Grzegorz WOJTASIEWICZ

THE NEW CONCEPT OF THE 2G HTS SUPERCONDUCTING TRANSFORMER

SUMMARY *The new 2G HTS tapes with high critical current and high resistivity in the normal state allow to build low-cost transformers with high short-circuit strength for the low and medium power distribution substations.*

The authors consider that currently the best chance of building have transformers, which rated currents of their windings do not exceed or slightly exceed the critical current of used superconducting tapes. Such units could be the low or medium voltage transformers with power less than 10 MVA, where the high voltage winding can be made with single HTS tape while the low voltage winding can also be made of single HTS tape or two – three tapes connected in parallel. This eliminates the need of tape transposition or application of the Roebel's cable. Superconducting transformers could stabilize the low or medium power network and increase the connectivity of renewable and dispersed energy sources.

The article presents an analysis of the possibility of using the low and medium voltage superconducting transformers. Such units could be e.g transformers working with renewable energy sources.

Keywords: *superconducting transformer, 2G HTS tapes, transformer windings, parallel tapes, current distribution, power losser*
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1. INTRODUCTION

The demand for electric energy is growing rapidly all over the world. It is estimated that the pace of this upward trend is about 2.2% per year. This means that the current world consumption of energy, which is about 20300 terawatt hours, with increase by the year 2030 to 31000 terawatt hours. At the same time there arises the challenge of ever more effective use of energy by limiting its losses. That involves modernization of outdated power infrastructures in many countries. Optimization of power systems involves many elements, starting with renewal energy sources, which should be better integrated with the system thanks to power storage units, the use of small power suppliers and more efficient transmission of energy [1].

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On the other hand, because of the development of energy industry, the wind power industry in particular, electricity networks which were designed to manage the electricity provided by large system power stations are not capable of absorbing such large excess of generated power, which threatens the development of renewable sources energy industry. Connection of new power generating units to the network must be not only safe for the entire network infrastructure but it should also secure the required parameters of energy quality. The connection of a new energy source causes an increase of short-circuit power at the connection point. This means that during a short circuit, the value of short-circuit current increases in such a network. The increased short-circuit current is a threat to the technical infrastructure of the network due to the dynamic and thermal effects of the passage of the short-circuit current. Limitation of thermal and dynamic effects of the flow of a short-circuit current can be obtained by limiting the short-circuit time and the value of the initial short-circuit current impulse – surge current. The possibilities to shorten the time of a short-circuit offered by network automation are limited. Lowering or maintaining current requirements concerting the short-circuit capacity of the elements of the power system can be achieved by using devices which limit the value of short-circuit current. However, selected means of limiting short-circuit currents must not violate the requirements concerning the allowable limit of the connected power, which is determined on the basis of the necessity to maintain the power quality standards [1].

In order to solve this problem, large network investments are required, and that is why we should seek new methods of increasing the connection capacity of the existing networks. Therefore, in order to obtain permission to connect new power generating installations to the network it may be required to modernize or even build entire new sections of a power network. It is the author's opinion that one of the methods of achieving these goals is to use superconducting power transformers with HTS windings [2] in the power distribution systems. Superconducting transformers, which are characterised with high current overload and better transformation efficiency as a result of elimination of loses in the superconducting windings, allow to improve the reliability of the network through limitation of short-circuit currents and voltage fluctuations in the network during a load change resulting from a lower impedance of the transformer. Moreover, cooling with liquid nitrogen makes superconducting transformers more environment friendly than conventional transformers which are cooled with oil.

The limitation of a short-circuit current by a superconducting transformer will also help lower the costs of switchgear and safety devices thanks to replacing the higher short-circuit currents devices with devices for the currents limited by the superconducting transformers [3].

2. SUPERCONDUCTING TRANSFORMER

Replacement of conventional transformers with superconducting transformers will bring the following benefits:

- short-circuit resistance and lower short-circuit reactance (short-circuit voltage may be lower). Short-circuit current is limited by the resistance of the winding in the resistive state – $R_{\mathrm{HTS77K}} = (60 - 125)\ \mu\Omega\mathrm{cm}$, ($R_{\mathrm{Cu350K}} = 2.1\ \mu\Omega\mathrm{cm}$),
- increased efficiently thanks to the elimination of load losses in the windings, resulting from zero resistance of the superconductor in the resistive state, and lower iron losses resulting from shorter yokes,

- greater overload capacity,
- smaller voltage drops, smaller voltage fluctuations during load changes,
- elimination of oil cooling system, greater safety – they are more user-friendly and environment-friendly.

In properly designed transformers with superconducting windings, exceeding the critical current of the superconductor causes its transition into the resistive state, which results in limitation of the fault current and increase of impedance of the windings caused by the occurrence of their resistance. Superconducting transformers are not without flaws. These include:

- high costs of the HTS tapes,
- long time of costs returns resulting from lower power losses,
- coil windings, due to the transversal dimensions of the tapes and their available lengths (100-200 m),
- technologies of connecting superconducting tapes are not yet well-developed.

There are many similarities in the designs of conventional and superconducting transformers. In both cases, there are a core and at least two windings of lower and upper voltage. Because of the thickness of superconducting tapes and cables, the radial sizes of superconducting windings are smaller than copper windings, and thus the lengths of magnetic core yokes in HTS transformers are shorter. This results in a smaller mass and volume of the device as well as the entire transformer, and in a decrease of power losses in the core. Superconducting windings in transformers also require cryogenic cooling systems.

The critical current of a superconducting tape specified by the manufacturer, determined for DC current, is regarded as the AC current rms value. Therefore, the allowable AC current in a single superconducting tape cannot exceed 70% of the value of tape critical current, which assures that the maximum allowable current in the winding will be lower that the tape critical current.

In case of transformer windings made of high-density current 2G HTS tapes, the value of the rated current of the windings may be within 0-70% of the tape critical current ($I_n < 70\% \ I_c$). If we assume that the value of the nominal current is, for example, 50% of I_c, the transformer can be loaded with another 20% of I_c without the risk of exceeding the value of the tape critical current. The above assumptions must be taken into consideration during the stage of designing transformer windings.

Currently, superconducting transformers are not built, mostly due to the costs (especially costs of CTC cables for the windings) of construction and maintenance. There are only a few prototypes operating in experimental or separated power networks.

3. CONSTRUCTION OF SUPERCONDUCTING TRANSFORMER WINDINGS

In a case where rated current of the windings are higher than the critical current of the used superconducting tape, the windings are made of a package of tapes connected in parallel. The necessity to use tapes connected in parallel leads to an increase of the thickness of the windings [4].

In case of many layers of tapes in a parallel connection, the layer which is farthest from the air gap is associated with the lowest leakage flux, and the layer which is closest to the gap is associated with the highest leakage flux. As a result, the currents flow in individual layers is uneven, the layer closest to the gap being under the greatest load. It results from the differences in the electromotive forces of the individual layers, whose effect is the flow of equalization currents which violate the even distribution of the current in the winding. Figure 1 shows an example of a winding consisting of four layers wound with three HTS tapes (1, 2, 3) connected in parallel, distribution of the leakage flux lines and signs for calculating the reactance of the individual winding layers.

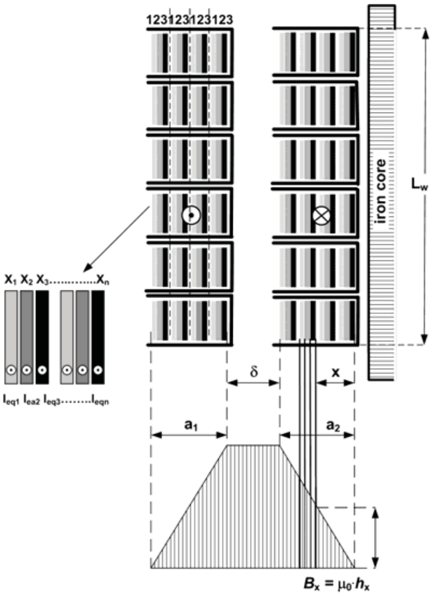

Fig. 1. Diagram of a winding and distribution of leakage flux lines; X_1, X_2, X_n and I_{eq1}, I_{eq2}, I_{eqn} are the reactance and equalizing current of individual parallel tapes

However, because of the thickness of the HTS tape, superconducting windings, even when made of a package of many tapes connected in parallel, are much thinner than analogous copper windings. For superconducting windings, the differences in the leakage flux values, associated with the layers closer to, as well as further away from, the air gap are small, and the differences in the reactance of individual layers are much smaller than in copper windings. The effect of the flow of equalization currents is the use of the superconducting tapes not to their full capacity. The total current in the most loaded parallel tape, which is the sum of the nominal current and the equalization current, may exceed the value of the critical current of the superconducting tape, which causes uncontrolled transition of the entire winding into the resistive state. In order to prevent that, it would be necessary to make the winding using a tape of higher critical current or a parallel package of a larger number of tapes. Both of these solutions would greatly increase the costs of the winding.

Equalizing of the reactance of the individual layers of the winding and thus elimination of equalization currents can be achieved thanks to transposition of the tapes. In case of the windings of conventional transformers, transposition is not problematic. However, it is virtually impossible to perform classical transposition of superconducting tapes due to their mechanical properties and the proportions of the length and width of the superconducting tape.

A method of limiting the equalization current in the windings of superconducting transformers is the use of CTC (Continuously Transposed Cable), also called Roebel's cable [5], [6]. The idea of the CTC is proper shaping and weaving of a package of parallel superconducting tapes which were cut to a given shape. The number of the tapes in the package depends on the required value of the critical current of the finished cable. For example, in order to obtain a Roebel's cable whose critical current value is 1000 A, it is necessary to use a package of 10 tapes of 5 mm wide tape (10/5 cable). These cables are very expensive because of the technological requirements which must be met by the process of cutting of the base HTS tape and the process of constant transposition, as well as due to and substantial losses of material during the cutting of the base HTS tape to shape. A meter of Roebel cable may cost as much as 1.5 – 2 thousand USD. Making of a transformer winding using a package of superconducting tapes connected in parallel is a much cheaper solution thanks to the price of HTS 2G tapes which is several times lower than that of Roebel cable (Tab. 1) [7]. The number of tapes in a package depends on the critical current of the winding.

TABLE 1
Critical current and the price of 2G HTS tapes made by SuperPower, and Roebel cable 10/5

2G HTS tape by SuperPower Inc	Width / thickness mm	Critical current I_c, A	price, USD/m
SCS 4050	4/0.095	100 – 150	60
SF 4050	4/0.055	80 – 120	50
SCS 12050	12/0.095	300 – 450	100
SF 12050	12/0.055	250 – 350	90
Roebel cable 10/5	12/2	1000	2000

Table 2 presents the number of tapes connected in parallel necessary to make a winding whose critical current is 1000 A, the thickness and the unit price of such a package.

TABLE 2
Number of tapes in the package, thickness and price of package for the critical current 1000 A

Tape	Number of tapes connected in parallel	Dimensions of the tape, mm	Price of the package of the tape, USD/m
SCS 4050 @ 100 A	10	1.5 x 4	600
SF 4050 @ 100 A	10	1.1 x 4	500
SCS 12050 @ 300 A	4	0.6 x 12	400
SF 12050 @ 300 A	4	0.5 x 12	360
CTC – Roebel calbe 10/5	10	2 x1 2	2000

3.1. Power losses in superconducting windings

Because of the strong anisotropy of the tape, the radial component of the external magnetic field, perpendicular to the winding surface, induces larger hysteresis losses than the axial component of the field – parallel to the winding surface. Total losses of the external field are the sum of the losses of both component of the external field in the entire length of the tape in every winding [8].

The hysteresis losses are in direct proportion to the thickness of the superconductor layer. The main method to limit them is to make a 2G superconducting tape with the thinnest possible superconductor layer. However, the minimum layer thickness is limited by technological factors. If the dimensions of the superconductor perpendicular to the magnetic field are small, we also achieve limitation of hysteresis losses.

The hysteresis losses value also depends on the type and design of the windings and their radial dimensions (thickness). Types of transformer windings include coil windings, in the form of single or double coils, and in the form of layer windings – screw windings.

Because of the thickness of superconducting tapes, the dimensions of superconducting windings (i.e. diameter and thickness of the windings) are smaller than those of copper winnings in a conventional transformer of the same power, and the external winding of a superconducting transformer will be closer to the core (Fig. 2).

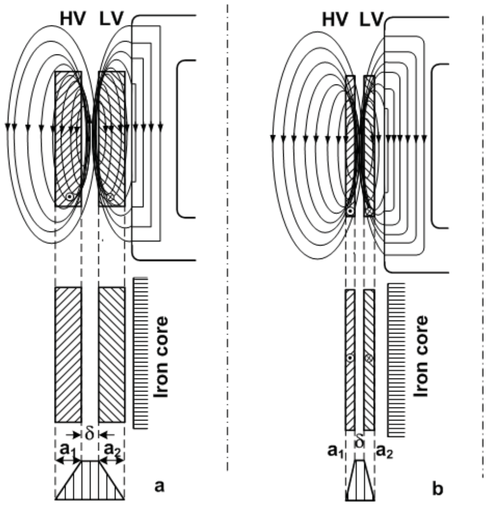

Fig. 2. The course and the distribution of the leakage flux force lines of transformer: a) conventional, b) superconducting

That is why HTS tapes and Cu leads in individual layers of the windings will be connected with other lines of the leakage flux.

During the winding of a package of parallel tapes, additional equalization currents occur in the winding. They result not only from the not fully used superconducting tapes but also from the occurrence of additional losses in the windings. However, because of the low values of the equalization currents the losses are negligibly small and do not affect the overall balance of the transformer [9].

Eddy-current losses are caused by eddy currents induced in the entire volume of the resistive layers of 2G HTS tapes. Those losses can be limited by lowering the percentage of the resistive layers in the entire superconducting tape. But because of the required mechanical strength and electrical parameters of HTS 2G tapes, this percentage is quite high, i.e. 90-95%. Also, increasing of the resistivity of the materials of the substrate layer at a temperature 77 K causes a decrease of those losses. Because of high resistivity of the substrate layers and the oxide base of the superconductor in 2G tapes, the eddy-current losses induced in them are greatly limited.

Self-field losses are caused by the field from the current flowing in the transformer windings. Their value depends on the current density.

The value of the sum of AC losses in HTS windings accounts for only a small percentage of the losses which occur in copper windings of conventional transformers with the same parameters.

4. ANALYSIS OF THE POSSIBILITY OF USING THE LOW AND MEDIUM VOLTAGE HTS TRANSFORMER

So far the much attention were devoted to high-power transformers, because of possibility to obtain higher gains by limiting losses (increase of efficiency). The lack of commercially available CTC Roebel's Cables and potentially their high cost, as well as misgiving of using many 2G HTS tapes connected in parallel, causes that the superconducting transformers did not go beyond the phase of design and prototypes.

According to the author, the most likely to be built are transformers of small and medium power where the windings rated currents do not exceed or slightly exceed the value of the critical current of the commercially available superconducting tapes. This eliminates the need for transposition of the tapes or the use of CTC cable, which will greatly reduce the costs of transformer windings. These conditions are usually met by transformers working in low and middle voltage networks.

In Poland, the total number of transformers in low and middle voltage networks is about 250,000 and their total power is about 45,000 MVA. These are in 96% percent transformers with HV of 15 kV or 20 kV. 60% of them are aged 10-40 and only about 28% are younger than 10 years old. Power losses in these transformers are in the order of 14% of which 9% are load losses [10].

Superconducting transformers which limit fault currents, which are characterised with low short-circuit reactance and high current overload capacity without lowering the voltage, may greatly improve the connecting capabilities of renewable and dispersed energy sources. Low power dispersed generation systems are usually connected to a low voltage network (400 V) or medium voltage (10, 15, 20 kV) directly or through separated line or substations. In both cases appropriate transformers are required. Parameters of the selected low and medium power conventional transformers are given in Table 1. There is also given a number of parallel tapes necessary to make 2G HTS winding.

TABLE 3
Electric parameters of low and medium voltage transformers

Power, kVA	Voltage, kV	Vector group	Windings rated currents, A	Number of parallel tapes HV/LV
10000	110/20	Yd11	52/166	1 / 1
16000	110/20	Yd11	84/266	1 / 1 -2
630	20/04	Dy5	10.5/910	1 / 3-5
400	15/04	Dy5	8.9/580	1 / 2-3
250	15/04	Dy5	5.5/360	1 / 1-2

The currently available 2G HTS tapes whose critical current is from 100 to 300 A at a temperature of liquid nitrogen (77 K) allow the construction of windings for transformers of 10 MVA and 16 MVA using a single tape in HV and LV windings. Also the HV windings in the remaining transformers can be wound using a single HTS tape. The LV windings of 400 kVA and 250 kVA transformer could be wound using 3 and 2 tapes connected in parallel. Only LV winding of 630 kVA transformer requires 4 or 5 parallel tapes.

Also the LV windings in the transformers (tab. 3) could be wound using a single HTS tape if it were possible to increase the critical current of that tape. A method to increase this value is to lower the temperature of the windings operation because as the temperature of the windings operation decreases, the value of the tape critical current increases. Figure 3 presents the characteristics of the tape critical current density in the function of temperature $J_c = f(T)$, obtained through experimental measurements of a tape, manufactured by SuperPower, whose critical current is 310 A at a temperature of 77 K.

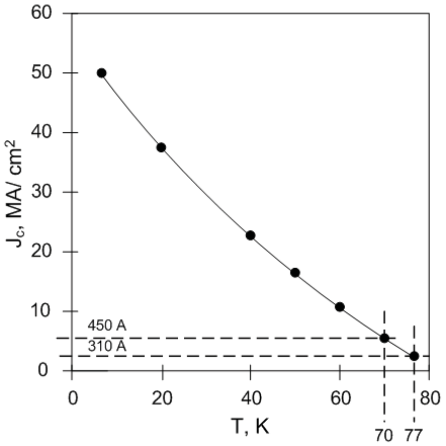

Fig. 3. $J_c = f(T)$ characteristic of 2G HTS tape

Lowering of the temperature to 70 K, i.e. by 7 K, causes an increase of the critical current of the tested tape from 310 A to 450 A, i.e. by 32%. Lowering of the temperature by 1 K causes an increase of the current by 4.5%, which opens possibilities of periodical current overloads at small voltage fluctuations.

Commonly available and more and more efficient (also cheaper in purchase and maintenance) cooling systems, operate on the basis of a mechanical cryocoolers, allow to easily lower the operation temperature and enable the windings to work at a temperature lower of 77 K. These are fully autonomous system, requiring only power to operate, so it could be fully automated.

The main factor contributing to the costs of maintenance of the cryocoolers is the cost of energy necessary to obtain the cryogenic temperature. For example, a 15-year old two-stage cryocooler SRDK 410D by Sumitomo, of cooling power of 1 W in 4.2 K (I step) and 40 W at 77 K (II step), is equipped with a 7 kW compressor, while a contemporary cryocooler CryoTel GT by Sunpower, cooling power of 16 W at 77 K, requires only 240 W power [11].

Taking into consideration the above, it become possible to build transformers of 400 kVA and 250 kVA using a single tape in a LV winding. The LV winding of a 630 kVA can be made using two tapes connected in parallel. In case of HV windings in all the presented cases, the nominal currents of the windings are smaller than the critical currents of the available superconducting tapes.

In order to level the distribution of currents in HTS 2G tapes connected in parallel, it is necessary to develop a technology of connecting the tapes using special connectors which will allow to freely connect tapes between the layers. Specially designed “transposicioners” may allow to change the order of tapes in the parallel package without having to change the shape and continuity of the tapes.

Transpositioners may be used in transformers of small and medium power where the windings rated currents do not exceed or slightly exceed the value of the critical current of the commercially available superconducting tapes In such transformers the HV windings can be made as cylindrical and the LV windings as pancake coils with transpositioners. The advantage of the coil winding is its hybrid design, allowing for a change in the number of the pancake coils depending on winding parameters.

5. CONCLUSSION

Currently available 2G HTS superconducting leads tapes and CTC cable, with a much higher mechanical strength, higher values of critical current and higher resistivity in the resistive state, allow building of power transformers cooled with liquid nitrogen.

Superconducting transformers have many advantages compared to transformers with copper windings. They are more energetically efficient, limit fault currents, assure smaller voltage fluctuation under the load changes and are environment friendly.

Properly made superconducting windings and well-selected superconducting tape allow to limit the fault current. During a short-circuit, the current is limited by the impedance of the short-circuit loops in which an important role is played by the transformer short-circuit impedance. After the superconducting transformer transits into the resistive state, an increase of the windings resistance causes the transformer impedance to increase from several to several tens times compared to its impedance in the superconducting state. Short-circuit voltage of a superconducting transformer in the superconducting state can have a low value because an increase of impedance in the resistive state is enough to limit the fault current.

The major obstacle to the use of superconducting transformers in the power industry is high cost of windings leads, especially CTC cable, and the conviction that only high-power units can be cost effective where expensive CTC lead is necessary, and also disregarding other advantages of superconducting transformers.

The development of renewable and dispersed energy sources causes the users of electricity to be also its producers, and they increase the network short-circuits power. This creates the necessity to maintain the parameters of the electricity quality. Superconducting transformers stabilise the network because they limit fault currents, stabilise the voltage (without changing the transformation ratio) and can be overloaded without causing an increase of windings losses.

Superconducting transformers allow to increase the connection capacity of renewable and dispersed energy sources without any changes to the infrastructure of low and middle power network. Rated power of the transformers in such networks does not exceed 10 MVA and their windings can be made of a HTS tape without the need to use CTC cables. Implementation of low power transformers is easier and connected with smaller risk.

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NOWA KONCEPCJA TRANSFORMATORÓW NADPRZEWODNIKOWYCH Z TAŚM HTS 2G

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STRESZCZENIE *Nowe taśmy nadprzewodnikowe 2G HTS o wysokim prądzie krytycznym i wysokiej rezystywności w stanie rezystywnym pozwalają na budowę transformatorów o wysokiej odporności na zwarcia dla sieci dystrybucyjnych niskich i średnich energii.*

Obecnie największe szanse na budowę mają transformatory, których znamionowe prądy uzwojeń nie przekraczają lub nieco przekraczają wartości prądu krytycznego zastosowanych taśm nadprzewodnikowych. Takimi jednostkami mogą być transformatory niskiego lub średniego napięcia o mocy poniżej 10 MVA, gdzie uzwojenie wysokonapięciowe może być wykonane pojedynczą taśmą HTS, a uzwojenie niskonapięciowe może być również wykonane z pojedynczej taśmy HTS lub dwóch - trzech taśm połączonych równolegle. Eliminuje to konieczność transpozycji taśm a tym samym zastosowania kabla Roebel. Zastosowanie transformatorów nadprzewodnikowych mogłoby ustabilizować sieć energetyczną niskiego i średniego napięcia i zwiększyć zdolność łączeniową odnawialnych i rozproszonych źródeł energii.

Słowa kluczowe: *transformatory nadprzewodnikowe, taśmy HTS 2G, uzwojenia transformatorów, taśmy równoległe*

Dr hab. inż. Grzegorz WOJTASIEWICZ urodził się w 1971 r. w Lublinie. Ukończył jednolite studia w Politechnice Lubelskiej na kierunku Elektrotechnika uzyskując tytuł magistra inżyniera w 1998 r. W 1999 r. dr hab. inż. Grzegorz Wojtasiewicz rozpoczął pracę w Zakładzie Badań Podstawowych Instytutu Elektrotechniki w Warszawie w Pracowni Krioelektromagnesów z siedzibą w Lublinie, która w 2004 r. została przekształcona w Samodzielną Pracownię Technologii Nadprzewodnikowych, a następnie w 2005 r. w Pracownię Technologii Nadprzewodnikowych w ramach Zakładu Wielkich Mocy IEL. Dr hab. inż. Grzegorz Wojtasiewicz od początku pracy w Instytucie zajmował się zastosowaniami technologii nadprzewodnikowych i nadprzewodników wysokotemperaturowych w urządzeniach elektroenergetycznych. Obecnie zajmuje się problematyka transformatorów nadprzewodnikowych. Podczas swojej pracy współuczestniczył w realizacji dziesięciu projektów badawczych, w tym dwóch trwających. Dr hab. inż. Grzegorz Wojtasiewicz jest autorem i współautorem 74 artykułów, w tym 32 indeksowanych w bazie JCR. Uczestniczył w 30 konferencjach międzynarodowych i krajowych, w tym kilkakrotnie w konferencjach: European Conferences on Applied Superconductivity – – EUCAS, Applied Superconductivity Conference – ASC oraz Magnet Technology – MT. W latach 2006 – 2007 dr hab. inż. Grzegorz Wojtasiewicz przebywał w Szwajcarii, gdzie pracował w Europejskiej Organizacji Badań Jądrowych – CERN w Genewie.