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Study of possible regulation range of a 735kV – 110MVAr single phase shunt reactor with on-load tap-changers

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SUMMARY

Today, compensation of reactive power due to capacitive load in power grids is becoming more and more important in power grids. Reactive power compensation is essential in order to achieve low losses and to avoid or to decrease occurring over-voltages. Furthermore, the grid complexity is increasing resulting in generation of more reactive power.

A commonly used solution for reactive power compensation is the switching of shunt reactor or shunt reactor banks, depending on the present load situation. Circuit breakers, which are capable of approximately 10'000 operations before maintenance, are usually used for the switching operation. These solutions have a significant footprint in the substations and allow only the full reactive power of each reactor to be switched on or off.

A variable shunt reactor (VSR) equipped with and an on-load tap-changer (OLTC) provides a flexible reactive power management solution, since it allows for regulation of reactive power in smaller steps when compared to the above mentioned solution. The advantage of a variable shunt reactor equipped with and an OLTC is that it keeps the line losses low and enables better control of the voltage variation due to changing load situations. Using OLTC's with vacuum interrupter technology, shunt reactors are capable of at least 300'000 operations before maintenance. Moreover, a variable shunt reactor requires less space in the substation compared to several fixed shunt reactors.

Variable shunt reactors using OLTC's for regulation are equipped with regulation windings in order to change the effective number of turns and therefore the resulting impedance of the reactor. Manufacturing technology used for the windings is essentially the same for transformers and VSRs with OLTCs. A coarse-fine regulation design is preferred in order to achieve low losses even in the upper reactive power regulation range. In order to obtain the maximum regulation range, the number of additional turns for each regulation step is the same. Consequently, the reactive power increase per regulation step is not uniform due to the fact that the change of impedance is approximately proportional to the square of the total number of turns.

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In the past, the regulation range of variable shunt reactors was mainly limited by the insulation levels of the OLTC. Due to these restrictions, regulation ranges of approximately 35 % of the maximum reactive power of the reactor (e.g. range from 71 to 110 MVAr) were achievable using conventional OLTC’s.

Using the newly developed advanced OLTC design, higher ranges of regulation are possible.

This paper presents a design study of a 110 MVAr, 735/√3kV single phase variable shunt reactor with a regulation down to 55MVAr (50% regulation range), achieved by employing the advanced OLTC design.

Parameters like total weight, outer dimensions, losses and reactive power steps of the design are also discussed, but the main focus of this design study is to determine the maximum regulation range which can be realized at this voltage level using the advanced OLTC technology.

KEYWORDS

UHV-Shunt Reactor – Reactive Power – Compensation – On-Load Tap-Changer – Variable Shunt Reactor

1. Need for reactive power compensation in power networks

The capacitive reactive power generated in electrical power grids increases with the voltage level and the length of the power lines. Also, the application of underground cables or submarine cables for offshore applications results in increased capacitive load currents.

Power frequency overvoltage can occur on lines with a capacitive reactive load due to the Ferranti effect if reactive power is not compensated. Furthermore, capacitive load currents lead to higher losses on power lines. The Ferranti effect is dependent on the load current. Even though the highest overvoltage occurs in the no load case, in case of a very low load, a significant voltage increase can also occur. In addition, the switching of an unloaded line can lead to additional transient overvoltages in the system.

In order to control the voltage of the network and to increase the power quality, the reactive power in the grid should be compensated.

2. Compensation of capacitive reactive power

Shunt reactors are primarily used to provide the inductive reactive power in order to reduce the unwanted effects of capacitive loads. Shunt reactors with a fixed rating are only able to match the compensation to a certain load case. Other load cases are over- or undercompensated. Using banks of several fixed shunt reactors switched on and off, depending on the actual load situation, the reactive power of a higher number of load conditions can be compensated. As a result, the power frequency voltage can be better controlled [1]. However, reactive power regulation steps of solutions using switching of several fixed shunt reactors are usually still quite coarse.

Utilizing a variable shunt reactor equipped with a vacuum type on-load tap-changer, smaller discrete steps of reactive power compensation can be achieved without the need to operate a circuit breaker. The finer regulation step allows for the reduction of overvoltages that can occur due to over- or undercompensation. Furthermore, the substation footprint of a VSR with OLTC is significantly smaller than a footprint of several fixed shunt reactors. Another advantage is the reduced number of operations the circuit breaker has to perform over a same period of time, thus increasing the maintenance intervals.

3. Design of gapped-core shunt reactors

The same winding design that is used in power transformers is used in the gapped-core shunt reactor design. The major difference compared to transformers is the design of the core and the clamping. The wound limbs of a gapped-core shunt reactor consist of grain-oriented electrical steel packages. These packages are radially stacked in order to keep eddy losses low and thus reduce the temperature-rise of these elements. The gap between these packages is realized by spacers made of ceramic.

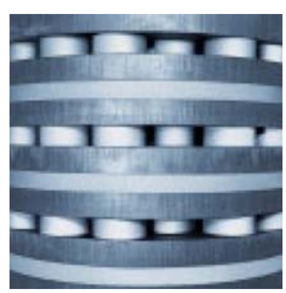

Fig. 1 Radially stacked core packages with ceramic spacers [2]

The major part of the magnetic energy in a reactor is stored in these gaps. Since this design allows for high flux density in the core gaps a compact design is reached. A smaller percentage of the reactors total magnetic energy is stored in the volume between core and windings and in the winding volume. This is due to the lower induction in these parts despite they occupy a higher volume. This is due to the fact that the magnetic energy density stored in each volume element is proportional to the square of the local flux density, see equation 1.

$$W = \int \frac{B^2}{2 \cdot \mu_0} dV \tag{1}$$

W = stored magnetic energy
B = magnetic flux density
V= volume

Applying equation 1 on the whole volume, the inductance of a reactor can be derived using equation 2.

$$L = \frac{2 \cdot W}{I^2} \tag{2}$$

I = peak value of current through reactor

Analytically, the inductance of a reactor can be calculated according to following equation:

$$L = \frac{N^2}{R_m} \tag{3}$$

N = number of turns
R_m = total magnetic reluctance of the reactor

R_m is the total effective magnetic reluctance of the reactor, which is determined by the core gaps and the winding geometry.

4. Adjustment of reactive power using OLTC

A variable shunt reactor employing an OLTC is equipped with additional regulation windings. By increasing the number of turns, according to equation 3, the inductance rises with the square of total number of turns. Consequently, the reactive power of the VSR is decreased with the increase of the effective number of turns. However, in practice the effective reluctance will change depending on the reactor design as well. Thus it will in addition increase or decrease the resulting inductance. As the voltage applied to the shunt reactor remains constant, the change of turns means variable flux regulation.

5. Limitation of the regulation range

The element which is limiting the regulation range of a VSR is the on-load tap-changer (OLTC). Maximum permissible voltages across internal insulating clearances and the maximum switching capacity are primarily determining the limits of the possible regulation range.

In this paper different regulation schemes and regulation ranges achievable up to the present day, using conventional OLTC's, are presented. Moreover the extended regulation range with a newly developed OLTC together with an UHV variable shunt reactor design for 735 kV network is introduced.

6. On-load tap-changer regulation of a variable shunt reactor

Shunt reactors used today at the 800 kV voltage level have are of fixed impedance type. Even so, regulation with on-load tap-changers at this voltage level could be feasible. Using standard on-load tap-changers with either coarse-fine or reversing regulation arrangements, the regulation range is limited to approximately 35% - 40% of the reactive power of the shunt reactor. The main factor restricting wider regulation ranges are the inner insulation of the tap-changer and the maximum allowed step voltage of the diverter switch. Mechanical aspects and space restrictions inside the reactor tank enforce limits on the tap-changer design. The possible regulation range can further be limited by the chosen design of the shunt rector to have an overall economically feasible solution of the reactor due to UHV design.

Through the development of a new advanced tap-changer, a wider regulation range is now possible. For 800 kV applications, variable shunt reactors are typically designed as three single-phase units. Therefore, concerning phase-to-phase distances, there are no insulation limits for the on-load tap-changer. With this design, each phase having its own tap-selector, the inner insulation distances "c1", which is the distance between the "-" contact of the coarse-fine change-over selector and the take-off terminal with the coarse-fine change-over selector in the "+" position, as well as the distance between the two ends of the coarse winding, can be optimized for extended regulating ranges. In addition, two sectors of one OLTC diverter switch can be connected in series by connecting the two sectors at the take-off terminal. Due to the mechanical design the two sectors operate at the same time, yielding the advantage of a double step voltage. The new advanced OLTC design, with diverter switch and tap-selector optimized for this application, can be seen in Fig. 2.

This new advanced OLTC is specifically designed for variable shunt reactor applications. The tap-selector consists of four planes, one for the odd and one for the even steps for each regulating winding. Consequently, the reactor has to be designed consisting of one main winding, two coarse regulating windings and two fine regulating windings.

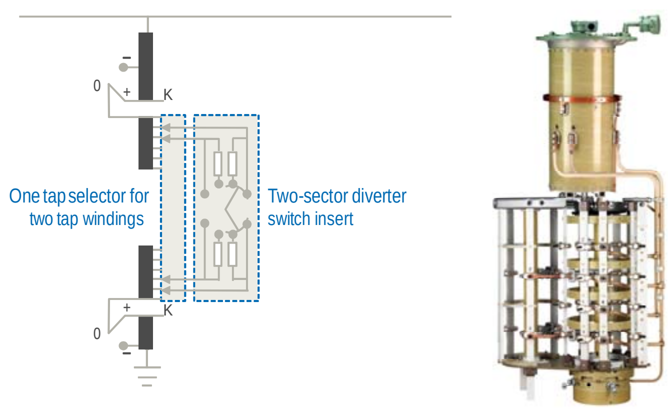

Fig. 2 Advanced OLTC design with two diverter switch sectors and optimized tap selector

This advanced design overcomes the step voltage limitations of the on-load tap-changer by increasing the effective step voltage, through the simultaneous switching of two steps. With this advanced on-load tap-changer design regulation ranges of at least 50% are possible for 800 kV shunt reactor applications. [3]

7. Boundary conditions for comparison of designs

The design study of a 735 kV single phase variable shunt reactor utilizing the advanced OLTC is developed and compared to the design of a fixed shunt reactor with the same maximum reactive power rating. In order to have a base for comparison, the losses (at maximum power tap position in case of variable shunt reactor) are kept constant for both designs. Moreover the same core diameter and gap dimensions are used. Subjects of variation are the number of core gaps and the number of turns of the winding. Due to additional regulation windings the outer diameter of the outermost winding increases as well.

8. Main performance data (fixed and variable)

The shunt reactors are specified applying following electrical parameters:

Voltage line to ground	U_r = 735 kV / √3
Max. voltage line to ground	U_m = 800 kV / √3
Rated reactive power	S_r = 110 MVAr
Rated frequency	f_r = 60Hz
Rated current at max. power	I_r = 259.2A
Max. continuous current at U_m	I_{max}= 282.1 A
Connection diagram	i
Rated inductance	L_r= 4.3424H +/- 2.5%
Linearity	150%
Cooling type	ONAN

Line terminal insulation levels [4]

Maximum system voltage	800 kV
Lightning impulse level (BIL)	1950 kV
Chopped wave level	2145 kV
Switching impulse level	1550 kV
Low frequency overvoltage test (phase to ground, one hour level)	750kV

Neutral terminal insulation levels [4]

Lightning impulse level (BIL)	350kV
Low frequency overvoltage test	140kV

Additional data on VSR design:

Control unit	OLTC
Reactive power at min. turn position (at 735kV)	110 MVAr

Applying above information a fixed and variable shunt reactor design study is performed.

9. Design study of variable shunt reactor

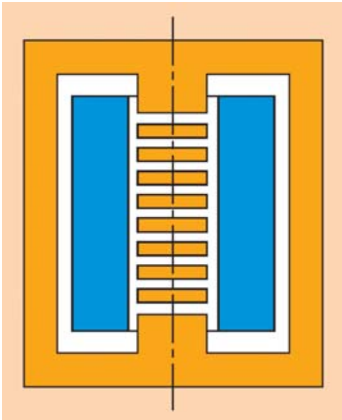

Fig. 3 Single-phase gapped core with return limbs [2]

First a fixed shunt reactor is designed and then used as an initial design for the VSR. Both designs have a single phase gapped core with return limbs, as can be seen in Fig. 3. The blue area indicates the cross sectional area of the windings. The working point is chosen arbitrarily; neither loss evaluations nor noise limitations have been considered. However, no noise damping measures have been implemented. The coarse-fine regulation scheme is preferred to keep the losses low at the maximum reactive power tap position. Constant number of turns per step and the maximum possible number of steps are chosen in order to realize the maximum possible regulation range.

Since the advanced OLTC design according to Fig. 2 is established in the VSR, two coarse windings and two fine windings have to be added to the initial design.

Considering the limits of the newly developed OLTC, a regulation range of up to 60% would be possible. The regulation range is further restricted by the UHV-design applied in this study, which leads to a maximum achievable regulation range of 50% as can be seen in the following figure.

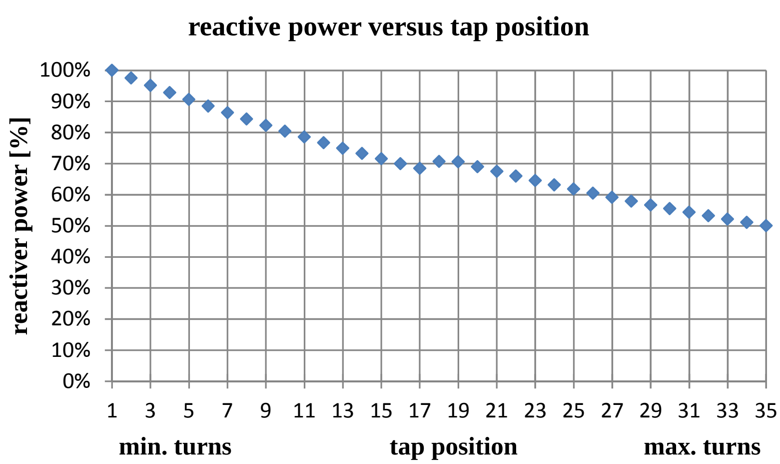

Fig. 4 Reactive power steps and regulation range of the VSR

The tap-changer used is vacuum type. This technology allows for 300'000 operations before maintenance is needed. In comparison a circuit breaker is capable of about 10'000 before maintenance is required.

10. Comparison of fixed and variable shunt reactor designs

Considering the basic design data mentioned above and designing according to the approach described before, a study of the two different shunt reactor designs is made. The designed parameters of the fixed shunt reactor and variable shunt reactor are subsequently compared.

Due to the need for additional windings, OLTC and additional leads, the dimensions and mass of the variable shunt reactor are increased when compared to the fixed shunt reactor.

	Fixed shunt reactor	Variable shunt reactor	Ratio (variable / fixed)	Difference (variable – fixed)
Total mass	132 t	190 t	1.44	58 t
Total losses @ 85°C and Ur	188 kW	188 kW	1.00	0 kW
Sound power level	~102 dB (A)	~102 dB (A)	-	-
Tank length [1]	3890 mm	5610 mm	1.44	1720 mm
Tank width [1]	3340 mm	3760 mm	1.13	420 mm
Tank height	4528 mm	4578 mm	1.01	50 mm
Approximate footprint [2]	43.5 m^2	58.3 m^2	1.34	14.8 m^2

[1] including stiffeners, [2] including turrets, compensator, radiators

In order to get a visual impression of the different dimensions of both designs, simplified 3D models are presented in the same scale.

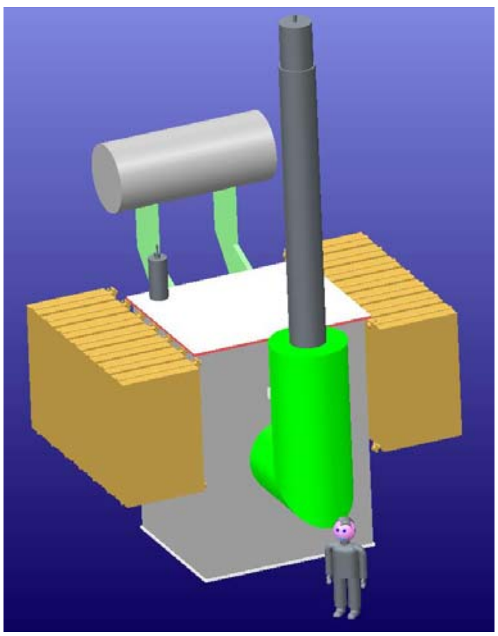

Fig. 5 Fixed shunt reactor design

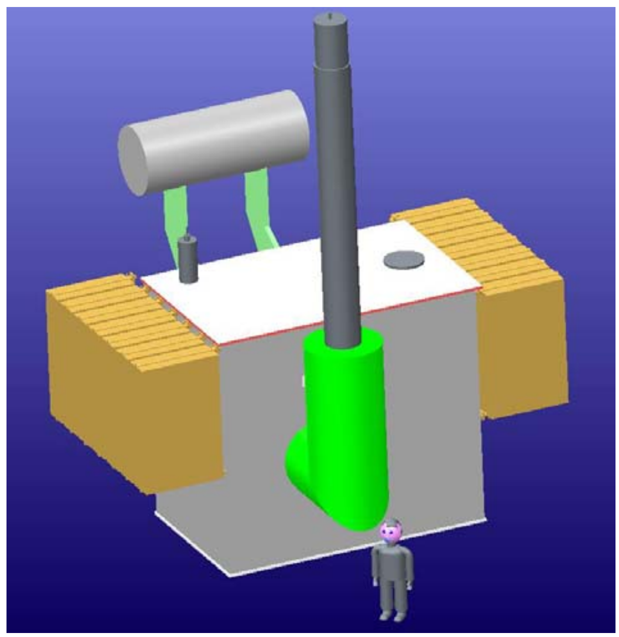

Fig. 6 Variable shunt reactor design

The fixed shunt reactor design is shown in Fig. 5. Comparatively, the variable shunt reactor with an OLTC is generally larger, as it can be seen in Fig. 6. When comparing the increase of dimensions and the substation footprint of single phase VSR and three phase VSR over the equivalent fixed shunt reactor designs, the increase of dimensions is relatively higher for the single phase units. This is mainly due to the fact that the space required for additional windings and OLTC in single phase units is relatively high compared to the design of a fixed shunt reactor. Nevertheless such a VSR design will pay off when several fixed shunt reactors are substituted by the VSR solution. In this case the total footprint of the single phase VSR on the substation will be lower than the footprint of several single phase fixed shunt reactors. Further savings can be made due to fewer circuit breakers needed.

11. Conclusion

This paper introduces a specific design study of a single phase variable shunt reactor at 800kV maximum voltage level. This particular design allows for a regulation range of 50% based on the maximum reactive power, employing the newly developed advanced on-load tap-changer design. In this case the power range varies from 110 MVAr to 55 MVAr at a rated voltage of 735 / √3 kV.

Moreover, variable shunt reactors present several benefits compared to the fixed shunt reactors - variable shunt reactors have a smaller footprint in substations, require fewer circuit breakers and provide savings by decreasing the frequency of the circuit breaker operations. Furthermore, a variable shunt reactor provides compensation of reactive power in smaller discrete steps.

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