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Status of the technology development of large scale HTS generators for wind turbine

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Abstract

Large wind turbine generators with high temperature superconductors (HTS) are in incessant development because of their advantages such as weight and volume reduction and the increased efficiency compared with conventional technologies. In addition, nowadays the wind turbine market is growing in a function of time, increasing the capacity and energy production of the wind farms installed and increasing the electrical power for the electrical generators installed. As a consequence, it is raising the wind power energy contribution for the global electricity demand. In this study, a forecast of wind energy development will be firstly emphasized, then it continue presenting a recent status of the technology development of large scale HTSG for wind power followed by an explanation of HTS wire trend, cryogenics cooling systems concept, HTS magnets field coil stability and other technological parts for optimization of HTS generator design – operating temperature, design topology, field coil shape and level cost of energy, as well. Finally, the most relevant projects and designs of HTS generators specifically for offshore wind power systems are also mentioned in this study.

Keywords: Wind energy, HTS generator's wind turbine, coated conductors, cryogenic technology

1. INTRODUCTION

Nowadays, around the world is facing through an energy crisis that is seriously affecting the lives of people. The main reason for the energy crisis is rapidly increasing the prices of hydro-carbon resources and lack of planning to foresee the increasing energy demand in the country. Fortunately, renewable energy can play an important role to minimize this crisis so most of the countries are interested to penetrate the renewable energy in their power sectors to obtain economic and environmental benefits, including appropriately chosen technology, adequate financing and payment arrangements, supportive national policies [1, 4].

The global share of renewable energy in the power sector was 22.1% of the global final energy consumption at the end of year 2013 [5]. Not let up with this trend, to cut a deep CO_2 emission, the International Renewable Energy Agency (IRENA) has initiated the development of a roadmap that examines the elements necessary to achieve a double renewable share by 2030, it means the total share of renewable energy in power generation grows from 20% in 2010 to nearly 42% in 2030 [6]. Taking account to this ambitious goal, wind energy is an essential solution because of its advantages – widespread availability around the world, diversification of rural economies by providing new types of income, no need to use fossil fuel, no costs of mining and transportation due to stable and free wind source [7]. Technically, wind energy has a short payback time and construction period [8], high average efficiency and low environmental impacts (CO_2 emission and water consumption, land occupied) for individual energy generation technology among others renewable energy – PV, geothermal [9]. Therefore, wind energy is honored the top rank of renewable energy not only by cleanness but also by sustainability [10].

Furthermore, deployment superconducting generators technologies aim to solve reliability and high mass-problems of existing technologies. It is also a great innovation and strongly consolidates the role of wind energy development [11]. This paper briefly review a recent status of the technology development of large scale high temperature superconducting generators (HTSG) for wind power followed by an explanation of HTS coated conductor challenges, cryogenics cooling system reliability, HTS magnets field coil stability and others researches of technological concerns as mentioned. It will show the high potential of HTSG wind turbine for contributing support the global energy demand in future. For increasing the concrete statement, the latest update of important projects by companies and research institutes which relate to the design and construction of HTSG for wind turbine is also mentioned in this article.

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2. FUTURE TREND OF WIND ENERGY

In the real world, energy is one of the top challenges we are facing in a global society. We know that energy demands are deeply tied to the other major challenges which include poverty, and health, and clean water because energy demands are only going to increase. The primary energy demand shown in Fig. 1 which is estimated by International Energy Agency (IEA), the total required energy is 14920 Mtoe (approximately 173x10^3 GWh) by 2035 [12]. Therefore, with the dramatic rising of this demand, energy security is no longer only about oil, and industrialized nations are no longer the only major consumers of energy. Fortunately, it is estimated that the technical potential wind energy is in a huge range from 20000x10^9 to 50000x10^9 kWh, and the expected saturation level capacity is 1900 GW during 2030-2035 [13]. Archer and Jacobson [14] estimated that just only 20% of the global total wind power potential could account for as much as 123 PWh (1.23×10^8 GWh) of electricity annually equal to seven times total current global consumption of electricity (comparable to present global use of energy in all forms). By the end of 2014, the worldwide wind capacity reached 370 GW, there is more than 50 GW of capacity were added during the year 2014. The total worldwide installed wind capacity can now generate closely 5% of the world's electricity demand [15].

For new strategies of wind power, Fig. 2 shows the breakdown of power generation according to REmap Options in the power sector by 2030, with the results of the 26 REmap countries scaled to the global level. In total, 5400 TWh of additional power will be generated from renewable sources in 2030. Wind has the largest additional generation of about 2350 TWh per year worldwide (three-quarters from onshore, a quarter from offhore) representing 43% of the total potential [16]. In addition, the expansion of non-hydro renewables depends on subsidies that more than double to 2035; additions of wind & solar have implications for power market design & costs as shown in Fig. 3 [12]. It is seen that for most developed country (Europe, Japan, and United States) will majorly focus on wind energy, whereas developing countries (India, Latin America, ASEAN and Africa) will invest largely in hydropower because the capital cost of wind energy is a little bit higher than hydropower right now. To overcome this challenge, it is shown that the larger the turbine is the greener the electricity becomes. With an increased cumulative production of wind turbines, manufacturers gain experience with the technology, which is commonly reflected in a reduction of the investment costs [13, 17].

Therefore, there is also a trend showing an increase in the average wind turbine unit rating every year with the prospects of the higher than 8 MW wind turbine project concept designs and installations for the coming decade [18], it shows the trend of wind turbine getting bigger and bigger by the time. However, for wind turbine electric ratings higher than 8 MW, its geometric dimensions and consequently the total weight of the generator increase exponentially. For this main reason, it is required to search for alternative technologies for offshore wind turbines with powers more than 8 MW to achieve the electrical power with a lower electrical generator volume and a low total weight with reasonable costs. In this case, HTSG is a best candidate because of their advantages mentioned above.

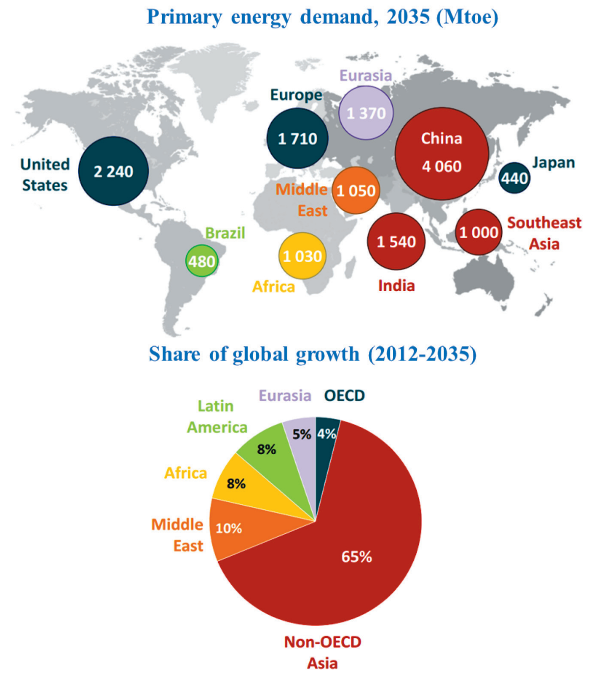

Fig. 1. Energy demand growth by 2035 [12].

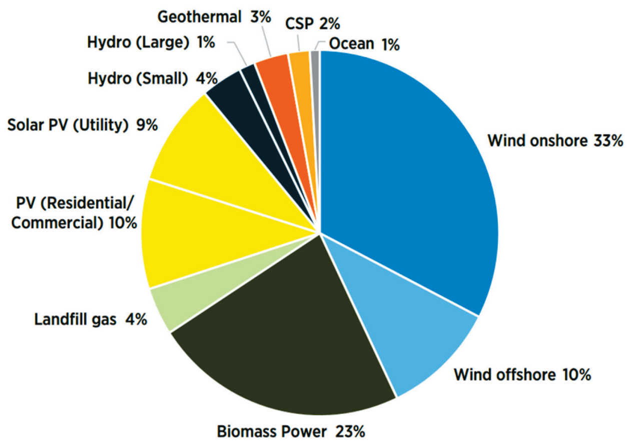

Fig. 2. Global power generation by technology [16].

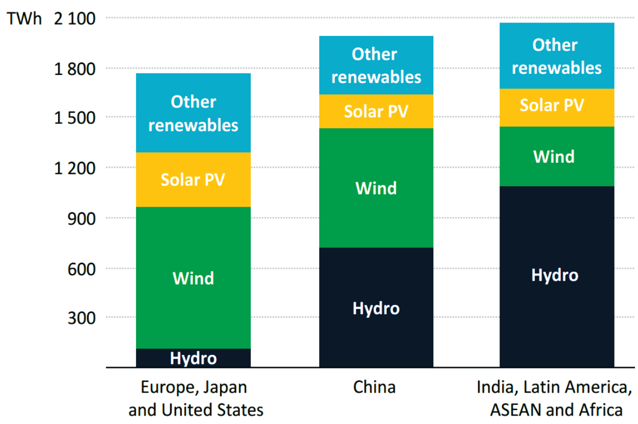

Fig. 3. Renewable power up around the world [12].

3. AN INDISPENSABLE TECHNOLOGY DEVELOPMENT OF HTSG WIND TURBINE

The HTS material can permit higher magnetic flux and a unique higher current-carrying capability than that of low temperature superconductor (LTS), so HTS rotating machines provide the highest power density when compared with conventional ones. Because of the significant increase in both electrical and magnetic loading, they are smaller and lighter in structure [19] and have less energy consumption, leading to a reduced energy cost [20]. However, there are three major challenges which must be addressed before a large scale utilization can be obtained. These challenges generally come from HTS material challenges, cryogenic cooling system and HTS field coil stability.

3.1. HTS Coated Conductor Materials Challenges

First of all, it is the price of the superconducting wires. We can easily see that HTS generator have a lower rate of refrigeration investment, refrigeration maintenance, least copper, magnetic field and structure material. The only thing is cost of superconducting material cost. If we can solve this problems, the HTS generator will much higher efficiency than LTS [21] as shown in Fig. 4.

Because of a huge progress has been made worldwide in increasing the length, performances, price trends for HTS coated conductors in the last 10 years and the achieved improvements in performance of HTS coated conductors produced at an industrial basis, it is assumed that superconducting wire can be manufactured at a cost of less than \$5/kAm in the future, which means cost-performance (C-P) ratio of superconducting wires. It is estimated that this should occur in the time frame 2025-2030 and that by 2020 the price should already come down to \$20-40/kAm [22]. While SuNAM gives an achievable estimation to get the price reduce to \$100/kAm in next two years (2017), and smaller than \$50/kAm in 5 years later [23]. Besides, between the two recent well-known HTS coated conductors, YBCO is the better one for design of HTSG in cases of both mechanic stress and construction cost of HTSG as we can see in Fig. 5 [24].

Furthermore, 3G HTS wire at liquid nitrogen (LN_2) can transmit with insignificant heat losses electric current density from 3 – 5 times decreasing heat losses compared to conventional copper conductor. In addition, the C-P ratio of 3G HTS wire is \$7–\$9/kAm, while copper wire has \$20–\$50/kAm. C-P ratio of 3G HTS wire is at the threshold of \$10/kAm being defined by the US DOE for the ability for HTS wire to compete with traditional copper electric wire. This makes 3G HTS wire very efficient for HTS cables and other electric engineering applications [25]. Although, 3G HTS wire technology is still equivocal, we should believe the innovation of new technology based on genius contribution of scientists and researchers around the world. Then, 3G HTS technology will be commercial soon to serve as a new role for energy applications.

3.2. Reliability of Cryogenic Cooling System

The second challenge is to demonstrate the reliability of the technology seen from a system perspective including the cooling technology. Among particular sub-system: HTS windings, electromagnetic shield, heat insulation, the cooling system is one of the important components of HTS machines, of which function is to take heat away rapidly and maintain the superconducting property. Therefore, the robust and reliable cooling system is required for HTS machines to operate for a long time. Relative to the development and improvement of HTS machines, investigations on the cooling system are also enhanced. The recommended cooling methods for HTS machines rotor are based on phase change heat transfer [26]. For motors with low rotate speed, pipe evaporative cooling is strongly recommended as an innovative cooling to avoid low centrifugal acceleration. It has also been successfully applied to [27-28].

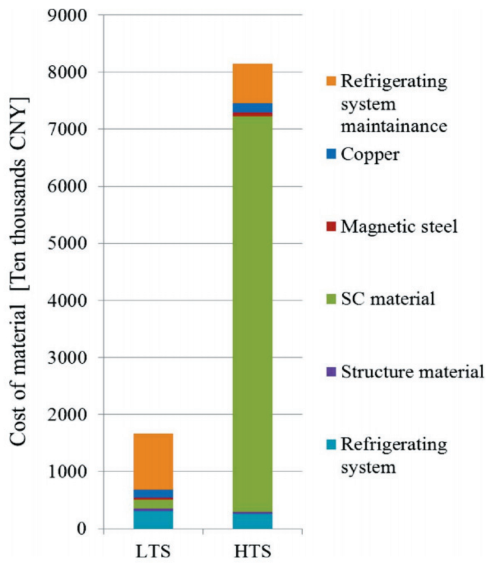

Fig. 4. Cost comparison of the designed LTS and HTS wind generator [21].

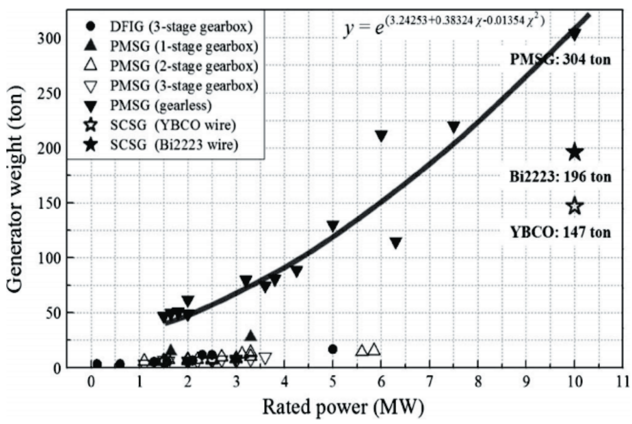

Fig. 5. Growth trend in weight of conventional generators, and the weight of the 10 MW SCSG using YBCO and Bi2223 wires [24].

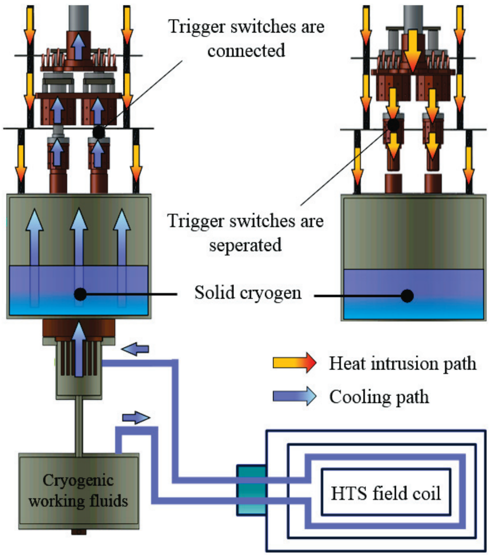

Fig. 6. The principle operation of a stand-alone cryogenic cooling system using thermal trigger switches [29].

As shown in Fig. 6, a design of a stand-alone cryogenic cooling system for a 10-MW class HTS rotating machine based on optimizing the thermal design and analyzing characteristics of using different types of solid cryogens. A high performance, reliability, and optimal cooling systems for off-shore wind turbine are characterized in [29]. The device's principle application is to eliminate parasitic heat loss from systems' non-operating cryo-coolers. Hence, it will optimize total volume of solid cryogens to remain in the HTS field coils, which are kept in a cryostat, and are kept below a certain temperature as long as desired. It can utilize cryo-cooler redundancy and downplay the cryogen usage in Dewar systems. Because of the significant savings in refrigeration power, cryogen consumption can be achieved with a short investment return time period and at a relatively low cost.

3.3. Stability of HTS Magnets for Field Coil

In cases of HTS field coil stability, the HTS wind turbine generator for large scale off-shore has two other crucial requirements in order to dominate wind power market compared with conventional large scale generators. Those are (1) improved operational robustness and stability, and (2) compact and lightweight than conventional generator [30].

The first one is a reliable and stable HTS magnet used for rotating field coil. In general, HTS magnets are thermally stable having stability margin 1000 times larger than LTS magnets. In other words, HTS magnets have slow normal zone propagation, if thermal heating at a local hot spot of magnet occurs, it is so difficult to detect quench and protect HTS magnets [31]. And also, HTS magnets are operated in electromagnetically vulnerable conditions than conventional stationary HTS magnet due to unexpected time-varying magnetic field by change of wind speed in real time [30]. This means electromagnetically unstable operation of HTS magnets for field coil brings out a local thermal heating and immoderate magnetic stress. As a result, quench and burn-out magnet arise.

The second issue is a compact and lightweight HTS magnet. In order to reduce the construction costs of wind turbine, it is essential to manufacture compact and lightweight generator as enhancing current density of HTS magnet. And also compact HTS magnets leads to stable operating condition thermally and mechanically.

Therefore, we should contrive novel design and manufacturing techniques in order to solve above technical issues. No and partial insulation (NI/PI) winding techniques can be considered as a way of HTS field coil windings. These winding techniques are developed by MIT's francis bitter magnet laboratory and introduced and studied in [32-38]. The key benefits of NI/PI technique detail as follows: a) thermal stability enhancement, b) self-protecting, c) compactness (enhanced overall current density), and d) mechanical robustness compared with insulated counterpart. However, NI/PI techniques also have some challenges in wind turbine application as follows: a) unproven in a "large" racetrack coil, and b) charging delay. Fortunately, PI technique can be possible to mitigate the adverse effect of the NI technique, which is charging delay without sacrificing the stability too much.

There has already had a design and performance analysis of a NI-type to practical application for field coil of HTS rotating machine [39]. It shows that by applying NI technique the magnet quenched at 180 A (40 % higher than the designed quench current at 128 A). Moreover, it also indicates that when the NI-type HTS field magnet current approaches its I_c, resistance of the HTS wire in the magnet increases and a portion of the power supply current starts bypassing through the other HTS wire layer, which results in a reduction of the center magnetic field. HTS rotating machine with NI-type HTS magnets was successfully fabricated and tested in the operation current level of 50 %.

4. TECHNOLOGICAL ISSUES FOR OPTIMIZATION HTS GENERATOR DESIGN

4.1. Optimal Operating Temperature Selection

Besides the three critical issues above, one more concern taking into account of a HTSG design is the operating temperatures of HTS windings. In the study of Y. Xu [40], the operating temperature are extended from 40 K to 77 K. Then, a preferable operating temperature is studied considering its influence on the basic performance and the cost of wind turbine HTSG based on 3D magnetic flux density simulation, the influence of the operating temperature on field leakage coefficient, maximum field coil operating current, and refrigerator power was clarified. In addition, the basic performance, including the generator weight, the HTS material length and the generator efficiency of wind turbine HTSG at different operating temperatures was compared with that of wind turbine based on conventional generator. Then, the wind turbine HTSG cost was estimated and compared with that of wind turbine conventional generator. Finally, it is found that the operating temperature of 68 K is preferable in practical HTSG application.

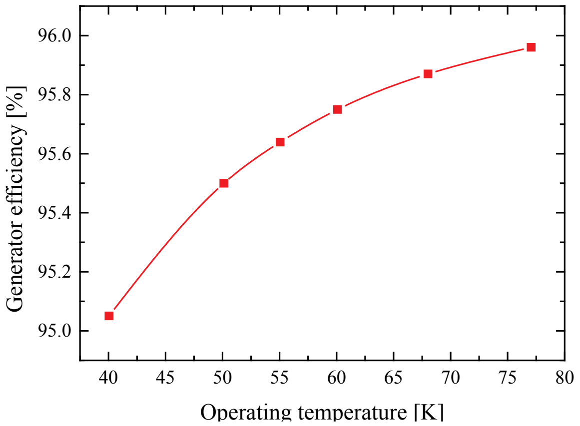

Fig. 7. Dependence of generator efficiency on the operating temperature [40].

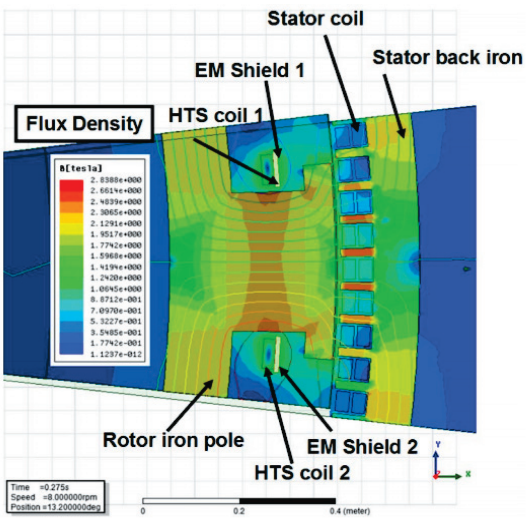

Fig. 8. Salient-pole iron rotor and magnetic stator teeth with back iron in cases of no load field distribution [41].

4.2. Generator Topology Design

Furthermore, a design topology for HTSG is also a significant aspect. Therefore, a concept design for an HTS direct drive wind turbine generator various to five different topologies is described in [41] – including (1) rotor iron yoke and stator air gap winding with back iron, (2) non-magnetic rotor yoke and stator air gap winding with back iron, (3) rotor iron yoke and magnetic stator teeth with back iron, (4) non-magnetic rotor yoke and (5) magnetic stator teeth with back iron and salient-pole iron rotor and magnetic stator teeth with back iron in Fig. 8. The main focus of this study was to minimize the amount and costs of the HTS field coils based on mechanical and thermal design. Final selection of the design is a trade-off between various performance metrics – quantity of HTS, the lowest weight, structural supports and level cost of energy (LCOE), and option (5) is a recommended selection.

4.3. Structural Shape of Field Coil

Moreover, existing studies concerning electromagnetic characteristic for large scale HTSG have been performed in [42-44]. One of significant research is the effect of field

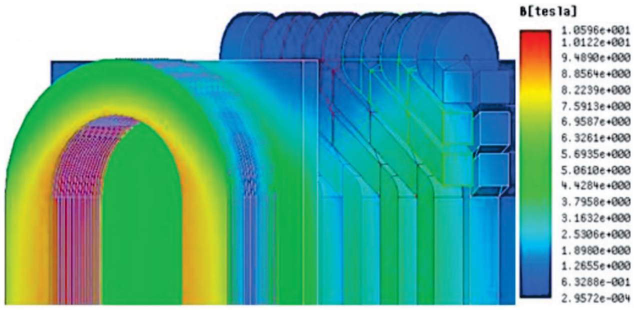

Fig. 9. 3D magnetic field distribution for different field coil shapes (rectangular shape model) [44].

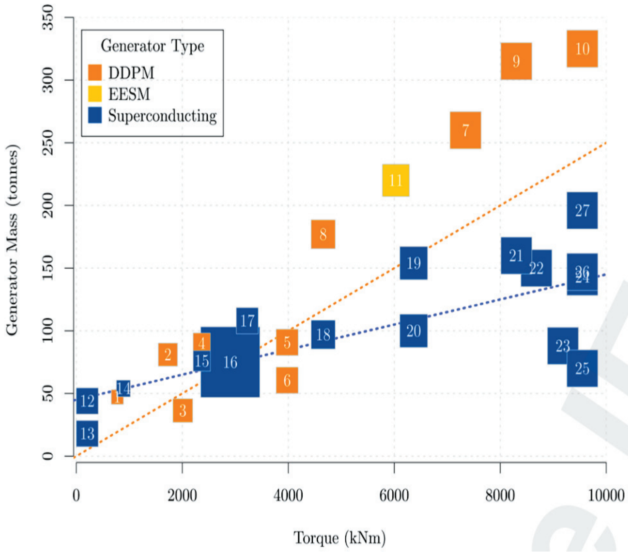

Fig. 10. Linear trend line for superconducting machines (blue line) [11].

coil shape. Then, designs and simulations of a 10-MW-class HTS generator with various superconducting field coil shape have been performed using 3D FEA according to the structural-shape changes – rectangular shape, pyramidal shape and spreadable shape. From each comparative analysis result, it is confirmed the effects on the HTS generator and field coil performance through function of inner radius (r_i), thickness (t_c), and height (h_c) and determine the effects of the air-gap shape change and the spreading DP coil arrangement. It is indicated that the optimal analysis results on the generator induced voltage in rectangular shape design, which has the largest r_i and generates the largest induced voltage and lowest magnetic flux density in the superconducting field coil [45].

TABLE I
RECENT HTSG CONCEPTUAL DESIGN [18].

Company	Model	Power (MW)	Status/year
Azimut		15	Concept/2020
GE		15	Concept/
AMSC	Sea Titan	10	Prototype/2011
TECHNALIA	SUPRAPOWER	10	Concept/2016
SUPERPOWER	REACT		Concept/2013

4.4. Level Cost of Energy (LCOE)

One more technological issue, according to [46], it has presented results of generator design optimization using LCOE as a measure of the best design. The results presented here use Monte-Carlo design space exploration to randomly vary the generator parameter values and the best topology selected. The results showed that there is an optimal HTS length such that if the conductor length was increased or decreased, would result in a non-optimal LCOE.

Lastly, Table I shows a huge number of existing projects related to electrical generators applying high temperature superconducting technology. The most relevant projects and designs of HTS generators specifically for offshore wind power systems are presented in [18]. It is also consolidated by the development trend of superconducting machines as shown in Fig. 10.

5. CONCLUSIONS

With the brief review of 2G HTS material trends, we hope that the prices of production will be reduce. Even though, the possibility of 3G HTS we can be believe that the innovation of 3G HTS can solve the biggest problems with HTSG design. In addition, based on a great number of simultaneous researches related to large scale of HTSG, this paper restates some significant works optimizing not only on the HTSG field coil stability various on 3D simulation of field coil shape, design topologies, different materials, operating temperature but also on correlation between HTSG cost and level cost of energy, as well. Finally, the latest updates for selected projects will consolidate completely the potential alternative of HTSG for their contribution to energy crisis. It also shows that many researches, prototypes, even commercial yield will dramatically increase on this technology in near future.

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