Thermal and Compressed Air Storage (TACAS) Technology: The Road to Commercialization

John R. Sears (Active Power, Austin, Texas, U.S.A); jsears@activepower.com

Background

Active Power has developed a new combination of energy storage technologies called Thermal and Compressed Air Storage (TACAS). This product grew out of customer requests for a product that combined the battery-free benefits of flywheels with longer ride-through times. Our engineers investigated a wide range of candidate technologies before narrowing the field to two: compressed air and thermal energy storage.

Compressed air storage is safe, non-toxic and sufficiently energy-dense at high pressures. Round-trip efficiency is only fair due to heat rejection during compression (although some of this energy may be reclaimed by heat absorption during gas expansion). Likewise volumetric efficiency is less than optimum because of the physical size of the air storage tanks. Recharge times of large pressure vessels is also a disadvantage.

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	20-25°C	0-40°C	0-40°C	0-40°C
Life in UPS app.	3-12 years*	20 years	20 years	20 years
Environmental	Toxic	Benign	Benign	Benign
Installed Cost	Low-Medium	Medium	High	High

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

Learning from CAES

The electric utility companies have been researching a load-shifting technique called Compressed-Air Energy Storage (CAES). Low-cost off-peak power is used to store compressed air in a below-ground cavern or aquifer. During peak hours, the compressed air can be released through a combustion chamber, acquiring enough heat energy to drive an expansion turbine. As of mid-2005, only two CAES plants have been completed and placed in operation. However, several other CAES projects have been funded for near-term construction.

One obvious limitation of the CAES technology is that it requires an unused geologic formation 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 proposed for utility-scale generating plants, typically over 100 MW. Figure 1 (next page) illustrates the key system components and the flow of air through the CAES system.

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. A small flywheel system is continuously connected, to give instantaneous response to step loads and brief outages. For outages more than one second in duration, compressed air and thermal energy drive an expansion turbine. The resulting hybrid technology has been called Thermal and Compressed Air Storage (TACAS).

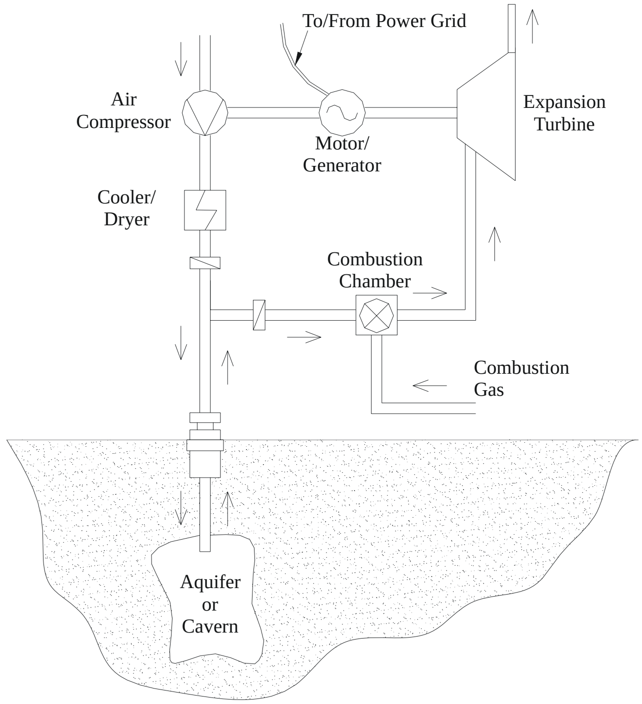

FIGURE 1: Compressed-Air Energy Storage (CAES)

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.

The Thermal Storage Unit (TSU) eliminates the need for an outside source of combustible gas. Our project team decided to use a stainless steel core with internal passages to transfer heat to the compressed air. Standard electric resistance heaters maintain the core at a temperature of approximately 1300° F.

The heated compressed air drives a single-stage expansion turbine. Conventional turbine engines have 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 can be extremely simple and compact. The low inertia enables it to reach full operating speed (70,000 rpm) in approximately one second.

The flywheel for this product is optimized for cost and manufacturability. It has 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 at least 3 seconds of backup power at full load.

The Complete TACAS System

Figure 2 shows a block diagram of TACAS. The 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 3 seconds in duration). When the systemTACAS detects a longer outage, it activates the control valves and sends compressed air through the thermal storage unit and into the expansion turbine. The turbine and attached alternator reach operating speed and assume the load in approximately one second.

The flywheel system remains connected to the DC bus, but now operates strictly as a buffer between the UPS and the other power train. It supplies short-term step loads and also absorbs energy during step-unloading events. The system controls direct a portion of the turbine/alternator output to the flywheel system, to raise the rotational speed of the flywheel to a predetermined level.

When normal input power is restored to the UPS, the TACAS system recharges itself. The flywheel regains full speed in a few seconds. The TSU heaters switch on, and begin restoring the TSU to full temperature. Likewise the air compressor begins recharging the air cylinders. The total time required to regain full readiness is proportional to the discharge time.

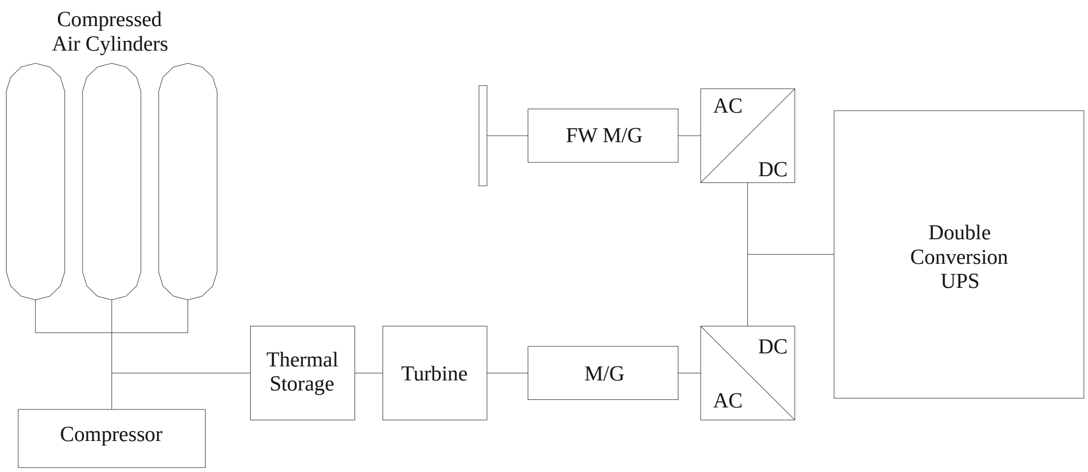

FIGURE 2: TACAS Block Diagram

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

TABLE 2: TACAS vs Batteries and Flywheels

	Lead-Acid Batteries	**Flywheels**	**TACAS**
Power Density	Good	Very Good	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	20-25°C	0-40°C	0-40°C
Life in UPS application	3-12 years*	20 years	20 years
Environmental Impact	Toxic	Benign	Benign
Installed Cost	Low-Medium	Medium	Medium

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

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. 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 to build a commercially viable product.

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.

TACAS for the UPS industry will be housed in two or more cabinets. The base cabinet will house the flywheel, TSU, controls, power converters and the turbine/alternator assembly. The other cabinet(s) will house compressed-air bottles and associated manifolds. Additional cabinets of compressed-air bottles may be added for extended runtime or for faster effective recharge times. Each cabinet of air tanks will give about 5 minutes of backup time at full load; three cabinets will provide enough compressed air to match the 15 minutes of full output that the TSU can support.

Figure 3 below shows how the components will be configured in the base cabinet.

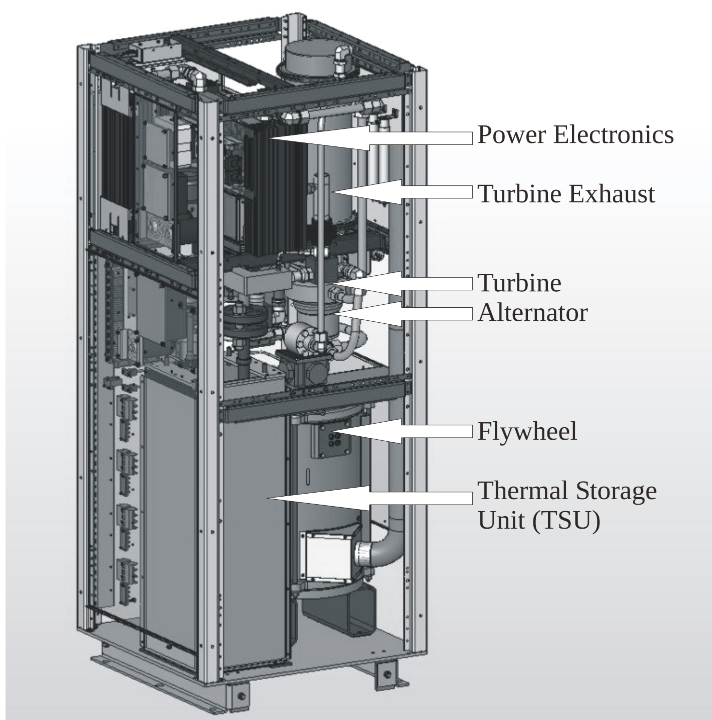

FIGURE 3: TACAS SYSTEM COMPONENTS (REAR VIEW)

Development Challenges: Heating or Cooling?

The expansion turbine efficiently extracts heat energy from the compressed air, and the outlet air temperature is directly related to the inlet temperature. Turbine inlet air temperature is controlled by a pair of control valves that blend heated air with cold air directly from the storage tanks. At the beginning of a discharge event, when the TSU is at maximum temperature, the valves will use proportionately less heated air and more unheated air. As the TSU cools off during the discharge, the valves compensate and use proportionately more flow through the TSU to maintain constant turbine inlet temperature.

Typical turbine inlet air is 450°F and produces outlet air at approximately 55°F. This outlet air temperature happens to be the target temperature of cooling air in data centers. TACAS airflow is about 700 cubic feet per minute (CFM) per TACAS unit at full load, so the cooling capacity of TACAS is roughly equivalent to the airflow from two conventional perforated floor tiles in a data center.

Some data center customers have requested an "extreme cooling" version of TACAS, with significantly lower turbine inlet and outlet air temperatures. To obtain the same power rating with less heat energy in the airstream, TACAS will need proportionately more compressed air. This will grow the footprint and cost of the compressed air cylinders. Active Power is planning to build some prototype equipment in 2006 to determine the exact performance and cost tradeoffs involved.

On the other hand, those customers who have the TACAS unit in an equipment room remote from the critical load will not be concerned about the outlet air temperature. In fact, the customer might gain a small amount of additional backup time for a given amount of compressed air by specifying higher turbine inlet and outlet temperatures. Another small boost in backup time might be gained by ducting warmer outlet air back over the compressed air tanks, which get extremely cold during a discharge event. The warmer exit air would actually transfer a small amount of heat energy into the air tanks.

TACAS for Telecom and Load-Shifting Applications

The TACAS design team initially concentrated on UPS applications because that was the area of greatest familiarity. Once initial prototypes were built and operating successfully, Active Power began discussions with the major telecom providers to see how the TACAS technology could be applied to their remote power needs. Every potential customer had a different set of priorities, but some consistent patterns emerged:

- Power levels were significantly lower than for UPS customers. Applications such as wireline repeaters might consume less than a kilowatt of power. Certain configurations of mobile telephone repeaters required about three kilowatts, while other configurations required ten kilowatts.
- Telecom customers expect significantly longer backup times. The UPS industry expects 5 to 15 minutes of backup, while the telecom industry expects anywhere from 2 to 8 hours.
- Depending on the manufacturer of the equipment, the telecom sites required backup power systems to be either 24 or 48 VDC nominal.
- Some sites were owned by the telecom carrier and could be visited and serviced at the carrier's convenience. These sites were candidates for having service trucks either deliver filled tanks or refill the tanks from a truck-borne compressor/reservoir. Other sites were leased from third parties and had relatively limited access. These sites need to be self-contained and have air compressors on premises to refill air tanks.

The telecom configuration appears to be mostly air tanks, at first glance. The turbine, alternator and power electronics will shrink significantly. The flywheel will completely disappear and be replaced by ultracapacitors. Eliminating the flywheel makes the system completely passive in the standby mode, which will have several benefits: fewer moving parts, less periodic maintenance and lower ambient noise.

The Thermal Storage Unit will not shrink in the telecom product. In fact, the long backup times requested by some carriers would push us to use even more thermal storage than the UPS configurations.

At the other end of the power spectrum, we have been asked to study megawatt-scale versions of TACAS for possible load-shifting applications. This would be especially attractive in Texas where we have ample supplies of wind power – at night. It would seem that conventional CAES plants at the wind farms would be the lowest-cost way to provide bulk energy storage for wind farms. Nevertheless, there are advantages to having self-contained storage devices near to the points of use, which could absorb off-peak energy from all sources and make it available in areas of greatest peak needs.

Figure 4 below shows how TACAS might be packaged for telecom or load-shifting customers:

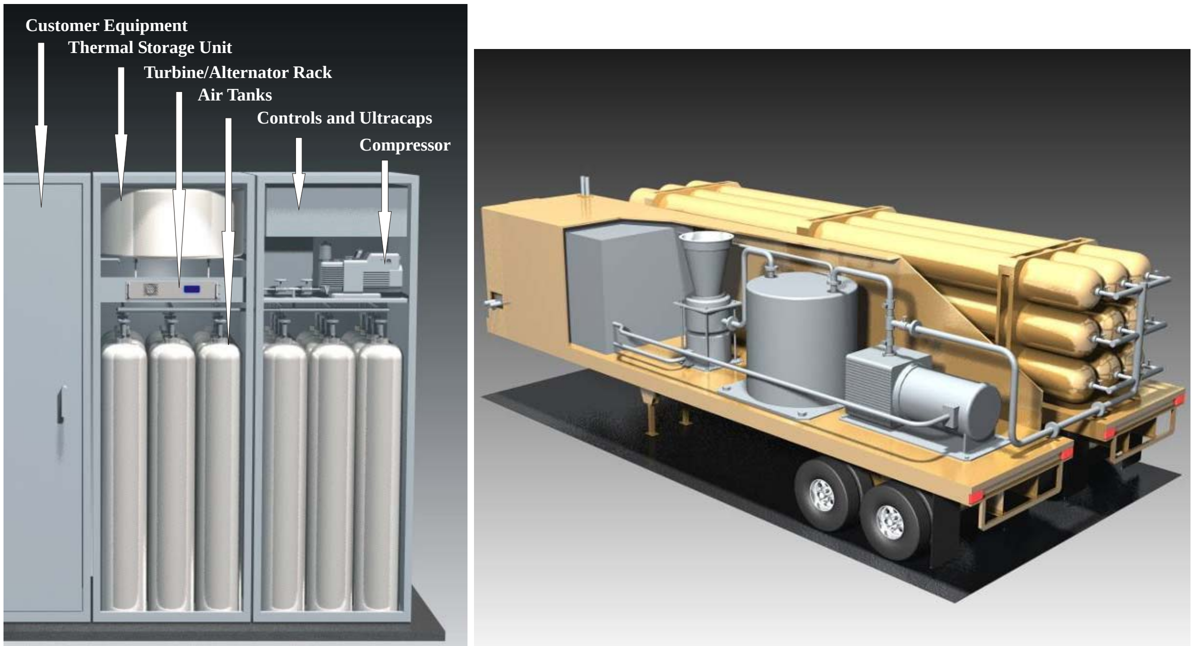

FIGURE 4: TACAS For Remote Telecom (left) and Load-Shifting Applications

Development Timetable

Prototype units for UPS applications began shipping to selected customer sites in December 2004. A total of six test systems are expected to ship by December 2005. To date, the prototype units have performed as expected and given our engineers valuable insights for future development projects.

In the fall of 2005, Active Power began Design Verification Testing (DVT) of the TACAS product intended for UPS applications. Testing for FCC compliance and the UL listing will be completed in Q4 of 2005. Pilot manufacturing will begin late in Q4 of 2005, with full manufacturing scheduled to begin in January 2006.

Development of the lower-kW telecommunications product is following a more-cautious development timetable. Our engineers have done calculations and preliminary designs for several different telecom variants. However, they have decided to keep their primary focus on the UPS product until the core design has proven itself. Then they will commit the time and development resources to building prototypes for the telecom marketplace.

Likewise we are proceeding carefully on the megawatt-scale product. We have specific materials-research goals to achieve before the load-shifting product will be ready for market.