

Variable Shunt Reactors: Applications and System Aspects

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SUMMARY

The report discusses the applications, benefits and system aspects of Variable Shunt Reactor (VSR). The interest in VSRs is rapidly growing in many regions of the world and a large number of this type of reactors are today in operation [1]. Examples of different system aspects calling for dynamic compensation of reactive power resulting in the use of VSRs are discussed. In particular; the experiences from the Norwegian Transmission System (TSO) operator Statnett where VSRs are extensively used are described and discussed. In addition, the phenomenon of zero missing when energizing high voltage cable networks is discussed and how the associated risks can be mitigated in a cost efficient manner by the use of VSRs.

At present, the Norwegian TSO Statnett has 8 VSRs in operation, 7 units will be installed during 2013 and an additional 6 units is planned for 2018. Of the 8 VSRs in operation, 6 are of voltage class 420 kV, 90/120-200 Mvar and two of voltage class 300 kV, 80-150 Mvar. The main driver behind these investments is the need to lower and control the voltage in the 300 kV and 420 kV grids which are connected with 800-1000 MVA autotransformers without On Load Tap Changers.

From a system perspective, the introduction of VSRs has given a better voltage profile and better voltage regulation, but in combination with substantial investments in capacitive compensation. The control of the shunt reactors is today performed manually by the operators at three dispatch centres via the SCADA system. To ease the control, three main positions have been defined; low, mid and high. The regulation speed is determined by the tap changer and meets the demands from compensating relatively slow load variations, which normally is the case (seasonal, daily or hourly).

Zero-missing phenomenon is defined as an AC current not crossing zero value during several cycles. If a current does not cross zero value it may not be possible to open the circuit breaker without risk of damage and can leave the system unprotected and vulnerable to failures. This may occur when energizing an HVAC cable system compensated by shunt reactors. One way to mitigate this risk is to use one VSR instead of two fixed reactors that proves to be a cost- and space efficient solution. The VSR is at its lowest rating when the cable is energized and then it is regulated to the desired rating.

KEYWORDS

Variable Shunt Reactors, VSR, system applications, zero missing

1. INTRODUCTION

The networks that transmit and distribute electrical energy are continually facing new demands due to changes in the generation- and load structure. For example, in many regions power grids are undergoing gradual changes, e.g., adding generation, interconnecting local/regional grids, switching from overhead lines to high voltage cables for environmental reasons, and so forth. Such changes are usually made step-wise and are often followed by a changed need for reactive power compensation. Further, the growing use of renewable energy sources is bringing fundamental change to traditional generation structures and is placing new demands on the transmission network. The dynamic and time-varying effects associated with renewable sources play a more pronounced role in networks when the system is, as a whole, optimized for energy efficiency [2]. In general, these factors favor the function of dynamic reactive power compensation. The trend towards increased controllability in the networks (“smartgrids”) also calls for this type of functionality. Here the VSR becomes an alternative to fixed reactors which provides regulation capability and, thereby, system benefits in terms of power quality, optimized grid operation and the possibility of interacting with other regulating devices such as SVCs. A VSR can also be used as a flexible spare as it can fit into several positions in the grid.

2. VARIABLE SHUNT REACTORS

2.1. General

A shunt reactor is an absorber of reactive power and is the device most commonly used for reactive power compensation. Its main function in HV grids is to provide voltage stability. The shunt reactor can be directly connected to the power line or to a tertiary winding of a three-winding transformer. The shunt reactor could be permanently connected or switched via a circuit breaker. By tradition, shunt reactors have been made with a fixed rating. Recently, shunt reactors with variable rating under load (VSR) have been introduced and is fast growing in importance.

2.2. Design

The variable reactors described in this paper are all of gapped core concept which is the dominating reactor concept on the market. The gapped core limbs are built of cylindrical core segments as shown in Fig. 1a. Each core segment (Fig. 1b) consists of radial laminated core steel sheets arranged in a wedge shaped pattern. The core segment is filled with epoxy resin and molded into one solid unit. Air gaps are created using cylindrical spacers normally made of steatite, a ceramic material, or any non-magnetic material with a very high stiffness in order to take the large magnetic forces appearing between the discs in a gapped core shunt reactor. The core segments are stacked and cemented together to form a core limb column. The yokes and side limbs, normally with a rectangular cross section, make up the magnetic circuit.

The winding arrangement in a fixed shunt reactor is simpler than in a transformer. A shunt reactor with fixed rating has only one winding per phase. Disc windings of interleaved type are often used for high line-voltages. A common solution is to divide the windings into two parallel circuits with the line terminal at the center and two neutral ends at the top and bottom yokes as shown in Fig. 2. By having the neutral ends of the two groups towards the yoke, the required insulation distances towards the yoke can be reduced giving a more cost efficient design.

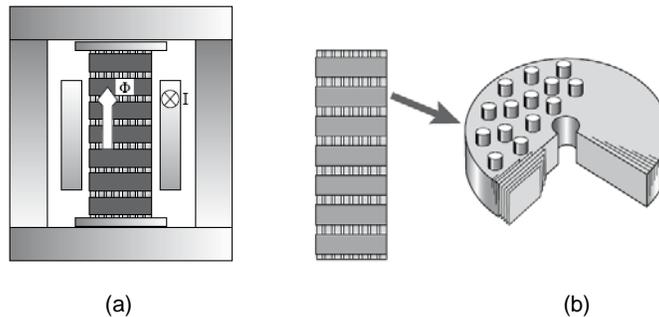


Fig.1: (a) Principle, single phase gapped core concept (b) Core segment with non-magnetic spacers

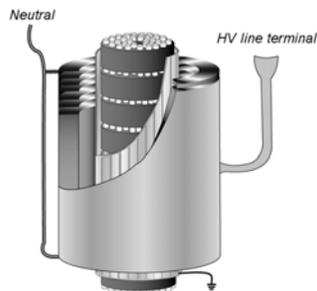


Figure 2: Typical winding arrangement for high voltage fixed reactors

2.3. Regulation

The regulation of a variable reactor is accomplished by a separate regulating winding, or windings, located outside the main winding. The taps from the regulating winding are led to the same type of tap changers used in transformers. Depending on the regulating range, voltage level and loss evaluation, the regulating type of winding configuration can vary.

Maximum reactive-power injection is achieved when minimum number of electrical turns is connected and vice versa. When using plus/minus regulation the highest current flows when all turns (highest resistance) are connected. The reactor will get higher losses. This is especially valid for large power rated regulated shunt reactors. A so-called coarse/fine regulation consists of two physical regulating windings in comparison with plus/minus that only use one physical winding. At maximum power, i.e. minimum number of turns, is achieved when the whole regulating arrangement is disconnected. Minimum resistance in the reactor winding at highest current will give lower losses than for plus/minus regulation. Therefore, at high loss evaluations and voltages equal or less than 400 kV, a yoke entry with a coarse/fine regulation is normally used. At low loss evaluations, plus/minus regulation is an alternative. Fig. 3 shows the principles of the different regulation types. The winding 1 is the main winding and 2 and 3 are regulating windings.

The regulating range is limited by the maximum step voltage and voltage range of the tap changer in combination with the specific design concept used. The feasible regulation range depends on the voltage rating of the reactor but is in the order of a factor of two depending on HV line voltage. The trend is however that larger regulation ranges are requested. As a result of this market demand, the VSR concept has recently been further developed to provide regulation ranges that are around 40 percent higher. As an example, a 420 kV VSR with a maximum rating of 200 Mvar can today be regulated between 90 Mvar and 200 Mvar compared with the 120 Mvar to 200 Mvar used a few years ago. Both types of VSRs are used in the Norwegian transmission grid. The regulation speed is determined by the tap changer and is therefore the same as for a transformer. For slow load variations, which normally is the case (seasonal, daily or hourly), the regulation speed of a VSR is fully sufficient.

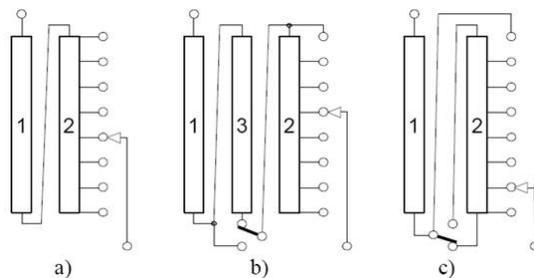


Figure 3: Regulation winding arrangements: a) linear, b) coarse/fine, c) plus/minus

The design and selection of the tap changer has an impact on the shunt reactor application and must be carefully considered in the design. Especially the leakage flux inductance in the regulating circuit could reduce the available valid step power curves for the tap changer. In addition, the regulating winding design and the design of the cleats and leads are additional challenges, in particular to meet requirements of large regulation ranges and low losses. Fig. 4 shows an example of the regulation leads of one of the VSRs discussed in this paper.



Figure 4: Active part of a 420 kV/90-200 Mvar VSR

3. VSR APPLICATIONS AND BENEFITS

The main function of a VSR is to provide a regulation function to situations where the need for reactive power compensation varies with time. There exist several situations when this occurs and where a VSR can bring direct benefits. In addition, also long term strategic motives can be a driver behind the introduction of variable shunt reactors. The flexibility provided by a VSR allows the grid owner to adapt to future changes in load- and generation patterns as well as to be a part of future “smart grids” where a higher degree of controllability will be required.

One example is wind power which has grown to becoming an important part of the energy mix in several European countries and its potential is still much bigger. Whereas large amounts of small scale embedded wind power will pose its challenges, the main challenge comes from large installations, often offshore, connected to the transmission or sub-transmission grid. An important difference between such wind parks and conventional large generation is the unpredictable and fluctuating active-power exchanges of the former. These active-power fluctuations cause in turn fluctuations in reactive-power losses, which are a serious concern for the operational security of the grid. Variable shunt reactors provide a way to control fluctuations in reactive power that requires too many switching actions for a switched reactor or capacitor but where the advanced control possibilities of an SVC are not needed. In such applications, a VSR is able to maintain either voltage or reactive power exchange (depending on the control algorithms chosen [2]) within small limits and will allow the operator of a wind park to comply with the connection requirements set in the grid code.

The use of VSRs in regular transmission networks will allow the system operator to adopt the reactive power compensation to the actual load and run the grid in an optimum manner. If SVCs or synchronous machines are installed in the grid, the use of VSRs can provide optimum headroom and allow operating the SVC in a minimum loss position. In addition, by a continuous regulation instead of switching reactors with fixed ratings in and out, power quality can be improved, in particular in weaker grids. Switching of fixed reactors procedure steps in the system voltage. The weaker the grid and the higher the rating of the reactor, the more predominant this effect will be. Step voltage in the network can result in power quality issues and affect other electrical equipment.

Another application for VSRs is when reactors are installed at HV lines that initially will carry a low load but where loading will increase with time. Such situation can occur e.g. in developing economies with a strongly growing energy demand and industrial expansion. In such case, two reactors of 50% rating each would be needed to cope with expected future load conditions. One VSR is a more cost effective solution than two fixed reactors, it is less expensive, requires less footprint and only one breaker.

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The use of VSRs as a mean to avoid “zero missing” in compensated cable networks is discussed in more depth later in this report.

4. VARIABLE SHUNT REACTORS IN THE NORWEGIAN TRANSMISSION GRID

4.1. The transmission grid, main data and background

Statnett is the Norwegian Transmission System Operator (TSO) responsible for developing and operating the Norwegian power grid to ensure that it meets society’s expectations for high quality electrical energy supply. The core activities are to maintain security of supply, ensure efficient system operations and necessary development and maintenance of the main grid. Statnett operates around 9800 km of overhead lines and 750 km of buried- or sub-sea cable with appr. 950 employees. Its operating revenues were around 5,5 BNOK (around 750 MEUR) in 2011. The Norwegian grid is connected to neighboring countries via both AC and DC links, e.g. including lines to Sweden (3 600 MW), Finland (120 MW), Russia (50 MW), Denmark (1 000 MW submarine cable) and the Netherlands (650 MW submarine cable NorNed). The next ten years Statnett will invest 50-70 BNOK (6,3-8,8 BEUR).

The background for the extensive use of VSRs in the National Grid in Norway was a decision by the Norwegian Directorate for Civil Protection (DSB), which also incorporates the Electrical Safety Authority, in 2010 to lower the operating voltages in the grid on the 300 kV and the 420 kV level to the maximum voltages stipulated in IEC 60038. Prior to this decision, Statnett had performed a study to investigate the possible deterioration of the different equipment in the grid depending on the factual voltage level used.

This study showed that even if the Statnett requirement was max 315 kV and 440 kV for max 15 minutes, it had been difficult to operate the grid according to this rule, experiencing 425-430 kV and 310 kV for much longer times in some substations, up to 70-80 % of the time higher than nominal voltage. Statnett defines the operating voltage (Rated Voltage U_r) in the 300 kV and the 420 kV grids to be the same as the system voltage (Highest Voltage for Equipment U_m) according to IEC 60038.

Figure 5 shows the "size" of the voltage problem in one substation. For this substation the Voltage-time curve (area under the curve) was calculated to be 16 500 kVh and year. To pay the generators to reduce production by ordering Special (down) Regulation was estimated to be 41 MNOK/year (5 MEUR/year) based on 50 MW/kVh and 50 NOK/MWh (6.25 EUR/MWh). Normally an increased line load is achieved by disconnecting the parallel line, with consequences for the supply security.

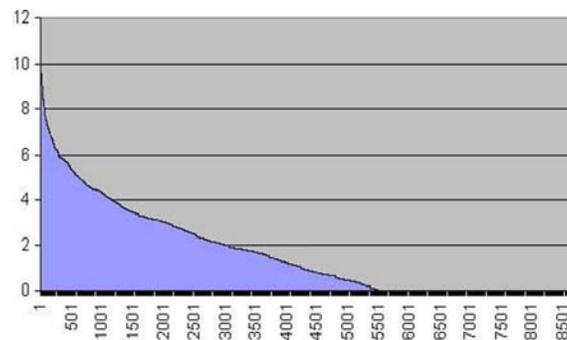


Figure 5 Voltage increase in kV ref. 420 kV vs. duration in hours in one substation

It was also shown that high voltage normally is a low load problem. The really high operating voltages are experienced when the load on the line is < +800 MW.

One reason for these high operating voltages was partly a consequence of the deregulation of the Norwegian electrical energy market in 1990. The grid operators furthered higher operating efficiencies and accepted a higher risk level to achieve this. This situation lasted until 2003 when some years with a weak energy balance in the Nordic system combined with some major black-outs in North-America

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and Europe set focus on security of supply. A reinforcement of the grid Mid-Norway in the years 2004-2010 included a new 420 kV power line, 900 Mvar Capacitor banks, 2 SVC +/- 250 Mvar and a voltage upgrade to 420 kV of a tie-line to Sweden. As a consequence, the capacitive generation from the power lines increased at low power flow. Other consequences were loss of reactive compensation from hydro generators when stopped due to power import. In this period, the first VSR rated 120-200 Mvar was installed. This had the benefit of less voltage drop/rise when switched (daily switching) and that reactive reserves in SVC and rotating synchronous compensator were secured by tuning of the reactor.

This combined with the later focus on electrical safety of porcelain explosions due to possible aging after years of operating the grid with high voltages, and the decision by the DSB, an extensive investment program was initiated including VSRs, SVCs and condenser batteries.

4.2. System aspects of Variable Shunt Reactors

Several VSRs are today in operation in the Norwegian transmission grid and will be followed by further units. System improvement of utilizing the Variable Shunt Reactors was estimated to be:

1. Less voltage drop/rise when low short circuit capacity in the grid as the number of voltage dips per day/week are part of the power quality regulation in Norway.
2. A 90-200 Mvar VSR is cost-effective compared to 2 reactors of 100 Mvar.
3. A VSR is an option when transient conditions are already been taken care of, but some slow "tuning" is of added value.
4. A VSR will secure reactive reserves by "tuning" the reactor to give optimal headroom in SVC's and synchronous compensators
5. A VSR may save losses by "fine-tuning", allowing SVC's to operate in "minimum losses" position.

In the period from 2010-2015 an extensive development of the grid furthered the need for more VSRs, SVCs and condenser batteries. At Feda sub even a new 170 Mvar rotating synchronous compensator is contracted.

The VSR's, as other components such as CB and disconnectors for OH-lines, transformers, condenser batteries etc., can be operated from three levels/places: The control cabinet (Near), the substation HMI (Local) and remote (Distant). There is a possibility to choose any of the tap changer steps on the VSR. However, to ease the control, three main positions have been defined; low, mid and high (taps, not power). These three positions are the most used in operation.

In addition to the normal interlocking, the VSRs shall not be used when there is a capacitor bank connected in the same substation. The coordination of reactors and capacitor banks in the same substations are sometimes coordinated via a supervision unit, and sometimes separate by using different voltage limits (hysteresis control). In stations with SVCs the control system of the SVC can be set to control reactors and capacitors. The goal is to keep the operating point of the SVCs as close to zero as possible. When the SVC is set to control all reactive components in the stations the control of the reactors and capacitors remote by the operators is blocked.

Statnett requires synchronized switching both for the in and out for reactors. This is to reduce the inrush currents and to lower the stress on the circuit breakers. In some cases there have been problems with saturation of CTs when energizing reactors. This has been solved by using generator protection with extra compensation for saturation.

Even though reactors are normally controlled manually in Statnett today, work is in progress to automate the control of Statnett's VSRs. As part of the installation of a new HVDC link from Norway to Denmark, Skagerrak 4, all components that can contribute to voltage control in the Kristiansand substation will be coordinated. This includes coordination between 4 HVDC links (three classic and one VSC), one SVC, 5 filter banks, one rotating synchronous condenser and one VSR. This Reactive Power Control (RPC) scheme will be implemented when the Skagerrak 4 VSC of 700 MW is

commissioned in 2014. The VSR will, in this application, be used for relatively slow voltage control so that the maintenance need is expected to be limited. A further discussion on control algorithms for VSRs can be found in Ref. [4]

5. ZERO MISSING

5.1. Definition

With the increasing use of high-voltage AC cables at transmission levels, phenomena such as current zero-missing start to appear more often in transmission systems [3,5]. Zero missing is defined as the absence of current zero-crossing for many cycles as shown in Fig. 6. This may considerably delay the opening of the circuit breaker, leaving the system unprotected and vulnerable to failures and may also damage or even destroy the circuit breaker. Unless the breaker is designed to interrupt DC currents or open at a non-zero current value, it will not be able to open until the current passes zero.

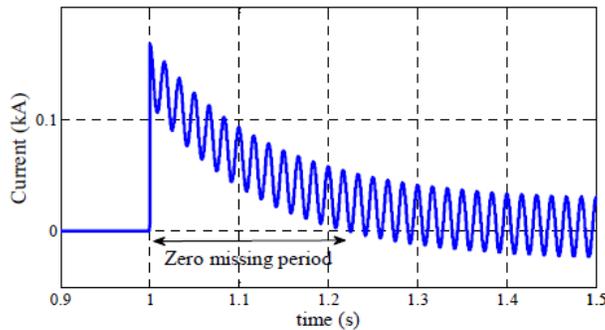


Figure 6 Voltage increase in kV ref. 420 kV vs. duration in hours in one substation [5]

Zero-missing phenomenon can occur when energizing cable lines with shunt reactors. For zero-missing phenomenon to occur, a shunt reactor has to compensate more than 50% of the reactive power generated by the cable.

To avoid zero-missing phenomenon the connection should be made when the voltage is at its peak, whereas the opposite applies when it comes to avoiding switching over-voltages. When the shunt reactor is directly connected to the cable it is necessary to choose between avoiding either zero-missing phenomenon or switching over-voltages.

5.2. Mitigation techniques

The inductive compensation shall theoretically be less than 50% of the capacitive load to make it possible for the breaking current to cross zero if an insulation failure on the cable. To ensure a maximum of 50% inductive compensation connected during the switching in operation of an AC cable, two shunt reactors each of half the rating needed for compensation of the cable can be installed. Switching is then made with one of the reactors disconnected [3]. However, in this case, it is very suitable to use one variable shunt reactor. The variable size of the reactor shall be dimensioned to a maximum value of 50% of rated or needed power at switch in operation of the cable and up to 100% under normal operation. The VSR is tuned to its minimum rating before switching, and then regulated up to the required compensation level after the switching operation. This solution is far more economical than two fixed reactors, both in terms of initial investment cost, required foot print, required substation equipment and transportation cost. This configuration also has lower losses.

The solution to use VSRs to mitigate the risks related to zero missing is used by several utilities. As an example, one North European TSO using many cables in its 400 kV transmission system have installed several VSRs with a typical 3 phase rating of 50-110 Mvar in order avoid the problem.

In Ref. [5], a study of an off shore cable connection is presented. The studied configuration consists of a 54 km 220 kV off shore cable connected to a 60 km on-shore cable. The required compensation is 270 Mvar. In this configuration, zero missing will appear and must be managed. Although not mentioned in the paper, a VSR, e.g. 90-200 Mvar in combination with a fixed reactor of 70 Mvar,

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could be considered as a useful and economical solution. Other mitigation techniques discussed are to distribute the reactors along the length of the cable transmission. The most favorable configuration to minimize the period of zero is to place the reactors on the off shore platform. However, in practice this is not a realistic option as it adds considerable weight and volume to the platform and therefore becomes uneconomical. Other options mentioned are to use breakers designed for braking current currents without zero crossing or to introduce breaker pre insertion resistors.

6. CONCLUSIONS

High power VSRs are a novel and economical solution for a number of grid challenges where the load and the need for reactive power compensation varies with time. Examples are wind parks, cable networks, and transmission systems with varying loads and/or generation. It also provides a way to mitigate the risk for zero missing phenomenon in compensated cable networks.

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