Low-Cost Flywheel Energy Storage for Mitigating the Variability of Renewable Power Generation

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Abstract

In the past year, the researchers at the Center for Electromechanics at The University of Texas at Austin (UT-CEM) and the NanoTech Institute at The University of Texas at Dallas (UTD) began research efforts on improved flywheel designs and flywheel materials to meet energy storage requirements for the grid.

UT-CM’s initial effort focused on determining the power and energy requirements for a flywheel energy storage system at various points on the grid. UT-CM researchers used real-world data from a newly developed community in Austin, TX to analyze the effect of energy storage at the home level, transformer level, and the community distribution level. With requirements defined, an optimization code was developed for sizing a flywheel energy storage system for the grid. Results of this optimization are shown for today’s flywheel using conventional materials. In future studies, UT-CM will incorporate superconducting materials and new material developments from UTD.

UTD’s initial materials development has shown successful fabrication of mechanically functional nanotube yarns and sheet stacks that comprise over 95 wt% of ferromagnetic particles or the MgB₂ superconductor. Their novel method for yarn fabrication (called bisscrolling) traps guest particles (presently magnetic nanoparticles or superconductor) in the helical corridors of twist-spun carbon nanotube host. In UTD’s companion method for fabrication of guest-host stacks (birolling), guest particles are deposited on ultrathin (50 nm thick when densified) sheets of the carbon nanotube guest as both are wrapped on a mandrel. The described results provide birolled sheet stacks containing from 80 to 99 wt% particles or nanoparticles of ferromagnetic Co, Fe, Fe₃O₄,
Ni, or SmCo$_5$. Initial magnetization measurements provided a low coercive field for biscrolled yarn containing as guest 95 wt% of 200 nm chip-shaped SmCo$_5$.

Introduction
The purpose of the proposed research and development program is to develop technology that drastically reduces the cost of energy stored in and delivered from utility-scale flywheels specifically for the benefit of renewable power generation. The goal is to store 50% of the grid capacity within 50 years. Successful completion of a well-focused flywheel design and material development program could provide the needed breakthrough enabling revolutionary gains in kinetic energy storage.

An underlying aspect of the project is to understand to what degree energy storage is needed throughout the grid. Energy storage placed in homes will have different requirements than energy storage at the transformer or community level. Similarly, energy storage for renewable sources, such as wind or solar, will vary depending on their intended use. For example, whether the energy storage is sized for overcoming wind forecast errors, or it is sized to provide power during the day when wind power may be low, will result in different power and energy requirements. Understanding the needs for energy storage will guide the flywheel development.

To meet the project goals, the flywheel designs developed in this research will need game-changing approaches. Such game-changing approaches will investigate novel flywheel designs for reducing mass and ultra-low loss bearings and motor-generators using superconducting materials. An enabling technology may be the development of multifunctional nanomaterials that combine high strength with the magnetic and superconducting properties needed to levitate rotors for flywheel batteries. More generally, strong magnetic materials having increased magnetic energy product are critically important for energy applications, like decreasing the weight and increasing the performance of magnets in generators and motors in electric vehicles and for electric generators on top of windmills (and corresponding decrease the weight, cost, and size of the windmill platform).

For this effort, the team will use carbon nanotubes as host for superconductors and improved magnetic materials, including spring magnets. While the extraordinarily high strength and modulus of individual carbon nanotubes is well established theoretically and experimentally, translating these individual nanotube properties to giant specific strength and specific modulus on the macroscale has not been very successful. An additional problem has been in economically assembling billions of miles of individual nanotubes necessary to make a pound of nanotube sheet or yarn. Breakthroughs at UTD’s NanoTech Institute provide high rate nanotube self-assembly in terms of meters per second [1, 2], but not in mass throughput per hour.

To develop high performance multifunctional materials for flywheel batteries, UTD will exploit their recently invented bisscrolling technology [3] and birolling technology, which enable them to trap magnetic and superconducting guest within a carbon nanotube host. Using bisscrolling, they have made sewable, knittable, braidable, and knottable yarns that contain over 95 wt% of host nanoparticles. UTD researchers plan to advance
their bisscrolling technology to enable nanotube yarns that robustly contain up to 95 wt% of targeted superconductors and magnetic materials for both rotor and stationary applications.

Novel and game-changing flywheel designs using UTD’s material development breakthroughs will be evaluated by UT-CEM researchers based on energy and power requirements throughout the grid. These flywheels will further be compared to other storage technologies in existence to determine the best energy storage approach for meeting the goal of storing 50% of the grid within 50 years.

**Background**

**Review of Grid Energy Storage**

Applications for grid and renewable energy storage can span a broad range of power and energy storage requirements depending on the end goal for storage. Energy storage can be used at multiple places in the grid to provide a wide variety of services spanning from long-term storage, or load shifting, to shorter-term storage for voltage and frequency regulation. Overviews on the span of energy storage sizing for grid and renewable sources have been presented in previous literature reviews [4], [5], [6], [7], [8]. For applications of annual load leveling of renewable energy sources, such as wind and solar, storage times on the order of months will be required. This level of very large scale energy storage is best met by using pumped hydro, or possibly producing a fuel such as hydrogen. Mid range levels of energy storage span from days to weeks, which smooth out variations in weather patterns. Below this range is diurnal energy storage which includes the daily cyclic nature of power consumption and power generation from wind and solar sources. During the day, short-term energy storage on the order of minutes to hours can be used to respond to peak loads, passing clouds over a PV array, drop in wind, wind gust, and frequency regulation. Table I summarizes potential energy storage applications from the literature.

**Table I**: Summary review of energy storage for the grid and renewable energy sources from literature [4], [5], [6], [7].

<table>
<thead>
<tr>
<th>Energy Storage Time Scale</th>
<th>Storage Requirements and Goals</th>
<th>Cited Energy Storage Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Months</td>
<td>Annual smoothing of wind and solar generation loads</td>
<td>Large pumped hydro, hydrogen production, biomass production</td>
</tr>
<tr>
<td>Days to Weeks</td>
<td>Smoothing weather patterns in wind and solar generation</td>
<td>Compressed Air Energy Storage (CAES), pumped hydro</td>
</tr>
<tr>
<td>12-24 Hours</td>
<td>Smoothing diurnal nature of renewable sources, load shifting, and arbitrage</td>
<td>CAES, Flow batteries, lead acid batteries, pumped hydro</td>
</tr>
<tr>
<td>Minutes to Hours</td>
<td>Passing clouds, wind gust, peak load shaving, spinning reserves</td>
<td>Lithium Ion batteries, flywheels, ultracapacitors</td>
</tr>
<tr>
<td>Seconds to Minutes</td>
<td>Frequency regulation and voltage control</td>
<td>Flywheels, ultracapacitors, superconducting magnetic energy storage</td>
</tr>
</tbody>
</table>
Flywheel Energy Storage

Current flywheel energy storage, such as Beacon Power Corporation’s 20 MW flywheel plant field trial in New England, have successfully demonstrated frequency regulation capability for the grid [9] but have yet to penetrate longer-term energy storage markets, such as diurnal smoothing of renewable sources. In a study performed by Barton and Infield, flywheel energy storage was cited as the most economical storage option for power demand requirements below 30 minutes in duration [4]. These duty cycles would cover spinning reserves, wind or solar power smoothing, and voltage or frequency regulation.

Although flywheels with efficiently designed motor-generators excel in charge/discharge efficiencies when compared to electrochemical batteries, they typically fall short for long-term energy storage needs due to their self-discharge inefficiencies. Flywheel losses are primarily due to frictional windage heating and iron losses through the magnetic bearings and motor-generator [10]. These running losses can impede implementation of flywheel energy storage for long duration applications. Advanced flywheels of today operate in a vacuum and use high strength carbon composite rotors, with active magnetic bearings for low loss capability. Even so, losses must be improved to meet the needs of diurnal energy storage. Frictional windage losses can be greatly reduced by operating in vacuums below 1 mTorr, while losses through the magnetic bearings can be addressed by implementation of superconducting magnetic bearings [11].

In addition, novel flywheel architectures and topologies are being investigated to increase energy storage density. Traditional flywheel designs use non-integrate or partially integrated approaches in which the motor-generator and flywheel designs are mostly decoupled from one another (Figure 1). These topologies offer flexibility in the design, but sacrifice specific energy storage and power. In order to increase energy and power densities, UT-CEM researchers have begun investigating fully integrated approaches with an “inside-out” topology, also referred to as a hubless or coreless flywheel. This design topology does not have a central shaft and utilizes an inside-out motor-generator configuration to increase overall specific energy storage (Figure 2). Such designs have been suggested and pursued by collaboration between the University of Maryland and NASA for grid and space applications [12], by Nexans Superconductors and Siemens for potential grid applications [13], and by UT-CEM for military applications [14].

![Figure 1: Conventional flywheel design from UT-CEM for transit bus flywheel](image-url)
Figure 2: Coreless flywheel topology for increased specific energy storage.

Materials Development

UTD’s approach to nanotube yarn and sheet fabrication starts with carbon nanotube forests (parallel arrays of typically 350 µm long carbon multiwalled nanotubes, MWNTs) that have an exceptional topology, which enables nanotube sheet draw and the twist-based spinning of sheet strips into nanotube yarn [1, 2]. The sheets, when densified, have a much higher gravimetric strength than the strongest steel sheet and the Mylar and Kapton used for ultra-light air vehicles. In their biscrolling process, UTD researchers deposit nanoparticle, microparticle, or nanofiber guest on the nanotube sheet (or thereby derived spinning wedge), and then insert twist. In the birolling process, the researchers laminate guest layers between forest drawn nanotube sheets (which are only about 50-100 nm thick when densified).

Results

Flywheel Sizing Requirement

An important first task for the flywheel design is to determine power and energy storage requirements. This task requires some information and assumptions about where the storage device will be located, and what the demands will be. Distributed energy storage throughout the grid, or in people’s homes, will have different requirements than storage demands at renewable generation plants (wind/solar farms) or other higher levels on the grid.

Using real world data leveraged from their work on the Pecan Street Project in Austin, TX, UT-CEM researchers studied the power and energy requirements at several locations within a 741 home community. The Pecan Street Project is unique in that it is collecting the deepest level of residential consumer information in the United States: electric, water, and gas. Electrical consumption data is available from rooftop solar panels, outside the homes, and inside the homes at the subcircuit level (e.g., HVAC, appliances, etc.). Also of great significance is the penetration of solar PV installations at the homes. Approximately 25% of the community has 6 kW solar PV arrays.

A simple way to model the dynamic behavior of flywheel energy storage in a system is shown in Equation 1. This equation states that the rate of change of stored energy, $Q$, is equal to the difference in grid power, $P_g$, and load demand, $D_L$, minus a spin down loss with time constant $\tau_{fw}$. A charge-discharge efficiency factor could also be incorporated into this equation but has not been added at this time.
\[
\frac{dQ_{fw}}{dt} = P_g - D_L - \frac{1}{\tau_{fw}} Q_{fw}
\]  \tag{1}

This simplified equation also allows the designer to explore the effects of running losses on energy storage performance by doing parametric studies through the flywheel time constant, \(\tau_{fw}\). The analysis showed that higher losses greatly impede diurnal storage effectiveness by leading to higher peak grid loads. For smaller energy storage, to provide power smoothing, the higher losses have reduced effects.

In order to determine the flywheel power and energy storage sizing requirements, an optimal control law was developed to minimize the cost function in Equation 2, which is applied to the dynamic model of Equation 1. The goal of this method is to investigate trade-offs between energy storage size, reduced grid power, and effect of flywheel losses on performance. The first term in the cost function is an end constraint which requires the flywheel stored energy at the end of the simulation to be equal to the initial amount of flywheel stored energy, \(Q_0\). In other words, the flywheel should not have a net charge or discharge throughout the simulation. The integral portion of the cost function seeks to minimize the sum of the grid power, \(P_g\), and the deviation of flywheel stored energy, \(Q_{fw}\), from the initial stored energy, \(Q_0\), subject to weighting factors \(a\) and \(b\).

\[
J(t_0) = \frac{1}{2} S_q \left( Q_{fw}(T) - Q_0(T) \right)^2 + \frac{1}{2} \int \left( a \left( Q_{fw}(t) - Q_0 \right)^2 + b P_g^2(t) \right) dt
\]  \tag{2}

An analysis was performed on data from the Pecan Street Project of homes in the Mueller Development in Austin, TX. The analysis examined the benefits and sizing requirements for a flywheel energy storage system throughout different locations in the community. These locations include the individual home level, local transformer level (supports approximately eight homes), and community level (all 741 homes). Sample load data for an individual home, transformer level, and the entire community is shown in Figures 3, 4, and 5, respectively for an Austin summer day in 2011. These plots show the power consumption throughout the day (red), the solar power generated (green), and the grid power required (black), which is the difference between the power consumed from the homes and generated by the PV arrays. At the individual home, power usage is characterized by high pulse loading of the air-conditioning system. At the transformer and community level, aggregation of loads smoothes out the profile.

The first step in the analysis evaluated placing small flywheel energy storage systems in individual homes. Flywheel energy storage with a spin-down time constant of 50 hours was assumed for this initial analysis. Thirteen different homes were selected from the Mueller data, each with solar PV generation, for a summer day in August 2011. Energy storage sizing curves were generated for each home to view the trade-off between flywheel size and decrease in peak grid power demand (Figure 6). As expected, there is a wide variance at the individual level due to individual customer preferences on home energy use.
Figure 3: Power data for individual home in Mueller development.

Figure 4: Aggregate power data of eight homes at transformer level.

Figure 5: Mueller community power consumption data.
Figure 6: Comparison of flywheel energy storage to peak grid power.

For each individual curve in Figure 6, the last point on the right represents diurnal energy storage to average the total load over the 24 hour period. Flywheels would need to deliver between 15-35 kWh of energy, with power levels up to 9 kW for diurnal energy storage. An example of the diurnal averaging is shown in Figure 7, where the grid energy use (black line) is nearly constant throughout the day.

Figure 7: Power and flywheel energy for home diurnal energy averaging.

Rather than diurnal averaging of the grid energy, a trade-off between the energy storage size and the degree of power smoothing can be made. The curves in Figure 6 show that for about 2.5 kWh of delivered energy, the flywheel can reduce the peak grid power load between 10 to 65%, depending on individual home usage. The flywheel peak power for this power smoothing case would be about 7 kW. The effect of this size flywheel at the home is shown in Figure 8. As shown, the flywheel now handles the peak, cyclic loads at the home, while the grid power demand is smoothed. For a comparison of this impact, note the grid power use in Figure 3 versus Figures 7 and 8.

A similar analysis was performed at the transformer and community levels. Figures 9 through 12 show these results graphically. As more homes are aggregated, the power and energy requirements for the flywheel increase, while the power to energy ratio decreases. The results for all three locations are summarized Table II.
Figure 8. Power and flywheel energy for home load smoothing.

Figure 9: Flywheel diurnal energy storage at transformer level.

Figure 10: Flywheel power smoothing at transformer level.

Figure 11: Flywheel diurnal energy storage at community level.
Figure 12: Flywheel power smoothing at community level.

Table II: Flywheel energy storage sizing results for single home, transformer, and community levels on the grid.

<table>
<thead>
<tr>
<th>Location</th>
<th>Peak Demand Power</th>
<th>Diurnal Storage Power</th>
<th>Power Smoothing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Home</td>
<td>5.7 kW (average)</td>
<td>15 kWh / 6 kW</td>
<td>2 kWh / 6.2 kW</td>
</tr>
<tr>
<td>Transformer (8 homes)</td>
<td>30.7 kW</td>
<td>70 kWh / 16.3 kW</td>
<td>6 kWh / 12 kW</td>
</tr>
<tr>
<td>Community (741 homes)</td>
<td>2500 kW</td>
<td>5.9 MWh / 1200 kW</td>
<td>450 kWh / 300 kW</td>
</tr>
</tbody>
</table>

A further analysis by the team investigated energy consumption and costs throughout the year. Data from ERCOT for 2011 was obtained for the market pricing in the South Central Texas weather zone and power demands for Austin Energy (Figure 13). The red line shows the power demand for this region, while the blue line represents the market price. Market variations in energy cost are rather constant throughout the year, on the order of $20/MWh, except for spikes that occur up to a $3000/MWh market cap.

An interesting observation from Figure 13 is that the market pricing spikes do not necessarily line up with peak load demands throughout the year. For example, between days 50 and 100 (Spring) and between days 300 and 350 (Fall) there are price spikes even though the load is relatively low compared to the Summer months. Other factors, such as power plant down time or transmission line congestion, are at play and pricing is not necessarily driven by overall power demands.

Figure 13: ERCOT data for Austin, TX area loads and pricing for 2011.
Using this data, the UT-CEM researchers were able to integrate the energy cost over the entire year for the Austin Energy load zone. This is shown by the red curve in Figure 14, with a cumulative yearly cost of $3BB. The black line in Figure 14 represents the cumulative costs of the price spikes throughout the year that exceed $100/MWh. Note that even though the spikes occur for a small percentage of the time throughout the year, they represent 40% of the electricity cost throughout the year.

![Cumulative energy costs for 2011 for the Austin, TX area.](image)

Figure 14: Cumulative energy costs for 2011 for the Austin, TX area.

Thus, if energy storage could be sized to offset factors contributing to the peak pricing throughout the year, such as high power demands, line congestion, or power plant downtime, then a significant savings in energy costs are realizable. Although this result may lead to the assumption that energy storage could cut energy expenses in half, the researchers note that the energy market is volatile and adding energy storage of this magnitude will cause some adjustment in the market. A true assessment of the benefits would require a thorough economic evaluation; however, the potential value and benefit based on this analysis suggests a high impact benefit for energy storage on the grid.

**Flywheel Optimization Results**

With an understanding of flywheel sizing requirements on the grid at various locations, UT-CEM researchers have begun developing preliminary optimization routines for designing flywheels per these requirements. Current work has focused on traditional flywheel and electromagnetic materials, such as composites bandings for the flywheel and steel laminations for the magnetic circuitry for the magnetic bearings. The low strength-to-weight ratio of magnetic steels is a limiting factor for overall flywheel performance. Summaries of typical materials for these applications are shown in Tables III and IV.

**Table III:** Material properties for steel laminations.

<table>
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<tbody>
<tr>
<td>1010 Steel</td>
<td>7800</td>
<td>200</td>
<td>365</td>
<td>305</td>
<td>1.3</td>
</tr>
<tr>
<td>4340 Steel</td>
<td>7800</td>
<td>205</td>
<td>965</td>
<td>855</td>
<td>1.5</td>
</tr>
<tr>
<td>Hiperco 50 HS</td>
<td>8110</td>
<td>207</td>
<td>1080</td>
<td>600</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Table IV: Material properties for composite bandings.

<table>
<thead>
<tr>
<th>Composite Bandings</th>
<th>Density [kg/m$^3$]</th>
<th>Modulus (hoop direction) [GPa]</th>
<th>Ultimate Strength [MPa]</th>
<th>Hoop Design Stress Limit [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM7</td>
<td>1564</td>
<td>172</td>
<td>2236</td>
<td>1380</td>
</tr>
<tr>
<td>T1000</td>
<td>1561</td>
<td>207</td>
<td>3100</td>
<td>1860</td>
</tr>
</tbody>
</table>

Results from the optimal design analysis, which considered radial and hoop stress limitations in the steel and composite materials, are shown in Table V for the different steel lamination materials. The lower strength and lower magnetic performance 1010 steel shows to be a significant limitation on overall flywheel performance, whereas the higher strength 4340 steel and Hiperco alloys show comparable performance. Even though the Hiperco alloy is magnetically superior to the 4340 alloy, the higher strength 4340 alloy allows the design to reach comparable performance.

To realize a high-impact of energy storage on the grid, material advancements are needed to increase energy storage density and reduce system level losses. For example, higher strength and multifunctional composites would allow higher energy densities, and superconducting magnetic bearings will allow lower losses.

Table V: Optimized analysis results.

<table>
<thead>
<tr>
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<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1010 Steel</td>
<td>0.74 m x 2.80 m x 1.0 m</td>
<td>280.7</td>
<td>12,222</td>
<td>633</td>
<td>25.0</td>
</tr>
<tr>
<td>4340 Steel</td>
<td>0.81 m x 2.25 m x 0.93 m</td>
<td>296.6</td>
<td>6,685</td>
<td>823</td>
<td>44.4</td>
</tr>
<tr>
<td>Hiperc 50s</td>
<td>0.77 m x 2.52 m x 1.0 m</td>
<td>365.1</td>
<td>9,300</td>
<td>790</td>
<td>39.2</td>
</tr>
</tbody>
</table>

Biscrolling Magnetic Materials

In the initial efforts by UTD researchers on biscrolling magnetic materials in nanotube host, the emphasis was on demonstrating high loading levels of magnetic materials in a mechanically robust nanotube yarn. Biscrolled yarns were fabricated by twisting CNT sheets covered with up to 95 wt% magnetic particles. The deposition of magnetic particles onto CNT sheets is currently achieved by one of three deposition techniques: aerosol spraying from an ultrasonic atomizer (Figure 15A); impregnation or drop casting CNT sheets and evaporating solvent by heating the CNT sheet with a hotplate (Figure 15B); and by vacuum filtration (Figure 15C).
Figure 15: Schematic diagrams showing the biscrolling fabrication process, where magnetic particles were deposited onto a CNT sheet or sheet stack, followed by twist insertion and collection of biscrolled yarn. Magnetic particles are deposited by: (A) spraying, (B) drop casting and (C) vacuum filtration.

Joint optimization of mechanical and magnetic properties is complex, and involves factors such as particle size and biscrolling conditions – especially the degree of twist insertion, since sufficient twist insertion is needed to stop rotation of quasi spherical magnetic particles and too high a twist insertion will degrade mechanical properties. Some of the fabricated samples are shown in Table VI, together with literature values of flux density. These sheet composites were fabricated from forest-drawn CNT sheets using the UTD birolling technology, which will be described later in this report.

The magnetic properties of yarns with biscrolled magnetic particles are being studied using a Quantum Design magnetic properties measurement system (MPMS) based on a superconducting quantum interference device magnetometer (SQUID) with a 7 tesla superconducting solenoid. Figure 16 shows a magnetization curve for an initially
investigated biscrolled SmCo$_5$ yarn. Magnetization measurements were performed in the temperature range of 100 to 300 K with precise stabilization of each targeted temperature (0.01 K) for 10 s followed by two scans and data acquisition. For dc magnetic measurements, yarn samples were aligned parallel to the applied field, sealed into moisture-resistant thermoplastic Parafilm, encapsulated into gelatin capsules (SPI supplied) and attached to the end of a diamagnetic rod (SPI, Part #AGC2) using a plastic straw. The measured signal was corrected with respect to the temperature-independent signal of the gelatin capsule in the plastic straw. The precision of the measured magnetization value was tested using Quantum Design’s standard Pd sample.

**Table VI:** Fabricated magnetic material-CNT sheet composites.

<table>
<thead>
<tr>
<th>Material</th>
<th>Flux Density in Literature (tesla)</th>
<th>CNT sheet layers</th>
<th>Weight Percent Magnetic material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt (Co)</td>
<td>1.72</td>
<td>8</td>
<td>96</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>2.20</td>
<td>8</td>
<td>80</td>
</tr>
<tr>
<td>Iron Oxide (Fe$_3$O$_4$)</td>
<td>0.64</td>
<td>8</td>
<td>98</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>0.60</td>
<td>8</td>
<td>99</td>
</tr>
<tr>
<td>SmCo$_5$</td>
<td>1.2</td>
<td>8</td>
<td>95</td>
</tr>
</tbody>
</table>

**Figure 16:** Magnetic hysteresis of biscrolled SmCo$_5$ yarn.

Magnetization and the corresponding coercive field are low for the data in Figure 16 for a biscrolled yarn containing 95 wt% of chip-shaped SmCo$_5$, which were produced by high energy ball milling by UTD’s collaborator Ping Liu at the University of Texas, Arlington. These chips are about 5 µm in width and about 200 nm in thickness. Subsequent measurements on our SmCo$_5$-containing biscrolled yarn to higher poling field in Ping Liu’s laboratory (while our magnetometer is being repaired), provided a substantially higher coercive field (H$_c$ = 1.3 kOe compared with the 0.72 kOe in Figure 16), possibly because of the dependence of coercive field on the poling field or partial twist release during sample handling. However, both of these measured coercive fields are much lower than expected from previously measurements by Ping Liu’s team for similarly prepared SmCo$_5$ that was poled and then frozen in a resin matrix (about 20 kOe, 3.1 kOe, 2.4 kOe, and 0.170 kOe at room temperature for samples 23 nm, 13 nm, and 6
nm thick, respectively) [15]. The origin of this discrepancy is not presently understood. One possible explanation is that the low demonstrated $H_c$ from both of these measurements arises from the ease of rotation of the magnetic particles in the nanotube host. UTD researchers have convenient ways to eliminate this potential problem: (1) infiltrate the magnetic particles in biscrolled or birolled composites with resin while these magnetic particle/CNT composites are poled, (2) increase inserted twist in biscrolled yarns so that the extremely high generated lateral stresses (which can collapse large diameter few walled nanotubes into ribbons) provides stresses that prohibit rotation.

UTD’s demonstration that they can make mechanically robust biscrolled yarns and biscrolled sheets containing over 95 wt% magnetic particles (in less than 5 wt% nanotube host) is important, since a major problem with prior-art magnetic particle/resin composite magnets is the low loading levels. The alternative use of sintered particle magnets has its own problems, like the difficulty, cost, and waste associated with machining the sintered magnetic particles and the brittleness of these sintered particle magnets.

Exchange coupled magnets, often called “spring magnets,” will provide the emphasis of continued research – once we better understand the relationship between host-guest structure and magnetic properties for our magnetic biscrolled yarns and birolled sheets. These spring magnets have the potential to provide higher energy products than conventional magnets, and our collaborative work with Ping Liu at the University of Texas, Arlington (who is a pioneer in the fabrication of spring magnet nanocomposites) will facilitate project efforts. If correctly assembled to have nanoscale interfaces between hard and soft magnetic phases (so that the dimension of the soft phase is less than twice the domain wall thickness of the hard phase), then a high energy product can be obtained by non-additively combining the high coercive field of the hard phase with the high magnetization of the soft phase. Exploiting the fact that UTD can use their biscrolling and birolling processes to make mechanically robust composites that are largely the magnetic particles, the team may be able to avoid the degradation in magnetic properties that normally results from magnetic particle growth during sintering processes.

**Biscrolling Superconducting Materials**

UTD researchers have selected MgB$_2$ as the initial prototype material for our studies on biscrolled and birolled superconductors. Despite having a critical temperature (39 K) that is much lower than for BSCCO ($T_c$~108 K) and YBCO ($T_c$~92 K), MgB$_2$ is attractive due to exceptionally high critical current densities, relatively low anisotropy, and the low cost of starting materials. Economically and technically, it is a prime competitor against conventional, high-performance superconductors such as NbTi and Nb$_3$Sn. The significant advantage of MgB$_2$-based superconductors over BSCCO and YBCO is that MgB$_2$ has “weak link” free grain boundaries and the supercurrent density is controlled by flux pinning rather than by grain boundary connectivity [16].

Chemical doping, including element substitution and/or inclusion of impurity particles, is one of the most effective and simplest ways to improve MgB$_2$ superconductor properties. Even though no dopant has been found that increases the transition temperature, substitutional and inclusional doping improved flux pinning, in-field critical current densities, upper critical field, and irreversibility field. The most significant effect
was observed for carbon and carbon-based compound doping [17]. Superconducting MgB$_2$-CNT composites show significantly improved superconducting properties due to enhanced flux pinning: critical current can be increased by more than one order of magnitude [18]. Additionally, CNTs can carry high currents and remain stable in composites, providing electrical connections between MgB$_2$ grains, as well as potentially providing mechanical properties improvements. Furthermore, the high CNT thermal conductivity is potentially useful.

Here UTD researchers present a method to produce MgB$_2$-CNT composite as an aligned nanowire network, which can be potentially spun into yarns of unlimited length. In the first step, the nanotubes were coated with a conformal layer of boron using laser-assisted chemical vapor deposition (Figure 17). CNT sheets have extremely low thermal capacity and high optical absorbance, so even a small laser source (0.4 W) can heat the nanotubes to approximately 1500-2000° C. BBr$_3$ was used as a precursor for boron deposition. When the laser beam is focused on carbon nanotubes and in constant hydrogen flow (20 sccm) with BBr$_3$ vapors at low pressure (0.6 torr), a thin layer of boron deposits on carbon nanotubes according to the reaction:

$$2BBr_3 + 3H_2 \rightarrow 2B + 6HBr$$

(Figure 17: Reactor setup for laser-assisted chemical vapor deposition.)

The laser spot can be scanned across the CNT sheet area using a mirror galvanometer scanning system. Depending on laser exposure time, the thickness of the coating can be adjusted from 20 nm up to several hundreds of nanometers. Finally, the boron coating the CNT sheets can be converted into MgB$_2$ either before or after bicrolling into yarn.

Magnesium diboride nanowires were produced by reaction of boron nanowires with Mg vapor. Boron/CNT sheet networks/yarns were suspended above a graphite crucible containing Mg flakes. Annealing in Mg vapors was done in a quartz tubular furnace at 900°C, for 2 hours in Ar/10% H$_2$ flow (total flow 300 sccm) at 1 atm. The vapor pressure of liquid magnesium at 900°C is about 109 Torr, which is sufficiently high to supply Mg vapor in the vicinity of the boron nanowire networks. High temperature promotes the diffusion of Mg inside the boron nanowires. The nanowire thickness
increases almost two-fold and crystal growth is observed in SEM images, which confirms magnesium penetration in the boron lattice and MgB₂ formation.

The electrical resistance of the MgB₂@CNT yarn was measured versus temperature using four-probe electrode configuration. The abrupt drop at ~35 K provides a well-defined superconducting transition of the MgB₂ coated CNTs (Figure 18, left). The critical temperature obtained is slightly lower than for bulk MgB₂ and the transition is relatively broad. These effects might be a result of doping with carbon, oxygen contamination, incomplete MgB₂ formation, and/or the presence of Mg-depleted phases (MgB₄, MgB₇). Conditions for annealing in Mg vapor need to be optimized for a high-yield transition of boron nanowires into MgB₂ nanowires.

Transport measurements measured for several different external fields up to 6 tesla (Figure 18, right). The critical temperature for the upper critical field Hc₂ was defined as the temperature at which ρ/ρn = 80%, and the irreversibility field Hirr (the field at which current largely vanishes) was defined the field for which ρ/ρn = 80%. While these results show considerable improvements in field dependence compared with results that we previously achieved by converting biscrolled Mg and B particles to MgB₂, further process optimization is required to obtain high performance Mg superconductors that are economically fabricable as mechanically robust yarns using our biscrolling technology.

![Figure 18](image_url)

**Figure 18:** Left: resistance vs. temperature in different fields; Right: upper critical field and irreversibility field vs. temperature.

**Birolling Technology for Fabrication of Magnetic and Superconducting Sheet Stacks**

As an extension of the biscrolling technique, the UTD team has also produce birolled magnetic and superconducting CNT composites, where guest materials are deposited from an aerosol (or by other deposition methods) on top of CNT sheets as these sheets are drawn from a forest and wrapped on a mandrel. See schematic representation in Figure 19. To avoid sheet collapse due to surface tension effects, guest deposition on free-standing sheets should be free of liquid carried. This was accomplished by heating the sheet environment so that liquid evaporates before contact with the sheet. After deposition, the film or laminate is removed from the collecting mandrel.
Figure 19: Schematic representation of the birolling fabrication process, where CNT sheets are collected onto a mandrel while guest material is deposited to form a CNT/particle stack. Inset: photo showing the dry drawing of CNT sheets from a CNT forest as it is being collected onto a mandrel.

Development of Continuous Biscrolling Process

The above described biscrolled yarns containing magnetic particles were made by the batch process of Figure 15C. As a result, biscrolled yarn lengths were limited by the diameter of the filter used for filtration-based deposition. To enable production of larger amounts of material for applications evaluations (and to initiate the upscale needed to produce commercially useful yarn amounts for flywheel battery and other applications), UTD has conducted research on the upscaling of biscrolling.

The presently devised process is divided into three major steps: (1) continuously draw a carbon nanotube sheet from a nanotube forest and deposit it onto a flexible substrate; (2) continuously deposit guest materials onto the substrate-supported carbon nanotube sheet; and (3) remove the carbon nanotube sheet from the substrate and insert twist to form the biscrolled carbon nanotube yarns. The scheme and design for automating this entire process is shown in Figures 20A and 20B, and the simplified prototype built is shown in Figure 20C.

In the process of Figure 20A, one or more carbon nanotube sheets are drawn from the corresponding number of nanotube forest and then laminated on a supporting plastic film substrate. By using this flexible substrate, researchers can avoid collapse of the nanotube sheet due to surface tension effects during subsequent densification and liquid-based guest deposition – a forest-drawn nanotube sheet is no more than 100 nm thick after liquid-based densification. The plastic substrate with attached nanotube sheet host and overlying guest layer is then drawn into a liquid bath, which enables separation from the substrate film sheet and insertion of twist to make biscrolled yarn. In order to allow release of the CNT sheet from the substrate when passed into water (or a liquid with similar cohesive energy density), the researchers exploited sheets that are hydrophilic (like surface-treated PET film: 3M #9960 anti-fog film). For initial demonstration of continuous bisscrolling, UTD researchers used both Al powder and magnetic particles from a ferrofluid as guest, which were applied by sieving and dip coating, respectively. The resulting biscrolled yarns are shown in Figure 21.
Figure 20: (A) Scheme for automating the biscrolling process, (B) schematic illustration of the corresponding apparatus, and (C) simplified apparatus used in the present study, where carbon nanotube sheet is drawn from the forest (on the left), attached to a hydrophilic plastic sheet, overlaid with guest, and then passed through a water bath, where the bilayer guest-host sheet is separated from the substrate and twist spun into biscrolled yarn.

Figure 21: SEM image of a bismilled CNT yarn containing Al micro-powder as guest (left) and an optical image of a bismilled CNT yarn containing iron oxide guest being attracted to a magnet (right).

Progress

Since October 2011, the researchers have compiled data from a community in Austin, TX to size a flywheel energy storage system at various locations on the grid. In addition, UT-CEM researchers have shown a large value potential if energy storage were adopted at levels that would handle spikes in the electric energy costs. With these results, the researchers have begun preliminary flywheel optimizations to meet the grid requirements based on traditional flywheel materials. These optimizations will lead to further studies.
using advanced materials and designs to increase energy storage densities and decrease losses in flywheel energy storage systems.

Materials development work by UTD researchers has shown they can fabricate mechanically functional biscrolled yarns and birolled sheets that contain 95 wt% and 99 wt% of ferromagnetic guest, respectively. This demonstration is important because it should enable fabrication of high-energy-product magnets that could lead to lighter, more energy efficient electric motors and generators for such applications as electric vehicles, windmill electric power generation, and mechanical energy conversion and levitation for flywheel battery energy storage.

In addition, upscaling the UTD biscrolling and birolling processes has been a problem when liquid-based guest deposition is used, since the 100 nm thick nanotube sheets can collapse due to surface tension effects during solvent evaporation. However progress by UTD researchers has demonstrated the feasibility of liquid-based biscrolling and birolling processes which enable them to make larger sample sizes for performance evaluations, and suggest strategies for eventual commercial production.

The current progress and research results show value in adding energy storage and have pointed to energy storage and power requirements for locations on the grid. When combined with advanced materials, breakthroughs in flywheels may be achieved. Although no ideal energy storage solution exists today, the inherent modularity and non-site specific nature of flywheels, as well as their low environmental signature, may provide a more economical and socially attractive solution for the future of energy storage. As a result, wide-scale use of flywheel storage should enable supplanting coal and gas plants and make renewable energy sources attractive as base load generators.

**Future Plans**

UT-CEM researchers plan to continue modeling efforts to size flywheel power and energy requirements by investigating use of energy storage at solar and wind farms. These analyses will closely mirror the community analyses of this progress report in which the flywheel requirements are determined for various levels within the farms. For example, a flywheel per wind turbine, a subset of turbines, or the entire farm will have vastly different energy and power requirements. Additionally, the analyses will help determine the most sensible use of the flywheel, whether for diurnal storage or power smoothing.

In addition, UT-CEM researchers will continue to investigate flywheel designs and their implications. One aspect the researchers foresee is a balance between energy and power requirements resulting from the grid and wind data analysis versus physical and practical constraints on material, fabrication, and installation capabilities. For example, a small home flywheel may very well be practical and meet the sizing requirements; however, a community level flywheel sized to meet those requirements may become unwieldy, requiring some degree of modularization.

Furthermore, the preliminary sizing analysis has highlighted the need to reduce losses for widespread implementation of flywheels in the grid. UT-CEM will investigate
utilization of superconducting magnetic bearings as a pathway to further reduce losses of magnetic bearings. Current superconducting bearing designs rely on interactions by discrete permanent magnets and bulk superconductors, which create inhomogenous magnetic fields that induce bearing losses [11]. Collaboration with UTD will be further pursued to develop hard permanent magnet and superconducting composite materials which can provide homogenous magnetic fields, and still meet the mechanical needs of high strength and low density.

For Example, exchange coupled magnets, often called “spring magnets”, will provide the emphasis of continued research, once UTD gains a better understanding of the relationship between host-guest structure and magnetic properties for their magnetic biscrolled yarns and birolled sheets. Exploiting the fact that they can use our biscrolling and birolling processes to make mechanically robust composites that are largely magnetic particles, they should be able to avoid the degradation in magnetic properties that normally results from magnetic particle growth during sintering processes.

Additional research will focus on obtaining economical, robust, and high performance superconducting properties in UTD’s biscrolling technology. In their initial program work on using biscrolling to produce superconductors, UTD researchers developed a novel route to superconducting biscrolled MgB$_2$ yarn. This yarn provides intergranular connectivity and a well-defined superconducting transition at $\sim$35 K, which enabled us to determine the temperature dependence of upper critical field and irreversibility field up to 6 tesla, which are important for application of MgB$_2$ for magnetic levitation. While these results show considerable improvements in field dependence compared with results that were previously achieved by converting biscrolled Mg and B particles to MgB$_2$, further process optimization is required to obtain high performance Mg superconductors that are economically fabricable as mechanically robust yarns using our biscrolling technology.

Publications and Patents
No publications or patents to date.

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