Testing and Loss Measurement of HV Shell-Type Shunt-Reactors at Very Low Power Factor

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Abstract
In general, shell-type shunt reactors have a lower loss, a mechanically stronger winding and more compact design than the core-form reactors. The very low loss makes the acceptance test more difficult since the loss-current to reactive-current ratio is lower than 1:500. Nevertheless, the loss has to be measured with a high accuracy since the cumulative cost of the loss-power dissipated during the shunt-reactor technical life may come close to its price. Utilities evaluate bids for delivery of shunt-reactor by the total cost, i.e. by the selling price plus the accumulated cost of loss. A competitive design requires a low loss and compact design that reduces the material cost. The winding insulation was designed to minimize the reactor physical dimensions while providing a sufficient safety margin during the impulse test. The dielectric tests as well as loss measurements were performed with a low-power supply source, and the huge reactive-power was compensated by a HV capacitor-bank. Design of the resonant test circuit and tuning procedure at 60 Hz and at 180 Hz are described in this paper, as well as the measurements of the shunt-reactor loss at very low power factor. Appropriate safety measures were taken to prevent an explosion of the large capacitor bank in operation.


1. Introduction
HV shunt-reactors have been manufactured for years and technical papers have been published [1,2] on their design, test techniques and loss measurements. With the growing demand for compensation of the reactive power of 400 kV and 800 kV transmission lines, the demand for shunt reactors is has increased, and more stringent requirement of a low loss has been imposed. The competitive market forces designers to reduce the size and weight of shunt reactors. At the same time, there is a strong incentive to reduce the loss, since the cumulative cost of loss dissipated over the reactor technical life is comparable to the sale price, and the these two cost components decide on the competitiveness of the design. The very low loss makes its measurement difficult, since the measuring system has to retrieve the minute active-current component from the reactive-current that is more than 500 times higher. The angular uncertainty of the measuring system shall be less than ~60 micro-radians to achieve ~3% uncertainty of the measured loss. This uncertainty projects on a penalty paid by the manufacturer for the loss exceeding the value specified in the contract. To prove the high accuracy of loss measurements the measuring system has to be calibrated by comparison to a reference from the national, or an international standard institution.

The reactor insulation was tested at 150% of the rated system voltage $U_{n}=400$ kV, and partial discharges were measured during one-hour test. The reactor was excited at a higher frequency to attain

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this test voltage without saturation of the magnetic shield. At HV laboratory 180 Hz test voltage is provided by a generator that has a low-capacity of approximately 1.1 MVA, and the shunt-reactor reactive power of 41.1 MVAr was compensated by a large capacitor bank. Tuning of the capacitor bank to resonance with the shunt-reactor was difficult and to some extent dangerous, as the generator may be damaged when loaded with a capacitive impedance. Fluctuations of power frequency made this tuning difficult since the resonance curve has a steep slope that translates to a narrow range of the operational frequency. Besides, the capacitor bank was protected against a faulty capacitor explosion that may initiate fire of the whole bank.

The winding size is largely determined by the impulse voltage distribution and this was optimized by a detailed analysis of the electric field distribution in the critically stressed parts of the insulation system. Shell-type reactor magnetic circuit is more compact and less complex to manufacture, since there is no need to install magnetic inserts that restrain magnetic flux inside the winding. In the shell type shunt-reactor the magnetic shields are attached to the tank inner side to prevent the stray flux from penetrating the tank wall, and to reduce the stray loss (figure 1).

An important reduction of the copper-loss was achieved by using the continuously transposed wire, rather than the conventional solid-copper conductor. The winding wound with the transposed wire ensures a sufficient mechanical rigidity owing to the shell-type geometry. As compared to power transformers, the shunt reactor is not prone to short-circuit currents, and no special requirements are imposed on the mechanical strength of the winding.

An optimum solution of design problems and development of the resonant test-circuits, as well as the complex process of loss measurements are addressed in this paper.

![Figure 1](image)

**Figure 1.** *Shell Type Shunt-Reactor showing magnetic flux lines and magnetic shields.*

### 2. HV insulation design

The stress distribution within the selected parts of the windings has been calculated, and the dielectric strength of oil-gaps was checked against “Weidmann Reference Curve - WRC”. This consisted in plotting the electric field along a chosen filed line in the critically stressed area, calculation of the cumulative field $E_{cum}(x)$ distribution, and comparison to the WRC that is expressed by the formula:

$$E_{cum}(x) = 2.3E_0/x^{0.37} \text{ [kV/mm]} \quad -----(1)$$

A factor 2.3 is introduced to account for the impulse test conditions, and $E_0=18$ kV/mm corresponds to the paper-coated electrodes. A safety margin of at least 30% was attained in all oil-gaps. The shell-type reactor winding is shown schematically in Figure 2.
3. Dielectric tests of the Shunt-Reactors

The shunt-reactor has passed all dielectric tests specified by the standards, but the most stringent insulation test consists in an application of the low-frequency test-voltage that amounts to $U_t = 150\%$ of $400 / \sqrt{3} \text{kV} = 346 \text{kV}$ for one hour, and measurement of partial discharges that should not exceed 300 pC. The test voltage of ~180 Hz is generated by 1.1 MVA rotating machine driven by an asynchronous motor.

However the reactive power of the Shunt-Reactors attains $S = U_t^2 / X_L = 37.5 \text{MVAr}$, where $X_L = 2\pi \cdot 180 \cdot 2.83 = 3.2 \text{k}\Omega$ and $L = 2.83 \text{H}$. To compensate the reactive power, a large capacitor bank is needed with the capacitance tuned to resonance with the shunt reactor a little above the test voltage frequency. The capacitor bank has to be operated at a lower voltage to avoid partial discharges from the six-level supporting structure and connections between the capacitors. Therefore a step-up transformer has to be introduced between the capacitor bank and the shunt reactor. The short-circuit reactance of this transformer has to be accounted for in calculation of the compensating bank capacitance.
The resonance curve has a very high Q-factor determined mainly by the reactor and step-up transformer loss. A ratio of the reactive and loss power is approximately 500:1, and the resonance characteristic has a very steep slope in the operating range. This results in a variation of the test voltage caused by power frequency fluctuation of approximately ±0.3Hz in the supply of the generator driving motor. The test frequency variation is nearly three times higher, and the working point of the resonant test circuit moves by ±1Hz during one-hour test.

To attain the test voltage on the examined shunt reactor the resonant test-circuit power must be ~40 times higher than the power available from the generator. On another hand, loading the generator with the capacitive load may result in an uncontrolled spinning and destruction of the rotating machine. For this reason, an utmost care shall be taken to operate the test circuit on the inductive load side of the resonance curve. In consequence, the test frequency has to be confined in a narrow operating-range that is limited by the test-circuit resonant frequency and by the lowest frequency at which the test voltage is attained. A final tuning of the resonant test-circuit was performed by changing regulation taps of the step-up transformer, and by connecting or disconnecting capacitors from each level of the compensation bank. This was somewhat tedious procedure, but unavoidable since no regulated-frequency generator is available in the HV laboratory.

The actual test voltage variations during most time the test time have stayed within ±3 kV as measured on the examined shunt reactor. Occasionally ±9 kV short-time fluctuations were recorded.

The test-circuit was simulated using Micro-Cap program. A computer model of the test-circuit is shown in Figure 4, and the frequency characteristic of the resonant test set-up parameters is plotted in Figure 5.

![Circuit parameters recalculated to the test-transformer 20 kV winding side.](image)

**Figure. 4.** The computer model composed of the test-voltage source V1, the generator and its transformer inductance $L_{gen}$ and resistance $R_{gen}$, the compensation bank capacitance $C_{comp}$ and resistance $R_{capac}$, the step-up transformer inductance $L_{trafo}$ and resistance $R_{trafo}$, and the examined shunt-reactor inductance $L_{react}$ and resistance $R_{react}$.

The resonant-circuit tuning involves such choice of the compensation bank capacitance, regulation tap of the step-up transformer and the reactance of the test voltage source to keep the frequency fluctuations around the central frequency at which the required test voltage is attained. A variation of the shunt-reactor current and the generator current ratio, as well as the ratio of the shunt-reactor power to the generator power is shown in Figure 6 within the frequency fluctuation range.

The measured parameters of the resonant test-circuit followed in general the calculated values, but the effective damping of the resonance was different than the assumed value, and capacitance of the compensation bank has slightly changed with respect to that calculated from capacitor name-plate.

4. Shunt-Reactor loss measurement

The shunt-reactor designer is striving to reduce the loss to as small value as possible. On another hand, measurement of such low loss represents a major challenge to the test laboratory. The measuring system used by all transformer manufacturers for the load-loss measurement of HV power transformers cannot be used for shunt-reactors [3]. A typical power factor ($\cos \phi$) of the shunt-reactors is an order of magnitude lower than that of large power transformers short-circuited for the load-loss measurement, and the loss-measuring system uncertainty has to be reduced accordingly. Typical $\cos \phi$ value of HV shunt-reactors and of short-circuited large power transformers is shown in Fig. 7.
Figure 5. Calculated frequency-characteristic of the resonant test-circuit. The voltage and current on the circuit components and the power drawn from the generator are indicated on this graph.

Figure 6. Ratio of the reactive power in the shunt-reactor and the power drawn form the generator in the operational frequency range is shown together with the shunt-reactor and the generator current ratio.

It should be pointed out that the loss measuring system derives the active power dissipated in the shunt-reactor copper and iron loss from the test voltage applied to the shunt-reactor and its current. The shunt-reactor power loss \( P = U \cos \varphi \) is lower than 0.2% of the test voltage and current product \( U \cdot I \). The total uncertainty \( \Delta P \) is dominated by the phase-angle error of the voltage-measuring compressed-gas capacitor \( \Delta U \), the precision current-transformer \( \Delta I \), and of the C-tg\( \delta \) bridge \( \Delta \phi \). These individual phase error contributions are added-up according to the formula:

\[
\Delta \phi = \sqrt{\Delta U^2 + \Delta I^2 + \Delta \phi^2}
\]  -- ( 2 )

Considering that \( \cos \varphi < 0.2\% \), \( \varphi > 89^\circ 53' \), and the uncertainty of the measured loss \( \Delta P \) shall be smaller than \( \sim 3\% \), the measuring system angular-uncertainty \( \Delta \phi \) has been derived from an approximate relation:

\[
\Delta \phi \approx \frac{\tan \phi}{\Delta P}
\]  -- ( 3 )

An uncertainty of the measured loss \( \Delta P \) is shown as a function of \( \cos \varphi \) for a few values of the angular uncertainty \( \Delta \phi \) in Figure 8.

Effectively, the measuring system angular uncertainty \( \Delta \phi \) shall be less than \( \sim 60 \mu \text{Rad} = 60 \text{ parts per million (ppm)} \) to achieve \( \Delta P \sim 3\% \) when \( \cos \varphi \approx \tan \delta \leq 0.2\% \), and such accuracy can be attained by the Schering bridge set-up for the reactor loss measurement [4-6].
This is one of the most difficult measurements in an industrial HV laboratory, where fluctuations of power frequency result in an imbalance of the loss measuring bridge. To compensate for the frequency fluctuations a special double-integrator was installed in the measuring system [7-8]. A conceptual schematic of the Schering bridge is shown in Figure 9 to explain the double integrator function. However the actual bridge used for these measurements is equipped with an automatic balancing system and a modern digital display.

There is no simple way to calibrate the shunt-reactor loss measuring circuit, and essentially two calibration techniques are used. The first one consists in measuring an uncertainty of the HV standard capacitor, the precision current-transformer and the bridge at a national standard reference institution, and calculating the total loss measuring uncertainty. This procedure is popular at the European test laboratories and accepted by inspectors of utilities that buy the shunt-reactors. An American practice requires an on-site calibration of the whole loss-measuring system, preferably with the actual shunt-reactor included in the circuit [9]. Such calibration has been performed by the National Research Council Canada at IEM HV laboratory

5. Capacitor bank

The capacitor bank is composed of more than 600 units rated at 200 kVAR, 11.56 kV at 60 Hz. These capacitors are installed in four towers, and each tower is composed of six level supported by station-type insulators. One level can contain up to 28 capacitors connected in parallel and individually protected by a fast-acting fuse. Current limiting reactors have been inserted between the towers at each level in order to reduce the short-circuit current that may flow into a capacitor that developed an internal insulation breakdown. These reactors prevent an explosion of faulty capacitor that otherwise could have occurred if all the whole capacitor bank had discharged without restriction into the damaged unit. Such accident has been reported in a large HV test laboratory [10] and resulted in a major catastrophe caused by fire and contamination of the building. As additional safety measures each tower was installed in a metal tub that can contain oil from broken capacitors and restrict the fire from spreading over the building floor.

A differential protection was installed to automatically switch off the supply when the input and output current of the capacitor bank are different, since this indicates a short-circuit to the ground.
Figure 9. Shunt reactor \((L_s \text{ and } R_s)\) loss measurement using Schering bridge with the compressed gas capacitor \((C_s)\) and precision current transformer \((CT)\) that reverses polarity of the shunt reactor current \((i_s)\). The bridge balance is affected \((\Delta i)\) by power frequency fluctuation, as shown in the left vector diagram. An additional double integrator \((\int\int)\) forced the standard capacitor current \(i_s\) to vary the same way as \(i_s\), with the fluctuating frequency, (see the right vector diagram) and ensured stable \(\text{tg}\delta\) readings.

Figure 10. Stabilization of \(\text{tg}\delta\) readings by the double integrator. The effect of fluctuating power frequency was effectively reduced, and Schering bridge balance was maintained despite relatively large power frequency swings.

Such protection cannot prevent a discharge of one capacitor section into a damaged unit, but reduces the consequences of an accidental flashover to a grounded object.

The capacitor bank can operate at 60 Hz and at 180 Hz. At power frequency the capacitors are charged close to their rated voltage, since the capacitor bank has to compensate 60 MVar reactive power of the shunt-reactor operated at 110% of its rated voltage plus the reactance of the step-up transformer. The capacitors have to operate at the full voltage, and this represents a high dielectric stress on their internal insulation, as well as on the capacitor-bank stage insulation and connecting cables.

At 180 Hz the capacitor bank voltage is reduced by factor 3, but the reactive power must high enough to compensate for the reactive power of the shunt-reactor operated at 150% of its system voltage that is specified as 400 kV/√3, and for the step-up transformer reactance. The dielectric loss of the capacitor insulation is a little higher than at 60 Hz, and eddy currents induced in the near-by steel structure by the heavy 180 Hz current flowing in the connecting cables contribute

Figure 11. Shunt Reactor and step up test transformer on HV Laboratory.
to the total loss of the capacitor bank. 

at 180 Hz operating mode the capacitor bank is connected to lower voltage (20 kV±5%) winding of the step-up transformer and at 60 Hz to the higher voltage winding (46kV±5%). Tuning to the required resonant frequency is performed by the step-up transformer off-load tap changer and by switching on or off capacitors in each level of the capacitor bank.

6. Conclusions

- An inherently rigid structure of shell-form winding enabled use of the continuously transposed wire that enabled a further reduction of the shunt-reactor loss. Although the major design achievement, the very low loss has been difficult to measure at the manufacturer HV laboratory, especially under the condition of power frequency fluctuations. A modified Schering bridge with double-integrator was used to measure this loss with a sufficiently high accuracy.
- Dielectric test of 50 MVA, 400kV shunt-reactor involved an excitation at 180 Hz by ~1 MVA generator. A large capacitor bank was designed and put in operation to compensate the reactive power, and several protection schemes were developed to prevent an explosion and fire of the six-level bank containing ~600 capacitors, each rated at 200 kVAR.
- Tuning of the capacitor bank to resonance at ~180 Hz with the shunt-reactor has been critical, since the rotating machine could have been damaged by a capacitive load, and the operating frequency must have been close enough to the tuned-circuit resonant-frequency to attain the required test voltage on the shunt-reactor.

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8. References