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HIGH POWER SATURABLE REACTORS FOR AC POWER TRANSMISSION LINES

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Abstract. This paper presents the results of research on controlled and saturated reactors conducted at Tallinn Technical University since 1971.

Depending on the saturation principle, saturable reactors can be saturated with alternating current (AC saturated reactors) or with direct current (DC controlled reactors). A high power saturable reactor can be used with a shunt reactor or instead of that for high, in particular, for extra-high-voltage lines. In such a reactor, some parts of the magnetic circuit are deeply saturated. The key problem here lies in current distortion. At the same time, the construction of the reactor must be simple and robust.

To satisfy these two requirements, long-term research and testing has been conducted. As a result, original constructions of DC controlled and AC saturated reactors have been developed. Also, a theory has been created for higher harmonics minimization, and methods have been proposed for the calculation of losses and of the active part of the reactor. The factors above are substantial in terms of manufacturing.

Key words: saturable reactors, high voltage transmission line, voltage control, reactive power compensation, higher harmonics, reactor design.

1. INTRODUCTION

The problems encountered with long distance extra-high-voltage (EHV) and ultra-high-voltage (UHV) AC transmission lines include voltage control, improvement of transient stability, suppression of system oscillations, limitation of overvoltages in the case of sudden loss of load and internal overvoltage limitation, and enhancement (extinguishing of arc) at single-phase reclosing. Traditional methods of line compensation include series capacitors, linear shunt reactors, synchronous compensators or combinations of these. Static VAR compensators are complicated and expensive. As a rule, power transmission lines of higher voltage levels operate with shunt reactors, their total power being equal to the power of the electric field (the charge power) of the line. For compact lines of increased surge-impedance loading, the power demand of the reactor is higher than with conventional lines. High power reactors are useful there. The requisite reactor unit power for UHV (1150 kV) AC transmission lines can reach 600–1000 Mvar.

The quest for making shunt reactors with high unit power, in view of performance and cost considerations, leads to hardly solvable problems associated with the control of the consumption of the reactive power, i.e., to difficulties due to a great number of reactor switching cycles, lowered stability limits, a need for controlled sources of the reactive power, and the problem of surge limitation. The use of the controlled reactors of the latter design enables us to overcome successfully these problems.

As a new tool, saturable reactors were proposed for transmission-design engineers about thirty years ago. The harmonically-compensated saturated reactors or DC controlled reactors (DCCR) were pioneered by the General Electric Company Ltd (Witton, Britain) by Friedlander and his colleagues. In such a reactor, some parts of the magnetic circuit are deeply saturated. Thus, the key problem of these reactors is current distortion. This problem was solved by internal harmonic-compensation with multi-phase windings (Quin-reactor, Twin-tripler reactor, and Treble-tripler reactor). Such a design of polyphase series (or shunt), a connected multicore reactor, has not proved economical for designs with direct connection at voltages above 132 kV. For higher voltages, a step-down transformer is required for connection to EHV and UHV lines. High power saturated reactors and DCCRs for direct connection to EHV lines must have simple and robust construction like power transformers or shunt reactors, allowing for the use of transformer technology. The other requirement is that for high power units, each phase of the three-phase reactor can be produced and transported separately. Over three decades, intensive studies were conducted in the former USSR (Moscow, Leningrad, Tallinn, Alma-Ata, Gorki, and Kishinev) to create such reactors. The first 525 kV 3 × 60 Mvar DCCR (one phase) was built in Zaporozh'e in 1992.

A controlled reactor provides reactive power flow and voltage control, increases transmission capacity, internal overvoltage limitation, extinguishing an arc at a single-phase automatic reclosing. Thus, controlled reactors can be used as a new economical tool to solve the problem of transmission line control. Their advantages are described in [1]. Saturable reactors can be used in electric power systems for reactive power and voltage control [1–3]. Many technical solutions have been proposed for saturable reactor construction [4,5]. Controlled reactors have the capability to reduce the voltage surges of transmission lines [6]. This capability is based on the fact that no fast changes can occur in the magnetic flux linkage of the phase and control windings when the terminal voltage changes rapidly. Thus, a DCCR has transient reactance, which tends to stabilize voltage without a need to change the control current from the regulator. Other reactor types do not have similar capabilities.

2. BASIC PRINCIPLES

In general, shunt reactors are linear air-cored or gapped reactors. AC saturated reactors (ACSRs) and DCCRs have a closed magnetic core like an ordinary transformer without the secondary winding. Transformers do not saturate at their operating voltage, and their magnetizing current is small in comparison with the rated current. However, in ACSRs and DCCRs, the magnetic core can be deeply saturated at their operating voltage.

Figure 1*a* shows the nonlinear volt-ampere characteristics of an ACSR, Fig. 1*c* those of a DCCR, and Fig. 1*d* those of a combined DCCR and ACSR.

Cold-rolled grain-oriented steel is typically used for a magnetic core. It is necessary to have high permeability in the unsaturated and low permeability in the saturated region. At very high saturation, the permeability will be nearly constant and approximately equal to air permeability. Hysteresis effect can be neglected because of its small influence.

If the operating voltage is sinusoidal, then the magnetic flux will be sinusoidal too, but the magnetomotive force and current waveform will be non-sinusoidal. Reactor supply voltage and current characteristic $U(I)$ is similar to the nonlinear magnetization characteristic $B(H)$ (Fig. 1*a*). The ACSR (Fig. 1*a*) has self-adjusting reactance without control. A DCCR (Fig. 1*c*) and a combined design of DCCR and ACSR (Fig. 1*d*, *e*) need DC control windings for DC saturation. Figure 1*a* shows the dynamic reactance of the ACSR (slope reactance) x_d at an operating voltage higher than the saturation voltage U_S. This reactance is the ratio of the voltage change ΔU to the corresponding change of the current ΔI

$$x_d = \frac{\Delta U}{\Delta I}$$

and the value of x_d is small. If an ACSR is used as a shunt reactor, it consumes reactive power in a self-adjusting (parametric) manner like an ideal shunt reactor with small inertia. Figure 1*b* shows the equivalent circuit for such a reactor.

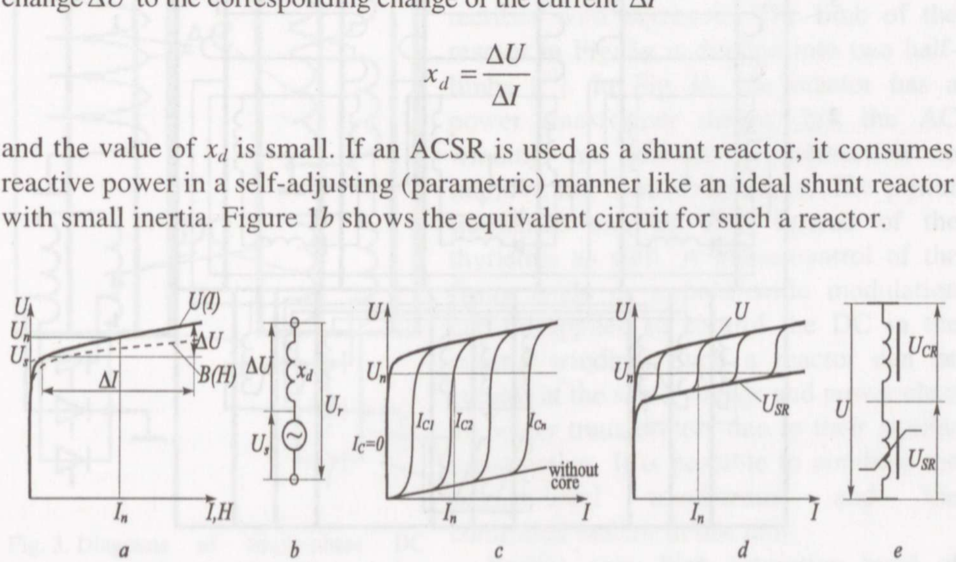

Fig. 1. Static volt-ampere characteristics of an AC saturated reactor (*a*), of a DC controlled reactor (*c*), and combined DC controlled and AC saturated reactor (*d*). Simplified equivalent circuit of an AC saturated reactor (*b*) and of a combined reactor (*e*).

Figure 1*c* shows a family of typical volt-ampere characteristics of a DCCR with the longitudinal bias. The reactor has multi-phase windings and internal harmonic compensation. The curves are given for different values of direct current in the control winding ($I_{C1}...I_{Cn}$). The top curve ($I_C = 0$) is the volt-ampere characteristic of the reactor without DC bias. The bottom curve has infinitely strong DC bias and corresponds to the reactor without a core. Figure 1*d* shows a family of volt-ampere characteristics of the combined design of DCCR and ACSR [7] developed at Tallinn Technical University (TTU). One version of a simplified reactor design is presented in Fig. 2.

Here, in the AC saturated part, three three-phase groups are connected in parallel. One of the groups has star- and delta-connected windings and two other groups have the windings connected to the left and right continued-side deltas. Each ACSR phase is series connected with the DCCR winding, located on both half-limbs of the magnetic core. DC controlled winding 2 has a special delta connection. In each phase, three thyristors of the DC-bias control small reactors 4 or, a specially designed leakage reactance of the control windings are added to improve the thyristor control.

The key problem for saturable reactors is distortion of the supply current, caused by the saturation of the magnetic circuit. Improvements of current waveform are discussed in [8,9]. In the following, some results of applications are described.

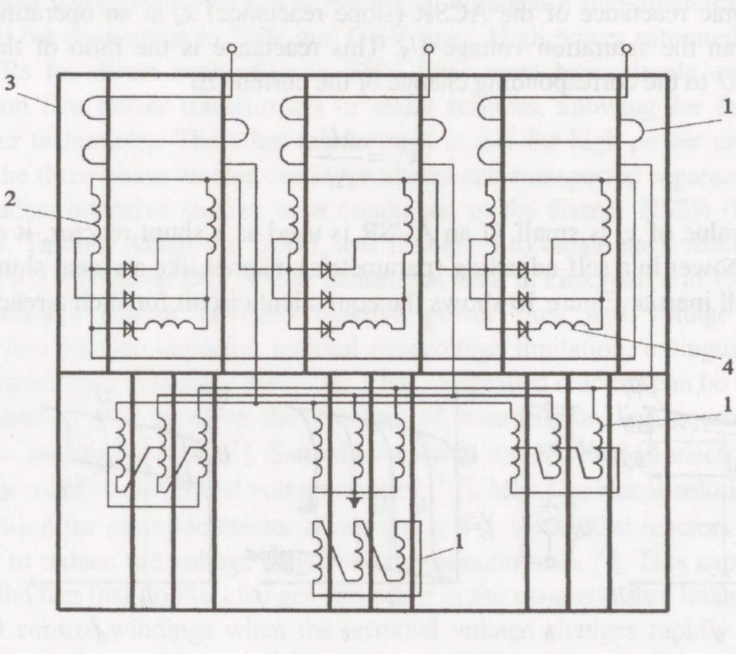

Fig. 2. Diagram of a three-phase combined DC controlled and AC saturated reactor: 1 – three-phase windings, 2 – DC control winding, 3 – magnetic core, 4 – small reactor or leakage reactance of the control winding.

3. SINGLE-PHASE DC CONTROLLED REACTORS

A DCCR ought to be as simple as a power transformer. It is possible to design large power reactors for high or EHV transmission lines without a step-up transformer. Such large power reactors are more simple and less expensive than thyristor controlled reactors (bi-directional thyristor valves are installed in series with the power circuit of reactors). The flow of inductive current is controlled by adjusting the firing angle of a thyristor valve.

In ACSRs, winding inductance is controlled by using the saturation of core iron. The basic element of a saturated reactor is the magnetic core with a strongly nonlinear magnetic characteristic. The inherent nonlinear magnetizing characteristic of the reactor provides a controlled variation of the inductive current proportional to the variation of the applied voltage above the saturation level. A DCCR is an iron-cored inductor whose power-winding reactance is controlled by changing the magnetic saturation of the core. The DC-bias flux created by a control winding is a source of saturation. Different harmonically compensated DCCRs and ACSRs have been constructed in England, Belgium, former USSR, India, and Australia. In modern controlled reactors, the properties of power electronics and the saturation phenomenon of the ferromagnetic core operate in effective collaboration.

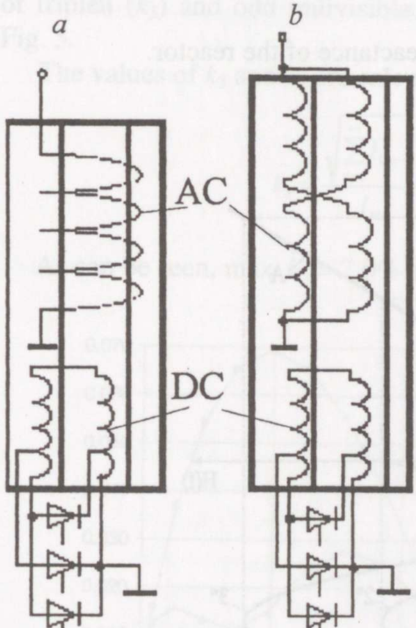

Fig. 3. Diagrams of single-phase DC controlled reactors: with split limb (*a*), with two active limbs (*b*).

A possible design for a single-phase DCCR is shown in Fig. 3. The reactor has an AC winding connected into the electric power system, a DC control winding creating the DC bias in the core, and a rectifier with thyristors. The limb of the reactor in Fig. 3*a* is divided into two half-limbs [10]. In Fig. 3*b*, the reactor has a power transformer design, but the AC winding has the cross connection to improve the control dynamics. The power transistors can be used instead of the thyristors as well. A phase-control of the firing angle or a pulse-wide modulation can be applied to control the DC in the control winding. Such a reactor can be created at the same voltage and power class as power transformers due to their similar construction. It is possible to combine the voltage-level transformer and the controlled reactor in one unit.

Earlier, very high saturation level of some parts of the magnetic core was used in some types of magnetic amplifiers. The same idea for a DCCR with a delta-connected winding was first used by Bryantsev from the Alma-Ata Power Engineering Institute (APEI). Theories and design methods for high-power reactor construction with a star-connected winding were developed at TTU and then at APEI.

The use of very high saturation level provides a partial solution to the current distortion problem in a DCCR. The basic idea is shown in Fig. 4. At very high saturation, the magnetization curve is close to an ideal piecewise-linear shape of the curve *A*. The equivalent induction has sinusoidal waveform because the supply voltage of the windings is sinusoidal. Figure 4 shows three cases of magnetization at the sinusoidal induction, 1, 2, and 3. In case 1, $B_{01} = 0$ and $H(t) = 0$. In case 2, $B_{02} = B_S$, field strength H and reactor current for the half-period will be sinusoidal. In the next half-period, the same magnetization is in the other limb (Fig. 3*b*). So the current in a parallel-connected winding is sinusoidal for the entire period. In case 3, $B_{03} = 2B_S$, the current is also sinusoidal if both limbs are saturated for the entire period. An additional increase in DC controlled current cannot further increase the reactor AC current.

The maximum current of the reactor is determined as

$$I_m = \frac{U}{X_r}, \tag{1}$$

where U is the voltage and X_r is the residual reactance of the reactor.

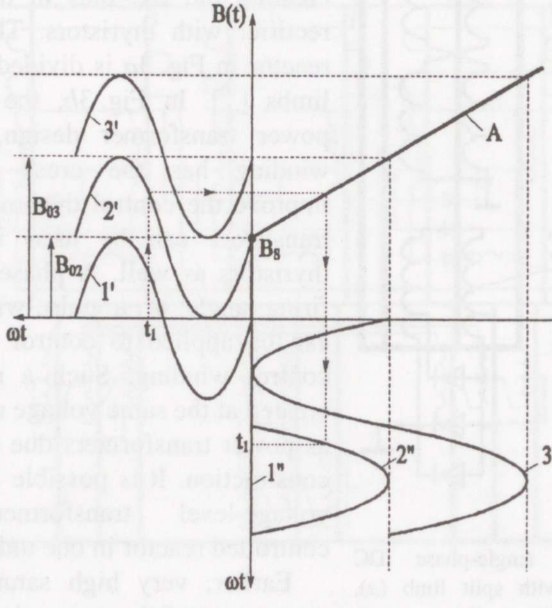

Fig. 4. The magnetizing process at sinusoidal induction (voltage).

When the reactor operates at the rated voltage U_N and the rated current of reactor is I_N, then the overload capacity of the reactor follows from Eq. (1) as

$$\frac{I_m}{I_N} = \frac{1}{x_{rr}}, \qquad (2)$$

where x_{rr} is the relative residual reactance. It can be shown that its value is determined as

$$x_{rr} = k_q \frac{A_k}{A_{Fe}} \frac{b_{1\sigma n}}{b_{1u}}, \qquad (3)$$

where k_q is the correction factor, which takes into account stray field unideality ($k_q < 1$), A_k is the fictitious area of the AC winding for the flux linkage, A_{Fe} is the cross-sectional area of core iron, $b_{1\sigma n}$ is the peak value of the induction for fundamental harmonic in a stray duct of the AC winding at the rated current, b_{1u} is the peak value of induction in the core iron at non-load.

The distortion of the main current depends on the duty ratio of the reactor I_1/I_m, where I_1 is the root mean square value of the fundamental harmonic. Levels of triplen (k_3) and odd indivisible by three (k_5) higher harmonics are given in Fig. 5.

The values of k_3 and k_5 are calculated from the following expressions:

$$k_3 = \frac{\sqrt{\sum_{n=1}^{\infty} I_{6n-3}^2}}{I_m}, \qquad k_5 = \frac{\sqrt{\sum_{n=1}^{\infty} I_{6n\mp1}^2}}{I_m}. \qquad (4)$$

As can be seen, max $\hat{k}_3 = 7.0\%$ and max $\hat{k}_5 = 2.7\%$, correspondingly.

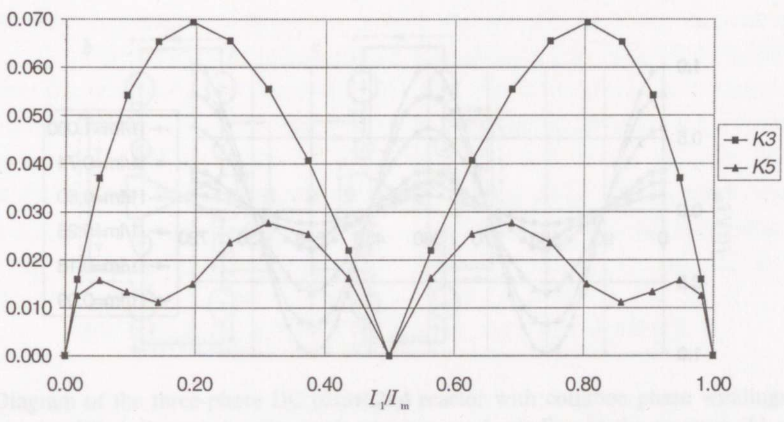

Fig. 5. Levels of triplen (k_3) and odd indivisible by three (k_5) higher harmonics versus a DC controlled reactor duty ratio (I_1/I_m).

The limbs with variable cross-section areas can be used to reduce the higher harmonics in the current [8].

In Fig. 6, for example, the computed values of k_3 and k_5 are shown for the DCCR that has the limbs with three cross-sections.

The waveforms of the main current for such DCCR are given in Fig. 7.

The limb with variable cross-section areas is created by special shifting of iron core. Owing to this design, the maximum level of the third harmonic $\hat{k}_3$ is lower than 1.6% of the maximum current of the reactor. The maximum total value of odd harmonics indivisible by three (5, 7, etc.) is lower than 1.6%. This means that value of $\hat{k}_3$ is reduced approximately four and $\hat{k}_5$ two times in comparison with the initial state.

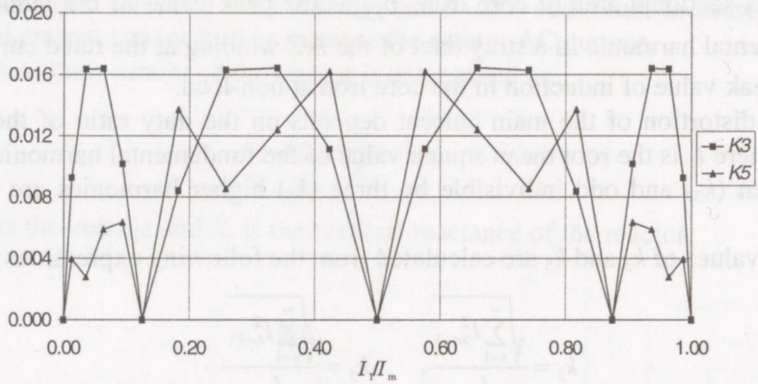

Fig. 6. Levels of triplen (k_3) and odd indivisible by three (k_5) higher harmonics versus duty ratio (I_1/I_m) for a DC controlled reactor that has limbs with three cross-sections.

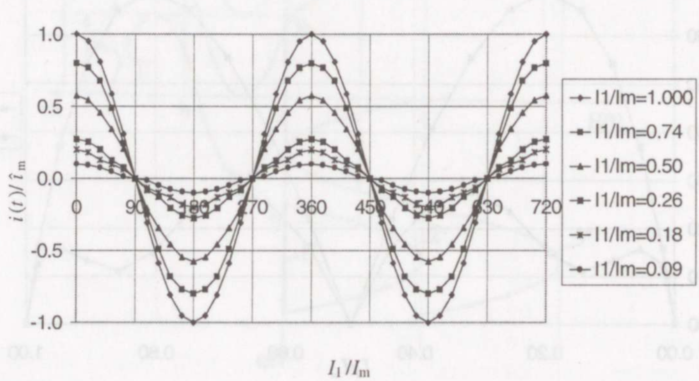

Fig. 7. The waveforms of the main currents for a DC controlled reactor that has limbs with three cross-sections at different duty ratios (I_1/I_m); $i(t)$ – instant value of the current, $\hat{\imath}_m$ – amplitude.

For the three-phase group, the control windings of single-phase reactors can be connected in delta and, therefore, the triplen harmonics are compensated. In addition, the maximum level of odd harmonics indivisible by three decreases to 1.0% by proper selection of cross-sections in the core. The design and technical and economic details of the DCCR are described in [5].

4. THREE-PHASE DC CONTROLLED REACTOR

Another DCCR design can be used in electrical power systems. In Fig. 8*a* three-phase reactor version is presented. It is assembled from three star-connected single-phase units with a slightly different connection of DC-windings. The control windings with thyristors are galvanically separated from the phase winding. This solves the insulation problems. The common AC phase-winding for both half-limbs solves the electrostatic problems for high-voltage (HV) and EHV reactors. The DC controlled windings are connected in delta for triplen-harmonics compensation.

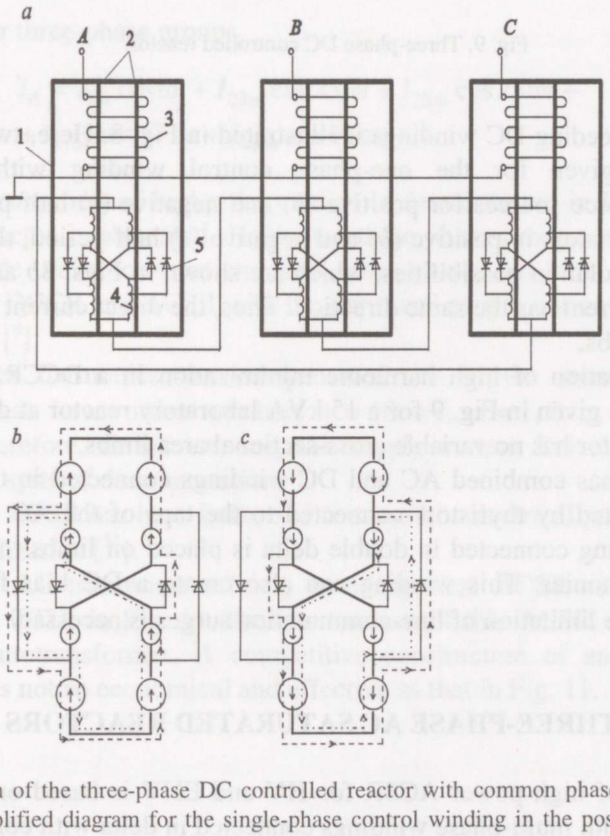

Fig. 8. Diagram of the three-phase DC controlled reactor with common phase windings for split limbs (*a*), simplified diagram for the single-phase control winding in the positive (*b*) and in the negative (*c*) half-period: 1 – magnetic core; 2 – limb divided into two parts (split limb); 3 – AC winding; 4 – DC windings; 5 – thyristor or power transistor.

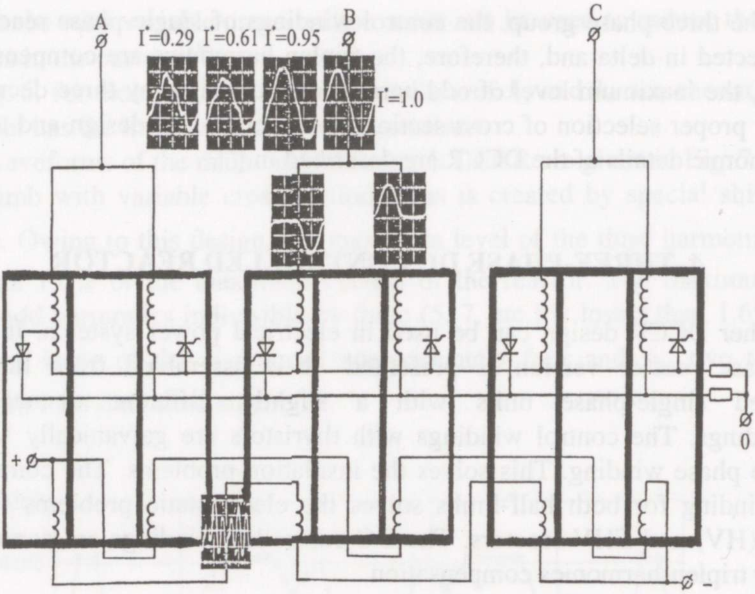

Fig. 9. Three-phase DC controlled reactor.

The idea of feeding DC windings is illustrated in Fig. 8. Here, two simplified diagrams are given for the one-phase control winding with equivalent electromotive force sources for positive (*b*) and negative (*c*) half-period. In the case of four thyristors in positive (*b*) and negative (*c*) half-period, there are only two current circulation possibilities, which are shown in Figs. 8*b* and *c*. In both half-periods, current has the same direction. Thus, the direct current saturates the half-parts of limbs.

As an illustration of high harmonic minimization in a DCCR, the current oscillograms are given in Fig. 9 for a 15 kVA laboratory reactor at different duty levels. This reactor has no variable cross-sectional area limbs.

The reactor has combined AC and DC windings connected in the grid. The DC bias is created by thyristors connected to the taps of the AC winding. An additional winding connected in double delta is placed on limbs to compensate the triplen harmonics. This winding can also create a DC bias from another source, when the limitation of line-commutation surges is necessary [6].

5. THREE-PHASE AC SATURATED REACTORS

The design of high power ACSR for HV and EHV is based on harmonics-compensation with multi-phase windings connected in delta with continued sides (continued-side delta connection).

In a three-phase saturated reactor, it is possible to compensate higher harmonics if the reactor construction is assembled symmetrically for ferromagnetic cores and windings. The magnetic similarity of phases is essential.

Conditions of harmonic compensation are discussed in [8,9]. If the saturated reactor has three-phase symmetrical groups and the voltage of each phase is sinusoidal, then the current of each phase can be described by an analytical equation.

The current of phase *A* for the ACSR is expressed as follows:

with two three-phase groups

$$
\begin{aligned}
i_A &= I_{1m}\cos\omega t + I_{11m}\cos 11\omega t + I_{13m}\cos 13\omega t + \\
&+ I_{23m}\cos 23\omega t + I_{25m}\cos 25\omega t + \ldots,
\end{aligned}
\tag{5}
$$

with three three-phase groups

$$
\begin{aligned}
i_A &= I_{1m}\cos\omega t + I_{17m}\cos 17\omega t + I_{19m}\cos 19\omega t + \\
&+ I_{35m}\cos 35\omega t + I_{37m}\cos 37\omega t + \ldots,
\end{aligned}
\tag{6}
$$

and with four three-phase groups

$$
\begin{aligned}
i_A &= I_{1m}\cos\omega t + I_{23m}\cos 23\omega t + I_{25m}\cos 25\omega t + \\
&+ I_{47m}\cos 47\omega t + I_{49m}\cos 49\omega t + \ldots
\end{aligned}
\tag{7}
$$

The compensation of higher harmonics is demonstrated in Fig. 10, where a nine-limb reactor is presented. Here, two three-phase groups of windings have continued-side delta connections and one group has the star and delta connections. DCCR and ACSR with the improved supply current can be realized according to [8].

All higher harmonics are compensated for in the reactor, except the harmonics that have order numbers $\nu = 18n \pm 1$, $n = 1, 2, \ldots$ (see also Eqs. (5)–(7)). Therefore, as we can see, the supply current has almost sinusoidal waveform in spite of deep saturation.

A similar ACSR has been built, and it is used in electrical power systems for voltage stabilization [11].

For EHV AC transmission lines, an economical ACSR solution has been developed at TTU. In Fig. 11, the construction of this ACSR is shown with a step-down autotransformer. A competitive construction of an ACSR with a transformer is not so economical and effective as that in Fig. 11.

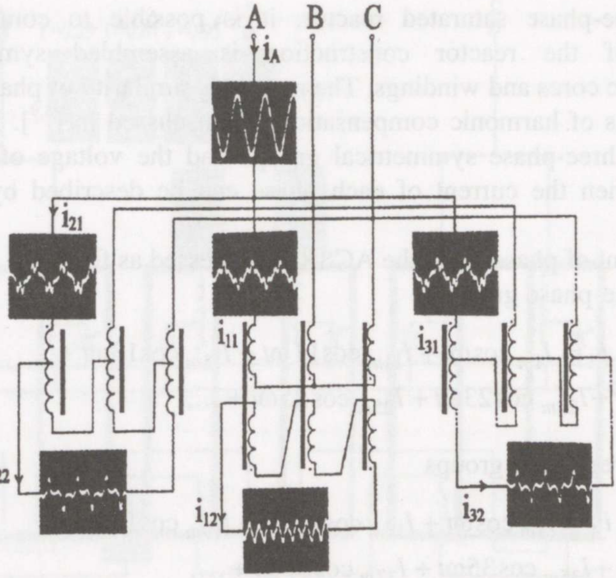

Fig. 10. Compensation of higher harmonics in a nine-limb saturable reactor.

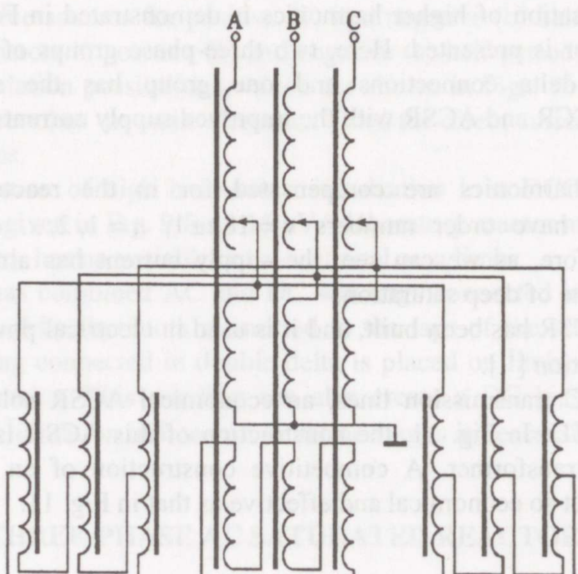

Fig. 11. Diagram of a harmonic-compensated AC saturated reactor with on-load tap-changer created at Tallinn Technical University.

6. PRINCIPLES FOR CREATING SATURABLE REACTORS

An important requirement for UHV reactors is a minimum number of windings on each core of the reactor. A device with one winding per core is formally ideal, the one with two (as in an autotransformer) or three (as is common in a large transformer) windings is poorer. An increased number of windings, owing to large insulation distances, makes the reactor cumbersome and poorly suited for use at EHV. This requirement can be satisfied according to [[12]].

The main characteristics of the reactor are: control range, sinusoidal characteristics of the consumed current, response time of the current control, power losses, etc. For practical purposes, the control range of inductive reactance (current) of 10:1 is fully adequate. Generally, this is easily ensured in controlled reactors [[13]]. The maximum admissible distortion of the current waveform depends on the parameters of the network feeding the reactors. Special studies are required to determine distortions. As the first approximation, the admissible nonlinear distortions can be assumed to be 5–10%.

The requirements on the response time of a controlled reactor vary significantly, depending on the purpose of the reactor. During the compensation of the excess energization power of the UHV power transmission lines, the natural control speed of a reactor is fully acceptable. However, with increasing operational stability of power transmission lines, a rise time of the power from 0.2 to 1.0 pu and a fall time of the power from 1.0 to 0.2–0.3 pu should be accomplished tentatively within 0.3–0.4 s. As shown by calculations in [[13]], the fulfilment of this condition requires the use of a control system that has a high ceiling factor [[14]], switching the rectifier into the inverter mode [[15]]. The rated power of controlled reactors depends on the voltage and length of the transmission line. This power can range from 100 to 1000 Mvar and more. If the controlled reactor will be used to limit switching surges of the line, then reactors can have 3–5-fold short-lived overload capacity [[12,13]]. The consumption of active materials and the cost are somewhat higher than in the reactors without overload capacity. However, the higher cost of the reactor can be compensated by the reduction of the line cost because distances between phases, and earth and phases can be smaller.

The study of the main requirements and indices allows for the choice of a rational reactor design.

Reactor design depends on the rated voltage and a rated power as the main parameters for a three-phase group of three one-phase reactors or one three-phase reactor. For an EHV DCCR, single-phase units with a shell-type core are preferable. The magnetic circuit 1 has two cores (half-cores) 2, two horizontal 3 and two lateral yokes 4 (Fig. 12).

The directions of the DC magnetic fluxes Φ_0 in the limbs are opposed and the directions of the AC fluxes are the same. Here, the AC field is closed through the lateral yokes, while the DC field is closed through the horizontal yokes and partially through the lateral ones. The active zone of the reactor is the saturated

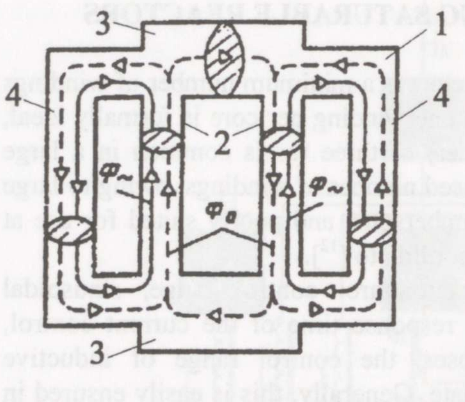

Fig. 12. Diagram of magnetic circuit for a one-phase DC controlled reactor: 1 – magnetic circuit, 2 – core, 3 – horizontal yoke, 4 – lateral yoke.

core zone with windings, and the passive zone consists of the yokes. Under all operating conditions of the reactor, the saturation of yokes should be avoided.

The principles for selection of a rational DCCR design are discussed in [5,13] and those for an ACSR in [12,16,17]. The core reactors with a plane magnetic system are the simplest and most suitable for manufacturers. The manufacturing process differs very little from that of a transformer. A controlled reactor, as a saturated reactor, is a generator of higher harmonics. In this case, the task of developers is to choose the simplest scheme for the compensation of higher harmonics to satisfy the imposed requirements.

Once the reactor design is chosen, the next step is electromagnetic calculation. At TTU, original methods for electromagnetic calculation have been developed [5,8,13,16–24] for different reactor designs. In [8], some parts of the theory for saturable reactors have been generalized for the first time. These include the simulation method based on the design of a magnetic multiport and a numerical solution to calculate steady-state saturation harmonics and magnetization processes. By means of this method, reactors with different kinds of topologies can be simulated without using network circuit equations. In the case of relative parameters, the results are extended, although the system is nonlinear.

An essential problem in saturable reactor design is the calculation of the influence of deep saturation on core losses. That is particularly important for the DCCRs in which DC and AC magnetic fields are superimposed. For this purpose, the analytical method, taking saturation into consideration, has been created and tested. To use the model, it is necessary to know the waveform of the induction and its spectrum. It is shown theoretically and through measurements that the higher the AC field induction the less the DC-bias field magnifies the hysteresis losses. If the field strength of DC bias is sufficiently high, iron losses are reduced considerably. Figure 13, as an illustration, shows the computed (*a*) and measured (*b*) [8] values of the increasing factors of the hysteresis losses k_{h0} by premagnetizing. The increasing factor is

$$k_{h0} = \frac{p_{h0}}{p_{hm}}, \tag{8}$$

where p_{h0} and p_{hm} are hysteresis losses at DC bias and in the symmetrical alternating field with the amplitude of the induction B_m.

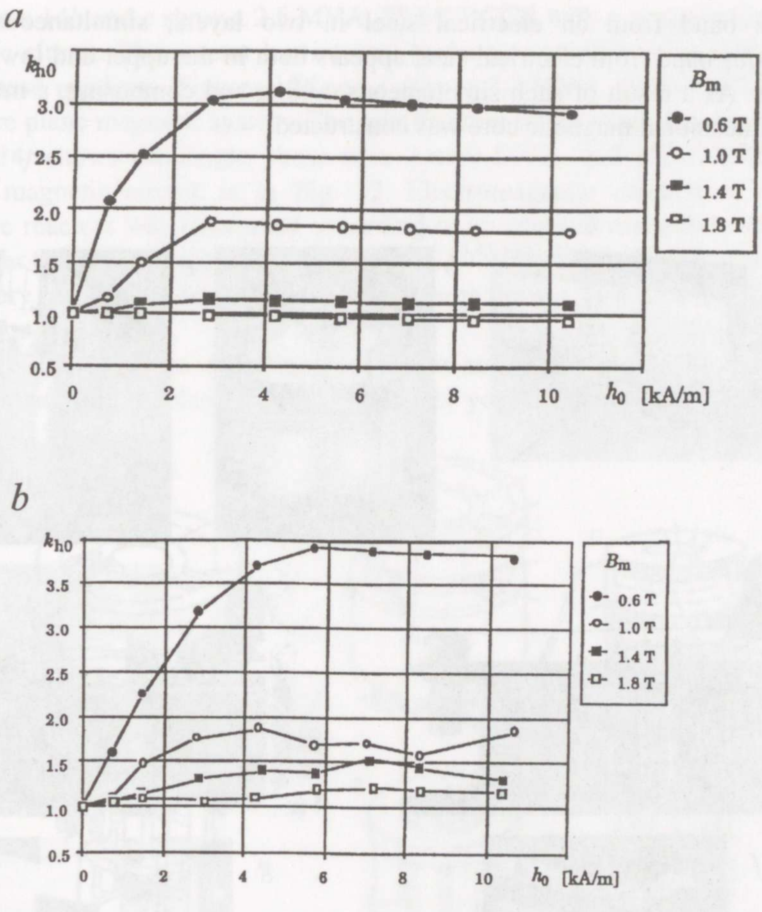

Fig. 13. Computed (*a*) and measured (*b*) values of the increasing factors of the hysteresis losses, with the AC windings in each phase connected in parallel.

All these calculation methods have been tested thoroughly by designing, manufacturing and testing the ferromagnetic saturable reactors. Figure 14 shows four units, the first three were built in Estonia and the fourth was constructed in Zaporozh'e in co-operation with the Zaporozh'e Transformer Plant, the APEI, and the USSR Energy Research Institute. Figure 14 shows the control, diagnostic and protection system for the controlled reactor 20 MVA, 35 kV. Ordered by the Moscow Plant of Electrical Engineering, it was developed, built and tested in the Power Supply Control Laboratory at TTU. The laboratory saturable reactor (Fig. 14*a*) has an original construction and manufacturing technology. The magnetic circuit includes nine split cores (limbs divided into two longitudinal parts), surrounded by two control windings, which are covered with a single-phase winding. In the first step, the windings were built, then they were fixed according to the designed location, with the magnetic circuit formed by strips and the band from an electrical steel in two layers, simultaneously. The continuous band from electrical steel appears both in the upper and lower yokes by turns. As a result of such simultaneous coiling and composing, a monolithic three-dimensional magnetic core was constructed.

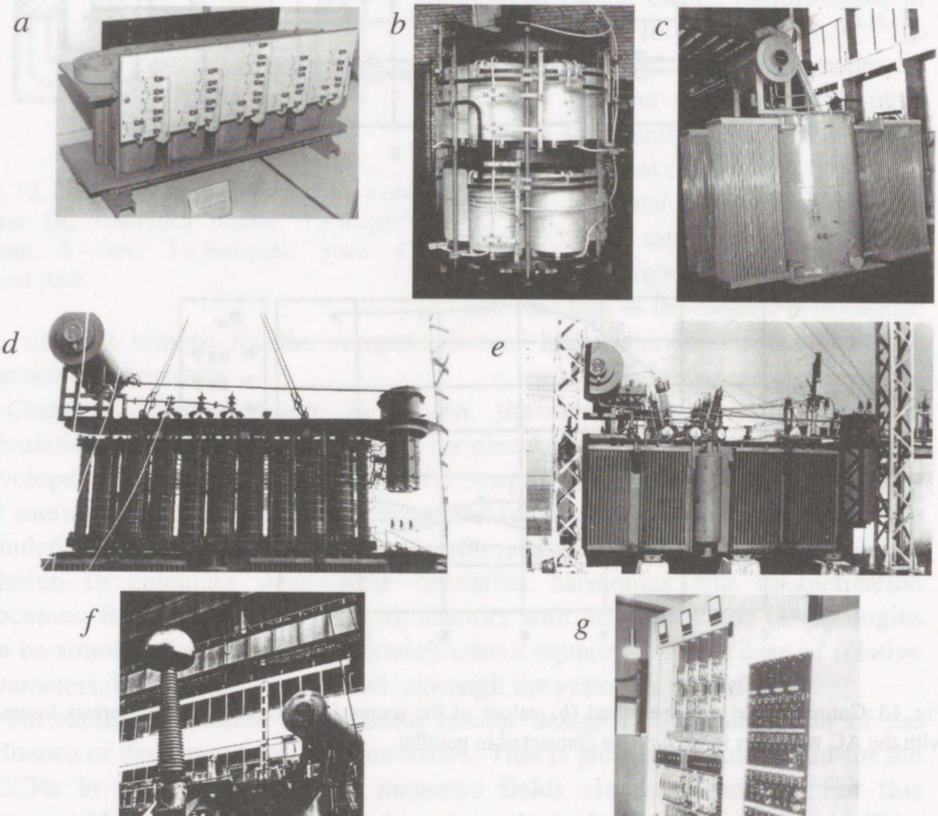

Fig. 14. Saturable reactors manufactured in Estonia and in Ukraine: *a* – nine core laboratory saturable reactor with special three-dimensional magnetic circuit; *b* and *c* – the 2.5 MVA, 35 kV DC controlled reactor – active part (*b*) and overview (*c*); *d* and *e* – 3.3 MVA, 10 kV AC saturated reactor – active part (*d*) and overview (*e*); *f* – 3 × 60 MVA, 525 kV DC controlled reactor (one phase); *g* – the control, diagnostic and protection system of the controlled reactor 20 MVA, 35 kV.

Figures 14*b* and *c* show a 2.5 MVA, 35 kV DCCR with a symmetrical spatial magnetic circuit. The reactor has internal harmonics compensation with special multi-phase windings. Figures 14*d* and *e* show a 3.3 MVA, 10 kV ACSR with a nine-core plane magnetic system. The specification of the reactor is given in [11]. Figure 14*f* shows the single phase of a 3 × 60 MVA, 525 kV DCCR with a similar magnetic circuit as in Fig. 12. Electromagnetic calculation of these saturable reactors was conducted according to an original method developed in the Power Supply Control Laboratory at TTU [5,8,9,13,17–25]. Tests have shown that the theory and know-how necessary for large power HV and EHV reactor production is adequate.

Figure 15 illustrates the magnetic circuit and high harmonics suppression development in saturable reactors in the last 27 years at TTU [7,9,10,12,26–31].

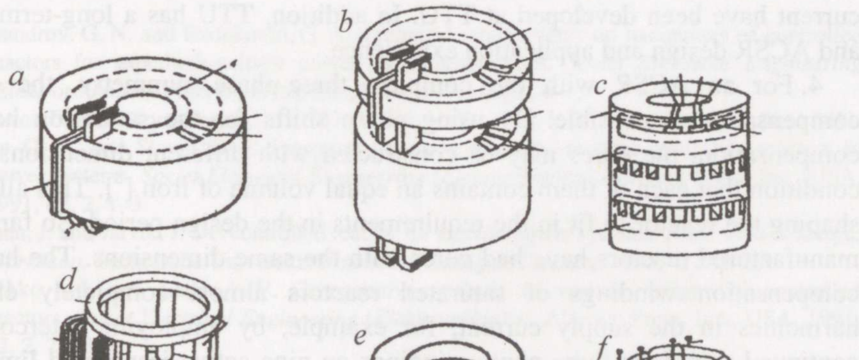

Fig. 15. Development of saturable reactor constructions at Tallinn Technical University in the last 27 years: *a* – DC controlled reactor (DCCR) with a rotating magnetic field; *b* and *c* – combined AC saturable reactor with DCCR; *d* – two-storeyed symmetric spatial reactor; *e*, *f*, *g*, *h*, and *i* – spatial magnetic circuits for laboratory reactors; *j*, *k* – multi-core plane magnet circuits; *l* – two-core or split-core magnet circuit.

7. CONCLUSIONS

1. To ensure the reactive power balance under all operating conditions is very important for AC power transmission lines. High power saturable reactors can be used for reactive power and voltage control together with uncontrolled shunt reactors or instead of shunt reactors. The requisite reactor unit power for EHV and UHV lines can reach 100–1000 Mvar.

2. Saturable reactors, depending on the saturation principle, can be saturated with alternating current (AC saturated reactors) or with direct current (DC controlled reactors) or combined ACSRs and DCCRs. Any kind of high-power saturable reactor suffers from current distortions, and constructionally, UHV reactors must be simple and robust.

3. Theory and design of large power saturable reactors with sinusoidal supply current have been developed at TTU. In addition, TTU has a long-term DCCR and ACSR design and application experience.

4. For an ACSR with the complete three-phase symmetry, the internal compensation is possible. By using phase shifts for the saturation harmonic compensation, the cores may be constructed with different dimensions on the condition that each of them contains an equal volume of iron [8]. This allows for shaping the reactor to fit in the requirements in the design period. So far, all the manufactured reactors have had cores with the same dimensions. The harmonic compensation windings of saturated reactors almost completely eliminate harmonics in the supply current, for example, by employing interconnected continued-side delta three-phase windings on nine active iron-cored limbs. The largest harmonic currents, 17th and 19th, do not usually exceed 1% of the full-rated current. In fact, these values are so low that they can be neglected, and these harmonics do not require any harmonic filters.

5. For a DCCR with three-phase symmetry, the internal compensation is possible too. The main difference in the active part of such reactors is that in a DCCR, each core with phase windings must be divided into two parts. Each of these parts is covered with the control winding and both parts together are surrounded with the phase winding. Other methods can also reduce current distortions in a DCCR. It is of prime importance to use very high saturation level, if necessary, to achieve additional minimization of higher harmonics. At this minimization, the core must be divided into many parts such that the induction in each part is the same, but the field strengths and volumes are different and chosen correctly.

6. If a reactor with a large overload capability is needed to reduce the voltage surges for transmission lines, then the phase-shift method (internal compensation) must be used for the compensation because, otherwise, the level of high harmonics can become too high. The reason is that the compensation is exact and does not depend on the DC bias, while the harmonics suppression (minimization) is not exact and depends on it.

7. During long-time team work, the theory for saturable reactors has been developed. It consists of the theories of higher harmonics, physical processes in reactors, hysteresis losses by high saturation and premagnetization, control and transient processes. Engineering calculation and design methods for DCCRs and ACSRs have also been developed. The theory and calculation methods were tested on laboratory reactors and then on 10, 35, and 525 kV reactors built in Estonia and Ukraine.

In [32], an ACSR analysis in the case of the parametric voltage control unit is described.

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VÕIMSAD KÜLLASTUSREAKTORID VAHELDUVVOOLU ÜLEKANDELIINIDE JAOKS

Jaan JÄRVIK ja Juhani TELLINEN

On tutvustatud Tallinna Tehnikaülikoolis 27 aasta jooksul küllastusreaktorite alal tehtud uurimistöö tulemusi. Sellised reaktorid on vajalikud kõrge- ja ülikõrgepingeliinide pinge ja reaktiivvõimsuse kiireks ja sujuvaks reguleerimiseks. Maailmapraktikas ei ole seni seesuguste parameetritega sujuvalt reguleeritavaid reaktoreid.

Küllastusreaktorid jagunevad küllastusviisi järgi alalisvoolu eelmagneetimisega juhitavateks reaktoriteks ning vahelduvvoolu küllastusega reaktoriteks. Reaktorite vajalik võimsus varieerub olenevalt liinide nimipingest vahemikus 100–1000 MVA. Reaktor peab olema oma ehituselt lihtne ja robustne, et seda oleks võimalik ehitada liini nimipingega võrdsele pingele.

Küllastusreaktorid töötavad sügavküllastuses, millega kaasnevad tarbitava voolu tugevad moonutused. Seepärast on reaktorite väljatöötamisel võtmeülesandeks leida sellised lahendused, mis muudavad tugevalt väljendatud mittelineaarsete omadustega reaktori toitevõrgu suhtes näivalt lineaarseks. Seega on voolu kõrgemate harmooniliste allasurumine lihtsa ja robustse konstruktsiooniga reaktoris üliraske probleem.

On välja töötatud küllastusreaktorite teooria, mis haarab kõrgemate harmooniliste kompensatsiooni ja mahasurumist, mittelineaarses keskkonnas toimuvate füüsikaliste protsesside kirjeldust, kadude arvutust sügavküllastunud elektrotehnilises terases ja muudes konstruktsioonielementides ning reaktoritüüpide kõiki harmoonilisi arvestavaid originaalseid insenerarvutus- ja projekteerimismeetodeid. Kõiki neid meetodeid on kontrollitud mitmekümnel erineval laboratoorsel reaktori mudelil ja ka võimsatel 10, 35 ja 525 kV reaktoritel, mis on ehitatud Eestis ja Ukrainas.