Power quality results in energy efficient aluminium smelter operation

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New aluminium smelters consume up to 2400MW of electrical energy making the energy efficiency aspect most important. Power quality, optimised power conversion systems and well engineered power plant interfaces are essential for highest energy efficiency. An early optimisation of the power system design will reduce the capital investment cost for the power plant and smelter substation as well as results in most energy efficient aluminium production.

Electrical energy accounts for 30 to 40 per cent of the aluminium production costs. This paper describes and intends to discuss the possible power quality improvement concepts and designs as well as energy cost reduction opportunities which a high power quality system can achieve. Power quality is assessed by the “harmonic currents” still remaining in the feeding power grid and the “power factor”. Well engineered systems can reduce the size of the power plant generation units or looking at a large 2 pot line smelter, at least one additional power generation unit is required if no power factor and harmonic current compensation system is installed. The investment cost for an additional power generation unit and the yearly operation cost are in no relation whatsoever to the investment cost for an optimised power quality system.

Introduction

THD, “Total Harmonic Distortion” is a measurable parameter which is used to evaluate power quality.
The smelter AC/DC conversion system “rectiformers” which converts the grid power (alternating current) to the DC power required by the pot rooms, create harmonic currents due the nature, of the technology.
These harmonic currents are created by the rectiformers when the DC current is transformed and looks like high frequency currents on top of the normal current.

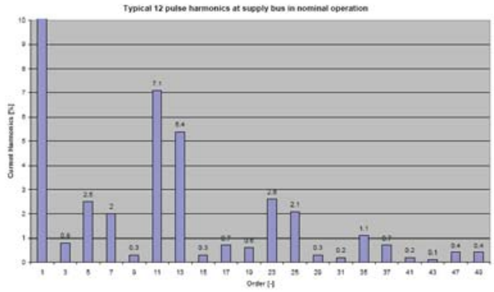

Fig 1 shows typical harmonic currents

These high frequency currents create electrical losses within all consumers if exposed to them. Low voltage motors for example will use up to 10% more electrical power if the power quality is very poor.
Looking at today’s new smelters with up to 2400MW, this means that nearly one additional power generation unit will be required just to compensate for poor power quality, if not compensated by appropriate systems.

PF, “Power Factor” is another measurable parameter to evaluate power quality. The power factor is the difference between the power, (active power) used to produce aluminium and the power generated by the power plant, (apparent power).
Some consumers within the smelter consume 80% active power and create 20% none active power (reactive power). Naturally the idea is to have a very high power factor in order to require minimal power generation.

Assuming a smelter requires 2400MW and would not have any PF compensation then the power plant would require one additional generation unit just to produce the apparent power. (100m$)

Smelters, therefore require systems to compensate harmonic current distortion and power factor displacement.

Generation of harmonic currents

The rectiformers unfortunately create harmonic currents with different frequencies. Within smelters these currents are reduced by the usage of 12 pulse rectifier units which are designed in such a way that the total rectiformer station will have a 60 pulse displacement creating minimal possible harmonic currents.
When however a single pot line with a power consumption of 600MW is operated in a low capacity grid their effect is having a serious impact on the power quality.

The next two figures show the impact of low and high capacity grids. When talking about capacity this means the strength of the power grid which in turn depends on the number of power plants connected together and the power line size and length to the smelter.

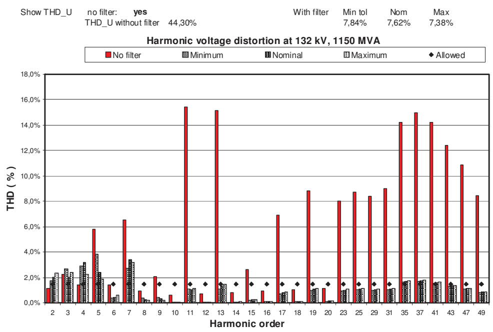

Fig 2 shows harmonic currents in a low capacity grid

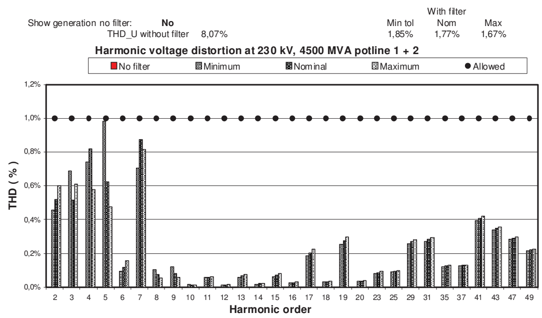

Fig. 3 shows harmonic currents in a high capacity grid.

Power factor of smelter electrical consumers

A typical motor consumes approximately 80% of active power and 20% none active power. (reactive power)
If a new two pot line smelter would only consist of a motor and no compensation installed, then five 240MW generation units producing the active power and a minimal of one 240MVA unit producing none active power would be required.
The main power consumer (rectiformers) of the smelter luckily does not have such a low power factor as typical motors but they still require a large compensation system.
Per large pot line at least 200-300MVA should be compensated.

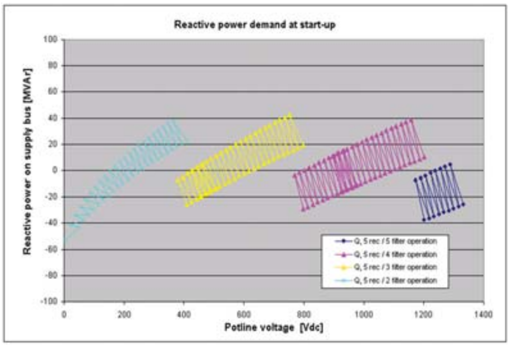

Fig. 4 power factor of smelter

Harmonic current and power factor compensation system

As it would not be practical to have one additional generator unit producing the extra electrical power required, due to none compensated of the harmonic currents, and one generation unit for the power factor compensation. The obvious solution is to combine the two compensation systems into one system.
Typically such a system consists of reactors and capacitors, which are also used to compensate the power factor and resistors to damp the tuned circuits to prevent resonances.
To compensate most of the harmonic currents these systems are split up into 2 to 5 sub systems tuned to compensate different harmonic currents.
The different tuning depends on the design of the rectiformer substation and the feeding grid.

Typical subsystems which are called filter branches are tuned to 3, 5, 7, and 11 times the normal frequency which is 50 or 60 hertz.

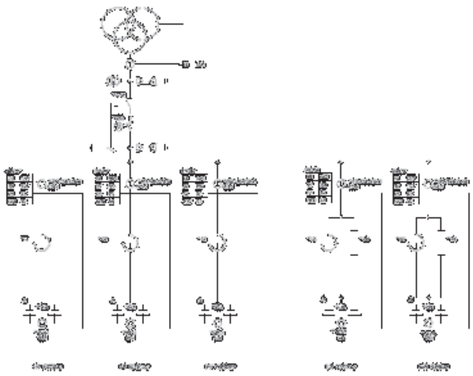

Fig. 5 shows a typical single line of a compensation system

Compensation system design

Two different compensation system concepts are commonly used and need to be evaluated during the early design stage of the power conversion station. Considering the turnkey cost of the two concepts they both seem to work out cost neutral.

Compensation at the medium voltage level 20-36kV

The medium voltage solution compensation systems are connected to the regulation transformer tertiary winding. Latest designs are fitted with a MV circuit breaker to allow step by step compensation. With this solution each rectiformer has a compensation system that is capable of meeting the power quality limits, even if only four out of five units are in operation. With this design, a high power factor is also possible during the initial smelter start up and harmonic currents do not reach the high voltage level grid. One additional advantage is that they can be designed and installed without in-depth system studies of the feeding grid. This compensation system solution will not, or only marginally be impacted by the power quality of the feeding grid.

Fig. 6 medium voltage compensation

Compensation at high voltage level 110-240kV

The high voltage compensation systems are connected to the utility power grid via the high voltage switchgear. These compensation systems require a more in dept system study which analyses their impact to the feeding grid, in both directions, as the system will also be loaded with possible existing harmonic currents from the utility grid.
They may be of a simpler design and may require a smaller footprint but their feeding switchgear needs to be rated to withstand high voltage surges during switching operation. Their design needs to be based on the power contract limitation so that they can also meet the power factor requirements during initial start up. Their performance is more suitable for higher grid capacities as it is very costly to install multi branch filters at higher voltages.

Fig. 7 HV compensation system (220kV)

Design consideration for compensation system at the high voltage level

As these compensation systems operate at the utility level, they have a direct impact on the grid and vice versa. Energising and de-energising of such compensation systems create a power quality disturbance on their own. These systems act similar to when a power line is energised or de-energised and create very high voltages which can destroy components or circuit breakers. When HV compensation systems are being considered, then the feeding / controlling switchgear needs to be capable of operating them. Fig. 11 and 12 shows the energising and de-energising of a 220kV compensation system with minimal power quality distortion due to the use of ABB's DCB/HPL 245kV circuit breaker with a power frequency withstand voltage of 460kV and the use of controlled switching device ABB Switchsync™ F236

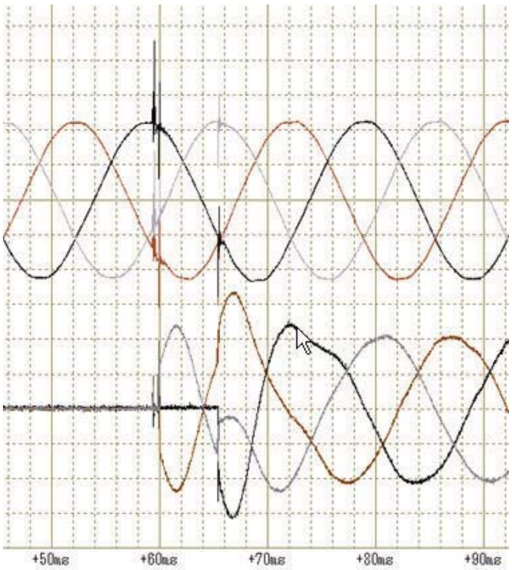

Fig. 8 voltage (top) and phase currents during energising of a 220kV compensation system

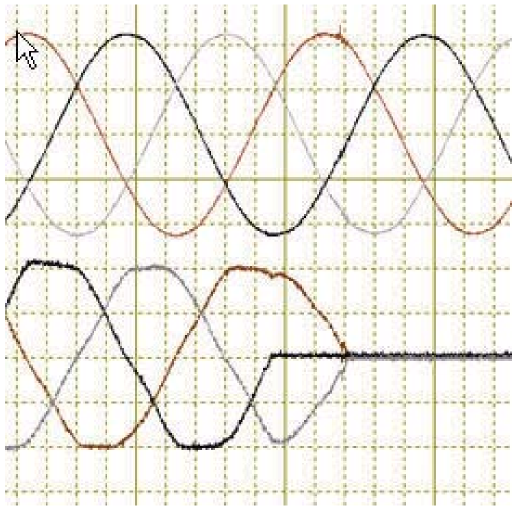
Fig. 9 De-energising of a 220kV compensation system

Voltage variation effect

When evaluating the two possible compensation system concepts, the impact of the voltage variation at the high voltage as well as the smelter medium voltage needs to be considered. The tertiary filters (MV) have a lower and similar effect on the primary voltage rise as the tap changers within the regulation transformers are normally installed on the secondary winding for simplicity reasons. As, however, there is impedance between the tertiary winding feeding the compensation banks, the voltage variation impact is not linear to compensation systems installed direct on the primary grid system.
It can be said that compensation systems connected direct to the feeding grid have a larger impact on the voltage variation. Fig. 10 shows the impact on the grid voltage when connecting branches of 55Mvar direct to the feeding grid. Also shown is the impact to the medium voltage during the connection of the branches.
Fig. 10 also shows the Mvar and grid voltage variation when a HV filter is connected to the feeding grid. In this case the feeding grid was 220kV.

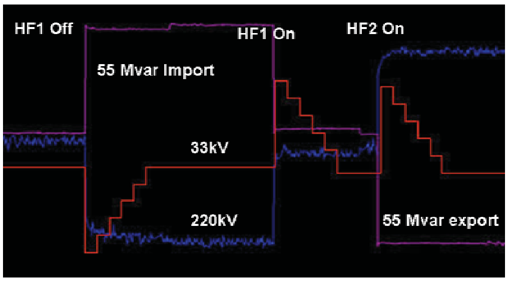

Fig. 10 Primary voltage (blue) and plant voltage 33kV (red) variation when disconnecting or connecting a HV compensation systems.

Installed compensation system per smelter pot line

The listing below shows the compensation systems installed during the last 15 years within Greenfield and Brownfield projects (per pot line) but not retrofit plants. The list intends to illustrate the comparison in numbers but should not be taken as absolute replica of all global projects.

No compensation	4
MV compensation	21
HV compensation	5

Conclusion on impact of power quality for energy efficiency

Harmonic currents create electrical losses and if not compensated create costs for additional electrical power. These additional costs for electrical power pay off the investment cost of the compensation system in a very short time. Compensation systems connected to the power grid require detailed studies and a high number of parameters need to be known or made available by the power utility. When installed and operated on the grid the power utility will normally ask to control them as they are connected to their grid. Their drawback is that should the feeding grid get polluted by other consumers during the years to come, they will be loaded with this power quality pollution. Compensation systems connected to tertiary windings of the regulation transformer are decoupled from the grids and are less affected by power quality pollution coming from the grid or which already exists in the grid.
Both compensation concepts eliminate the need for additional power generation units which cost many times the initial cost of a compensation system, or additional cost for electrical power due to electrical losses created by poor power quality.

Power plant Aluminium smelter interface for increased power plant efficiency

When looking at the smelter power plant interface, many issues come up and need to be looked at such as power demand and fluctuations, power quality, potline start-up and trip. Other critical issues are the power plant efficiency during normal operation or what happens if one of the generation unit trips in island operation mode. Here ABB's blackout protection control plays a critical role for the smelters operation stability since a smelter requires stable power supply and load shedding with diode rectifier is only possible with a slow ramp.

Different requirements from power plant and smelter

The points below show power plant interface issues which are to be addressed to the power plant and need to be made available to the smelter substation.

- SCC (Short Circuit Capacity) for all power plant operation conditions;
- Max. allowed THD (Total Harmonic Distortion) by power plant or grid
- Max. power swings and rate possible in MW
- Max. reactive – active power swing
- Max. allowed harmonic current loading of cables
- Voltage dips to be expected and allowed
- Power factor required
- Grid codes to be complied with
- Max. 2nd Harmonic current loading during transformer energizing
- Max. power (delta u phase) unbalance

- Explain process of generator synchronising and minimal block load
- Explain Grid and Island operation (start up SCC)
- High speed signal available for load decrease

Smelter information to the power-plant

The points below show what the smelter requirements are towards the power plant:

- Power swings, daily anode effects create a sharp 15MW power swing
- Potline may trip more than 5 times in the first year (600MW immediate drop)
- Potline initial start up power demand increases by 3.5MW/day
- Potline restart after trip, preferred 20MW per/min ramp up
- Power factor 0.82 during restart for short time
- Voltage dip to 70% on smelter bus when rectiformers are energised without synchronisation of the feeder breakers, if 5xSCC vs transformer rating
- The higher the SCC, the lower the efforts are required to meet power quality demands;
- If max. allowed THD is 2%, smelter tertiary filters are required if SCC is <10x smelter rating

Interface parameters to be considered

The points below show what the smelter power plant parameters to be considered in the overall system design.

- Is island operation required? If yes, a detailed study is required
- Diode rectiformers can not shed load fast, max 5MW/3sec
- Synchronised switching of transformers reduces power disturbances and voltage dips as well as mechanical stress on rectiformers and harmonic current filters
- Without synchronised switching, island mode of operating may not be possible
- GIS or AIS breakers need to be able to switch with +/- 1ms accuracy between phases
- IEEE 519 (power quality guide) can only be met with tertiary filters on the rectiformers in island mode
- Harmonic current filters on the HV side may be critical and need to be studied as they get loaded with harmonic currents which may be in the grid
- Power plant control systems need to be able to generate and send a high speed load drop signal

Load rejection of the smelter is one of the most critical design issues

The graph below shows what the smelter voltage and current load curves which will be seen by the power plant and have to be considered in the overall system design.

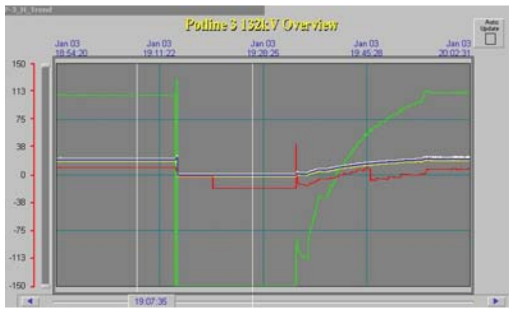

Fig. 11 load rejection after potline trip

Load Shedding capabilities of a Smelter substation

The diagram below shows the load that the smelter substation can shed with and without ABB's blackout protection.

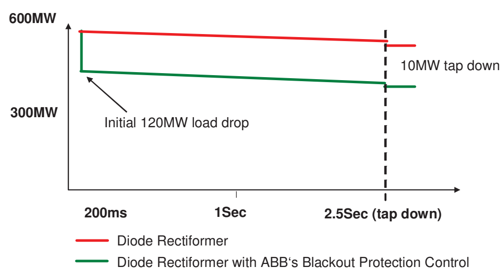

Fig. 12 load shedding with and without BPC

Power quality vs. grid power strength

The diagram below shows the smelter substation power quality vs. strength of the feeding grid. This is, in particular, to be considered should the grid be disconnected and island operation will continue. Some of the smelter power consumers such as UPS, inverters and AC drives are very susceptible to high harmonic current distortions.

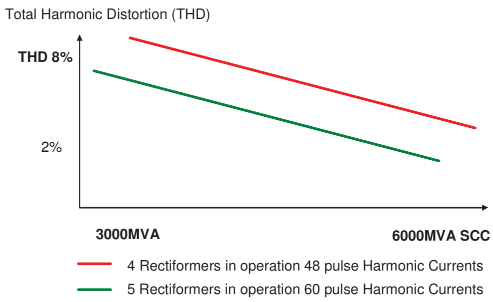

Fig. 13 THD vs grid SCC

Power factor during start-up of the smelter

The following graph shows the power factor of a smelter during start-up. This power factor applies for the initial start up as well as after a potline restart. The design of the rectifier needs to be selected based on the power supply agreement as well as power quality during such operational points.

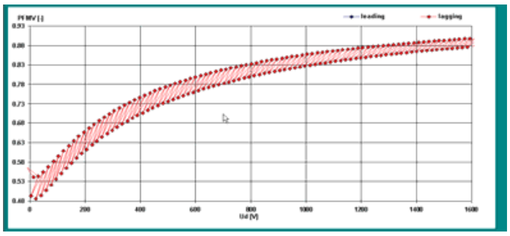

Fig. 14 PF during potline restart

Voltage drops during energising of rectiformers

Within captive power plant smelter systems there may be some operation scenarios where the power plant will feed the smelter in island operation. During such operation, the available short circuit capacity may be considerably reduced. As rectiformers become ever larger for these large smelters, their network impact during energising is very large. The diagram below shows the impact with and without controlled energising. The voltage dips may result in tripping of already energised consumers. Such voltage drops may be very critical for captive power plant smelter projects. This is because the voltage on the MV may drop by up to 25% of the nominal rating, which is far beyond the normal allowed value of 10%.

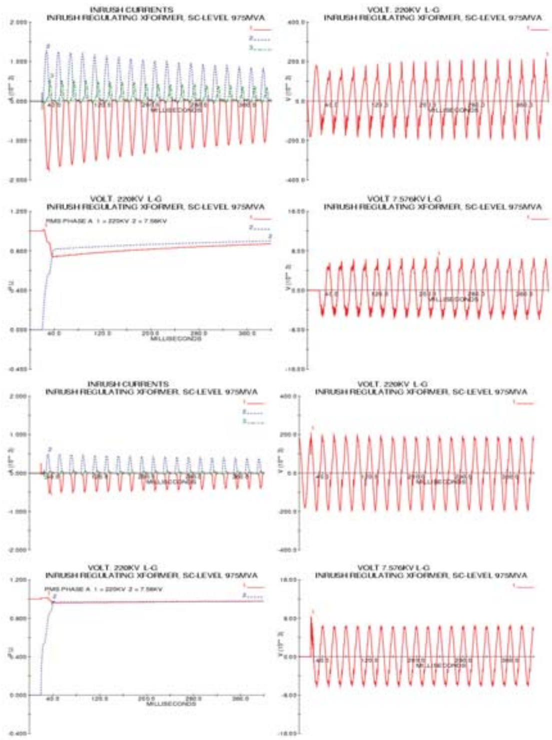

Fig 15 voltage dips on the MV power energising large transformers, with and without controlled switching.

Case Studies
ALBA, Kingdom of Bahrain

Aluminium Bahrain (ALBA) had some blackouts during the recent years of operation. Due to the mix in generation and 5 potlines, the de-energising of a potline is not so critical. ALBA’s operation modes, however, are such that the smelter auxiliary consumers are operated on different grids to the smelter pot lines, making the system very immune to voltage dips or load drops.

DUBAL, Dubai, UAE

Dubai Aluminium (DUBAL) has a very large numbers of pot lines, some of them with less that 100MW as well as a good mix of generation. The grid can easily compensate should one pot line trip. .. The large number of potlines as well as their low rating also has an easier effect on the power quality level as the harmonic currents are compensated with the multi-pulse operation. Start-up power demand and load rejection are of no concern. Auxiliaries are fed from a different grid supply

Nordural, Iceland

The Icelandic grid is becoming increasingly stronger; however, most of generation originates from low inertia geothermal steam turbines and with non-industrial power demand fluctuating from day to night by more than half. Aluminium smelters create an ideal load. The very large daily change of grid stability asks for a very flexible smelter substation design to allow for high speed load shedding and highest power quality performance. Due to this requirement, Nordural selected to use tertiary filter on the regulations transformers as well as thyristor rectiformers for high speed load shedding.

Highest power quality was achieved with the installation of controlled switching of the rectiformers as well as of the tertiary filters.

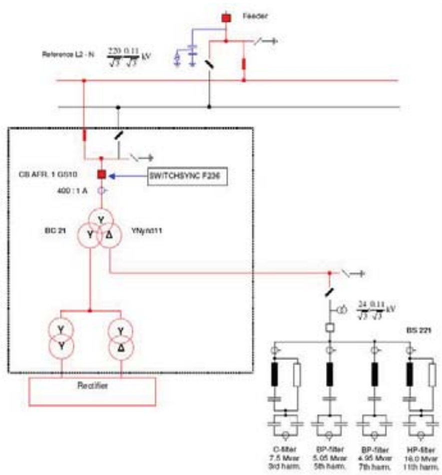

Fig. 16 Single line of a rectiformer unit with tertiary winding compensation

Fjardaal, Iceland

This single 500MW potline smelter will be fed from a captive hydro power plant. A weak 132kV grid inter-connection is possible at the power plant substation. The distance between the power plant and the smelter is approx 60km. The auxiliary power for the smelter will be taken from the same power lines feeding the smelter rectiformers. Should the potline trip, the power plant will need to be idled as the Icelandic grid will not be able to take the power.
The available short circuit capacity has to be considered low to very low during initial start up and normal operation.

Sohar, Sultanate of Oman

This new smelter design is for up to three 550MW potlines and is fed from a captive combined cycle power plant. A 220kV grid inter-connection is possible at the power plant substation. The distance between the power plant and the smelter is approx 12km. The auxiliary power for the smelter will be taken from the same power lines feeding the smelter rectiformers. Should the potline trip, the power plant will need to be idled as the Omani grid will not be able to take the power.
The available short circuit capacity has to be considered low to very low during initial start up and normal operation.

Summary

- With an available short circuit of 2500 MVA from a power plant and a 600 MW smelter load, the ratio of 2500/600 = 4 represents a very weak system. In such a case, it is estimated that if one gas turbine were to trip at the power plant this will trip the smelter. This is a very important item to consider when specifying the power plant. Diode rectifier systems cannot shed load, island operated GT power plants may trip on under-frequency within less than 2 seconds.
  To avoid a power plant trip a "dummy" load may be required. The dummy load will allow starting the smelter and protecting the power plant from complete disconnection in case of a pot line trip. To protect the smelter from tripping after a GT trip, there are two options: The power plant is designed such that the smelter load ramp and trip can be followed (ABB's BPC) or the smelter has thyristor rectifiers which allow immediate load shedding.
- If a THD of 2% or power factor correction to 0.98 are required, and the power contract is such that always a high power factor is required, then the harmonic current filters connected to the regulating transformer tertiary is the most economical method. This method is also required if the power system is weak. Synchronised switching should be used on the filter banks to reduce inrush current stress and over-voltages. Nordural's (Iceland) new conversion station is the most advanced in this respect with:
  - Full range regulation transformer with tertiary filters allowing for always optimal power factor.
  - Thyristor rectifiers to follow the grid power capabilities.
  - Synchronised switching of transformers and filters for minimal network distortion, in a very weak grid, and minimal stress on filters, switchgear and transformers.

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