Economical and stable grid operation

Shunt and series reactors for medium- and high-voltage grids
Reactors enhance grid stability and economic efficiency

A secure power supply system requires a well-built supply grid. State-of-the-art technology, high quality, and reliability are fundamental prerequisites. Reactors offer grid operators benefits at various levels for achieving this goal:

• Technical: Better voltage control, lower reactive power load through optimized reactive power compensation, compliance with contractual requirements (shunt reactors), short-circuit current limitation, and impedance adjustment of line sections (series reactors).

• Economical: Most cost-efficient solution for reactive power compensation and short-circuit current limitation, lower reactive power demand, lower losses, higher grid capacity, and balanced load flows and line loads.

• Entrepreneurial: Flexibility and independence from other connected grid operators.

Every one of our products is an individual, custom-tailored fabrication that always meets all product requirements governing voltage, rating, mode of operation, noise and losses, connection technology, and cooling type as well as transport and installation.

Reactors can be used for a wide range of applications:

Series reactors are deployed for short-circuit current limitation and load flow changes.

Shunt reactors provide voltage control and reactive power compensation, and can also be designed as variable shunt reactors with tap changers. They serve to:

• compensate for capacitive reactive power of transmission lines – particularly on grids operating at low- or no-load condition
• reduce network frequency overvoltage in case of load variation, shedding, or network operating at no load
• improve the stability and economic efficiency of power transmission

Expertise combined with customer proximity

For over 100 years we’ve partnered with notable energy providers and grid operators. We have developed our own design tools for reactors, implementing decades of experience. Our network of manufacturing plants spread around the world enables us to combine the advantages of a large company while still maintaining close proximity to our customers. In this way, we support our customers daily and help them on their way to success. No matter where you are, our experts are always on hand to offer support.
Systematic quality

For us, quality is a thorough, consistent philosophy pervading all our company locations, and one that is reflected in all our processes. Each of our manufacturing plants has been individually certified to ISO 9001 and holds other, local certifications which are available for viewing. The products manufactured meet all required standards, from IEC to ANSI and IEEE.

As leaders in quality on the transformer market, we define quality as an interplay of know-how, top-quality materials, and qualified personnel throughout our work procedures. Every manufacturing step is accompanied by quality controls; final inspection and acceptance testing are performed in our high-voltage test bays in the manufacturing facility. We can also conduct special tests upon request. We regularly invite customers to attend such tests and inspections so they can be sure of the quality of their product.

With quality assurance in mind, we go even one step further in the service we provide for our customers: We already advise them in advance on desired, necessary, and possible additional design features. At all our company locations, project management and order execution are entrusted to service-focused employees on whom our customers can rely. And Siemens’ after-sales service is, of course, also there for you once our reactors have been delivered.

Measurable reliability
The validity of our design rules are confirmed by the high number of units in service (over 800 just in the last ten years). We work to the highest possible precision and always use high-quality materials. Our qualification system for contracting suppliers worldwide is based on the same standards we hold ourselves to. The result is a failure rate that is nothing short of impressive – and we’ll gladly provide you with our latest mean time between failures (MTBF) figures.

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[Image of certificates]

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Grid troubleshooter

Possible application areas
Reactors are real all-rounders. In conventional electricity transmission grids, they are used for voltage control, reactive power compensation, load flow changes, and for short-circuit current limitation.

In today’s new energy landscape that features growing numbers of distributed power generation and higher fluctuation in power feed-in, the scopes of application particularly for variable reactors have expanded significantly; for example:
• grid-connection of large wind and solar power farms
• compensation of voltage fluctuations due to distributed power generation or the wide load fluctuations of private households
• connection of future large energy storage systems which, during charging and use, cause higher loads and, during storage time, lead to no-load conditions on lines
• accommodation of topological changes such as grid extensions or changeover from overhead power lines to cables

Furthermore, owing to the steadily growing range of voltage/power combinations, variable reactors offer the option of flexible spare units for multiple power classes simultaneously, minimizing the number of replacement units that have to be kept for a spares plan.

Fixed or variable?
Fixed reactors are the most suitable economical solution for constant loads and grid conditions. However, variable reactors are the best solution for accommodating wide load fluctuations on the line and changing grid conditions in the future (for example due to grid expansion or changes in the power generation structure), as well as for use as flexible spare units. A fixed reactor would overcompensate under rising load, which would lead to unwanted further drop in voltage and to additional inductive reactive power transport through the line. Variable reactors can be adapted to the given load situation and thereby always offer the precise compensation needed.
Typical application area for reactors: the power transmission grid

Hydro-energy storage can lead to increased load as well as no-load conditions on power lines

Difference between fixed and variable reactors: fixed reactor may overcompensate

Precise compensation by a variable reactor
Precision in every work step

Three-leg core of a reactor with air gaps

Close-up view of core with air gaps

Wooden bracing on the return circuit leg of a reactor core
Our oil-filled reactors are manufactured in two design types:

- without an iron core, with a magnetic-flux return circuit (series reactors up to 800 kV / 1,500 MVAR)
- with the iron core divided by air gaps (shunt reactors up to 800 kV / 300 MVAR)

Achieving low vibration, noise, and losses that remain constant over the entire operating period requires precision. We accomplish this not only by drawing on our decades of experience, but also by using exact and tested design analysis programs and the highest possible precision in every stage of the manufacturing process.

For windings, insulation, tank, monitoring devices, connection equipment, and the tap changer, Siemens uses proven technology known in transformer design and manufacturing.

The centerpiece of a reactor, however, is the core, which is very different to the cores used in power transformers.

Series reactors are generally designed and manufactured without an iron core (air core), and with only a magnetic-flux return circuit.

In our shunt reactors, Siemens uses an iron core divided by air gaps, achieving a compact design with low noise, vibration, and losses. Another benefit of the iron core with air gaps is a dampening effect (knee-point voltage) that limits voltage under extreme overcurrent conditions. The core is made from radially laminated iron packages, while ceramic spacers ensure precise compliance with the specific air gap requirements. The core is clamped together by tie rods made of steel and/or wooden limbs, and held in place together with the iron yoke and return circuit in a clamping frame. Siemens has two concepts to offer and adapts the design as needed: With inner clamping, the tie rods are inserted through holes in the core, which in particular at high voltages results in a compact design and, due to the optimized force transmission, in minimum noise.

With outer clamping, the tie rods are located outside the core and winding which, at low voltages or in single-phase reactors, reduces the unit weight (in particular of core and winding). Siemens’ unique spring technology between the tie rod and crossbeam ensures constant core pressing.

In this way, Siemens’ design constantly maintains low vibration and noise levels over the entire service life of these units.

The design process for reactors also differs quite radically from that of transformers. Most notably the mechanical design, owing to its special core, can be much more complex and therefore demand particular attention to control certain physically determined characteristics. This is why it is so important to be able to rely on the manufacturer and its expertise, especially for these products. Siemens uses software and simulation tools developed in-house to ensure in subsequent testing that the guaranteed performance values are indeed met.

**Measurement is better than calculation**

Not every test bay designed for transformers can also perform the tests required for reactors. In the test bays at our Siemens locations that manufacture reactors, tests can be conducted under real operating conditions right up to the highest voltage levels and power ratings. This means, for example, that the manufacturing plants that produce the three-phase reactors can also test them under three-phase conditions. Guarantee values do not need to be extrapolated: with Siemens, you can rely on the real measured data.
Five production locations – one design concept

Siemens Transformers’ organization has a large manufacturing network at its disposal. Reactors are manufactured in five production facilities located on three continents. Every reactor is a customized product, tailored to meet the customer’s needs. Our manufacturing network, working to uniform, standardized internal guidelines governing the design and manufacturing of reactors, ensures that all our customers worldwide have access to the same extensive know-how and quality, irrespective of location. At the same time, our manufacturing plants adhere to all local standards and conditions of the countries to where our products are delivered.

This ensures that you as a customer enjoy the following benefits:

• prompt preparation of proposals and quotations
• optimized, thorough, and consistent project management
• highly reliable on-time delivery
• flexibility, security, and reliability thanks to backup manufacturing plants
• uniform documentation
• punctual delivery
Increased reliability thanks to series reactors

In 2014, Siemens delivered the largest series reactor in the world for use at the 400-kV level at 408 MVar-rated power and 2,770 MVar throughput power.

Series reactors are used to control current and increase impedance. As their name suggests, these reactors are arranged in series with the existing line and serve, for example, as:

- short-circuit current limitation reactors
- load flow change reactors
- arc-furnace reactors
- (motor) start-up reactors to limit starting current

The main application area is current limitation. The series reactor constitutes an impedance in the grid and thereby increases the resistance of the arrangement.

- With short-circuit current limitation reactors, the possible short-circuit current is limited in the event of a fault. The reactance of these reactors is designed to achieve effective short-circuit current limitation while the voltage drop across the reactor is still acceptable during normal operation. Because short-circuit current limitation reactors cause the voltage to drop and also impact the transient behavior within the grid, the site of installation and the reactor dimensions must be chosen carefully. Our colleagues at Siemens Transmission Solutions will gladly assist you in this regard and can perform the necessary network studies.

- Arc-furnace series reactors provide an additional reactance to stabilize the arc and increase efficiency.

- In motor start-up reactors, the starting current is limited where appropriate in combination with a speed controller.

- Grounding reactors are a special application where they serve to increase the impedance at the neutral point of transformers. In case of a fault, the reactor limits the fault current at the neutral point, ideally precisely compensating the capacitive grounding current and supporting restoration of the line.

- Another application area is for one-time impedance adjustment of a subsystem in order to change the load flows. For such one-time adjustment, a series reactor is usually the most economical solution. If load flow control needs to be permanently flexible, it is recommended that a phase-shift oscillator is used.

Siemens Transformers manufactures series reactors up to 800 kV and 1,500 MVar, usually as oil-filled units with an air core. Depending on customer needs and wishes, however, they can also be designed with an iron core (particularly neutral-point grounding reactors).
Increasing efficiency by reactive power compensation and voltage control

Contrary to series reactors, shunt reactors are arranged between line voltage and ground. Their place of installation is usually located at the start or end of a long overhead power line or cable connection, or in central substations. While overhead power lines are of comparably low capacitance and therefore only require compensation at high voltages and/or along very long power lines, cables have a significantly higher conductor-to-ground capacitance (by a factor of 20). Therefore, compensation should be provided already for lower voltages and shorter cable lengths.

Shunt reactors fulfill three main functions:

• They protect high-voltage equipment by reducing local overvoltages.
• They reduce unnecessary reactive power transport through compensation of capacitive reactive power (for example from high-voltage cables and overhead transmission lines, connected power producers, or industries), thereby reducing line losses and increasing the possible active power transport through the line.
• They compensate for the Ferranti effect.
• Under no-load/low-load conditions voltage increases steeply along line capacitance above voltage levels given by the grid code. Reactors adjust the voltage to the rated value.

The advantages of fixed shunt reactors from Siemens are obvious:

Fixed reactors are simple devices that can be easily switched into operation when needed. The compact design combined with low maintenance needs make reactors a perfect solution to increase efficiency. Our unique spring technology, paired with high-quality materials and precise design and manufacturing by our highly trained, expert personnel, guarantees a consistently high-performance product that has been delivering added value to our customers for decades.
High economic efficiency thanks to full flexibility

Variable reactors combine the proven design of shunt reactors with the reliability of the tap changers that have been successfully used in transformer fabrication for decades. Variable reactors display their full advantages especially for varying voltages and load fluctuations: With a large control range of 20 to 100%, variable reactors offer grid flexibility, enabling operators to achieve the highest grid efficiency.

Use of variable reactors is particularly recommended if fluctuations occur at the customer end (such as load differences between day and night) or at the power producer side. This is the case for an increasing number of grids, due to the increased use of renewable power sources. Depending on the actual demand, the reactive power can be adjusted to the actual grid. Interesting side effects of flexibility:

• switching in the variable shunt reactor with a low reactive power rating results in a smaller switching impulse
• if the variable shunt reactor operates at low power rating, the operator profits from lower losses and less noise emissions

Siemens places its trust in the reliable VACUTAP VRG series of tap changers from Maschinenfabrik Reinhausen (MR), which have a long proven history in transformers. These tap changers can execute up to 300,000 switching events maintenance-free. Variable shunt reactors from Siemens are thus not only designed for regular adjustment to changes in grid conditions (for example due to fluctuating load conditions), but are also low-maintenance units with minimal service demands.
Economic efficiency and sample calculations

Reactive power behavior over the course of one day

While procurement of fixed reactors in particular is driven by technical needs, these units also always increase efficiency.

Compared to power operations without reactors, there is less need for reactive power sourcing from a third party, which might not be free of charge. Reactive power transport can also be minimized, which reduces power losses and increases the active power capacity of the lines.

Procuring a variable shunt reactor can in many cases lower costs for operators even further. Various benefits lead to quick amortization of the higher procurement price:

- reactive power purchase is reduced even further
- reduced losses from transmission lines and connected equipment
- lower average losses of variable shunt reactor compared to fixed reactor
- possibility to respond flexibly to changing grid conditions

Sample calculation: fixed or variable reactor?

Particularly in cases where operators incur expenses for reactive power, procurement of a (variable) reactor is almost always economically worthwhile. The sample presents a case of combined feed-in from wind and solar power sources into the 380-kV grid via a 380/110-kV grid transformer and a 110-kV cable connection. The active power feed-in at the 380-kV grid transformer is shown in green. The reactive power demand is marked in dark red. A fixed reactor is designed for the maximum reactive power demand. With increasing power feed-in, the fixed reactor is overcompensating and additional capacitive reactive power has to be purchased from the grid (light red line). What is more, the capacitive reactive power transport over the 400-kV grid causes additional losses. A variable reactor, on the other hand, enables continuous adjustment of reactive power in such a way that no additional reactive power costs are incurred (orange line).
Sample calculation for fixed reactor

Calculating the cost-effectiveness of the case study described, the cost column includes the purchase price of the reactor as well as the unit’s power losses and operating costs. The savings gained by reducing the reactive power required and reducing losses in the connected grid transformer and high-voltage line are so high that procurement of the fixed reactor pays off within five months.

If reactive power has to be purchased, investment in a shunt reactor is definitely worthwhile.

<table>
<thead>
<tr>
<th>Components of economic value calculation</th>
<th>Amount</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment for a 110-kV/70-MVAr fixed reactor</td>
<td>€–1,100,000 (one-time)</td>
<td>• Investment includes foundation and connection equipment</td>
</tr>
<tr>
<td>Additional losses of reactor</td>
<td>€–5,830,000</td>
<td>• Reactor is continuously in operation with 135-kW losses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Power generation costs: €0.06 per kWh (average in Germany)</td>
</tr>
<tr>
<td>Operating costs</td>
<td>€–200 (per month)</td>
<td></td>
</tr>
<tr>
<td>Reduction of reactive power purchasing</td>
<td>€+225,800 (per month)</td>
<td>• Reduction of 941 MVArh per day at point of coupling (POC) – determined by grid simulation of a standard day and extrapolating the result to one month (4d/month corresponds to a load factor of renewable energy sources of approx. 13%)</td>
</tr>
<tr>
<td>Reduced losses in upstream TSO grid transformer and the 380-kV line</td>
<td>€+760 (per month)</td>
<td>• Reduction of losses in the grid transformer and the 380-kV line of –0.42 MWh per day, determined by simulation of a standard day and extrapolating the result to one month</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Power generation costs: €0.06 per kWh (average in Germany)</td>
</tr>
<tr>
<td>Total savings per month</td>
<td>€+221,000 (per month)</td>
<td>• Discount factor for calculating the discounted cash flow (DCF): 9% p.a.</td>
</tr>
</tbody>
</table>

Sample calculation for variable reactor

The purchase price for procuring a variable reactor compared to that of a fixed reactor is slightly higher. In operation, however, the variable reactor offers only benefits: The unit’s lower average losses as well as the lower demand for reactive power purchase and reduced losses in the adjacent transformer and HV grid quickly compensate for the higher price.

In the sample presented above, the operator would have recovered the additional spendings for a variable instead of a fixed reactor within three months.

In operation, the variable reactor offers only benefits. When line loading fluctuates, a variable reactor is the most economical solution.

<table>
<thead>
<tr>
<th>Components of economic value calculation</th>
<th>Amount</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional investment for a 110-kV/28–70-MVAr variable reactor</td>
<td>€–300,000 (one-time, additional to cost for fixed reactor)</td>
<td>• Additional investment for a 110-kV/28–70-MVAr variable reactor compared to a 110-kV/70-MVAr fixed reactor</td>
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<tr>
<td>Variable reactors reduce average losses compared to fixed reactors</td>
<td>€+1,260 (per month)</td>
<td>• Reduction of 0.7 MVArh per day at the POC compared to the fixed reactor – determined by grid simulation of a standard day and extrapolating the result to one month (30 days per month)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Power generation costs: €0.06 per kWh (average in Germany)</td>
</tr>
<tr>
<td>Reduction of reactive power purchasing (compared to fixed reactors)</td>
<td>€+92,400 (per month)</td>
<td>• Reduction of 385 MVArh per day at POC in comparison to the fixed reactor – determined by grid simulation of a standard day and extrapolating the result to one month (4d/month corresponds to a load factor of renewable energy sources of approx. 13%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Reactive power price: €0.06 per kVArh</td>
</tr>
<tr>
<td>Further reduced losses in upstream TSO grid transformer and the 380-kV line</td>
<td>€+950 (per month)</td>
<td>• Reduction of losses in the grid transformer and the 380-kV line by –0.53 MWh per day, determined by simulation of a standard day and extrapolating the result to one month</td>
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<tr>
<td></td>
<td></td>
<td>• Power generation costs: €0.06 per kWh (average in Germany)</td>
</tr>
<tr>
<td>Total savings per month</td>
<td>€+94,600 (per month)</td>
<td>• Discount factor for calculating the DCF: 9% p.a.</td>
</tr>
</tbody>
</table>
1. Variable reactors for Cyprus
Two variable, three-phase reactor units, each 132 kV/27–75 MVAr (in 18 taps), intended to adjust reactive power to the varying load cycles of the Cypriot grid. The noise level is extremely low, at 60 dB. With these units, the customer is preparing to accommodate further expansion into renewable energy sources, which involves an increase in volatility.

2. Low-loss shunt reactors for US
Delivery of 40 one-phase units (765/√3 kV, 100 MVAr) over a period of ten years, targeting voltage adjustment by compensating line capacities. The units are designed with 146 kW to provide particularly low-loss performance.

3. Series reactors for Singapore
Siemens supplied the first series reactors for the city-state’s grid. Three units, each with 500 MVA for the 230-kV level, have been delivered for short-circuit current limitation.

4. Full flexibility for the German grid (currently ongoing)
Up to five units, each with 400 kV/50–250 MVAr, are aiming to meet the high demand for compensation that arises due to power generation from renewable energy sources. Even more, the solution provides sufficient, sustainable flexibility for allowing further renewable expansion. The high regulation range is improving the customers black start capabilities in the event of a blackout, for instance after a wind farm failure.

5. Low vibration for India
Siemens Transformers has supplied eight reactor units to a customer on the Indian subcontinent, each delivering 50 MVAr/420 kV, and operating at extremely low vibration of 5 μm on average.

6. Reactors for a reliable grid in Argentina
To increase the stability and reliability of Argentina’s electricity transmission grid, Siemens Transformers supplied 44 reactors (28 8.33-MVAr units, 12 16.66-MVAr units, and four 26.66-MVAr units), which unite Argentina’s major power consumption centers into one single loop grid.