THERMAL AND COMPRESSED-AIR STORAGE (TACAS): THE NEXT GENERATION OF ENERGY STORAGE TECHNOLOGY

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INTRODUCTION: THE NEED FOR PERSPECTIVE

Last year, Active Power introduced a hybrid energy storage technology called TACAS, an acronym for Thermal and Compressed Air Storage. TACAS is based on a combination of mature and well-understood technologies, and has drawn considerable interest from the trade press. In addition, TACAS has attracted the attention of many potential customers with difficult energy storage problems.

The question to be answered is where TACAS will fit into spectrum of energy storage solutions. Based on prototype testing, it appears that the new technology can replace lead-acid batteries in some applications. This paper will discuss which applications are feasible for near-term TACAS products, which are feasible for second-generation products, and which will require extensive research to achieve commercial viability.

A CLEAN SHEET OF PAPER

TACAS was conceived at a “Vision” session at Active Power. Management had challenged Engineering and Marketing to dream up the next generation of battery-replacement products. The new product needed to be safe, reliable, non-toxic, and compact (high energy density) like flywheel energy storage. It should have low installed cost and low life-cycle cost. The technology needed to be relatively mature, to enable the new product to reach the market in a reasonable length of time. It should also have the capability of extended runtime, comparable to conventional UPS battery systems. The extended runtime was an especially important goal, since potential customers have cited the relatively short backup time as a disadvantage of flywheel energy storage systems.

Compressed Air

Several of the “Vision” participants favored Compressed Air Energy Storage (CAES). Many electric utility companies are investigating CAES for large-scale load-shifting applications. The concept is to use low-cost off-peak power, or the irregular output of a wind farm, to store compressed air in a below-ground storage chamber. When needed, the compressed air can be released through a combustion chamber, acquiring enough heat energy to drive an expansion turbine. As of this writing, only two CAES plants have been completed and placed in operation, but several additional projects have been funded and are underway. Figure 1 on the next page shows a functional diagram of a typical CAES plant.

The obvious limitation of the CAES technology is that it requires a nearby empty salt dome, aquifer or abandoned mine for compressed-air storage. Furthermore, the system is not self-contained, as it depends upon a pipeline to supply natural gas for the combustion chamber. For these and other reasons, CAES has only been attempted on utility-scale generating plants, typically over 100 MW.

In general, compressed air has great promise. The technology is mature and well documented. But compressed air alone did not meet enough of our team’s requirements for a new energy storage product.

Thermal Energy

Other participants in the “Vision” session favored thermal energy storage. By comparison to compressed air, thermal storage has excellent energy density – in fact, it has up to 3 times more joules/cubic foot than lead-acid batteries. Unfortunately direct thermoelectric conversion is not yet commercially attractive at UPS power levels. Approaches based on sensible (change of temperature) or latent (change of state) heat conversion are more practical in the near term.

Table 1 on the next page shows the relative strengths and weaknesses of batteries, flywheels, compressed air and thermal energy as applied individually.

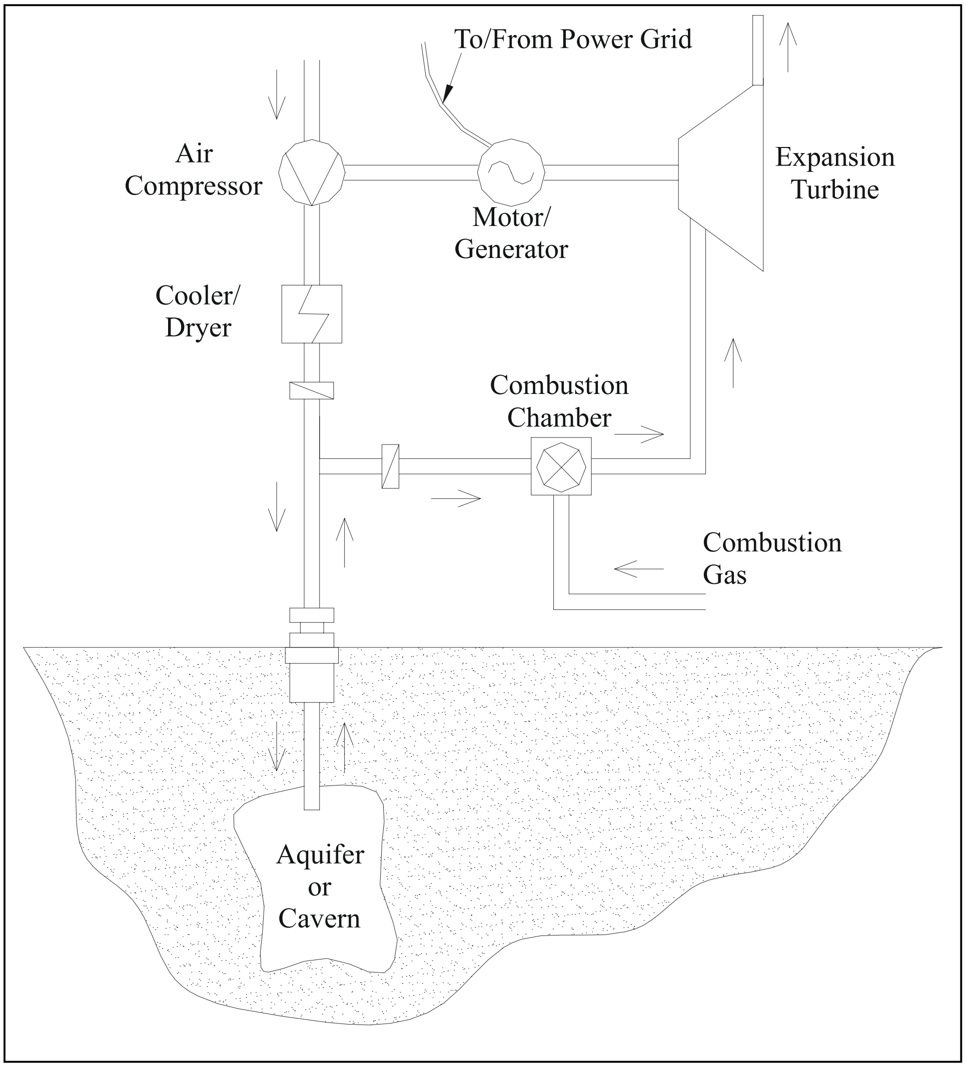

Figure 1. Compressed-Air Energy Storage (CAES)

Table 1. Energy Storage Technologies Compared

	Energy Storage Technology			
	Lead-Acid Batteries	**Flywheels**	**Compressed Air**	**Thermal Storage**
Power Density	Good	Very Good	Fair	Excellent
Energy Density	Very Good	Fair	Good	Excellent
Cycle Life	Fair	Excellent	Very Good	Very Good
Footprint	Good	Excellent	Fair	Excellent
Runtimes	Very Good	Fair	Good	Very Good
Recharge Time	Good	Excellent	Fair	Very Good
Dynamic Response	Very Good	Excellent	Poor	Poor
Maintenance Cost	Fair	Very Good	Good	Very Good
Ambient Temp Range	20-25°C	0-40°C	0-40°C	0-40°C
Life in UPS applications	3-12 years*	20 years	20 years	20 years
Environmental Impact	Toxic	Benign	Benign	Benign
Installed Cost	Low-to-Medium	Medium	TBD	TBD

* 3-5 years for VRLA, 8-12 years for flooded jars.

COMBINING ENERGY STORAGE TECHNOLOGIES

The breakthrough was deciding to take elements of both flywheel and CAES technology to create a self-contained energy storage system. Compressed air and thermal energy drive an expansion turbine for long-duration outages, while a small flywheel system gives instantaneous response to step loads and short outages.

Compressed-Air System

TACAS begins with compressed air stored in conventional gas cylinders or pressure vessels rather than underground caverns. In order to meet the system's performance targets, it is necessary to store compressed air at high pressures, ideally 4500 pounds per square inch (PSI) or more. These pressures are routine for Self-Contained Breathing Apparatus (SCBA) compressors and fill stations used by fire departments and diving operations. Gas cylinders rated up to 6000 PSI are widely available throughout the world.

Thermal Storage Unit (TSU)

The heart of TACAS is a self-contained Thermal Storage Unit (TSU), to eliminate the need for an outside source of combustible gas. After some discussion, our project team decided to use a stainless steel core with internal passages to transfer heat to the compressed air. Standard cartridge-type electric resistance heaters were selected to maintain the core at a temperature of approximately 1300° F.

Flywheel Energy Storage

All commercially available flywheel systems have various types of performance-enhancing technologies, including vacuum pumps (to minimize spinning friction), magnetic bearings (to levitate the wheel), integrated flywheel/motor generator devices (for compactness), etc. But for the new hybrid product, cost and manufacturability were paramount. The resulting all-new flywheel design is a model of austerity: no vacuum pump, no magnetic bearings, no carbon-fiber composites and no integrated flywheel/motor generator. The wheel spins in air and is designed to supply up to 4 seconds of backup power at full load.

Expansion Turbine

The heated compressed air is used to spin a single-stage expansion turbine. A conventional turbine engine has three stages: a compression stage for pressurizing incoming air; an ignition stage, where the fuel and compressed air are injected into a combustion chamber and ignited; and an expansion stage, where the expanding exhaust gas drives the turbine blades connected to the output shaft of the engine. Since the new hybrid product stores compressed air in gas cylinders and heats the air in the TSU, only the third stage of the turbine (the expansion stage) is required. This device is extremely simple and compact. The turbine has one moving part (the turbine wheel) directly connected to the input shaft of the alternator. The low inertia enables the turbine/alternator assembly to reach full operating speed (70,000 rpm) in approximately one second.

The Complete TACAS System

Figure 2 (next page) shows a block diagram of TACAS. In normal operation with utility power available to the attached UPS, the TACAS TSU is maintained at full operating temperature and the compressed-air cylinders are kept fully charged. The flywheel system is continually online with the DC bus of the UPS, supplying power for step loads and for very short outages (up to 4 seconds in duration).

For an actual discharge event, TACAS activates the control valves and sends compressed air through the TSU and into the expansion turbine. The turbine and attached alternator reach operating speed and assume the load in approximately one second. During the discharge event, the flywheel system remains connected to the DC bus, as a buffer between the UPS and the rest of the TACAS power train. It supplies short-term step loads and also absorbs energy during step-unloading events. A portion of the turbine/alternator output is directed to the flywheel system, to maintain the rotational speed of the flywheel at a predetermined level.

When normal input power is restored to the UPS, the TACAS system recharges itself. The total time required to regain full readiness is proportional to the discharge time. The flywheel regains full speed in a few seconds. The TSU heaters switch on, and can usually restore the TSU to full temperature within a couple of hours. Likewise the air compressor begins recharging the air cylinders. Compressing the air is generally the slowest of the three processes, depending on the size of the compressor and the number of air cylinders involved. Unlike batteries – which cannot support full load until they have a minimum period of period of recharge – the TACAS product recharges linearly, and it will provide some measure of backup energy almost from the beginning of the recharge cycle.

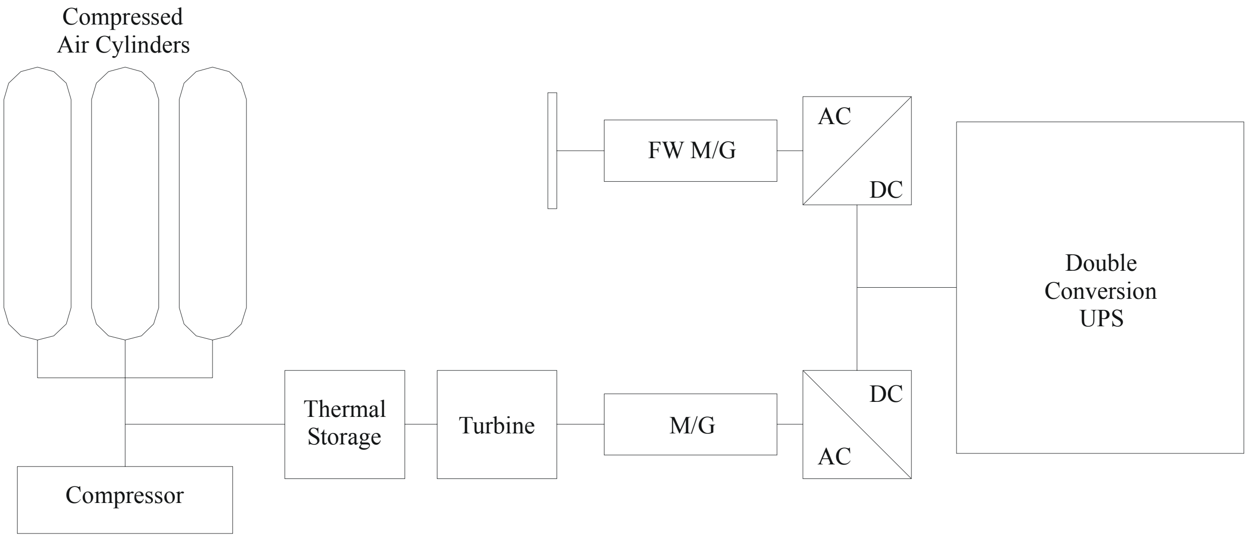

Figure 2: Thermal and Compressed-Air Storage (TACAS) Diagram

Table 2 shows how the new combined system compares to lead-acid batteries and flywheels.

As you can see, each energy storage technology in TACAS brings a different set of strengths to the system, compensating for the limitations of the other technologies. The flywheel provides instant dynamic response and excellent durability in heavy cycling service. The thermal and compressed-air storage together provide the longer runtimes that flywheels lack. The fast-recharge times of the flywheel and the Thermal Storage Unit help compensate for the slower recharge time of the air tanks. All three technologies are environmentally benign and capable of providing 20 years of service with normal maintenance.

Table 2: TACAS vs Batteries and Flywheels

	Energy Storage Technology		
	Lead-Acid Batteries	**Flywheels**	**TACAS**
Power Density	Good	Excellent	Good
Energy Density	Very Good	Fair	Very Good
Cycle Life	Fair	Excellent	Excellent
Footprint	Good	Excellent	Good
Runtimes	Very Good	Fair	Very Good
Recharge Time	Good	Excellent	Good
Dynamic Response	Very Good	Excellent	Excellent
Maintenance Cost	Fair	Very Good	Very Good
Ambient Temp Range	20-25°C	0-40°C	0-40°C
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Environmental Impact	Toxic	Benign	Benign
Installed Cost	Low-Medium	Medium	Medium

3-5 years for VRLA, 8-12 years for flooded jars.

One surprising fact is that most of the system's stored energy is in the TSU. The flywheel and compressed air combined provide less than half of the stored energy. The compressed air is primarily a vehicle for transporting the heat energy to the expansion turbine. But perhaps the most remarkable aspect of TACAS is that all three energy storage technologies are mature and well-proven. The only novelty is bringing them together into a commercially viable product.

TURNING CONCEPT INTO REALITY

The first task in testing the concept was creating the mathematical model to predict performance of the completed system. The development team's calculations showed that they could use many off-the-shelf products to build the first working TACAS model: standard compressed-air bottles, air compressor, process-control air valves, turbine, alternator, resistance heaters, etc.

The biggest design-from-scratch task was engineering the size, shape and internal flow route of the TSU. Another challenge would be developing a cost-optimized flywheel system – after a decade of development in which performance was more important than initial cost.

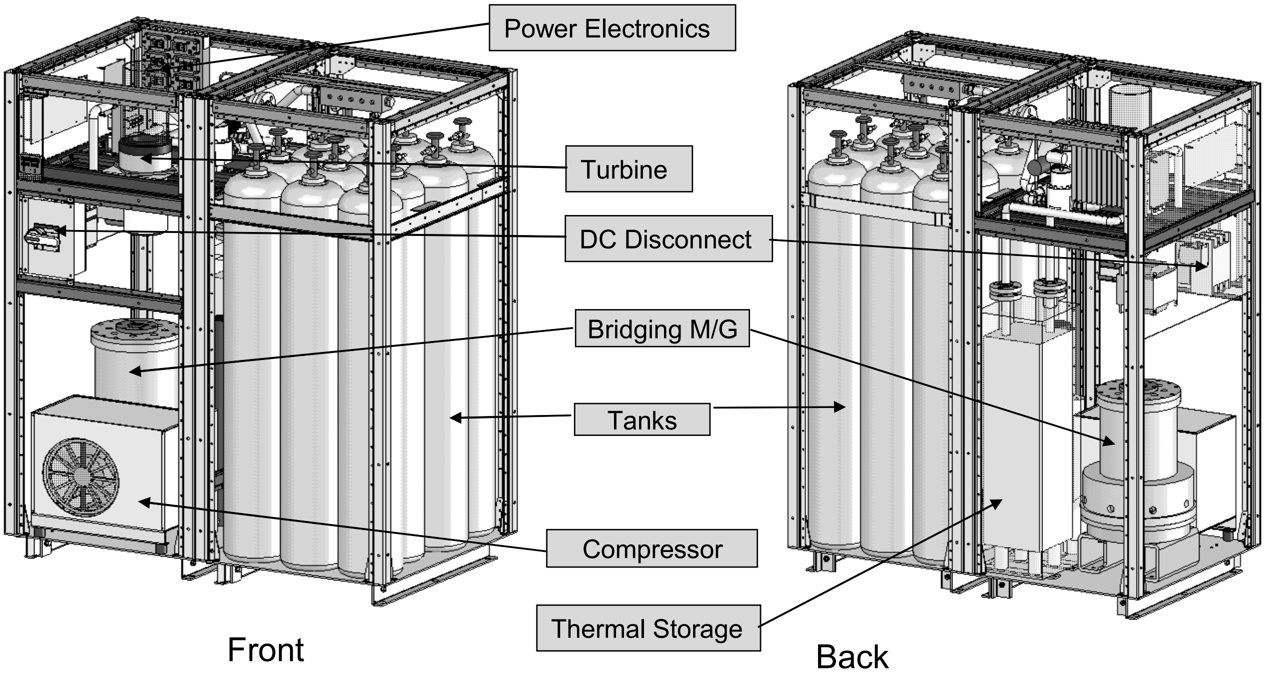
When the math was finished and the first working model assembled, there was no recognizable product in view except for the air tanks and compressor. The TSU was just a shiny metal cylinder and the turbine was housed in a nondescript enclosure. In between was an assortment of pipes, valves and wires.

Amazingly, everything worked as the math predicted. The first working model was able to sustain a load of 20 kilowatts for 15 minutes.

Early Product Development

The next challenge was identifying the types of customers who would benefit the most from the TACAS technology. As a general statement, UPS customers have more reliability issues with lead-acid batteries than their telecom counterparts. So the first TACAS products were designed as plug-compatible replacements for three-phase UPS battery cabinets. The target TACAS power output will be 85 kW, to support UPS systems rated up to 100 kVA/80 kW. Figure 3 below is an early conceptual drawing of how the components might be configured for UPS applications.

Figure 3: TACAS Component Layout



The first thing to notice about the initial TACAS product is that it's a two-box design. One box will contain the turbine, thermal storage unit (TSU), flywheel, compressor, DC disconnect and power electronics – elements that will determine the system's power (kW) rating. The other box (or boxes) will contain tanks for air storage, which will determine the amount of backup time (kW hours) the system can produce. Each tank cabinet can provide enough compressed air for 5-7 minutes of full-load operation. Two cabinets will have enough compressed air for 10-13 minutes. Adding a third cabinet will extend the backup time to 15-17 minutes. The standard TSU can maintain the airflow at optimum turbine inlet temperature (450° F) for approximately 15 minutes. If any compressed air remains after that time, the turbine will continue to operate but the efficiency will fall proportionately as the TSU temperature drops and the turbine inlet air gets cooler.

Initial Applications

The first TACAS products will function as battery replacements for three-phase UPS products in the 40-80kW range. In this power range, extended runtime (compared to flywheels) is an important design consideration since relatively few of these sites have backup generators. Compared to batteries, TACAS will offer the advantages of lower maintenance, better reliability, accurate runtime prediction, extensive internal monitoring, and the ability to provide backup cooling during discharge.

Figure 4. Prototype TACAS System, Front and Rear Views

The expectation is that TACAS will have installed cost and footprint approximately equal to that of flooded lead-acid batteries on racks. Unlike flooded batteries, TACAS will not require environmental conditioning, hydrogen ventilation, eyewash stations or spill containment. The early adopters will be facility managers who want the extra reliability and extended working lifetime of a flywheel system, but need the additional backup time provided by TACAS.

As with any technology, TACAS involves some tradeoffs:

- The compressor should be located nearby, in a location where the noise of refilling the air cylinders will not be an issue. Fortunately, complete discharges rarely occur more than twice per year at most locations, so compressor noise won't often become an issue.

- The compressor, with its noise, can be completely eliminated if the site can be serviced by a commercial gas supplier who would furnish filled tanks and bring empty tanks back for refilling.

- Air compression is the slowest process within TACAS. Larger compressors greatly reduce recharge time, but can cost more and create more ambient noise than smaller compressors.

- TACAS extracts heat energy from the compressed air stream, so the turbine outlet air temperature is typically cooler than room ambient air. This flow of cooling air, usually 55°F, is relatively modest at approximately 700 cubic feet per minute. This airflow is equivalent in temperature and volume to two perforated tiles in a raised-floor environment. Furthermore, the air cylinders become very cold during discharge events, so they could conceivably be used to extract heat from ambient room air. Initial TACAS products, however, will be limited to just the cooling provided by the turbine outlet air.

- Until building inspectors become more familiar with TACAS, the factory will need to help customers navigate their particular regulatory environments.

FUTURE APPLICATIONS

Since the TACAS technology was unveiled last September, we have received requests for TACAS variants in non-UPS applications. Telecom customers have asked for units with lower power (2-10 kW) and longer runtimes (4-12 hours) to power remote unattended sites. At the other extreme of the power spectrum, several electric utility companies have expressed interest in a megawatt-scale TACAS for load shifting.

The question is whether TACAS technology can be scaled to either power extreme and still remain within reach of commercial viability. The answer is “Yes” and “Maybe.” The next sections of this paper will explain the constraints of the technology and where development efforts are most likely to bear near-term benefits.

Telecom Remote Sites: 2-10 kW

The most-intriguing potential application is for remote telecom sites such as wireless base stations, wireline repeater sites, DLC terminals and optical regeneration sites. Most cell sites, for example, have a continuous load of 3-5 kW or less at either 24 or 48 volts DC. These sites are subjected to an extreme range of ambient temperatures, from cold mountain peaks to hot deserts. The extreme heat is especially damaging to conventional lead-acid batteries. In addition, regular preventive maintenance on remote sites is time-consuming and costly. Battery lifetimes can be extended significantly by air conditioning the battery enclosure. But air conditioning also increases the system's complexity, maintenance requirements, capital cost and operating costs.

The initial TACAS turbine/alternator has been tested extensively at a range of connected loads between 10 kW and 85 kW. Peak system efficiency is obtained with loads between 40 and 85 kW. With a connected load of 20 kW, an early development machine provided over two hours of backup with the standard turbine/alternator assembly and the standard TSU. This proved the concept that extended-runtime versions were feasible.

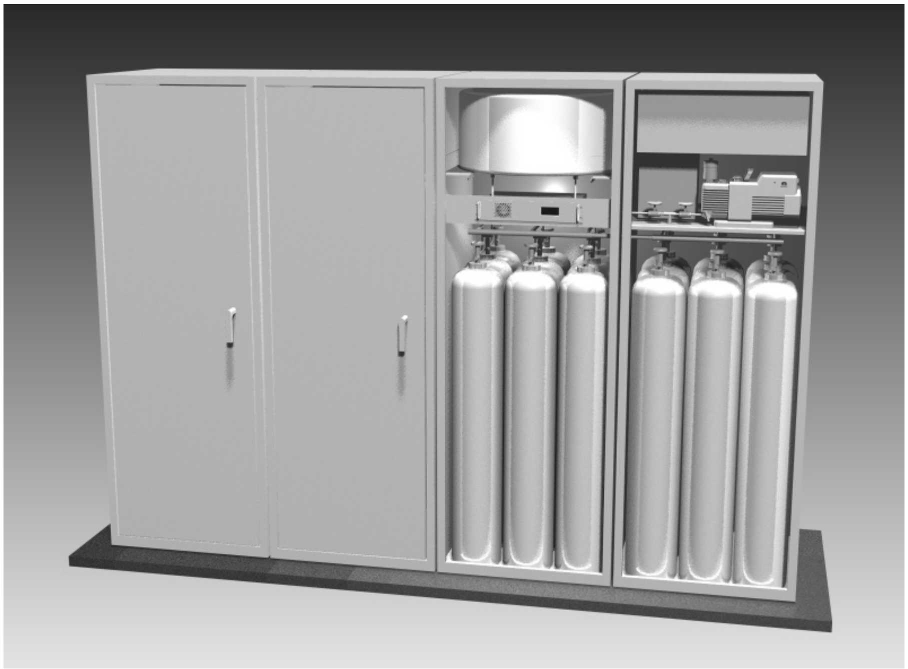
The biggest challenge will be designing a downsized turbine/alternator assembly that will have maximum volumetric efficiency at the lower power levels. This assembly could be approximately the size of a 12 ounce beverage can, and be packaged with the control and power electronics in a very small enclosure. The eventual size could be under four rack units of a 23-inch rack enclosure.

A key determinant of the future turbine design will be selecting the inlet and outlet temperatures for the stream of compressed air. Higher inlet temperatures mean that the TSU is providing proportionately more energy than the compressed air. This increases the physical size of the TSU by a significant amount, but the reduction in the number of compressed air tanks more than compensates for the larger TSU. Increasing the inlet temperature means a corresponding increase in the outlet temperature of air. For remote sites where the outlet air can be ducted outside the enclosure, this will not be an issue. If the customer has a need for some amount of backup cooling during TACAS discharge, the higher outlet temperature will be a disadvantage. From early discussions with telecom providers, the higher-inlet-temperature approach will be favored because of the overall reduced system footprint.

The second challenge will be cost-optimizing the TSU. The original-design steel TSU performs well at the low flow rates associated with telecom applications. But the price of steel has increased in recent months. Increasing the TSU size to allow relatively higher turbine inlet temperatures will have a definite effect on total system cost. The design team is exploring alternate materials and fabrication techniques that might neutralize the effect of raw material price increases.

Overall, the telecom application should be practical within a reasonable development cycle. Figure 5 below shows one possible configuration of a telecom TACAS system.

Figure 5. TACAS System for Remote Telecom



Utility Applications: Many Megawatts

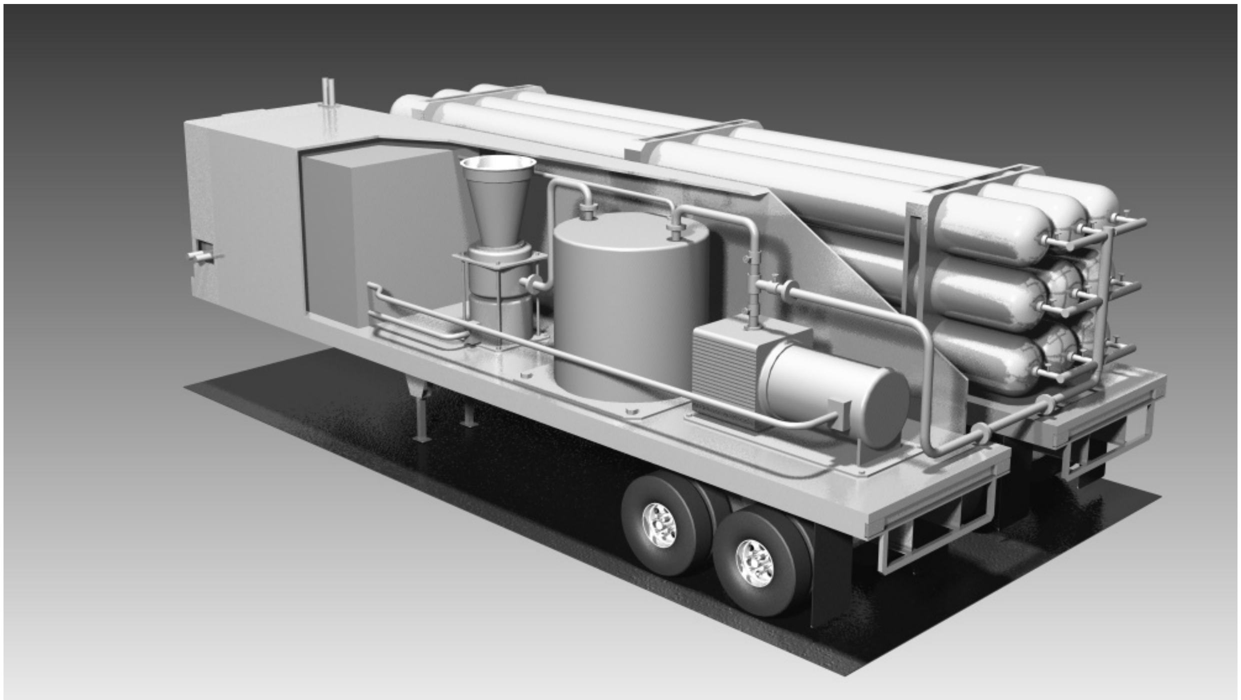
Many electric utility companies have requested a megawatt-scale TACAS product. There is increasing political pressure for utilities to purchase power from renewable energy sources like wind power and photovoltaics. The problem is the uncertain availability of those power sources, which fluctuate from minute to minute, hour to hour and day to day. The entire electrical power industry is challenged to find ways to store the output of these energy sources and make them available during peak usage periods; this process is called “load shifting.”

Our utility customers have asked about the feasibility of deploying groups of megawatt-scale TACAS units to absorb off-peak energy and keep it available for peak usage times. Their ideal system would be rated for 2-5 megawatts, provide up to four hours per day of power and be capable of recharging completely during the 12 hours of off-peak time.

One utility company engineer envisions these storage systems deployed at substations that have been identified as nearing capacity. They have already acknowledged the need to eventually upgrade these substations to meet peak demand during summer afternoons. However, they hope a system like TACAS could provide enough additional power so that upgrades could be postponed for a reasonable length of time. Other engineers would like to have mid-sized TACAS units deployed at major office and industrial buildings downtown. These units would be recharged by low-cost power at night and controlled by utility company dispatchers during the day. The dispatchers could remotely activate the TACAS units to essentially remove the buildings' load from the grid at peak load times.

The megawatt-scale TACAS will require more development time than the telecom TACAS. At the megawatt scale, the material cost of the TSU becomes a significant factor. Our design engineers have identified some alternative TSU materials and fabrication techniques, but it will take time to bring them to maturity. Another issue at the megawatt scale is the cost of the compressed air storage vessels. Existing commercial tube trailers could be used for early demonstration systems, but our design team intends to study lower-cost alternatives. Figure 6 shows a proposed system built with standard tube trailers.

Figure 6. Megawatt-Scale TACAS



DEVELOPMENT TIMETABLE

As of this writing, several prototype TACAS systems have been assembled for shipment to customers. These units are configured as battery cabinet replacements for 3-phase UPS products. Testing of these Alpha units is scheduled to run through the Spring of this year (2005). Additional customers are scheduled to receive Beta units in late Spring and early Summer. If test results are favorable, commercial manufacturing could begin as early as Thanksgiving or Christmas.

The telecom version of TACAS is following a parallel development track. Active Power intends to ship prototype units this Fall, with production beginning in the Spring of 2006. The larger-scale versions of TACAS is on a slower development schedule. The market for such a product is not as well defined as for telecom, and we need to do more materials research in order to meet our customers' price targets.

CONCLUSION

TACAS combines the durability and longevity of flywheels with the longer backup times of conventional batteries. TACAS is based upon several mature technologies, and should soon be a cost-effective alternative to batteries in specific UPS and telecom applications.

AUTHOR’S BIOGRAPHY

John Sears is Product Marketing Manager at Active Power. He has been a key member of the TACAS development team, in addition to his other power system marketing responsibilities. Before joining Active Power, John was Technical Marketing Manager for Liebert Corporation’s 3-phase UPS business. John’s 20 years of power systems experience also includes applications engineering and marketing for photovoltaic systems and switching power supplies.