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Overview of High Temperature Superconductor Machines

DOUINE B., MENANA H., BERGER K., LÉVÊQUE J.
University of Lorraine, Nancy, France

KOVALEV K., IVANOV N.
MAI (NRU), Moscow, Russia

Electrical machines are important parts of different power systems. The application of high temperature superconductors (HTS) in electrical machines is very promising due to high transport currents. This paper reviews various topologies of superconducting motors and generators using HTS published in the literature in recent time. It begins with a brief presentation of the HTS material used in electrical machines. The description of AC losses and cryogenic systems is done afterwards. Then we offer a striking description of the various realizations of HTS electrical machines such as half HTS synchronous machines, fully HTS synchronous machine, machines with HTS bulks and stacks. Some of these machines are totally innovative compared to conventional ones and their operating principle is strictly related to the presence of HTS materials.

K e y w o r d s : *high temperature superconductor, AC losses, electrical machine*

High Temperature Superconducting (HTS) materials used in large-scale applications have the potential to reduce the overall size and the volume of devices and increase their efficiency. In case of electrical machines, performances increase if the magnetic field increases. This can be done with the help of HTS material. Two properties of superconductors are very useful to reach this goal. Firstly, the joules losses are null with DC current if the current is less than a limit named the critical current and allows to reach very high current density. This way it's possible to reach high magnetic field with or without ferromagnetic material. The second advantage is the ability of a bulk superconducting material to shield or to trap high magnetic field.

In this article an overview of electric machines which use High Temperature Superconducting (HTS) materials made in recent years is presented. One of the advantages of a superconductive machine is its virtual elimination of inductor losses and, as a result, an increase in efficiency of 1 or 2%. This increase may seem marginal, but in certain applications such as in the oil industry or in gas compression, the accumulated increase in energy is likely to interest users. Another advantage which is linked to the increased current density is the smaller sizes of motors or the alternators. It should be possible to increase mass torque or power density by a factor of at least 2 [1].

The crucial factors in the design are the transmission of the torque and the achievement of the cryostat. Indeed, it is necessary to mechanically connect cold parts at around twenty Kelvin in recent achievements, to warm parts at room temperature, while minimizing heat flux toward the superconducting field system. Additionally, the cryostat, the key component of the low temperature environment which rotates, must be particularly neat, otherwise the benefit in terms of electric productivity is lost due to thermal losses which leads to an increase in cooling power. These machines like those of the first generation because of their cryostat have an electromagnetic air gap of around several centimeters implying a much weaker synchronous reactance in the order of 60%, than in classic machines. As the cryostat thickness does not change too much with the dimensions of the machine, this configuration seems to lend itself better to large power units.

Firstly, the HTS used in electrical machine are presented. Understanding the HTS properties is essential in many aspects. Secondly, the AC losses in HTS and the cryogenic environment which is essential for the operation of electric superconducting machines are exposed. The progress made in recent years in cooling methods has considerably eased the implementation of electric machines including high power electric ones. Finally, several types of machines are presented, some of them are fully HTS.

HTS materials used in electric machines. In electric machines HTS are used either as tape conductors to build inductors and/or armatures, or as bulk to make magnetic shield, flux concentrators or magnets.

HTS materials are ceramics and a lot of work has been done in recent years to convert them into usable conductors in practice. Two based on copper-oxide candidates make up a large proportion of the world market: $YBa_2Cu_3O_7$-x (commonly known as YBCO) and $i_2Sr_2Can_{-1}CunO_{10}$ (BiSCCO 1<*n*<3). These materials enable conductors for machines to be produced, but also bulks HTS tapes are essentially obtained by two processes. In the first process precursor powders are enclosed within a tube (oxide powder in tube, OPIT) which is drawn and thermally treated. This is the case for BiSCCO tape named first generation HTS (1G HTS, Fig. 1). The second process consists of making a deposit of around 1 μm on several substrate layers. This is the case for YBCO tape named second generation HTS (2G HTS, Fig. 2).

HTS material is a superconductor depending on three critical criteria, critical temperature, critical magnetic field and critical current density.

It is difficult to define precisely the critical temperature. The criterion of resistance less than 10^{-14}W.m is often utilized. The critical temperatures of the most used materials are 92 K for the YBCO and 110 K for BiSCCO-2223 compounds.

The critical current density of these materials depends on their internal structure. For monocrystals this value is relatively high in *a-b* plane. In polycrystalline materials made up of superconducting grains separated by normal zones, we distinguish two types of current: intragrain and intergrain. While the critical current density of the intragrain current Jcm is very high (several kA/mm^2), the critical current density of transport current *Jc* is much weaker (~100 A/mm^2). This comes from the fact that the transfer current passes from grain to grain, and moves between zones using the Josephson effect. It is also necessary to know that *Jc* diminishes quickly in the magnetic field.

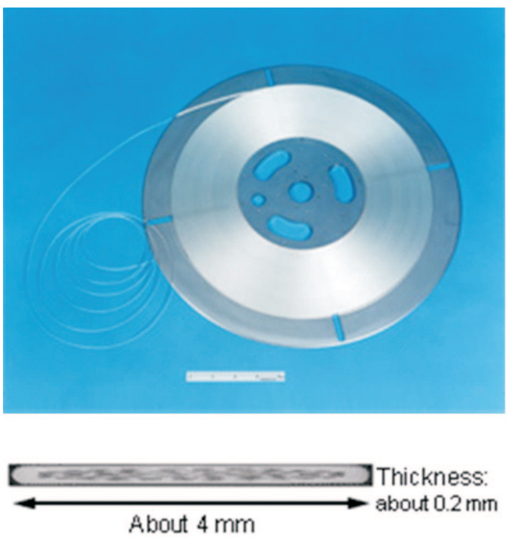

Fig. 1. BiSCCO tape made by SUMITOMO

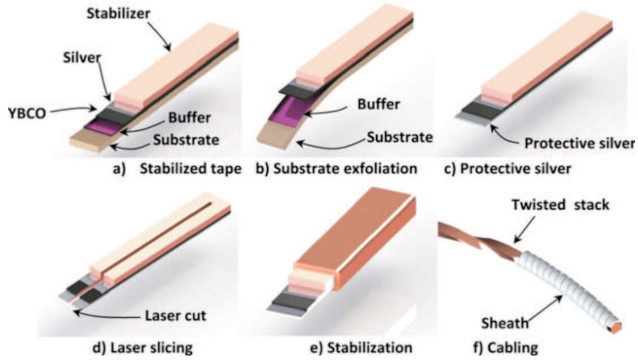

Fig. 2. YBCO tape made by Superox

In HTS material there are several critical magnetic fields Hc1 and Hc2 between them there is a field of irreversibility denoted by H* that defines the effective maximum magnetic field because the critical current density is then null over H*. Because HTS are anisotropic, Hc1 Hc2 and H* depend on the direction of applied magnetic field (Table 1).

Table 1

HTS material characteristics

Material	T_c (K)	m_0 Hc1 (T)	0 Hc2 (T)	*J* (A/mm^2)
YBCO	92	0.02 (//) 0.07 (^)	400 (//) 19 (^)	100 (75K, 7T//) 1,000 (75K, 3.5T//)
BiSCCO	80		400 (//) 19 (^)	1,500 (4.2 K, 30 T)

Recent HTS bulks are mainly monocrystals. To manufacture them YBaCuO monocrystals are used.

AC Losses in HTS superconductors and cryogenic system. One of the difficulties in producing an electric machine with superconductors is the specification of the cryogenic system. The primary source of heat in superconducting electrical machine is the AC loss in the superconductor. The works of numerous authors deal with evaluation of these losses [2–13].

AC Losses. AC losses in superconductor, are mainly due to hysteresis phenomena. To calculate the losses the Bean model is generally used. This model which is known as Bean's critical state model, states that the local current density in a superconducting material is either null or equal to ±*Jc*, where *Jc* is the critical value of this current density. This is a "local macroscopic" law.

This hypothesis which may seem strong leads to analytical expression of losses and gives reasonable values in simple cases of time variable current. The critical current density *Jc*, is considered as a constant in Bean's model. We can also take account of the variation of *Jc* as a function of the magnetic field, but the calculations in this case are a lot more complex. The calculations presented here will be limited to the cases where *Jc* is constant.

In addition, as we saw in the previous paragraph, the superconductor is surrounded by numerous conductive materials in which any variation in magnetic field induces eddy current losses which then need to be added to calculated in the superconductor.

Cryogenic system. The design of the cryogenic system which is adequate for each manufactured machine presents a number of difficulties to optimize. There are two main types of cooling system, cryogenic liquid or cryocooler system. A number of cryogenic liquids can be used in the manufacture of superconducting devices and their principal properties are summarized in Table 2.

Table 2

Cryogenic liquids

		^4He	H_2	Ne	N_2	O_2
Boiling point	K	4.2	20.4	27.1	77.3	90.2
Freezing point	K		14	24.15	63.15	54
Triple point	K		13.95	22.7	64.5	54.40
Critical point	K	5.2	33.2	44.4	126.1	154
Volume of gas per liter of liquid	Liter	700	790	1,355	646	798
Density of liquid	kg/m^3	125	71	1,210	810	1,140
Latent heat	kJ/kg	21	452	88.7	199	213

The main difficulty is due to the heterogeneity of materials making up the machine and combined with a particularly high gradient of temperature (sometimes the temperature of the constituent parts ranges from 4 to 300 K over a relatively short length). The range of temperatures in which the majority of applications which interest us, function between 1,8 and 77 K.

The current trend is to design motors where the superconducting coil temperature is around 20 K. This data is strongly linked to the current performance of cryocoolers and therefore cannot be considered as sustainable. The lower is the temperature, the better is the performance of superconducting materials, the performance of cryocoolers constitutes a major challenge.

To work with a cryogenic liquid, the boiling point of the fluid is the essential factor in its choice. Liquid nitrogen and liquid helium are the most common cryogenic fluids. The choice of another gas will depend on its ease of use and its cost.

Cryocoolers are thermodynamic cold production cycles, as Joule-Thomson cycle and Brayton cycle. They allow to cool down HTS without cryogenic liquid.

HTS electrical machines. The history of superconductive machines began in the late 1960s and early 1970s, when many studies took place, notably in the United States, Germany, USSR, France and Japan. The key reason for this research and the industry interest in this type of machine is in the benefit in terms of power density and specific power.

The availability of reasonable cost cryocooler and the possibility of operating at a higher temperature than that of liquid helium (4.2 K), have notably increased interest in HTS electrical machines. Table 3 summarizes the possible topologies for HTS machines based on the properties of HTS materials which are currently available on the market.

The most promising HTS types of electrical machine are presented in this paper, synchronous machine using HTS tapes and flux concentration machine and superconducting magnet machine using HTS bulks.

Table 3

HTS material and their applications

Type of material	Useful property	Promissing application
YBCO or BSCCO tapes	Increased JT	Rotating or fixed inductor
YBCO bulks	Perfect "shield"	Channeling of fields
	Trapped field	Strong field magnet

Synchronous machine. HTS synchronous machines are currently manufactured with BSCCO or YBCO high critical temperature superconducting tapes. Most of the machines are half superconducting, the armature of these machines is usually ironless with copper coils only the field system being superconducting. A few of them are fully HTS.

Half HTS synchronous machine. In half HTS machine only the inductor fed by DC current is made with HTS tape. The armature fed by Ac current is generally made with copper wire because the AC losses in HTS would be considered prohibitive for the cryogenic system.

This inductor winding is the subject of particular attention in terms of calculations and implementation:

each of the characteristic quantities of the superconductor must remain, at any point of coil winding, very much below its critical value;

changes in the exterior field direction (including the winding overhang) can, as we have seen, dramatically influence the values of the critical current density;

the winding is composed of individual coils (in the form of stadium track and called race-track coils) which are soldered together. Particular care must be taken on these solder joints.

Some examples of the recent prototype are presented below. This list is not exhaustive.

Moscow Aviation Institute prototypes. In Moscow aviation Institute (NRU) 50 and 200 kW [14] synchronous motors with YBCO field windings cooled with LN2 were designed, developed and manufactured.

The 50 kW machine has 30A current in the HTS field winding. For HTS coils, YBCO SuperPower tape (100 A, 77 K, self-field) was used. Testing the 50 kW HTS motor revealed the advantages and disadvantages of modern 2G HTS materials.

After successful 50 kW HTS motor testing project, the team started the development of 200 kW synchronous motor shown on Fig. 3. This motor is designed for electric transport applications.

The project team investigated new approaches to design electrical machines because traction drives have their own characteristics, such as high torque, high voltage (compared to the usual network 380/220 V) and powered by frequency converters.

The first challenge was a refuse of submersible motor design due to high friction losses in liquid nitrogen. Losses were high due to the high rotor speed – up to 4000 rpm. The rotor was placed in a rotating cryostat. In this regard, the air gap of HTS motor was increased for placing thermal insulation in the cryostat. Increased air gap demanded excitation winding magnetomotive force increase. For these purposes the number of double-pancake HTS coils was increased up to 3 on one pole. The stator of 200 kW HTS motor was cooled by water. This feature allows to increase stator current density if necessary.

The rotor of 200 kW HTS motor consists of 5 main parts: HTS field coils, rotating cryostat, rotor yoke, shaft and liquid nitrogen supply for the HTS coil area. The HTS field coils are located on the rotor yoke directly. They are made of 2G HTS tape AMSC (100 A, 77 K, self-field). On each pole there are 3 double pancake coils with total number of turns 34x6 = 204. The HTS tape is wound directly on the pole core through the electric insulating material. Additional compounding is not applicable. The Application of different compounds and epoxy resin for HTS coils leaded to decreasing of critical currents. Kapton was used to isolate HTS tapes from each other. There were 6 excitation coils on the rotor. They created magnetic field in the gap (7 mm) up to 1.2 Tesla. General view of the rotor with HTS coils is shown on Fig. 4.

The builders used the rotating cryostat for thermal insulation of 2G HTS field coils. It consisted of structural materials and superinsulation «Cryogel-Z». There was no vacuum in the cryostat, and that greatly simplifies the design and increases the simplicity of operation.

The rotating cryostat isolated the outer and the lateral sides and the inner surface of the rotor from the external environment. The cores and the yoke of the rotor were cooled along with HTS coils steel. It

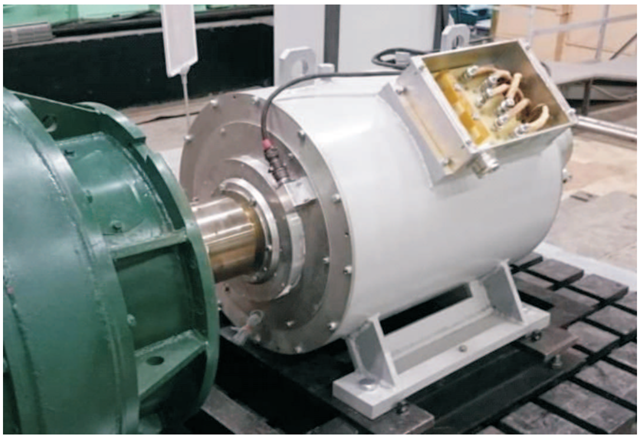

Fig. 3. The 200 kW 2G HTS motor on the test bench

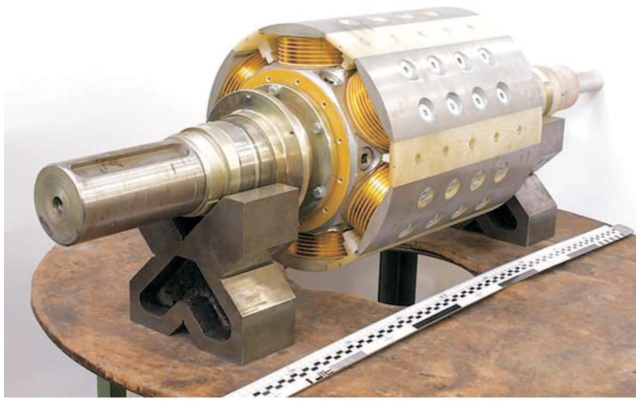

Fig. 4. The general view of the rotor with HTS coils of the 200 kW HTS motor

provides greater thermal stability of 2G HTS coils, especially in case of possible accidents in the cryogenic supply system.

The cooling system of the 200 kW HTS rotor was designed for operations at the temperature range of 65–77 K. However, it can operate at lower temperatures.

The use of separate rotor (cryogenic) and stator (water or air) cooling allowed to decrease demands for the rotor bearings. In such cases traditional bearings could be used, because the temperature in the bearings is above 0 Celsius.

Kawasaki Heavy Industries (KHI). In Japan, Kawasaki Heavy Industries, Sumitomo, Electric Industries, TUMSAT, Yokohama, Sophia and Niigata university and National Maritime Research Institute build and test a HTS synchronous motor (Fig. 5) [15]. The coils, made in DI-BSCCO are cooled down to 30 K by conduction cooling using helium gas. These coils generate a field up to 5 T, ironless. The armature is made with copper wire and is also ironless. They work on a 20 MW project.

Fig. 5. 3 MW motor from KHI group [15]

Doosan Heavy Industries. In South Korea, Doosan Heavy Industries in collaboration with KERI (Korea Electrotechnology Research Institute) has developed a 2-pole, 1 MW generator rotating at a speed of 3600 rpm (Fig. 6) [16]. The inductor is made with a BSCCO tape cooled with liquid neon at 30 K and ironless.

Siemens. In 2008 Siemens build a 4MW slow speed motor for marine propulsion, powered by a variable frequency inverter (Fig. 7) [17]. The setup required a significant amount of superconducting BSCCO tape. The cooling system is made using a thermosiphon with liquid Neon.

IHI Corporation. In this HTS machine [18] made by IHI in Japan, the magnetic field is axial. It is considered to be more compact than radial magnetic field machines, even for conventional copper machines. One of the specific problems posed by this type of machine is the axial forces that must be maintained. For these reasons, the Japanese company IHI makes an important effort to develop this structure. In this case it is a conventional permanent magnet motor with a superconducting armature. The Japanese Frontier Research Group and IHI have developed the most powerful engine cooled to 77 K: 400 kW-250 rpm

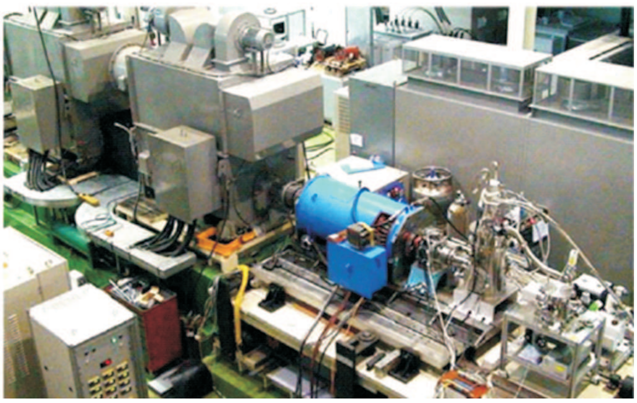

Fig. 6. 1 MW motor from Doosan [16]

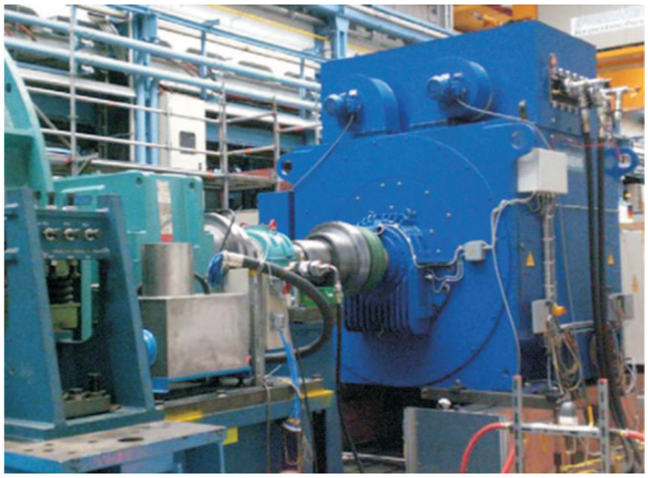

Fig. 7. 4 MW HTS motor from Siemens [17]

(Fig. 8), with DI-BSCCO tapes cooled by liquid nitrogen.

ULCOMAP project. In France the first HTS machine was manufactured by Converteam Nancy in 2008 in collaboration with GREEN [19]. The 250 kW-1500 rpm demonstrator (Fig.9) was realized within the framework of the ULCOMAP European project (ULtra-COmpact MArine Propulsion). This project aims to demonstrate the compactness gain of HTS motors compared to conventional machines for use in marine applications. This machine was made and tested at full load. The main specifications of this motor are given in Table 4.

Table 4

Specification of the 250 kW HTS motor realized by Converteam Nancy

Parameters	Values
Power	250 kW
Voltage Supply	380 V
Current supply	360 A
Field coils current	30 A
Speed	1500 rpm
Cooling system	30 K, Ne
HTS wire	BSCCO 2223
Reactance *d*-axis	0.22 pu
Reactance *q*-axis	0.10 pu

Fully HTS synchronous machine from MAI. Only a few fully HTS machines have been made. Here is presented the one made by MAI in Russia [20]. The application of HTS inductor and HTS armature windings allows to increase electromagnetic loads of machine and its specific power. The significant number of parameters and factors which affect HTS windings makes analytical analysis of the machine very complex. That is why it is very important to manufacture and test

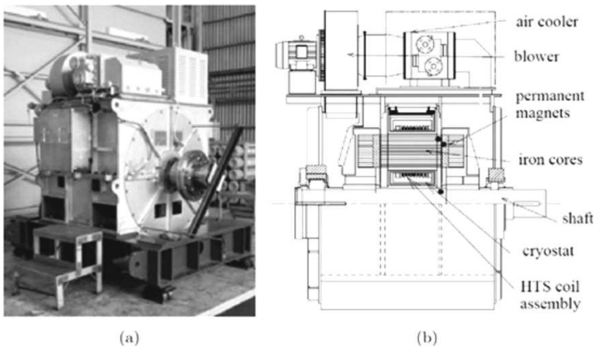

Fig. 8. 400 kW axial magnetic flux motor from IHI Group

Fig. 9. 250 kW HTS motor realized by Converteam Nancy and GREEN

HTS machine especially when it has AC HTS windings.

The considered machine has HTS DC field winding on the rotor and HTS AC armature winding on the stator. The rotor and the stator have racetrack coils due to limitation of bending radius of tape and decreasing of critical current when twisting. Besides, the application of racetrack form makes manufacturing of coils simpler. The principal scheme of the machine and the main dimensions are shown on Fig. 10. The main aim of production and testing of 10 kW prototype is to verify calculation methods and to estimate AC losses in HTS winding operating in machine environment. The following limitations are used during the project: only racetrack coils with one double pancake are used, the machine is filled with LN2, the maximum field current is 40 A, and the maximum armature current is 25 A. The machine was manufactured and tested in MAI, Russia. The External view of the machine is shown on Fig. 11. The main parameters are summarized in Table 5.

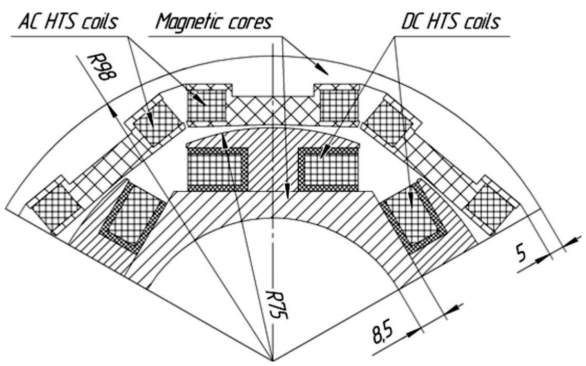

Fig. 10. Principal scheme of fully HTS machine

Table 5

Parameters of 10 kW prototype

Parameter	Value
Nominal output power, kW	10
Rotational speed	2500
Field winding current, A	40
Armature winding current, A	20
HTS tape	AMSC 5x0.5 mm
Operating temperature, K	77
Rotational speed, rpm	2500
Axial length, m	0,220
Number of phases	3
Electrical frequency, Hz	125
Inductive reactance *Xd*, ohm	5,08
Inductive reactance *Xq*, ohm	4,46
EMF for *If*=40A, V	206,3
Power factor	1
Maximum output power, kW	12,5

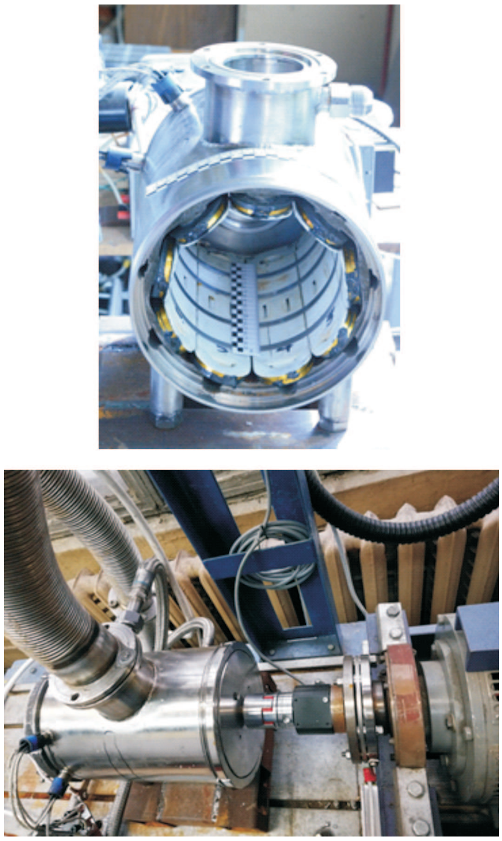

Fig. 11. Fully HTS machine

Machines with HTS bulks Magnetic flux concentration machines from GREEN lab. GREEN lab designed, build and tested many HTS machine using magnetic shielding producing magnetic field concentration.

The first one is distinguished from a classic synchronous machine by its inductor which has a new and particularly original structure [21]. The inductor (Fig. 12) is comprised of the following elements: two superconducting solenoids in opposition which enable to create a flux density having high radial component between the two coils; four superconducting pellets are used as magnetic field shields.

Behind a HTS pellet, the magnetic flux density is virtually null, but between plates it is concentrate. This spatial variation of magnetic field enables to generate a periodic FEM between the terminals of moving conductors for a generator operating or a torque on the rotor of a motor. A demonstration motor (Fig. 13), based on this principle has been built and tested [22]. HTS materials enable to reach levels of magnetic flux density much higher than that obtained by using classic magnetic materials.

Following the first machine, a collaboration began few years ago between SAFRAN and GREEN about HTS motor for aeronautic (Fig. 14).

In this second magnetic flux concentration motor [23], HTS coil produces a high axial magnetic field and five HTS pellets rotating, shield the magnetic field and concentrate the magnetic field between them. The armature is made with copper winding at room temperature because of the AC losses that would be too high at low temperature (Fig. 15).

HTS permanent magnet machine. HTS YBCO pellet, initially cooled and then subjected to field pulses, traps magnetic flux [24–26]. It allows to produce machine prototypes where HTS bulk pellets, distributed around the rotor, are magnetized and used as permanent magnets. In Japan, Professor Izumi and his team have been working on this topic for many years and have built several prototypes [27–29]. In England, Dr Coombs has built one prototype [30]. One of problems concerning this kind of HTS motor is to choose whether to magnetize the HTS bulks inside the machine (in-situ) or outside of the machine (ex-situ). The prototypes already made used ex-situ magnetization because it seems the simplest option. However, many teams [26] are working on in-situ magnetization for future industrial applications because it should be simpler for the end user.

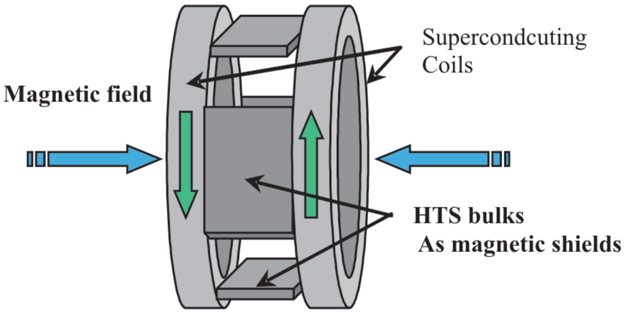

Fig. 12. Principle of magnetic flux concentration with HTS bulks

Fig. 13. Magnetic flux concentration with HTS bulks motor

Fig. 14. HTS motor from GREEN and SAFRAN for aeronautic

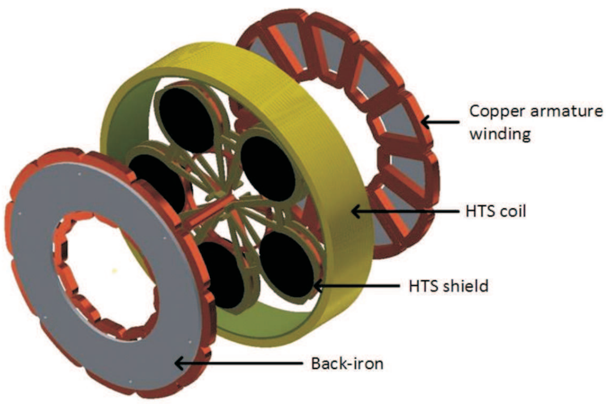

Fig. 15. HTS coils producing axial magnetic field, HTS bulks as magnetic shield and armature windings

Conclusion. In this paper an overview of HTS electrical machine has been presented.

It appears that up to now many HTS motors have been produced. They are not only prototypes, there are also industrial demonstrators among them. Their efficiency and even their reliability have been proved.

Another difficulty is the availability and the reliability of HTS tapes. Standardized products as superconducting tapes and coils are also required for the industrial applications. For motor manufacturers the challenge is to industrialize the process of fabrication of HTS motor.

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The authors: ***Douine Bruno*** *(University of Lorraine, Nancy, France) – Professor; member of the Research Group in Electric Energy of Nancy (GREEN), PhD.*

Menana Hocine *(University of Lorraine, Nancy, France) – Senior Lecturer; member of the Research Group in Electric Energy of Nancy (GREEN), PhD.*

Berger Kevin *(University of Lorraine, Nancy, France) – Assistant Professor; member of the Groupe de Recherche en Energie Electrique de Nancy, PhD.*

Lévêque Jean *(University of Lorraine, Nancy, France) – Professor; member of the Groupe de Recherche en Energie Electrique de Nancy, PhD.*

Kovalev Konstantin *(Moscow Aviation Institute (The National Research University), Moscow, Russia) – Head of Electrical Power, Electromechanics and Biotechnical Systems Dept., Dr. Sci. (Eng).*

Ivanov Nikolay *(Moscow Aviation Institute (The National Research University), Moscow, Russia) – Senior researcher of Electrical Power, Electromechanics and Biotechnical Systems Dept., Cand. Sci. (Eng).*

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Обзор высокотемпературных сверхпроводниковых электрических машин

ДУЭЙН Бруно – *доктор философии в области электротехники, профессор университета Лоррейн, Член Исследовательской группы «enEnergieElectriquedeNancy», Нанси, Франция.*

МЕНАНА Хосин – *доктор философии в области электротехники, старший преподаватель университета Лоррейн, Член Исследовательской группы «GREEN» по электрической энергии, Нанси, Франция.*

БЕРГЕР Кевин – *доктор философии в области электротехники, доцент университета Лоррейн, Член Исследовательской группы «enEnergieElectriquedeNancy», Нанси, Франция.*

ЛЕВЕК Жан – *доктор философии в области электротехники, профессор университета Лоррейн, Член Исследовательской группы «enEnergieElectriquedeNancy», Нанси, Франция.*

КОВАЛЕВ Константин – *доктор техн. наук, заведующий кафедрой 310 «Электроэнергетические, электромеханические и биотехнические системы» Московского авиационного института (национального исследовательского университета), Москва, Россия.*

ИВАНОВ Николай – *кандидат техн. наук, старший научный сотрудник кафедры 310 «Электроэнергетические, электромеханические и биотехнические системы» Московского авиационного института (национального исследовательского университета), Москва, Россия.*

Электрические машины являются важной частью различных энергетических и силовых систем. Применение высокотемпературных сверхпроводников (ВТСП) в электродвигателях – перспективное направление исследований, что связано с высокой токонесущей способностью ВТСП. В статье рассматриваются различные топологии сверхпроводящих электродвигателей и генераторов, использующих ВТСП. Дана характеристика ВТСП материалов, используемых для электрических машин. Приводится описание потерь переменного тока и криогенных систем. Представлена информация о реализации различных типов высокотемпературных сверхпроводниковых электрических машин, таких как машины с одной ВТСП обмоткой, полностью ВТСП машины, а также машины с ВТСП объемными элементами и стопками лент. Некоторые из этих машин являются полностью инновационными, а и их принцип работы строго связан только с наличием ВТСП материалов.

Ключевые слова: *высокотемпературный сверхпроводник, потери переменного тока, электрическая машина*