Technical characteristics of fifth-generation induction heating generator thyristor frequency converter-5 (TFC-5) series in the range from 50 Hz to 22 kHz, from 25 kW to 4 MW (2014)

1. Basic data

1.1. Fifth-generation TFC-5 frequency converters series has been extended relative to the previous generations of TFC in the range of frequencies and capacities, frequency from 50 Hz to 22 kHz, capacity from 25 kW to 4 MW (in separate TFC). TFC-5 series General operating conditions are stated in the Table 1, basic parameters are stated in the Table 2.

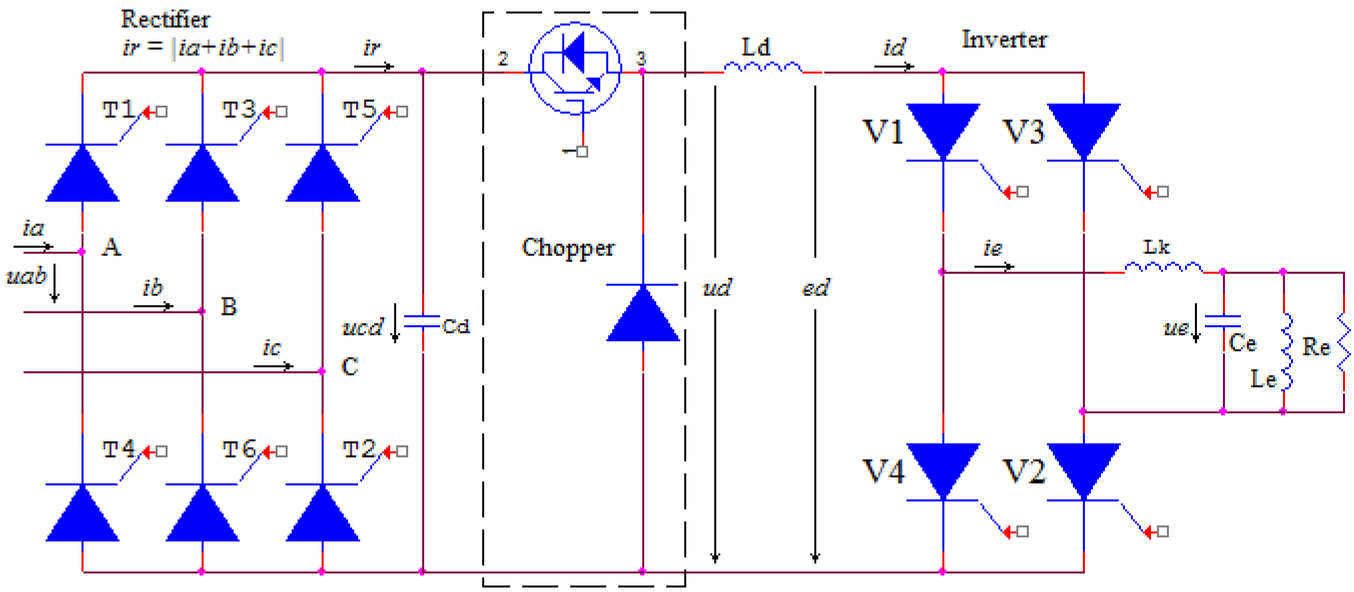
Table.1. TFC-5 series' General operating conditions

№	Name of index	Units of measurement	Value
1	Environment temperature	^{o}C	0 ÷ 40
2	Cooling water entering temperature, not more than	^{o}C	35
3	Ambient humidity, not more than	%	90
4	Dust level, not more than	mg/m^3	20
5	Ingress Protection in the cabinet, not less than	IP	55
6	TFC-5 warranty period from shipment date	1 year	2.5

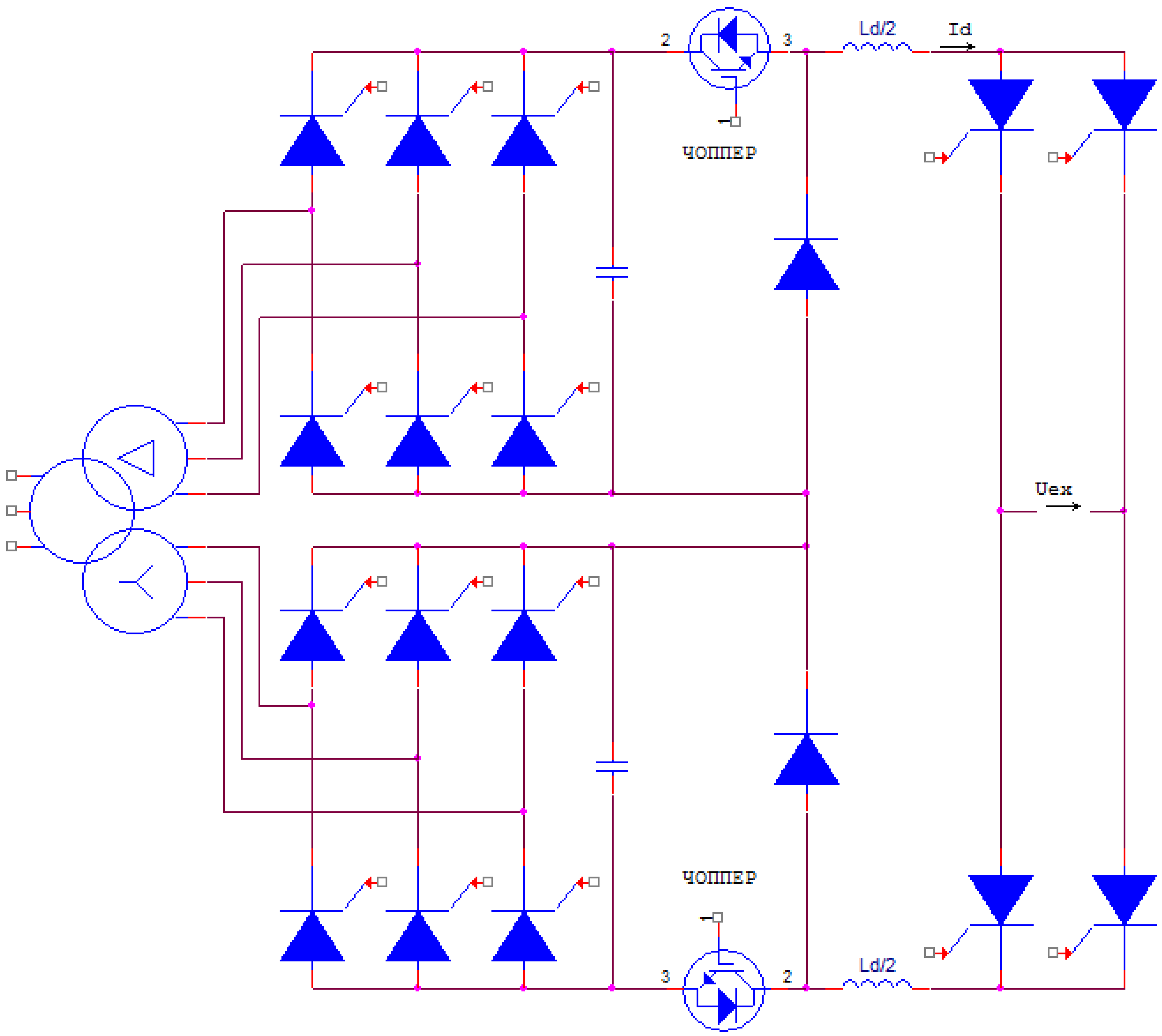
Table.2. TFC-5 series' basic parameters

№	Name of index	Units of measurement	Value
1	Series of nominal output power Pn *1)	kW	25; 32; 40; 50; 63; 80; 100; 125; 160; 200; 250; 320; 400; 500; 630; 800; 1000; 1250; 1600; 2000; 2500; 3200; 4000
2	Series of frequency ranges, where each range with double frequency variation refers to certain design of TFC-5 *1)	kHz	0.05÷0.1; 0.15÷0.3; 0.25÷0.5; 0.5÷1; 0.75÷1.5; 1.25÷2.5; 2÷4; 5÷10; 8÷16; 11÷22
3	Series of nominal output voltage **Un** *1)	B	400; 500; 800; 1000; 1600; 2000
4	Series of nominal line input voltage **Uab**, 50 or 60 Hz 1*)	B	3x380; 3x550; 3x660; 3x1000
5	Allowable input voltage deviation	%	±5
6	Output voltage control range: - at nominal voltage **Un**=800B and less - at nominal voltage **Un**=1000B and more	B	 100 ÷ **Un** 200 ÷ **Un**
7	Power-control range relative to maximum	%	1 ÷ 100
8	Allowable range of variation of parallel active circuit resistance component Re, rate setting is made in relation to Re=Rn value in nominal conditions	Re/Rn	0.5 ÷ 5
9	Accuracy of voltage stabilization **Ue** on Re 2-fold change at any segment of Re allowance range (if there is no current limitation)	%	±2

*1) Out of range value can be ordered by agreement



Pic. 1. Basic circuit of TFC-5 series in the range from 50Hz to 22 kHz, from 25 kW to 1.25 MW



Pic. 2. Scheme of power design TFC-5C from 1.6 MW to 4 MW

1.2. Example of source's design marking:

TFC	-	5	M	-	320	-	1.0	-	800	-	380
1		2	3		4		5		6		7

1. Series name
2. Fifth generation
3. Design group (A, M, C), item 1.6
4. Nominal output power, Table 2, item 1
5. Highest possible frequency, Table 2, item 2
6. Nominal output voltage, Table 2, item 3
7. Nominal line voltage, Table 2, item 4

The source should meet the requirements of all items in the Table 2 in double frequency variation range (50…100%) without changes in power (only load circuit changes, which specifies frequency).

1.3. Basic circuit of TFC-5 (Pic.1) includes rectifier (Rectifier), DC link and inverter (Inverter). On picture 1 instantaneous values appear in lower case letters in italics. In the tables and text, for designation of average or effective values bold capital letters without italics are used, for example: average choke current is **Id**, effective circuit voltage is **Ue**, effective line voltage is **Uab**. DC link contains a filter capacitor Cd, a choke Ld and IGBT-based diode transistor chopper (Chopper). The chopper controls current in the choke Ld. Parallel oscillatory load circuit CeLeRe is connected to inverter output and determines inverter's output frequency, which is higher than the resonance frequency of the circuit.

1.4. In order to improve quality of power supply in the network, the scheme of power design TFC-5 is based on 12-pulse rectifier (Pic.2). The rectifier is energized from the transformer with two sets of secondary coils with 30^o phase shift, the first set in star-connected circuit and the second set in delta circuit. As a result, on the input side of transformer the high quality of consumption current waveform is reached (close to sinusoidal).

1.5. Sources' nominal output voltage matches with nominal voltages of circuit's capacitors. By agreement between the Manufacturer and the Customer off-standard nominal voltage can be used – see Note to the Table 2.

1.6. TFC-5 sources are divided into 3 groups according to their design:

1.6.1. In the group TFC-5A (letter "A" is for "Air"), from 25 kW to 320 kW, all heat-generating components are cooled with air. Semiconductor elements are modular-type and they are screwed to the common heater, see construction in the item 3.4. At low power, up to 80kW, a fan is not set up - natural cooling is used.

1.6.2. In the group TFC-5M (letter "M" is for "Module"), from 125 kW to 500 kW, thyristors of modular type are used, which are screwed to a liquid-cooled (water) plate. Water is insulated, it has no electric potential, so there are no strict requirements to water's purity and electrical conduction. It is allowed to use running water according to GOST 16323-79 standard, taking into account additional requirements:

- A grid with mesh size of 1x1 mm maximum should be installed at system input;
- Quantity of insoluble residue (mechanical impurities) should be less than 12 mg/l;
- electrical resistivity should be 4 kiloohm•cm minimum.

1.6.3. In the group TFC-5C (letter "C" is for "Capsule" – wafer), from 100 kW to 4 MW (in separate TFC), wafer-type thyristors with liquid cooling (water) are used. Water is under electric potential, there are strict requirements to electrical resistivity: not less than 50 kiloohm•cm. The quality of water should be achieved by the use of dual-cycle water cooling system with centralized or individual heat exchangers.

1.7. Generally, characteristics of TFC are defined by the type of thyristors, used in the inverter. Types of thyristors and their basic parameters are stated in the Table 3. As a rule, in all source groups TFC-5A, 5M, 5C in each inverter arm one thyristor is used. However, in case of using the thyristors with a little turn-off time and low class, it is possible to use two sequential thyristors in the arm.

Table 3. Basic parameters of inverter's thyristors in design groups TFC -5A, 5M, 5C

№	Manufacturer	Type of thyristor in the inverter	Construction	Average current, A	Class, V	Turn-off time tq, µs

TFC -5A, 5M design						
1	Semikron	SKKT-330/18	Modular	330	1800	50…150
2	Semikron	SKKT-570/18	Modular	570	1800	100…200
3	Proton	MTF3-375-15-A2	Modular	375	1500	16; 20; 25
4	Proton	MTFS3-305-11-A2	Modular	300	1100	5; 6.3
5	Proton	MTFS3-400-15-A2	Modular	400	1400	8; 10; 12.5; 16
6	Proton	MTFS3-630-15-A2	Modular	630	1500	16; 20; 25; 32
7	Proton	MTF3-420-21-A2	Modular	420	2100	16
TFC -5C design						
1	Proton	ТБ953-630-36	Wafer	630	3600	50
2	Proton	ТБИ233-320-24	Wafer	320	2400	25; 32; 40
3	Proton	ТБИ243-630-22	Wafer	630	2200	32
4	Proton	ТБИ153-800-15	Wafer	800	1500	10; 12.5; 16
5	Proton	ТБИ353-800-34	Wafer	800	3400	63; 80; 100
6	Proton	ТБИ153-1000-15	Wafer	1000	1500	12.5; 16; 20; 25
7	Proton	ТБИ153-1250-15	Wafer	1250	1500	16; 20; 25; 32
8	Proton	ТБИ873-1600-40	Wafer	1600	4000	125; 160
9	Proton	ТБЧ123-200-14	Wafer	200	1400	6.3
10	Proton	ТБЧ133-400-12	Wafer	400	1200	5; 6.3; 8
11	Proton	ТБЧ143-500-11	Wafer	500	1100	5; 6.3
12	Proton	ТБЧ343-500-11	Wafer	500	1100	5; 6.3
13	Proton	ТБЧ153-800-14	Wafer	800	1400	8; 10; 12.5; 16

1.8. Besides the series connection of thyristors in the arm, the parallel connection of two inverters to the common rectifier can be used, each with its Ld choke and its line to the circuit, which ensures uniform current division. In this case, individual impulse control and emergency control (“breaking”, overstress, breakdown of sequential thyristors in 4 arms) should be added for the second inverter.

1.9. A group operation of TFC-5 sources to the common load circuit is provided for the power increase. For example, grouping of two sources with unit capacity of 4 MV will give total capacity of 8 MV. The start and operation of one source for the circuit without detaching the second source can be provided, if necessary.

1.10. In the Table 2, items 1…4 a wide variety of basic output parameters of standard TFC-5 is presented for the Customer. Wide variety is provided by TFC-5 Manufacturer by using customized computer-aided design technology. In each case we propose to the Customer several design versions with prices, appropriate for Customer’s specific need. Designs are submitted to the Customer as standard tables with parameters (datasheet) where, besides the basic parameters from Table 2, items 1…4, some additional parameters are also stated: :

- maximum temperatures of semiconductor devices in area of TFC-5 operation ;
- current maximum values: in choke, at TFC-5 entry and exit ;
- losses in power units, coefficient of efficiency and TFC-5 output power at different voltage and frequencies;
- water discharge and pressure drop, fan power and noise;
- layout with designation of electrical values;
- mass and dimensions parameters.

If necessary, the Customer is assisted in the final choice of design.

1.11. Previous generation TFC sources generate higher current harmonics to the supply network, their frequency is ten and hundred times higher than the frequency of the supply network. Higher current harmonics deform a sinusoidal form of the network's stress curve and cause disturbance for other electrical consumers, connected to the same network node. An outdated state standard GOST 13109-67, updated in 1970 and 1987, and functional until 01.01.1999, specified a rate for a mean-square voltage nonsinusoidality ratio KU=5%, its calculation included only 12 harmonics – from 2 to 13. At the same time, network voltage distortion, due to TFC influence, occurred from the higher current harmonics. As a result, TFC sources before the 4th generation could pass standards for the mean-square ratio KU de jure, but de facto they disturbed other consumers

The new interstate standard GOST 13109-97, conforming to IEC international standards, signed by 9 countries and instituted from 01.01.1999, provides not only the rate for a mean-square ratio KU=8% (in which now 39 terms are included), but also the rates for separate harmonic components from 2 to 40, and ad infinitum.

The power filter in DC link of the fifth-generation TFC-5 source is designed in such a way as to ensure the rates for all harmonic components and for the mean-square ratio KU at the same time. TFC-5 sources are allowed to be connected to network node of sufficient power, observing the regulations of electromagnetic compatibility, stated in the Annex A.

1.12. The Table 4 shows the advantages of TFC-5 series regarding the product mix and parameters, compared to similar sources of other manufacturers (consideration up to 22 kHz).

1.13. Fifth-generation sources TFC-5 have the improved reliability and capability in all aspects of operation, compared to the previous generations of TFC – see section 2.

Table 4. Basic parameters of sources from different manufacturers

<table>
<tr><th>№</th><th>Parameter</th><th>Unit</th><th>aljuel.eu
Tallinn</th><th>termolit.com
Ukrain</th><th>reltec.biz
Ekaterinburg</th><th>inductotherm.ru
USA</th><th>ameritherm.com
USA</th><th>kuraist.narod.ru
Ufa</th><th>rocinduktor.ru
Chelya-binsk</th></tr>
<tr><td>1</td><td>Frequency range</td><td>kHz</td><td>0.05÷22</td><td>1.0÷8.0</td><td>0.15÷10</td><td>0.2÷10</td><td>0.5÷15</td><td>0.5÷22</td><td>0.2÷6.0</td></tr>
<tr><td rowspan="11">2</td><td colspan="9">Minimum/maximum nominal power for designs with different frequencies</td></tr>
<tr><td>- 0.05÷0.1 kHz</td><td>kW</td><td rowspan="5">50/4000</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>- 0.25 kHz</td><td>kW</td><td>-</td><td>800/3600</td><td rowspan="4">150/1750</td><td>-</td><td>-</td><td rowspan="3">1000</td></tr>
<tr><td>- 0.3 kHz</td><td>kW</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>- 0.5 kHz</td><td>kW</td><td rowspan="2">50/1600</td><td>320/3600</td><td rowspan="2">200/800</td><td>800</td></tr>
<tr><td>- 1.0 kHz</td><td>kW</td><td>320/1500</td><td>250/500</td><td>100/750</td></tr>
<tr><td>- 2.5 kHz</td><td>kW</td><td rowspan="2">40/1600</td><td>50/630</td><td>250/1000</td><td>50/320</td><td rowspan="2">35/500</td><td>63/320</td><td>100/750</td></tr>
<tr><td>- 4.0 kHz</td><td>kW</td><td>50/500</td><td>160/800</td><td>-</td><td>63</td><td>50/200</td></tr>
<tr><td>- 8.0 kHz</td><td>kW</td><td>40/1250</td><td>50/350</td><td>100/250</td><td>-</td><td rowspan="3">20/500</td><td>160/320</td><td>-</td></tr>
<tr><td>- 10.0 kHz</td><td>kW</td><td>40/800</td><td>-</td><td>63/320</td><td>15/35</td><td>12/100</td><td>-</td></tr>
<tr><td>- 16÷22 kHz</td><td>kW</td><td>25/400</td><td>-</td><td>-</td><td>-</td><td>16/100</td><td>-</td></tr>
<tr><td>3</td><td>Group operation to common circuit (item 1.9)</td><td></td><td>+</td><td>-</td><td>-</td><td>-</td><td>-</td><td>+</td><td>-</td></tr>
<tr><td>4</td><td>Options of cooling:
- liquid
- air</td><td></td><td>
+
+</td><td>
+
-</td><td>
+
-</td><td>
+
-</td><td>
+
-</td><td>
+
+</td><td>
+
-</td></tr>
<tr><td>5</td><td>Observance of standards of network influence acc. to GOST 13109-97</td><td></td><td>+</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>6</td><td>Universality (automated parameterization, item 2.16)</td><td></td><td>+</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>7</td><td>Multifrequency mode (item 2.17)</td><td></td><td>+</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>8</td><td>Black Box (item 2.18)</td><td></td><td>+</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>9</td><td>Internet-Diagnostics (item 2.19)</td><td></td><td>+</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>10</td><td>Model support of commissioning (item 2.20)</td><td></td><td>+</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>11</td><td>Warranty period (item</td><td>year</td><td>2.5</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

	4.7)								

2. *Improved performance technical characteristics relative to TFC of the previous generations*

2.1. **High coefficient of efficiency**. In TFC-5 losses are reduced due to the use of innovative technology. A diode-transistor chopper (IGBT-based) is introduced in the classical circuit of parallel inverter, which gives particularly significant advantages at low (lower than 0.5 kHz) and high (more than 4 kHz) frequencies. Inverter input current is discontinuous, current pause time is held with chopper at the limit: not less than 5^o at frequencies up to 2.5 kHz, or not less than 10^o at higher frequencies. The advantage of discontinuous current at low frequencies is that installed choke capacity is reduced due to the decrease of inductance, as well as the losses in it are reduced. The advantage at high frequencies is that there is no switching of the current (like in the classic current inverter), di/dt is lowered, there are no switching losses in inverter's thyristors and damping circuits. As a result of loss reduction the high efficiency is achieved. For example, in powerful high-frequency design TFC-5C-900-10.0-800-660 the efficiency value in nominal conditions is 97.3%. At the frequencies up to 1 kHz the efficiency value is higher than 98% in a majority of designs.

2.2. **Resistance to short circuit** – this quality is preserved in TFC-5, as well as in the previous generations, as a most valuable quality of the classic circuit. External (under load) and internal short circuits (damage of any power semiconductor) in all cases don't result in structural damage and violation of market condition (soot, melted copper's spatter, etc.). In case of thyristors' damage and short circuits in any point of the circuit, protection system switches off IGBT, it results in termination of abnormal current. Also, the damage of IGBT itself (switching-off failure) shouldn't't result in damage of other power components, because the inverter remains in operation for absorption of residual energy (at the time of failure) in DC link. Inverter's back emf prevents the abnormal current rise in the choke Ld while the last pair of rectifier's thyristors is burning down. Then comes a safe discharge of Cd filter capacity to the inverter which is remained in operation. The resistence to short circuits is an essential advantage relative to the transistor voltage inverters, where a switching-off failure of IGBT due to any reason (damage of IGBT or control failure) leads to severe consequences (violation of market condition).

2.3. **Optimal choice of cooling**. Options of cooling are described in item 1.6. For a low-power design the air cooling is preferable (TFC-5A group), as it gives a maximum operating reliability. There is no problem with "dirty" water and there are no leaks. Such reliability can provide long operation without intervention of maintenance personnel. At relatively low power, up to 160 ÷ 250 kW, sources of TFC-5A group are rather inexpensive and compact. However, starting from power about 250 ÷ 320 kW the sources of TFC-5M group are more compact, they are cooled with flowing water which has conductivity, but is insulated from electric potential, in order to prevent connecting pipes' erosion from the current in the water. For a high-power designs, about 500 kW and more, a wafer design of TFC-5C and dual-cycle cooling system with use of centralized or individual heat exchangers, where "clean" (not electroconductive) water interchanges heat with flowing water, would be economically sound. Also, the advantage of operation of the wafer design is cheapness and high availability of the thyristors after the expiry of TFC's warranty period. At the same time, the customer can purchase any spare parts from TFC's manufacturer (item 4.5).

2.4. **Improved thermal conditions** of a low-current equipment (control system) due to decrease of air temperature inside the cabinet by separation of the choke to the detached heat-insulated ventilated compartment, see items 3.3, 3.4. In the old TFCs heat leakage from the water-cooled choke to the air was significant, about 20…30%. Such heat leakage caused considerable heating of air in the cabinet, which could result in failures in the control system at the maximum permissible environmental temperature (40^oC) and at the maximum permissible entering water temperature (35^oC) at the same time.

2.5. **Rectifier is open (angle α=0)** in all working range of TFC-5. In the supply main the current phase shift cosine is close to 1. As a result, reactive power is saved, and distortion in the mains is minimal. Rectifier adjustment is used only for a smooth start of TFC-5, firstly in order to avoid current rush at filter charge, secondly, in order to prevent severe emergency mode in case if the power component is initially damaged (for example, defective IGBT) or failures in power circuit and control.

2.6. **Reduced (eliminated) peak voltages** on inverter's thyristors. Introduction of chopper allows using of intermittent current of the inverter. The inverse-peak voltage on the thyristors is zero (at certain combination of input and output voltage of TFC-5), or it is insignificant even if damping RC-circuits are absent. As a result, the requirement to thyristors' class is considerably lowered, losses in the damping RC-circuits are reduced a lot, or RC-circuits are not used at all. Inverter's reliability is improved, one of the most common causes of thyristors' damages - a back-voltage breakdown (in the old TFC – about 40% according to statistics) is eliminated.

2.7. **Current rush is eliminated** in case of inverter's commutation failure. Current rush is typical for TFC of the previous generations, and dangerous in some cases, because the rectifier has a delay in transition to the inverted mode at TFC's emergency shutdown. For example, if accidental commutation failure (due to disturbance) had occurred when the choke is empty, as a result the current has increased, then, if oscillation is recovered (it is real when choke is empty) the load voltage becomes notably higher than the nominal voltage, so occurs danger of thyristor's breakdown by forward voltage. However, in TFC-5 any emergency mode is safe due to cutoff from the energy source by means of chopper.

2.8. **The most common cause of thyristors' damages - a back-voltage breakdown – is eliminated.** In TFC of the previous generations, in case of some failure there was a problem of inverter's voltage rise above the nominal value. If this voltage rise occurs when the rectifier is open, it's impossible to stop it and prevent it, due to rectifier's delay. This disadvantage is a most common cause of thyristors' damages – about 50% according to statistics. In this case the cutoff from the energy source is made by means of chopper, which surely prevents the voltage rise.

2.9. **Controlled rectifier, chopper and inverter – it's a combination having a quality of mutual self-protection**. If some failure occurs in rectifier or inverter (in power or control - it doesn't matter), then chopper's switching-off results in breaking of circuit, in all cases. If the chopper is suddenly failed (IGBT switching-off failure), then the inverter absorbs residual energy of DC link (see item 2.2). Double failure simultaneously in the chopper and in the inverter is so unlikely, that it's almost unreal. Global failure, for example, the loss of one supply voltage in the control system always leads to chopper's switching-off and circuit breaking.

2.10. **Efficiency in the current limiting mode**. According to Table 2, item 8, the source should allow the change of parallel active resistance component (Re) towards the nominal point (Rn) in 2 times decreasingly Re/Rn=0.5, and 5 times increasingly Re/Rn=5. In both cases the power lowers down below nominal. In the old TFC power reduction in point Re/Rn=0.5 is about minus 55…60%. In TFC-5 the4 rectifier is always open, so the percent of power reduction in point Re/Rn=0.5 is considerably lower, which depends on input and output voltage ratio. For example, at input voltage **Uab**=660V and output voltage **Un**=1000V the power change in TFC-5 is minus 20%, and at **Uab**=380V and **Un**=800V (or 1000V) the power in TFC-5 doesn't reduces at all – i.e. in all current limiting range Re/Rn=0.5…1 the power equals nominal. Such effect considerably shortens heating cycle.

2.11. **Improved start method**. The start method (starting capacitor discharge) in TFC of the previous generations requires starting capacitor of at least 20% of the circuit capacitance. At low frequencies a rather powerful discharging circuits and charging circuits in the Start Block are also required. In TFC-5 the start method is updated: chopper allows starting of TFC-5 without the starting device, therefore there is no need to select a starting capacitor for specific load. The new method has a high commutation resistance, which gives a possibility of fail-safe start in any point of the ranges, stated in the Table 2.

Also, the imperfection of the old method - fire risk – is excluded. In the old method the discharging circuit is connected parallel to the circuit. Since the thyristors of the Start Block are under high voltage of the circuit in operating mode, there is a risk of breakdown due to class' defect, disturbance switching and other disturbance of control. Breakdown with formation of bilateral conductivity (short circuit) will lead to condition where the starting capacitor will be parallel-connected to the circuit as a series capacitor. In principle, the inverter can continue operation (with high di/dt value during commutation) until the occurrence of severe accident with inflammation of the Start Block's digital wires and simultaneous inverter thyristors' breakdown. In order to prevent wires' inflammation, it's necessary to put expensive high voltage fuses in the Start Block's discharging circuit. The fuses prevent the inflammation, but the inverter's thyristors break down. Besides, the fuses can break down sometimes, during regular discharge of starting capacitor. This can happen when a large starting capacitor is needed at rather large circuit capacity, which lowers reliability of operation.

2.12. **TFC state control is extended.** Rectifier and inverter's current sensors and heat contacts remain in all heat-generating units. Feedback transformer is replaced with more fail-safe voltage sensor, in which there are less phase shift errors and the frequency range is wider. Also, two additional voltage sensors are introduced: for the control of inverter's back emf and for the control of rectifier voltage. Such control allows making the protection system more fail-safe.

Back emf sensor allows controlling forward voltage, as well as reversing peak voltage on the thyristors, which improves protection efficiency.

Rectifier voltage sensor is useful because it provides more precise and more reliable diagnosis of severe emergency states, which are saved in the Black Box and TFC Internet-Diagnostics Data Base at the same time. Rectifier voltage sensor is not used in the regulating system. In case of need, it is possible to connect sensor's input wires to any other points of the power diagram for the control of some voltage. After sending the required Oscillogram to the Black Box and (or) to the Data Base, it is recommended to restore initial connection.

The signal of rectifier current sensor is used in the regulating system and for smooth start, also it's very useful for the analysis of abnormal Oscillograms. The signal of rectifier current sensor is an assembly of TFC phase input currents (before rectifier), in order to remove rectifier's impulses as soon as possible in case of current increase in any phase. Such precautionary measure is useful, because in case of rectifier's failure it will exclude severe consequences: structural damage and violation of transformer's market condition, breakdown of the automatic power circuit breaker, faults in Consumer's supply network.

2.13. **The succession of local control station (LCS) and remote control station (RCS) is preserved** with regard to the previous generations of TFC. The scheme of RCS remains the same, but, at the same time, galvanic insulation of C5 controller from LCS and RSC is provided. As before, LCS has buttons and lamps Start, Stop, Emergency, Automat Q1 and a separate voltmeter for load voltage. Information on LCS is shown with pointer instruments (which is more habitual and comfortable for visual perception, as compared with display) in 4 measurement channels: output power and frequency, inverter input current and voltage. For space saving on LCS four devices can be replaced with one device with 4 position switch. The innovation is that, in case of TFC-5 emergency shutdown, all 4 instrument readings "freeze" for observability of pre- emergency condition, i.e. all pointers stop in the position, preceding the emergency. Emergency reset (and reset of "freezing") is made with STOP button. A more complete control (monitoring) of TFC-5 condition is made on PC – see item 2.14.

2.14. **USB and RS-422 channels.** USB port is provided for PC connection, where a software utility launches, which shows readings from 4 channels of LCS measuring instrument, all adjusting Constants, and facilitate its adjustment and "upgrade". In addition, long-haul communication output RS-422 (hundreds of meters) is provided for monitoring and automation commands' reception. The commands allow setting TFC-54 output voltage, thereby ensuring certain mode of blank's temperature control in the choke. The format of command and command history are agreed with the Customer.

2.15. Controller C5 has extensive service system, inclusive parameterization, commissioning and maintenance of TFC-5 in operation. Components of service system are posted on site www.aljuel.eu pages: Service, Diagnostics. Service system includes the following instruments:

- **Automatic parameterization** ensures universality of TFC-5 source (item 2.16);
- **TFC-5 multifrequency mode** provides automatic selection of active set of adjusting Constants in case of TFC-5 output bus' switching to another circuit (item 2.17);
- **Black Box** ensures auto save (in Flesh-memory) of emergency mode's Oscillogram, if it occurs (item 2.18);
- **Internet-Diagnostics** provides a base of « quick response » in operation (item 2.19);
- **Model support** provides receiving of model Oscillograms of starting methods on TFC-5 mathematical model (item 2.20).

2.16. **Automatic parameterization** ensures universality of TFC-5 source. The source should have a possibility of operation with different circuits within all requirements in accordance with Table 2. Individual adjusting for specific circuit is based on automatic parameterization – configuration file (CF) gets ready to "upgrade" by means of service. All adjusting Constants of CF are calculated automatically at the input of circuit's individual parameters (capacitance, natural frequency, line inductance). "Upgrade" of CF into Flash-memory is made upon User command. If necessary, the service also provides for online correction of particular adjusting Constants.

2.17. **TFC-5 multifrequency mode.** Configuration file (CF) includes 4 sets of set of adjusting Constants for 4 different load circuits, whose natural frequencies get different points of allowable frequency range. Maximum frequency difference at the range edges is double, according to Table 2, item 2. If frequency difference of separate circuits is more than double, then an additional winding end (tap) should be available in the choke Ld. The use of tab gives possibility of changing Ld inductance and obtaining the range of sources' frequency difference of more than double. When starting TFC-5, the circuit is recognized automatically and, as a result, the set of active Constants conforming to this circuit is adjusted. If TFC-5 operates with one circuit, all 4 sets of Constants are the same.

2.18. **Black Box** ensures saving of 5 last emergency Oscillograms. Means of service provide accessible reading of Oscillograms from Flash-memory and detailed signals' presentation in graph form. Oscillogram includes 6 analog signals and 11 logic signals with sufficient resolution (2 ms) and covers a range for reliable diagnostics of emergency mode (tens of inverter periods). Also there is a possibility of saving the non-emergency (normal) Oscillogram.

2.19. **Internet-Diagnostics.** Each Oscillogram saving in the Black Box is followed by Oscillogram passing to the Internet. The passing is made with GSM modem, integrated in the controller by means of standard cellular network, with use of SIM card of any mobile network operator. Oscillograms come to the data base at the following url www.aljuel.eu/c5/index.html , where the summary table of Oscillograms from all TFCs is shown on a web-page. The developed Oscillograms classification system, available at www.aljuel.eu/Archive1/Diagnostics/html+pdf/c5-diagnostics.pdf , it allows to record precisely the results of detailed diagnostics for each Oscillogram – Diagnosis. In the summary table there are strict and short records of thousands of Oscillograms, forming a "knowledge base". Internet-Diagnostics is a powerful tool, which allows TFC-5 Manufacturer to react quickly in case of emergency and render prompt assistance to the Customer during the warranty and postwarranty period.

2.20. **Model support** provides free transfer of starting method Oscillograms, received on TFC-5 mathematical model where the actual circuit parameters are set, to the Customer. Model Oscillograms are used as reference for comparison with actual Oscillograms, which simplifies the commissioning

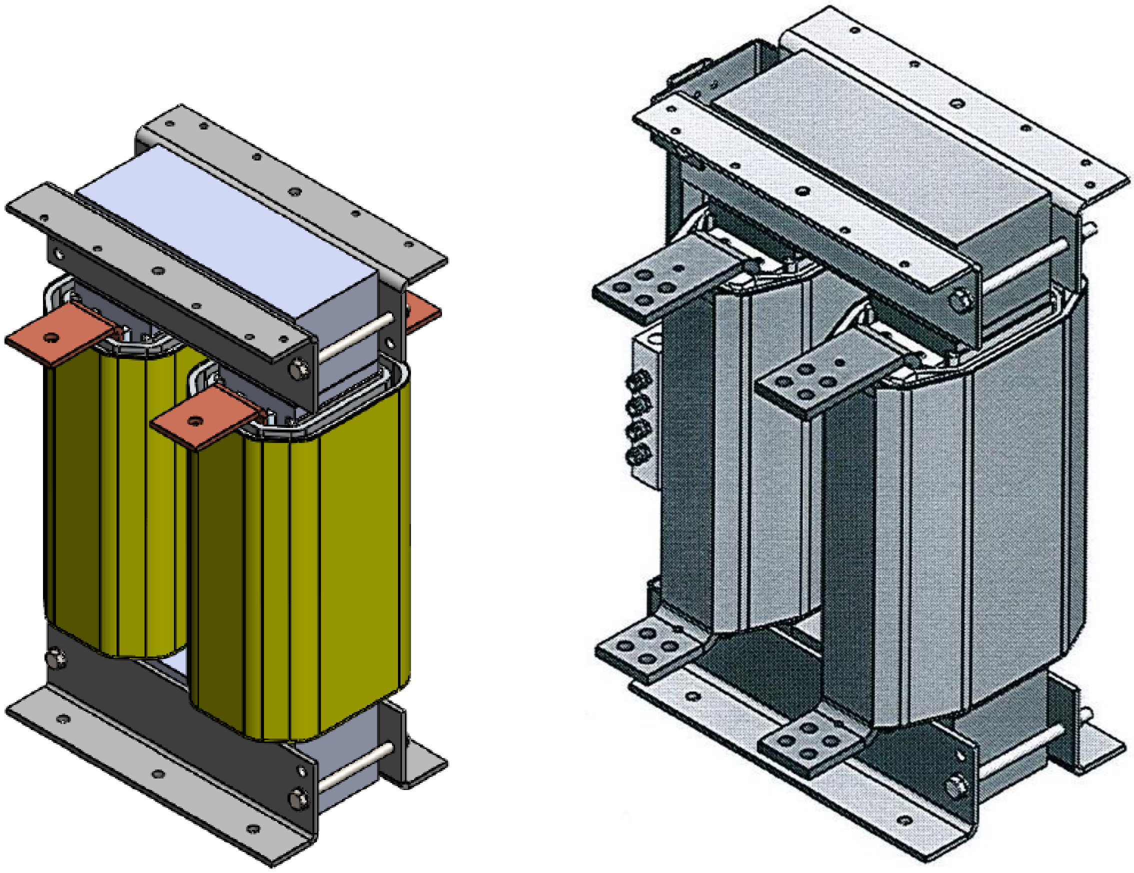
2.21. **Maintained standards** of tolerable supply violtage distortion caused by TFC-5 source's influence. See in item 1.11 implementation of the new interstate standard GOST 13109-97. Network power requirements, specification of TFC-5 connection to the network node and assurance of electromagnetic compatability you can find in the Annex A.

2.22. Cooling liquid (water) in choke Ld in TFC-5 sources has zero electrical potential – it is insulated from the winding (item 3.1).

2.23. **Reliability evaluation.** De facto TFC series sources of the previous generations have service life of 25 years and more. The above-stated technical solutions of the fifth generation bring in additional reliability, due to this the guaranteed service life is extended (item 4.8) against the TFC of previous generations and other manufacturers if the sources.

3. Design

3.1. In the sources with power up to 1.25 MW the chokes with air cooling are used (Pic.3a), with power from 1.6 MW – with liquid (water) cooling (Pic.3b).



a) b)

Pic.3. External view of chokes with air (a) and liquid (b) cooling

The winding of both types on chokes is made of wide thin (1 mm) aluminium sheets – a foil. Special patented technology ensures a contact of aluminium foil with copper outside lead. The use of foil allows combining minimization of electric loss and a good heat removal both at the air and liquid cooling. In the second case the cooling profile is inserted inside the coil (at the front and behind), in which the cooling liquid, electrically insulated from the winding, is circulating (cooling with flowing water is allowable).

The winding of choke is covered with three coats of insulating paper, impregnated with varnish. The choke goes through the stage of varnish impregnation, for which it is put in the hot warmish tank, after this it dries during many hours. Varnish coat is an effective dust protection and also it reduces choke's noise considerably. Besides, interwinding dampers are used for noise reduction. Two or three varnish coats can be used at the Customer's request. In the latter case the protection is maximal (technology for underwater use).

3.2. Choke with liquid cooling has 4 liquid flow channels. Inputs and outputs of 4 channels are connected to the transfer box, which can be seen on the Pic. 3b on the left side. The case has 4 inlet connections of the cooling channels, and on the other side of the case there are 4 outlet connections. When connecting the hose couplings to the connecting branches, it is possible to turn on the channels in series or in parallel, as well as parallel-series. Options of cooling channels' commutation allow matching pressure fall and water flow rate in the choke with other part of the cooling system, which cools a semiconducting power block.

3.3. Losses, removed from the choke with liquid cooling are divided in proportion: 80% are removed with liquid, 20% pass in the air. The issue of air heat removal for both types of chokes, air and liquid, is solved identically: the cabinet is divided with barrier into two insulated compartments, in the lower compartment the choke is located and ventilation is provided. In the upper compartment there are no ventilating holes and high level dust and moisture protection (table 1? Item 5) of electrical equipment without air circulation (see item 3.4).

3.4. In group TFC-5A a ribbed part of radiator is placed in closed vertical ventilation channel, which is included in the lower compartment of the cabinet. Heat leaks into the air from the side of semiconductors' contact with the cooler are insignificant in all TFC-5A, 5M, 5C groups. Heat leaks are led through the walls of cabinet's upper section without forced air circulation

3.5. Three input buses in the basic version are located on the left side in the upper part of the cabinet, alternative version is at the top. Two output buses to load are located at the bottom in the basic version, alternative version is – on the right of cabinets' lower part. Horizontal mirror symmetry and other positions of input and output buses are possible upon agreement at the time of order.

3.6. Line load inductance from below isn't restricted, zero inductance is allowable. A restrictive choke, like in the old TFC, is not needed. Line inductance restriction from above should be agreed at the time of order, because the maximal allowable inductance depends on many parameters of TFC-5.

3.7. Transformer for feedback signal is not needed – see item 2.12.

3.8. TFC-5 separate sources should be connected to high-power unit (network transformer) by separate lines, i.e. the rule of radial power distribution of separate sources should be observed, in order to prevent adverse influence. The length of TFC-5 connection line to the network node and network node's power (at short circuit current) should be stipulated in the order.

4. Prices, terms, guarantees

4.1. The Customer submits an order to TFC-5 manufacturer within the requirements of Table 1, Table 2, items 3.5, 3.6, 3.8. If it is necessary, the Customer informs of the additional demands. The Manufacturer submits to the Customer possible TFC-5 design variants together with prices, in form of standard tables with parameters (datasheet), see item 1.10. As a result, the final variant of design is agreed. The Manufacturer guarantees an optimal ratio price/quality to the Customer.

4.2. If the order is not provided with an acceptance, the price is effective within 3 months from the moment of agreement.

4.3. Remote maintenance of commissioning and operational Internet-Diagnostics are included in TFC-5 price.

4.4. The standard set of spare parts is included in TFC-5 price. The set of spare parts can be enlarged upon particular agreement. If necessary, after expiration of warrantee period for TFC-5 the power semiconductor devices, thyristors and IGBT transistors can be sold to the Customer at agreed fixed prices.

4.5. The payment should be made in three parts: 50% prepayment; 40% - payment before shipment ; 10% - payment after finishing of commissioning.

4.6. TFC-5 delivery period is 3…6 months from the moment of 50% prepayment.

4.7. TFC-5 warrantee period is 2.5 years from the date of shipment (customs clearance).

ALJUEL, Estonia, Tallinn ООО «С5-Сервис», Saint Petersburg www.aljuel.eu
(+372) 6-355-088, (+372) 53-731-742