Journal of Fundamental and Applied Sciences

ISSN 1112-9867

Available online at http://www.jfas.info

Research Article

# MATHEMATICAL OPTIMIZATION OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE FOR WIND ENERGY SYSTEMS

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Received: 28 June 2017 / Accepted: 20 June 2018 / Published online: 01 September 2018

## ABSTRACT

Wind variability coupled with conditional changes in the level of energy consumption has made the need for energy storage unavoidable in increasing wind energy penetration. The quest for an environmentally friendly device with fast dynamic response and nearly infinite cycling has resulted in superconducting magnetic energy storage (SMES) being proposed as a novel storage technology for wind energy systems. This paper builds on previous work in our lab that uses a magnesium diboirde SMES to address wind interruptions. Mathematical optimization was conducted to design large capacity toroid storage specifically to address sustained interruptions from wind turbines. The toroidal configuration consisting of 4 modules exhibited the highest normalized efficiency with least superconductor requirement.

**Keywords:** Superconducting magnetic energy storage (SMES), Superconductor, Magnesium diboride ($MgB_2$), Wind Energy Integration, Wind Energy Variance Mitigation.

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doi: http://dx.doi.org/10.4314/jfas.v10i3.5

## 1. INTRODUCTION

The stochastic nature of wind hinders its wide-spread adoption into the electric infrastructure [1]. One major challenge in electrical engineering is increasing wind energy penetration into the grid. Micro-siting studies are normally used for wind integration, in this process assessment tools determine the area on the land where maximized wind production is available so as to set the wind turbine on that location. In this way maximum wind energy can be injected into the grid [1]. The success of this method ultimately depended on the wind data accuracy at the potential site and the information on site constraints [1]. Power electronics and accurate wind forecasting have contributed immensely to the current success of wind energy integration [2]. However, they do not address the challenges of wind intermittency, grid stability and flexibility simultaneously. Efforts to improve forecasting of wind energy have included probabilistic models [3, 4], site specific constraints [5] and grouping greater amounts of wind data. In addition, the recent progress and explosion in power electronics especially flexible alternating current transmission systems (FACT devices) has aided in improving the transmission capacity of wind energy but has not enabled an increase in the maximum output of the transmission line. Thus on reaching a transmission line's capacity, curtailment of wind energy will have to be done [2, 6]. Energy storage addresses the above mentioned challenges simultaneously, by providing a wide range of power system security related benefits such as spinning reserve, frequency control, peak shaving and improvements in the quality of power [6]. Publications reviewing energy storage technologies were found in literature [7-9], in which the main technical indicators like energy rating, power rating, capital cost, round trip efficiency, response time and cycle life were provided. Our previously published work comparing multiple storage technologies and their efficacy in relation to wind curtailment demonstrated that SMES with their high efficiency and quick response time were superior to batteries and flywheels [10]. The energy in a SMES systems is stored in the form of magnetic energy which is created by the flow of direct current in a superconducting coil [11]. High Temperature Superconductor (HTS) SMES operating at 15 K have a simpler design and lower operating refrigeration cost than their 4 K counterparts [11]. Communication with industry stake holders as well as literature analysis revealed that a majority of the current small scale wind turbines installed onsite range from 250 kW to 800 kW with sustained interruptions lasting from a couple of minutes to ~ 0.5 hours [6, 12]. This paper goes beyond recently published literature to design a conceptual 20 MJ magnesium-diboride SMES to reduce sustained interruptions in small scale wind turbines. Detailed analysis on $\mathrm{EMTDC}^{\mathrm{TM}}/\mathrm{PSCAD}^{\mathrm{TM}}$ simulations that demonstrate the effectiveness of SMES at alleviating sustained interruptions for small scale wind turbines can found in our previously published work [10].

## 2. METHOD

A literature search was completed for publications containing the keywords "superconductors", "SMES" and "HTS". Publications and papers were studied if they contained data on the five magnet grade superconductors [Yttrium barium copper oxide YBCO, Magnesium diboride $MgB_2$, Bismuth strontium calcium copper oxide BSCCO, Niobium titanium NbTi and Niobium tin $Nb_3Sn$]. The year 1969 was established as a cutoff since it was during this period that the first proposal for a superconducting coil for utility applications was proposed by Ferrier [13]. Papers were excluded if they did not represent a robust source of information, presented data in a nonstandard manner, or incorrectly reported data. Units were standardized to values of Critical temperature in Kelvin (K), Upper critical field in Tesla, Irreversibility field in Tesla, and Critical current density in $A/cm^2$.

### 2.1 DESIGN OF SMES COIL

The first step in designing a SMES is to choose an appropriate magnet grade superconductor (MGS). The characteristics of the superconductors are analyzed based on their superconducting transition temperature ($T_c$), critical current density ($J_c$), the engineering critical current density ($J_e$), the irreversibility field ($H^*$), and the superconducting critical magnetic field ($H_c$). High $J_c$, $J_e$, and $H^*$, rather than a high $T_c$ govern the application of the MGS in SMES [14]. Our findings also imply that the disposition of SMES for wind energy is best characterized by an $MgB_2$ conductor [15]. Additionally, the coils are maintained at 15K using a two stage GM cryocooler which is readily available in the market [16]. A strong electromagnetic force caused by high magnetic fields and large coil currents posture a threat to SMES stability. In this research we used a unique combination of non-linear programming (NLP) and the genetic algorithm (GA) detailed in Figure 1 to design a toroidal SMES in order to reduce the external magnetic field and electromagnetic forces in the winding. The toroid configuration exhibited reduced stray magnetic fields compared to solenoids since the field in a toroid was confined within the coil [17, 18]. An 800 kW wind turbine on average would produce 184 kW of power assuming a capacity factor of 23% (current operational wind turbines have a capacity factor ranging from 20% to 25% [1]). Additionally, a wind turbine required a storage system rated at 6% of its capacity to combat sustained interruptions [6]. Therefore, a 20MJ SMES is useful for ~0.5 hours. The toroidal system consists of a modular double pancake coil (DPC) based on [17, 19]. The superconducting wire used in this design was a 14 filament rectangular $MgB_2$ tape from Columbus Superconductor [20, 21]. The width of the tape was 3 mm with a 0.7 mm tape thickness. The $MgB_2$ tape characteristics are presented in Table 1.

**Table 1.** $MgB_2$ tape characteristics [19]

| **Number of $MgB_2$ filaments** | **14** |
|---|---|
| **Preparation technique** | Ex-situ PIT |
| **Tape width** | 3mm |
| **Tape thickness** | 0.7mm |
| **Total cross section ($mm^2$)** | 2.1 |
| **Superconductor Cross section ($mm^2$)** | 0.42 |
| **Filling factor (%)** | 20 |
| **Wire unit length** | 3km |

The $MgB_2$ tapes have a copper core for thermal stabilization, surrounded by 14 Ni-sheathed superconducting filaments with a Fe barrier in order to prevent the diffusion of Cu in $MgB_2$. The wires have a unit length of 3 km and cost USD 5/meter for orders up to ~ 10 km. These tapes have a width of 3 mm and thickness of 0.7 mm with a superconducting cross section of 0.42 $mm^2$. $I_c$ at 1.8T and 16 K was 403 A [20].

Although, the toroid module is composed of double pancake coils (DPC), for the purpose of this design single pan-cake coils (SPC) were assumed [17].

*Design Constraints*: The load factor which was the ratio between the operating current to the critical current of the superconductor was set to 70% for the magnet safety [22, 23]. The temperature of operation was set to 15K to minimize the total length of superconducting tape

[22, 24]. The design variables considered are the inner radius of DPC module ($r_i$), total number of coil modules ($N_c$), number of winding turns ($N_r$). The design constraints included the maximum energy of 20 MJ and $r_i$ varied from 200 mm to 900 mm with $k > 1$, where K is the ratio of outer radius to inner radius. The peak field at $r_i$ could not exceed 2T to ensure magnet safety. As the thickness of the superconducting wire was 0.7mm [21], the outer radius of the DPC module was evaluated using the number of turns.

The energy stored in the coil is given by,

$$E = N_c\,(1/2\, LI^2) \quad (Eq.1)$$

L and I represent the inductance of the coil and current through the coil. The conductor length per module $L_c$ [24] is expressed as

$$L_c = ((4\Pi B_p)/\mu_0 I)(kr_i^2 - r_i^2 + (\mu_0 E(k+1))/2\Pi B_p^2 (k-1) r_i \quad (Eq.2)$$

$$r_0 - r_i = N_r * 0.7mm \quad (Eq.3)$$

$$r_0 = kr_i \quad (Eq.4)$$

Bp is the peak field at inner radius $r_i$, $r_0$ is the outer radius. A combination of NLP and GA is used to establish the minimum quantity of superconductor required for the toroid design using the minimization function described in Figure 1[17, 22, 23, 25-27]. This combination, generates solutions to the optimization problems which for this case is the minimization of $L_c$ using techniques inspired by natural evolution like cross over mutation. In this process an initial population of potential solutions (containing a set of properties or genomes) represented in binary as strings of 0’s and 1’s is mutated and altered to set a mating pool. From the mating pool a cross over selection is performed to specify a new population. The fitness of every individual in the new population is evaluated. In our analysis the fitness is established as the minimum conductor length defined by Eq.2. The better fit individual populations are stochastically selected from the current list and each individual’s genome is modified by crossover mutation to form the new population [27]. The new population is then selected for the next iteration and the process carries on until the global minimum is obtained.

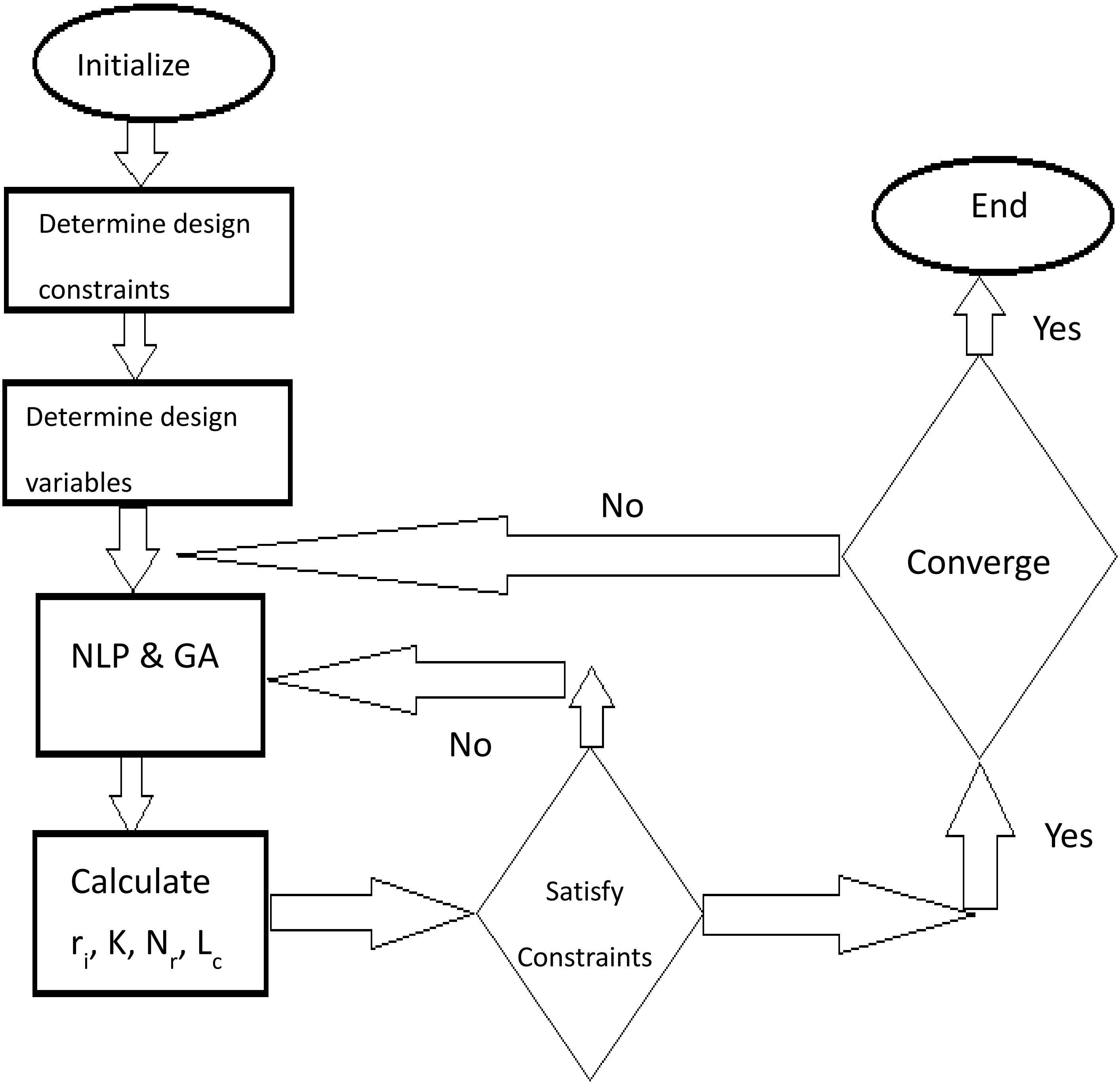


**Fig.1.** Optimal design process of a 20 MJ SMES magnet

## 2.2 MAGNETIZATION LOSS AND STRESS ON SMES COIL

An elliptical model of Haken’s formula for wires gives the most precise solution for magnetization loss [28].

$$Q=(2/3\Pi).J_c.wd.B_{\Pi}.q(\beta)\ [J/m^3.cycle] \qquad (Eq\ .5)$$

Where w and d are the width and thickness of the superconductor, $B_\Pi$ is the penetration magnetic field and q(β) is the normalized energy loss per cycle [29-31]. In order to preserve the electrical performance of the wire, the wire hoop strain should be lesser than 0.5% [32]. The hoop stress was estimated using the BJR model as described by [33], with a Young’s modulus for $MgB_2$ at ~100 GPa [32,35].

## 3. RESULTS AND DISCUSSIONS

The low irreversibility field of BSCCO-2223 [33, 34], an increased tendency for flux jump in NbTi and $Nb_3Sn$ [36], the short conductor lengths of (~200 m) for YBCO (ReBCO) and high cost ($120/m) guided our choice towards $MgB_2$ as the SMES conductor.

### 3.1 SMES DESIGN

To combat sustained interruptions in small scale wind turbines ranging from 20 kW to 800 kW, 20 MJ SMES storage was designed. Optimal parameters for the SMES were obtained using NLP and GA on a toroid design composed of 4, 8, 12, 16 and 20 coil modules. The results are presented in Table 2. The toroid design with 4 coil modules had the least superconductor requirement.

**Table 2.** Optimal design results for the 20 MJ SMES operating at 15K

| **Design Type** | **I** | **II** | **III** | **IV** | **V** |
|---|---|---|---|---|---|
| **Number of coil modules** | 4 | 8 | 12 | 16 | 20 |
| **Peak Magnetic Field $B_p$ at $r_i$ (T)** | 2 | 2 | 2 | 2 | 2 |
| **$I_{op}$ [A]** | 140 | 140 | 140 | 140 | 140 |
| **Inner Radius ($r_i$) [mm]** | 500 | 396 | 342 | 315 | 290 |
| **Max. perpendicular magnetic (T) @ 140 A** | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 |
| **Outer Radius ($r_0$) [mm]** | 1000 | 710 | 574 | 513 | 458 |
| **k** | 2 | 1.79 | 1.68 | 1.63 | 1.58 |
| **Number of winding turns ($N_r$)** | 714 | 450 | 334 | 283 | 240 |
| **Angle between coils** | $45^0$ | $22.5^0$ | $15^0$ | $11.25^0$ | $9^0$ |
| **Energy (MJ)** | 20 | 20 | 19.2 | 20 | 20 |
| **Inductance (H)** | 510 | 255 | 164 | 128 | 102 |
| **Length of wire/module [km]** | 250 | 176 | 143 | 127 | 116 |
| **Normalized Efficiency** | 0.27 | 0.19 | 0.16 | 0.14 | 0.12 |

Figure 2 shows the basic structure of the DPC using a 0.7mm $MgB_2$ tape. The SMES has an assembly of multiple DPC's, conduction cooled to 15K.

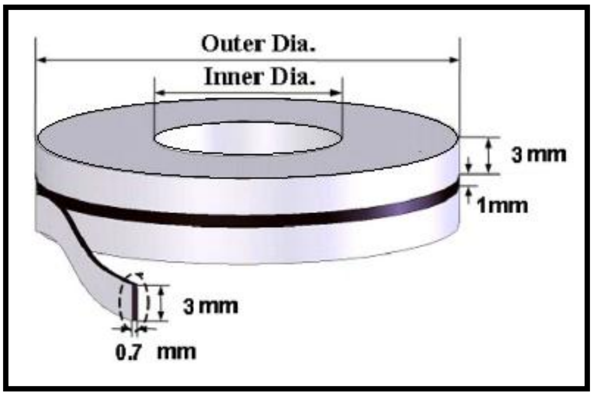


**Fig.2.** Configuration of double pancake (DPC) type coil

The total length of $MgB_2$ tape required per module is 250 km. Currently such long $MgB_2$ tapes do not exist, hence either improvements in splice technology or increasing wire lengths will aid in developing this SMES. Another area of research to look into for superconducting wire manufacturers would be to increase the superconducting fill factor in the tape in order to improve the tape's critical current and operating current, doing so would aid in reducing the minimum length of superconductor tape required.

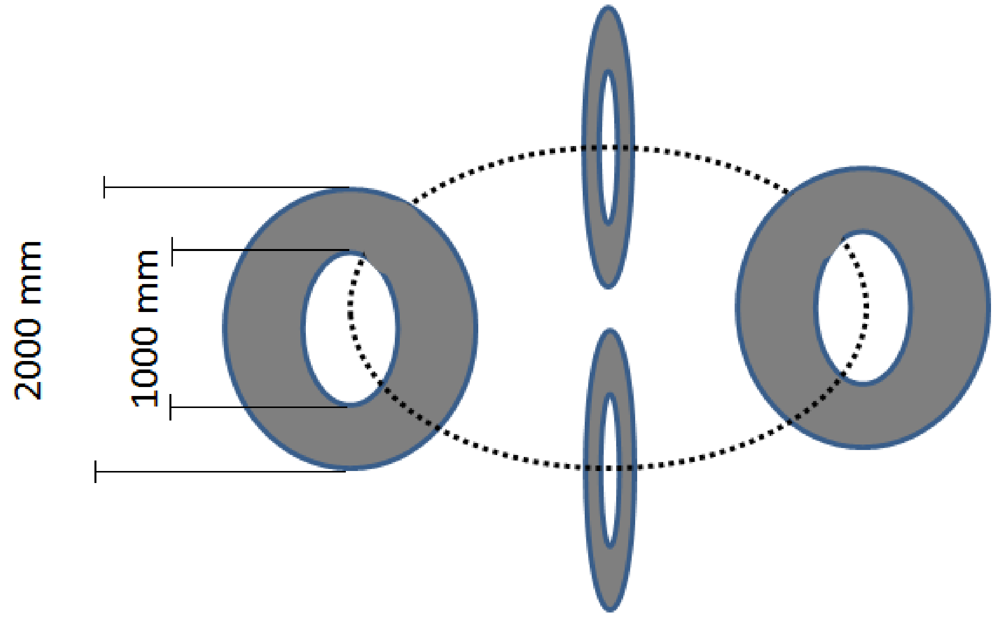
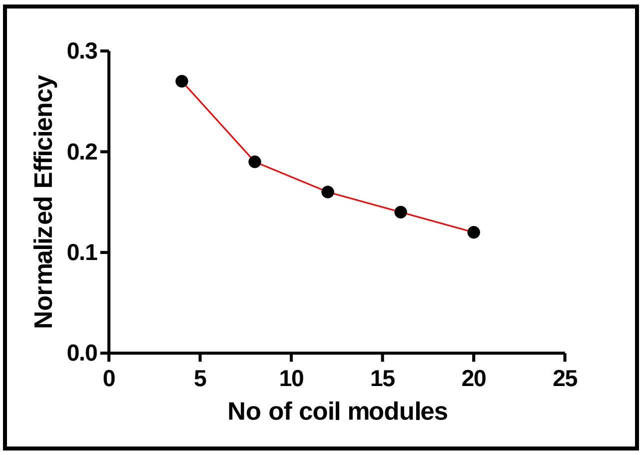


**Fig.3.** Shape of optimized toroidal model

The design of a 20 MJ toroidal magnet containing 4 coil modules, each with an inner diameter of 1000 mm and outer diameter of 2000 mm is shown in Figure 3.

Although the toroid design with 4 coil modules have the least superconductor requirement, ultimately it is expedient for stake holders concerned to choose the appropriate toroid design based on the inductance the system can tolerate. As it is to be noted that the inductance per coil module decreases when the number of coil modules increase.

The compiled results of normalized efficiency (η) and the number of coil modules ($N_c$) are presented in Table 2. A strong negative correlation was observed for the relationship of η and $N_c$ (Figure 4). The η scaled as an exponent of – 0.49. This could be attributed to the increase in required conductor length as the module numbers increased and a decrease in energy capacity per coil module.



$\eta = 0.5327(N_c^{-0.49})$
$R^2 = 0.9956$

**Fig.4.** Normalized efficiency with the number of coil modules

### 3.2 MAGNETIZATION LOSS AND STRESS ON SMES COIL

Superconductor characteristics are mostly affected by the perpendicular magnetic field, critical current and magnetization loss. The magnetization loss generates a lot of heat. Using the elliptical model of Haken's formula [27] the magnetization loss when the current charges from 0 to 140 A in 10 sec is calculated as 22mW per SPC, and the total estimated magnetization loss of 4 DPC is 0.18W. The computed safe hoop stress was < 0.25% thus maintaining the electrical performance of the wire.

## 4. CONCLUSION

An optimal 20 MJ $MgB_2$ magnet was designed. To avoid the drawback of stray magnetic fields that are characteristic with solenoid coils storing huge amounts of energy a toroid shaped coil was implemented. A combination of NLP and GA was used to optimize the underlying parameters of the toroidal coils composed of 4, 8, 12, 16 and 20 coil modules. After optimization, the toroidal configuration composed of 4 modules exhibited the highest normalized efficiency with the least superconductor requirement. Additionally, the computed safe hoop stress was < 0.25% thus maintaining the electrical performance of the wire. Further improvements in superconducting splice technology and in developing long length uniform room temperature superconductors capable of withstanding high magnetic fields would make SMES ubiquituous along the electric grid.

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**How to cite this article**:
Paul Antony A and Shaw D. Mathematical optimization of superconducting magnetic energy storage for wind energy systems, J. Fundam. Appl. Sci., 2018, *10(3), 54-67*.