required reactive-power range in the most economical way. The filter design ensures adherence to the prescribed limits for voltage distortion (< 1.5 percent).

The thyristor converter configuration for the nominal data of the DC link has four thyristors connected in series and three branches connected in parallel. Like the GTO thyristor converter, this installation can continue to operate unrestricted if one thyristor per branch should fail. Failure of a second thyristor in the same branch results in controlled shut-down of the installation. This ensures that the healthy part of the branch is not endangered. The current distribution in the parallel branches is monitored. If one branch does not participate in the current conduction (e.g., due to a fault in the gate unit), the DC link current is limited accordingly.

Any surplus energy that is present in the traction power supply is fed into Stadtwerke Bremen's electricity grid via a second, antiparallel thyristor converter operating as an inverter. The converter's control system allows fast power reversal.

A high priority was given to the protection of the converter when it is being operated in inverter mode. This protection is provided by a common turn-off circuit comprising static devices for forced commutation (Image 1).

Unlike conventional HVDC installations with current-controlled converters on both sides, the circuit in the Bremen station does not allow control of the fault current in the DC link. Even when the inverter control is carefully designed, commutation failures (eg, during transients in the three-phase AC network) can never be entirely excluded.

Inverter commutation failures are detected by two independent measuring circuits, both sides of the converter being blocked as soon as a failure is identified. A negative reverse current is applied to the defective inverter valve, which is turned off as a result. Approximately one power system period is required for the entire turn-off process. After a short time of about 1 s, which is needed to restore the turn-off function to its original status, transmission starts up again automatically. The functional availability of the common turn-off circuit is monitored continuously.

Valve base electronics

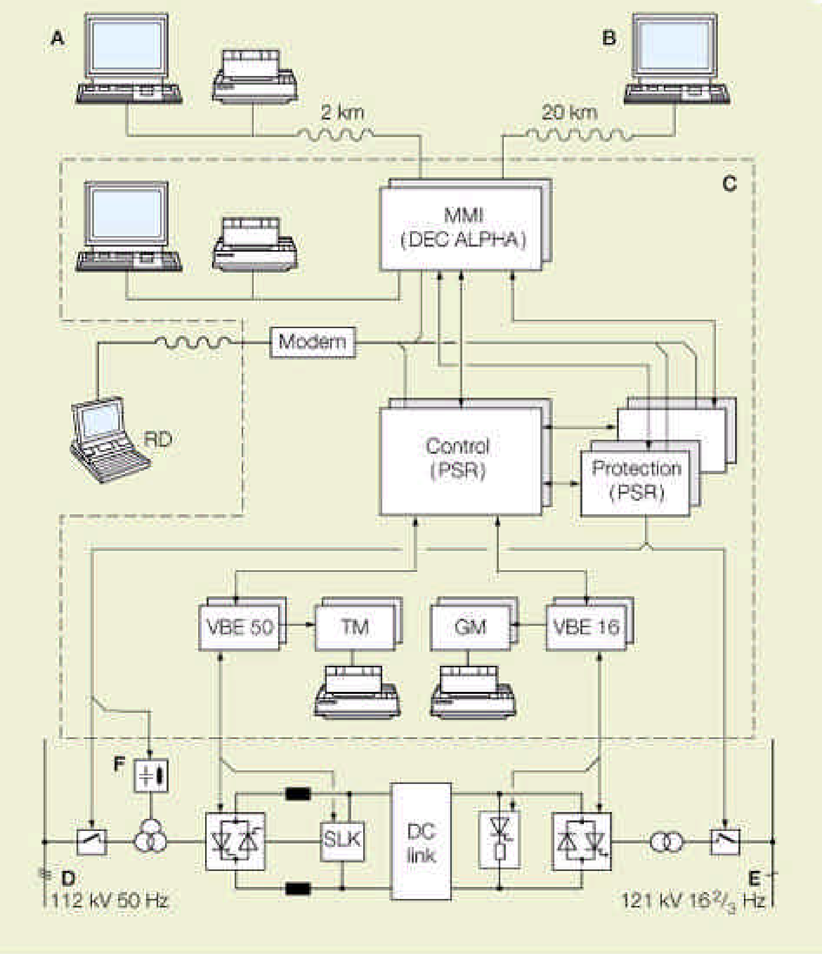
Every converter is assigned an electronics package which generates the pulse telegrams from the firing commands given by the controller and transmits them over fiber optic wires to the individual semiconductor locations, where they are converted by indirect light pulse firing (via the thyristor electronics) into electrical firing pulses. The valve base electronics also monitors, with the help of return signals from the thyristor electronics, the redundancy of the series-connected semiconductor devices, producing an alarm or trip signal whenever the level of redundancy is reduced. Semiconductor devices which have failed are identified and can be replaced the next time routine maintenance is carried out.

The overvoltage limiter in the DC link of the GTO thyristor converter is also controlled by the valve base electronics. The same electronics is further responsible for high-speed detection (in redundant mode) of shoot-throughs and for tripping the protection firing of the GTO thyristor converter.

In the case of the thyristor converter, this electronics package also controls the common turn-off circuit. Return signals enable the controller to quickly identify commutation failures when the converter is operating in inverter mode.

Control and monitoring system

The installation is controlled and monitored by a S.P.I.D.E.R. MicroSCADA system run on an ALPHA workstation. This system, which also records status changes and disturbances, can be operated from a local control room, from the nearby Mittelbüren power plant, or from Stadtwerke Bremen's load dispatching center approximately 20 km away. The operating authority can be selected as required. The installation itself is unattended.



Hierarchical structure of the supervisory control system

A	*Power plant belonging to Stadtwerke Bremen*
B	*Load dispatching center of Stadtwerke Bremen*
C	*Frequency link control system*
D	*Substation belonging to Stadtwerke Bremen*
E	*Substation belonging to German Railway*
F	*Filter*
MMI	*Man-machine interface with DEC workstation based on ALPHA processor*
RD	*Remote diagnostics*
PSR	*Programmable high-speed controller (control and protection)*
VBE	*Valve base electronics (50-Hz and 16²/₃-Hz sides)*
TM, GM	*Failure monitoring, recording of thyristor and GTO thyristor converter statuses*
SLK	*Common turn-off circuit*
DC	*DC voltage link*

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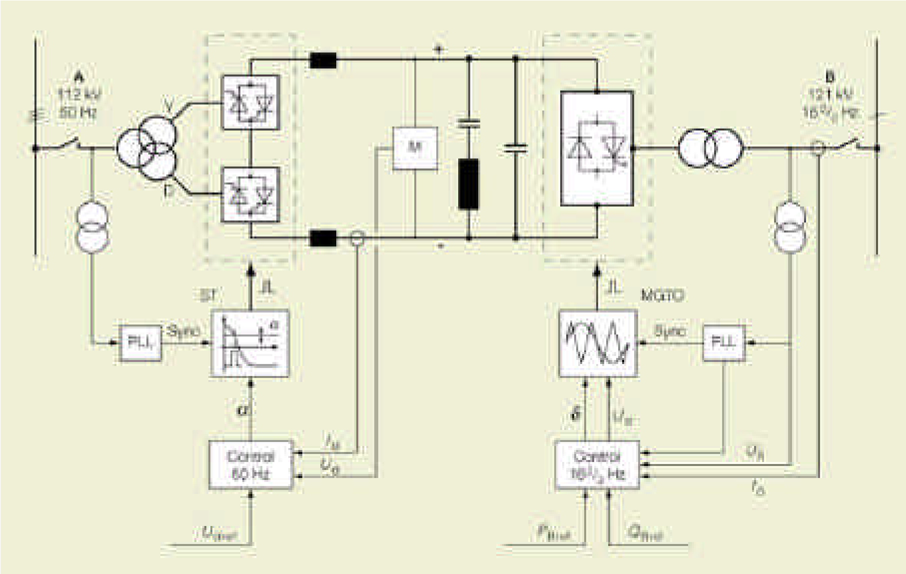
Control and protection of the frequency link are based on ABB's programmable high-speed control system, PSR2 [5]. PSR2 was developed especially for complex power electronics systems, making it the ideal solution for the Bremen link. It combines a high processing speed with an extremely user-friendly graphic programming language (FUPLA 2). The combination of these two features ensures a high level of operational flexibility. Both the graphic programming interface of the system and S.P.I.D.E.R. MicroSCADA can be accessed over a telephone line for diagnostics purposes.

The control system is responsible for sequential start-up and shut-down of the installation as well as for ensuring stable operation.



Basic circuit diagram of the control concept adopted for the 100-MW static frequency link

A Three-phase AC power system
B Traction power supply
α Firing angle
M Measurements
ST Gate control unit of thyristor converter
MGTO Modulator of GTO thyristor converter
PLL Phase-locked loop
U_d, I_d Voltage and current in DC link
U_{st}, δ Control voltage and phase angle (output variables of control system)
U_B, I_B Traction power supply voltage and current
$U_{d\,ref}$, $P_{B\,ref}$, $Q_{B\,ref}$ Voltage and power reference values

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The main control task on the 50-Hz side is to keep the DC link voltage constant. To optimize the dynamic response and for protection reasons, a configuration with cascade controller, superimposed voltage regulator and subordinate DC current controller was chosen. Control on this side also includes the switching of the thyristor converters when the power is reversed. As with HVDC converter stations, the triggering equipment is synchronized by means of a phase-locked loop (PLL).

The current (*I*B) and voltage (*U*B) measured on the 16 2/3-Hz traction power side are used to calculate the active and reactive power. Active power is controlled according to a load-frequency characteristic, and reactive power on the basis of a voltage/reactive power curve. The pulse-width modulator is synchronized by means of a phase-locked loop, which is also used to measure the traction power system frequency.

The protection is designed with two channels for full redundancy. If a system fails as the result of a hardware fault, its tripping channels are automatically blocked. The installation protection as a whole is not affected by this. The operating staff are informed of the fault and of the defective equipment involved via the man-machine interface. Replacement of the hardware, parameterization and testing of the protection functions can be carried out for every protection system with the installation still in operation.

Design and verification

The Bremen frequency link was designed and verified with the help of three tools:

- Analytical software
- Simulation software
- ABB simulator (with 50-W scale, for the physical simulation)

Cubicles containing the control system for the Bremen static frequency link

1 Processing and interface units of PSR controller
2 Modulator of converter and I/O units on 16 2/3-Hz side
3 Gate control unit of thyristor converter and interface for fiber-optic cables
4 Various monitoring and supply units
5 Local control panel

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The first two tools offer high accuracy and reproducibility over a wide frequency range, while the special strength of the simulator is its real-time capability. This allows the entire system to be safely tested using real-world control and monitoring equipment.

For example, it was possible to develop the main functions of the control system on the physical simulator using the

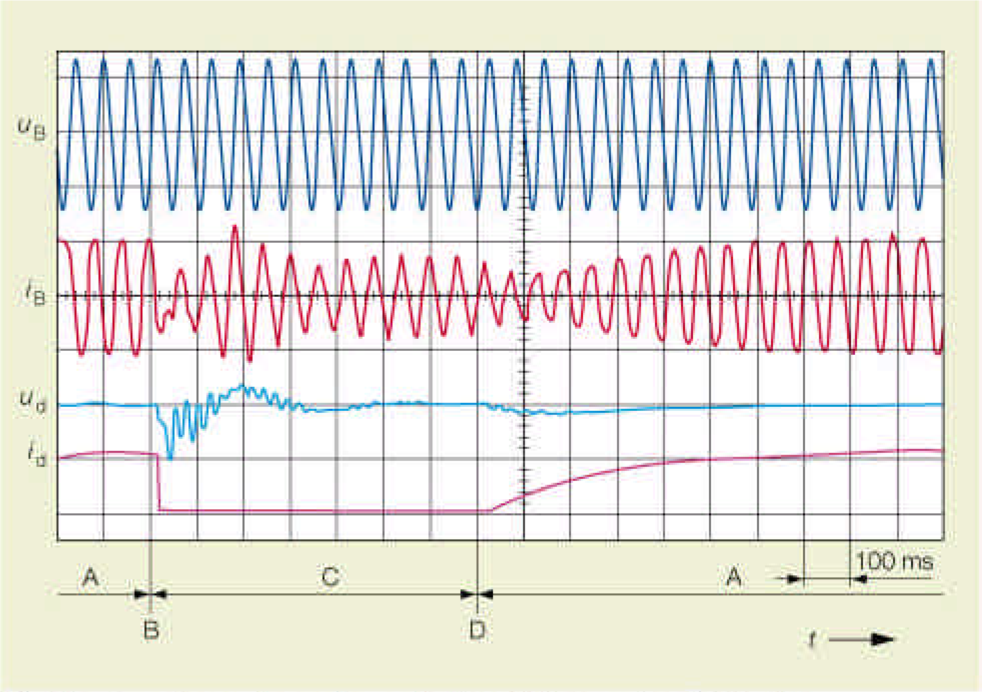
DC link values of 200 V and 250 mA. Before being delivered, the control system cubicles were tied into the simulator configuration and tested in collaboration with Stadtwerke Bremen under very realistic normal and fault conditions.

Commissioning

During commissioning, high priority was given to step-by-step verification of the correct electrical, thermal and mechanical design of all parts of the installation. After all the standard pre-commissioning tests had been carried out (voltage tests, tests on the control system and protection, etc), the subsystems were tested in the following order:

- No-load test, 50-Hz infeed
  The filter and compensation equipment, converter transformer, thyristor converter and DC link had voltage applied to them for the first time. Converter control system components (eg, the triggering equipment) were tested by means of a high-ohm converter load.
- Short-circuit test, 50-Hz infeed
  A continuous test at the maximum direct current of 10.5 kA was carried out to verify the correct thermal design of all the subsystems, and particularly the 50-Hz cooling plant. Also tested was the control, including the supervisory control system of the thyristor converter.
- No-load test, GTO thyristor converter
  The voltage formed by the GTO thyristor converter voltage was tested initially with a reduced DC link voltage and with an open circuit-breaker on the 16 2/3-Hz side.
- Protection-related tests
  Vital protection functions, such as protection firing of the GTO thyristor converter, overvoltage limitation in the DC link and operation of the common turn-off circuit in cases of inverter commutation failure, were tested under real-world conditions.
- Short-circuit testing, GTO thyristor converter
  A continuous test was carried out (16 2/3-Hz side short-circuited and a maximum load current corresponding to 100 MVA) to verify the correct thermal design of the converter, 16 2/3-Hz transformer and cooling plant.
- System tests, 16 2/3-Hz side
  These tests included testing and optimization of the control system under real-world operating conditions. In addition, all the guarantee values (power output, efficiency, mains pollution, etc) were verified.

The oscillogram in Image 14 shows, as an example, the DC link voltage, DC link current and voltage, and current at the point of connection of the traction power supply during switching from normal transmission to phase shift mode. This sequence is switched on automatically whenever there is a disturbance in the three-phase AC system. The reversal sequence (right-hand side of the oscillogram) is also automatic, being carried out as soon as the AC network conditions have been restored to normal.



Oscillogram of an auto-reclosure lasting 700 ms on the 50-Hz side

A	*Power transmitted to traction power supply: 121 kV, 30 MW, 20 MVAr underexcited*
B	*Tripping of thyristor converter, automatic switchover to phase-shift mode*
C	*50-Hz side disconnected: phase-shift mode with 20 MVAr underexcited*
D	*Automatic reclosure of 50-Hz side, automatic active power start-up*
u_B	*Traction power supply voltage*
i_B	*Traction power supply current*
u_d	*DC link voltage 10 kV, 1 scale div = 1.3 kV*
i_d	*DC link current*

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Following successful trial operation of the static frequency link, the installation was handed over to Stadtwerke Bremen for commercial service.

References

[1] *O. Gaupp, G. Linhofer, G. Lochner, P. Zanini*: Powerful static frequency converters for transalpine rail routes. ABB Review 5/95, 4-10.
[2] *D. Lönard, J. Northe, D. Wensky*: Statische Bahnstromrichter - Systemübersicht ausgeführter Anlagen. Elektrische Bahnen 6/95, 179-190.
[3] *P. Mathis*: Statischer Umrichter Giubiasco der Schweizerischen Bundesbahnen. Elektrische Bahnen 6/95, 194-200.
[4] *P. Steimer, H. Grüning, J. Werninger, P. Dähler, G. Linhofer, R. Boeck*: Series connection of GTO thyristors for high-power static frequency converters. ABB Review 5/96, 14-20.
[5] *P. Steimer, P. Hartmann, C. Perrin, A. Rufer*: PSR - the world's fastest programmable controller with function block language. ABB Review 2/93, 21-28.