# MODERN REACTIVE POWER GENERATORS

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***Abstract* – The paper reviews main stages of development of reactive power generators, describes the 1-st and 2-nd generation of synchronous condensers with conventional cooling systems and a new generation – superconductive synchronous condensers. Asynchronous non-salient pole condensers expand the class of rotating compensating devices. Comparison of dynamic performance of conventional synchronous condensers, cryogenic condensers and SVC is presented. The variant of a model 5 MVA HTSC synchronous condenser intended for wind power plants is described.**

***Keywords* – reactive power, reactive power generator, synchronous condenser, asynchronous condenser, superconductive synchronous condenser.**

## I. INTRODUCTION

Reactive power is the power of AC circuits utilized for supporting magnetic fields in inductive loads (transformers, electrical motors, inductive stoves, etc.) or electric fields for capacitors, cables, etc. The specific feature of reactive power is the fact that it cannot be transformed into another form of energy.

Reactive power compensation is defined as reactive power management with the aim of improving the performance of AC power [1, 2]. Reactive power compensation is considered in two aspects: load compensation and voltage support. In load support the objectives are to increase the power factor, to balance the load and to eliminate current harmonics from nonlinear industrial loads [1]. Voltage support reduces voltage fluctuations at a certain terminal of transmission line and improves the stability of AC system by increasing the maximum active power that can be transmitted It helps to attain a flat voltage profile at all levels of power transmission, increases transmission efficiency, controls steady-state and temporary over-voltages and helps to avoid catastrophic black-outs [1].

Synchronous condensers allow to increase the throughout transmission capacity of individual transmission lines, intersystem or interstate long distance transmission lines. They are responsible for correction of electrical power flow along the circuits with different voltage values in multi-contour electrical grids to obtain positive technical or commercial effect [2].

As reactive power compensation is an effective way to improve the electric power network, there is an urgent need for controlled reactive power generation. Reactive power generator is one of the devices, responsible to solve the above mentioned tasks.

Previously reactive power generators and synchronous condensers were synonyms. They represented a multi-pole synchronous machine without mechanical load on the shaft, operating with variable excitation and armature currents in accordance with U-curves [3].

In Russia there exists an excess of volume of reactive power in transmission networks. In 500 kV lines the level of compensation equals approximately 45 %. In the 330 and 200 kV transmission lines reactive power is practically not compensated [2].

## II. FIRST GENERATION OF CONVENTIONAL SYNCHRONOUS CONDENSERS

The development of synchronous condensers started in 1911 by the General Electric (USA). The first alternator rated at 10 MVA was manufactured in 1919 [4]. It was an air-cooled machine, ordered by Ontario Hydro.

Till the end of 70-s of the previous century synchronous condensers as reactive power generators dominated in electric grids, they were manufactured by numerous electrical machine-building companies with the largest one produced and tested in Sweden [5]. It had the rating 345 MVA and was a fully water-cooled machine, intended for Dumont station.

At 70-s synchronous condensers started to be replaced by electronic devices: static reactive power compensators (SVC – static VAR compensator, STATCOM – static shunt compensator), based on application of power electronics, capacitor banks and reactors. They possessed certain advantages, including fast response ability. Later flexible AS transmission systems (FACTS) were introduced.

Synchronous condensers stayed to operate, working out their resource. There appeared publications, justifying the advantages of rotating electrical devices [6]. Nevertheless the 1-st generation of synchronous condensers manufacturing with mainly air- and hydrogen cooling systems faded out about 1980-s.

Around 15 years ago a revival of rotating synchronous condensers could be witnessed in many countries. The change in energy mix is leading to replacement of conventional energy production with synchronous generators by low inertia and low thermal time constant power park modules [7]. These park modules are represented by wind farms and solar power plants.

As a result the second generation of conventional synchronous condensers started to develop alongside with one more type of reactive power generators – asynchronous condensers.

## III. SECOND GENERATION OF CONVENTIONAL SYNCHRONOUS CONDENSERS

The era of the 2-nd generation of synchronous condensers started beginning from 2000 [4]. Main manufacturers are ABB, GE, Siemens. The unit rating exceeds 400 MVA. There practical application is associated with wind- and solar power installations and high-voltage DC transmission lines (HVDC). Their main advantages are evaluated as follows [8]:

- increased short-circuit MVA strength,
- response to lower system fluctuations,
- improved high-response excitation systems,
- voltage and frequency ride-through capability,

- overload capability,
- high short and mid-term overload capability,
- improved reliability and increased service life, low maintenance.

Fig. 1 represents the design of synchronous condenser, manufactured by GE. It is a salient four pole alternator.

There are developed different methods of synchronizing with the network: with pony motors or with reactors in the armature circuit, depending on the demands of the consumer.

As an example the plan of installation of synchronous condensers in Denmark is shown in Fig.2 [9].

Fig.1. Illustrations referring to GE 2-nd generation synchronous condenser

| Station | Area | PCC kV | Sn MVA | Year |
|---|---|---|---|---|
| Vr. Hassing | DK1 | 150 | 100 | 1965/2013 |
| Tjele | DK1 | 150 | 160 | 1976/2012 |
| Bjæverskov | DK2 | 400 | 270 | 2013 |
| Herslev | DK2 | 400 | 200 | 2014 |
| Fraugde | DK1 | 400 | 200 | 2014 |
| | | | | |
| Kyndbyværket | DK2 | 132 | 330 | 1976/199x |
| Enstedværket | DK1 | 150 | 880 | 1979/2013 |

Fig. 2. Application of 2-nd generation of synchronous condenser in Denmark.

## IV. ASYNCHRONOUS CONDENSERS

After manufacturing and successful exploitation of a number of asynchronous turbogenerators there was developed and manufactured by OJSC «Power Machines» a non-salient pole air-cooled asynchronous condenser rated at 100 MVA (Fig. 3) [2, 10]. Two alternators were installed in a Beskudnikovo 500 kV substation (Russia, Moscow region). Main parameters: voltage - 20 kV, frequency of rotation - 1500 rpm, total mass – 250 t. The main difference as compared to synchronous condensers lies in the fact that the rotor contains two excitation windings. The second one is in the q-axis. Magnetomotive force of the second winding is less than the one of the main winding. Two windings are operating with two excitation systems.

Fig. 3. Asynchronous condenser rated at 100 MVA.

Advantages of asynchronous condensers with non-salient pole rotor are as follows [2]:

1. Wide range of reactive power regulation from 100% to -100%.
2. Higher response of reactive power or voltage regulation due to possibility of current reverse in excitation windings.
3. Better damping of rotor oscillations during disturbances in the network.
4. High survivability due to presence of two excitation windings.

It should be nevertheless noted that a non-salient pole machine with two excitation windings and two excitation systems is relatively expensive.

## V. SUPERCONDUCTIVE SYNCHRONOUS CONDENSERS

In 80-s - 90-s there were manufactured and tested several superconductive generators which showed they may operate as synchronous condensers with the rated reactive power generation and consumption due to better U-curve and more favorable relation of magnetomotive forces of excitation and armature windings.

It allowed to exclude the limitations in the under-excitation mode because of better summary magnetic fields in the armature end-zone.

The 20 MVA, 3000 rpm superconducting generator was manufactured in the USSR in 1979 (Fig. 4, a).The excitation winding was wound of *Nb-Ti* low-temperature superconductor (LTSC).

From 1982 it was operating as a synchronous condenser in the network “Lenenergo” and allowed to reveal advantages as compared to SVC. The peculiar feature of this alternator was the fact that the armature was cooled by an insulating liquid and the armature cooling system was equipped with a flux-pump. The same liquid was a working medium of the flux-pump. The armature losses were used for water heating [11].

In Japan there were produced an LTSC synchronous condensers rated at 30 MVA and 70 MVA LTSC generator, which operated in Kansai Electric Power Company grid in Osaka synchronous condenser (Fig. 4, b) [12].

In 1986 high-temperature superconductivity (HTSC) was discovered and stopped the works with LTSC alternators due to the main advantage of HTSC – higher operating critical temperature.

Basing on obtained practical experience with LTSC synchronous condensers the USA started development and manufacturing of a new generation of synchronous condensers – dynamic HTSC synchronous condensers.

Dynamic synchronous condenser design is based on HTSC field winding, which requires only a small change of current in under- over-excitation modes due to low synchronous reactance.

There was developed a trailized 8 MVA HTSC condenser (Fig. 5.), which was installed in 2004 on the Tennesy Valley Authority (TVA) grid and showed positive results of operation. TVA ordered several HTSC condensers of higher rating [13, 14].

a

b

Fig. 4. Helium-cooled 20 MVA alternator (Russia) and 70 MVA alternator (Japan).

To evaluate a possibility of development of a high-response synchronous condenser we have developed a project of high-voltage synchronous condenser rated at 200 MVA, 220 kV with increased excitation current, decreased reactance and original electromagnetic screen on the rotor (Fig. 6). The main demands are presented below. Comparison with other types of synchronous condensers is given in Table 1.

The preliminary evaluation of the variant for 550 kV revealed a lot of technical problems. One of them showed it is practically impossible to set the high-voltage terminals on the condenser outer diameter of the frame because of relatively small machine size.

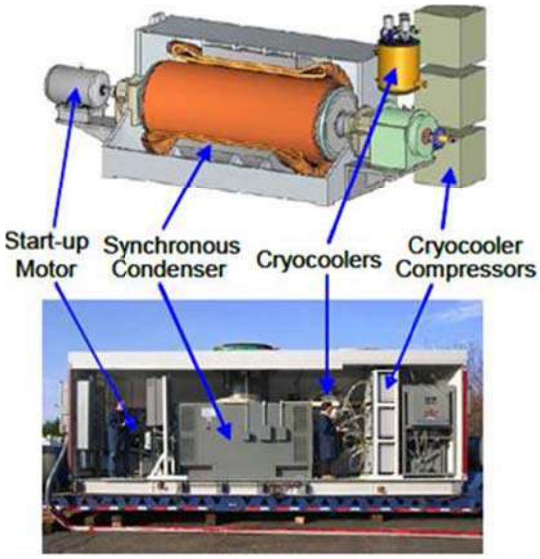

Fig. 5. Trailized 8 MVA SuperVAR HTSC synchronous condenser.

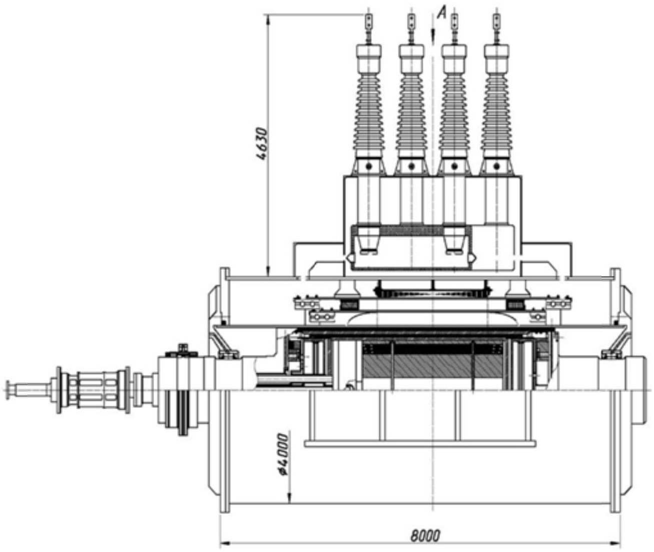

Fig. 6. Longitudinal cross-section of 200 MVA HTSC synchronous condensers.

The machine was developed according to the following data:

1. Electric voltage – 220-500 kV.
2. Armature overload – double for 60 s.
4. Range of reactive power variation Q = ± (160 - 200) MVA.
4. Time of attaining of rating from Qc = 0 to $Q_c$ = ±(160 - 200) MB·A - 0.4 – 0.6 s.
6. Synchronous inductance – $x_d = x_q$ - (0.3 - 0.6) p.u.

Table 1

Comparison of conventional and cryogenic synchronous condensers

| Parameters | Value | | |
|---|---|---|---|
| | Cooling system | | |
| | Hydrogen | Water | Cryogenic |
| Rated power, MVA | 160 | 345 | 200 |
| Linear voltage, kV | 15.75 | 20 | 220 |
| Current, A | 5860 | 10100 | 525 |
| Rotor speed of rotation, rev/min | 750 | 750 | 750 |
| Frequency, Hz | 50 | 50 | 50 |
| Number of phases | 3 | 3 | 3 |
| Stator diameter, mm | 2500 | 4000 | 3270 |
| Rotor diameter | 2440 | 3800 | 2200 |
| Active length, mm | 3200 | 3600 | 2200 |
| Stator yoke height, mm | 375 | - | 120 |
| Housing diameter, mm | 5200 | 6500 | 4000 |
| Synchronous reactance, p.u. | 2.05 | 1.9 | 1.0 |
| Transient synchronous reactance, p.u. | 0.45 | 0.502 | 0.58 |
| Subtransient synchronous reactance p.u. | 0.21 | 0.245 | 0.37 |

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- Time of attaining of rating from Qc = 0 to Qc = ±(160-200) MVA - 0.4 – 0.6 s.
- Synchronous inductance – xd = xq = (0.3 - 0.6) p.u.

Main advantages of HTSC synchronous condensers are considered to be as follows:

- wide range of reactive power regulation,
- possibility of twofold overload,
- absence of thermal stresses in the cryogenic windings due to stable operating temperature,
- improved reliability,
- decreased losses, comparable with static compensating devices,
- lower mass and size indexes,
- highly sinusoidal output voltage,
- decreased synchronous reactance value and increased limits for reactive power regulation in the under-excitation mode,
- possibility of fast response to transient voltage variation,
- possibility of unit rating increase,
- possibility of operating at zero field current at xd=1 p.u,,
- feasibility of high output voltage (up to 200 kV and more).

Comparison of U-curves and losses is given in Fig. 7.

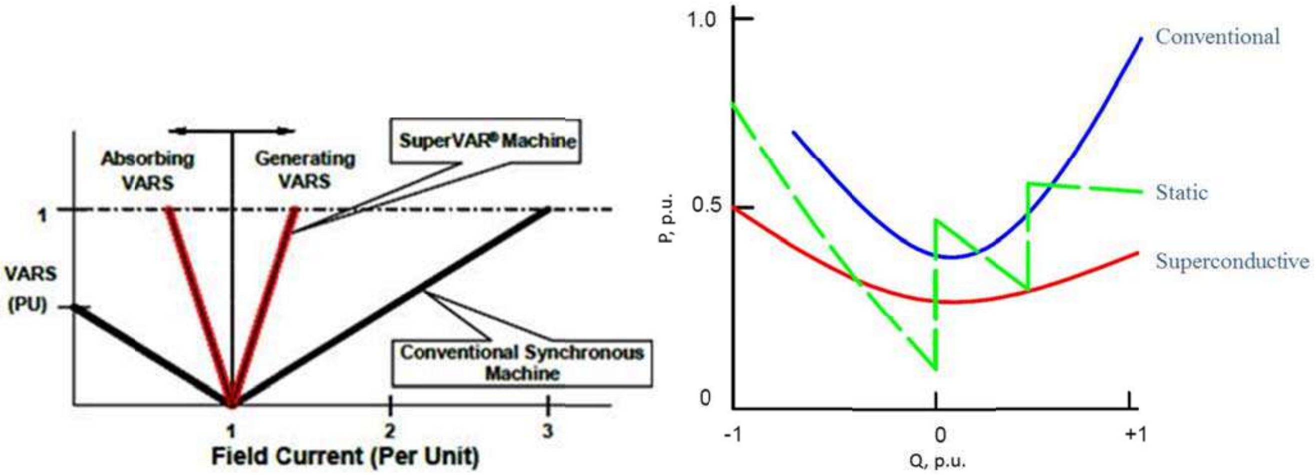

Fig 7. U- curves and loss variation for different types of compensating devices.

## VI. COMPARISON OF DYNAMIC PERFORMANCE OF COMPENSATING DEVICES

In [1] a comparison of dynamic operation of different types of reactive power compensating devices is performed. Simulaton of different fault types show the following.

In case of a single phase to ground fault the SVC injects reactive power after a delay caused by the delay in the controller, but after a delay it injects more reactive power due to faster voltage control. The synchronous condenser reacts instantly due to the change in the thermal voltage. Superconductive condenser injects more reactive power at the instant of the fault as compared to conventional one due to lower synchronous reactance. But at the fault clearance both types of condensers act similar.

During a two-phase to ground fault the positive-sequence voltage reaches the rated value faster with both types of synchronous condensers. It is because SVC injects less reactive power during and after the fault until the line is connected back.

In case of three phase to ground fault the positive-sequence voltage drop is still larger with the SVC. The reactive power injected by both synchronous condenser types is still higher. The results are given in Tables 2 and 3.

Table 2

Minimum positive sequence voltage during the fault at 36-kV bus

| | Fault Type | 1ph | 2ph | 3ph |
|---|---|---|---|---|
| Min. Ter. V (p.u.) | | | | |
| With SVC | | 0.89 | 0.60 | 0.30* |
| With Conv. S.C. | | 0.89 | 0.67 | 0.42 |
| With SuperVAR | | 0.89 | 0.70 | 0.45 |

Table 3

Maximum injected reactive power by synchronous condensers and SVC during the fault

| | Fault Type | 1ph | 2ph | 3ph |
|---|---|---|---|---|
| Injected Q (p.u.) | | | | |
| SVC | | 0.67 | 0.48 | 0.10* |
| Conv. S.C. | | 0.54 | 0.69 | 0.74 |
| SuperVAR | | 0.54 | 0.93 | 1.07 |

During severe faults synchronous condensers perform better and bring the terminal voltage to rated value faster.

A very interesting experimental investigation was carried out at Vyborg substation (Leningrad region) with parallel operation of conventional synchronous condenser and STATCOM [15].

## VII. MODEL 5MVA HTSC SYNCHRONOUS CONDENSER

There is now under development by our team a version of HTSC 5 MVA, 750 rpm, 10.5 kV prototype SC for wind power plants [16]. It should be specially noted that all the variants have LN2 cooling system. On the first stage there was discussed a variant with a slotless armature as well. But later on it was rejected because it came out to be more expensive, than the 1-st variant of SC, described later.

Below are presented the results of development of two variants of SC. The 1-st one contains a 2G HTSC 8 pole field winding placed in the cold zone (Fig. 8).

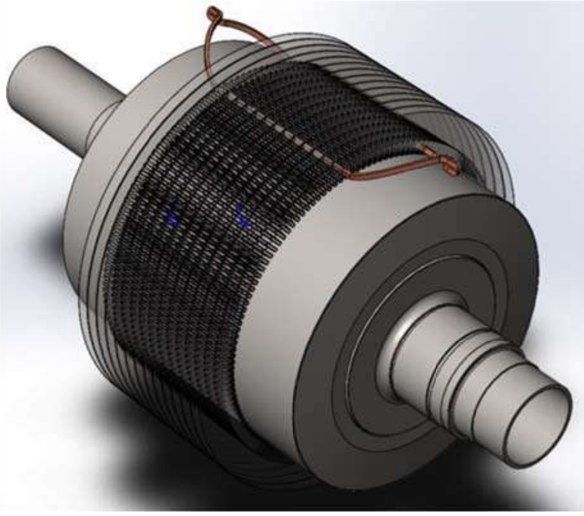

Fig. 8. A variant with 2G HTSC 8-pole field winding and conventional armature winding.

The rotor represents an 8-pole design with salient poles and field winding with concentric coils. The magnetic core is positioned inside the cryostat. The field winding coils are produced of 2G HTSC tape. The electromagnetic screen and the damper winding are provided in the rotor design to ensure reliable operation. The vacuum cavities reduce heat transfer to the cold zone and decrease the flow of cooling agent during the SC operation. When developing the rotor design during the cool down process the coefficients of linear shortening of the elements were taken into account. The synchronous condenser stator is a conventional one to reduce, as mentioned above, the cost of the new machine.

The second variant is based on the design with HTSC armature. The armature winding contains 12 saddle-shape coils of 2G HTSC, positioned in a single cryostat with amorphous alloy core. The coils are laid out in special slots formed of amorphous alloy tape and are fixed from the rotor side by fiber glass cylinder (Fig. 9). The outer and side surfaces of the cryostat are made of stainless steel

The armature current value equals 262 A, therefore the coils are being wound of 4 HTSC tapes in parallel. We do not consider it reasonable to transpose tapes along the coil length and are making the transposition when connecting the coils with each other. As a result the circuit branch for circulating currents increases. Such a method of transposing saves space and simplifies the process of winding manufacturing. The method was successfully implied during the 20 MVA LTSC turbogenerator armature manufacturing.

Main data of calculations for both variants of SC is presented below in Table 4.

Table 4

Comparison of two variants of HTSC synchronous condensers

| Parameters of HTSC synchronous condenser | Value | HTSC rotor | HTSC stator |
|---|---|---|---|
| Rated total power | MVA | 5.0 | 5.0 |
| Rated linear voltage | kV | 10.5 | 10.5 |
| Rated speed of rotation | rpm | 750 | 750 |
| Rated phase voltage | кV | 6.3 | 6.3 |
| Rated current | A | 262 | 262 |
| Rated magnetic induction | T | 0.82 | 0.82 |
| Inner armature diameter | mm | 1588 | 1777 |
| Active armature length | mm | 811 | 907 |
| Number of armature winding bars/coils | unit | 144 | 12 |
| Armature current density | A/mm$^2$ | 4.16 | 65 |
| Air gap | mm | 5 | 7 |
| Synchronous reactance along longitudinal axis | p.u. | 1.198 | 0.826 |
| Synchronous reactance along quadrature axis | p.u. | 0.671 | 0.587 |

## VIII. CONCLUSIONS

Reactive power generators are represented now by both synchronous and asynchronous electrical machines. The renewed interest to rotating reactive power compensating devices is associated mainly with the development of wind- and solar power stations and high-voltage DC transmission lines. As a result the 2-nd generation of conventional synchronous condensers is developing.

The investigations of superconductive condensers are continued. In many aspects this alternators may compete successfully with static compensating devices and with conventional synchronous condensers as well. To win in this competition there is an urgent need for improved types of HTSC wires and cables, intended for high currents (several kA).

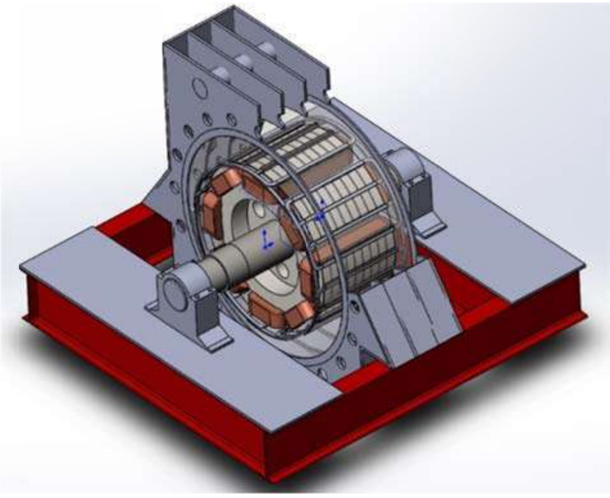

Fig. 9. A variant with conventional 8-pole field winding and 2G HTSC armature winding.

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